Biopolymers for 3D Printed Bone Structure

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Abstract

Bone substitute materials can replace damaged bone structures and significantly reduce the surgery and recovery times. Three-dimensional (3D) printing is a new rapid method to make these substitutes with exact shape and structure, based on actual individual bones medical measurement data. The goal of this work was to investigate the influence of the printing orientation on the smoothness and the percentage of void volume on the mechanical properties of biocompatible and biodegradable thermoplastic materials that can be applied for three-dimensional printing of human bone structure substitutes. Fused Deposition Modeling (FDM) is used to produce 3D printed shapes of bones created from DICOM images of CT and MRI scans.

Three samples of acrylonitrile butadiene styrene (ABS) were printed utilizing or having different number of layers. That is, one, two and three layers at a 45° (head angle) were printed. The angle is related to the direction of the printing, which is controlled automatically by MakerWare software of the 3D printer itself, without any external control from the operator or technician. Thickness and roughness for each sample were subsequently measured. One sample of polylactic acid (PLA) was printed with one layer at 45° and its thickness and roughness were measured. Two other samples of ABS, having one and two layers, were printed at 90° then thickness and smoothness were measured. Polyvinyl alcohol (PVA) was printed with one layer at 45° and 90°. Thickness and roughness of printed 3D samples were measured using a White Light Interferometer.

Introduction

Three–dimensional Printing

Three-dimensional printing is a new technology that creates 3D items using a wide range of materials. This technology is also called rapid prototyping, because it is a programmed process where 3D items are rapidly made. A 3D model can be scaled and sized according to the desired shape from 3D printer software. 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 [1].

Biomaterials

The study of biomaterials for bone replacement has progressed significantly over many years [2]. 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 the 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 [3]. We are studying and testing several biocompatible and biodegradable materials to print bone structures using the Fused Deposition Modeling technique. In this project, we will optimize the inside bone building structure through modifying the printing process. Some of thermoplastics have been tested so far are Acrylonitrile butadiene styrene (ABS), Polyvinyl Alcohol (PVA), Polycarbonate and Polylactic Acid (PLA).

Bioprinting

Three-dimensional printing can improve medical care in some processes, and it will 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. 3D printing refers to only such technologies that use constructive manufacturing ways. 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 modeled and built for further application in a few hours, even inside medical facilities. Several processes can be only accomplished with use of a 3D printer.

Biofabrication is a process that doctors conventionally do by hand, or ask specialized companies to produce. However, they can now be more successfully accomplished by using 3D printing technologies [4].

Fused Deposition Modeling

Fused Deposition Modeling (FDM) is chosen to make 3D printed items from thermoplastics, because it enables high precision when working with many biocompatible polymers. During the printing process, a plastic filament is heated until it reaches the melting point. Then the extruder drives the molten plastic through the extrusion nozzle and puts it on the plate to build an object layer by layer. First, a 3D model is created by using special software, and then the model is converted to Stereo Lithography (STL) format to produce a 3D printed object. This format simply maintains the shape of the 3D model and modifies its geometry including scaling and quality [5].

Once the STL file is imported to the FDM software, it is sliced into multiple parallel thin slices that become layers prepared for 3D printing. These slices represent 2D profiles that the FDM process will produce, which, when stacked on top of each other, will be built into the 3D object that matches the original design. Thinner layers enable higher precision for objects to be printed [6]. FDM mechanism works as shown in Figure 1.

Motors move the head on the X-Y plane to structure a specific shape of the layer and the extrusion nozzle puts down the material in accordance with the sliced information taken from the STL file. Once the layer is produced, the plate moves vertically in the z direction to start building a new layer on the top of the previous. The process keeps repeating until the entire object is totally built [6].

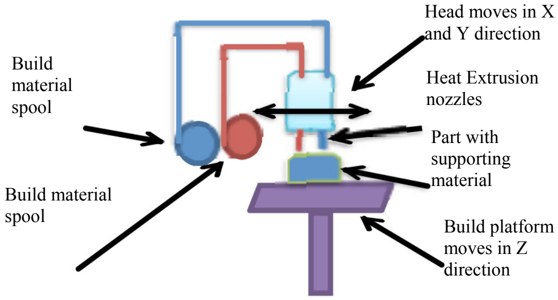

Figure 1. *Fused Deposition Modeling Schematic.*

Methodology

3D printing of test samples

Using 3D printing technology, three different samples of thermoplastic materials were printed. These were ABS (Acrylonitrile-Butadiene-Styrene, manufacturer), PVA (Polyvinyl Alcohol, manufacturer) and PLA (Polylactic Acid, manufacturer). Some of the mechanical properties and melting points of these thermoplastic materials are shown in Table 1 [7-9].

Table1. Mechanical properties of thermoplastic materials.

Material	Tensile [MPa]	Elongation [%]	Melting Point [C°]
ABS	42.5-44.8	25	100*
PVA	65-120	3	191-224
PLA	70	3.8	170

*Melting temperature equals the glass transition temperature (Tg), for ABS, since this material cannot be crystalized.

Solid Works software was used to design and make specific sample files [10]. These files were then converted to STL format for 3D printing. Figure 2 shows PLA specimen after printing at 45° print head orientation.

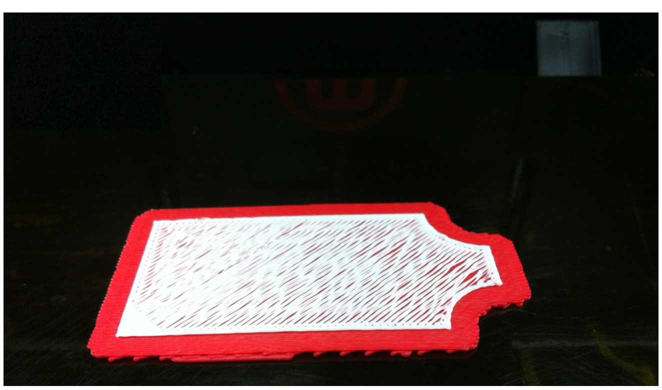

Figure 2. *3D Printed specimen one layer of PLA at 45°.*

After printing a white light interferometer was employed to measure the roughness and thickness of each sample. The surface topography was measured for ABS tensile test specimen before and after the samples being tested to check how the tensile strength test affects surface topography. For testing the tensile strength standard specific dimensions, test specimen was printed by using CAD software, the model was converted to STL format to be printed by an FDM 3D printer (MakerBot Replicator 2x).

Figure 3 shows the test sample after it was imported from the STL data file to the Makerware software. 3D printing operation process parameters can be controlled and adjusted according to the mechanical properties of the material. These parameters are melting temperature, extruding speed, resolution, infill percentage (100 – void percentage), build plate temperature, etc.

Table2. Conditions of the thermoplastic polymers printing.

Polymer	Extruding Temperature [C°]	Extruding Speed [mm/s]	Infill [%]	Resolution
ABS	230	90	100	High
PVA	230	90	100	High
PLA	220	90	100	High

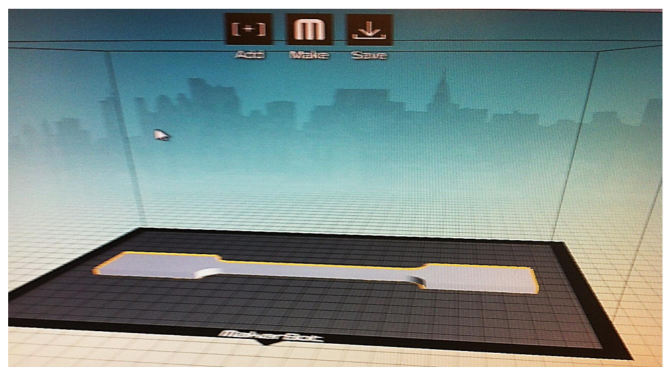

Figure 3. *Specimen imported by Makerware software to be printed.*

After importing of the 3D model and setting the parameters, the test sample was printed automatically by the FDM machine. Figure 4 shows the MakerBot in the process of printing the tensile test sample. The next step is building and printing bone structures.

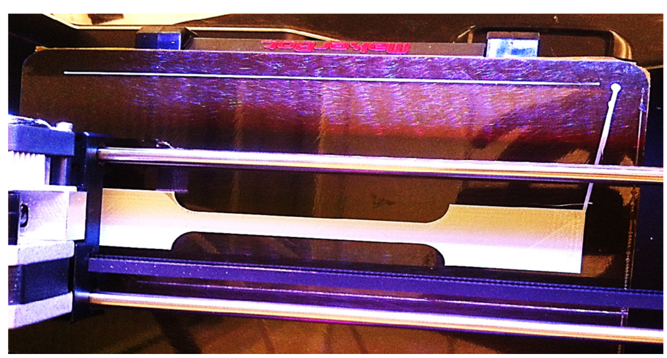

Figure 4. *3D Printing of the tensile test sample.*

Creating 3D Bone Structure Model

To enable the printing of actual bone structures, models need to be made from authentic human body scans. 3D models of genuine bone structures are built from CT and MRI scan DICOM medical images. Magnetic Resonance Imaging (MRI), CT (Computerized Tomography), DICOM (Digital Imaging and Communications in Medicine) and Ultrasounds scans are methods used in radiology for medical procedures. The same DICOM images, used by doctors in their medical practice to build 3D models of bone structures were employed. Since DICOM images are only two dimensional images, slices of a 3D body, "3D Slicer" software was engaged to create high quality 3D models.

Several software applications were applied to create the 3D models, one of these being "3D Slicer", open source software that is widely used in the medical field [11]. 3D Slicer allows doctors and biomedical researchers to focus on applications, such as data communication, visualization and analysis. 3D Slicer is open source that is being constantly upgraded and optimized by the actual users providing important feedback. 3D slicer provides a common set of base functionality to assist progress and support of medical image computing techniques, simplifies the doctors work and does not require users to understand or modify complicated computational algorithms [12]. To create a model using 3D Slicer, there are several steps that need to be performed. The first step is to load CT scan data as shown from Figure 5.

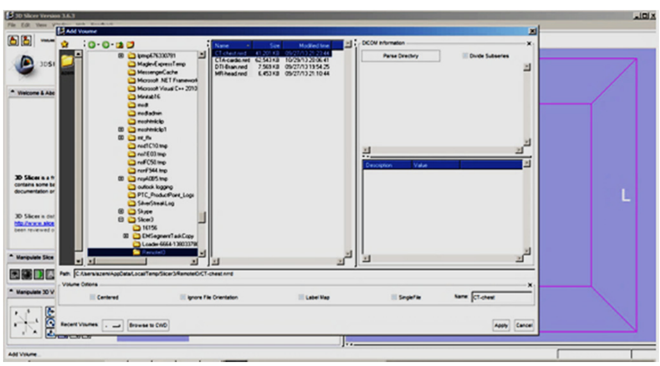

Figure 5. *Data loading in 3D Slicer [11].*

After the images are loaded, the Region of Interest (ROI) is determined on each image and then segmentation is performed on the organ, in our case bone structure. Figure 6 shows three cross slices of a chest image (3 planes) used to determine ROI and segmentation to make the 3D model.

Further, segmentation through all images on each slice is produced within the ROI by thresholds. When the segmentation is finished on all the slices, a volumization is performed to produce a 3D shape. The 3D slicer software can visualize the 3D model (Figure 7). The user can then modify the 3D bounding box, rotate and export the model to several 3D formats.

After the model is created, it is exported to STL format to be visualized, simulated and finally printed by the 3D printer. The mechanical properties of the samples were tested, once they are printed, by using a tensile test machine or special equipment built for this purpose. The tensile test of the samples was measured by a tensile test machine, MTS system, at ambient temperature 20 Cº. The results of this tests are reported elsewhere [13].

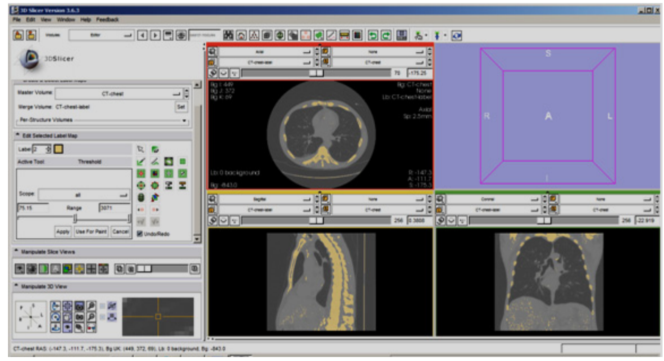

Figure 6. *ROI and segmentation in 3D slicer [11].*

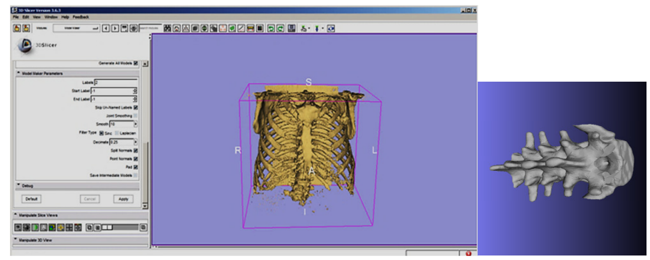

Figure 7. *3D models created after segmentation by 3D slicer [11].*

We printed a sample of bone structure designed with 3D Slicer from MRI and CT scan data to test the precision of the 3D printer (MakerBot) as shown in Figure 8.

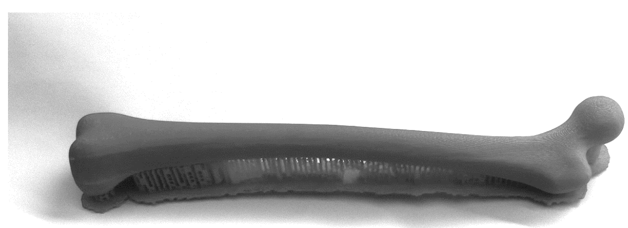

Figure 8. *3D printed bone femur structure [11].*

Results and Discussion

The FDM method to print three different thermoplastic samples ABS (Acrylonitrile-Butadiene-Styrene), PVA (Polyvinyl Alcohol), PLA (Polylactic Acid) was chosen. The samples were printed using two different print-head orientations 45° and 90° to better understand the influence of orientation on specimen roughness. Three different samples of ABS were printed with different number of layers: one, two or three layers at 45°. Also, one layer of both PLA and PVA were printed at 45° and measured. The thickness and roughness were measured each time and the results as shown in Table 3.

Table 3. Thickness and Roughness ABS, PLA and PVA printed in 1-3 layers, oriented at 45°.

Material	Thickness (μm)	Roughness (μm)
ABS1	42.9	7.4
ABS2	70.0	13.3
ABS3	118.1	18.4
PLA1	104.6	8.1
PVA1	76.8	5.7

The surface topography for ABS1, ABS2 and ABS3 prints are shown in Figures 9-11.

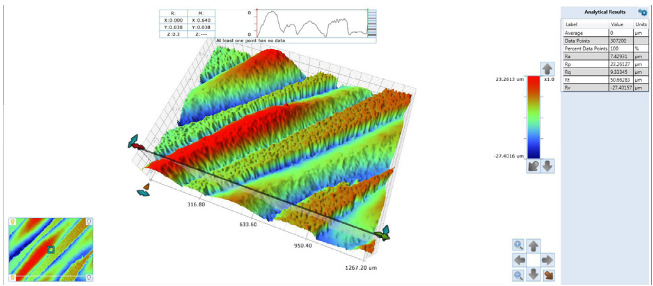

Figure 9. *Topographic map of first layer Abs1.*

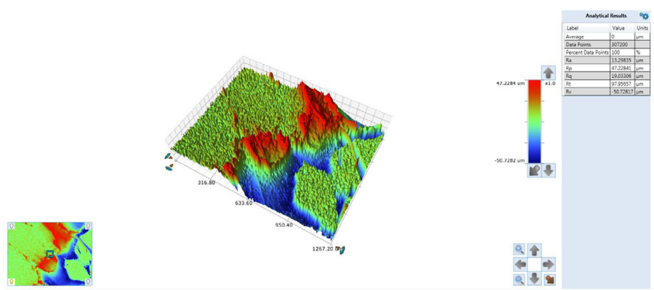

Figure 10*. Topographic map of second layer ABS2.*

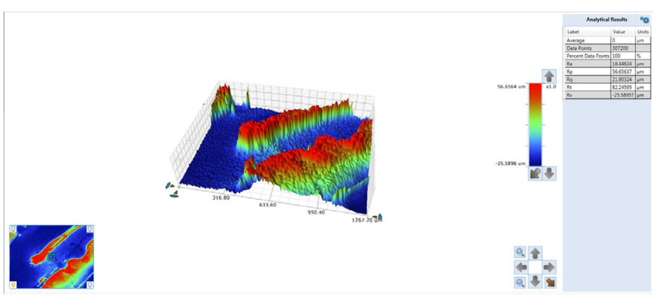

Figure 11*. Topographic map of third layer ABS3.*

Figures 9-11 clearly show that these printed surfaces display both macro roughness and micro roughness. The macro roughness clearly corresponds the spacing between lines of print (see Figure 2). This results since the ABS hardens on the support plate before it can level. This is because the support plate is held at 100 ° C, which is the Tg of ABS.

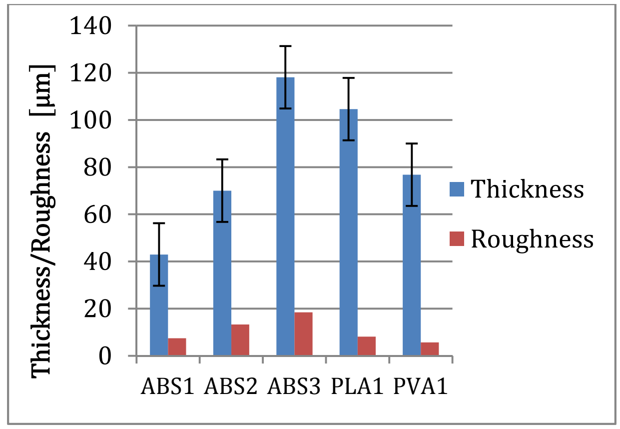

Figure 12. *Thickness and Roughness for ABS, PLA and PVA 1-3 layers printed at 45°.*

Two samples of ABS with one and two layers were printed at 90° and PVA with one layer was printed also at 90°. The results are shown in Table 4.

Table 4. Thickness and Roughness ABS and PVA oriented at 90°.

Material	Thickness (μm)	Roughness (μm)
ABS1	76.78	3.74
ABS2	86.96	10.35
PVA1	61.23	3.01

Note that ABS printed a 90° is both thicker and smoother than at 45°. This is expected since more material is deposited when printed along raster lines in 2 dimensions. The second layer at 90° is also thicker and smoother than at 45°. However, it is much less than twice the thickness of the first layer, indicating that the second layer fills in between the previous lines.

On the other hand, the first layer of PVA is thinner than at 45°, but still smoother. This may be due to better leveling of the PVA, since its Tg is 85°C [9]. What is clear is that for FDM to succeed at producing uniform smooth layers is an annealing step (raising the temperature of the build platform following initial deposition.

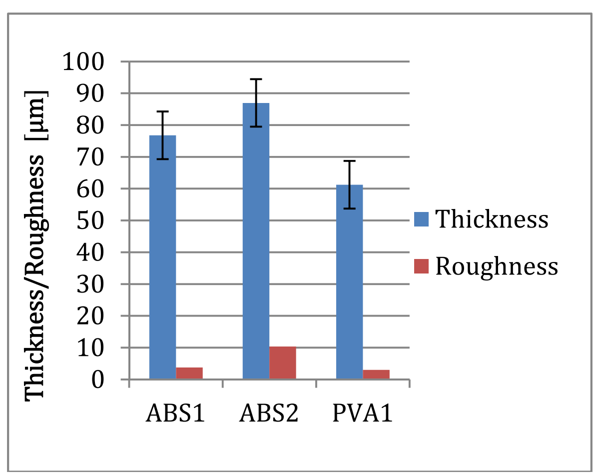

Figure 13. *Thickness and Roughness for ABS (1 or 2 layers) and PVA layers printed at 90°.*

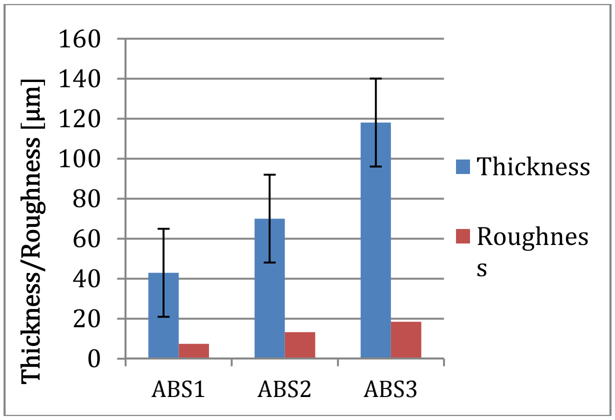

Figure 14. *ABS thickness and roughness with 1,2 and 3 layers printed at 45° orientation of print head*

From Figures 9-14 and Tables 3 and 4, it is obvious that the 90° creates smoother specimen surfaces than the 45° orientation. From Table 3, it may also be seen that for ABS material, increasing the thickness also increases the roughness at 45°. At the thickness of 42.96 µm, the roughness was 7.43 µm. For the two layers of ABS the thickness is 70.03 µm and the roughness is 13.3 µm. Finally, when printing three layers the thickness became 118.1 µm with a roughness of 18.45 µm (Table 3). To achieve higher smoothness, higher platform temperature may be necessary, or annealing may be needed. Figure 14 shows ABS and the relation between thickness and roughness for layered samples when the material was printed at different levels of thickness, one two and three layers consecutively, printed at 45°head orientation.

The standard deviations of thickness for ABS1, ABS2 and ABS3 (Fig.12-14) is quite similar, which may show that the layer structure eventually conforms after certain amount of layers. The difference in standard deviation was not significant among the different materials (ABS, PLA, PVA), which points out that difference is due to printer rather than due to the material being printed.

Conclusion

ABS, PLA and PVA were printed by using the fused deposition modeling (FDM) method. ABS was printed at 45° with different levels of thickness applying one, two or three layers. Roughness and thickness of the samples were measured each time by using a White Light Interferometer. One layer of PLA was printed at 45° and both thickness and roughness were measured. Two other samples of ABS were printed with one and two layers at 90°. Two samples one layer each of PVA were printed at 45° and 90°. Then both roughness and thickness were measured using the White Light Interferometer. The results show that the roughness of ABS at 45° increased with increasing thickness. In addition, the results show that the samples that printed at 90° were smoother than 45°, which means the orientation had a significant influence on roughness, but little on thickness. Additional studies are needed to target more realistic and smoother structures for bone replacement. Later, bones created according to actual CT and MRI scans will be printed and tested to loads experienced by humans.

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Author Biography

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