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Polymers for 3D Printed Structures, Precision, Topography and Roughness

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ABSTRACT

Three-dimensional (3D) printing is a new rapid additive method to make 3D objects with exact shapes and structures. 3D printing is being used for a variety of applications, including automotive, medical, dental, aerospace, consumer goods, toys, novelty items, embedded electronics and appliances. The goal of this work was to investigate the smoothness, precision and topography of plastic materials that can be used for three-dimensional printing applications. These three performance characteristics are crucial to performance of any 3D printed product. Fused Deposition Modeling (FDM) and PolyJet™ technology were used to produce 3D printed shapes for testing these performance measures for the different processes.

Three samples of acrylonitrile butadiene styrene (ABS) were printed utilizing different numbers of layers. That is, one, two and three layers at a 45º (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 45º and its thickness and roughness were also measured. Two other samples of ABS, having one and two layers, were printed at 90º then thickness and smoothness were measured. Polyvinyl alcohol (PVA) was printed with one layer at 45° and 90º. Digital ABS™ was printed at 6 different layer thicknesses. Thickness and roughness of printed 3D samples were measured using a White Light Interferometer.

The results show that the roughness of ABS at 45° and 90° increased with increasing thickness. The samples printed at 90° were smoother than at 45°, which means the orientation had a significant influence on roughness, but little on thickness. We found that the minimum thickness that MakerBot can reach is 50 µm, while with Flash Forge it is 80 µm. The samples that were printed by Stratasys 500 Objet Connex3 were smoother than those printed by Maker Bot replicator 2X and Flash Forge Creator Pro. Also, Stratasys 500 Objet Connex3 is more precise than either and it can reach thinner levels than either of them. However, the highest performance printer does not produce sufficient precision and smoothness for most 3D printing applications.

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 the 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 are 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, consumer goods, embedded electronics, toys, novelty items, appliances, dental and medical applications [1-4].

Materials

The study of biomaterials for tissue engineering has progressed significantly over the past few years [5,6]. 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 [6].Materials that will be 3D printed depend on application. The materials for medical and dental applications need to be biocompatible or biodegradable [5,6]. For the other applications strength and thermal stability are important. However, for all applications smoothness, precision and topography are the most important performance characteristics, which is the aim of current study. We tested several 3D printable materials to print structures using Fused Deposition Modeling (FDM) [7] and PolyJet™ [8] technology, such as acrylonitrile butadiene styrene (ABS), polyvinyl alcohol (PVA), polylactic acid (PLA) and Digital ABS™.PVA and PLA are biocompatible polymers, while ABS and digital ABS™ are not biocompatible.

Bioprinting

Three-dimensional printing can improve medical and dental care in some processes, and it will also open new opportunities for tissue engineering. 3D models are produced through constructive processes. 3D printing refers to only such technologies that use constructive manufacturing ways. It 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. Bio fabrication 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 [9].

Fused Deposition Modeling

Fused Deposition Modeling (FDM) is chosen as a method to make 3D printed items from thermoplastics, because it enables working with many 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 a plate to build an object layer by layer. First, a 3D model is created by using CAD software (e.g. Solid Works), 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 [7].

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 [10]. The 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 downward (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 [10].

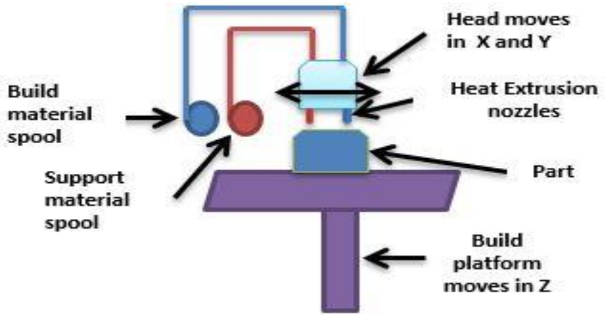

Figure 1. Fused Deposition Modeling Schematic.

PolyJet Photo polymerization

The Poly Jet printer is manufactured by Stratasys [8] and its working mechanism is based ona UV cured inkjet printer that uses Ricoh inkjet heads [11]. Generally, it jets layers of curable liquid onto a build plate instead of jetting drops of ink onto paper. The build platform moves vertically downward to leave a space for the following layers. The layers gather on the build platform to produce the desired part. The process can produce smooth, exact parts with a nominal layer resolution of 16µm. Also, it can produce thin walls and complex geometric shapes with many materials. To avoid deflection due to movement by the printing mechanism and to allow the printing of complex objects, 3D printers need support structures. The software of the printer automatically adds supports through the printing process. PolyJet printers use support resin structures that can be removed easily by flushing with water [12].

Osseo integration

For medical and dental applications, it is necessary to consider osseointegration [13]. Osseo integration is the contact between living tissue and implant. The implant is considered osseointegrated when there is no movement in progress between the implant and the local environment [13]. There are several factors that can improve osseointegration, such as: implant design, chemical composition, implant surface topography, material, shape, length, and diameter, surface treatment of the implant, coatings, the mechanical stability and loading conditions applied on the implant. On the other hand, there are other factors that inhibit osseointegration and they include excessive implant mobility, inappropriate porosity of the porous coating of the implant, radiation therapy, and pharmacological agents [13].

The implant surface properties have an impact on the body’s response. For instance, the composition is a significant issue for cell attachment. The hydrophilic surfaces like the interactions with cells and biological fluids, unlike the hydrophobic ones, and hydrophilicity is influenced by the chemical composition of the surface [14]. To enhance the biological surface properties that favor the mechanism of osseointegration, many methods of surface treatments have been studied and applied [14]. The purpose of these is to improve osseointegration mechanism with quicker development, and provide good stability through the healing process. Enhancing the implant with surface modifications can enhance the clinical performance and speed up the healing process [14]. The surface properties of biomaterials are important to the response of cells at biomaterial interfaces, influencing the quality and the progress of newly shaped tissue.The smoothness degree is a significant issue and implants can have smooth or rough surfaces. In vitro studies have found that osteoblastic cells attach, spread and increase faster on smooth surfaces than on rough ones [14]. The biocompatibility of implants has a significant role with the physiological environment in which they are placed. Osseointegration delivers a steady implant connection that is able to support prosthesis and transfer applied loads with no stresses between the environment and the implant [15].

Surface Topography

For all 3D printed applications, surface topography of the resulting object can control its surface quality. The chemical, physical, mechanical and topographical properties of the surface are related to the surface quality. The property of surface quality is significant for product effectiveness. Additional significant factors are the material, design and loading conditions of the product. Unlike properties work together, such as change in surface topography can cause a change in surface energy and surface chemical composition [16]. A real surface smoothness value does not exist. It differs, among other things, with the measuring equipment length scale [16]. A smooth surface is described as a surface with good reflective capacity, while a rough surface has poor reflective capacity [16].

Methodology

3D printing of test samples

Using 3D printing technology, three different samples of thermoplastic materials were printed. These were ABS (Acrylonitrile-Butadiene-Styrene, RTP Company), PVA (Polyvinyl Alcohol, Sekisui) and PLA (Polylactic Acid, Nature Works). Some of the mechanical properties and melting points of these thermoplastic materials are shown in Table 1 [17-19].

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 is taken as the glass transition temperature (T_g), for ABS, since this material cannot be crystalized. Solid Works software was used to design and make specific sample files [20].These files were then converted to STL format for 3D printing. Figure 2 shows a PLA specimen after printing at 45° print head orientation. Note the visible banded structure at 45°, which is responsible for the rough structure discussed below. Table 2 lists the printing conditions.

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

After printing, a white light interferometer was employed to measure the roughness and thickness of each sample. The surface topography was measured for an ABS tensile test specimen before and after the sample being tested to check how the tensile strength test affects surface topography. For testing the tensile strength, a standard specific dimension test specimen was printed by using CAD software. The results of these tests are presented elsewhere [21, 22]. The model was converted to STL format to be printed by an FDM 3D printer (MakerBot Replicator 2X).

Figure 3 shows the screen capture of test sample image 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

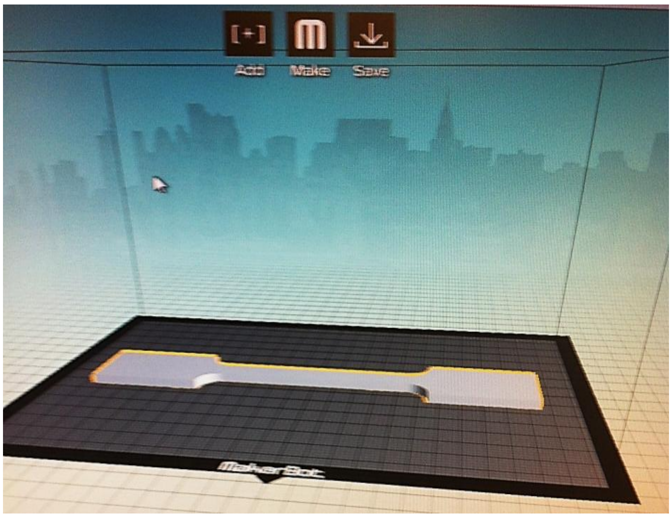

Figure3. Specimen imported by Maker ware software to be printed.

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.

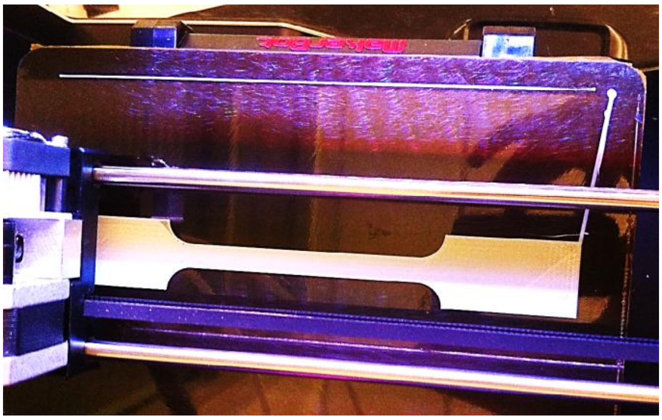

Figure 4. 3D Printing of the tensile test sample.

Creating 3D Structure Model

We illustrate printing a prototype implant, based on a bone structure. To enable the printing of such structures, models need to be made from authentic human body scans. 3D models can be built from CT and MRI scanned DICOM medical images. Magnetic Resonance Imaging (MRI), CT (Computerized Tomography), DICOM (Digital Imaging and Communications in Medicine) 3D optical scans and Ultrasound scans are methods used in radiology for medical procedures. Since DICOM images are only two-dimensional images, slices of a 3D body, "3D Slicer" [23] 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 [23]. 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 functionalities 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 [23]. 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.

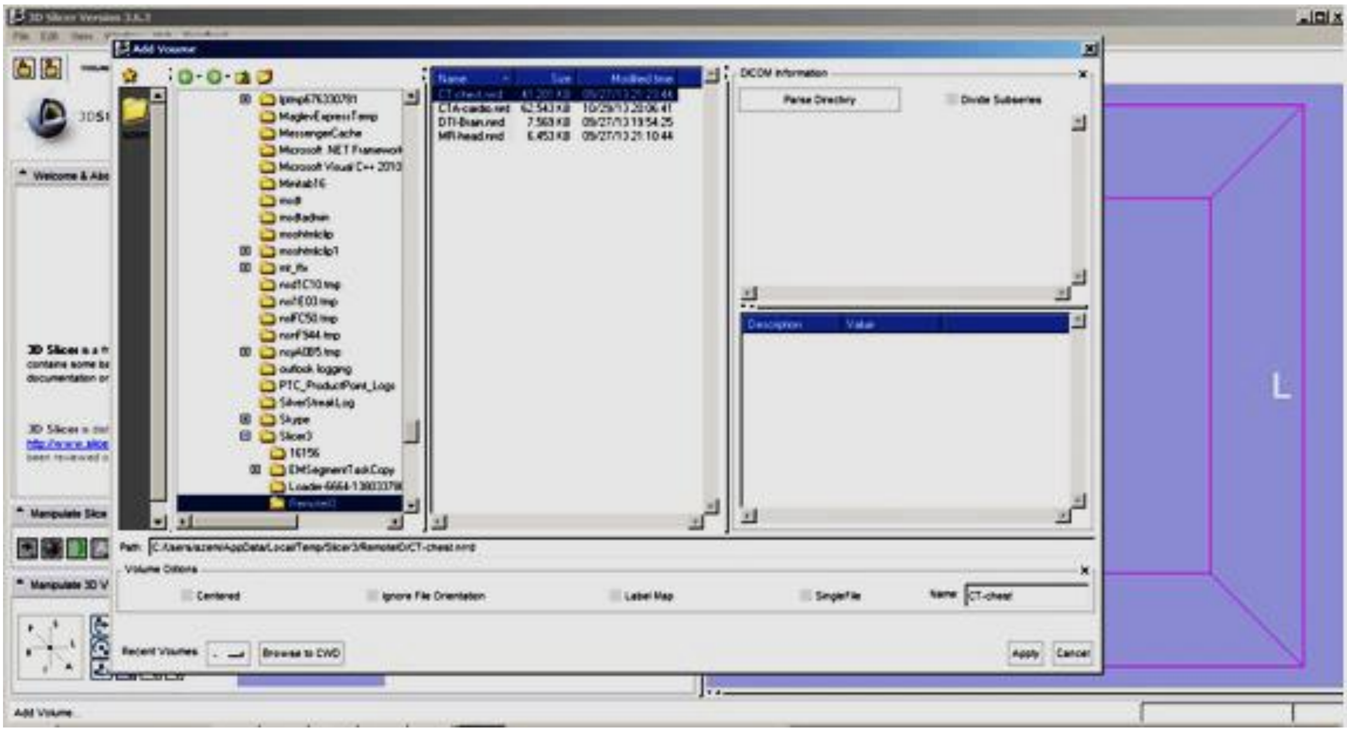

Figure 5. Data loading in 3D Slicer [15].

After the images are loaded, the Region of Interest (ROI) is determined on each image and then segmentation is performed on the organ. 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 performed by a tensile test machine, MTS system, at ambient temperature 20 Cº. The results of these tests are reported elsewhere [21,22].

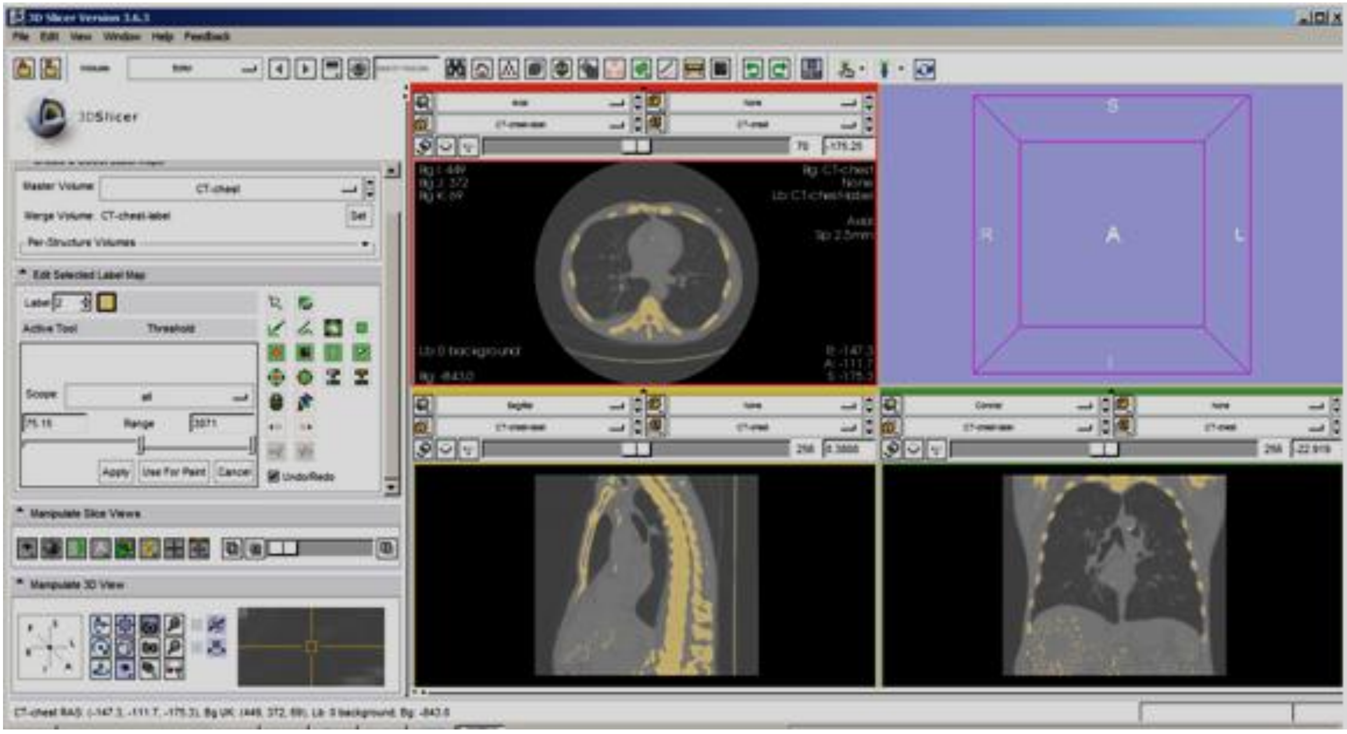

Figure 6. ROI and segmentation in 3D slicer [13].

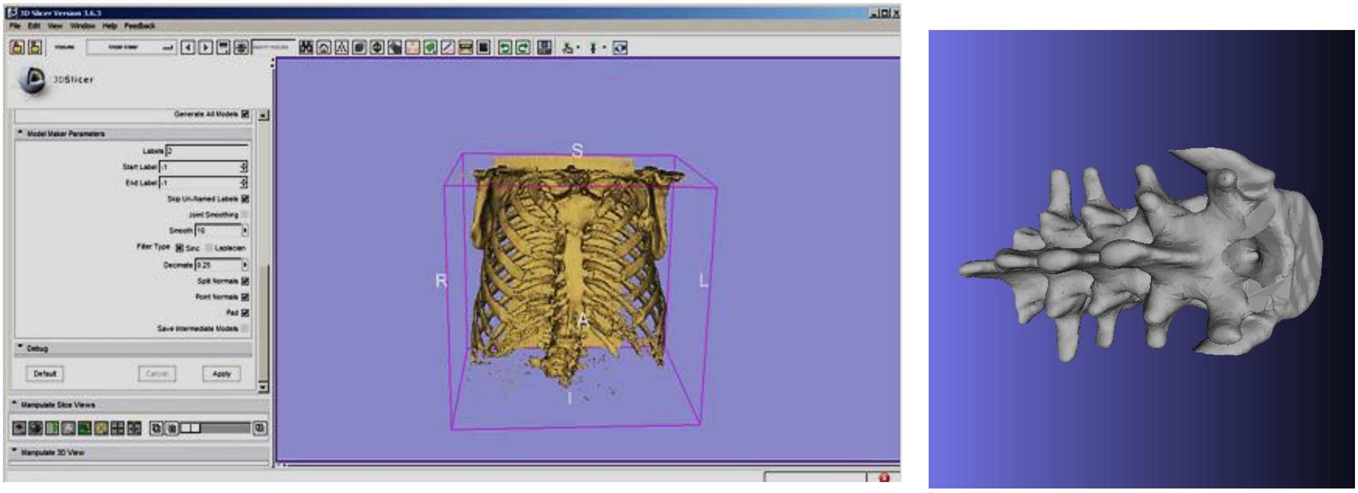

Figure 7. 3D models created after segmentation by 3D slicer [13].

On order to test the differences in thickness, roughness and designed thickness vs actual thickness for multiple materials and deposition methods, we printed several different polymers. ABS, PLA and PVA were printed using MakerBot replicator 2X. We also printed ABS using Flash Forge Creator Pro. The thickness of the designed samples ranged from 0.4 mm (400 µm) for the thickest down to 0.05 mm (50 µm) for the thinnest. The samples were printed at 45º. The measured thickness and roughness were measured using a White Light Interferometer (Bruker, Contour GT-K). After that, other samples were printed by Poly Jet Technology using a Stratasys Objet 500 Connex3 printer with digital ABS™ material and the thickness of the samples this time ranged from 0.4 mm (400 µm) for the thickest down to 0.016 mm (16µm) for the thinnest. They were printed to investigate if the Stratasys Objet 500 Connex3 can produce the minimum thickness that the manufacturer claimed, 0.016 mm (16 µm), and the highest precision the printer can reach with the smoothness level. Then, we compared the results with the previous printers that use the FDM method (MakerBot replicator 2X and Flash Forge Creator Pro).

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 numbers 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 are 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	78	7.4
ABS2	83	13.3
ABS3	118	18.0
PLA1	105	8.0
PVA1	77	5.7

The surface topography for ABS1, ABS2 and ABS3 prints are shown in Figures 8-10.

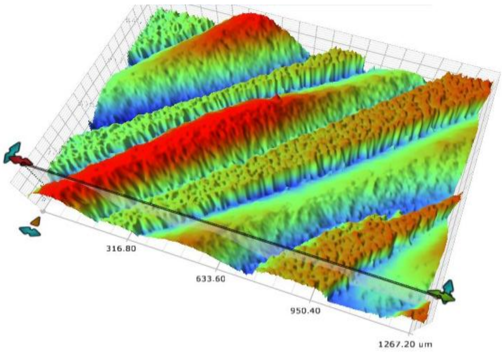

Figure 8. Topographic map of first layer ABS1.

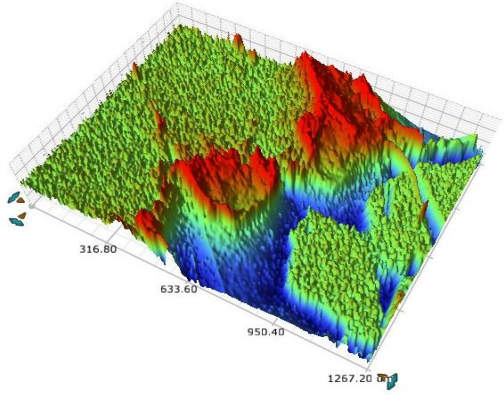

Figure 9. Topographic map of second layer ABS2.

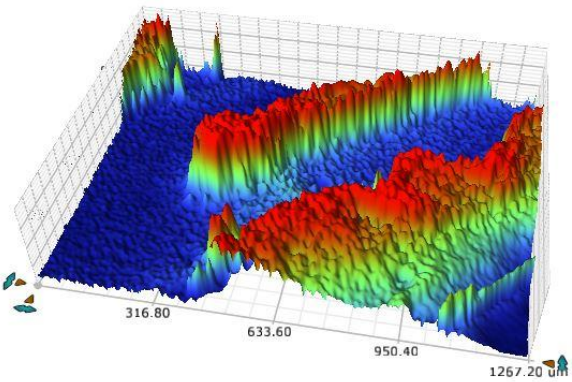

Figure 10. Topographic map of third layer ABS3.

Figures 8-10 clearly show that these printed surfaces display both macro and micro roughness. The macro roughness clearly corresponds the spacing between the banded 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 T_g of ABS.

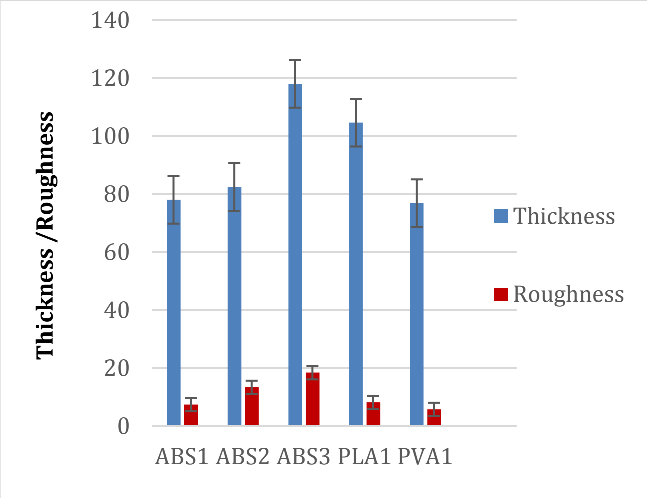

Figure 11. Thickness and Roughness for ABS, PLA and PVA1-3 layers printed at 45°.

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	80	3.7
ABS2	87	10.4
PVA1	62	3.0

Note that ABS printed at 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 T_g is 85°C [19]. What is clear is that for FDM to succeed at producing uniform smooth layers, an annealing step (raising the temperature of the build platform following initial deposition) is needed. This will improve the leveling and smooth the bands of material in the layers.

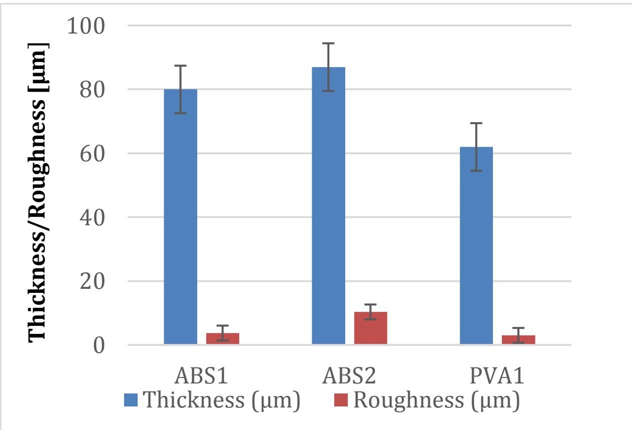

Figure 12. Thickness and Roughness for ABS (1 or 2 layers) and PVA layers printed at 90°.

From Figures 11-12 and Tables 3 and 4, it is obvious that the 90° print orientation 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 78 µm, the roughness was 7.4 µm. For the two layers of ABS the thickness is 83 µm and the roughness is 13.3 µm. Finally, when printing three layers, the thickness became 118 µm with a roughness of 18 µm (Table 3). This increase in roughness for successive printed layers is consistent with observations for multilayer printing of functional materials in printed electronics applications [24]. To achieve higher smoothness, higher platform temperature may be necessary, or annealing may be needed. Figure 12 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.11-12) are quite similar, which may show that the layer structure eventually conforms after a certain number 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 the printer rather than due to the material being printed. Table 5 shows the specific thickness of the designed samples using Solid Works software compared with the thickness and roughness after the samples were printed using MakerBot replicator 2X. The samples were printed using ABS and PVA. Then thickness and roughness were measured using a White Light Interferometer (Bruker, Contour GT-K).

Table 5. Thickness and roughness of ABS and PVA printed at 45º using MakerBot replicator 2X**.**

Nominal Thickness (µm)	ABS Thickness (µm)	ABS Roughness (µm)	PVA Thickness (µm)	PVA Roughness (µm)
400	400	43	400	34
300	300	29	305	27
200	198	15	222	22
100	101	13	127	20
80	100	8	69	17
50	70	8	58	17

Figures 13-14 show the thickness and roughness for ABS and PVA printed using MakerBot replicator 2X. The samples were printed at 45º with specific designed thickness that ranges from 400 µm for the thickest sample down to 50 µm for the thinnest one. The minimum thickness that MakerBot can achieve is 50 µm. From the figures, it is obvious there is a consistency between the thickness and roughness of the samples.

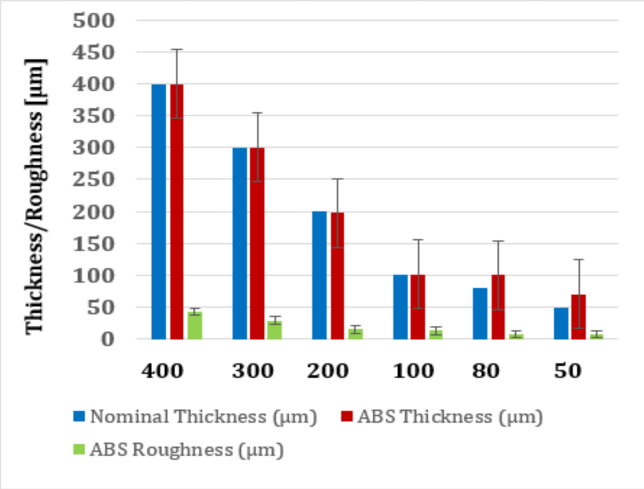

Figure 13. ABS thickness and roughness for layers printed at 45ºwith different designed thickness using MakerBot replicator 2X.

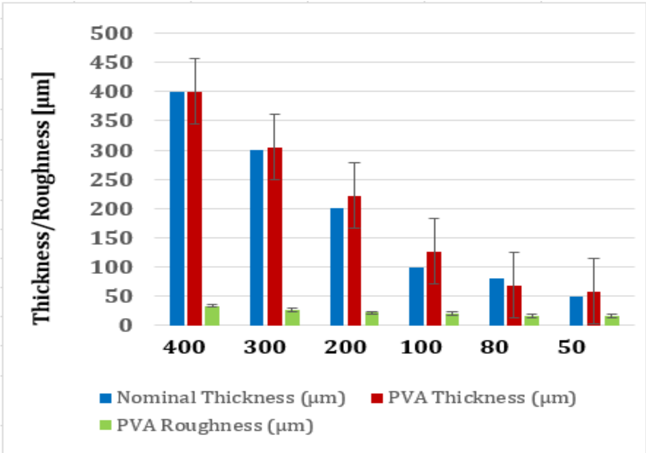

Figure 14. PVA thickness and roughness for layers printed at 45º with different designed thickness using MakerBot replicator 2X.

Table 6 shows the designed thickness of the samples using Solid Works software compared with the thickness and roughness after the samples were printed using ABS with two different printers, MakerBot replicator 2X and FlashForge Creator Pro.

Table 6. Thickness and Roughness of ABS printed at 45º using MakerBot replicator 2X and FlashForge Creator Pro.

Nominal Thickness(µm)	MakerBot Thickness(µm)	MakerBot Roughness(µm)	Flash Forge Thickness (µm)	Flash Forge Roughness (µm)
400	400	43	482	50
300	300	29	364	35
200	198	15	145	30
100	101	13	100	28
80	100	8	88	13.8
50	70	8		

Figure 15shows the thickness and roughness for ABS samples printed using the FlashForge Creator Pro. The samples were printed at 45º with specifically designed thicknesses that range from 400 µm for the thickest sample to 80 µm for the thinnest one. The minimum thickness that MakerBot can reach is 50 µm while, the lowest thickness that FlashForge can do is 80 µm. There is a consistency between the thickness and roughness of the samples for both printers, but it is obvious that MakerBot samples are smoother than FlashForge ones. On the other hand, in terms of precision, the MakerBot seems more accurate or precise than the FlashForge because the thickness of samples that are produced by the MakerBot better matches the designed thickness than the FlashForge.

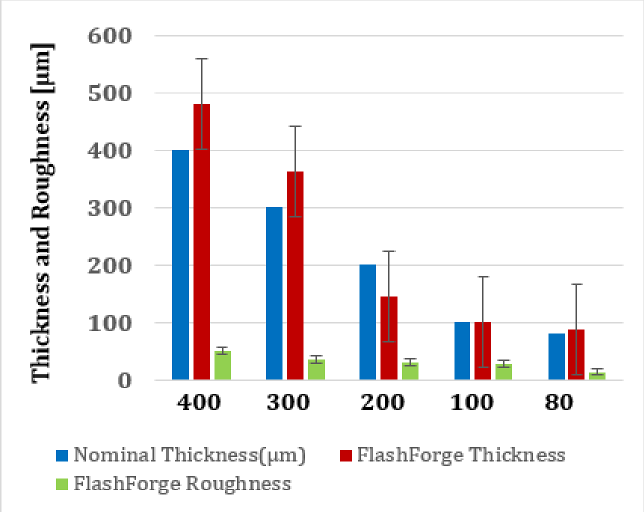

Figure 15. ABS thickness and roughness for layers printed at 45º with different designed thickness using FlashForge Creator Pro.

Table 7 shows the specific thickness of the designed samples using Solid Works software compared with the thickness and roughness after the samples were printed using a Stratasys Objet 500 Connex3. The samples were printed using digital ABS™. Then, the thickness and roughness were measured using the White Light Interferometer (Bruker, Contour GT-K).

Table 7. Thickness and roughness of digital ABS™printed using Stratasys Objet 500 Connex3**.**

Nominal Thickness (µm)	Stratasys Objet 500 Thickness (µm)	Stratasys Objet 500 Roughness (µm)
400	400	7.0
300	300	5.0
200	200	3.9
100	105	3.1
80	85	2.7
50	57	2.0
25	30	1.7
16	22	1.6

Figure 16 shows the thickness and roughness for digital ABS™ samples printed using the Stratasys Objet 500 Connex3. The samples were printed along raster lines in 2 dimensions (90º) with specifically designed thicknesses that range from 400 µm for the thickest sample down to 16 µm for the thinnest one. There is great consistency between the thickness and roughness of the samples. From the obtained results, it is obvious that the samples produced by Stratasys 500 Objet Connex3 are smoother than MakerBot replicator 2X and FlashForge Creator Pro that use the FDM technique. Also, Stratasys 500 Objet Connex3 is more accurate or precise, and can produce thinner layers. This is because the printing mechanism of PolyJet technology. The printer jets layers of liquid material onto the plate and then cures the liquid photopolymers with the help of UV lights, solidifying the model rapidly that’s why PolyJet technology is more precise and produces smoother surfaces than FDM. Even the Object printer does not produce smooth enough surfaces with multiple layers for most applications. Roughness values of order of 2-3 µm are required in general. Layer precision of order 50 µm is unacceptable.

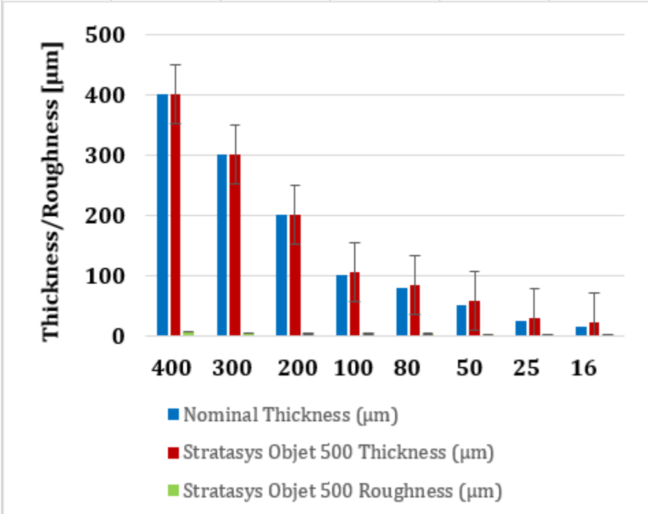

Figure 16. Digital ABS™ thickness and roughness for layers printed at 90º with different designed thickness using Stratasys 500 Objet Connex3**.**

Conclusion

ABS, PLA and PVA were printed using the 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 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 (Bruker, Contour GT- K).

The results show that the roughness of ABS at 45° and 90° increased with increasing thickness, as observed in printing multilayer devices for printed electronics [24]. In addition, the results show that the samples printed at 90° were smoother than at 45°, which means the orientation had a significant influence on roughness, but little on thickness.

For the designed layers using Solid Works software, different specific thickness values ranging from 400 µm down to 50 µm were printed. We printed these samples with both materials ABS and PVA using the MakerBot. We found there is a consistency between thickness and roughness for both materials, but the thickness of ABS better matches the designed one than PVA. For the comparison between ABS samples that were printed using both printers (MakerBot and FlashForge), different thickness samples were printed with each. We notice that there is a consistency between the thickness and roughness of the samples for both printers. But MakerBot samples are still smoother than FlashForge ones. In terms of precision, MakerBot seems more precise, because the thickness of the samples that were produced by MakerBot better matches the designed thickness than FlashForge.

The minimum thickness that MakerBot can reach is 50 µm, while FlashForge it is 80 µm. For the samples that were printed by using Stratasys 500 Objet Connex3, it is obvious that they are smoother than MakerBot replicator 2X and FlashForge Creator Pro. Also, Stratasys 500 Objet Connex3 is more precise than either of the FDM printers and it can reach thinner levels than either of them. We are interested in smoothness, because almost all 3D printed products need to be smooth. Otherwise, they may be rejected by the human body or the resulting friction can cause infection or other negative side effects for medical and dental applications or seriously impair, if not destroy, the performance of the final product for manufacturing applications.

It is not surprising that the less expensive (MakerBot and FlashForge) printers deliver rougher and less precise objects than the more expensive Connex3, which is designed to be a robust prototyping and production machine. The takeaway from this study is that, even the high-end 3D printer is not precise enough or smooth enough for most target applications, which require roughnesses and precision of order 2-3 µm.

References

1. Charles Bell, Maintaining and Troubleshooting Your 3D Printer, Springer Science+Business Media New York, 2014.
2. Barry Berman, 3-D printing: The new industrial revolution, Business Horizons (2012) 55, 155—162.
3. David Espalin & Danny W. Muse & Eric MacDonald & Ryan B. Wicker, 3D Printing multifunctionality: structures with electronics, Int J Adv. Manuf. Technol. (2014) 72:963–978.
4. Robert Bogue, (2013) "3D printing: the dawn of a new era in manufacturing?", Assembly Automation, Vol. 33 Issue: 4, pp. 307-311.
5. Stevanovic, S., Chavanne, P., Braissant, O., Pieles, U., and Gruner, P. (2013). Improvement of Mechanical Properties of 3d Printed Hydroxyapatite Scaffolds by Polymeric Infiltration. *Bioceram Dev Appl S*, *1*, 2.
6. Kern R., 3-D Printed Implants Hit The Market, Pave The Way For More Personalized Devices, The Gray Sheet, 39, Nov 4, 2013, Retrieved 12/06/2016 from http://tissuesys.com/trs_media/publications/The_Gray_Sheet_3D_Printer.pdf
7. Ahn, S. H., Montero, M., Odell, D., Roundy, S., and Wright, P. K. (2002). Anisotropic material properties of fused deposition modeling ABS. *Rapid Prototyping Journal*, *8*(4), 248-257.
8. Aitor Cazón, Paz Morer, Luis Matey, “PolyJet technology for product prototyping: Tensile strength and surface roughness properties”, Journal of Engineering Manufacture, 228, pp1664-1675, 2014.
9. Adam E Jakus, Alexandra L Rutz and Ramille N Shah, Advancing the field of 3D biomaterial printing, Biomed. Mater. 11 (2016)
10. Hutmacher, D. W., Schantz, T., Zein, I., Ng, K. W., Teoh, S. H., and Tan, K. C. (2001). Mechanical properties and cell cultural response of polycaprolactone scaffolds designed and fabricated via fused deposition modeling. *Journal of biomedical materials research*, *55*(2), 203-216.
11. Vince Cahill, “A Very Brief History of Industrial Inkjet Printing”, Screen Web, posted Wed Oct 28, 2015, downloaded 6/6/17 from http://www.screenweb.com/content/a-very-brief-history-industrial-inkjet-printing?page=0,3 - .WExU68n_o1g.
12. Groth, C., Kravitz, N. D., Jones, P. E., Graham, J. W., and Redmond, W. R. (2014). Three-dimensional printing technology. *J Clin. Orthod.*, *48*(8), 475-485.
13. Mavrogenis, A. F., Dimitriou, R., Parvizi, J., & Babis, G. C. (2009). Biology of implant osseo - integration. *J Musculoskelet Neuronal Interact*, *9*(2), 61-71.
14. Novaes Jr, A. B., Souza, S. L. S. D., Barros, R. R. M. D., Pereira, K. K. Y., Iezzi, G., & Piattelli, A. (2010). Influence of implant surfaces on osseo-integration. *Brazilian Dental Journal*, *21*(6), 471-481.
15. Alla, R. K., Ginjupalli, K., Upadhya, N., Shammas, M., Ravi, R. K., & Sekhar, R. (2011). Surface roughness of implants: a review. *Trends in Biomaterials and Artificial Organs*, *25*(3), 112-118.
16. Wennerberg, A. (1999). The role of surface roughness for implant incorporation in bone. *Cells and Materials*, *9*(1), 1.
17. ABS Material Data Sheet, retrieved 04/15/2014 from http://teststandard.com/data_sheets/ABS_Data_sheet.pdf.
18. Bijarimi, M., Ahmad, S., and Rasid, R. (2012). Mechanical, thermal and morphological properties of PLA/PP melt blends. *In International Conference on Agriculture, Chemical and Environmental Sciences (ICACES 2012)* (pp. 6-7).
19. Jelinska, N., Kalnins, M., Tupureina, V., and Dzene, A. (2010). Poly (vinyl alcohol)/poly (vinyl acetate)

blend films. *Sci. J. of Riga Techn. Univ., Mater. Sci. Appl. Chem*, *1*, 55-61.

20. Rosidah Sam, Kamarul Arrifin, Norlida Buniyamin, Simulation of Pick and Place Robotics System Using Solidworks Softmotion, 2012 International Conference on System Engineering and Technology, September 11-12, 2012, Bandung, Indonesia.
21. Azem Yahamed, Pavel Ikonomov, Paul D. Fleming, Alexandra Pekarovicova, Peter Gustafson,Arz Qwam Alden and Saif Alrafeek “Mechanical Properties of 3D Printed Polymers”, *J. Print Media Tech. Res*., Vol. V – No. 4 (273–290), December 2016
22. Azem Yahamed, Pavel Ikonomov, Paul D. Fleming, Alexandra Pekarovicova, and Peter Gustafson, “Designed structures for bone replacement”, *J. Print Media Tech. Res*. Vol. V – No. 4 (291–308), December 2016
23. Fedorov, A., Beichel, R., Kalpathy-Cramer, J., Finet, J., Fillion-Robin, J. C., Pujol, S., and Kikinis, R. (2012). 3D Slicer as an image computing platform for the Quantitative Imaging Network. *Magnetic resonance imaging*, *30*(9), 1323-1341.
24. Michael J. Joyce, Paul D. Fleming III, Alexandra Pekarovicova and Massood Zandi Atashbar, “Self-Supported Printed Multi-Layer Capacitors”, *J. Print Media Tech. Res.*, 4, (2015) 4, 285-200.