Application of 3D Printing for Human Bone Replacement

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Abstract

This paper aims to test the mechanical properties of thermoplastic materials that can be used for 3D printing of human bone structure substitute. In many cases bone replacement is required. That’s why bone substitute is a significant issue in such situations. As a result, the artificial bone substitute materials are widely used in medical applications. The most common method to produce 3D printed items out of thermoplastic materials is Fused Deposition Modeling (FDM). The most used thermoplastic materials are ABS, PLA, PCL, PVA and Nylon.

1. Introduction

1.1. Building bone structure

3D geometry of bones can be acquired using MRI or CT scan of the actual body organs [1]. After that, the 3D modeling software is used to produce the new part or the model of the missing bone structure. The 3D model then is imported to the 3D printing software for building the substitute bone structure [1]. There are many successful tries recently to print 3D items for human bone substitutes using 3D printing technology [2-3]. Therefore, many biocompatible materials have been studied and researched to investigate their strength and the possibility of their use in bone structures by 3D printing.

1.2. Fused Deposition Modeling (FDM)

FDM is a modern method widely used to produce 3D printed items from thermoplastics. It takes the plastic filament and drives it through the extruder heats it up and deposit the molten plastic on the build platform to start building a 3D item layer by layer. The first step is to make 3D model and then convert it to STL format to produce the 3D object. STL format has advantages and disadvantages. The advantage of this format is that it facilitates the geometry of the object by reducing to it is initial components. The disadvantage of this format is that the object loses some of its resolution because it uses just triangles to represent the geometry [4].
Once the STL file format is imported to Makerware software to be prepared for 3D printing, it is sliced into many similar thin slices that become layers. These layers describe the two dimensional lanes that the 3D printing process will build, which when stacked upon one another, will create directly a 3D item matching the original design. It is obvious that, the thinner is the layer, and higher is the precision of the lane movement, the higher is the precision that can be carried out for the item [5].

The working mechanism of the FDM technique is shown in figure 1. It takes plastic filament from a coil and drives it through the extruder. Then the plastic is heated and melted by the heat extrusion nozzle and the molten filament flows through the nozzles and is deposited on the building plate to form layers. The heads move on the X-Y axes to form the specific shape of the layer and the platform moves vertically on the Z axes [5].

3D printing is used to produce fulfilled products because the thermoplastic has become a common material widely used and in some applications, it is the only choice to create parts with specific properties [6].

1.3. Thermoplastics

Thermoplastics have been used successfully as a replacement for certain metals for many years and recently the biomaterials used widely in medical application. 3D printing has a very significant role in improving these materials with high performance, minimum cost and enhancing resistance to environment conditions. The low melting temperature used in 3D printing is considered as the advantage of the technology to create high quality parts for manufacturing and in medical applications also allowing precise replacement of tissue, specifically bone structures [7-10].
2. Methodology

2.1. 3D printing of test samples

Using 3D printing technology four different samples of thermoplastic materials were printed. ABS (Acrylonitrile-Butadiene-Styrene), PVA (Polyvinyl Alcohol), PLA (Polylactic Acid) and Nylon 618 were selected. The mechanical properties and structure of these thermoplastic materials are different as shown in table 1 below [11-14].

<table>
<thead>
<tr>
<th>Material</th>
<th>Tensile strength</th>
<th>Elongation</th>
<th>Melting Point</th>
</tr>
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<tbody>
<tr>
<td>ABS</td>
<td>70 MPa</td>
<td>25%</td>
<td>220°C</td>
</tr>
<tr>
<td>PVA</td>
<td>65 MPa</td>
<td>3%</td>
<td>185°C</td>
</tr>
<tr>
<td>PLA</td>
<td>70 MPa</td>
<td>3.8%</td>
<td>178 °C</td>
</tr>
<tr>
<td>nylon 618</td>
<td>66.0 MPa</td>
<td>300%</td>
<td>218 °C</td>
</tr>
</tbody>
</table>

Table 1. Mechanical properties of thermoplastic Materials

We use 3D slicer or OsiriX software to design 3D models and then we convert it to STL format for 3D printing. Figure 2 below shows the test sample imported by the software in STL format. We can control the sample size and dimensions as we need as well as we can control the other parameters such as temperature, extruder speed, travel federate, plate temperature, infill percentage and resolution. In addition, figure 3 shows the 3D printer running during printing the test sample.
2.2. Creating of 3D bone structure model using OsiriX

OsiriX is free open software used to create 3D models of human organs from CT and MRI scans. Computed Tomography (CT), Magnetic Resonance Imaging (MRI) and ultrasound scans are high quality images used for medical applications including surgeries. To create 3D models for 3D printing bone structure in addition to CT and MRI we can use DICOM images and slice information from actual patients [15].

For creating 3D model there are several steps required to be achieved. The initial step when we get started is the region of interest (ROI) must be selected on the image. After that the segmentation should be performed to separate the borders of the organ. An example of using OsiriX to make 3D model is shown in figure 4.
OsiriX aims to view, approximate, read and post processing the images. OsiriX software presents very developed post processing techniques for 2D imaging, database, and 3D models. Figure 4 illustrates collection of images used to describe the ROI (region of interest) and segmentation as illustrated in the upper right corner to create the 3D model. Once the segmentation is finished through all the slides, the volumization is carried out to make the 3D shape. As shown in figure 5, the 3D model is visualized by OsiriX. Then the model is exported to 3D format, which is STL in our case to be printed by 3D printer.

![Figure 5. 3D model created after segmentation in Osirix](image)

The mechanical properties of the thermoplastic material can be investigated after printing the test sample. Then we will be able to make a decision if the thermoplastic biomaterials can be used for bone structure. The mechanical properties of the samples are ready to be tested once the samples are printed by using tensile test machine (MTS) at ambient temperature.

2.3. Cleaning 3D model using MeshLab

We use MeshLab software for cleaning a mesh, which means trying to remove all the tiny geometrical irregularities that may be found in shelf meshes. Common problems we usually check, such as duplicated vertices, unreferenced vertices, null faces, self intersecting faces, non manifold faces and small holes. For filling holes, we use the holes filler tool that allows us to select holes and edit them in different ways. The basic filling algorithm uses a technique inserts a face between two adjacent border edges. This algorithm selects every time the best pair of adjacent borders edge into the hole. Then we smooth the model and the smoothing process can be performed by several different criteria as shown in figure 6 below [16].
We printed bone structure sample to test the accuracy of 3D printer as shown in figure 7 below. OsiriX was used to design 3D models from CT and MRI scans using segmentation techniques to create specific bone structures. 3D models were exported to STL format to be printed by the 3D printer. Designing and building specific fixtures for bone structures mechanical properties being tested and investigated is our goal.

3. Results and Discussion

We use FDM techniques to print four different thermoplastic materials. Two samples were printed from each category and tested. We use an MTS machine to test the tensile strength of the thermoplastics. The software of MTS in figure 8 shows the breaking point of ABS is 727.8 N after 17.58 sec at 0.2 mm/sec and 15% infill.
Consequently, the breaking point of PVA was 563 N after 65.92 sec, PLA was 394 N at 14 sec, Nylon 618 was 239 N after 80.8 sec all the samples were tested with 15% infill at the same speed 0.2 mm/sec and the same room temperature 20 C°.
Table 2 shows the results of the tensile strength after testing with the MTS machine.

<table>
<thead>
<tr>
<th></th>
<th>Tensile strength (N/mm²)</th>
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<tbody>
<tr>
<td>ABS</td>
<td>14.6</td>
</tr>
<tr>
<td>PLA</td>
<td>48.1</td>
</tr>
<tr>
<td>PVA</td>
<td>9.27</td>
</tr>
<tr>
<td>Nylon 618</td>
<td>4.8</td>
</tr>
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</table>

By making a comparison between the results of the tensile strength of 3D printed samples that we get and the values of the material safety data sheet (MSDS) of the manufacturer, we found that our results are less than the ones we get from the manufacturer. This difference was obviously marked due to the structure filling of the tested thermoplastic samples, which was 15% rather than a 100% solid filling structure. Further study of the actual bone structure substitutes will be tested and investigated including bone strength, porosity and biodegradability.
4. Conclusion

In brief, four different tested samples of thermoplastic materials were printed by using fused deposition modeling (FDM) and investigated by using an MTS machine. The thermoplastic materials were tested ABS, PVA, PLA and Nylon 618. The results show that the tensile strength of these thermoplastics shrink and were less than the tensile strength that we get from manufacturers data sheets, but is still durable enough to be used as a bone replacement.

5. References


Biography

Azem Yahamed is PhD Student in the Department of Chemical and Paper Engineering at Western Michigan University, Kalamazoo, Michigan, USA. I am working on 3D printing for Medical Applications, specifically Bone Structures.

Dr. Pavel G. Ikonomov is Associate Professor of Industrial and Manufacturing Engineering at Western Michigan University, Kalamazoo, Michigan, USA. His main focus has been 3-D modeling design and VR simulation in manufacturing and assembly, nano-technology, medical application, robotics, and large scale dynamic simulation in various research organizations in Japan such as Hokkaido University (Vis. Researcher), Tokyo Metropolitan Institute of Technology (Vis. Assoc. Prof), 3D Incorporated and Virtual Reality Center Yokohama (CTO), UCLA (2001-3) and NIST (2002-3)-Vis. Prof. At NIST he was responsible for industrial Virtual Reality Assembly (VADE) and worked with VR simulation for the optical nano-tweezers. Dr. Ikonomov has more than 100 journals and refereed conference proceedings publications, three books and a book chapter.