Additive Manufacturing with High Density Polyethylene: Mechanical Properties Evaluation

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ADDITIVE MANUFACTURING WITH HIGH DENSITY POLYETHYLENE: MECHANICAL PROPERTIES EVALUATION

BY

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This thesis is approved as a creditable and independent investigation by a candidate for Master's in Civil Engineering degree and is acceptable for meeting the thesis requirements for this degree. Acceptance of this does not imply that the conclusions reached by the candidate are necessarily the conclusion of the major department.

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ABBREVIATIONS

ABS = Acrylonitrile Butadiene Styrene

AM = Additive Manufacturing

FFF = Fused Filament Fabrication

HDPE = High Density Polyethylene

PET = Polyethylene Terephthalate

PLA = Polylactic Acid

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ABSTRACT

ADDITIVE MANUFACTURING WITH HIGH DENSITY POLYETHYLENE: MECHANICAL PROPERTIES EVALUATION

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High-density polyethylene is a common recyclable plastic that has a large potential as an additive manufacturing material due its economic and environmental benefits. However, high-density polyethylene has undesirable thermal properties that cause the material to shirk and not adhere to the printing bed during an additive manufacturing processes. Researchers have attempted to combat these thermal properties but have only created novel filaments of high-density polyethylene without being able to create 3D printed specimens for mechanical property testing. This paper presents several methods to create 3D printed specimens with pure high-density polyethylene filament on a fused filament fabrication type 3D printer. The methods show that using a plastic bag composed of high-density polyethylene on the printing bed in conjunction with clamps can be used to 3D print high-density polyethylene specimens consistently. These methods were used to create specimens for tensile, compression, impact, flexural, and shear mechanical property tests. The results of this study showed that following the recommended methods for 3D printing with high-density polyethylene presented in this paper will yield consistent specimens and data for mechanical property testing on a fused filament fabrication type 3D printer.

INTRODUCTION

Additive manufacturing (AM), also commonly referred to as 3D printing, is the process of joining materials by depositing the material in layers on a two-dimensional plane to create three-dimensional objects that are modeled from computer software. AM is beginning to challenge the traditional method of modeling plastic materials as it becomes more economically feasible and environmentally friendly than injection molding and other traditional methods (Ford, 2016; Baumers, 2016; and Franchetti, 2017). Multiple areas have been studied for AM, which ranging from high strength composite materials to various AM methods (Wang, 2017). Printing with recyclable materials and being able to reuse the material after it has been printed is also beginning researched extensively due to the cost and environmental benefits (Rejeski, 2017).

AM is becoming more affordable and common for commercial and individual applications due to downsized fused filament fabrication (FFF) devices. These FFF devices are readily available to the average consumer at an affordable cost and are seeing a wide variety of applications, such as education, rapid prototyping, and independent research. Due to this wide range of applications and potential to solve complex problems, the author of this paper is researching the use of 3D printers in poverty-stricken communities. More specifically, using 3D printers to reduce a community's environmental impact, develop necessary structures and objects for the community, and educating the community on how to develop solutions to problems facing their community using AM devices.

This paper will discuss research on using a recyclable material, High Density Polyethylene (HDPE), as a feasible AM material and potential construction material. HDPE was selected for three major reasons over other recyclable plastic. First, HDPE has a high availability, as it is one of the most commonly used and recycled materials (Singh, 2017). Secondly, Kreiger et al. (2014) has studied the benefits of using HDPE as an AM material and, based on their models, they found the material can have high economic and environmental benefits for society. Lastly, there is a small amount of research conducted on HDPE for AM due to the difficulty of working with the material. HDPE is known to have undesirable thermal properties, which can cause the HDPE to clog the nozzle, warp during printing, and not adhere to the printing bed (Chong, 2017). The aim of using HDPE for this project is to have a strong and readily available material for communities to use for construction or other applications at a low cost and low impact to the environment.

This paper is designed to be a proof of concept and provide guidance for communities on how to use AM methods. The goal of the research is to determine the mechanical properties of pure 3D printed HDPE and techniques to combat the undesirable thermal properties of HDPE when printing. This paper will discuss the current research on the effects of printing parameters on AM materials, using recyclable materials for AM methods, the economic and environmental benefits of AM, and the current state of research on AM in civil engineering applications. The paper will then discuss the materials and equipment used to conduct the research, the methods used to test and analysis the data collected from the research, and then the results and conclusions found from this research will be discussed. Finally, future applications and recommendations will be discussed.

LITERATURE REVIEW

Several aspects of the AM field were examined for this paper to provide the author with guidance and background for the research. Multiple printing parameters of various AM materials were analyzed to determine the best printing parameters to yield the highest printing quality and mechanical properties. Studies on recycling AM materials after being manufactured were also analyzed to determine the feasibility of using some AM materials through multiple recycling life cycles. Economic and environmental studies on HDPE and other recyclable materials were also investigated to determine how using HDPE as an AM material would impact society. Then the use of AM in civil engineering was explored to determine the feasibility of this application.

2.1 Printing Parameter Studies

Numerous studies have been conducted on the mechanical and physical properties of materials that underwent an AM process. Studies have examined multiple AM materials, printing parameters, and the characteristics of the material post processing. This section will discuss and evaluate multiple studies on these topics to determine the best printing parameters and methods to use for this research.

FFF is the most common type of consumer based AM. Thus, the studies examined for this literature review will focus on FFF. Several printing parameters can be modified for FFF including raster orientation, layer height, travel speed, temperature, and fill percentage. Raster orientation is the angle the material is deposited for each layer. A study by Letcher and Waytashek (2014), examined the effects raster orientation had on the tensile strength of polylactic acid (PLA) manufactured from a FFF device. The project studied 3 raster orientations, one at 0° (horizontal), 45° (crisscross), and 90° (vertical). The results showed that the 45° orientation exhibited the highest tensile strength. The 0° orientation was second and the 90° orientation was last. Several other authors have found this trend to be true for PLA as well (Bayraktar et al., 2017; Tanikella et al., 2017, and Chacón et al., 2017). Acrylonitrile butadiene styrene (ABS) was examined by Dawoud et al. (2016) and found that a raster orientation of 45° yielded the highest tensile strength as well. The authors of these studies concluded that the 45° raster orientation allowed the stress to be more uniformly distributed throughout the material, which resulted in higher tensile strengths.

Layer height is another printing parameter for AM that can affect the mechanical properties. Bayraktar et al. (2017) studied the effects of layer height on PLA with a FFF device. Their research discovered that smaller layer heights would yield higher tensile strength for specimens at a 45° raster orientation. The increase in tensile strength was due to additional "welds" between the layers of deposited filament. The increase in welds with the decrease in layer height caused the tensile strength of PLA to increase.

FFF materials exhibit anisotropic properties due their manufacturing process. Song et al. (2017) studied the anisotropic characteristics of PLA manufactured on a FFF device. The study showed the material had notably different mechanical properties when loaded in the axial and transverse direction and found the tensile and compressive specimens were strongest in the axial direction (loaded parallel to the layers) with the impact specimens were stronger in the transverse direction (loaded perpendicular to the layers). Ahn et al. (2002) conducted a similar study on ABS material and found that ABS exhibited the same anisotropic properties. Additional studies have also been conducted to reduce the anisotropic effect of AM materials. Shaffer et al. (2014) studied the effects of used ionizing radiation to combat the effects of anisotropic materials. The ionizing radiation increased the crosslinks between the polymer's layers and improve the overall strength of the material.

2.2 Recycled material studies

A crucial issue with AM is waste/excess material that is produced during the process. Typically, the waste/excess material is discarded because there is no standard recycling system for many of these thermoplastics used in AM (Hunt et al., 2015). Reusing this waste/excess material has become a high interest in the field of AM due to the economic and environmental benefits.

Anderson investigated recycling PLA after it underwent an AM process on a FFF device in 2017. The recycled PLA was compared to non-recycled PLA through tension and shear testing. Anderson's paper found that the recycled PLA had reduced in tensile strength and hardness. This reduction in mechanical properties is due to the degradation process of recycling. Reusing the material and forming the PLA into a filament again will reduce the crosslinks and performance of the material.

Researchers have considered multiple methods to reduce this degradation process. Jiun et al. (2016) explored using ultraviolet rays and antioxidant fillers in the recycled thermoplastics to decrease thermal degradation. Ultraviolet rays and antioxidants were both found to significantly improve the performance of the recycled thermoplastics. Cruz and Zanin (2003) conducted a study that showed antioxidants reduce the thermal degradation process for HDPE as well with only 0.2% of antioxidants added to the matrix. Pan et al. (2016) investigated using various particulate fillers blended with the recycled thermoplastic to improve the quality of the recycled material. Iron (Fe), silicon (Si), chromium (Cr), and aluminum (Al) nano-crystalline powders were blended with the recycled thermoplastics. With the addition of 1% weight of the particulates, the mechanical properties of the recycled composite showed a notable improvement from the original non-recycled thermoplastic. Researchers have also investigated using surface treatments to improve their adhesion of the recycled thermoplastics. Zhao et al. (2018) conducted a study using polydopamine as a surface treatment for recycled PLA. The surface treatment reduced the degradation process and increased the crosslinks between the layers. This improve the mechanical properties and performance of the material.

Common recyclable plastics have also been formed into filaments for AM and compared to traditional thermoplastics used in AM. A study on using recycled polyethylene terephthalate (PET) as an AM material was conducted by Zander et al. in 2018. The filament was created from post-consumer plastics with a PET recycling code and formed using a custom in-house filament extruder. The authors of the paper did not use any additional processes or additives to improve the properties of the filament. Zander et al.'s research found that PET is a great candidate as a recycled filament, but the material lost nearly half of its strength when compared to its injection molded counterpart. Chong et al. (2017) evaluated HDPE as recyclable filament and compared it to pure ABS filament. The study produced two HDPE filaments. One filament was created from post-consumer products containing HDPE recycling code and the second filament was created from recycled HDPE pellets from a local recycling plant. The study showed that both HDPE filaments exhibited favorable qualities for an AM material. No mechanical properties test where conducted on these filaments due to difficulty of obtaining consistent print quality.

2.3 Economic and Environmental Studies

Many researchers have conducted studies and created computer models on the environmental and economic impact AM has on society. Kreiger et al. (2014) created a life cycle analysis on HDPE as an AM materials using post-consumer products. Their model showed that using HDPE as a filament would use less energy and emission rates than the current recycling systems in use. Other life cycle analysis on other AM materials investigated using in-house recycling methods. Kreiger et al. (2013) also conducted a different study on using in-house recycling on ABS. They found that using in-house recycling would significantly reduce emission rate and save on material expenses. Baechler et al. (2013) had a similar study that measured the energy usage of in-house recycling. The results showed that in-house recycling of various thermoplastic had a notable reduction in energy usage when compared to traditional methods.

AM is also becoming more cost effective than other traditional manufacturing methods, such as injection molding. Franchetti and Kress (2017) compares AM to injection molding in an economic study. Their research found that AM is more cost effective than injection molding at its current state for smaller scale, but not for large scale production. However, with the rapid development of AM, it has the potential for large scale production in the near future. Baumers et al. (2016) also had similar findings in their economic models that AM in its current state is cost effective for small scale production but has not matured enough for larger scale production.

2.4 Additive manufacturing in civil engineering

AM for civil engineering is currently in the commercial prototype and proof of concept stage. Researchers have explored and assessed the idea of using AM for construction of buildings or other large structures; however, the research stage of AM for civil engineering applications is in the beginning stage of its life. Gosselin et al. (2016) recently experimented with AM with ultra-high strength concrete on a 6-axis robotic arm. The authors of that research paper were able to print large complex structural members without sacrificial supports. The success of that project has sparked development in AM for civil engineering applications, with 36 researchers citing this paper in their publications in 2018 alone. Several research projects are also being conducted at South Dakota State University and these are studying the structural engineering behavior of AM material. Caballero (2018) investigated the compressive behaviors of 3D printed PLA hollow cylinders filled will aggregates. Hindieh (2018) explored the flexural behavior of 3D printed PLA hollow beams filled with various materials. The aim of these projects was to characterize how 3D printed materials will behave from a structural engineering point of view. The various projects currently being researched will accelerate the growth of AM for civil engineering application.

Commercial companies have also shown interest in development of AM for civil engineering applications. Due to the enormous cost benefits of creating structures autonomously, commercial companies have developed various prototypes to advance this technology. The company, Foster and Partners, has been developing an AM process to create structures on Mars using indigenous materials and thermoplastics. Fosters and

Partners' paper by Wilkinson et al. (2017) describes their custom material and how it is printed on a 6-axis robotic arm. This development was inspired by the NASA Centennial Challenge: 3D Printed Martian Habitats. This competition has driven other companies to pursue this field of research and development. Contour Crafting Corporation is another company that is creating prototypes for the NASA competition (2018). Their website displays a full scale FFF style printer capable of extruding cementitious material. These prototypes and preliminary research conducted by commercial companies will accelerate the field into more practical and common applications in the future.

MATERIALS

3.1 HDPE Filament Physical Properties

The HDPE used for this testing was purchased from Filaments.ca, which is an online company in Canada that creates standard and experimental filaments for 3D printing. The HDPE filament was created from solid pure pellets of HDPE. The HDPE filament was stored on a spool in a vacuum sealed container. One spool of HDPE filament contains one kilogram of material. The diameter of the filament was 1.75 mm. Density of the filament is 0.953 g/cm^3. The color of the HDPE filament was natural and did not include any dyes. An image of the HDPE filament can be seen in Figure 3.1.

Figure 3.1. HDPE filament spool.

3.2 HDPE Storage

The HDPE filament was kept in a temperature controlled room while in storage. The HDPE filament was kept in a vacuum sealed container while stored to reduce the amount of water absorption from humidity in the air. 3D printed test specimens created from the HDPE filament were also kept in a temperature controlled room and kept in a vacuum sealed container. The samples were all left in storage for a minimum of 1 week before they were tested

3.3 Printing Bed Material

A sacrificial HDPE thin film was used to bond the HDPE filament to the 3D printer's heated bed. The HDPE thin film was simply a plastic bag that can be found at many commercial retail stores. The bags are marked with the plastic recycling symbol #2 to signify HDPE plastic. Standard adhesives were also used to adhere the HDPE film to the printer's bed to prevent the film from moving during the AM process.

METHODS AND PROCEDURE

4.1 Additive Manufacturing Device

A Flash Forge Creator Pro was used for this research project. The Flash Forge Creator Pro is a fused filament fabrication (FFF) device. The Flash Forge Creator Pro is a very common and affordable 3D printer and uses open source software. This printer was used for all preliminary testing and final fabrication of the test specimens. An image of the Flash Forge Creator Pro is shown in Figure 4.1. Common parts that are referred to in this paper, such as the heated bed and extruders, are labeled in Figure 4.1.

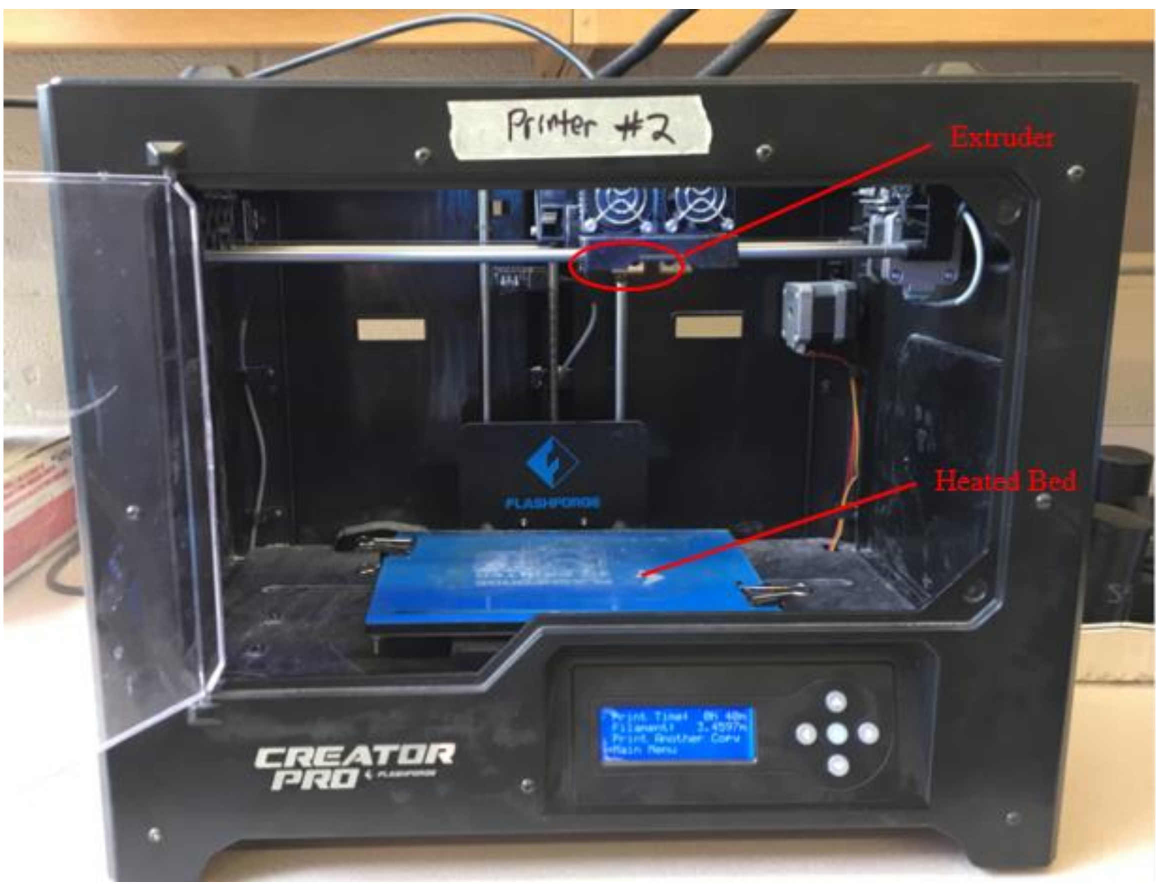

Figure 4.1. Flash Forge Creator Pro 3D printer

4.2 Printing Parameters

HDPE filament tends to have poor adhesion to surfaces other than polyethylene materials. Warping is also an issue with HDPE because once the filament has been heated and deposited on the bed it immediately begins to cool and shrink. The shrinkage will cause the next layer to be offset, which will result in a wrapped and uneven 3D object. Several printing parameters were investigated to minimize these unwanted characteristics. Table 4.1 shows the optimal printing parameters to minimize warping and maximize the mechanical properties of the 3D printed test specimens. These values were determined from preliminary testing and from the guidance of the information on printing parameters presented in the literature review section of this paper. Several observations were gathered from the preliminary testing of the printing parameters and are noted in the following list:

Notes from Preliminary Testing:

- Less wrapping and shrinkage would occur with lower fill percentages. However, 100% fill was chosen so the specimen would maintain a consistent cross section for more accurate results.
- 0.4 mm is the largest layer height available on the printer, with 0.05 mm being the smallest layer height. A smaller layer height does yield stronger test specimens, however, a larger layer height yielded high quality prints. Thus, a larger layer height was chosen to obtain more consistent test specimens.

Table 4.1. Summary of printing parameters used to create test specimens

Parameters	Value
Fill Percentage	100%
Raster Angle	45° Interchanging directions each layer
Layer Height	0.4 mm
Shell Layers	2
Printing Feed Rate	60 mm/s
Printing Head Traveling Speed	80 mm/s
Extruder Temperature	220°C
Printing Bed Temperature	125°C

4.3 Printing Bed Adhesion

Several materials and methods were investigated to increase the adhesion between the printing bed and the HDPE filament. Table 4.2 summarizes the different materials and methods tested for this investigation. Cost, ease of use, and performance were all examined for each method. Each category was based on a scale of 1 to 3, where 1 is the best and 3 is the worst. Cost was based on the price of the material, a 1 ranged from $0 to $5, a 2 ranged from $5 to $20, and a 3 ranged from $20 and up. Ease of use was based on the amount of time and skill required for each method. The methods that used the glass plate ranked as a 3 because the glass had to be sized and cut to fit the printer bed with specialized tools. While the methods that used the plastic poster board ranked as a 1, because only scissors are required to cut and size the plastic poster board. Performance was based on adhesion to the bed and printing quality. The best method for printing smaller objects was HDPE plastic bags and stick glue, which was the method used to print the test specimens for the tensile, shear, and flexural tests. The best method for printing larger objects was HDPE plastic bags, stick glue, and clamps, which was the method used to print the test specimens for the compression and impact tests. An image of this method is shown in Figure 4.2.

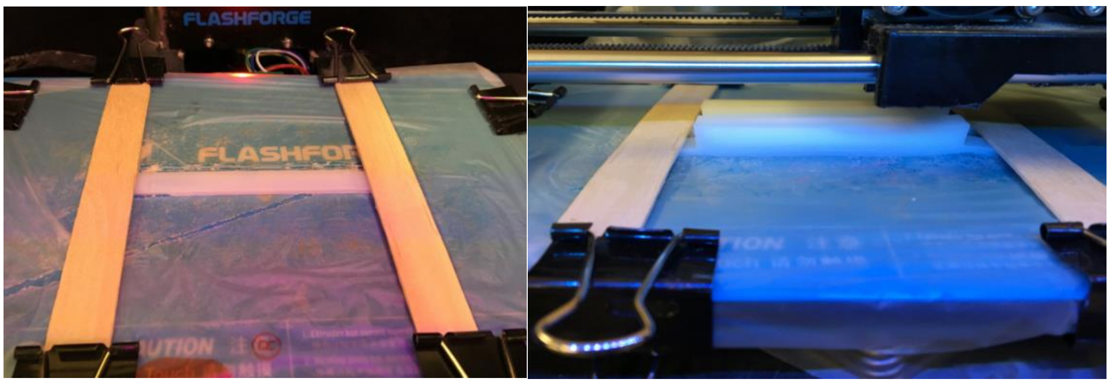

Figure 4.2. Image of Plastic bag, Stick glue, and clamps method for larger 3D objects

Table 4.2. Summary of material investigation for HDPE adhesion to printing bed

Method	Cost	Ease of Use	Perfor-mance	Total	Notes
None (no materials or methods applied)	1	1	3	5	No adhesion to the surface at all. extruder would clog up and unable to continue print
Stick Glue Only	1	1	3	5	No adhesion to the surface at all. extruder would clog up and unable to continue print
Glass Plate Only	2	3	3	8	No adhesion to the surface at all. extruder would clog up and unable to continue print
Glass Plate and Stick Glue	2	3	2	7	Some adhesion to the surface. Only able to print of 1 to 2 layers before corners of print would peel up and cause the extruder to clog.
Glass Plate and High Temp. Glue	3	3	2	8	High temp. glue had same effect as stick glue. Only able to print of 1 to 2 layers before corners of print would peel up and cause the extruder to clog.
Plastic Poster Board	1	1	3	5	No adhesion to the surface at all. extruder would clog up and unable to continue print
Plastic Poster Board and Stick Glue	1	1	2	4	Some adhesion to the surface. Only able to print of 1 to 2 layers before corners of print would peel up and cause the extruder to clog.
Plastic Poster Board and High Temp Glue	3	1	2	6	High temp. glue had same effect as stick glue. Only able to print of 1 to 2 layers before corners of print would peel up and cause the extruder to clog.
HDPE Plastic Bag	1	1	3	5	Great adhesion to surface. Plastic bag would not stay static during print and would clog the extruder
HDPE Plastic Bag and Stick Glue	1	1	1	3	Great adhesion. Able to print up to 10 to 15 layers before excessive shirking would cause the corners to peel up
HDPE Plastic Bag, Stick Glue, and Clamps	1	2	1	4	Great adhesion. Clamps kept corners from peeling up and clogging the extruder. Able to print 25 plus layers.

Several observations were gathered from this trial process and are noted in the following list.

Note from Trial Testing:

- The methods that used an additional surface other than the default heating bed did experience heating loss. The heating loss was due to the heat being transferred from the heating bed to the additional surface. This heating loss was significant for the glass plate and plastic poster board and minimal for the plastic bag. Images of the surface temperatures can be seen in Figure 4.3 through 4.6. The images show that nearly 10°C was lost on the glass plate, while only 1°C was lost with the plastic bag surface.
- Higher bed temperatures tended to promote more adhesion between the HDPE and printing surface. The upper limit on the bed temperature was found to be 127°C to 130°C. Any surface temperature hotter than this would not allow the HDPE to cool down enough to remain static. The HDPE would flow and cause the extruder to clog at these higher temperatures.

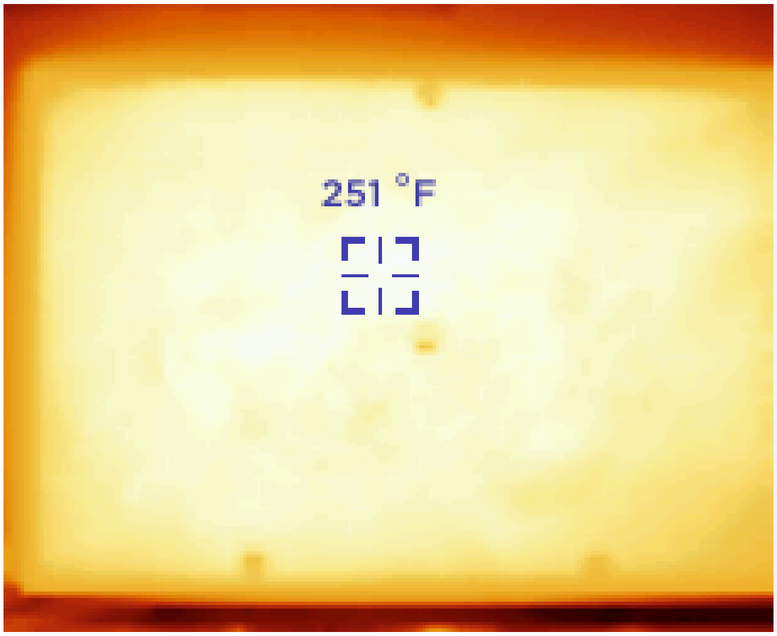

Figure 4.3. Surface temperature of heated bed only (121°C)

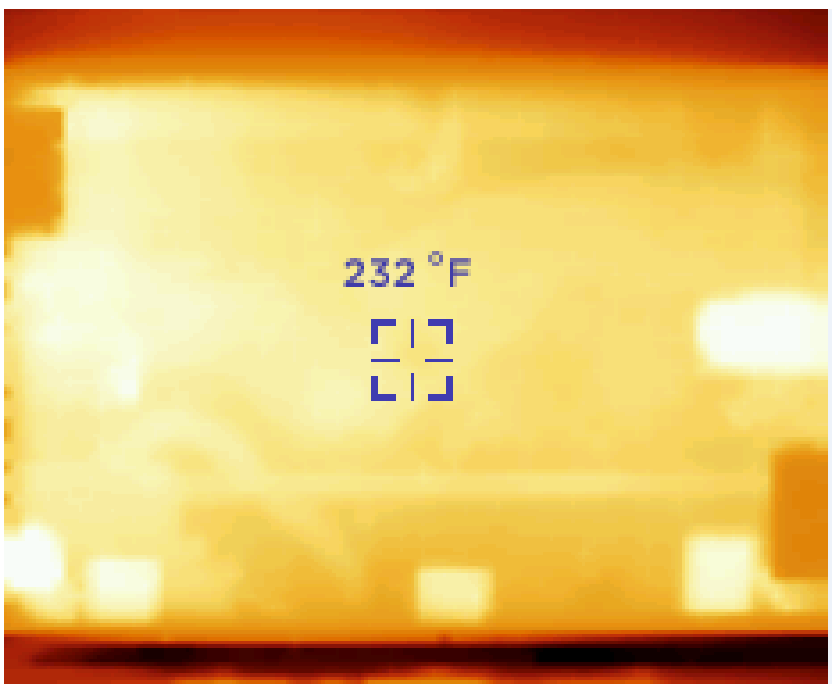

Figure 4.4. Surface temperature of glass plate (111°C)

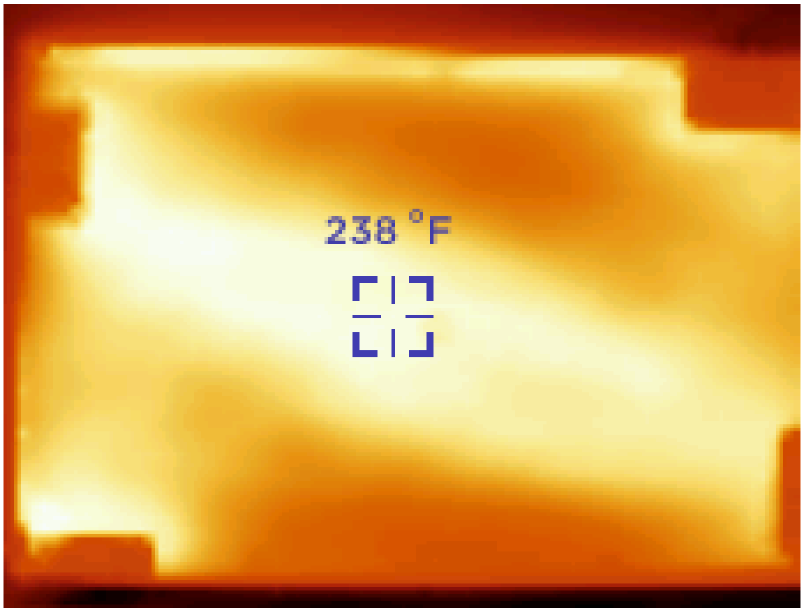

Figure 4.5. Surface temperature of plastic poster board (113°C)

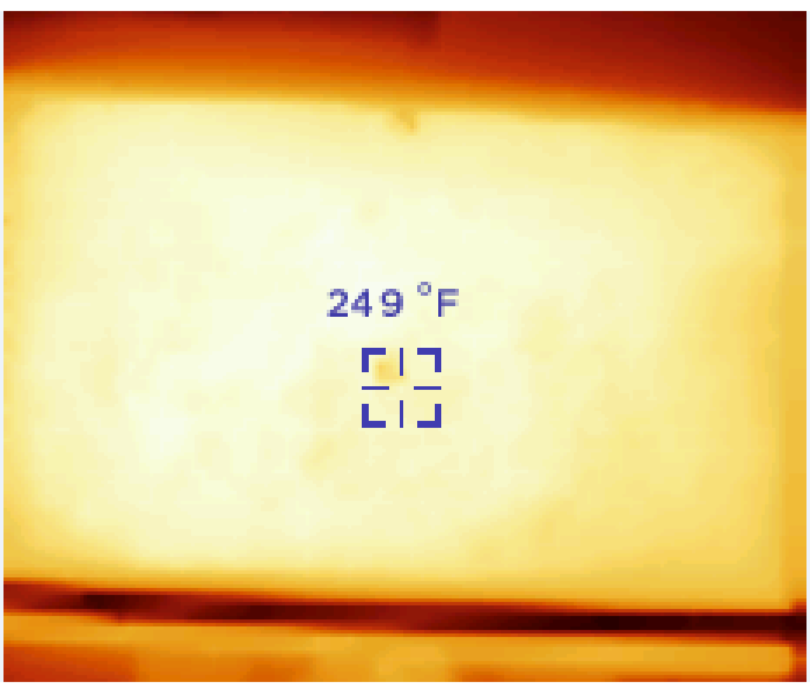

Figure 4.6. Surface temperature of plastic HDPE bag (120°C)

4.4 Mechanical Property Testing

Five different tests were run on the HDPE filament; a tensile test (ASTM D638, 2014), a compression test (ASTM D695, 2015), an impact test (ASTM D6110, 2004), a flexural test (ASTM D790, 2003), and a shear test (ASTM D5379/D5379M, 1998). Test specimens for each test were modeled on Solidworks in accordance with their ASTM specifications. The Solidworks models were then converted to an STL file and uploaded to the FlashPrint program. From there the files where uploaded to the Flash Forge Creator Pro for manufacturing.

4.4.1 General Calculations

For each mechanical property test, an average value was calculated to represent the group of values collected from the test. The equation used to calculate the average for each mechanical property value is shown as equation 1. Standard deviation was also calculated to determine the amount of uncertainty for each mechanical property value. The uncertainty values are presented next to the average values with a plus/minus symbol (±). The equation used to calculate the standard deviation is shown as equation 2.

$$Average = \bar{x} = \frac{\sum_{i=1}^{n} x_i}{n} \text{ - (Equation 1)}$$

Where:

n = number of specimens

x_i = each of the values from the collected data

$$Standard\ Deviation = SD = \sqrt{\frac{\sum_{i=1}^{n}(x_i+\bar{x})}{n-1}} \text{ - (Equation 2)}$$

Where:

n = number of specimens

x_i = individual values from data series

$\bar{x}$ = average value of data series

4.4.2 Tensile Testing

The tensile test was performed in accordance with ASTM D638 (2014) Standard Test Method for Tensile Properties of Plastics. A type IV specimen was used for testing. Six specimens were created on the Flash Forge Creator Pro using the method described earlier. An image of a tensile test specimen is shown in Figure 4.7. The machine used for the tensile test was the MTS Insight Universal Testing Machine. The specimens were tested at a constant deformation rate of 5 mm/min. The applied force was recorded with a load sensor and an extensometer was used to record the strain of the specimen. Data was analyzed using an Excel spreadsheet. Average and standard deviation values were calculated from equations 1 and 2 respectively. The equation used to find the Modulus of Elasticity, E, is shown as equation 3. The Modulus of Elasticity was found from the initial linear slope of the stress versus strain curve. The yield stress was determined from the 0.2% offset method as described in the ASTM D638 (2014).

$$Modulus = E = \frac{\sigma_2 - \sigma_1}{\epsilon_2 - \epsilon_1} \text{ - (Equation 3)}$$

Where:

σ = stress of specimen (MPa)

ϵ = strain of specimen (mm/mm)

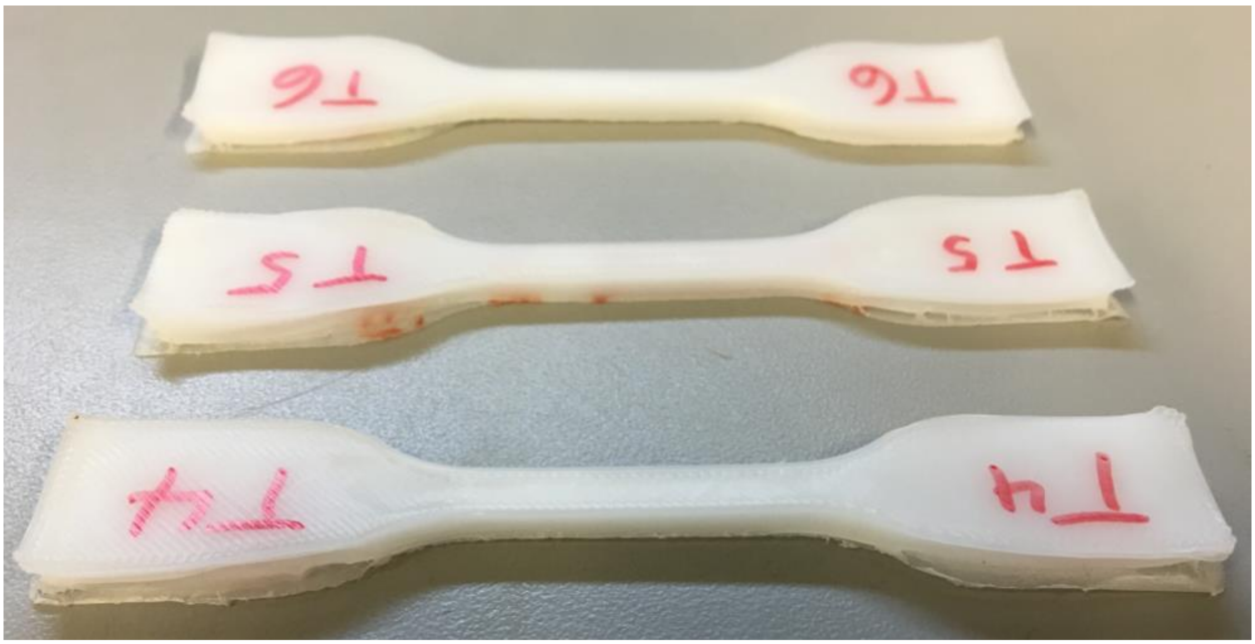

Figure 4.7. Tensile test specimens

4.4.3 Compression Testing

The compression test was performed in accordance with ASTM D695 Standard Test Method for Compressive Properties of Rigid Plastics. Two different types of specimens were tested for the compression test. Four specimens were tested with the layers of the test specimen perpendicular to the loading force and 4 specimens were tested with the layers parallel to the loading force. The test specimens were created on the Flash Forge Creator Pro using the method described earlier and were cut to the appropriate length with a miter saw. An image of a compression test specimen is shown in Figure 4.8. The machine used for the test was the MTS 858 Universal Testing Machine. The specimens were tested at a constant displacement rate of 1.3 mm/min. The applied force was recorded with a load sensor and the displacement of the head was used to record the change in length, which was used to calculate strain. Data was analyzed using an Excel spreadsheet. Average and standard deviation values were calculated from equations 1 and 2 respectively. The Modulus of Elasticity, E, of the specimen was determined from the linear region on the stress versus strain curve, ignoring the initial slope from the seating of the specimen. The equation used to find E was equation 3. The yielding stress of the compressive samples were determined from a 0.2% offset method as described in the ASTM 695 (2015).

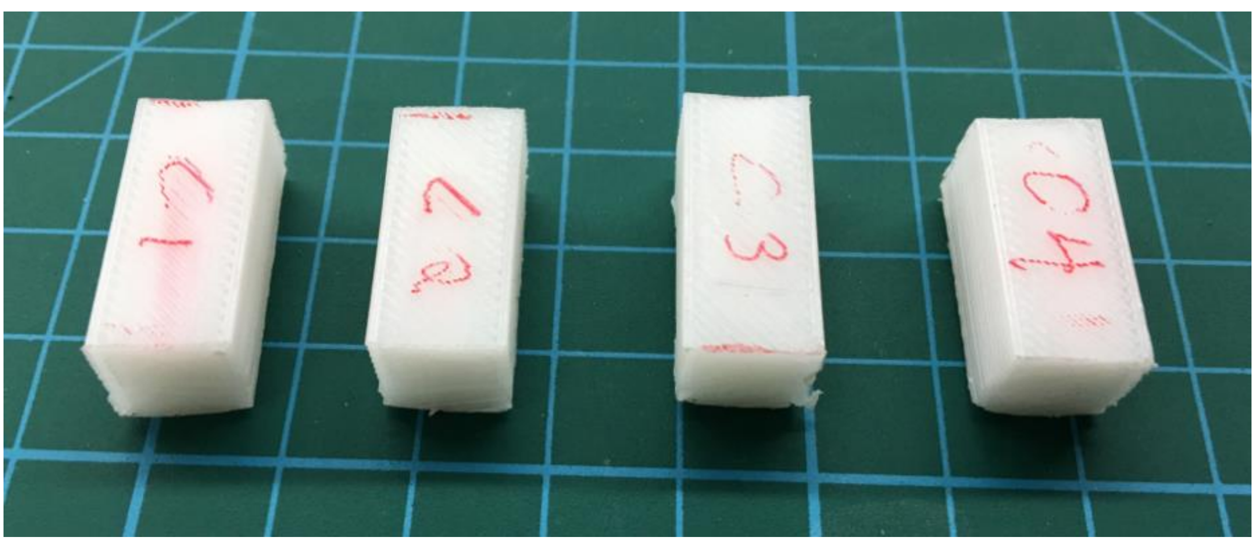

Figure 4.8. Compression test specimens

4.4.4 Impact testing

The impact test was performed in accordance with ASTM D6110 Standard Test Methods for Notched Bar Impact Testing of Metallic Materials. A type "A" specimen was used for testing. Impact specimens were created on the Flash Forge Creator Pro using the method described earlier in this section. An image of an impact test specimen is shown in Figure 4.9. The machine used for the test was a standard pendulum arm that conformed to the ASTM D6110 (2004) specifications. The angle of the swinging pendulum was recorded with a data acquisition device. Data was analyzed using an Excel spreadsheet. Average and standard deviation values were calculated from equations 1 and 2 respectively. The impact energy was determined from the equation presented as equation 4.

$$Impact\ Engergy = IE = \frac{(wgL\cos(\theta)-\cos(\theta_i))-F_L}{t} \quad \text{- (Equation 4)}$$

Where:

w = weight of pendulum mass (kg)

g = acceleration of gravity (m/s^2)

L = length of pendulum arm = 0.327 m

θ = angle after pendulum contacted the specimen (degrees)

θ_i = initial angle of pendulum (degrees)

F_L = friction loss from pendulum (J)

t = thickness of specimen (m)

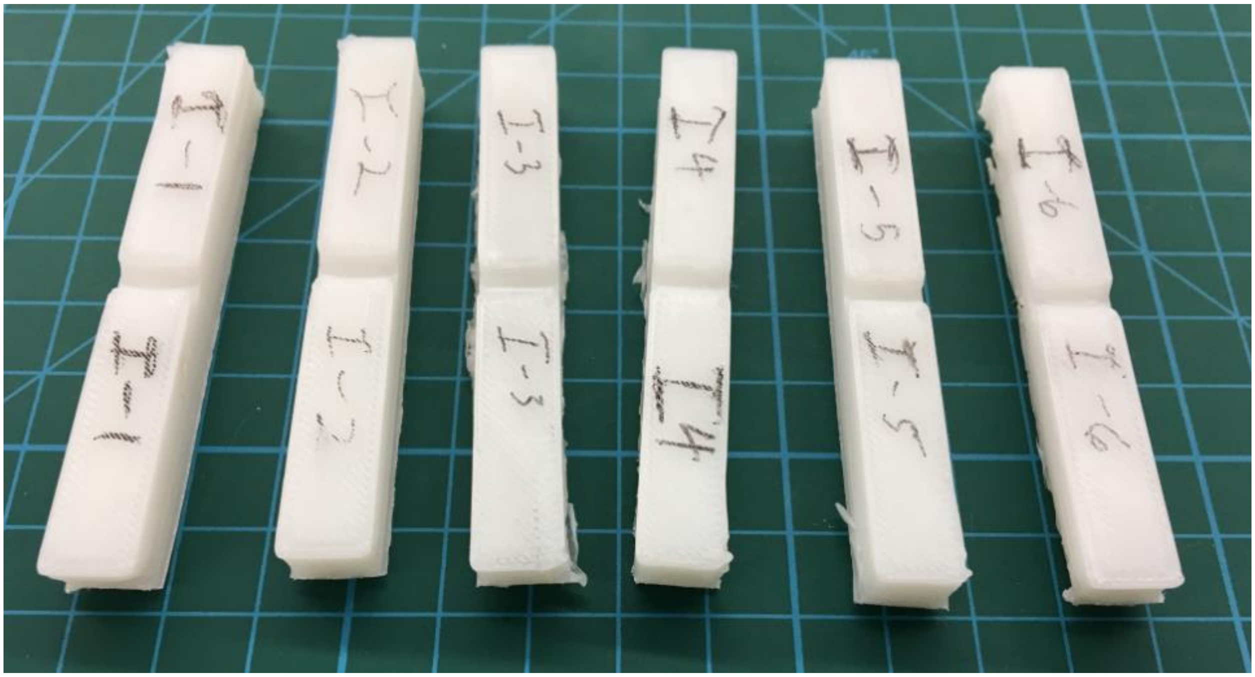

Figure 4.9. Impact test specimens

4.4.5 Flexural Testing

The flexural test was performed in accordance with ASTM D790 Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials. Procedure “B” was followed for this test, which is designed for materials that undergo large deflections during testing. Six specimens were created on the Flash Forge Creator Pro using the method described earlier. An image of a flexural test specimen is shown in Figure 4.10. The machine used for the test was the MTS Insight Universal Testing Machine. The specimens were tested at a constant deformation rate of 1.3 mm/min. The applied force was recorded with a load sensor and the displacement of the head was used to record the change in length which was used to calculate the strain. Data was analyzed using an Excel spreadsheet. Average and standard deviation values were calculated from equations 1 and 2 respectively. The flexural modulus was calculated using the recommended equation from the ASTM D790 (2003) for a 3-point flexure test, which is shown as equation 5.

$$Flexural\ Modulus = E_F = \frac{L^3 m}{4bd^3} \text{ - (Equation 5)}$$

Where:

L = span between supports (mm)

m = Modulus of Elasticity from the first initial linear region (see equation 3)

b = width of specimen (mm)

d = thickness of specimen (mm)

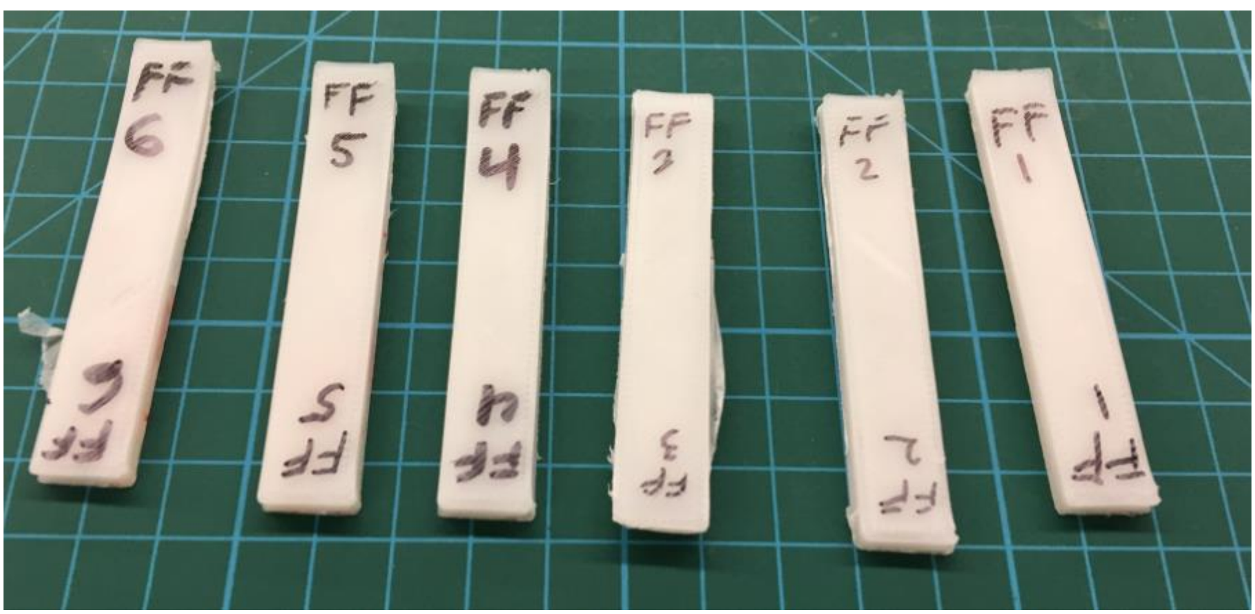

Figure 4.10. Flexural test specimens

4.4.6 Shear Testing

The shear test was performed in accordance with ASTM D5379 Standard Test Method for Shear Properties of Composite Materials by the V-Notched Beam Method. Six specimens were created on the Flash Forge Creator Pro using the method described in earlier. An image of a shear test specimen is shown in Figure 4.11. The machine used for the test was the MTS Insight Universal Testing Machine. The specimens were tested at a constant deformation rate of 2 mm/min. The applied force was recorded with a load sensor and the displacement of the head was used to record the change in length of the sample which was used to calculate angular strain. Data was analyzed using an Excel spreadsheet. Average and standard deviation values were calculated from equations 1 and 2 respectively. The Modulus of Elasticity of the specimen was determined form the initial linear region on the stress-strain curve, ignoring the initial slope from the seating of the specimen. The Shear Modulus of Elasticity was calculated using equation 6..

$$Shear\ Modulus = G = \frac{\Delta\tau}{\Delta\gamma} \text{ - (Equation 5)}$$

Where:

$\Delta\tau$ = difference in applied shear stress between the two strain points (MPa)

$\Delta\gamma$ = difference between the two strain points (mm/mm)

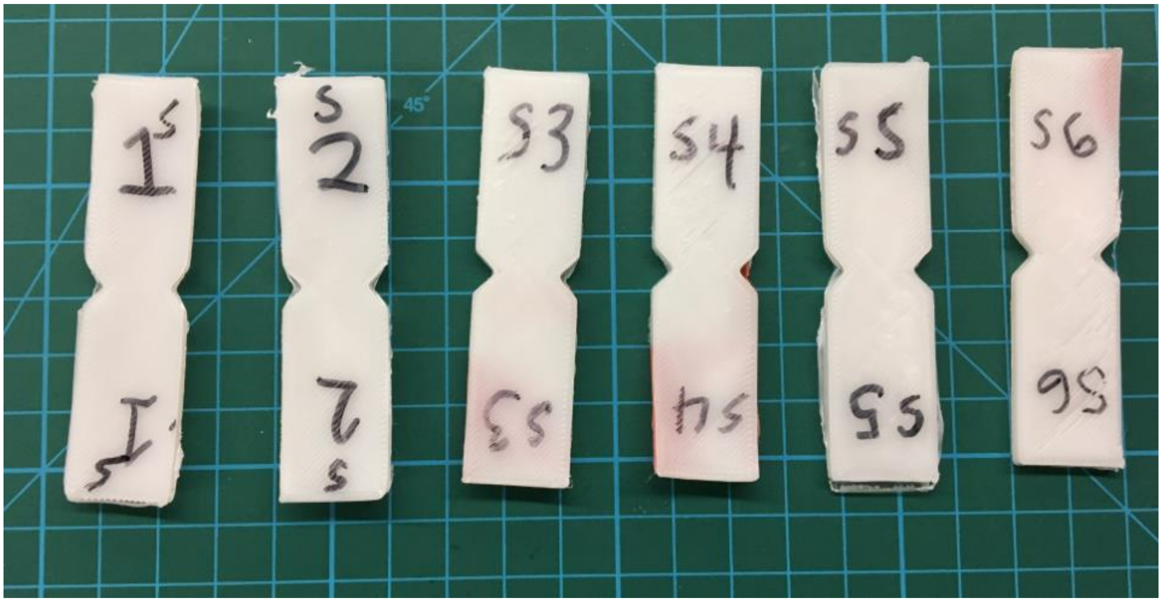

Figure 4.11. Shear test specimens

RESULTS AND DISCUSSION

5.1 Tensile

A total of six specimens were tested and analyzed to determine the tensile behavior of the HDPE material. A representative stress versus strain curve of the tensile specimens is shown in Figure 5.1. Ultimate Tensile Stress, Yield Stress, and Tensile Modulus of Elasticity values were collected from the tensile testing. The values obtained from these results are also compared to injection molded HDPE tensile specimens (Shackelford, 2005). These values are displayed in Table 5.1.

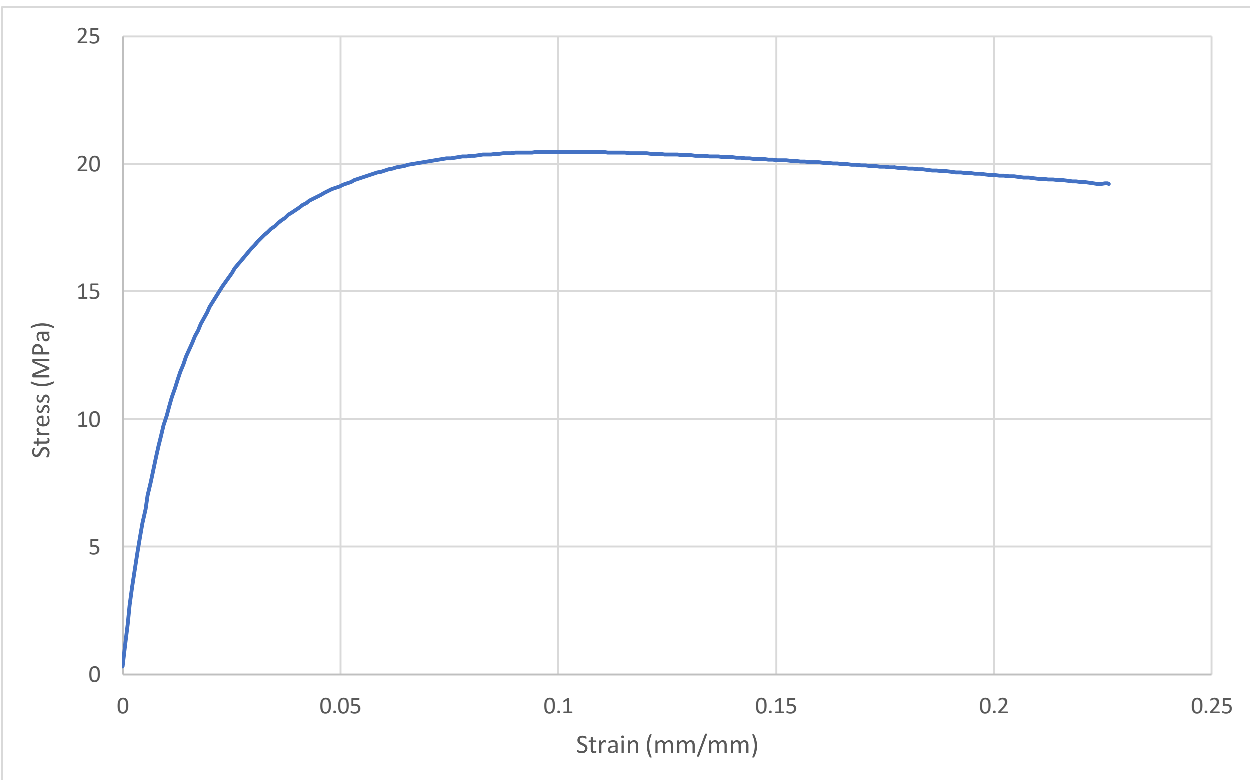

Figure 5.1. Stress strain curve of tensile specimens

Table 5.1. Tensile values for HDPE specimens

Mechanical Properties	3D Printed HDPE specimens	Injection molded HDPE specimens
Ultimate Tensile Stress (MPa)	20.2 ± 0.7	28 ±
Yield Stress (MPa)	14.0 ± 2.8	-
Tensile Modulus (MPa)	904 ± 250	830

The 3D Printed HDPE specimens had a lower ultimate tensile stress value than bulk injection molded HDPE specimens at a difference of 32.4%. The Tensile Modulus of Elasticity for the 3D Printed samples was higher than the value for the injection molded samples with a difference of 8.5%. These are relatively small but notable differences between the two types of specimens. The specimens undergo very different manufacturing processes for AM and injection molding, which will change the characteristics of the material. Injection molded specimens are considered isotropic while specimens that undergo an AM process are considered anisotropic and will contain more voids. Thus, the differences between the mechanical properties of the two types of HDPE specimens are not surprising.

The voids in-between the layers for the 3D Printed specimens contribute to the reduction of the ultimate tensile strength when compared to the injection molded specimens. 3D printed specimens are also known to have fewer cross-links between their molecules due to the layer beneath cooling before the next layer is placed on top during the manufacturing process (Bayraktar et al., 2017). These aspects of AM caused the 3D printed samples to have lower ultimate tensile stress values than the injection molded specimens.

All the specimens were tested until failure. The specimens experienced necking along the gauge length when they began to plastically deform. As the necking continued the specimens would break into long fibrous strands. Individual strands would break until the specimen reached the failure point. Figure 5.2 displays an image of these fibrous strands.

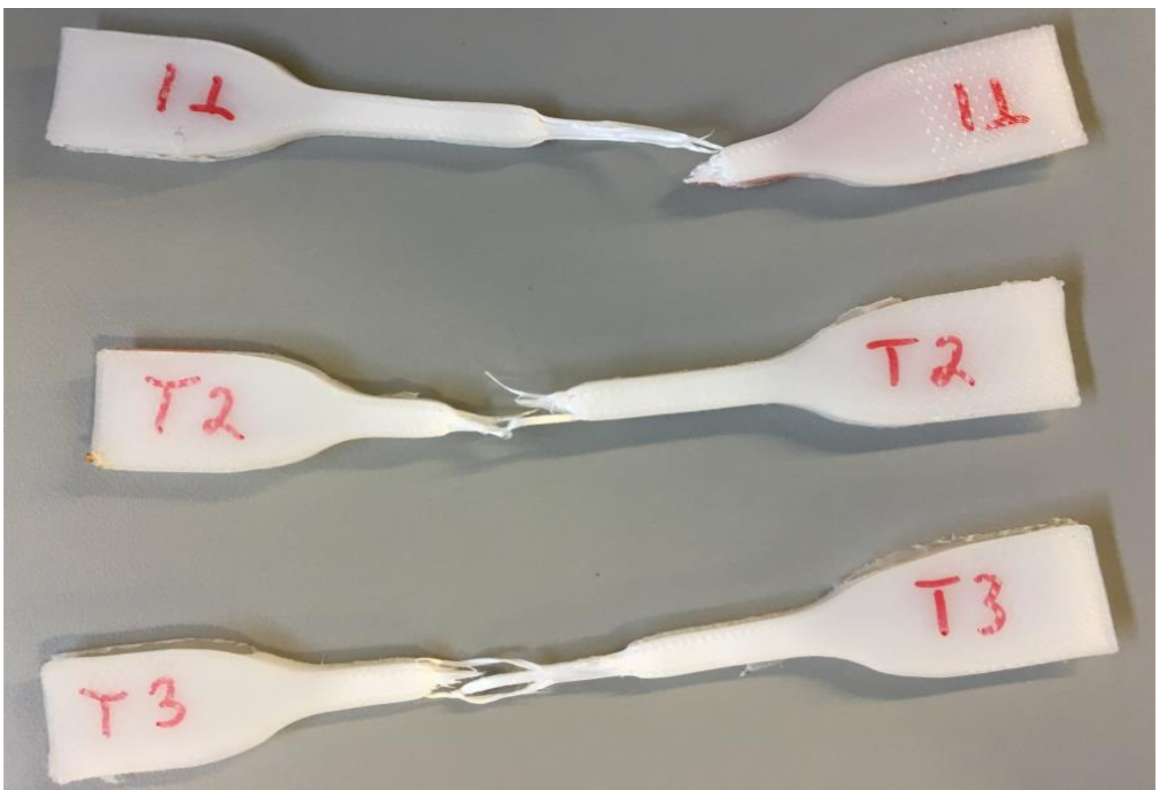

Figure 5.2. Fibrous strands after tensile failure

5.2 Compression

A total of eight compression specimens were tested. Four specimens were tested with the 3D printed layers perpendicular to the loading force and four specimens were tested with the 3D printed layers parallel to the loading force. A representative stress versus strain curve for both tests is shown in Figure 5.3. Generally, the important values reported from a compressive test are Ultimate Compressive Stress, Failure Strain, Modulus of Elasticity, and Yielding Stress. However, the compressive HDPE specimens were found to be very ductile during the test and did not experience a distinct failure point. The specimens were merely flattened or buckled during testing. The specimens with the load perpendicular to the layers were flattened during testing and the specimens loaded parallel to the layers would buckle during testing. Images of both specimens after testing can be seen in Figure 5.4. Therefore, the ASTM D695 (2015) recommends not reporting ultimate compressive stress or failure strain for these specimens due to their ductility.

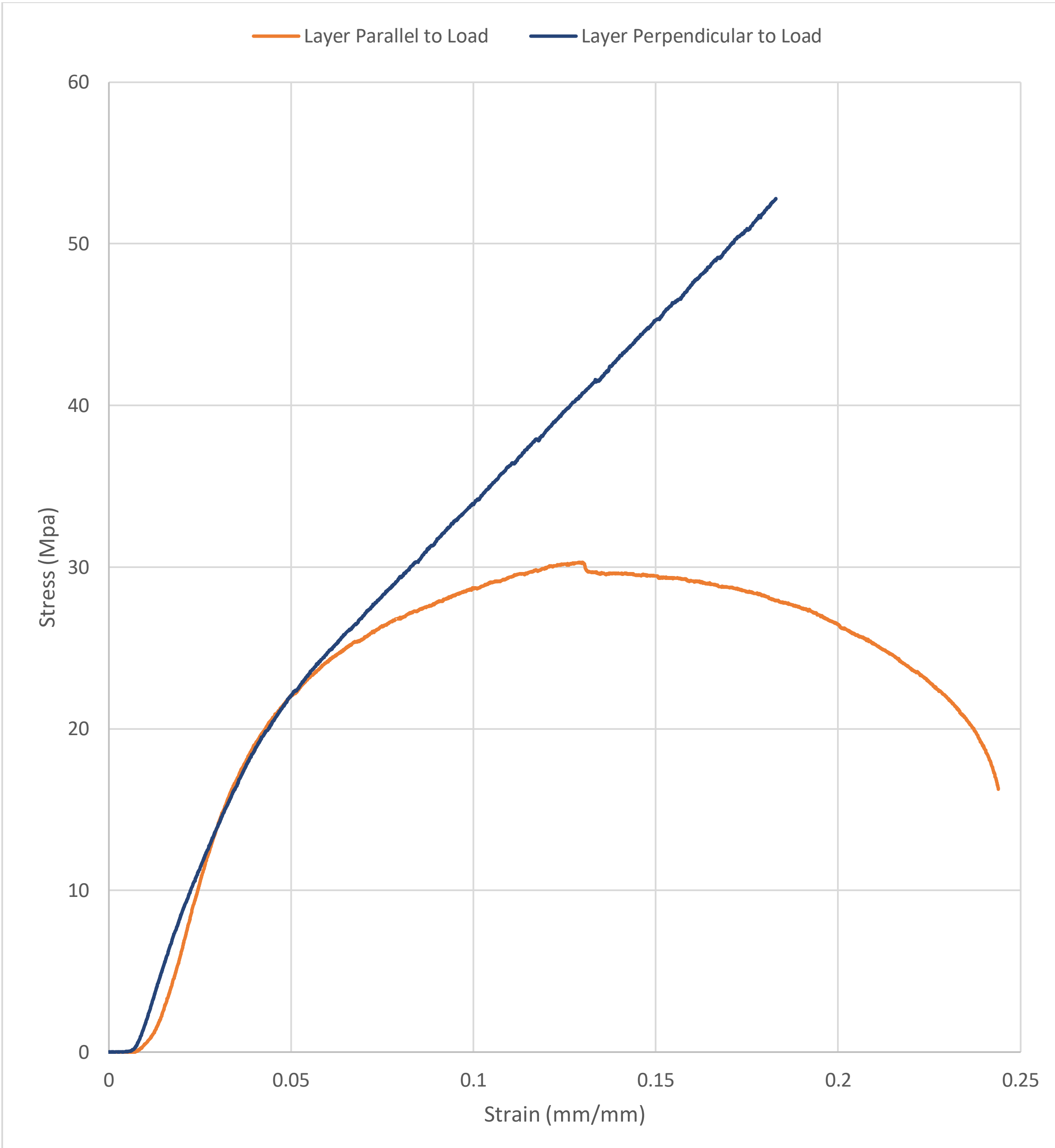

Figure 5.3. Stress strain curve of compression specimens.

Figure 5.4. Compressive HDPE specimens after load testing (loaded perpendicular to the layers on the left and loaded parallel to the layers on the right)

The Modulus of Elasticity of the specimens with their layers perpendicular and parallel to the loading surface was found to be 649 ± 95 MPa and 619 ± 190 MPa respectively, which is a difference of 4.7%. The yielding compressive stress for the specimens with their layers perpendicular and parallel to the loading surface was found to be 17.5 ± 1.8 MPa and 19.1 ± 1.4 MPa respectively, which is a difference of 8.7%. The values reported from the compressive test are summarized in Table 5.2. The Modulus of Elasticity and Yield Stress values are very similar for both loading tests, which is surprising due to the anisotropic nature of the material. This suggests that the direction of the load has less of an impact on the compressive properties of 3D printed HDPE.

Table 5.2. Results from HDPE compressive test

Mechanical Properties	HDPE specimen layers perpendicular to load	HDPE specimen layers parallel to load
Modulus (MPa)	649 ± 95	17.5 ± 1.8
Compressive Yielding Stress (MPa)	619 ± 190	19.1 ± 1.4

5.3 Impact

A total of six specimens were tested for the impact test. Only five specimens were used in the analysis due to poor layer adhesion and print quality for the sixth specimen. The impact specimens were tested at room temperature varying from 20°C to 22°C. The specimens were tested with a swinging pendulum with a mass of 0.45 Kgs. All specimens broke all the way through during the impact test. The failure planes appeared brittle and broke at a horizontal angle from the tip of the V-notch. The failure surface of the specimens appeared as a clean cut with no fibers or strands present. A representative image of a specimen after the impact test is presented in Figure 5.5. The impact energy was calculated for each specimen and the average value determined from the five specimens was 15.9 ± 1.7 J/m.

Figure 5.5. HDPE impact specimen after test.

5.4 Flexural

A total of six specimens were tested for flexural properties. Due to the ductility of the HDPE specimens, none of the specimens broke during the test and all of them reached the 5% strain limit. ASTM D790 (2003) recommends only reporting the Flexural Modulus and not the Ultimate Flexural Stress of the specimens due to the inconsistency of the results. A representative load versus displacement curve for the flexural specimens is presented in Figure 5.6. The average Flexural Modulus for the six specimens tested was found to be 957 ± 81 MPa.

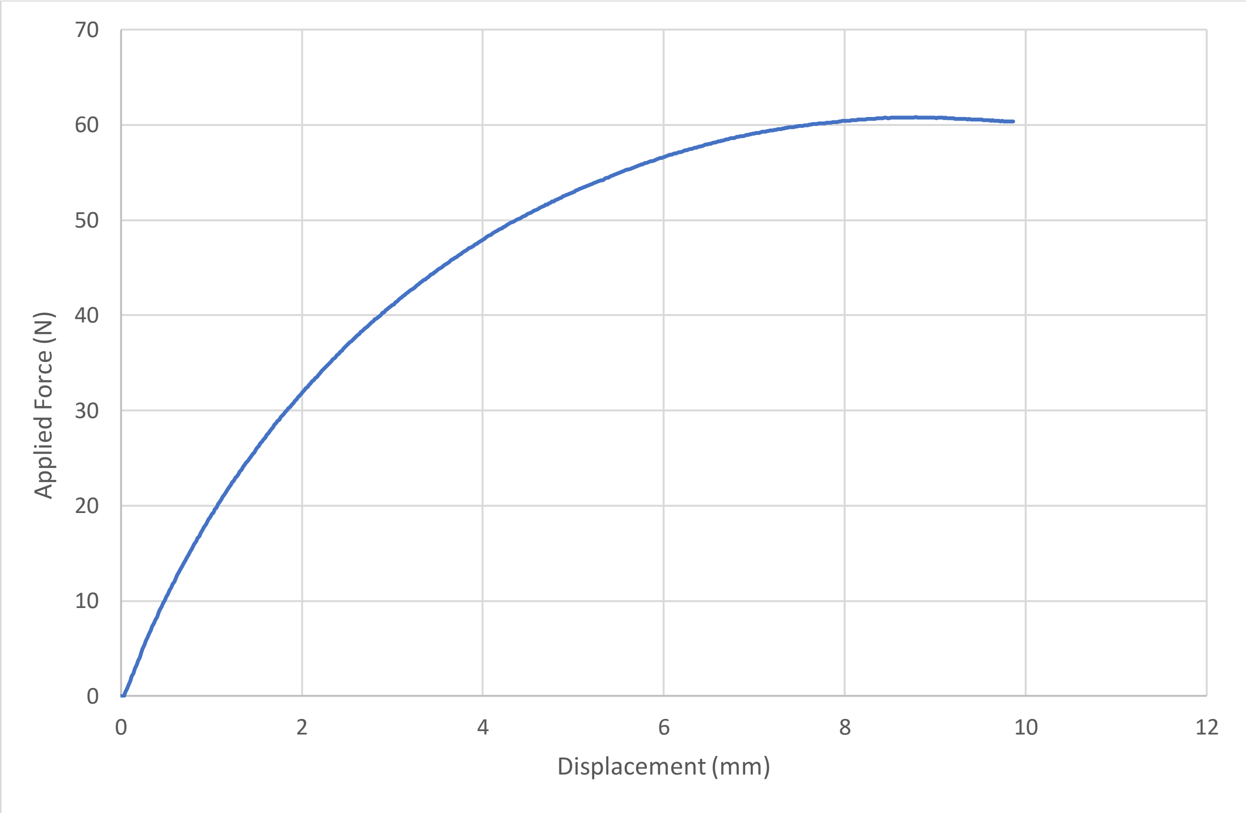

Figure 5.6. Load vs displacement for flexural specimens.

The flexural specimens experienced high deformations during the test and no surface cracks or breaks were observed after the test was complete. Several minutes after the flexural test was concluded, the flexural samples returned to their original forms from prior to the test with little plastic deformation. Figure 5.7 displays the difference between the test specimens immediately after the test and several minutes after. This suggests that the majority of the test was conducted in the elastic region of the material due to the small plastic deformation the specimens experienced. This also suggests that 3D printed HDPE is a very ductile material.

Figure 5.7. HDPE flexural specimen immediately after the test (top image) and several minutes after the flexure test (bottom image).

5.5 Shear

A shear test was conducted on six specimens to determine the shear properties of the material. The test resulted in a wide range of values. This wide range was due to poor print quality of the shear test specimens. The specimens had a curved surface due to the HDPE shrinking after the AM process. This curved shape caused the specimen to close in on themselves or folding while they were being tested. Due to this issue, none of the specimens were able to yield a definitive shear failure, thus, no results will be reported from this testing. An image of the shear specimens after testing can be seen in Figure 5.8.

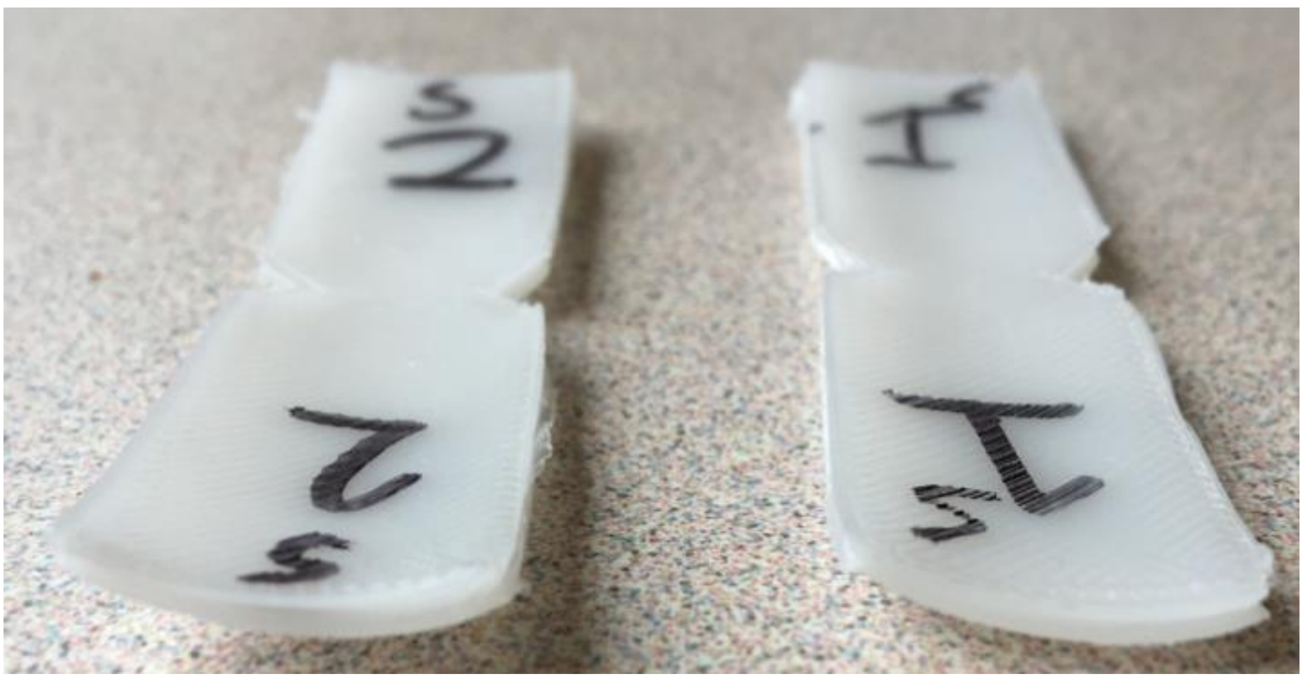

Figure 5.8. HDPE shear specimen after testing.

CONCLUSIONS

HDPE is one of the most common recyclable plastic material and, if it can be utilized as an AM material, it can have high environmental and economic impacts. This paper evaluated the best printer parameters, printing conditions, and mechanical properties of 3D printed HDPE. This paper also presented cheap and efficient ways to print small to large 3D objects for a consumer based 3D printer with easily obtainable materials. The paper also provides a basis for the performance and characteristics of 3D printed HDPE. The conclusions draw from this research are listed as follows:

- The ideal extrusion temperature and bed temperature was found to be 220°C and 125°C respectively. Larger layers height reduced shrinkage and warping of the material than smaller layer heights. Feed rate and travel speed had little effect on the printing quality. Lowering the fill percentage reduced shrinkage and warping of the material at the cost of the material's strength.

- Plastic HDPE bags (shopping bags) can be used as a sacrificial adhesion surface when 3D printing with HDPE for small 3D objects. The addition of tabs and clamps will allow larger 3D objects to be printed with HDPE.

- 3D printed HDPE Ultimate Tensile Strength was 32.4% lower than injection molded HDPE and the Tensile Modulus of Elasticity of 3D printed HDPE was 8.5% higher than injection molded HDPE. Voids in the 3D printed HDPE and less cross linkage contributed to the reduction of the ultimate tensile strength of the material.

- Ultimate Compressive Strength of 3D printed HDPE could not be determined due to the high ductility of the material. Analysis of the Compression Modulus of Elasticity showed that the material does not exhibit anisotropic properties under a compression load.

- Impact tests showed that the 3D printed HDPE fails with a clean fracture surface under a swinging pendulum. The average impact energy found from the analysis was 15.9 ±1.7 J/m.

- The flexural specimens did not break during the test and reached the ultimate strain limit of 5%. Very little plastic deformation was observed after the test as well, suggesting that 3D printed HDPE is a very ductile material. Ultimate Flexural Stress could not be reported due to this high ductility, but the Flexural Modulus was found to be 957 ± 81 MPa.

- Shear data was not reported due to the large variability in the results and the print quality of the specimens. Further investigation into the print quality and the analysis will be required in the future to yield accurate and notable results for shear properties.

FUTURE WORK

In this paper, HDPE was successfully printed consistently on a commercially available 3D printer to produce high quality specimens for mechanical testing. Through the exploration of using HDPE as an AM material, several aspects of additional research on HDPE arose. Three main aspects of future research applications are identified as follows:

1.) Recycling and reusing HDPE after it has undergone the AM process. This type of study has been conducted on PLA and other materials but has not been applied to pure HDPE for AM. Studying the number of generations of HDPE filament that can be produced from the same parent material would determine if HDPE is a sustainable AM material with a long-life cycle. Analyzing the degradation process and its effect on the mechanical and physical properties of the material would also have to be explored in this research to ensure the performance of the material.

2.) The compression and flexural testing of the HDPE specimens showed that the material exhibits very ductile properties. These ductile properties will have to be reduced if HDPE will become a viable construction material. A study on composite HDPE material that explores various additives and fillers to increase the strength and rigidity of the material would determine if a composite HDPE material would show more desirable characteristics as a construction material.

3.) The methods presented in this paper to combat the thermal properties of HDPE worked well for small scale applications but would not be applicable for large scale structures. Singh et al. (2018a, 2018b) reported on two different studies that showed how using the addition of hollow fly-ash cenospheres in the HDPE matrix reduced the undesired thermal properties of HDPE when undergoing an AM process. This paper only explored small scale applications. Larger scale applications of this composite material can be studied to determine if this material would be a practical material for larger scale AM printed objects or structural members.

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