Anisotropy Evolution Due to Surface Treatment on 3D-Printed Fused Deposition Modeling (FDM) of Acrylonitrile Butadiene Styrene (ABS)

2017

Blake E. Lozinski
University of Central Florida

Recommended Citation

http://stars.library.ucf.edu/honorstheses/269

This Open Access is brought to you for free and open access by the UCF Theses and Dissertations at STARS. It has been accepted for inclusion in Honors in the Major Theses by an authorized administrator of STARS. For more information, please contact lee.dotson@ucf.edu.
ANISOTROPY EVOLUTION DUE TO SURFACE TREATMENT ON 3D-PRINTED FUSED DEPOSITION MODELING (FDM) OF ACRYLONITRILE BUTADIENE STYRENE (ABS)

by

BLAKE LOZINSKI

A thesis submitted in partial fulfilment of the requirements for the degree of Bachelors of Science in the Department of Mechanical and Aerospace Engineering in the College of Engineering and Computer Science at the University of Central Florida

Fall Term
2017

Major Professor: Dr. Alain Kassab
© 2017 Blake Lozinski
ABSTRACT

Purpose: This paper will present insight to the methodology and results of the experimental characterization of Acrylonitrile Butadiene Styrene (ABS) using Fused Deposition Modeling (FDM). The work in this research explored the effects of print orientation, surface treatment, and ultraviolet (UV) light degradation with the utilization of Digital Image Correlation (DIC) on ABS tensile specimens.

Design/methodology: ABS specimens were printed at three build orientations (flat (0 degrees), 45 degrees, and up-right (90 degrees)). Each of these specimens were treated with three different surface treatments including a control (acrylic paint, Cyanoacrylate, and Diglycidyl Bisphenol A) followed by exposure to UV light to the respective batches. This experiment design will provide tensile direction properties with the effect of thermoset coatings and UV degradation. Dogbone FDM specimens based on ASTM standard D638 type IV were printed on a Stratasys Dimension SST (Soluble Support Technology) 1200es 3D Printer and loaded into a MTS Landmark Servohydraulic Test Systems. Analysis was performed on the fracture section of the tensile specimens utilized DIC and comparing Ultimate Tensile Strength (UTS) and Ultimate Fracture Strength (UFS).

Findings: From the results UV light did not play a large factor in the strength of the specimens. The print orientation showed the largest anisotropic behavior where some specimens experienced as much as a 54% difference in ultimate tensile strength. Thermoset coated specimens experienced a maximum of 2% increase in strength for the Cyanoacrylate and Diglycidyl Bisphenol A specimens where the acrylic paint and natural did not. Several findings were of value when looking at the stress strain plots.

Originality/value: This paper provides knowledge to the limited work on print build orientation, thermoset coatings and, UV light on ABS specimens. Very little to no work has been done on these
three properties. This paper can serve as the foundation of future work on external applications on ABS plastics.
ACKNOWLEDGMENTS

This research was performed at the University of Central Florida through funding from Limbitless Solutions Inc. Limbitless Solutions Inc. (non-profit) was established as a direct support organization of the University of Central Florida to research, design, create, and deliver advancements in disability technology infused with artistic design, and to promote access and engagement STEM/STEAM education. Albert Manero (co-founder and executive director) and Dominique Courbin (co-founder and director of production) are mentors on this project.
# TABLE OF CONTENTS

LIST OF FIGURES ................................................................. viii

LIST OF TABLES ................................................................. ix

CHAPTER 1: INTRODUCTION ......................................................... 1

  Motivation ................................................................. 2

  Coatings ................................................................. 3

  Ultraviolet Light ......................................................... 4

  Digital Image Correlation ............................................... 6

  Confidence Interval and t-Test .......................................... 7

CHAPTER 2: FABRICATION METHODS, EXPERIMENTAL SET UP, AND PROCEDURE ......................................................... 8

  2.1 Materials and fabrication ........................................... 9

  2.2 Testing and experimental set-up ................................... 14

  2.3 Experimental procedure ........................................... 16

CHAPTER 3: EXPERIMENTAL RESULTS AND DISCUSSION ................. 18
LIST OF FIGURES

Figure 1.1: Specimens print orientations .................................................. 2
Figure 1.2: Specimens exposed to UV light ................................................. 5
Figure 1.3: Specimens exposed to UV light ................................................ 6
Figure 2.1: Schematic representation of the ASTM D638 Type IV geometry in mm [22] 9
Figure 2.2: A batch of Diglycidyl Bisphenol A specimens ............................ 12
Figure 2.3: Finished specimens ready for UV light exposure .......................... 13
Figure 2.4: Specimens exposed to UV light ................................................ 14
Figure 2.5: Testing set-up ............................................................................ 15
Figure 2.7: Testing grips set to 400 psi ........................................................ 17
Figure 3.1: Stress strain plots for the UV light exposed specimens ................. 23
Figure 3.2: Stress strain plots for the non-UV light exposed specimens ............ 25
Figure 3.3: Gauge sections of each of the sample types for no UV light exposure . . . 26
Figure 3.4: Gauge sections of each of the sample types for no UV light exposure . . . 27
Figure 3.5: Gauge sections of each of the sample types for UV light exposure .... 28
Figure 3.6: Gauge sections of each of the sample types for no UV light exposure . . . 28
LIST OF TABLES

Table 2.1: 3D printing settings and specifications for Stratasys Dimension 1200es . . . . 8

Table 2.2: Number of specimens at each level (no UV light) . . . . . . . . . . . . . . 10

Table 2.3: Number of specimens at each level (UV light) . . . . . . . . . . . . . . . . 11

Table 3.1: Data set for UV exposed analyzed data . . . . . . . . . . . . . . . . . . . 19

Table 3.2: Data set for non-UV exposed analyzed data . . . . . . . . . . . . . . . . . 20
CHAPTER 1: INTRODUCTION

Fused deposition modeling (FDM) is an additive manufacturing technique commonly known as 3D printing [1,2,21,23]. FDM is the most common method for 3D printing and rapid prototyping cases [14]. 3D printing works by extruding molten polymeric material through a heated nozzle by creating multiple layers upward until finished [1,2,3,4]. This technique has gained acceptance and popularity in the manufacturing and educational settings [3,5,6]. The FDM process is made possible by creating a computer-aided design (CAD) file of the projected part and exporting it to a stereo lithography (STL) file. From here the STL file can be uploaded to a slicer program in which the cross section of the model is broken down into individual layers of the variable height the user may choose. The slicer program then converts the file to a G-code in which the printer can read. Once the printer is setup it will start by heating up the nozzle to the specific temperature to melt the polymer filament. Once achieved the printer will begin to extrude the material and create the part.

The material filament is fed through a heated nozzle where the extrusion is specified by the diameter in the extrusion head. The head moves in the x-y plane depositing the material on the platform creating the part. Once one layer is finished the build platform moves downward in the specified z direction and continues the next layer. This process is repeated until the print job is complete.

Currently, there are limited number of polymers that are able to be used for 3D printing due to the specific properties [6,16,17,20]. Some of materials properties that play a factor are, glass transition temperature, melting point, and tendency to shrink upon solidification [24]. When considering these properties two very common materials come into play, Acrylonitrile Butadiene Styrene (ABS) and Polylactic Acid (PLA) are two polymer materials that are abundant in the rapid prototyping world, where ABS will be looked into further in this paper [16,17,18,24]. Other materials
are able to be used in FDM but are not as common as ABS and PLA [18,19]. Along with limited material selection the applications for these materials are restricted. Other 3D printing applications have progressed from a prototyping era to a product of everyday use. This applications have increased to 3D printing metals and cell structures but follow other process similar to FDM [4,17,20]. The development of polymer matrix composites (PMC) is a rising path to use in 3D extrusion with ease of material compounding and blending with low prices but can be a factor in the material properties [8,9,10].

Figure 1.1: Specimens print orientations

Motivation

The motivation of this study is to study the effects of print orientation, surface treatment and UV light exposure that will directly correlate to Limbitless INC. 3D printed arms. The children arms are designed to withstand high stresses and be exposed to outside environment. The surface treat-
ments in this study will help understand the effect it plays on the material and in return determine if they strengthen the material and in what way. The print orientation aspect will future the way Limbitless INC prints arms in such a fashion that the arms will hold the highest strength.

Coatings

The surface coatings in this study added another factor to look into [12]. Here three coatings and a control are identified as acrylic paint, Cyanoacrylate, and Diglycidyl Bisphenol A. The common names for these substances are acrylic paint, super glue, and Plastic Fusion Epoxy respectively. These coatings may play a role in the treatment of the outer surface of the specimen where it may melt the outer surface bonding the plastic together leading to higher strength or in the case of the acrylic paint allow the blockage of the UV radiation [9, 11].

Cyanoacrylate is a fast acting vinyl polymer adhesive of the acrylate family that has found use since its introduction in the early 1940’s [10, 11]. Cyanoacrylate is a clear, low viscosity liquid at room temperature and is commonly known as ”super glue” as it readily reacts with water; even such small amounts as surface moisture or moisture in the air to polymerize and form a thermoplastic resin. It has been known that the complete curing process can takes up to 24 hours but noticeable strengthening can be shown instantly this is an exothermic reaction that can produce high temperatures. Extensive heating can cause de-polymerization. Cyanacrylate based formulas are known for their rapid curing, excellent adhesion strength, and easy to use properties. The disadvantages include low solvent and temperature resistance and undesirable peel and impact resistance.

Diglycidyl Bisphenol A (BADGE) is a resin 95% and has a strength of up to 3770 psi when applied to an object specifically plastics. Major uses for BADGE epoxy resins are adhesives, potting and encapsulating media and coatings. The product is equipped with resin and harder where the
adhesive must be mixed and allowed to cure. This epoxy was chosen by random selection hence it showed an increase in strength when applied to plastic.

Ultraviolet Light

In this study the effect of UV light was incorporated using accelerated degradation to see impact on the ABS specimens. The nature’s light source is an important variable to keep in mind for polymers that will be used in an outdoor setting. Depending on the resin based thermoplastic UV light can play a major role in its degradation [7,8,9]. The UV-C spectrum was looked into in this study and exposed half of the specimens to the light source. The UV-C range was chosen because it gives off enough radiation and is most effective. In this range a 254 nanometers (nm) 110 volt 200 watt UV towel warmer walled with reflective borders was used to place the specimens in. When looking for a light source it is require for the object to get full 360 degree exposure to the light therefore a enclosed space was chosen for this test. This factor in the testing gave a benchmark test to determine the damage brought upon the specimens exposed to the light source to the non exposed specimens.
Figure 1.2: Specimens exposed to UV light
To be able to measure the shear modulus, the average shear stress is calculated by dividing the load by the original cross sectional area of the test section. To be able to measure this during testing a electrical resistance strain gauge is typically used. In this case the use of strain gauges are not able to be used due to the gauge section and the self heating during use. In doing so this study adopted the method of Digital Image Correlation (DIC), this is a non contact method for obtaining the shear strain [15,24]. The stain has to be measured throughout the entire test section to be able to be uniform. The specimens are painted white and then coated with small black dots that the DIC software can track through images giving the strain reading. The tensile stress was calculated by dividing the load by the cross sectional area shown in the stress.
Confidence Interval and t-Test

In the study the confidence interval was calculated for the raw data displayed in the results section. The confidence interval is the range of values that act as an estimate of the unknown population parameter. To calculate the confidence interval the mean is calculated by the summation of the data values divided by the sample size. Next the standard deviation can be determined by taking the square root of the sum of the difference of the mean squared divided by the sample size. Lastly, confidence interval can be calculated by the confidence coefficient multiplied by the standard deviation divided by the square root of the sample size. A student t test was incorporated in this study where the test compares the averages and standard deviations of two samples to see if there is a significant difference between each other. The comparison was used in the UV light exposure testing. Here the specimen exposed to UV was compared to the non UV specimen.

\[
\text{Mean, } \bar{x} = \frac{\sum_{i=1}^{5} x_i}{n}
\]

\[
\text{Standard deviation, } S_x = \sqrt{\frac{\sum_{i=1}^{5} (x_i - \bar{x})^2}{n}}
\]

\[
\text{Confidence Interval, } Z \times \frac{\sigma}{\sqrt{n}}
\]

\[
\text{Student t Test, } t = \frac{(x_1 - \bar{x}_2)}{\sqrt{\frac{(S_1)^2}{n_1} + \frac{(S_2)^2}{n_2}}}
\]
CHAPTER 2: FABRICATION METHODS, EXPERIMENTAL SET UP, AND PROCEDURE

The experiments in this study were designed to show the effect of print orientation, thermoset coatings, and UV light exposure in the tensile direction with the use of DIC. The respective specimens were printed in the flat (0 degrees) orientation, 45 degrees, and up-right (90 degrees) orientation. Where a total of 120 specimens were printed, prepared and tested.

Table 2.1: 3D printing settings and specifications for Stratasys Dimension 1200es

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Stratasys Dimension SST 1200es 3D Printer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>ABSplus</td>
</tr>
<tr>
<td>Support material</td>
<td>Soluble (SST 1200es)</td>
</tr>
<tr>
<td>Air Gap (mm)</td>
<td>0.0</td>
</tr>
<tr>
<td>Layer thickness (mm)</td>
<td>0.254</td>
</tr>
<tr>
<td>Layer height (mm)</td>
<td>0.01</td>
</tr>
<tr>
<td>Filament color</td>
<td>Ivory</td>
</tr>
<tr>
<td>Fill (percent)</td>
<td>100</td>
</tr>
<tr>
<td>Liquefier temperature (Celsius)</td>
<td>270</td>
</tr>
<tr>
<td>Size (mm)</td>
<td>254x254x305</td>
</tr>
</tbody>
</table>
2.1 Materials and fabrication

The material specimens tested in this research were acrylonitrile butadiene styrene (ABS) that were printed in a Stratasys Dimension™SST 1200es 3D printer. The geometries were printed following the ASTM standard D-638 Type IV dimensions shown in table 2.1 [22]. The specimens were printed at a thickness of 5 mm that were created in Dassault Systmes SOLIDWORKS™, then exported to a stereo lithography STL format, and imported into a slicer software to create a G-code that the printer uses to print each specimen type. The Stratasys Dimension™1200es printed were held to constant parameters in which can be found in table 2.1. The raster pattern was kept constant throughout printing where the specimens were printed upward at ±45.

Figure 2.1: Schematic representation of the ASTM D638 Type IV geometry in mm [22]
### Table 2.2: Number of specimens at each level (no UV light)

<table>
<thead>
<tr>
<th>Orientation</th>
<th>Thermoset Coating</th>
<th>Number of Specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat (0 degrees)</td>
<td>Natural</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Acrylic Paint</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Cyanoacrylate</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Diglycidyl Bisphenol A</td>
<td>5</td>
</tr>
<tr>
<td>45 degrees</td>
<td>Natural</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Acrylic Paint</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Cyanoacrylate</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Diglycidyl Bisphenol A</td>
<td>5</td>
</tr>
<tr>
<td>Up-right (90 degrees)</td>
<td>Natural</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Acrylic Paint</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Cyanoacrylate</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Diglycidyl Bisphenol A</td>
<td>5</td>
</tr>
</tbody>
</table>
Table 2.3: Number of specimens at each level (UV light)

<table>
<thead>
<tr>
<th>Orientation</th>
<th>Thermoset Coating</th>
<th>Number of Specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat (0 degrees)</td>
<td>Natural</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Acrylic Paint</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Cyanoacrylate</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Diglycidyl Bisphenol A</td>
<td>5</td>
</tr>
<tr>
<td>45 degrees</td>
<td>Natural</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Acrylic Paint</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Cyanoacrylate</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Diglycidyl Bisphenol A</td>
<td>5</td>
</tr>
<tr>
<td>Up-right (90 degrees)</td>
<td>Natural</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Acrylic Paint</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Cyanoacrylate</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Diglycidyl Bisphenol A</td>
<td>5</td>
</tr>
</tbody>
</table>

The thermoset coatings chosen were a control specimen, acrylic paint, Cyanoacrylate, and Diglycidyl Bisphenol A. The cyanocrylate is a superglue compound and Diglycidyl Bisphenol A is an epoxy based compound. Each of the respective specimens were coated by painting on the coating using foam brushes and let to dry at room temperature. The coated specimens were then painted white with black speckles allowing for the use of DIC. Each of the coated and painted specimens were then exposed to the UV light source.
Figure 2.2: A batch of Diglycidyl Bisphenol A specimens
Accelerated degradation was added to this experiment by exposure to UV irradiation. The thermoset coated specimens were exposed to 254 nm of UV-C ultraviolet light for a total of 48 hours in a UV chamber. A total of 20 of the same specimen type were exposed at once and kept in at room temperature until tested. The UV chamber used allowed the specimens to get full radiation of light compared to a single light source.
2.2 Testing and experimental set-up

The specimens were tested at a rate of 5 mm/min at room temperature 23 degrees Celsius. The test was conducted on a MTS Landmark Servo-hydraulic Test Systems with the use of 647 Side-Loading Hydraulic Wedge Grips. The grips were set at 400 psi to grip the specimen without slipping. The universal testing machine was equipped with a 2.5 kN load cell. Figure 2.7 show the grip clamps used to hold the specimen. The load values were acquired using the MTS software at a rate of 0.1 seconds.
The tensile Lagrange stress was calculated by dividing the load by the cross sectional area shown in Figure 2.5.
the stress equation. To collect the correct strain data, DIC was chosen for the strain measurement. Along with DIC the calculated strain was used for reassurance. To calculate strain the displaced specimen minus the original length divided by the original length was calculated shown in the strain equation. DIC is a second method and more sophisticated method because the displacement it measures is independent of grip slippage, and load cell compliance. Moreover, other methods such as electrical resistance strain gauges will alter the mechanical properties of the polymer and cause significant uncertainties in the results. will be affected and cause issues. A single 2D digital image camera was set up to capture the movement of the specimens. Specimen preparation required each to be painted white and a light speckle pattern over the white coat. The camera was set to record at 0.5 images per second where the images were interpreted using the VIC-2D System software.

2.3 Experimental procedure

Each of the test specimens followed the same procedure. Each batch started off with the single DIC specimen and collected the data followed by the 4 remaining specimens. Each test was loaded by placing the bottom of the specimen in the grips and applying the 400 psi pressure while keeping it balanced vertically. From there the top grip was lowered and applied the pressurized grips to 400 psi. Once the specimens was secured in the Side-Loading Hydraulic Wedge Grips the station manager MTS software was zeroed and started the test at 5 mm/min along with the start of the DIC software simultaneously. The test continued until failure where the test and DIC software were stopped and the grips were unpressurized and removed the specimen. Each of the 120 specimens were tested in the same fashion. After the testing was complete, a MATLAB™script was developed and the data was imported the MATLAB™code allows the user to calculate and create plots to compare the effects of the different variables, in this case the print orientation, thermoset coating, and UV light exposure.
Figure 2.7: Testing grips set to 400 psi
CHAPTER 3: EXPERIMENTAL RESULTS AND DISCUSSION

Tensile Testing

The specimens were tested in batches of five for each of the four coatings and three print orientations. In the results it can be found that the average of the seven tests was taken and used for that set. In previous papers, the authors were concerned with several components while testing. These include the Youngs Modulus, yield strength, ultimate strength, and failure modes of the specimens [1,2,3,4]. This paper incorporates the Ultimate Tensile Strength (UTS), Ultimate Fracture Strength (UFS) and Digital Image Correlation (DIC) due to the fact that the main objective of this research was to identify the effect of the three variables (print orientation, surface treatment and UV light exposure) and how they affect mechanical properties. The ultimate strength was recorded at the material’s maximum point; and the ultimate fracture strength was taken at the point where the specimens completely fractured. DIC was incorporated in this study where it is used to examine the strain at failure from the last DIC image before complete failure.
Table 3.1: Data set for UV exposed analyzed data

<table>
<thead>
<tr>
<th>Orientation</th>
<th>Coating Type</th>
<th>Ultimate Tensile Strength (MPa, 95% CI)</th>
<th>Ultimate Fracture Strength (MPa, 95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat (0 degrees)</td>
<td>Natural</td>
<td>43.986±1.244</td>
<td>39.650±1.915</td>
</tr>
<tr>
<td></td>
<td>Paint</td>
<td>44.524±1.583</td>
<td>40.439±1.565</td>
</tr>
<tr>
<td></td>
<td>Cyanoacrylate</td>
<td>47.393±2.338</td>
<td>46.342±2.339</td>
</tr>
<tr>
<td></td>
<td>Diglycidyl Bisphenol A</td>
<td>47.137±3.002</td>
<td>44.135±3.063</td>
</tr>
<tr>
<td>Up-right (90 degrees)</td>
<td>Natural</td>
<td>27.398±2.517</td>
<td>27.398±2.517</td>
</tr>
<tr>
<td></td>
<td>Cyanoacrylate</td>
<td>33.197±2.005</td>
<td>33.197±2.005</td>
</tr>
<tr>
<td></td>
<td>Diglycidyl Bisphenol A</td>
<td>28.592±2.994</td>
<td>28.592±2.994</td>
</tr>
<tr>
<td>45 Degrees</td>
<td>Natural</td>
<td>39.676±0.910</td>
<td>39.026±1.037</td>
</tr>
<tr>
<td></td>
<td>Paint</td>
<td>39.919±1.732</td>
<td>38.668±1.642</td>
</tr>
<tr>
<td></td>
<td>Cyanoacrylate</td>
<td>42.012±0.606</td>
<td>41.685±0.655</td>
</tr>
<tr>
<td></td>
<td>Diglycidyl Bisphenol A</td>
<td>42.744±2.891</td>
<td>40.459±3.050</td>
</tr>
</tbody>
</table>
Table 3.2: Data set for non-UV exposed analyzed data

<table>
<thead>
<tr>
<th>Orientation</th>
<th>Coating Type</th>
<th>Ultimate Tensile Strength (MPa, 95% CI)</th>
<th>Ultimate Fracture Strength (MPa, 95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat (0 degrees)</td>
<td>Natural</td>
<td>43.468±0.927</td>
<td>40.571±0.891</td>
</tr>
<tr>
<td></td>
<td>Paint</td>
<td>42.258±0.943</td>
<td>38.592±0.954</td>
</tr>
<tr>
<td></td>
<td>Cyanoacrylate</td>
<td>44.394±2.594</td>
<td>42.352±2.171</td>
</tr>
<tr>
<td></td>
<td>Diglycidyl Bisphenol A</td>
<td>45.586±1.228</td>
<td>41.833±1.349</td>
</tr>
<tr>
<td>Up-right (90 degrees)</td>
<td>Natural</td>
<td>27.209±3.260</td>
<td>27.209±3.260</td>
</tr>
<tr>
<td></td>
<td>Paint</td>
<td>28.961±3.788</td>
<td>28.961±3.788</td>
</tr>
<tr>
<td></td>
<td>Cyanoacrylate</td>
<td>34.224±3.235</td>
<td>34.224±3.235</td>
</tr>
<tr>
<td></td>
<td>Diglycidyl Bisphenol A</td>
<td>32.458±1.561</td>
<td>32.458±1.561</td>
</tr>
<tr>
<td>45 Degrees</td>
<td>Natural</td>
<td>39.956±1.283</td>
<td>37.951±1.463</td>
</tr>
<tr>
<td></td>
<td>Paint</td>
<td>40.121±3.469</td>
<td>40.571±3.711</td>
</tr>
<tr>
<td></td>
<td>Cyanoacrylate</td>
<td>42.367±1.021</td>
<td>42.042±1.126</td>
</tr>
<tr>
<td></td>
<td>Diglycidyl Bisphenol A</td>
<td>40.434±1.030</td>
<td>38.563±1.487</td>
</tr>
</tbody>
</table>
Analyzing the data, it can be noticed that there is anisotropic behavior when comparing print orientation with differences as great as 54%. The entire data set can be found in table 3.1 and 3.2. Considering the UV light exposure, analysis of the specimens exposed to the light on average were 0.19% stronger for the ultimate strength and 0.09% stronger for the ultimate fracture strength. This was not an expected outcome as the light was intended to degrade the specimens and make them weaker. The short amount of UV exposure may have further cured the polymer increasing the overall strength of the specimens. The specimens were exposed to 48 hours of direct UV light, and in future studies, the specimens should be exposed to a longer duration allowing for the degradation of the polymer to accumulate resulting in expected degradation of the mechanical properties. The largest difference was in the Diglycidyl Bisphenol A 90 degrees specimens where the ultimate strength was 12.67% weaker when exposed to UV light. It can be noticed that the print orientation played a factor in the ultimate strength and ultimate fracture strength for both UV and non-UV specimens. The 90 degrees specimens had the lowest ultimate strength where the UV natural specimens were on average 36.61% weaker than the 45 degree and 46.47% weaker than the 0 degrees specimens for the ultimate strength. The ultimate fracture strength was calculated to be smaller but still show the 90 degrees UV natural specimens to be overall weaker. Here the 90 degree specimens were 35.01% weaker than the 45 degree and 36.54% weaker than the horizontal specimens. This trend can be seen throughout the data set where the 0 degree specimens had the highest ultimate strength and ultimate fracture strength followed by the 45 degree specimens and lastly the 90 degrees specimens. Examining the surface coatings, the Diglycidyl Bisphenol A seemed to be the only treatment that was affected by the UV light showing the UV light increased the ultimate strength by 7.19% on average between the orientations. From the data set, the Cyanoacrylate and Diglycidyl Bisphenol A did enhance the ultimate strength and ultimate fracture strength by nearly 2% where the natural and paint specimens were relatively close in comparison.

To complement the tables showing the overall data set the tensile test data was plotted in a stress
strain curve to display the data visually. Each specimen type was plotted and then average using the MATLAB\textsuperscript{TM} code. This will give an overall picture of the data spread and represent the true stress-strain relation.
Figure 3.1: Stress strain plots for the UV light exposed specimens
Figure 3.2: Stress strain plots for the non-UV light exposed specimens

From the figures above each data set was plotted to show the characteristics of the materials. It can be noticed that the plots are separated into two set showing the UV specimens and the non UV specimens. As shown in figures 3.1 and 3.2 it can be noticed that the brittle behavior is seen in the 90 degrees specimens because the strain is dependent on the adhesion of the layer in which the force is being applied. The 0 degrees specimens clearly show the longest plastic deformation but it can be noticed that the Cyanoacrylate 0 degrees specimens do not represents this plastic deformation for both UV and non UV types. The 45 degrees specimens seem to show a mix between the 90 degrees and 0 degrees specimens where an average ultimate strength was 40.9 MPa. The coatings variation can be seen in the graphs where the Cyanoacrylate and Diglycidyl Bisphenol A can replicate the data table and see a slight increase in the ultimate strength compared to the natural and paint specimens.

The DIC images from each of the tests were used to evaluate material characteristics and show
potential patterns. The strain patterns can show potential failure at an early stage due to non-symmetric loading and print defects in the specimens. These may effect the longevity of the test and can cause pre-mature failure that would provide invalid data. Figures 3.3 and 3.4 display representative samples of the DIC specimens. The images show the Hencky’s elasticity model that is an isotropic finite elasticity model showing a linear relation between the Kirchhoff stress and the logarithmic strain [13]. Throughout the DIC testing there was a strong correlation between loading conditions and displacements as well as the strain variations. The Hencky’s elasticity model show where the highest stress and strain are located and according to the scale will show where the fracture will occur.

Figure 3.3: Gauge sections of each of the sample types for no UV light exposure
Figure 3.4: Gauge sections of each of the sample types for no UV light exposure
Figure 3.5: Gauge sections of each of the sample types for UV light exposure

Figure 3.6: Gauge sections of each of the sample types for no UV light exposure

After the testing each specimen was visually evaluated to determine if there was a clean fracture.
All of the specimens fractured in the gauge section with two samples in the high or low region but still allowed for valid data. It was noticed that all of the 45 degree specimens fractured at a angle close to 45 degrees. This could be due to the fact that adhesion between the layers were 45 degrees out of phase of the tensile direction therefore causing the specimen to fracture this way.
CHAPTER 4: CONCLUSION

In this study Acrylonitrile Butadiene Styrene (ABS) specimens were produced, prepped and tested according to ASTM standard D-638 to analyze the materials properties [22]. The experiment included the comparison of three print orientations (0 degrees, 45 degrees and 90 degrees) and four surface treatments including a control (acrylic paint, Cyanoacrylate and Diglycidyl Bisphenol A). The study incorporated the use of digital image correlation (DIC) to ensure symmetric loading and to locate print defects if found. The main component examined the motivation of the ultimate tensile strength and the ultimate fracture strength for the specimens in this study. Anisotropy originated when comparing the ultimate tensile strength and the ultimate fracture strength on the print orientations where the 90 degrees specimens had the lowest ultimate strength. The 90 degrees UV natural specimens were on average 36.61% weaker than the 45 degree and 46.47% weaker than the 0 degrees specimens for the ultimate strength. Some print orientations experienced as much as 54% difference in ultimate tensile strength.

When examining the UV light exposure effect, the specimens exposed to the light were 0.19% stronger on average for the ultimate strength and 0.09% stronger for the ultimate fracture strength. When computing a comparison of mean’s student t test, t is shown to be 0.655 showing a small likelihood that there is a significant difference between the two populations. A conclusion cannot be made, but based on assumptions the specimens will need to be exposed to a longer degradation period. In this study the UV specimens were exposed to 48 hours of UV light where future studies should looking into long term effects. The short duration of UV light exposure shows the specimens with surface treatment were further cured strengthening the material. Lastly the surface coatings were analyzed as showed that the Cyanoacrylate and Diglycidyl Bisphenol A specimens did enhance the ultimate strength and ultimate fracture strength by nearly 2% but the natural and paint specimens were not effected. The Diglycidyl Bisphenol A was the only treatment that was
affected by the UV light where the light increased the ultimate strength by 7.19% on average.

The stress strain curves were created and plotted to helped display the anisotropy in the specimens displayed in figures 3.1 and 3.2. The 90 degrees specimens clearly showed little to no plastic deformation resulting in a brittle fracture where the 0 degrees specimens had a long plastic deformation period except for the Cyanoacrylate thermoset coating specimens. The Cyanoacrylate specimens showed a decreased plastic deformation section in the stress-strain curves. The 45 degree specimens showed a mix between the 90 degrees and 0 degrees specimens and had a ultimate tensile strength of 40.9 MPa on average. When using DIC, strain patterns can show pre-mature failure (figures 3.3 and 3.4) with asymmetric loading and print defects in the material. It can be concluded that anisotropy was found in all of the studied specimens. When producing 3D printed models, these factors should be incorporated depending on the design and product.
APPENDIX A: REFERENCES


