THE PENNSYLVANIA STATE UNIVERSITY
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DEPARTMENT OF MECHANICAL AND NUCLEAR ENGINEERING

EFFECTS OF EXTRUSION TEMPERATURE AND PRINTER NOZZLE SPEED ON
THE TENSILE PROPERTIES OF 3D PRINTED POLYLACTIC ACID

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ABSTRACT

The notion of additively manufacturing or “3D printing” objects has existed only for the past few decades, yet it has become one of the most promising technologies for the future of manufacturing. As the technology has matured, the focus on additive manufacturing (AM) has begun to shift from simply what it is capable of producing to how the product performs in a real engineering scenario. This layer-by-layer type of manufacturing inherently creates part specimens that are heterogeneous in structural composition, which creates difficulty in pinpointing exact material strength characteristics. The aim in this thesis is to perform experiments that isolated two key variables of additive manufacturing in order to correlate them with changing material strength characteristics. The two variables of printer nozzle speed and extrusion temperature were selected due to the lack of prior research on their impact to material characteristics. The material extrusion method of additive manufacturing was used to create tensile test specimens out of polylactic acid (PLA) that were strained to failure. After analyzing the tensile stress/strain curves, it was clear that increased extrusion temperature correlated positively with specimen ultimate tensile strength, while increased nozzle speed correlated negatively. An increase in nozzle temperature from 190°C to 220°C produced an 8.2% increase in strength, and an increase in print speed from 30mm/s to 90mm/s produced a 3.5% decrease in strength. Other tensile characteristics such as modulus of elasticity, toughness, or strain at failure did not correlate strongly with either of the variables.
# TABLE OF CONTENTS

List of Figures ........................................................................................................... iv
List of Tables ............................................................................................................... v
Acknowledgements .................................................................................................... vi

1. Introduction ......................................................................................................... 1
   1.1 Background and Overview of Additive Manufacturing .......................... 1
   1.2 Project Motivation ............................................................................... 4
   1.3 Research Objectives .......................................................................... 8

2. Literature Review ............................................................................................... 10
   2.1 Effects of Bulk PLA Composition on Material Properties ............. 10
   2.2 Effects of Thermal History on PLA Material Properties .......... 12
   2.3 Effects of Print Geometry and Slicing Settings on Material Properties 16

3. Procedure ......................................................................................................... 20
   3.1 Experimental Design ....................................................................... 20
   3.2 Production of Test Specimens ......................................................... 22
   3.3 Tensile Testing of Specimens ......................................................... 27
   3.4 Troubleshooting Procedures ......................................................... 28

4. Analysis and Results ....................................................................................... 30
   4.1 Converting Raw Data to Meaningful Data .................................... 30
   4.2 Tensile Test Results ...................................................................... 32
   4.3 Potential Sources of Error .............................................................. 35

5. Conclusions ....................................................................................................... 37
   5.1 Contributions .................................................................................. 37
   5.2 Recommendations for Future Work .............................................. 38

References ........................................................................................................... 40

Appendices ........................................................................................................... 43

Appendix A: Thermal Imaging During Specimen Production ..................... 43
Appendix B: MATLAB Data Processing Script ............................................. 46
Appendix C: Raw Experimental Tensile Data ................................................................. 51
Appendix D: Smoothed Stress-Strain Curves for PLA Specimens ......................... 52
LIST OF FIGURES

Figure 1: Sketches included in Wyn Swainson's 1971 patent.................................................................2
Figure 2: Slic3r software layout..................................................................................................................3
Figure 3: Visual depiction of extrusion and gantry speed on a 3D printer (Barrett, 2015)........5
Figure 4: Fishbone diagram of variables influencing 3D printed mechanical properties (Barrett, 2015), Boxed topics are the focus of this thesis.................................................................6
Figure 5: Penn State's "Strategic Roadmap for the Next Generation of Additive Manufacturing Materials" (Palmer et al., 2015) ........................................................................................................7
Figure 6: Molecular structure of polylactic acid (Sin et al., 2013) .........................................................10
Figure 7: Analytical model of heat transfer between filament by Thomas and Rodriguez (2000) 13
Figure 8: Graphical comparison of model predictions and experimental filament cooling data (Thomas and Rodriguez, 2000).................................................................................................................14
Figure 9: Visual effects of changing infill density (Bastian, 2014) ..........................................................16
Figure 10: Examples of various infill patterns. Left to right: Honeycomb, Concentric, Line, Rectilinear, Hilbert Curve (Hodgson, n.d.) ..................................................................................................................17
Figure 11: Blevin's graph depicting actual density versus infill density percentage (Blevins et al., 2015) ........................................................................................................................................18
Figure 12: Dimensions (in mm) of modeled ASTM D638 Specimen .........................................................22
Figure 13: 0/90° infill orientation used in test specimens............................................................................23
Figure 14: Image of test specimen loaded into testing machine grips ......................................................26
Figure 15: Image of Tensile Testing Setup..................................................................................................27
Figure 16: Load/Disp. data plot before smoothing ..........................................................30
Figure 17: Stress/Strain data plot after smoothing......................................................................................31
Figure 18: UTS and Density Correlations.................................................................................................32
Figure 19: Strain at Failure versus Extrusion Temperature and Print Speed........................................33
Figure 20: Elastic Modulus versus Extrusion Temperature and Print Speed........................................34
Figure 21: Modulus of Toughness versus Extrusion Temperature and Print Speed .....................35
LIST OF TABLES

Table 1: Mechanical properties of poly(L-lactide) specimens (Sin et al., 2013) ......................11
Table 2: Mechanical properties of poly(D, L-lactide) specimens (Sin et al., 2013) ..............11
Table 3: Variables used in Thomas and Rodriguez (2000) model ........................................13
Table 4: Strength properties of annealed PLA ...........................................................................15
Table 5: Thermal characteristics of PLA before (U) and after (T) annealing (Perez-Fonseca et a.
   l., 2016) ..................................................................................................................................15
Table 6: Outline of Tensile Test Runs Keeping Speed Constant at 30mm/s .........................21
Table 7: Outline of Tensile Test Runs Keeping Temperature Constant at 200°C ...............21
Table 8: List of printing variables kept constant throughout experimentation .....................23
Table 9: Specified versus Actual Extruder Temperature .........................................................25
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Chapter 1
Introduction

1.1 Background and Overview of Additive Manufacturing

Contrary to popular belief, the concept of creating objects by fusing layers of material in a specific, computer-controlled pattern has been around for over forty years. A patent filed in July of 1971 by Wyn Swainson entitled “Method, medium and apparatus for producing three-dimensional figure product,” outlined the idea to form a three-dimensional object by using two intersecting radiation beams that trace the object’s surface elements to cause a localized reaction in a volume of media (Swainson, 1977). Charles Hull, to whom most give credit for the invention of additive manufacturing, later refined the concept depicted in Swainson’s patent photo in Figure 1. Hull, now a member of the U.S. National Inventors Hall of Fame, had a significant impact on the commercialization of this technology which he coined “stereolithography” (Davis, 2014). By the late 1980s, Hull had developed a machine ready for sale to companies such as General Motors and Mercedes Benz, while also pioneering the standard tessellation language (STL) file format that is still in use by 3D printers today. Just a few years later in 1992, Scott Crump and his new company Stratasys patented its version of additive manufacturing called Fused Deposition Modeling (FDM). This method went on to set the precedent for relatively simple and affordable 3D printing machines that eventually ended up in the businesses and homes of consumers. FDM has now been refined to where it is the preferred method of additive manufacturing for an array of applications and consumers spanning engineering to culinary arts (Davis, 2014).
FDM (or more generally, material extrusion) uses a position-controlled nozzle that is heated to extrude plastic filament in the desired pattern and layers to create a three-dimensional object. The filament is most commonly polylactic acid (PLA) or acrylonitrile butadiene styrene (ABS) plastic, and the nozzle temperature is controlled to heat the material beyond its melting point, where it is then capable of extrusion through a small diameter nozzle (approximately 0.4mm). To prevent print warpage due to uneven cooling, most 3D printers beyond base-level
consumer models feature a heated surface to deposit the printing material on, commonly referred to as a heated bed or heated build platform.

3D printed objects begin in a computer-aided design (CAD) software such as Solidworks, Creo, or Google Sketchup, where a user can then save the model as a .STL file (most commonly) or a .OBJ file. The next step is another program known as a “slicing” software, such as Slic3r (see Figure 2), Repetier, Cura, or Skeinforge. This software converts the model into a layered structure with a “plan” of nozzle movement and printer settings that will successfully produce the print.

![Figure 2: Slic3r software layout.](image)

It is within the model slicing process that a multitude of printing variables are able to be adjusted; these adjustments have an important role in the printing time, quality, and strength of the finished part. Printing variables revolve around the metrics of layer height, nozzle speed, infill percentage/geometry, and nozzle/bed temperature. After the settings for a print are refined
and the printer is able to create the part successfully, it is removed easily by hand from the build platform.

1.2 Project Motivation

Since its inception, additive manufacturing has been primarily utilized for rapid prototyping of parts, producing scale models, and creating objects of unusual geometry that are not able to be manufactured via traditional methods. In recent years, manufacturers and researchers have begun to adopt the idea that 3D printed parts can be of structural use in their products (Fell, 2016). However, there has been a fundamental dilemma in using printed parts for applications where material properties matter, because their properties can vary significantly depending on printer settings. Proper design for a structural part relies on material data for inputs to both hand and computer calculations. In 3D printed material, strength varies based on the bulk material characteristics of the filament, its thermal history, and the multitude of settings that can be changed in the printing process. Among these settings are infill geometry, fill density, layer height, extrusion temperature, and extrusion/gantry speed (Barrett, 2015). Extrusion speed and gantry speed are essentially a paired variable, as a change in either warrants a corresponding change in the other to produce a quality print; Figure 3 depicts the two variables visually. For brevity, this coupled set of variables is referred to as print speed for the rest of this thesis.
While online 3D printing forums encompass a large amount of the “research” performed for producing quality prints, it is just that – optimizing settings to get an aesthetically pleasing and structurally sound finished product. In the academic setting, work related to this thesis has been conducted by researchers such as Tymrak et al. (2014), Rodriguez et al. (2000), and Thomas and Rodriguez (2000). Their experiments explored tensile property dependencies on variables such as infill geometry, density, and layer height in a lab setting. In relation to extrusion/gantry speed, “mesostructural microscopy produced by Rodriguez et al. (2000) found that extrusion speed influences the shape of the extruded fibres: if the extrusion speed is above the gantry speed, too much plastic is extruded, and the fibre is squished in the horizontal plane by the nozzle; if the gantry speed is above the extrusion speed, not enough fibre is extruded, and the fibre cross-section shrinks as the nozzle is pulled away” (Barrett, 2015). This qualitative observation is an important consideration in the hypothesis of this project, as a higher print speed may “stretch” the fibers like Rodriguez et al. observed, causing a reduction in strength.
A more complete listing of these variables is displayed in Figure 4, which was created by Barrett (2015) as part of a master’s thesis. The impact of print speed and extrusion temperature on strength characteristics is a topic that has had relatively little attention in a research setting, making it an excellent topic for this undergraduate research project. Even in Barrett’s comprehensive paper on factors affecting FDM specimen properties (Barrett, 2015), the focus on temperature history of printed plastic centers around whether annealing it after production would reduce any residual stresses. Upon reviewing several additional literature sources related to FDM strength, it was clear that the variables researched in this project would be a welcome addition to the additive manufacturing knowledge base.

![Fishbone diagram of variables influencing 3D printed mechanical properties](image)

*Figure 4: Fishbone diagram of variables influencing 3D printed mechanical properties (Barrett, 2015). Boxed topics are the focus of this thesis.*
Further motivating this research is Penn State’s strong reputation and continued leadership in the world of additive manufacturing (AM). AM is quickly becoming an emphasis of the mechanical engineering curriculum, and the university continues to create knowledge in the field through its Center for Innovative Materials Processing through Direct Digital Deposition (CIMP-3D). In fact, a document entitled the “Strategic Roadmap for the Next Generation of Additive Manufacturing Materials” was published in December of 2015 by university researchers spanning across departments including the Applied Research Laboratory. According to ARL senior research associate and associate professor Todd Palmer, the document involved more than 120 participants from industry, government and academia, who graciously contributed their time and effort to help define a pathway for future materials development (Palmer et al., 2015). The five-tiered approach (shown in Figure 5) outlined by the roadmap aims to organize research efforts to drive future innovation in the rapidly developing field.

Figure 5: Penn State’s "Strategic Roadmap for the Next Generation of Additive Manufacturing Materials" (Palmer et al., 2015)
This research project can be categorized into both Tier 2 and Tier 3, which are codependent processes in the roadmap. The first aspect of the project works to reinforce existing notions about using traditional methods for characterizing material properties with tensile testing; this is defined by Tier 3. The analysis of collected data and any process-property relationships discovered falls under Tier 2. Clearly, there is ample motivation in both the academic and industry settings for adding to the knowledge base in the 3D printed materials sector.

1.3 Research Objectives

The goal in this work is to explore the influence of extrusion temperature and printing speed on tensile strength properties such as ultimate tensile strength, modulus of elasticity, and toughness. All other variables such as infill geometry/density, layer height, and bed temperature will remain constant throughout the experiment. A hypothesis for any discovered strength variations was formed using background literature combined with consultation from additive manufacturing experts. Both the macroscopic and microscopic properties of 3D printed PLA are examined in order to support this reasoning.

The experiments are designed so that statistically significant data can be produced while minimizing costly lab time for tensile testing. Strength dependencies on extrusion temperature and extrusion speed are investigated as separate variables. In the next chapter, a review of relevant literature is presented. This background information formed the basis on which this experiment is carried out. Following the literature review is Chapter 3, where experiment design, procedure of specimen production, and testing procedures are discussed. In Chapter 4, the data
analysis procedure is detailed, along with a presentation of results and findings from data.

Finally, Chapter 5 contains a conclusive summary of work performed, contributions made to the knowledge base, and suggestions for future work related to this topic.
Chapter 2
Literature Review

2.1 Effects of Bulk PLA Composition on Material Properties

The bulk material properties of polylactic acid (PLA) are a topic of importance for characterizing its mechanical properties upon extrusion into a part. According to Sin et al. (2013), mechanical properties of commercially available PLA can be varied significantly based on parameters such as crystallinity, polymer structure/orientation, molecular weight, and material formulation (blends, plasticizers, composites, etc.). Variations in these attributes could produce PLA that ranges from soft and elastic to stiff and high-strength. Glass transition temperature, or the temperature (or range) at which a brittle material begins to act elastically, is a material property that is also influenced strongly by polymer composition.

PLA is a biodegradable, semi-crystalline organic polymer that is synthesized from its monomer – lactic acid. There are three possible stereoforms of PLA that can be made from the lactic acid monomer; these are L-lactide, D-lactide, and meso-lactide. PLA composed of L or D lactides are known as PLLA or PDLA, respectively. An equimolar blend of the two lactides is known as PDLLA. The vast majority of PLA available to consumers is crystalline PLLA, as large lactic acid sources come from microorganism activity that produce the L-isomer (Sin et al., 2013).

Figure 6: Molecular structure of poly lactic acid (Sin et al., 2013)
Material properties such as melting point, crystallization rate, extent of crystallization, and mechanical behavior have significant dependence on the stereochemical composition (Sin et al. 2013). Sin et al. reported that experimentation performed by Perego et al. (1996) found the PLLA and PDLLA samples exhibited an approximately 30% strength difference (compare highlighted values in Tables 1 and 2). Additionally, Perego et al. reported that changes in molecular weight had little effect on tensile strength (Sin et al., 2013). The hypothesis for this significant difference is that the introduction of the L and D stereoisomers cause crystalline irregularities (stress concentrations of a sort) that negatively affect strength. This indicates that the L and D isomers of PLA do in fact have a significant difference in properties, and thus it is important to keep this variable constant throughout experimentation.

Table 1: Mechanical properties of poly(L-lactide) specimens (Sin et al., 2013)

<table>
<thead>
<tr>
<th>Sample</th>
<th>PLLA I</th>
<th>PLLA II</th>
<th>PLA III</th>
<th>PLA IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular weight, M_w (g/mol)</td>
<td>23,000</td>
<td>31,000</td>
<td>58,000</td>
<td>67,000</td>
</tr>
<tr>
<td>Tensile Properties</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yield strength (MPa)</td>
<td>−</td>
<td>65</td>
<td>68</td>
<td>70</td>
</tr>
<tr>
<td>Tensile strength (MPa)</td>
<td>59</td>
<td>55</td>
<td>58</td>
<td>59</td>
</tr>
<tr>
<td>Young’s modulus (MPa)</td>
<td>3550</td>
<td>3550</td>
<td>3750</td>
<td>3750</td>
</tr>
</tbody>
</table>

Table 2: Mechanical properties of poly(D, L-lactide) specimens (Sin et al., 2013)

<table>
<thead>
<tr>
<th>Sample</th>
<th>PDLLA I</th>
<th>PDLLA II</th>
<th>PDLA III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular weight, M_w (g/mol)</td>
<td>47,500</td>
<td>75,000</td>
<td>114,000</td>
</tr>
<tr>
<td>Tensile Properties</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yield strength (MPa)</td>
<td>49</td>
<td>53</td>
<td>53</td>
</tr>
<tr>
<td>Tensile strength (MPa)</td>
<td>40</td>
<td>44</td>
<td>44</td>
</tr>
<tr>
<td>Young’s modulus (MPa)</td>
<td>3650</td>
<td>4050</td>
<td>3900</td>
</tr>
</tbody>
</table>
Stereochemically pure PLLA was found by Drumright et al. (2000) to exhibit a glass transition temperature of 60°C and an equilibrium melting point of 207°C. When contaminants such as meso or D-lactide PLA were introduced into the material, glass transition temperature was not affected – this is welcome news, as the manufacturer of PLA filament for this experiment could not be reached for exact bulk material properties after it was purchased. Because of its ubiquity, it is assumed that PLLA is used in this experiment.

In summary, PLA in its highest degree of crystallinity has the largest tensile strength, but it lacks toughness during impact. The D and L isomers of PLA sacrifice tensile strength at the gain of toughness and a higher molecular weight. It is becoming a common practice in research using PLA to use copolymerization or fiber reinforcement to modify its properties to best fit the needs of the application (Sin et al., 2013).

2.2 Effects of Thermal History on PLA Material Properties

Perhaps more important than initial bulk material composition are the molecular changes PLA undergoes during manufacturing, printing, and post-processing (if applicable). In the printing cycle alone, the material goes from room temperature to above glass transition temperature in a matter of seconds, then solidifies after being melted and extruded through a small orifice. This extrusion process and the cooling that immediately follows deposition have been significant topics of study for researchers such as Thomas and Rodriguez (2000). Additionally, the post-processing technique of annealing has gained attention in 3D printed polymers, with the goal of increasing strength. The effects of cooling and annealing extruded PLA are investigated in this section.
Sun et al. (2008) reported that “the temperature history of the filament is a critical parameter in dictating part strength. This temperature history depends upon the rate at which the filament cools upon leaving the extrusion head.” Thomas and Rodriguez (2000) developed an analytical model of heat transfer in material extrusion by approximating the filament cross-section as a square, and assuming perfect contact between stacked layers. The governing equations are shown in Figure 7, with the variables listed in Table 3.

\[
T_{\text{ave}}(x, y, t) = T_E \left[ 1 + \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} (a_{mn} \sin(\lambda_m x) \cos(\beta_n y)) e^{-\alpha^2(\lambda_m^2 + \beta_n^2)t} \right] \tag{1}
\]

where:

\[
a_{mn} = \frac{4T_L^2}{E_m^2 E_n^2 \lambda_m \beta_n} \sin \left( \frac{9\lambda_m H}{2} \right) \sin \left( \frac{\lambda_m H}{2} \right) \sin \left( \frac{\beta_n W}{2} \right) \tag{2}
\]

\[
E_m^2 = \frac{1}{2} \left( 5H - \frac{\sin(10\lambda_m H)}{2\lambda_m} \right) \tag{3}
\]

\[
E_n^2 = \frac{1}{2} \left( w - \frac{\sin(\lambda_n \beta_n W)}{\beta_n} \right) \tag{4}
\]

\[
\alpha^2 = \frac{k}{C \rho} \tag{5}
\]

\[
\lambda_m \cot(5\lambda_m H) = \frac{h}{k}, \quad \beta_n \tan \left( \frac{\beta_n W}{2} \right) = \frac{h}{k}. \tag{6}
\]

Figure 7: Analytical model of heat transfer between filament by Thomas and Rodriguez (2000)

Table 3: Variables used in Thomas and Rodriguez (2000) model

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(T_E)</td>
<td>Build envelope temperature</td>
</tr>
<tr>
<td>Extruder temperature</td>
<td>Extruder temperature</td>
</tr>
<tr>
<td>(T_{\text{ave}})</td>
<td>Average of (T_E) and (T_L)</td>
</tr>
<tr>
<td>(H)</td>
<td>Filament height</td>
</tr>
<tr>
<td>(W)</td>
<td>Filament width</td>
</tr>
<tr>
<td>(t)</td>
<td>Time</td>
</tr>
<tr>
<td>(C)</td>
<td>Heat capacitance</td>
</tr>
<tr>
<td>(k)</td>
<td>Thermal conductivity</td>
</tr>
<tr>
<td>(\rho)</td>
<td>Density</td>
</tr>
<tr>
<td>(\lambda_m)</td>
<td>Eigenvalue, root of eqn. 6</td>
</tr>
<tr>
<td>(\beta_n)</td>
<td>Eigenvalue, root of eqn. 6</td>
</tr>
</tbody>
</table>
Based on Thomas and Rodriguez’ finding that transient heat transfer between filament became quite negligible after the next highest layer is deposited, a much simpler lumped capacitance model was developed by Li et al. (2003) to simulate the cooling process of extruded filament – this approach was valid due to the low Biot number of thin filament. A comparison of the two models is shown in Figure 8. Note that at high temperatures, cooling is closer to that of the LC model, then converges to the prediction of both the 2D model and LC model at low temperatures.

Figure 8: Graphical comparison of model predictions and experimental filament cooling data (Thomas and Rodriguez, 2000)
Annealing, or heating a material beyond recrystallization temperature and then slow cooling, is another important discussion topic in the thermal history of PLA. This post-processing technique is well proven in metallurgy, but its effects on layered polymers are still being investigated. Sin et al. (2013) reported a slight increase in tensile strength for the lowest and highest molecular weight PLLA samples in Table 4, compared to their non-annealed counterparts in Table 1.

Table 4: Strength properties of annealed PLA

<table>
<thead>
<tr>
<th>Sample</th>
<th>Ann. PLLA I</th>
<th>Ann. PLLA I</th>
<th>Ann. PLLA I</th>
<th>Ann. PLLA IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular weight, ( M_w ) (g/mol)</td>
<td>20,000</td>
<td>33,500</td>
<td>47,000</td>
<td>71,000</td>
</tr>
<tr>
<td><strong>Tensile Properties</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yield strength (MPa)</td>
<td>—</td>
<td>63</td>
<td>68</td>
<td>70</td>
</tr>
<tr>
<td>Tensile strength (MPa)</td>
<td>47</td>
<td>54</td>
<td>59</td>
<td>66</td>
</tr>
</tbody>
</table>

Perez-Fonseca et al. (2016) recently conducted a study investigating the effect of thermal annealing on fiber-reinforced PLA. Specimens were manufactured according to ASTM D638 Type IV and tensile tested in a manner similar to this study. Measured with differential scanning calorimetry (DSC), it was found that annealing increased crystallinity (see Table 5), thus increasing brittleness.

Table 5: Thermal characteristics of PLA before (U) and after (T) annealing (Perez-Fonseca et al., 2016)

<table>
<thead>
<tr>
<th>Samples</th>
<th>Fiber content (%)</th>
<th>( T_g ) (°C)</th>
<th>( T_m ) (°C)</th>
<th>( T_c ) (°C)</th>
<th>( \Delta H_m ) (J/g)</th>
<th>Crystallinity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>T</td>
<td>U</td>
<td>T</td>
<td>U</td>
<td>T</td>
<td>U</td>
</tr>
<tr>
<td>PLA</td>
<td>0</td>
<td>59.9</td>
<td>61.3</td>
<td>167.2</td>
<td>166.9</td>
<td>96.0</td>
</tr>
</tbody>
</table>

Contradictory to Sin et al.’s results in Table 4, Perez-Fonseca et al. reported slight decreases in tensile and flexural strength after annealing. These mixed results postulate that
annealing has a negligible effect on the tensile strength of PLA. Barrett (2015) confirms this finding after performing similar experiments. While annealing PLA may increase crystallinity, its effect on strength is negligible, and thus is not explored experimentally in this thesis.

2.3 Effects of Print Geometry and Slicing Settings on Material Properties

Some of the most relevant variables for 3D printed material strength are related to how dense the infill of the part is, and in what pattern the material is layered. In order to conserve material and shorten print time, not all printed parts are completely solid throughout – hence the term “infill density.” Infill density, usually expressed as a percentage, describes how much solid space versus free space there is on the interior of a part (within the solid outer skins). Figure 9 depicts a visual example of varying infill density.

![Figure 9: Visual effects of changing infill density (Bastian, 2014)](image-url)
An array of different infill patterns have been in use as additive manufacturing has been in use, with some patterns (rectilinear or honeycomb) being more popular than others (Line or Hilbert Curve). Figure 10 shows examples of a few types of infill geometries. These patterns have a direct effect on both stiffness and strength of 3D printed objects, and they also influence tensile/compressive characteristics.

![Figure 10: Examples of various infill patterns. Left to right: Honeycomb, Concentric, Line, Rectilinear, Hilbert Curve (Hodgson, n.d.)](image)

As one would expect, infill density has a positive correlation with overall density of a part. However, some correlations are more linear than others, depending on which infill geometry is selected. Blevins (2015) explored the effects of infill density and geometry on specimen tensile strength both analytically and experimentally. One aspect of the analysis, corresponding to Figure 11 was the variation of specimen density and strength depending on infill density. It was concluded that although the ±45° rectilinear (successive layers of filament overlap at a 45° angle) and honeycomb infills had an overall higher density than 0/90° rectilinear, the 0/90° specimens had a more linear trend overall.

It was also found by Blevins that a 0/90° rectilinear pattern exhibited the most consistent trends in tensile characteristics (ultimate tensile strength, strain at failure, elastic modulus, etc.) based on infill density. In general, the ±45° rectilinear and honeycomb specimens had a higher UTS and elastic modulus, but the trends were less consistent with infill density. Additionally, the analytical model used to predict these characteristics was much more accurate for the 0/90° specimens compared to the other two, postulating that this is the much more predictable and
consistent geometry (similar to a solid metal specimen). This consistency was a major factor in the decision to use a $0/90^\circ$ infill geometry for the testing in this thesis, in an effort to eliminate any undue variability in the results.

![Figure 11: Blevin's graph depicting actual density versus infill density percentage (Blevins et al., 2015)](image)

Apart from the print setting details, an important factor to consider in this experiment is the size and shape of the actual tensile specimen. The National Institute of Standards and Technology (NIST) specifies the use of only two standards for tensile testing 3D printed plastic or composite materials: ASTM D638 for injection molded plastics, and ASTM 3039 for composites (Forster, 2015). Material extrusion is not categorized as either of these, but the D638 standard was selected for this experiment due to its widespread prior use and greater alignment with the standard’s test material. One problem observed in past studies using D638 is the discretization of the radii in the “dog bone” shape. This discretization causes stress concentrations at the radii, causing premature failure outside the gauge region. While not exactly desirable, this behavior is still able to produce valid stress/strain curves up to the necking phase,
which is of the most importance for determining tensile properties. In the next chapter, the experimental procedure of manufacturing and testing these dog bone specimens is detailed.
Chapter 3

Procedure

3.1 Experimental Design

In order to keep the two variables tested in the study separate, two separate experiments were formed to focus on each variable separately (outlined in Tables 6 and 7). Originally, a combination of the two variables was proposed, but since there is no prior research on this specific experiment, it was decided to isolate them to avoid confounding the results. The first experiment kept gantry speed constant at 30mm/s (with extrusion speed proportional), and the second experiment kept extruder temperature constant at 200°C while speed varied between 30, 60, and 90mm/s. As recommended by the ASTM D638 standard, it was decided to use several repetitions of each level of the experiments rather than do more (and more closely spaced) levels with fewer repetitions. This stems from the inherent microscopic and macroscopic differences in composition that arise in each PLA specimen. Producing four copies at each level of the experiments would create a data set that could be averaged and mitigate the effect of print-to-print variances. The specimens were printed in groups that corresponded to their variable; this meant runs 1-4, 5-8, etc. were printed together. However, the groups were produced in a random order to equalize potential variations from entrainment of air in the PLA filament (as it sat for a period of time between printing sessions). When evaluating results, it was clear that a better option for mitigating this effect was to print every specimen in a random order, not just the groups of four. This error is addressed in section 4.3.
Table 6: Outline of Tensile Test Runs Keeping Speed Constant at 30mm/s

<table>
<thead>
<tr>
<th>Run #</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>190</td>
</tr>
<tr>
<td>2</td>
<td>190</td>
</tr>
<tr>
<td>3</td>
<td>190</td>
</tr>
<tr>
<td>4</td>
<td>190</td>
</tr>
<tr>
<td>5</td>
<td>205</td>
</tr>
<tr>
<td>6</td>
<td>205</td>
</tr>
<tr>
<td>7</td>
<td>205</td>
</tr>
<tr>
<td>8</td>
<td>205</td>
</tr>
<tr>
<td>9</td>
<td>220</td>
</tr>
<tr>
<td>10</td>
<td>220</td>
</tr>
<tr>
<td>11</td>
<td>220</td>
</tr>
<tr>
<td>12</td>
<td>220</td>
</tr>
</tbody>
</table>

Table 7: Outline of Tensile Test Runs Keeping Temperature Constant at 200°C

<table>
<thead>
<tr>
<th>Run #</th>
<th>Speed (mm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>30</td>
</tr>
<tr>
<td>14</td>
<td>30</td>
</tr>
<tr>
<td>15</td>
<td>30</td>
</tr>
<tr>
<td>16</td>
<td>30</td>
</tr>
<tr>
<td>17</td>
<td>60</td>
</tr>
<tr>
<td>18</td>
<td>60</td>
</tr>
<tr>
<td>19</td>
<td>60</td>
</tr>
<tr>
<td>20</td>
<td>60</td>
</tr>
<tr>
<td>21</td>
<td>90</td>
</tr>
<tr>
<td>22</td>
<td>90</td>
</tr>
<tr>
<td>23</td>
<td>90</td>
</tr>
<tr>
<td>24</td>
<td>90</td>
</tr>
</tbody>
</table>
3.2 Production of Test Specimens

Production of the tensile specimens used in this study began with selecting the appropriate “dog bone” specimen type from the American Society of Testing and Materials (ASTM) D638 Standard. Although this standard was written for use with injection-molded plastics, it is accepted by NIST as the preferred standard for testing 3D printed plastic (Forster, 2015). The standard-preferred Type I specimen was selected and modeled in SolidWorks, shown in Figure 12, using the dimensions outlined in D638 as a guide.

![Figure 12: Dimensions (in mm) of modeled ASTM D638 Specimen](image)

Once the SolidWorks model was created, an STL file of the model was imported into Slic3r, the software responsible for slicing the model into layers and creating G-Code for the print. The advantage of using Slic3r as a stand-alone program was that printing variables could be saved into their own configuration files, making it easier to toggle between settings for the different test runs. For example, files named “temp190” and “speed 60” were created for each parameter variation and saved into Slic3r, keeping settings consistent across identical specimens.
and eliminating the chance of accidentally changing a variable within the setting between runs. A 0/90° raster infill pattern was chosen, as discussed in section 2.3.

![Figure 13: 0/90° infill orientation used in test specimens](image)

The variables kept constant through all runs are shown in Table 8. Note that not every Slic3r variable that can be changed is shown for brevity; any variable not listed is the Slic3r default value. Once G-code was generated for all six test variations, printing could begin.

### Table 8: List of printing variables kept constant throughout experimentation

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer Height</td>
<td>0.2 mm</td>
</tr>
<tr>
<td>First Layer Height</td>
<td>0.3 mm</td>
</tr>
<tr>
<td>Nozzle Diameter</td>
<td>0.4 mm</td>
</tr>
<tr>
<td>Horizontal Shells (top &amp; bottom)</td>
<td>3 layers</td>
</tr>
<tr>
<td>Vertical (Perimeter) Shells</td>
<td>3 layers</td>
</tr>
<tr>
<td>Infill Density</td>
<td>60%</td>
</tr>
<tr>
<td>Infill pattern</td>
<td>0/90° Rectilinear</td>
</tr>
<tr>
<td>Speed for non-print moves</td>
<td>80 mm/s</td>
</tr>
<tr>
<td>First layer speed</td>
<td>30 mm/s</td>
</tr>
<tr>
<td>Infill/perimeters overlap</td>
<td>15%</td>
</tr>
</tbody>
</table>
A Printrbot Simple Metal printer was used in conjunction with Repetier-Host software to produce the test samples. The filament selected for production was 1.75mm diameter natural (clear) PLA produced in the United States by 3D Solutech. As outlined in Chapter 2, PLA was chosen because of its widespread use in material extrusion applications, low cost, and compatibility with all consumer-level printers. Care was taken to ensure that the printing process of each specimen was as close to identical as possible.

Before each round of specimen production, the printer was warmed up by printing the first few layers of a specimen to get the nozzle and bed to a steady state, then the print was restarted. After each specimen’s printing had completed, the specimen was allowed to cool until the bed reached 45°C, as indicated by Repetier-Host. At this temperature, the specimen was cool enough to separate (albeit carefully) from the bed without deforming. The exterior dimensions of the dog bones were measured, their mass was recorded, and each was labeled with masking tape before being organized into plastic bags for tensile testing.

When printing tensile test specimens, an important variable to take note of identified by Tymrak et al. (2014) is thermistor placement on the printer: “Thermistor placement can vary substantially between models relative to the extruder heating element and nozzle … Observation has shown that a 5°C temperature change causes visible quality differences of a 3-D print, which is assumed to change the mechanical strength as well.” Additionally, Sun et al. (2008) reported in their study with ABS that “the temperature of the filament as it leaves the tip and is deposited onto the platform was found to range from 235 to 245°C, which is significantly lower than that specified for the liquefier (270°C) as well as that measured for the tip (260°C). The control system in the liquefier, the time gap in measurement and the response time of thermocouple are the most probable reasons to explain this difference.”
To identify this variance in the Printrbot, a Fluke Ti 125 infrared thermal imaging device was utilized to observe temperature gradients and maximum temperatures at the extruder. It was clear from the thermal images (located in Appendix A, videos on file) that the extruder’s heating element was located approximately one inch above the nozzle’s exit. Upon inspection, the Printrbot’s thermistor is integrated into the heating element, providing (theoretically) the most accurate feedback data possible. In Table 9, an eleven percent temperature drop (average) between the heating element and the nozzle is shown. This is a relatively large step towards the PLA’s glass transition temperature, and thus could influence bonding characteristics upon deposition. It is, however, a positive sign that all temperature drops were within a few degrees of each other, with the exception of the 220°C sample which had a 5.6° difference from the next closest temperature drop.

<table>
<thead>
<tr>
<th>Software Specified Temperature (°C)</th>
<th>Highest Recorded Temperature at Nozzle (°C)</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>190</td>
<td>167.9</td>
<td>11.6%</td>
</tr>
<tr>
<td>200</td>
<td>178.8</td>
<td>10.6%</td>
</tr>
<tr>
<td>205</td>
<td>185.5</td>
<td>9.5%</td>
</tr>
<tr>
<td>220</td>
<td>192.3</td>
<td>12.6%</td>
</tr>
</tbody>
</table>
The final step of specimen preparation was to apply retroreflective tape to the gauge surface in order to use a laser extensometer for strain measurement. Two pieces of tape were applied to the rough face (the face exposed to air during printing) of each specimen approximately 20 mm apart, center to center. The tape bounded the center point of the gauge region, as shown in Figure 14. The testing setup is described in the next section.

Figure 14: Image of test specimen loaded into testing machine grips
3.3 Tensile Testing of Specimens

The machine used for testing was an MTS 810 load frame, capable of exerting a 3,000 pound load (see Figure 14). This was more than adequate for breaking PLA dog bone specimens based on the 0/90° infill UTS results from Blevins (2015). To measure strain, an Electronic Instrument Research LE-01 laser extensometer was set up in front of the load frame. An image of the test setup is shown in Figure 15.

Figure 15: Image of Tensile Testing Setup
After all 24 specimens were prepared and organized corresponding to the changed variable (e.g. four specimens for 190°C, four specimens for 200°C, etc.), they were loaded individually into the grips of the load frame and secured by turning the locking mechanism of each grip. The load cell and extensometer were zeroed before commencing each run. A movement rate of 5 mm/min was selected for the crosshead, which is the specified strain rate in ASTM D638 for Type I specimens. All data was collected through LabView and saved into .csv files for later processing through MATLAB and Excel.

3.4 Troubleshooting Procedures

As with any experimental process, there were problems that arose during the specimen production and testing processes. The first of these observed was an issue during printing specimens at 190°C; the lower extrusion temperature caused poor adhesion to the bed, making the specimen corners peel up during printing. This was resolved by lowering the Z offset of the Printrbot 0.1mm closer to the bed, effectively “pressing” the extruded plastic onto the bed to create better adhesion. Additionally, 91% isopropyl alcohol solution on a tissue was used to clean the Kapton layer on the bed before each run. This was found to significantly help adhesion, as it removed any dust or oil that had contaminated the printing surface.

It was also found that the printer performed much more consistently after a few minutes of printing. Due to this, a warm-up print of a specimen was performed for one or two layers, then restarted (after cleaning off the bed) for a new specimen. Keeping the printer’s extruder and bed temperatures as consistent as possible was a priority throughout specimen production.
Producing specimens with varying speeds proved to be somewhat difficult on the 60 and 90 mm/s samples; to correct this, the Slic3r setting for the first layer speed was lowered to 30 mm/s. This allowed adequate adhesion for the first layer to the print bed, and all other layers were more easily printed at higher speeds in accordance with the testing process.

The only issue to arise during testing was one that is common among tensile testing of 3D printed specimens. This is that specimens tend to break outside of the gauge region near the radius that joins the gauge region and grip region. This was the outcome for 22 of the 24 specimens in this experiment. The reason for this is detailed further in the next chapter, but it is attributed to the discretized radii that must be used when slicing the .STL model. Averaged across multiple runs, the strain results are still acceptably accurate even though failure occurred outside the gauge region. The results are disclosed in the next chapter.
Chapter 4
Analysis and Results

4.1 Converting Raw Data to Meaningful Data

All data generated during tensile testing was in the form of time vs. voltages (two voltage values that represent load cell and extensometer readings). In order to convert the voltages to loads and strains, filter noise, and produce accurate values/plots for tensile characteristics, a MATLAB script written by Bartolai was modified for use. In the code, provided for reference in Appendix B, a seven point smoothing algorithm developed by Gorry (1990) is used to create smooth stress/strain plots for a specified range of the data. As an example of how the script works, plots of the raw data and smoothed data for Run 5 are shown in Figures 16 and 17.

Figure 16: Load/Disp. data plot before smoothing
The ability to select which data to consider for plotting and generating tensile data values was vital, as some of the samples experienced slippage in the grips of the load frame which caused a spike in data around .005 strain. Only the data points after these spikes (usually occurring in the first few seconds of testing) were considered for analysis.

In addition to smoothing the stress/strain plots, the MATLAB script produced values for elastic modulus, toughness modulus, strain at failure, and ultimate tensile strength. These were computed using basic algorithms (see end of Appendix B) on the arrays of data that produce each curve, such as the maximum stress value, area under the curve, etc. Once all data had been processed and recorded in Excel (Appendix C), simple bar plots were created to see overall trends in the specimens.
4.2 Tensile Test Results

The data for initial specimen measurements and measured tensile characteristics is included in Appendix C, and all 24 smoothed stress/strain curves are included in Appendix D. Note that there is an additional data series for the temperature plots due to an overlapping variable with the Speed 30 runs. After examining plots comparing the results, there were indeed trends that corresponded to changing print variables. The most prominent of these trends was seen in the UTS and density data. Strength and density clearly increased with temperature and decreased with speed, as seen in Figure 18. For reference, density was calculated using the measured specimen mass divided by its volume from exterior dimensions.

Figure 18: UTS and Density Correlations
UTS vs. Extrusion Temperature had the largest change in values of any statistic taken in the experiments – 4.16 MPa, or 8.2% difference across the range of temperatures. The modulus of elasticity, modulus of toughness, and strain at failure did not produce any statistically significant trends – the results are shown in Figures 19, 20, and 21. While it appears the moduli of elasticity and toughness increase with print speed, the values are so close that they could have easily been influenced by a source of error discussed in section 4.3.

Figure 19: Strain at Failure versus Extrusion Temperature and Print Speed
Figure 20: Elastic Modulus versus Extrusion Temperature and Print Speed
4.3 Potential Sources of Error

It is important to reiterate that in any form of testing 3D printed material, there is inherent variability on a print-by-print basis. In this experiment (and all others in the academic setting), the use of multiple specimens for each variable was chosen to mitigate this error by producing an averaged value for data. Considering that the specimens were printed with a consumer-grade printer in an unregulated build environment (ambient air), there are surely potential error sources that may have caused unwanted specimen variations.
Entrainment of air molecules in the filament before it was printed was certainly possible, as it took about one month to finish all the printing properly. This would cause lower specimen density, and thus lower UTS. During production, the specimens were printed in batches according to the variable being tested. Although the six groups of prints were printed in random order, individual specimens for each group were printed successively. This may have caused entrainment of air in the specimens printed later, because the PLA spool was not kept air tight between printing sessions.

An error source that was quite apparent in the data was slippage of several specimens in the grips of the load frame. This stemmed from having only a “hand tight” method of torquing the locking mechanisms, which sometimes resulted in one being looser than the other and slipping once the load was applied. This slip in the data was able to be removed for processing using the MATLAB script, but it still certainly had an impact on final results.

A final notable point of error was discussed earlier in section 3.2; this is the difference in extruder temperature between what the software commands and what is actually produced. With a difference averaging approximately 10% across the four temperatures, there is no sure way to print at a constant temperature without a more advanced feedback loop than the Printrbot’s. Aside from these variables that were out of user control for this experiment, there is obviously potential for variation in printing procedure (small differences in filament-to-filament or filament-to-bed adhesion), testing setup (such as where exactly the retroreflective tape is applied), and data collection (noise in strain gauge data). Conclusions and recommendations for future work are offered in the next chapter.
Chapter 5
Conclusions

5.1 Contributions

After all analysis was completed, a holistic view of this study indicated a clear conclusion. Increasing temperature from 190°C to 220°C caused a significant increase in ultimate tensile strength (8.2%), while increased speed (from 30mm/s to 90mm/s) causes a decrease in UTS, though not as prominent as the temperature effect (3.5%). Density correlates in the same manner as UTS in regards to the effect of temperature and speed, but not as markedly. These trends follow intuition that Rodriguez et al. (2000) observed in their experimentation with 3D printed ABS. At extrusion temperatures approaching 220°C, PLA is much further past its glass transition temperature, and moving towards the point of being liquid. This increases the rate of molecular diffusion of the PLA between filament strands, increasing bond strength overall. The matching correlation in density can also be explained with this theory, as more filament deposited in the same amount of volume will lead to a larger density. Conversely, a faster extrusion and gantry speed allows very little time for the filament to be deposited and form bonds before cooling below its glass transition temperature, forming a weaker structure overall. Again, the lower density correlates for the same reason.

In an effort to compare these findings with other published results, further literature review was conducted following the experiments. Previous experiments focus mainly on the effects of envelope temperature and how cooling or post-processing affects mechanical properties; no prior studies draw direct correlations to extruder temperature or print speed to mechanical properties. For example, Sun et al. (2008) reported that “both the envelope
temperature and variations in the convective conditions within the building chamber have strong effects on the mesostructure and the overall quality of the bond strength between [ABS] filaments. Results suggest that better control of the cooling conditions may have strong repercussions on the mechanical properties and accuracy of the final part fabricated using the FDM process” (Sun et al., 2008). Extrusion temperature was in fact changed by 20°C in this study, but it was found that no significant strength difference was produced after a three-point bending test of the specimen.

Presently, only qualitative observations of mesostructural variations due to a changing extrusion temperature and printer speed exist. This is especially true for PLA because of its inferiority in strength compared to ABS, which drives industry funding toward research of the latter. This thesis provides quantitative backing to the theories of increased diffusion between 3D printed PLA filament at higher extrusion temperatures. Additionally, it verifies the concept that at higher print speeds, filament is “stretched,” and bond strength decreases (Rodriguez et al., 2000). However, to more completely characterize tensile properties relating to extrusion temperature or printer speed, further experimentation is required.

5.2 Recommendations for Future Work

The underlying reason behind this study was to increase the knowledge base for the strength characteristics of material extrusion 3D printed plastic. A clear next step for this experiment would be to combine the effects of high temperature and slow speed to determine an optimized setting for high strength PLA prints considering only these variables. There is a host of variables affecting tensile UTS; the eventual goal is to perform experiments that optimize all
possible settings for strength. Although this experimentation would require a good deal of time, a well-designed testing array would minimize the amount of runs needed and eliminate repeated trials. To increase accuracy of the prints themselves, a recommendation would be to use a professional grade FDM printer with a controlled build environment, such as the Stratasys Fortus. Finally, it is important to ensure that the bulk material properties of the selected filament are well documented before purchasing.
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Appendices

Appendix A: Thermal Imaging During Specimen Production

Figure C-1: Thermal image of printing at 190°C
Figure C-2: Thermal image of printing at 200°C

Figure C-3: Thermal image of printing at 205°C
Figure C-4: Thermal image of printing at 220°C
Appendix B: MATLAB Data Processing Script

% Tensile data smoothing
% note: save variables / figures after smoothing

% first import data as column vectors, isolate data points of interest

% rate of data capture
f=5; % Hz

% figure(1)
% plot(VarName3, VarName2)
% title('Raw Load vs. Strain Data')
% xlabel('Gauge Length Voltage')
% ylabel('Load Voltage')

% sample name
sample_name='Run 24: Temperature= 200C Speed= 90mm/s'

% specimen dimensions
area = 42.7652; % mm^2

% first datapoint
aa=15;
% last datapoint
bb=(length(VarName1)-15);
% lower measurement point for E
cc=106;
% upper measurement point for E
dd=169;

% clear previous variables
clearvars glV glVs loadV loadVs stressMPA strain;

% assign variables
time=VarName1(aa:bb);
loadV=VarName2(aa:bb);
glV=VarName3(aa:bb);%*-1;

% Convolution smoothing (Gorry 1990)
% cubic, seven point

clearvars glVs loadVs

h=1/f;
X(1,:)=(1/42)*[39 8 -4 -4 1 4 -2]; %i=-3
X(2,:)=(1/42)*[8 19 16 6 -4 -7 4]; %i=-2
X(3,:)=(1/42)*[-4 16 19 12 2 -4 1]; %i=-1
X(4,:)=(1/21)*[-2 3 6 7 6 3 -2]; %i=0
X(5,:)=(1/42)*[1 -4 2 12 19 16 -4]; %i=1
X(6,:)=(1/42)*[4 -7 -4 6 16 19 8]; %i=2
X(7,:)=(1/42)*[-2 4 1 -4 -4 8 39]; %i=3

%filter passes
fp=200;
%endpoint hold after
fpe=10;

for kk=1:fp
  %gage length filtering
  for k=4:length(glV)-3
    if kk==1
      W=[glV(k-3) glV(k-2) glV(k-1) glV(k) glV(k+1) glV(k+2) glV(k+3)]'
    else
      W=[glVs(k-3,kk-1) glVs(k-2,kk-1) glVs(k-1,kk-1) glVs(k,kk-1) glVs(k+1,kk-1) glVs(k+2,kk-1) glVs(k+3,kk-1)]'
    end
    if kk<fpe && k==4
      glVs(k-3,kk)=X(4,:)*[W(2) W(1) W(1:4)']
      glVs(k-2,kk)=X(4,:)*[W(2) W(1) W(1:5)']
      glVs(k-1,kk)=X(4,:)*[W(1) W(1:6)']
      glVs(k,kk)=X(4,:)*W
    elseif k==4
      glVs(k-3,kk)=X(1,:)*W;
      glVs(k-2,kk)=X(2,:)*W;
      glVs(k-1,kk)=X(3,:)*W;
      glVs(k,kk)=X(4,:)*W;
    elseif kk<fpe && k==length(glV)-3
      glVs(k,kk)=X(4,:)*W;
      glVs(k+1,kk)=X(5,:)*[W(2:7)' W(7)]
      glVs(k+2,kk)=X(6,:)*[W(3:7)' W(7) W(6)]
      glVs(k+3,kk)=X(7,:)*[W(4:7)' W(7) W(6) W(5)]
    elseif k==length(glV)-3
      glVs(k,kk)=X(4,:)*W;
      glVs(k+1,kk)=X(5,:)*W;
      glVs(k+2,kk)=X(6,:)*W;
      glVs(k+3,kk)=X(7,:)*W;
    else
      glVs(k,kk)=X(4,:)*W;
    end
  end
end
%load filtering
for k=4:length(loadV)-3
  if kk==1
    W=[loadV(k-3) loadV(k-2) loadV(k-1) loadV(k) loadV(k+1) loadV(k+2) loadV(k+3)]'
  else
    W=[loadVs(k-3,kk-1) loadVs(k-2,kk-1) loadVs(k-1,kk-1) loadVs(k,kk-1) loadVs(k+1,kk-1) loadVs(k+2,kk-1) loadVs(k+3,kk-1)]'
%% calculate stress and strain

clearvars stressMPA strain stress2 strain2

% convert load to N
loadN=loadVs(:,fp)*(3000/10)*(1/.2248);
stressMPA=loadN/area;

% convert to strain
strain=(glVs(:,fp))./ 20;  % divided by 20, since 20mm was the original gauge length (distance between reflective tape)

% convert all raw data to stress and strain
for nnk=1:5
    nk=[1 10 100 100 fp];
    for nnnk=1:length(glV)
        if nk==1
            strain2(nnnk,nk)=(glV(nnnk))./ 20;
            stress2(:,nk)=loadV(:)*(3000/10)*(1/.2248)./area;
        end
    end
end
strain2(nnnk,nk)=(glVs(nnnk,nk))./ 20;
end
stress2(:,nk)=loadVs(:,nk)*3000/10*(1/.2248)./area;
end

%Tensile test results
UTS=max(stressMPA), fprintf('MPa'),
strain_at_failure=max(strain), fprintf('mm/mm')

%calculate Modulus of Elasticity
E=polyfit(strain((cc-aa):(dd-aa)),stressMPA((cc-aa):(dd-aa))*10^6,1),
fprintf('Pa')

%Calculate Modulus of Toughness
for k2=2:(length(strain)-1)
ds(k2)=stressMPA(k2)*(strain(k2)-strain(k2-1));
end
T=sum(ds)

%% plots

%plot stress v strain
figure(3)
plot(strain,stressMPA)
ylabel('Stress (MPa)')
xlabel('Strain (mm/mm)')
%axis([0 strain_at_failure*1.15 0 UTS*1.15])
title(sample_name)
clearvars VarName1 VarName2 VarName3
figure(4)
clf
hold on
plot(strain2(:,1),stress2(:,1),'x')
plot(strain2(:,10),stress2(:,10),'r')
plot(strain2(:,100),stress2(:,100),'g')
%plot(strain2(:,1000),stress2(:,1000),'k')
plot(strain2(:,fp),stress2(:,fp),'b')
plot raw vs filtered load and displacement
figure(5)
clf
hold on
plot(glV,'x')
plot(glVs(:,1),'r')
plot(glVs(:,10),'g')
plot(glVs(:,100),'k')
plot(glVs(:,fp),'b')
title('Raw vs. Smoothed Disp')
figure(6)
clf
hold on
plot(loadV,'x')
plot(loadVs(:,1),'r')
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title('Raw vs. Smoothed Load')
Appendix C: Raw Experimental Tensile Data

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Appendix D: Smoothed Stress-Strain Curves for PLA Specimens

Run 1: Temperature= 190°C Speed= 30mm/s
Run 16: Temperature = 200°C Speed = 30 mm/s

Run 17: Temperature = 200°C Speed = 60 mm/s
Run 24: Temperature = 200°C Speed = 90 mm/s

Stress (MPa) vs Strain (mm/mm)
ACADEMIC VITA

Academic Vita of Alexander Walsh
apw5143@gmail.com

EDUCATION
Major: Mechanical Engineering
Minor: Off-Road Equipment
Honors: Cum Laude

Thesis Title: EFFECTS OF EXTRUSION TEMPERATURE AND PRINTER NOZZLE SPEED ON THE TENSILE PROPERTIES OF 3D PRINTED POLYLACTIC ACID
Thesis Supervisor: Timothy Simpson

WORK EXPERIENCE
Date: May-August 2015 & May-August 2016
Title: Continuous Improvement Engineering Intern
Description:
• Member of the Compact Utility Tractor group
• Designed and implemented solutions to resolve manufacturability and product issues identified with current-production John Deere compact tractor
• Collaborated with a team of interns to conceptualize, design, and fabricate a working prototype of an assisted-lift foldable Rollover Protection Structure (ROPS) for 1 Family tractors

Institution/Company: John Deere – Augusta, GA
Supervisor’s Name: James Franks

Date: May-August 2015 & May-August 2016
Title: Product Validation & Verification Intern
Description:
• Member of the Harvester Cab/Electrical Product Validation & Verification Group
• Conducted software and electrical field testing on model year 2017 John Deere combines
• Validated new iterations of software released to machines through physical operation of the combines and meticulous documentation of failures

Institution/Company: John Deere – Moline, IL
Supervisor’s Name: Joel Werling

GRANTS RECEIVED
Schreyer Travel Grant for trip to Tijuana, MX (see below)

AWARDS
Penn State Provost Award, Schreyer Honors Scholarship, John D. Bare Memorial Scholarship, Ford Blue Oval Scholarship, Yoskowitz Honors Scholarship, and Mr. & Mrs. John Bender Honors Scholarship.

PROFESSIONAL MEMBERSHIPS

Society of Automotive Engineers, International Council on Systems Engineering

INTERNATIONAL EDUCATION

Spring Break 2017 service trip to Tijuana, MX as part of Mission Mexico, an organization through Catholic Campus Ministries.