Mechanical Properties of Rapid Manufacturing and Plastic Injection Molding

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By

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The undersigned, appointed by the Dean of the Graduate School, have examined the thesis entitled

MECHANICAL PROPERTIES OF RAPID MANUFACTURING AND

PLASTIC INJECTION MOLDING

Presented by Joseph C. Ahlbrandt

A candidate for the degree of Master of Science

And hereby certify that in their opinion it is worthy of acceptance

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Chapter 1: Introduction

1.1 Rapid Prototyping

Rapid prototyping (RP) is sometimes called additive manufacturing or three dimensional printing, but it will be referred to as RP in this thesis. RP can be traced back to at least 1988 when there was one system in existence. By 1996 there were 2,234 RP systems utilizing 20 different processes [1]. Since the creation of this technology, there have been a lot of other advances that had to take place to get us where we are today. The biggest change is the improvement in computing power and software. Computer aided design (CAD) software has improved allowing 3D models to be made more easily and has helped the RP process come closer to being just a ‘click and print’ process. Once the 3D model is created it must be saved as the appropriate file format, usually .stl, and uploaded on the computer connected to the printer. The fundamental difference between RP and traditional manufacturing methods is that it is an additive process and not a subtractive, or destructive, process [2]. Instead of removing material to make a final product, “RP components are built-up gradually in layers until the final geometry is obtained” [2].

There are many different technologies used for RP, but the following are some of the most popular used today: fused deposition modeling (FDM), selective laser sintering (SLS), stereolithography (SLA), three dimensional printing (3DP), and 3D inkjet printing (PolyJet) [3]. Each of these different technologies uses a different process to create a final product, but they are all an additive process. All of these different processes follow the same basic process that can be described in five steps:

1. Create a CAD model of the design.
2. Convert the CAD model in to STL format.
3. Slice the STL model in to thin cross sectional layers.
4. Construct the model one layer atop another.
5. Clean and finish the model. [4]

To understand how the product is made we can look at the FDM process. It is essentially a hot glue gun that follows a computer generated path to build the final product. Plastic filament is fed through a heated nozzle and solidifies as it exits. This process creates the product layer by layer, and only wastes material when a support structures is required. The nozzle or bed (where the product sits) will move on the X, Y and Z axis. Once the product is finished the operator can remove and clean the product (remove any support material) and the process is finished.

1.2 Rapid Manufacturing

As this field advances, we are starting to see the use of rapid prototyping technologies emerge as a manufacturing method. Throughout this thesis, this emerging method will be referred to as rapid manufacturing, or RM. Since RM is still in the early stages of becoming a viable manufacturing method, RM is defined in many different ways. This thesis will use Neil Hopkinson's definition of RM, "the use of a computer aided design (CAD)-based automated additive manufacturing process to construct parts that are used directly as finished products or components" [5]. What makes RM different from RP is that the parts it creates are produced as a finished product or component of a finished product. The function of RP is to create a prototype and to assist in the design process of a finished product, not to create an end-use product. While RP and RM have different definitions, they do currently use the same technology.

Some companies have already started to use RM, however most of these companies are creating specialized and unique products that have a very small production run. The Boeing Company is a prime example of a company that uses RP extensively, and has started to use the same technology for RM. Since Boeing produces a small number of products each year, it is practical to build some components using RM. Boeing might build a button, or nob that is used in a cockpit with RM, but they do not build any load bearing parts with RM. The transition to RM is starting to grab the attention of many manufacturers, but there is a lot of research that needs to be done before RM can become a common manufacturing method.

1.3 Plastic Injection Molding

As RM grows in popularity, it attempts to replace what is referred to as traditional manufacturing methods. These methods fall into the following categories: casting, molding, forming, machining, joining, or other. Though much improvement has occurred, the actual methods by which products are manufactured has seen very little and very slow change. Plastic injection molding, or PIM, is considered a traditional manufacturing method and can be dated back to the late 19th century. If RM comes to fruition, it could replace any manufacturing method that is used to create plastic products. This thesis focuses on PIM because it is one of the more commonly used manufacturing methods for polymers and products created using PIM will be some of the first to switch over to RM.

The basic process of PIM is described in this section. Two to three millimeter polymer pellets are placed in a hopper and the pellets fall into a heated chamber. The pellets are then heated to a desired temperature to achieve viscosity that will allow the polymer to flow into the mold. The plastic is then pushed through a nozzle by an electric, hydraulic, or pneumatic piston. The mold is filled with the melted polymer and begins to cool immediately. Once the product is cooled to the required temperature it is removed from the mold and the excess material, usually a sprue and runner, must be removed. PIM is a very cheap process because it can be repeated quickly and at a low cost. There is, however, a high start cost because the tooling and design process used to create the mold is very expensive.

One of the main issues PIM faces is that once a mold is created there is no way to change or modify the product without creating a new mold. Creating a mold for PIM is the most expensive part of the process. To create the mold, a 3D model of the mold must be created and then the numerical code (NC) must be generated using a computer aided process planning (CAPP) program. Using the code generated for the machine, a machinist must mill the part. The CAPP process and the actual milling are very expensive processes. This, however, has been one of the most common ways to create a plastic product for almost a century. The processes of PIM and the expected results are well known and tested. Meld and weld lines are also an example of one of the major issues with PIM [6]. These are lines that are created from the meeting of the mold halves and they can be either cosmetic blemishes, or structural catastrophes [6].

There are methods used to avoid these issues, but most of the structural integrity of PIM parts depends on the designing and manufacturing of the mold.

1.4 PIM vs Rapid Prototyping

Now that there is a basic understanding of the two manufacturing methods, one new and one old, a look at current manufacturing needs is necessary. The clear advantage of RM is that the products are highly customizable and the complexity of a design is no longer an issue. The advantage of PIM is the extremely low cost for mass production and the ability to create consistent, proven products. A disadvantage of RM is that it can take hours to produce a final product while PIM may take seconds, and PIM is not customizable and requires extensive time on product/mold design and machining. While RM takes longer than PIM, the process to design and create a mold for PIM is very long and expensive. These advantages and disadvantages are well known, but there are some that are not. Very little is known about how the same materials used in RM will compare to those used in PIM. A comparison of the mechanical properties of a part made by PIM and RM has not been researched. By defining the unanswered questions of these two methods, there will be a better understanding of RM's ability to compete with traditional manufacturing methods like PIM.

1.5 Objectives

In manufacturing and product design, an engineer considers the form, fit and function of the product. RP has proven ability to achieve form, which makes it great for prototyping. However, the performance of fit and function are still partially unknown. If RP technology is going to transition to RM it is important to better understand its fit and function capabilities. A graduate of the University of Missouri, Chen-Yu Liu, has completed research on the mechanical properties of parts created by RP technology for his master's thesis. Since Liu's procedures, data, and results are available, this thesis reviews the same testing on parts created using PIM. To help reduce error and bias, the parts created by PIM used materials taken directly from the machines that Liu used in his research. The objective of this thesis is to compare the mechanical properties of a part created by RM and PIM when identical materials are used in each process. To compare the fit of RM and PIM, the dimensional accuracy of each process will be compared. The function of RM and PIM is compared by the following tests: tensile strength, Shore hardness, water absorption, and microscopy. By exploring the fit and function of RM and PIM, we can better understand if RP is ready to transition to RM. This research will also help determine what areas need improvement before RM starts replacing traditional methods like PIM.

Chapter 2: Literature Review

Rapid prototyping (RP) has been around since the 1980s, but only recently has the idea of using RP for end use products become plausible. Rapid manufacturing (RM) is the term we use when RP is used to create finished products. According to Neil Hopkinson and Phill Dickens, RP is the “group of commercially available processes” that are used to create a 3D part and RM “utilizes these processes for the direct manufacture of solid 3D products” [7]. Currently RP is much more common than RM, but as the abilities of RP grow there is a larger push towards RM. It is common to see companies use RM for small volume parts, meaning they will only manufacture the products once or twice. For example, Boeing “used selective laser sintering (SLS) to manufacture low volume parts such as for the space lab and space shuttles” [7]. While there have been some comparisons of RM and injection molding, they are usually focused on cost analysis, lead times or production rates [8].

2.1 Rapid Prototyping Properties

One of the greatest attributes of RP and RM is its ability to create parts that have extremely complex geometries. Mansour and Hague discuss the impact of RM on design for manufacturing (DFM). When using DFM in injection molding, some of the limitations are “associated with minimizing complex geometries and features such as undercuts, blind holes, screws, etc.” [9]. The ability to remove these limitations with RP is one of the key reasons that it is such an exciting technology. The ability to create complex geometries can also help reduce the production time and cost of prototyping [9].

Rapid prototyping has been widely successful because it improves the current prototyping process by providing a faster and cheaper product realization process. Kochan writes, “RP is being used as a communication and inspection tool in the procedure of product development and realization of the rapid feedback of the design information” [1], and provides the visualization in Figure 1. RP in product design allows for more feedback and creates a more agile system. Changes made in CAD can be turned into physical models quickly, which helps improve the design process and helps bring a product to market faster. Kochan further explains how RP can provide quality prototypes that are developed quickly, “There are almost no restrictions on geometrical shapes; and the layered manufacturing allows a direct and simple interface with CAD to CAM which almost completely eliminates the need for process planning, a complex procedure for CNC machining” [1].

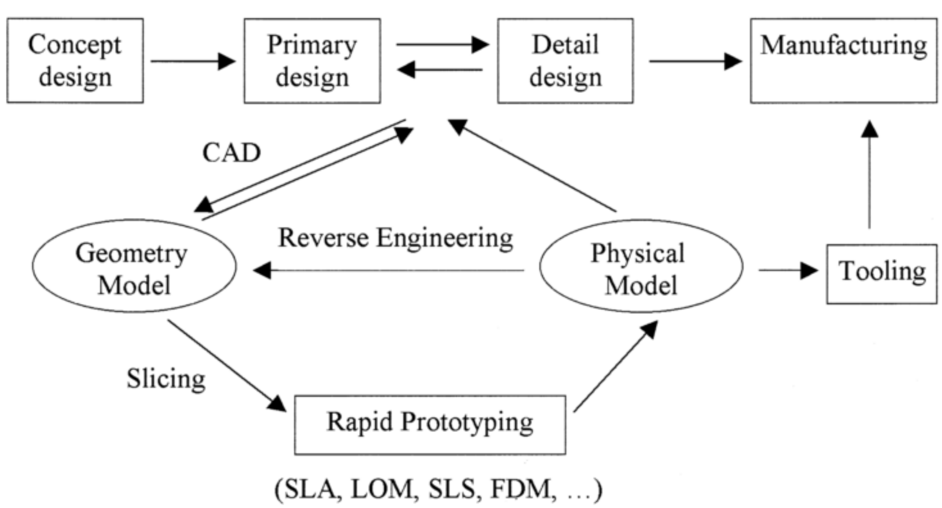


Figure 1 - Product Development Process with RP (Kochan)

While there are some clear advantages to RP, it also has its own limitations. Some of these include the following: poor surface finish, lack of dimensional accuracy, range of available materials, and build time [9]. A review of RP/RM discusses one of the current research needs, “It will be important to continue to apply materials science analysis (microstructure, properties, performance) to AM like other manufacturing processes (welding, forming, casting, etc.) with the objectives of understanding limitations and exploiting unique features of AM while meeting the requirements of processability and performance” (AM refers to additive manufacturing) [10]. What is still unknown in RM is how the final product will hold up against a proven method like injection molding. There has been no direct comparison of product strength and durability. Since these parts are produced using different methods, the finished products should have different properties. “Material properties for parts made by current LMTs (layered manufacturing technique) seldom match those of their counter parts produced by traditional processes such as injection molding however significant improvements have been made and should continue to do so” [7]. Hopkinson and Dickens suggest that future materials for RP/RM will continue to evolve and eventually have proven properties like those used in injection molding. While RP evolved rapidly in its first 10 years (and still is), it took injection molding 20 years to have a useable material [7]. Knowing the reliability, strength and durability of a part made by RP may help show us the future of manufacturing.

2.2 Plastic Injection Molding Properties

Plastic injection molding (PIM) was first invented shortly after the first plastic, celluloid, was invented and the current process has not changed much since the

1940’s [11]. Since the process of PIM has been around for so long, there are well defined best practices for the design of parts and molds. A few of these design features that must be considered are as follows: wall thickness, uniform wall thickness, avoiding sharp corners, minimizing weld lines, minimizing sink marks, draft angles, minimizing re-entrant features, parting line, and ejection pin marks and gate marks [9]. Even with knowledge of best practices and design constraints in PIM, the design process is still very long and expensive. In the *Injection Molding Handbook,* Beaumont writes, “a mold must be custom designed and built that can easily cost tens to hundreds of thousands of dollars…the process of designing, building a mold, and molding the first plastic part can easily take 20 weeks.” Beaumont goes on to discuss that after the first part is made it is very rare to not redesign the part and have to recreate the mold [11].

The *Injection Molding Handbook* offers a recommended design process with eight steps. It is mentioned that this process will vary from each project, but this provides insight into the expense and length of the process.

1. Data collection and product specifications
2. Project plan
3. Preliminary design
4. Material selection
5. Develop detailed design
6. Testing/Prototyping
7. Review design and revise through steps 4 to 6
8. Commit to the design and develop project plan to bring to production [11]

Further, there are four building blocks of plastic part design that are discussed. The first block is material, the second is product design, the third is mold design and machining, and the fourth is process [11].

When selecting the material, the required properties of the product and the preferred properties of the material must be considered. These properties may include chemical resistance, thermal resistance, impact strength, modulus, and tensile strength. Material selection should also consider mechanical properties, ability to survive its environment, wear, production process, and cost [11].

Product design attempts to satisfy the functional, structural, aesthetic, cost and manufacturing requirements. It is common that meeting one of these requirements means not meeting another requirement. An example of this would be sacrificing an aesthetic characteristic of a product to help reduce shrinkage or warpage. While there have been advances in computer aided engineering (CAE) software, including molding simulation, predicting the success of a design is very difficult since each product is unique [11].

Mold design and machining is the most difficult part of the plastic part design process. According to the *Injection Molding Handbook*, the following are the fundamental requirements of mold design, "the cavity can be filled with the specified plastic, be robust enough to accommodate the internal and external forces, and be built so the molded part can be ejected from the mold". There is also a more specific list of aspects that must be considered: machinability of mold components, sized cavity dimensions to account for part shrinkage, adequate and uniform cooling, venting of gases, product surface finish, tolerances, delicate inserts, delivery of melt, automatic separation of runner and part, built to withstand millions of cyclic internal loads from injection pressure, and built to withstand external clamp pressures [11]. Again, CAE offers some help in designing molds, but most of these aspects are handled by machinist and engineers who have years of experience and have insight into the design process that is not readily available.

The last of the four building blocks, process, deals with finalizing all of the other processes. When this stage is reached there should be an understanding of what the product will look like, how it is expected to perform, and the cost to produce the part. Once an actual part is created, "alterations in material, part design, and the mold" may occur before the desired specifications are met. The process deals with determining shrinkage, warpage, flow of molten plastic, and any other factors that will change the final product. This building block is vital because of the intrinsic difficulty of dealing with polymers. Each polymer is different than another and chemical makeup affects how it flows in a mold and how it will shrink. Understanding these aspects are important before creating a finished product [11].

There is an abundance of research material pertaining to PIM and despite all limitations it is a leading method of creating plastic products. With the high cost relating to product and mold design, it is clear why there is a need for advancement in technology and methodology. A large part of product design focuses on the required mechanical performance of the product, and while this information is available for PIM, it is not for RM.

2.3 Cost Analysis

Hopkinson and Dickens compare the cost of creating parts using stereolithography and injection molding. It is a common thought that in order for RM to be used the number of total parts has to be very small, but Hopkinson and Dickens reported that for a small part (3.6 grams) it is cheaper to use RM up to 7,500 parts [7]. In Figure 2, you can see the intersection, or breakeven point of PIM and RM. The cost per product is constant with RM, but the cost per product for PIM decreases as the quantity of products increases. This same research also compared large plastic parts, but the breakeven point was much lower (below 400 products) [7]. Cassandra Telenko and Carolyn Conner Seepersad investigated selective laser sintering (SLS) and injection molding of nylon parts [12]. When making a small production run and including the cost of material production, mold production, and object production, it was confirmed that using SLS is cheaper than injection molding [12].

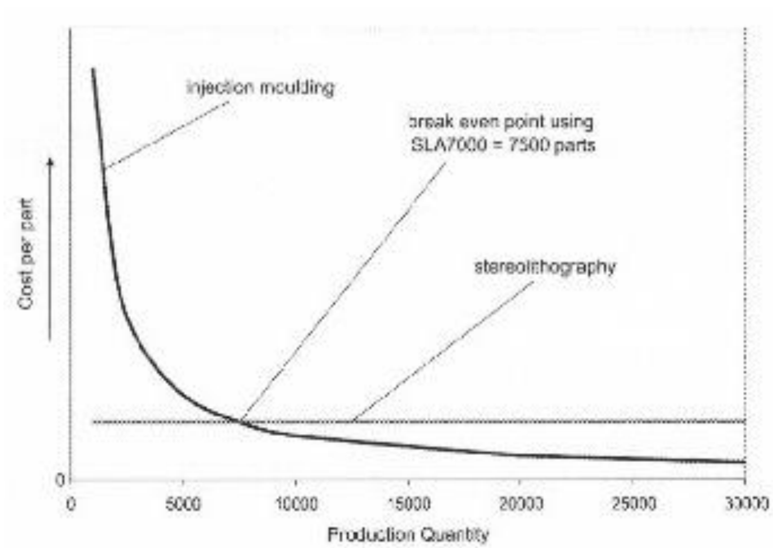


Figure 2 - Cost per Part vs Production Quantity (Hopkinson)

2.4 Chen-Yu Liu's Thesis

The research in this thesis is a follow up to the thesis titled *A Comparative Study of Rapid Prototyping Systems* written by Chen-Yu Liu [13]. Liu's research compared the mechanical properties of parts created using four different RP systems. His research also tested parts built in three different build directions (horizontal, side and vertical) for each method, which provided insight into the anisotropic nature of parts created using RP. The testing that Liu did on parts created by RP was repeated on parts created using PIM in this thesis. The results from this research are compared to Liu's results and analyzed in this thesis. Following the same procedures used by Liu, a comprehensive comparison of the mechanical properties of parts created by PIM and RP can be compared. For information on the testing that was used in this research and Liu's research you can refer to Chapter 3:. Below is a summary of the result from Liu's research [13].

Table 1 - Summary of RP Dimensional Accuracy (Liu)

RP System	Build Orientation	Dimensional Accuracy (%)
SLS	Horizontal	2.2136
	Side	1.4834
	Vertical	0.5093
PolyJet	Horizontal	0.3227
	Side	1.2217
	Vertical	1.8137
FDM	Horizontal	1.1025
	Side	2.2129
	Vertical	2.1845
3DP Before Harden	Horizontal	2.6872
	Side	4.0884
	Vertical	2.9351
3DP After Harden	Horizontal	2.5302
	Side	3.9861
	Vertical	2.8356

Table 3 - Summary of RP Tensile Properties (Liu)

RP System		Tensile Properties		
		Tensile Strength (psi)	Elongation (%)	Elongation at Break (%)
SLS	Horizontal	**7367.4**	7.4545	**16.5334**
	Side	7122.8	7.3296	15.7361
	Vertical	6801.8	**7.7414**	12.4673
	Company	*6962*	*NA*	*24*
PolyJet	Horizontal	8868.2	3.9132	5.0635
	Side	**9728.2**	**4.0884**	**5.7542**
	Vertical	5137.4	1.608	1.6235
	Company	*7250-9450*	*NA*	*10-25*
FDM	Horizontal	4283.8	**2.2187**	3.3834
	Side	**5572.2**	2.1818	**3.7104**
	Vertical	3563.2	1.4076	1.4230
	Company	*5300*	*3*	*NA*
3DP	Horizontal	2182.375	**0.4984**	**0.5139**
	Side	**2442.25**	0.4971	0.5127
	Vertical	2249.875	0.3831	0.3985
	Company	*2059.535*	*NA*	*0.23*

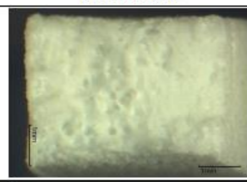
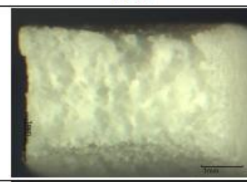
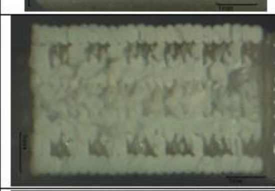
Table 2 - Summary of RP Water Absorption (Liu)

RP System	Sample #	Weight (g)		The relative rate of Water Absorption (%)
		Before	After	
SLS	1	6.83	6.94	1.6105
	2	6.77	6.86	1.3294
	AVG	6.80	6.90	**1.4700**
PolyJet	1	7.70	7.79	1.1688
	2	7.69	7.78	1.1704
	AVG	7.70	7.79	**1.1696**
FDM	1	5.86	6.47	10.4096
	2	5.85	6.56	12.1368
	AVG	5.86	6.52	**11.2732**
3DP	1	10.65	11.20	5.1643
	2	10.65	11.46	7.6056
	AVG	10.65	11.33	**6.3850**

Table 4 - Summary of RP Shore Hardness (Liu)

RP System	ASTM D2240 Type D scale	Standard Deviation
SLS	77.1667	1.7495
PolyJet	84.7500	0.7538
FDM	78.4167	2.1088
3DP	82.3333	1.3027

Table 5 - Summary of RP Microscopy (Liu)

RP System	Horizontal	Side	Vertical
SLS			
PolyJet			
FDM			
3DP			

Chapter 3: Methodology

Rapid prototyping is in progress with revolutionizing manufacturing and has already started to be used for the manufacture of final products. The mechanical properties of rapid prototyped parts have not yet been put to the test against those from traditional methods of manufacturing. The following tests will compare the mechanical properties of specimens that were created using rapid prototyping and injection molding.

3.1 Tests

There are five areas that will be compared to help understand the difference in mechanical properties from each manufacturing method. The rapid prototyped parts were tested for dimensional accuracy, tensile strength, water absorption, Shore hardness and microscopy. These are the five areas that will be used to test the injection molded specimens. The results from the injection molded parts and rapid prototyped parts will help us understand if rapid prototyping can be used for manufacturing.

3.2 Material Selection and Melt Testing

The research for the rapid prototyped parts has been completed previously by Chen-Yu Liu, in his thesis titled “A Comparative Study of Rapid Prototyping Systems.” In his research, Liu compared four different methods of rapid prototyping: Selective Laser Sintering (SLS), PolyJet, Fused Deposition Modeling (FDM), and 3D Printing (3DP). Since the data and methodology of Liu’s tests were readily available, the materials were selected based on what were used in his thesis. Each of the four rapid prototyping methods that were used in Liu's research use a different material. The material that is used in each of the methods is listed in Table 6. The manufacturer and model of each machine used in Liu's research can be found in Table 7.

For this experiment, only thermoplastic polymers can be used in injection molding, so the 3DP material cannot be used because it is gypsum. This left the other three materials to be tested for a specific melting temperature. Both the ABS and Polyamide 12 (Nylon) are commonly used in injection molding, so there were no expected issues with either of them. However, the acrylic plastic used by the PolyJet process is a photopolymer and it is cured by a UV light, not heat. While a heat deformation temperature (HDT) is known for the PolyJet material, it is unknown if it will melt or become fluid enough for injection molding. The University of Missouri-Columbia has obtained a new rapid prototyping technology, stereolithography (SLA), but this occurred after Liu did his research. The SLA, which also uses a photopolymer material, is included in this test. Polystyrene is also included in this test because it was available in pellets for injection molding and the melting temperature was known. Since the exact melting temperatures of the rapid prototyping materials are unknown, they must all be tested to find the correct temperature setting for injection molding. The following is the procedure that was used for determining a melting temperature:

- Cut/grind the material down to a small pellet size (~3 mm). If the material started as a powder (SLS) or liquid (SLA and PolyJet) it had to be printed and then cut/ground.

- Heat the Carbolite furnace (Figure 3 - Carbolite Furnace) to a temperature that is expected to be below the material's theoretical melting temperature.
- Put one of the materials into a small 4 ounce crucible and place a metal weight on top of the material. The metal weight will help deform the plastic once it has reached a melting temperature. The deformation of the plastic will be the indicator that the plastic has melted.
- Place the crucible in the oven. After about five minutes the crucible can be removed and the plastic can be observed. If there is no deformation the crucible is put back in the furnace and the temperature is raised 25 degrees Fahrenheit. This step is repeated until the deformation is observed.
- If there is discoloration or burning the material is removed and assumed to have no melting temperature.
- The melting temperature of each material is then recorded. The results are summarized in Table 8.

This testing was relevant because it revealed that the materials from the PolyJet and SLA methods do not melt, or become fluid enough for the injection molding process. They would have jammed and possibly broken the Mini-Jector if they were used. For the remainder of this research, only Polyamide 12 (Nylon 12) from the EOS Formiga P100 machine, ABS from the Stratasys Dimension Elite 3D Printer machine, and the polystyrene pellets will be tested and analyzed.

Table 6 - RP Methods and Materials

RP Method	Material	Building Method
SLS	PA 2200 Balance 1.0 Polyamide 12 (Nylon 12)	Heat/Laser
PolyJet	FullCure 835 VeroWhitePlus (UV curable acrylic plastic)	UV Light
FDM	ABSplus-P430 (ABS plastic)	Heated Nozzle
3DP	ZP 131 (gypsum)	Liquid Binder
SLA	Accura 55 Plastic	UV Light

Table 7 - RP Manufacturers and Models

RP Method	Manufacturer	Model
SLS	EOS	Formiga P100
PolyJet	Objet	Eden 350V
FDM	Stratasys	Dimension Elite 3D Printer
3DP	Z Corporation	Spectrum Z510

Figure 3 - Carbolite Furnace

Table 8 - Melting Temperature Results

Material	Actual Melting Temperature	Material After Testing
Polyamide 12 (SLS)	430 degrees Fahrenheit	
Acrylic Photopolymer (PolyJet)	Did Not Melt	
ABS (FDM)	380 degrees Fahrenheit	
Accura 55 Plastic (SLA)	Did Not Melt	
Polystyrene	485 degrees Fahrenheit	

3.3 ASTM D638-10 Type IV

The test specimen that was used in all of the experiments is designed by the American Society for Testing and Materials (ASTM). The ASTM provides the specifications for the specimen, shown in Table 9 and Figure 4, and the procedure for testing the specimen for tensile strength. This specimen is designed to test the tensile strength of different rigid plastics. Chen-Yu Liu used this identical test specimen in his testing of the different rapid prototyping methods. Using this same part will help provide an accurate comparison between rapid prototyping and injection molding.

Table 9 - ASTM D638 Type IV Dimensions (Liu)

ASTM D638-10 Type IV	Dimensions (mm)
W –Width of narrow section	6
L –Length of narrow section	33
WO –Width overall, min	19
LO –Length overall, min	115
G –Gage length	25
D –Distance between grips	65
R –Radius of fillet	14
RO –Outer radius	25
T –Thickness	4

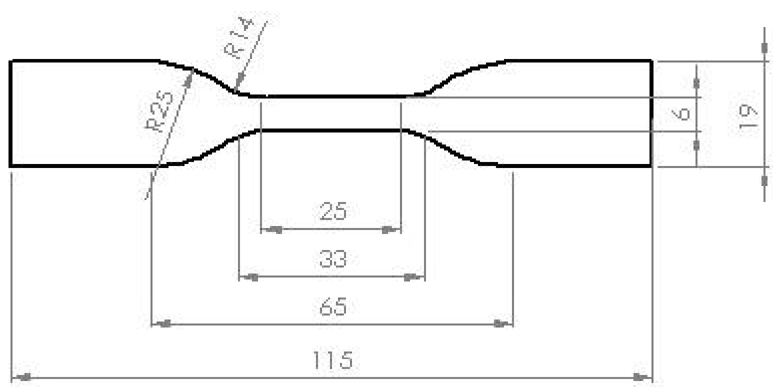


Figure 4 - ASTM D638 Type IV Design (mm) (Liu)

3.4 Creating Test Specimens

Part Design

In order to create the test specimen a mold had to be made that could be used for injection molding. First, a 3D model of the ASTM D638-10 Type IV part was designed in SolidWorks (Figure 5). Next a 3D model of the mold was created in SolidWorks by using Boolean subtraction, as seen in Figure 6. The mold blank was made out of aluminum and the dimensions of each half were 5 x 2.81 x 0.3 inches, shown in Figure 7. Once the mold was created in SolidWorks, the file was exported to MasterCAM for computer aided process planning, including the location of the sprue, runner and gate (Figure 8). The numerical code (NC) was generated once the tool paths were created in MasterCAM.

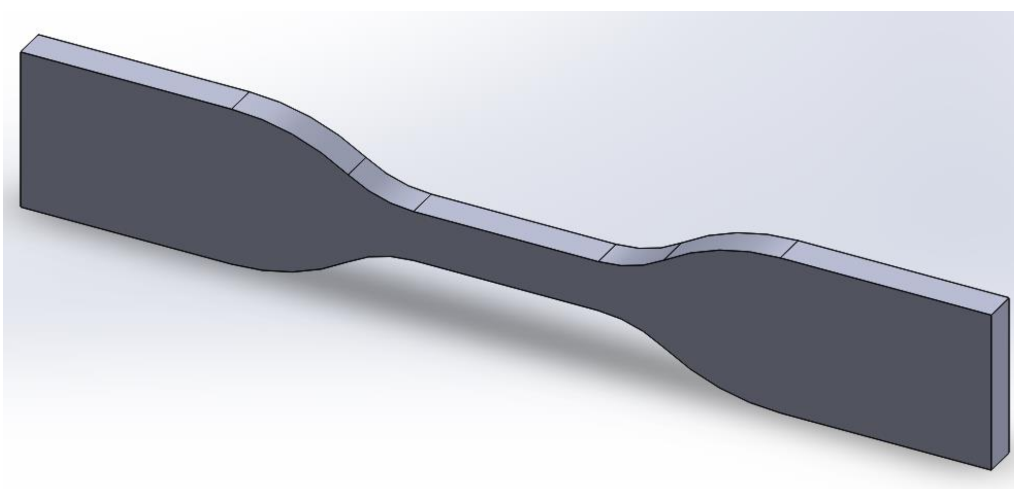


Figure 5 - ASTM D638-10 Type IV 3D Model

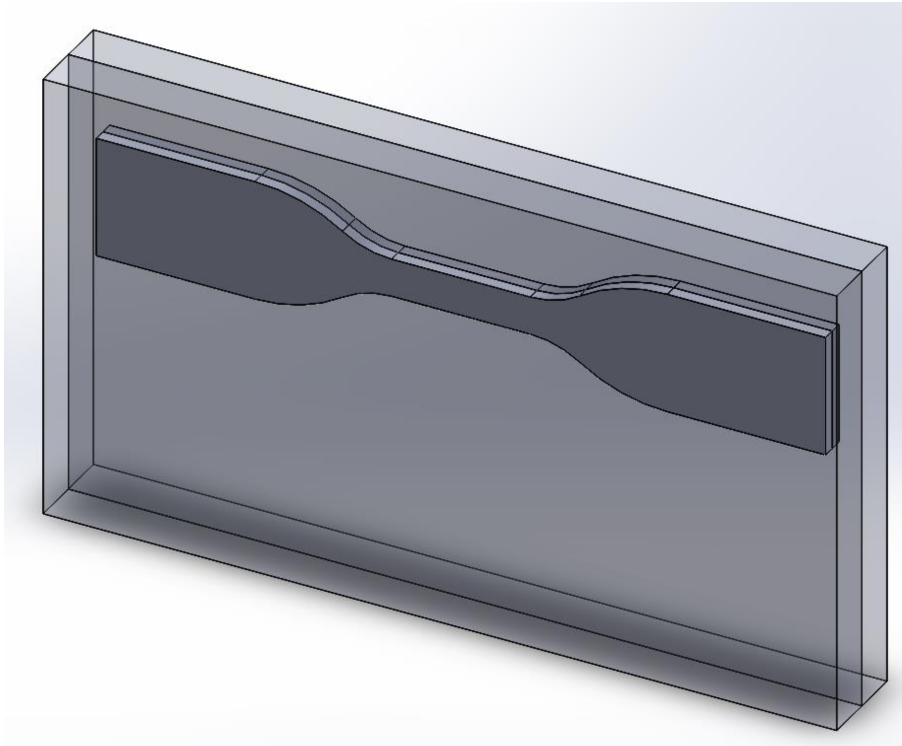


Figure 7 - SolidWorks 3D Model of

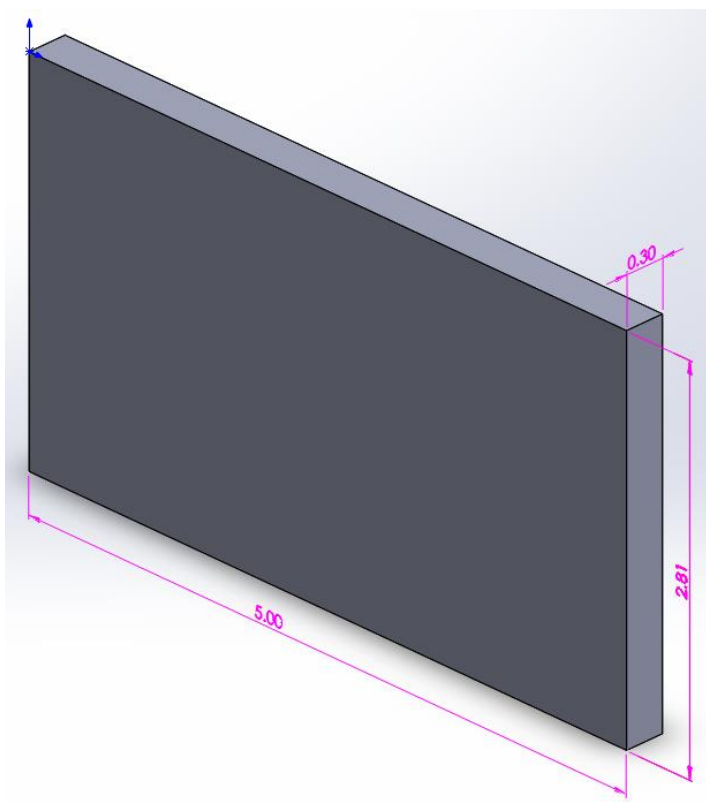


Figure 6 - Aluminum Mold Blank Dimensions

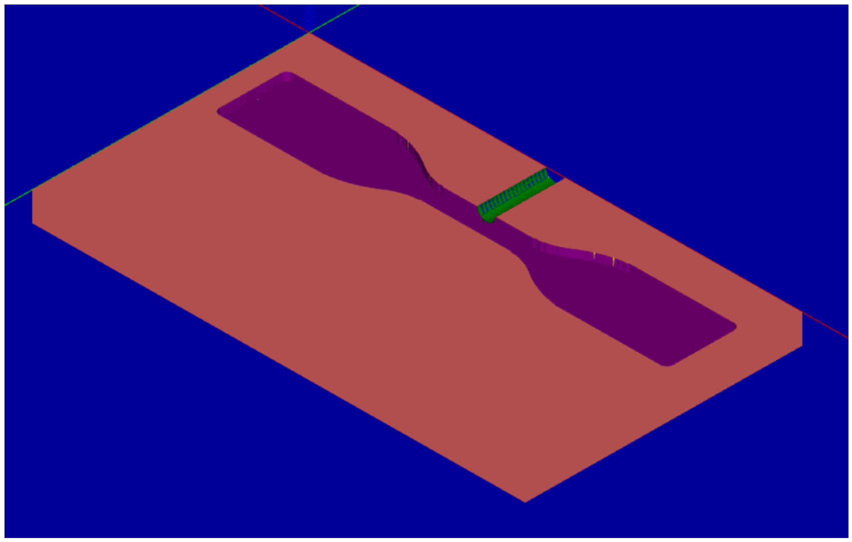


Figure 8 - MasterCAM Process Planning

Milling

To create the mold a Lagun Mill with a Lagunmatic 250 conversion and a Centroid controller (Figure 10) was used to mill the aluminum blank. A 1/8 inch flat end mill was used to cut the D638 Type IV part and a 1/8 inch ball nose mill was used to cut the sprue, runner and gate. The initial design had the sprue going directly down into the thin part of the D638 Type IV part. This design created a weakness in the part during tensile testing, so the mold was modified using a sprue, runner and gate that would enter on one of the wider grips. This area was selected because it was clamped to the machine and there should be no stress in the wider section during testing. Figure 9 shows the mold with the original design on the bottom and the final design added on the top.

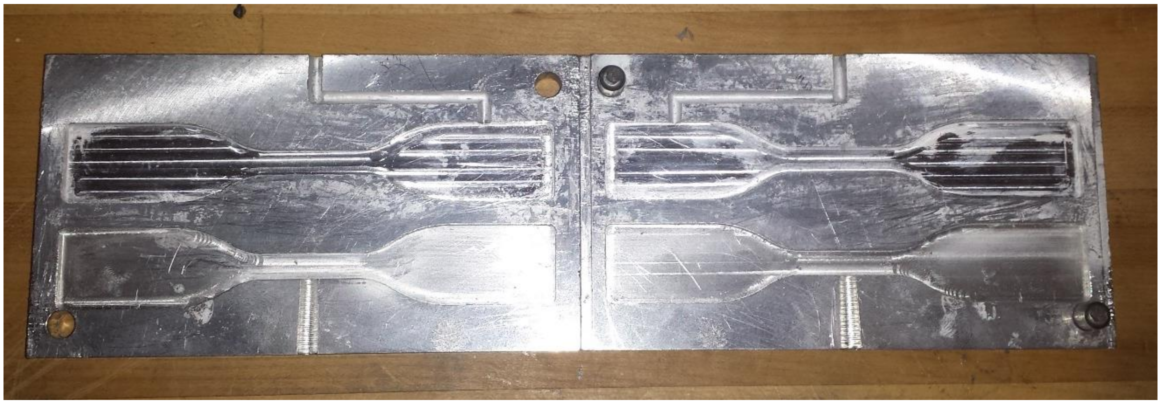


Figure 9 - Final Mold Design (Top)

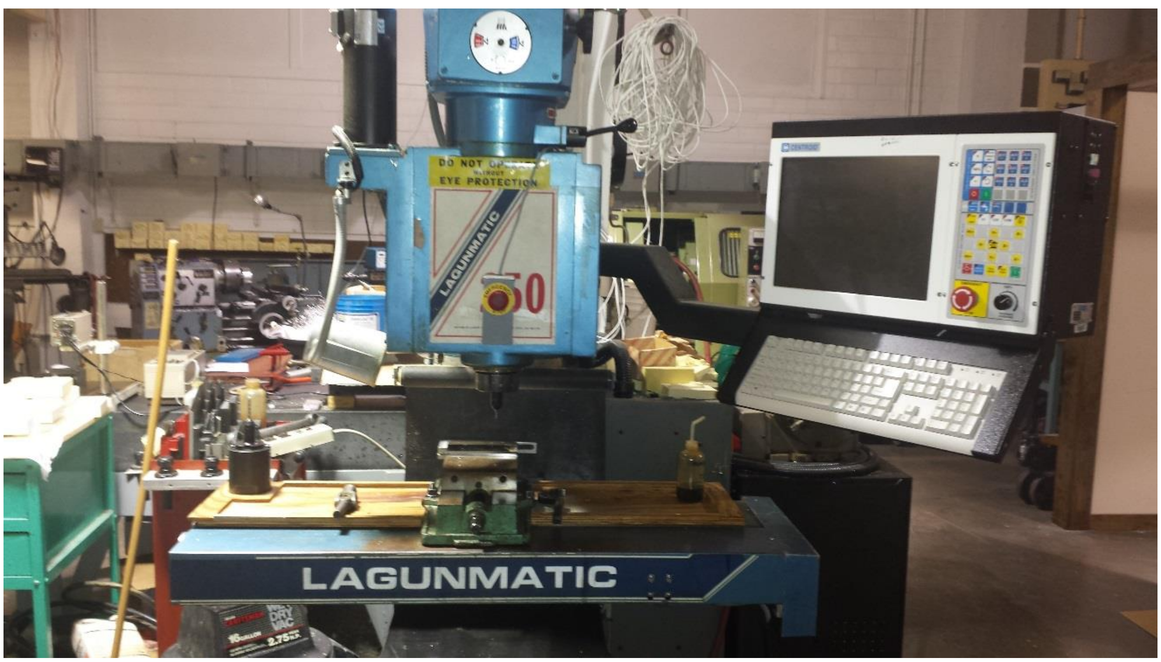


Figure 10 - Lagun Mill and Centroid Controller

Injection Molding

Once the mold was created the test specimen could be created. The mold was designed to be used with a Mini-Jector Model 45 injection molder (Figure 11), which can be used to injection mold small to medium sized plastic parts. The plastic materials must be in a solid, pellet size form. Since the ABS plastic that is used for rapid prototyping comes in a filament form, it was cut into pieces that were about 1/8 inch long. The Nylon 12 came as a powder for the SLS printer, which meant the material needed to be printed and then cut into small pieces. The polystyrene, which is not used in any of the rapid prototyping methods, comes in pellet form. Each material was fed into the hopper of the Mini-Jector. The chamber and nozzle of the Mini-Jector were heated up to the appropriate temperatures for each material (Figure 11). The pneumatic pressure was set to approximately 80 psi. Once the desired temperatures were reach, the mold was placed in the Mini-Jector and the plastic was injected into the mold. Depending on the material, it took between six and eight seconds to fill the mold. The mold was then removed and allowed to cool for up to two minutes. The plastic test specimen was then removed from the mold and inspected for any visual flaws. If there were any laws the part was not used. To complete the experiments, nine parts of each material were required.

Figure 11 - Mini-Jector Model 45

3.5 Shrinkage

In Liu's research, the dimensional accuracy was tested for each of the rapid prototyping methods. Since the dimensional accuracy is much more easily controlled in injection molding, the shrinkage of each material will be compared to the dimensional accuracy. Every polymer has a unique shrinkage rate, which means the type of material that is being used must be considered when creating a mold. Using five specimen for each material, Liu measured the dimensional accuracy in four different locations, which are shown in Figure 12. The width-outside (WO) was measured on each side of the specimen and the thickness (T) was measured at three locations on each specimen. To calculate the shrinkage, the dimensions of the mold were measured using a Neiko 0-150 mm digital caliper with a resolution of 0.01 mm (Figure 13). Then, using the same caliper and being measured by the same person, the test specimens that were created by injection molding were measured. The measurements were recorded and used to calculate the average and standard deviation of each point. The percent shrinkage is calculated using the formula in Figure 14.

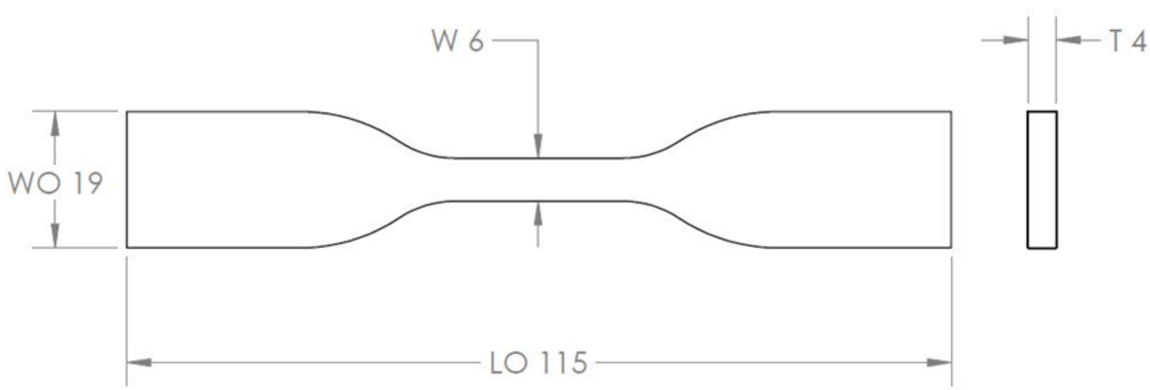


Figure 12 - Measurements for Shrinkage

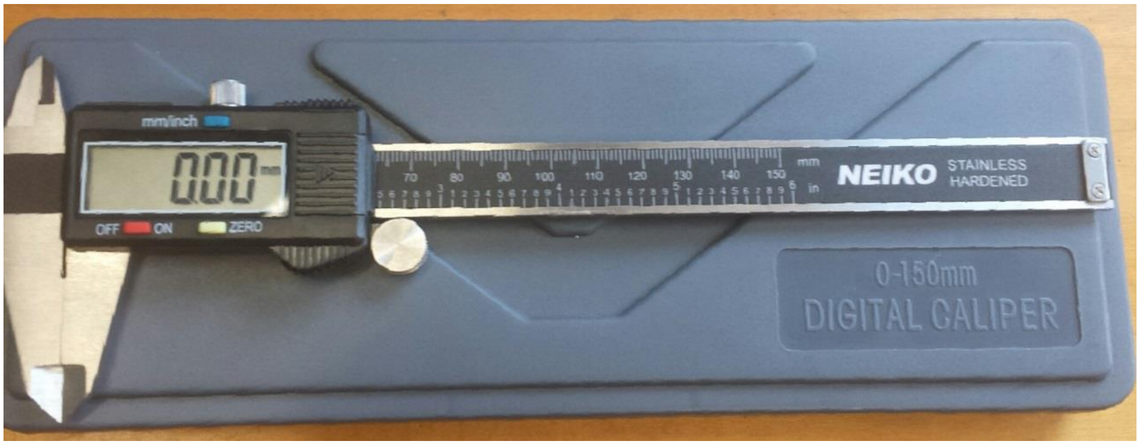


Figure 13 - Neiko Digital Caliper

$$Percent\ (\%)\ Shrinkage\ = \left(\frac{Mold\ Dimension - Specimen\ Dimension}{Mold\ Dimension}\right) \times 100$$

Figure 14 - Percent Shrinkage

3.6 Tensile Strength Testing

Tensile strength testing was performed on ABS, Nylon 12 and Polystyrene test specimens. Following the ASTM D638-10 standard, five specimen of each material were tested. The same ADMET eXpert 2611 universal testing machine that was used in Liu's research was used in this experiment. The testing machine is equipped with a 10 kN load cell. Each material was tested in an air conditioned environment at a temperature of 72 degrees Fahrenheit. The test specimen is held in place by two clamps, as shown in Figure 15. The top clamp is connected to the 10 kN load cell and pulls the specimen upward, putting stress on the specimen. The clamps separate at 5 mm/minute until the test specimen ruptures. Liu tested his parts at 5 mm/minute and this is in accordance to the ASTM D638-10 standard procedure. The ADMET software records the tensile strength in psi and elongation as a percentage increase in length. These data points were recorded and then tested for significance against the rapid prototyped parts using analysis of variance, or ANOVA.

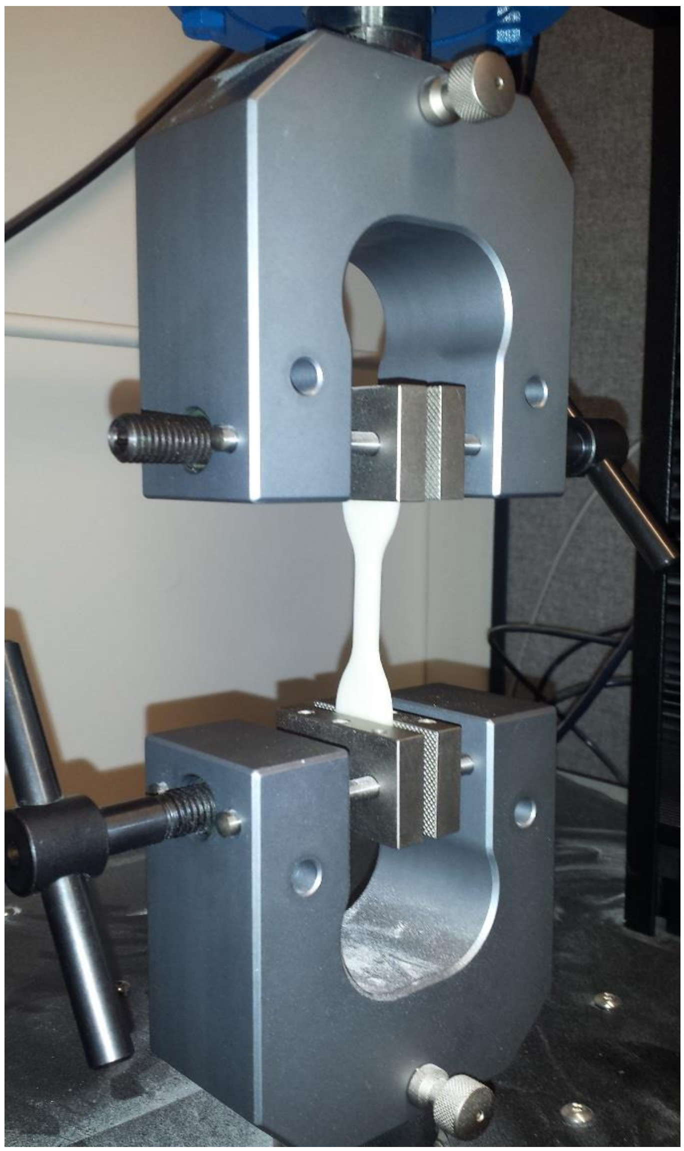


Figure 15 - ADMET eXpert 2611

3.7 Water Absorption

The water absorption test is used to observe differences in how much water is absorbed based on manufacturing method; rapid prototyping or injection molding. The same procedure that Liu used for the rapid prototyped specimen was used for the injection molded specimen. The ABS and Nylon 12 material was used to compare the two manufacturing methods and the Polystyrene was used as an extra reference for the parts that are manufactured using injection molding. Two specimens of each material were used for this experiment.

Prior to this experiment, the specimens that would be submerged under water were placed in a plastic bag and left in an air conditioned and controlled environment for one week, or 168 hours. This helped reduce error by making sure each part was held in the same environmental conditions. Once the 168 hours were over, each part was weighed using an OHAUS Scout Pro Series SP200 precision scale (Figure 16) and the data was recorded in grams. Next, each specimen was put in a zip-lock bag that was filled completely full with distilled water. The parts were submerged in water for 24 hours at 72 degrees Fahrenheit. At the completion of the 24 hours, the parts were removed from the bags and dried off with paper towels. They were immediately weighed using the same precision scale and the weight was recorded in grams. The water absorption was measured as a percent change in weight, demonstrated by Figure 17.

Figure 16 - OHAUS Scout Pro Series SP200
(Chen-Yu Liu)

$$Water\ Absorption\ (\%) = \left(\frac{weight\ after\ 24\ hour\ \text{Submersion}\ (\text{g}) - initial\ weight\ (g)}{initial\ weight\ (g)}\right) \times 100$$

Figure 17 - Water Absorption Equation

3.8 Shore Hardness

Shore hardness is used to measure the hardness of a polymer. The D scale is used for harder and more rigid polymers, while other scales like the 00 and A are used to measure softer, more flexible polymers. The D scale was used for this experiment because ABS, Nylon 12 and Polystyrene are considered hard plastics. To measure the Shore hardness a Pacific Transducer Corp. Model 409 ASTM Type D Durometer (Figure 18) was used. The Shore hardness D scale goes from 0 to 100, and the higher reading indicates a harder plastic. The durometer has a pointed indenter that is pressed into a plastic. As the indenter is pushed into the plastic, the durometer calculates the hardness based on how much force it takes to penetrate the plastic. Once the end of the durometer is flat with the plastic, the highest reading from the durometer is recorded.

For this experiment two test specimen of each material were used. The Shore hardness was tested at three location on each side of each test specimen. The value was recorded at each location. The average and standard deviation was then calculated for each material. To help reduce error, the exact same durometer that was used in Liu's research was used in this experiment. The location of each test was consistent with Liu's research also (Figure 19).

Figure 18 - Pacific Transducer Corp. Model 409 ASTM Type D Durometer

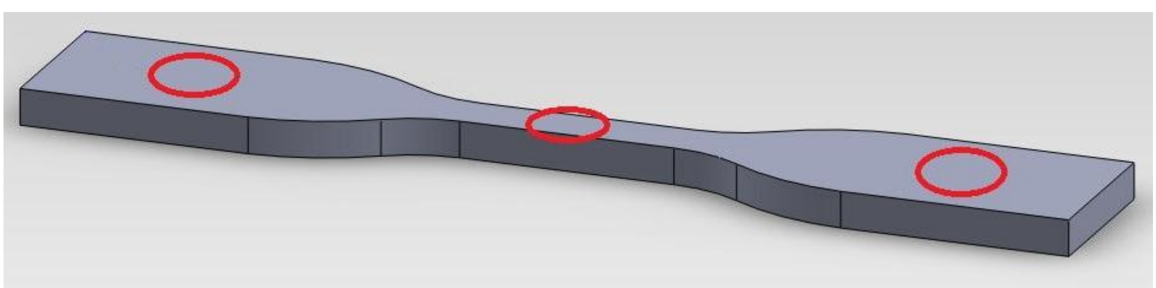


Figure 19 - Location of Shore Hardness Testing (Liu)

3.9 Microscopy

Post tensile testing, images of the ruptured test specimen were taken to observe the internal structure. The exact equipment that was used in Liu's research was also used in this experiment. The equipment includes the following: a MEIJI Techno EMZ-5TR stereo microscope equipped with an MA502 eyepiece (Figure 20), a Moticam 10 digital camera, and Motic Images Plus 2.0 software. An image of one specimen from each injection molded material was taken and compared to the images of the rapid prototyped parts. This experiment is meant to help explore the isotropic nature of injection molding versus the anisotropic nature of rapid prototyping.

Figure 20 - MEIJI Techno EMZ-5TR stereo microscope (Liu)

Chapter 4: Results and Analysis

4.1 Shrinkage

The shrinkage is measured as a percent change in size, comparing the dimensions of the mold to the dimensions of the final object. To analyze and compare these results, the standard deviations will be used to indicate how controllable these factors are in rapid prototyping and injection molding. The method with the lower standard deviation will provide a better manufacturing method because of its ability to have consistent results. If the standard deviation is low enough, the mold design can account for the shrinkage, and the product design can be altered for rapid prototyping. While comparing the results, only the build orientation from Liu's study with the smallest standard deviation will be considered for rapid prototyping.

4.1.1 ABS

The measurement data of the ABS test specimen is located in Table 10. The largest measured shrinkage was the thickness (T) at 2.273%. The injection molded parts had a lower average error (shrinkage or dimensional accuracy) and a lower standard deviation than the rapid prototyped parts. Using injection molding, the part shrunk an average of 1.049%. The dimensional error of the rapid prototyped part was 1.833% (Figure 21). The injection molded part had a very low standard deviation of 0.0369 and the rapid prototyping has a larger standard deviation at 0.9519, shown in Figure 22. Injection molding holds the advantage over rapid prototyping (using FDM technology) because of the lower standard deviation. The size of the mold can be enlarged to account for the shrinkage and a more consistent result can be expected from injection molding. The design of a product can be adjusted to compensate for inaccuracies in rapid prototyping, but the higher standard deviation indicates that there will be inconsistency with the finished product.

Table 10 - ABS Injection Molding Shrinkage Data

Material	W	WO 1	WO 2	WO TOT	LO	T 1	T 2	T 3	T TOT
ABS 1	6	18.86	18.78		114.11	4.3	4.33	4.36	
2	6	18.79	18.8		114.22	4.25	4.27	4.31	
3	5.98	18.79	18.84		114.03	4.32	4.3	4.31	
4	5.99	18.78	18.83		114.22	4.26	4.31	4.32	
5	5.98	18.79	18.83		114.11	4.26	4.29	4.31	
AVG	5.99	18.802	18.816	18.809	114.138	4.278	4.3	4.322	4.3
SD	0.00894427	0.02925748	0.02244994	0.027	0.07304793	0.02712932	0.02	0.01939072	0.02875181

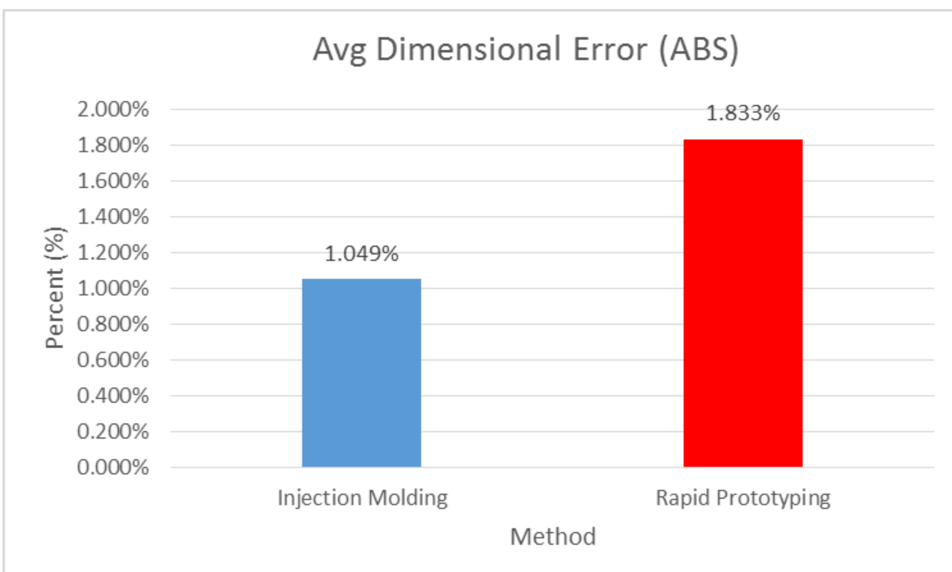


Figure 21 - ABS Dimensional Error Chart

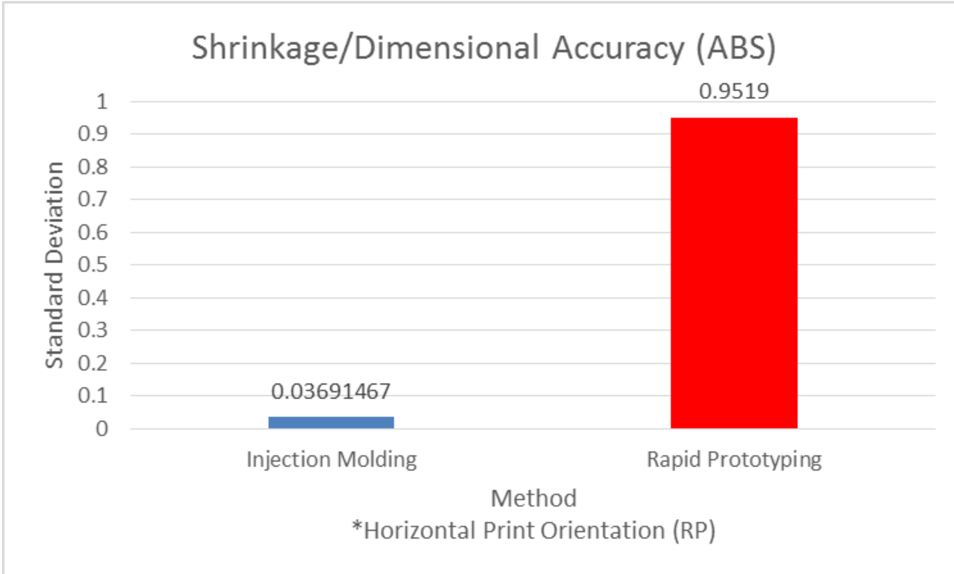


Figure 22 - Standard Deviation of ABS Dimensional Error

4.1.2 Nylon 12

The measurement data of the Nylon 12 test specimen is located in Table 11. The largest measured shrinkage was the thickness (T) at 4.21%. The injection molded parts had a higher average error than the rapid prototyped parts, but a lower standard deviation. Using injection molding, the part shrunk an average of 2.955% and the dimensional error of the rapid prototyped part was 1.402% (Figure 23). The injection molded part had a very low standard deviation of 0.06127 and the rapid prototyping has a larger standard deviation of 0.6335, shown in Figure 24. Again, injection molding holds an advantage over rapid prototyping because of the lower standard deviation. The standard deviation is used to indicate how consistent the completed parts will be. Adjustments can be made to the mold or part design that account for the error, but it cannot control the precision of the process. Injection molding will provide a more precise and consistent product.

Table 11 - Nylon 12 Injection Molding Shrinkage Data

Material	W	WO 1	WO 2	WO TOT	LO	T 1	T 2	T 3	T TOT
Nylon 12 1	5.84	18.41	18.47		112.81	4.18	4.23	4.24	
2	5.84	18.46	18.54		112.8	4.19	4.19	4.19	
3	5.85	18.39	18.41		112.72	4.21	4.21	4.22	
4	5.82	18.35	18.37		112.49	4.15	4.16	4.18	
5	5.86	18.48	18.48		112.83	4.27	4.31	4.29	
AVG	5.842	18.418	18.454	18.436	112.73	4.2	4.22	4.224	4.21466667
SD	0.0132665	0.04707441	0.05885576	0.05624944	0.12569805	0.04	0.05059644	0.03929377	0.04485037

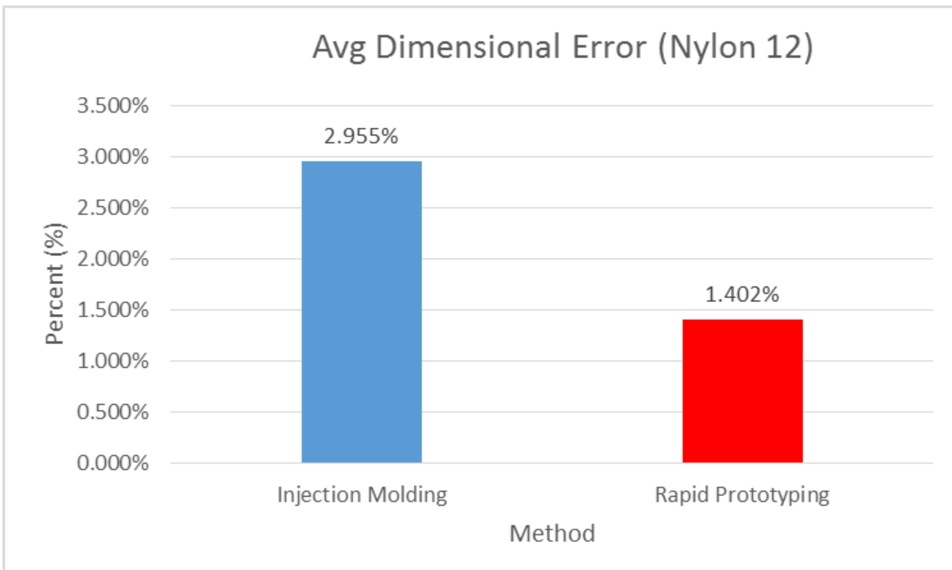


Figure 23 - Nylon 12 Dimensional Error Chart

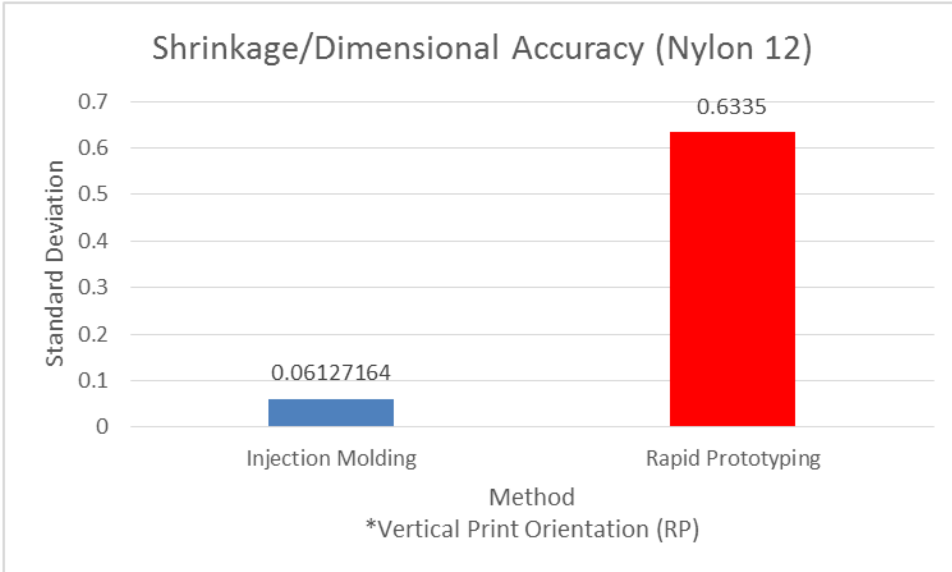


Figure 24 - Standard Deviation of Nylon 12 Dimensional Error

4.1.3 Polystyrene

Polystyrene observed the lowest shrinkage of all three materials. Its largest shrinkage is in the width overall at 1.005%, shown in Table 12. The average shrinkage of polystyrene is 0.5595%. This material was not used for any of the rapid prototyping process, but these results help show the differences in properties between polymers in injection molding. Using this third material also helps verify that the injection molding process can create finished products with a much lower standard deviation. The polystyrene had an overall standard deviation of 0.2687, which is lower than any of the rapid prototyping processes.

Table 12 - Polystyrene Injection Molding Shrinkage Data

Material	W	WO 1	WO 2	WO TOT	LO	T 1	T 2	T 3	T TOT
Polystyrene 1	5.99	18.86	18.89		114.38	4.4	4.4	4.41	
2	5.97	18.81	18.8		114.34	4.41	4.38	4.37	
3	5.98	18.8	18.79		114.39	4.43	4.37	4.32	
4	5.98	18.73	18.78		114.44	4.35	4.38	4.42	
5	5.98	18.79	18.84		114.37	4.35	4.38	4.39	
AVG	5.98	18.798	18.82	18.809	114.384	4.388	4.382	4.382	4.384
SD	0.00632456	0.04166533	0.04049691	0.04253234	0.03261901	0.03249615	0.00979796	0.03544009	0.02847221

4.1.4 **Summary**

The injection molded parts performed better than the rapid prototyped parts in dimensional accuracy. While some of the rapid prototyped parts have a lower average error than the injection molded parts, the standard deviation of the injection molded parts is lower than their rapid prototyped counterpart. The shrinkage that is experienced in injection molding is a controllable error. The design of a mold can be altered, specifically enlarged, to account for how much a polymer is going to shrink. The design of a part can be altered to account for dimensional error in rapid prototyping, but this experiment shows that there is greater variation between the parts that are being created. This is significant because even if the error is known, it will still be hard to produce a product with great precision. In terms of manufacturability, accuracy and precision are both extremely important. Using the traditional method of injection molding will provide a more precise product and the design can be adjusted to provide a more accurate part. A lot of products are manufactured with very tight tolerances, and the results from the rapid prototyping processes that were tested indicate that they cannot repeatedly produce a part that will meet the specifications. Table 13 summarizes the results from the injection molded parts and Figure 25 and Figure 26 are charts that summarize the dimensional error of injection molding and rapid prototyping. The chart in Figure 27 summarizes the standard deviation of each material for injection molding and rapid prototyping.

Table 13 - Summary of Injection Molding Shrinkage

ASTM D638 Type IV		ABS	Nylon 12	Polystyrene
W 6	AVG	5.99	5.84	5.98
	SD	0.00894427	0.0132665	0.00632456
	AVG Shrinkage (%)	0.167	2.667	0.333333333
WO 19	AVG	18.809	18.436	18.809
	SD	0.027	0.05624944	0.04253234
	AVG Shrinkage (%)	1.005	2.968	1.005263158
LO 115	AVG	114.138	112.73	114.384
	SD	0.07304793	0.12569805	0.03261901
	AVG Shrinkage (%)	0.750	1.974	0.535652174
T 4.44	AVG	4.3	4.21467	4.384
	SD	0.02875181	0.04485037	0.02847221
	AVG Shrinkage (%)	2.273	4.212	0.363636364
SD		0.03444	0.06002	0.02749
AVG - Shrinkage (%)		1.049	2.955	0.559471257

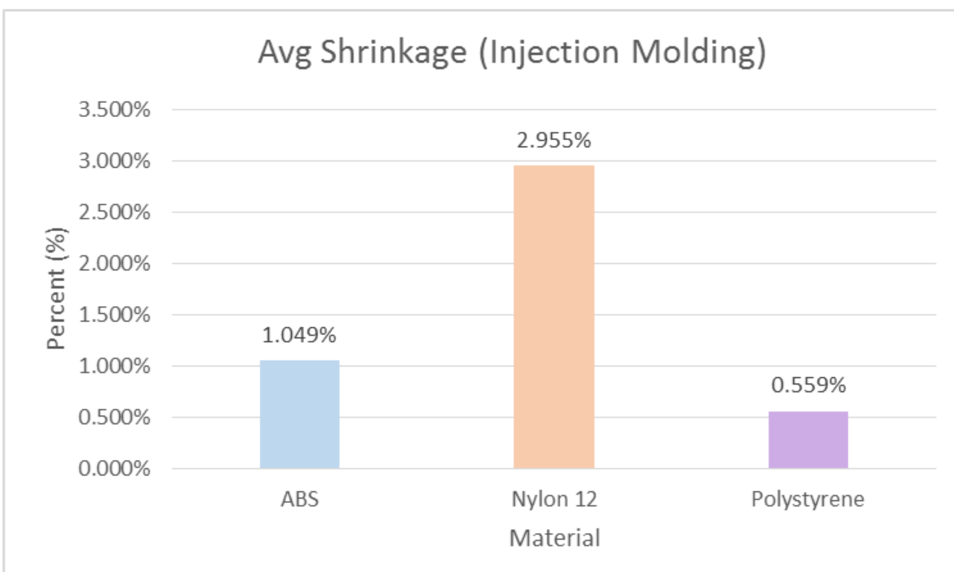


Figure 25 - Average Dimensional Error in Injection Molding

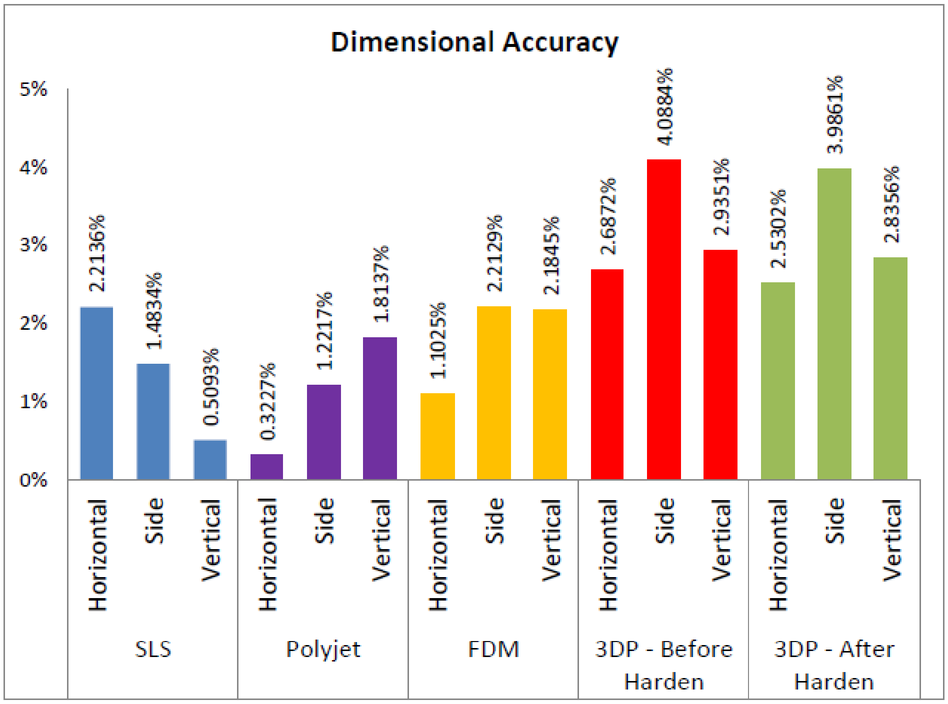


Figure 26 - Dimensional Accuracy of Rapid Prototyping Methods (Chen-Yu Liu)

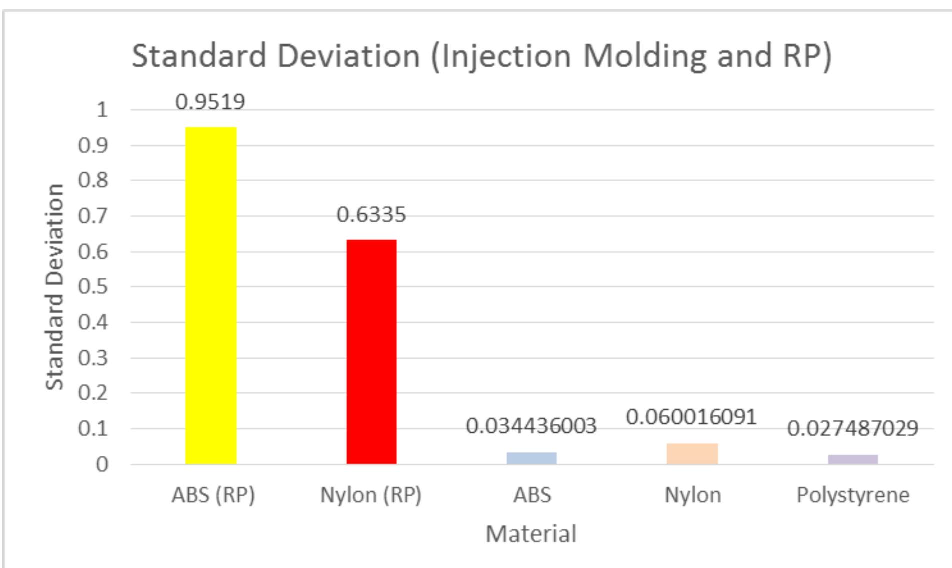


Figure 27 – Summary of Dimensional Accuracy Standard Deviation

4.2 Tensile Properties

This section contains the results of the testing described in section 3.6. Five test specimen, of each material, were created by injection molding and used in this experiment. The ABS and Nylon 12 are the exact same materials that were used in Liu's research and the Polystyrene was used for additional for further analysis of the mechanical properties of injection molded parts. The Admet software calculated and recorded the tensile strength, elongation and elongation at break of each test. If the test specimen did not rupture in the thin section, or there was a cavity caused by an air bubble at the break, the test was not considered in this analysis and a new part was tested. The following sections discuss and analyze the results and compare them to the results found in Liu's research.

4.2.1 ABS

The results of the five injection molded ABS test specimens will be analyzed in this section. Table 14 shows the results from this test and the results of the rapid prototyped parts from Liu's research. The letter in parenthesis next to rapid prototyping results represents the build orientation that was used. The average tensile strength of the injection molded test specimen is 6,310 psi and that is 737.8 psi higher than the rapid prototyping average. The standard deviation of tensile strength for the rapid prototyped parts is much lower than the standard deviation of the injection molded parts. This indicates that there was more inconsistency in the parts made by injection molding. This shows that there is more precision with the FDM rapid prototyping method than injection molding.

The injection molded parts have a lot more variability due to the cooling of plastics, mold design, and the injection molding process in general. Without using a clear plastic, it is hard to know if there might be air bubbles in an injection molded part that will make it weaker. It is these factors that cause the injection molded part to have a larger standard deviation. Table 14 also shows that the average elongation and elongation at break is larger for the injection molded part, but the standard deviation is better (lower) for the rapid prototyped parts. The biggest concern for this experiment was to determine which manufacturing method created the stronger part. Figure 28 compares the tensile strength of injection molding rapid prototyping.

The graph in Figure 29 shows the stress vs position during the testing of an ABS test specimen created using injection molding. You can see that after the ABS plastic peaks, it starts to lose strength and then eventually ruptures. This graph also shows that there was no strain hardening after the yield strength, which means the ultimate strength is equal to the yield strength. Running at approximately 0.2 inches/minutes, the graph shows that the test took less than one minute to complete.

Table 14 - ABS Tensile Properties

ABS	Injection Molding	RP
Avg Tensile Strength (psi)	6310.000	5572.2 (s)
SD Tensile Strength	325.792	61.674 (s)
Avg Elongation at Break (%)	13.003	3.710 (s)
SD Elongation at Break	8.368	0.107 (v)
Avg Elongation (%)	3.998	2.219 (h)
SD Elongation	0.354	0.030 (s)

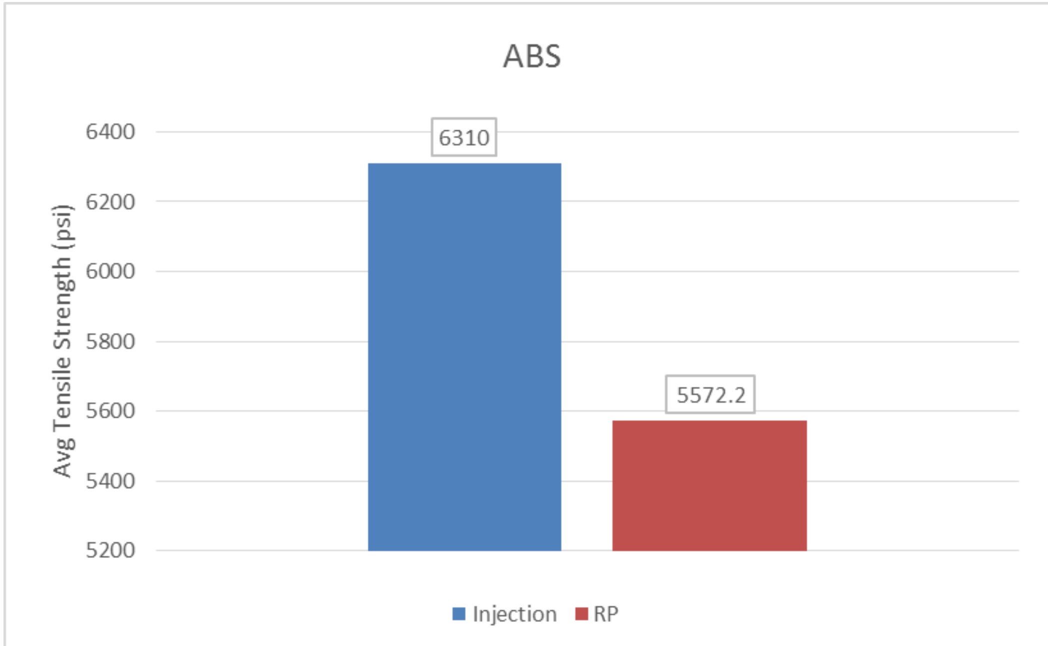


Figure 28 - ABS Average Tensile Strength

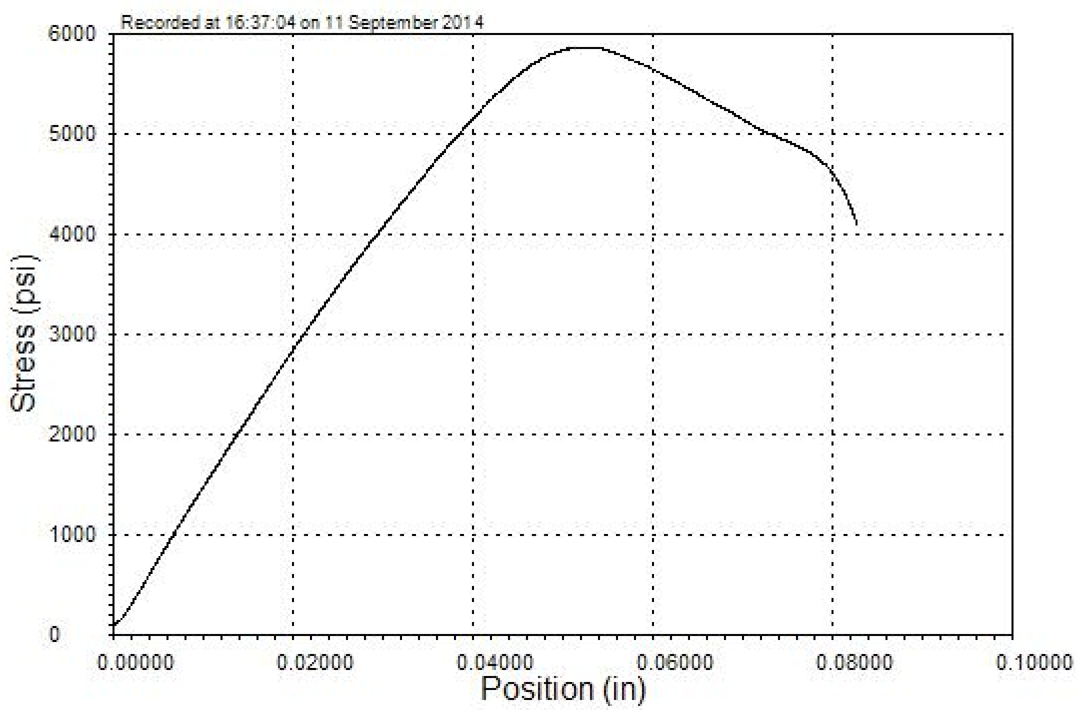


Figure 29 - Stress vs Position Chart of ABS Tensile Testing

Statistical Analysis

Using ANOVA we are able to determine if the two methods, injection molding and rapid prototyping, have a significant impact on tensile strength. A p-value that is below 0.05 indicates that there is a significant difference between the two methods being evaluated. The ANOVA table in Table 15 has a p-value equal to 0.002, so it is confirmed that the method used to build the test specimen has an effect on the tensile strength. The points on the normal probability plot, in Figure 30, appear to be normal and indicate the expected normal distribution. The box-plot in Figure 31 demonstrates the larger range of the injection molded parts, but it also shows that their results are all higher than the rapid prototyped parts.

Table 15 - ANOVA Table for ABS Tensile Strength

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Method	1	1360872	71.37%	1360872	1360872	19.94	0.002
Error	8	545917	28.63%	545917	68240		
Total	9	1906789	100.00%				

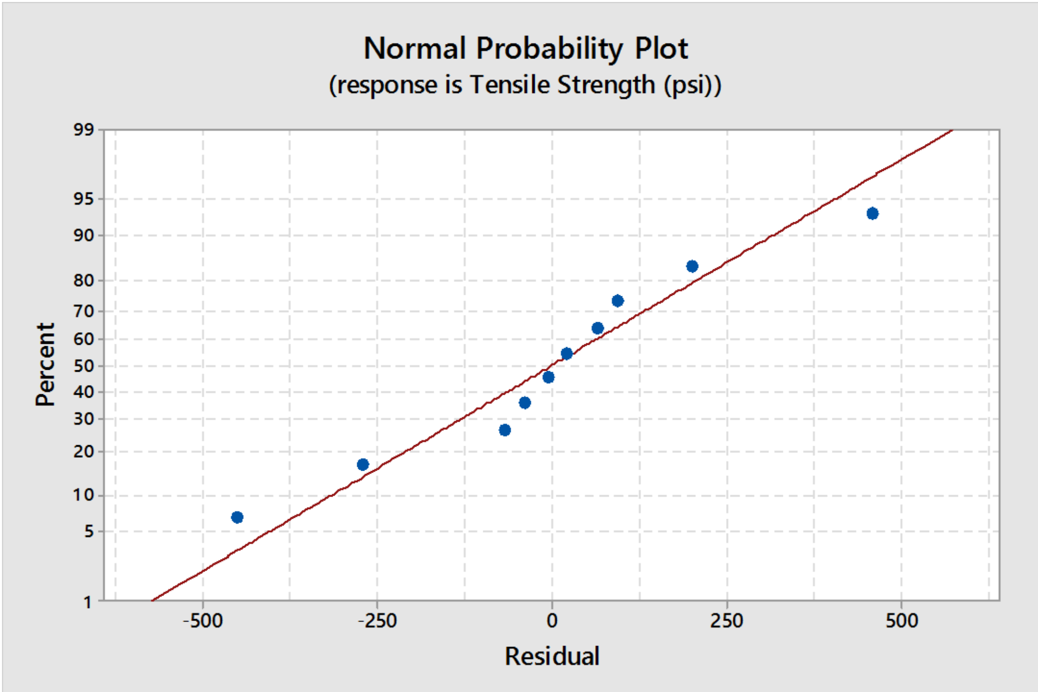


Figure 30 - Normal Probability Plot for ABS Tensile Strength

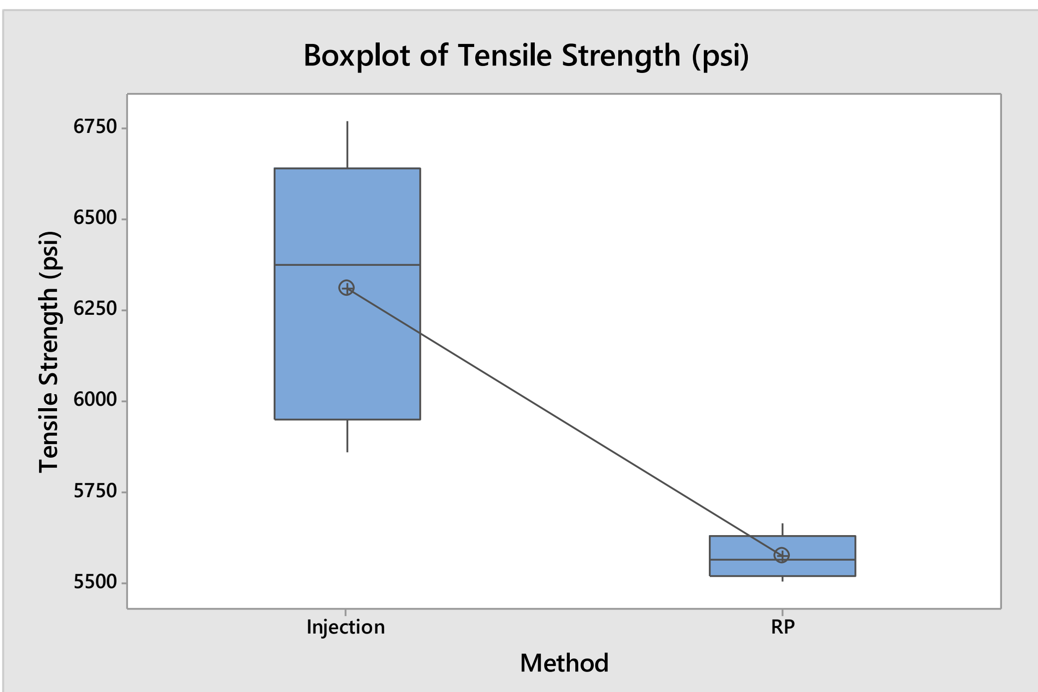


Figure 31 - Boxplot for ABS Tensile Strength

4.2.2 Nylon 12

The results of the five injection molded Nylon 12 test specimen will be analyzed in this section. Table 16 shows the results from this test and the results of the rapid prototyped parts from Liu's research. The average tensile strength of the injection molded test specimen is 7953 psi and that is 585.6 psi higher than the rapid prototyping average. The standard deviation of tensile strength for the rapid prototyped parts is much lower than the standard deviation of the injection molded parts. This indicates that there was more inconsistency in the parts made by injection molding. This shows that there is more precision with the Nylon 12 rapid prototyping method than injection molding. The injection molded parts have a lot more variability due to the cooling of plastics, mold design, and the injection molding process in general. Without using a clear plastic, it is hard to know if there might be air bubbles in an injection molded part that will make it weaker. These factors may have caused the injection molded part to have a larger standard deviation. Table 16 also shows that the average elongation and elongation at break is larger for the injection molded part, but the standard deviation is better (lower) for the rapid prototyped parts. The injection molded test specimen elongated 233% more at the break and 267.85% at yield than the rapid prototyped part. The objective of this experiment was to determine which manufacturing method created the stronger part. As seen in Figure 32, the injection molded part creates a stronger product. The graph in Figure 33 shows the stress vs position during the testing of a Nylon 12 test specimen created using injection molding. You can see that after the Nylon 12 plastic peaks, it loses some strength, but then it experiences strain hardening and results in an ultimate strength that is higher than the yield strength. Running at approximately 0.2 inches/minutes, the graph shows that the test took approximately 16 minutes to complete.

Nylon 12	Injection Molding	RP
Avg Tensile Strength (psi)	7953.000	7367.4 (h)
SD Tensile Strength	128.675	27.364 (h)
Avg Elongation at Break (%)	249.536	16.533 (h)
SD Elongation at Break	49.039	0.449 (s)
Avg Elongation (%)	275.592	7.741 (v)
SD Elongation	36.666	0.166 (s)

Table 16 - Nylon 12 Tensile Properties

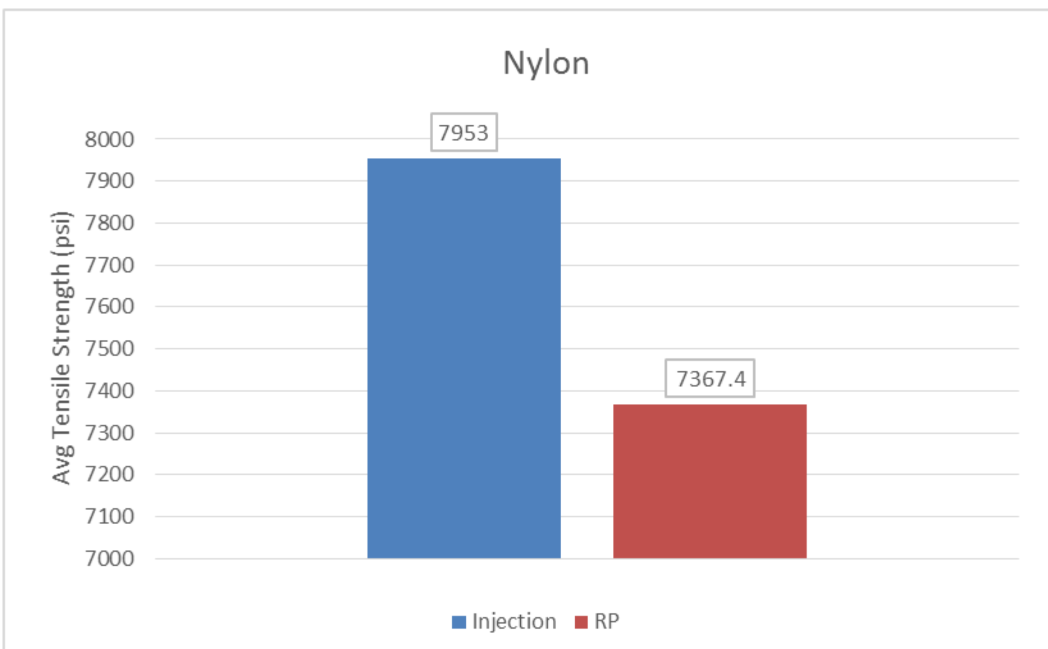


Figure 32 - Nylon 12 Average Tensile Strength

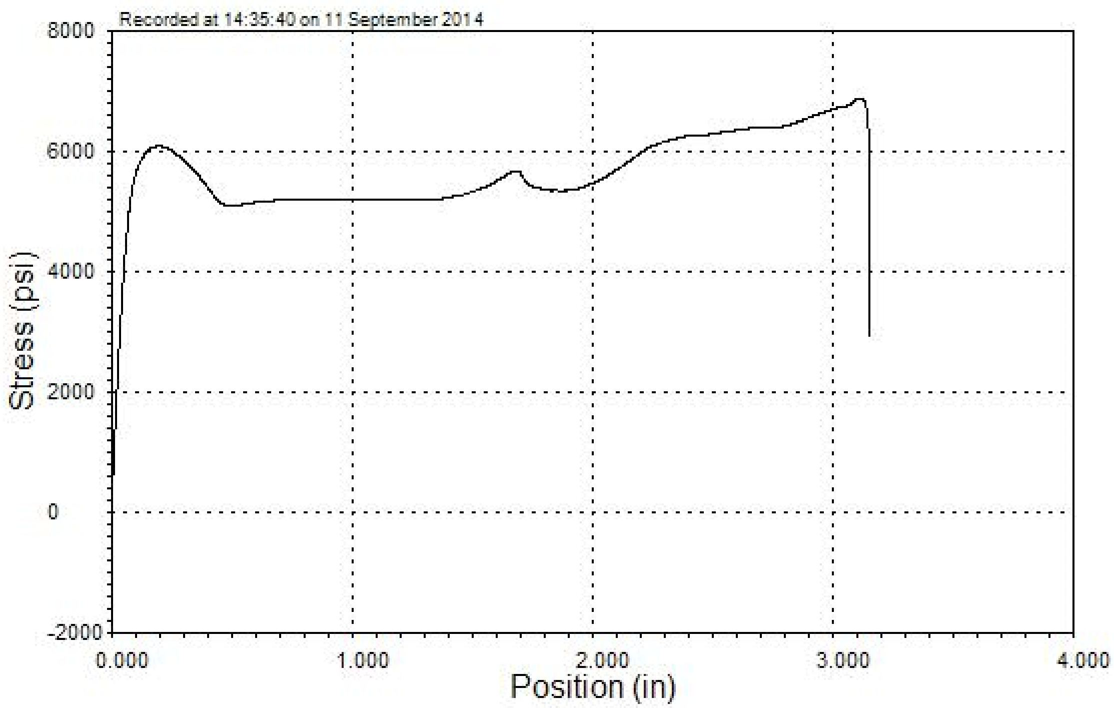


Figure 33 - Stress vs Position Chart of Nylon 12 Tensile Testing

Statistical Analysis

Using ANOVA we are able to determine if the two methods, injection molding and rapid prototyping, have a significant impact on tensile strength. A p-value that is below 0.05 indicates that there is a significant difference between the two methods. The ANOVA table in Table 17 has a p-value equal to 0.000, so it is confirmed that the method used to build the test specimen has an effect on the tensile strength. The points on the normal probability plot, in Figure 34, appear to be normal and indicate that the model is sufficient. The box-plot in Figure 35 demonstrates the larger range of the injection molded parts, but it also shows that their results are all higher than the rapid prototyped parts.

Table 17 - ANOVA Table for Nylon 12 Tensile Strength

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Method	1	857318	90.90%	857318	857318	79.95	0.000
Error	8	85781	9.10%	85781	10723		
Total	9	943100	100.00%				

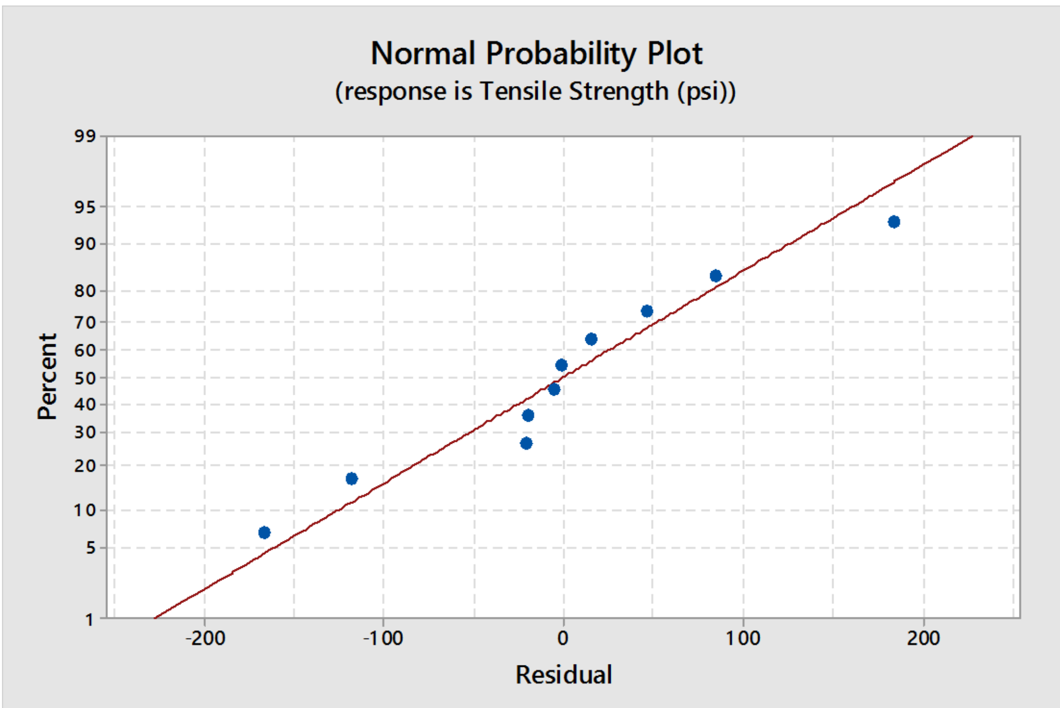


Figure 34 - Normal Probability Plot for Nylon 12 Tensile Strength

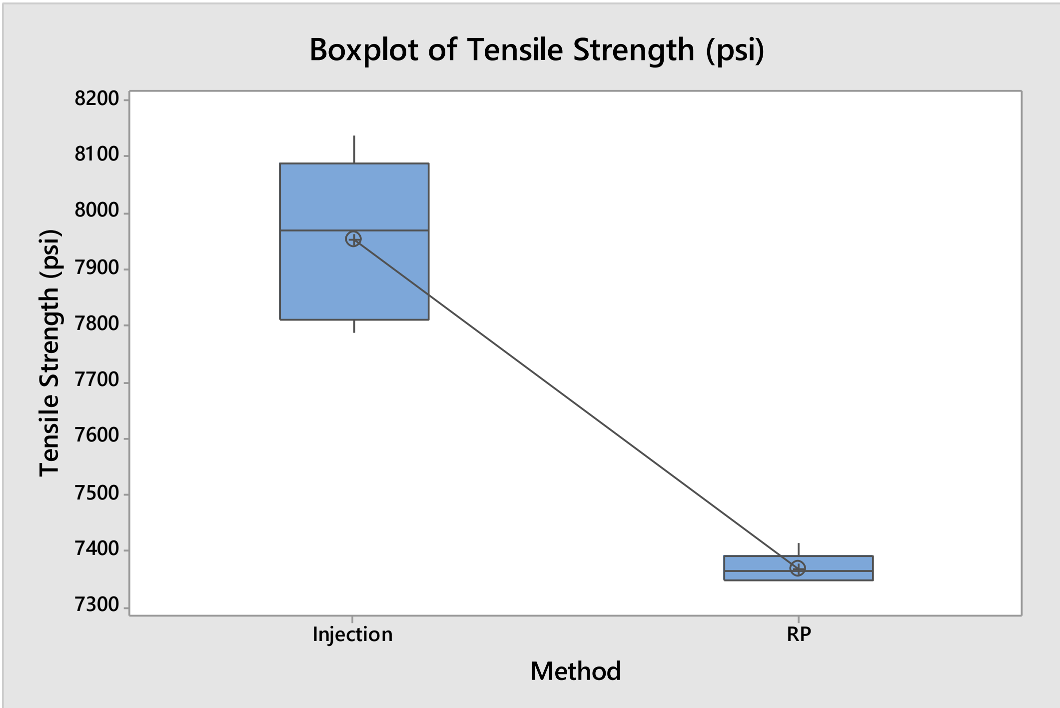


Figure 35 - Boxplot for Nylon 12 Tensile Strength

4.2.3 Polystyrene

None of the rapid prototyping machines used this material, so it was not used in Liu's research. Because of the availability of this material, it was used to help verify the results of the injection molding process. Table 18 shows the results for tensile testing. The average strength was 6010.8 psi and the standard deviation was 151.451. This material was not very elastic and had very low elongation and elongation at break. The results of this test are beneficial because they show that the standard deviation of the injection molded parts is consistently higher than those of the rapid prototyped parts, regardless of the material used.

Polystyrene	Results
Avg Tensile Strength (psi)	6010.800
SD Tensile Strength	151.451
Avg Elongation at Break (%)	1.814
SD Elongation at Break	0.443
Avg Elongation (%)	2.422
SD Elongation	0.040

Table 18 - Polystyrene Tensile Properties

4.2.4 Summary

A summary of all the tensile testing results can found in Table 19. This experiment confirms that the injection molded test specimen have a higher tensile strength, a larger elongation, and elongation at break than the rapid prototyped specimen. The results that were taken from Chen-Yu Liu's thesis only include the build orientation that created the best results. While the injection molded test specimen had better averages (Figure 36), they did experience larger standard deviations than the rapid prototyped test specimen. This indicates that the rapid prototyping processes can create parts with a more consistent tensile strength. However, there are procedures that can help control and reduce the variation in the injection molding process. The injection molded test specimen also had better results in average elongation (Figure 37) and elongation at break (Figure 38). The injection molded Nylon 12 results for elongation were 267.8506% higher than the rapid prototyped Nylon 12 results. The injection molding process is discussed in chapters one and two. By following best practices such as optimal mold temperature, clamp force, and cooling time, the consistency of an injection molded part can be improved. The most significant error that was experienced in the injection molding process was the presence of air bubbles that created cavities in the test specimen. If a cavity was present at the break of one the test specimen, it was not included in the results.

In conclusion, the rapid prototyping methods that were tested have a lower tensile strength than the injection molding method. If strength is a primary concern for a manufactured good, then the rapid prototyping process is not ready to replace injection molding. It is also worth noting that a complex three dimensional part that is created by rapid prototyping will not have the same tensile strength in all orientations. The injection molding process does not depend on build orientation and will have the same strength throughout a product. This research finds that the rapid prototyping method deals with less standard deviation than the injection molding process. Despite the larger standard deviation of the injection molded test specimen, ANOVA verifies that there is a significant difference between the two manufacturing methods. The results of this research do not support a move from rapid prototyping to rapid manufacturing if tensile properties are the main concern.

Table 19 - Summary of Tensile Testing

Method & Test	Material	Range	Avg	SD
Injection Molding Tensile Strength (psi)	ABS	5859-6768	6310.000	325.792
	Nylon 12	7787-8137	7953.000	128.675
	Polystyrene	5746-6206	6010.800	151.451
RP Tensile Strength (psi)	ABS	N/A	5572.200	61.674
	Nylon 12	N/A	7367.400	27.364
Injection Molding Elongation (%)	ABS	3.501-4.328	3.998	0.354
	Nylon 12	228.2-323.3	275.592	36.666
	Polystyrene	2.378-2.49	2.422	0.040
RP Elongation (%)	ABS	N/A	2.219	0.034
	Nylon 12	N/A	7.741	0.057
Injection Molding Elongation at Break (%)	ABS	5.511-28.874	13.003	8.368
	Nylon 12	180.2-324.6	249.536	49.039
	Polystyrene	1.187-2.525	1.814	0.443
RP Elongation at Break (%)	ABS	N/A	3.710	0.107
	Nylon 12	N/A	16.533	0.449

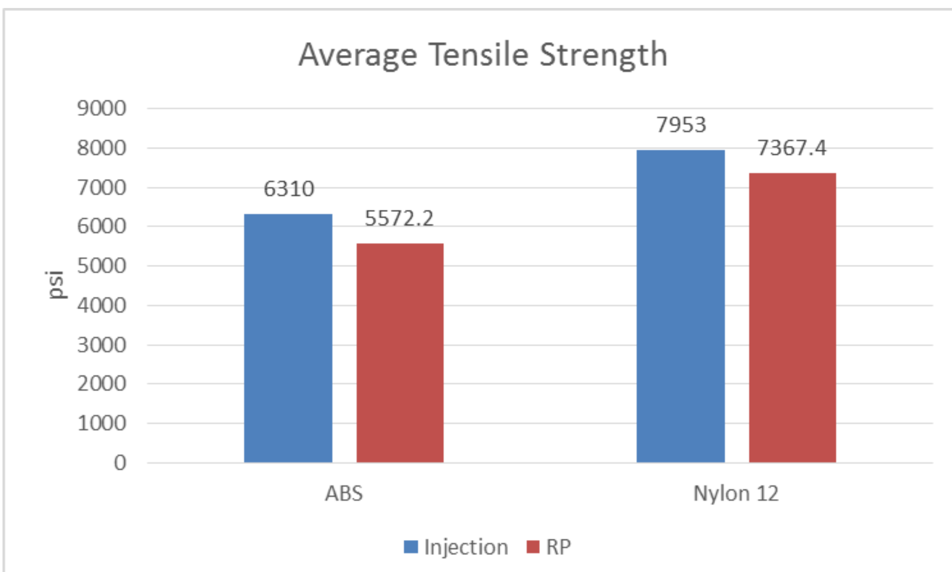


Figure 36 - Summary of Average Tensile Strength

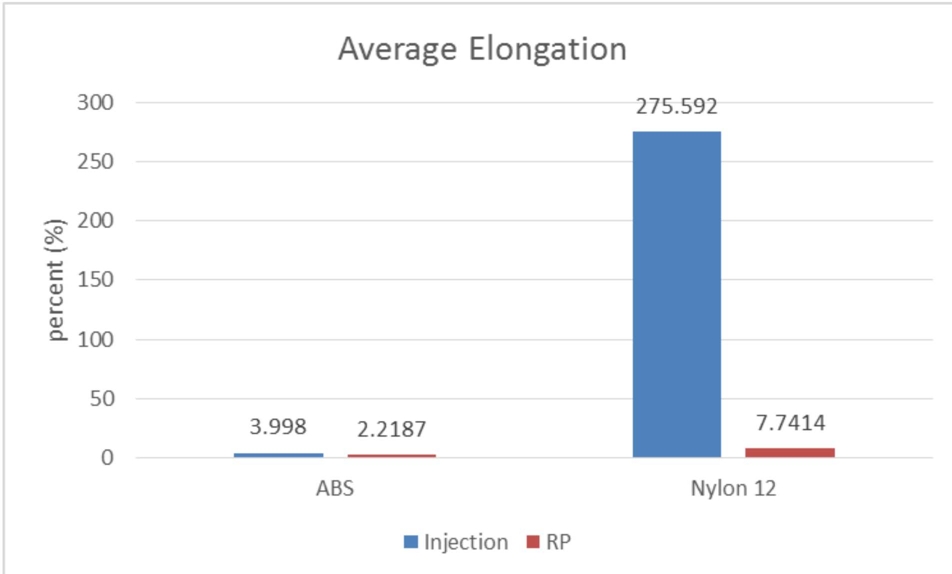


Figure 37 - Summary of Average Elongation

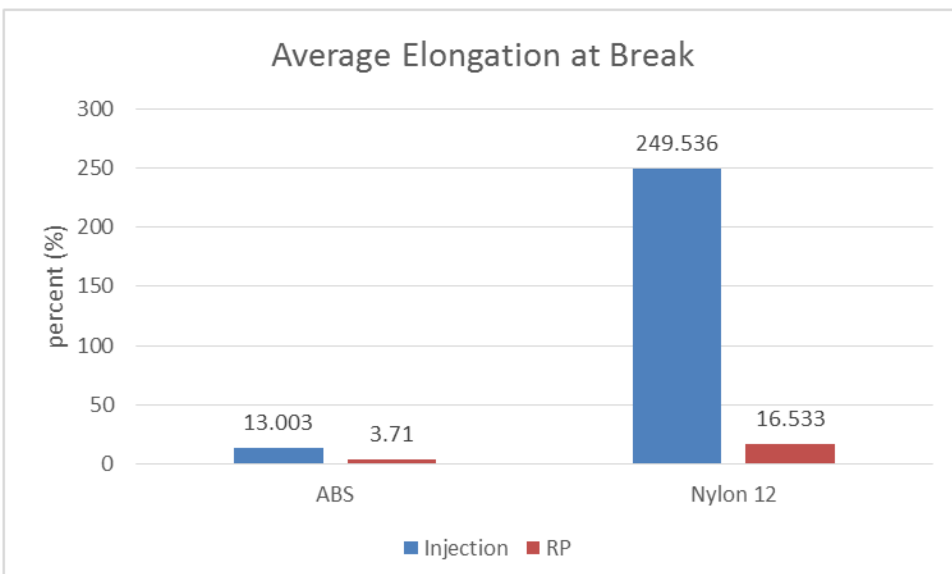


Figure 38 - Summary of Elongation at Break

4.3 Water Absorption

Water absorption was included in Liu's research because "the increase in weight, dimensional variations, and the change in electrical and mechanical properties may need to be considered when plastic materials are used for different purposes" [13]. In this section, the results from the test described in section 3.7 will be presented and compared to the rapid prototyping results found in Liu's research. The relative weight change rate of water absorption is measured by the equation below:

$$Relative\ Weight\ Change\ Rate\ (\%) = \left(\frac{weight\ after\ 24\ hour\ \text{submersion}\ (g) - initial\ weight\ (g)}{initial\ weight\ (g)}\right) \times 100$$

Table 20 shows the results from the injection molded parts and the results of the rapid prototyped parts in Liu's research. The injection molded test specimen absorbed significantly less water than the rapid prototyped parts. The weight of the ABS injection molded test specimen increased by an average of 0.35586% and the rapid prototyped test specimen increased by an average of 11.27315%. The weight of the nylon 12 injection molded test specimen increased by an average of 0.22143% and the rapid prototyped test specimen increased by an average of 1.46997%. This test shows the significance of the isotropic structure of the injection molding versus the anisotropic structure of the rapid prototyped parts. The rapid prototyped parts absorb more water because there are cavities between the layers of the material. Figure 39 shows the results, comparing injection molding and rapid prototyping. Testing the polystyrene helped verify that the isotropic nature of injection molding absorbs less water.

The difference between the two manufacturing methods for nylon 12 is much lower than the ABS plastic because of the method used in rapid prototyping. The SLS method, which is used for nylon 12, fuses the layers better than the FDM method, which is used for ABS. The SLS method still creates an anisotropic structure, but there are smaller cavities in the final product because of the improved fusing between layers. When using a rapid prototyping to create a product, it should be known that the product will absorb more water than a part that is created by injection molding. It is also important to note that the rapid prototyping method will make a difference in water absorption.

Table 20 - Summary of Water Absorption Results

Water Absorption Results					
Method	**Material**	**Sample**	**Before (g)**	**After (g)**	**Change Rate (%)**
Injection Molding	ABS	1	6.970	7.000	0.43042
		2	7.110	7.130	0.28129
		Avg	7.040	7.065	0.35586
	Nylon 12	1	6.590	6.600	0.15175
		2	6.870	6.890	0.29112
		Avg	6.730	6.745	0.22143
	Polystyrene	1	7.220	7.230	0.13850
		2	7.240	7.250	0.13812
		Avg	7.230	7.240	0.13831
Rapid Prototyping	ABS	1	5.860	6.470	10.40956
		2	5.850	6.560	12.13675
		Avg	5.855	6.515	11.27315
	Nylon 12	1	6.830	6.940	1.61054
		2	6.770	6.860	1.32939
		Avg	6.800	6.900	1.46997

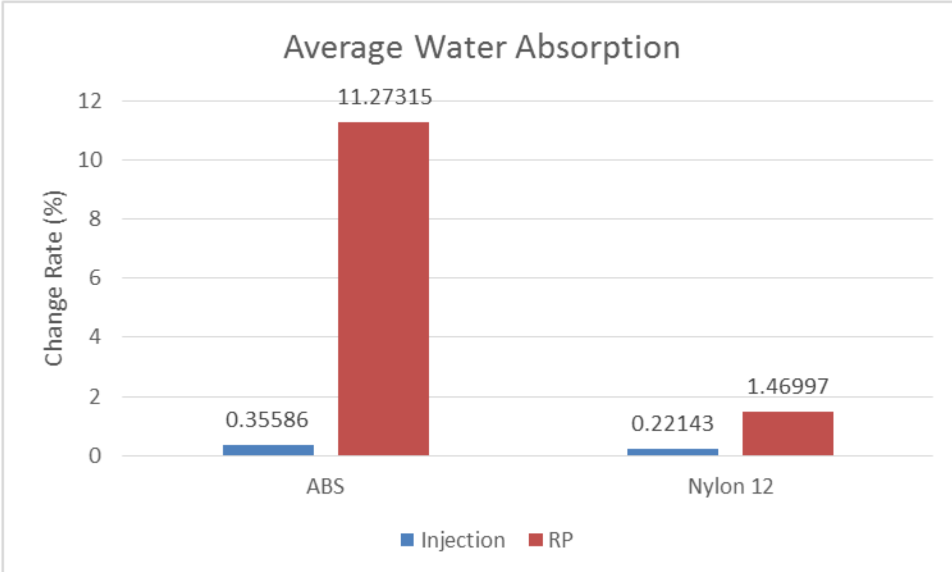


Figure 39 - Summary of Average Water Absorption

Statistical Analysis

One way ANOVA testing was selected for the analysis of the water absorption results. Using ANOVA the significance of injection molding versus rapid prototyping can be confirmed. The two manufacturing methods will be compared for both ABS and Nylon 12 plastics. A p-value less than 0.05 confirms that there is a significant difference between the two methods. The normal probability plot and boxplot are used to help further analyze the data. In this ANOVA testing the method is used as the input and the water absorption value is the output.

ABS

The ANOVA table below (Table 21) displays the results of injection molding versus rapid prototyping for ABS plastic. The p-value is equal to 0.006 and indicates that there is a significant difference between the two manufacturing methods. The data points on the probability plot shown in Figure 40 appear to be normal and follow the model. The boxplot in Figure 41 provides a good illustration of the lower absorption rate for injection molding and it also shows that there was more variation in the rapid prototyping method.

Table 21 - ANOVA Table for Water Absorption

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Method	1	119.187	119.187	158.63	0.006
Error	2	1.503	0.751		
Total	3	120.690			

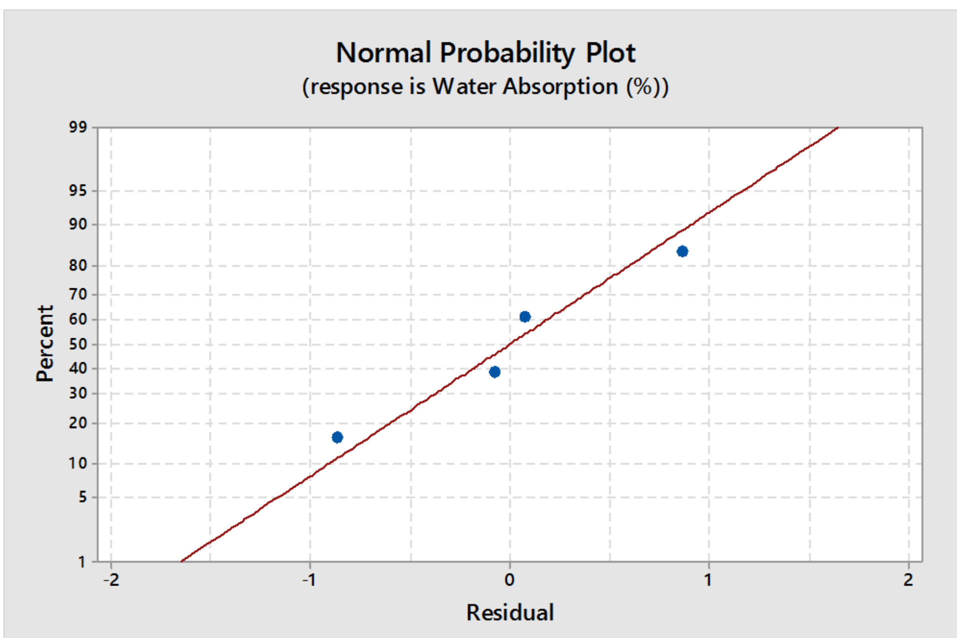


Figure 40 - Normal Probability Plot ABS Water Absorption

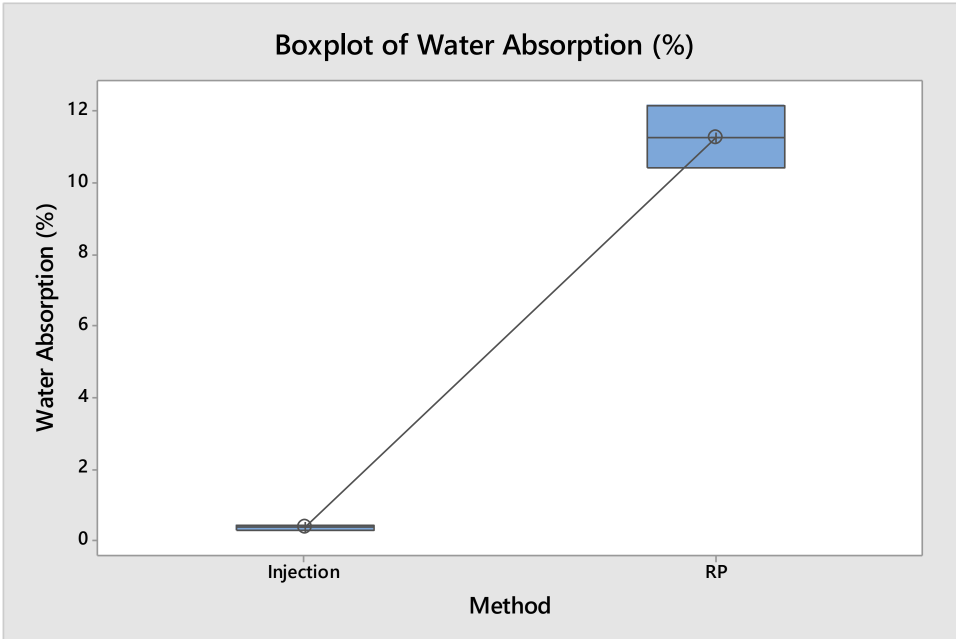


Figure 41 - Boxplot for ABS Water Absorption

Nylon 12

The ANOVA table below (Table 22) displays the results of injection molding versus rapid prototyping for Nylon 12 plastic. The p-value is 0.015, indicating that there is a significant difference in water absorption between the two manufacturing methods. Similar to the ABS plastic, the probability plot in Figure 42 appears to be normal and follows the model. The boxplot in Figure 43 shows the larger range in rapid prototyping and it also helps illustrate the difference between the two methods for all of the collected data.

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Method	1	1.55883	1.55883	63.32	0.015
Error	2	0.04923	0.02462		
Total	3	1.60806			

Table 22 - ANOVA Table for Nylon 12 Water Absorption

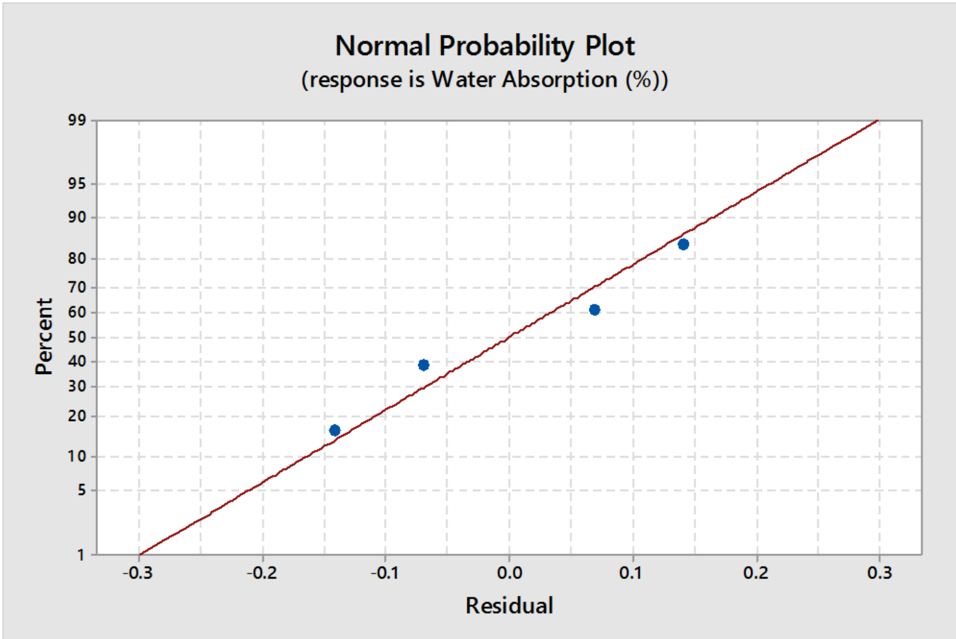


Figure 42 - Normal Probability Plot for Nylon 12 Water Absorption

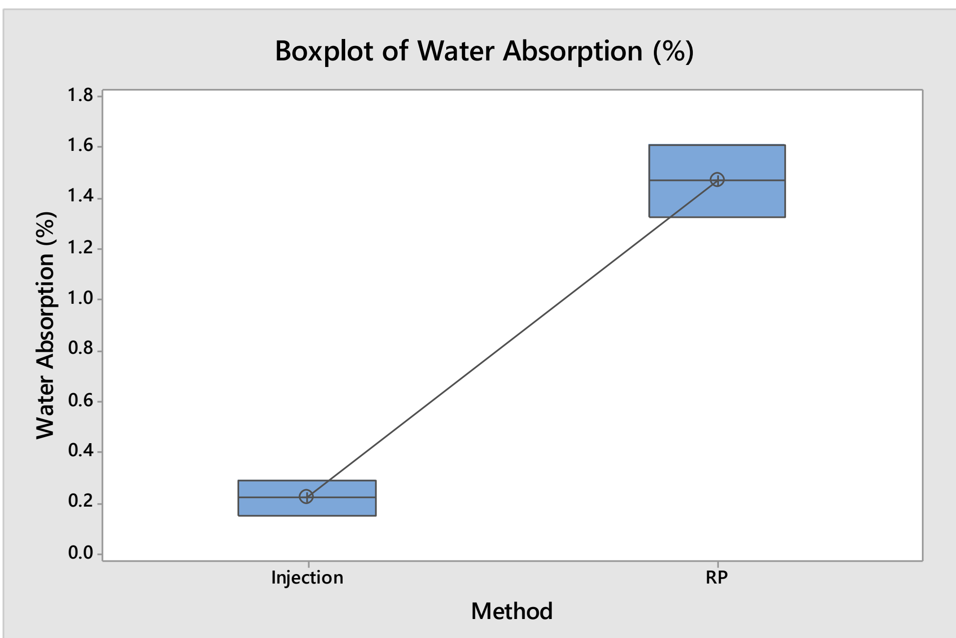


Figure 43 - Boxplot for Nylon 12 Water Absorption

4.4 Shore Hardness

As explained in 3.8, the Shore Hardness D scale is used to determine the hardness of rigid polymers. The scale is 0 – 100 and the higher number indicates a harder polymer. A durometer is used to measure the hardness. Twelve measurements were taken for each material and the scores are summarized in Table 23. The results are compared to Liu's rapid prototyping results in Table 24. Averages of the ABS test specimen are 75.50 for injection molding and 78.42 for rapid prototyping. The Nylon 12 test specimen had an average of 70.17 for injection molding and 77.17 for rapid prototyping. The rapid prototyping method creates a harder product for both ABS and Nylon 12 polymers.

The difference in scores for the ABS material is only 2.92 and 7.00 for the Nylon 12 plastic. On a 100 point scale this may not seem like a lot, but there is significance here. Shore hardness is not an indicator of flexibility, but there is a correlation between the two. More testing would need to be done to confirm this, but a hypothesis could be made that the plastic injection molded parts might be more flexible than the parts created using rapid prototyping. The hardness of a polymer indicates how well the plastic will hold up against penetrating forces. Since the Shore hardness measurement is taken on the surface of the part, the anisotropic and isotropic structure of the part is most likely not the cause of the difference in scores. It is more likely one, or more, of the many variables that are different between each method caused the difference in Shore hardness scores. For example, the highest temperature the materials were exposed to and the rate the final part cooled were different between each method. It should be noted that the injection molded test specimen were heated and melted multiple times and the rapid prototyped parts were not. The maximum temperature that the materials were exposed to in the two methods were different and that may cause a difference in the Shore hardness score. Since all of the data points for Shore hardness in Liu's thesis are not available, statistical analysis was not performed.

Table 23 - Shore Hardness Data

Injection Molding Shore Hardness Data (D Scale)					
ABS					
78	74	75	76	73	76
75	76	75	76	76	76
Nylon 12					
62	70	65	74	70	73
69	72	72	74	70	71
Polystyrene					
84	77	82	79	79	75
79	82	81	84	83	84

Table 24 - Summary of Shore Hardness Results

Shore Hardness D Scale				
Method	Material	Range	Avg	SD
Injection Molding	ABS	73-78	75.50	1.190
	Nylon 12	62-74	70.17	3.412
	Polystyrene	75-84	80.75	2.832
Rapid Prototyping	ABS	N/A	78.42	2.109
	Nylon 12	N/A	77.17	1.750

4.5 Microscopy

Below are 10x magnified images of the PIM test specimen at their breaking point after tensile testing. In Figure 44 and Figure 45 the horizontal weld lines are visible and fracturing around them can be seen. These images show the isotropic structure of parts created using PIM. The isotropic structure means that the part is one solid piece. Since these are images of the tested parts, the internal breaks can be seen. Comparing the magnified images of the injection molded parts to the rapid prototyped parts provides a better understanding of the different internal structures. Table 5 shows the magnified images of the parts created using rapid prototyping in Liu's thesis. The ABS test specimen shows a lot more internal stress and cracking during the testing, and the Nylon 12 part is relatively smooth. The polystyrene part has an area that looks like it might have been an air bubble, but it is actually the last spot to break off during tensile testing. Understanding the internal structure of these parts is important if the rapid prototyping method is trying to become a standard manufacturing method.

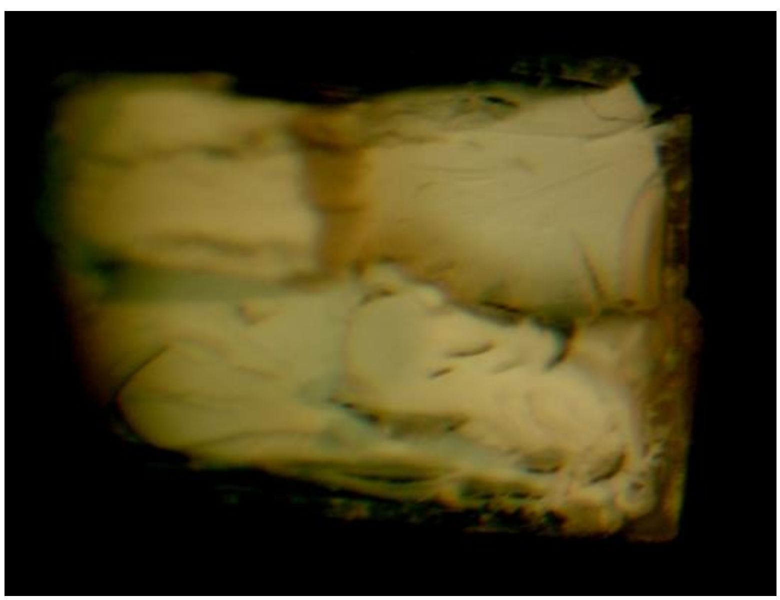


Figure 44 - ABS at Break Point 10x Magnification

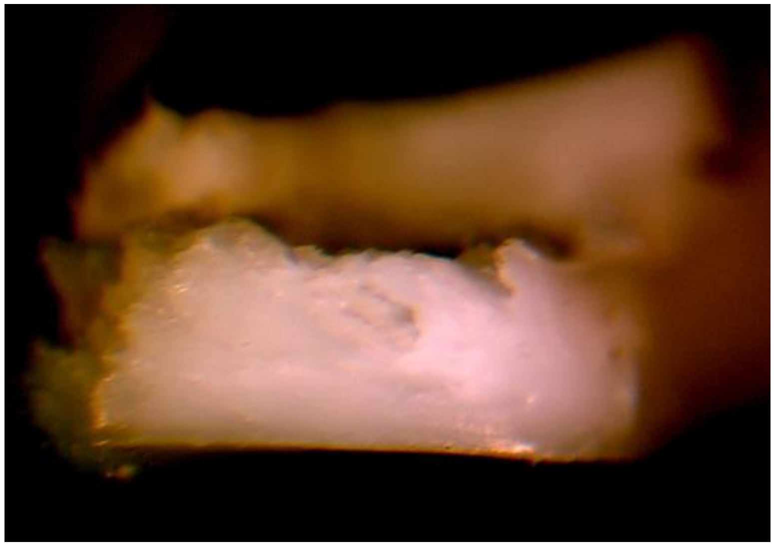


Figure 45 - Nylon 12 at Break Point 10x Magnification

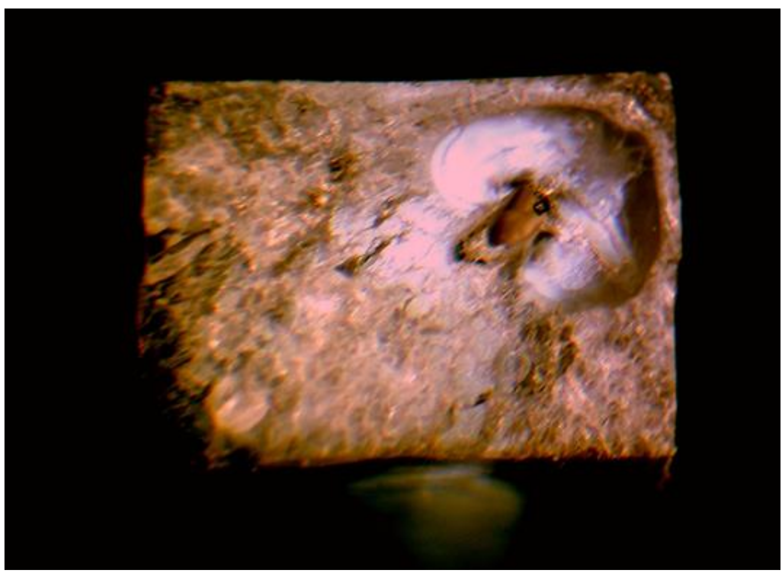


Figure 46 - Polystyrene at Break Point 10x Magnification

Chapter 5: Conclusion and Future Work

5.1 Conclusion

By completing a comprehensive study and comparison of several mechanical properties of rapid prototyping and injection molding, a greater understanding of the needs for improvement in rapid prototyping and rapid manufacturing has been obtained. This research may be used as an indication of necessary improvements for rapid prototyping to transition to rapid manufacturing. It can also be used as a reference for comparing the performance of a product created using either method. The results and recommendations are based off the comparison of test specimen created using an EOS Formiga P100, Stratasys Dimension Elite 3D Printer and Mini-Jector Model 45. Results may vary if other manufacturing methods or rapid prototyping technologies are used.

The research in this paper includes results from tests including the following: shrinkage/dimensional accuracy, tensile strength, elongation and elongation at break, water absorption, and Shore hardness. All of the tests were performed on three different plastic parts that were created using plastic injection molding. Two of these plastics, ABS and Nylon 12, are the same materials used in rapid prototyping processes and the third plastic, polystyrene, was used for comparison purposes. By comparing the results of plastic injection molding in this research to the results found in Chen-Yu Liu's research, the performance of plastic injection molding and rapid prototyping was evaluated for the first time. Using analysis of variance, or ANOVA, significance between the two methods was confirmed in dimensional accuracy, tensile testing and Shore hardness. A p-value of 0.05 or less indicated that there was a significance between the two methods. The data points for Shore hardness were not available in Liu's research, but an analysis of means and standard deviations suggests that there is a significant difference between the two methods of manufacturing.

Measuring the dimensional error of injection molding was accomplished by calculating the shrinkage of each part, and the dimensional error of rapid prototyping was measured by calculating the accuracy of the printed dimensions compared to the specified dimensions. The methods of calculating dimensional error were different, but they are both used as a predictor of how precise these two methods can be. The accuracy of plastic injection molding can be controlled by altering the mold and other parameters. Some of the rapid prototyping technologies have built in tolerances for dimensional accuracy, and others can be adjusted or calibrated. Since inaccuracies can be accounted for, the precisions of each method is of higher concern. Looking at the standard deviations of dimensional error is more suggestive of these manufacturing methods' ability to produce consistent parts. Plastic injection molding out performed rapid prototyping in standard deviation for both ABS and Nylon 12. ABS had standard deviations of 0.03691 and 0.9519 for PIM and RP respectively. Nylon 12 had standard deviations of 0.06127 and 0.6335 for PIM and RP respectively. Polystyrene, which was only used in PIM, also had an extremely low standard deviation of 0.02247, validating that the PIM process creates products with high precision. This result shows that even with top of the line RP methods, the traditional method of injection molding is the better solution if a product relies on very tight tolerances. The repeatability of rapid prototyping needs to be improved before it is ready transition to rapid manufacturing.

The mechanical properties evaluated in this paper are tensile strength, elongation and elongation at break. The tensile strength is measured in pounds per square inch, psi, and provides insight into the strength of the part. Since identical materials were used across the two manufacturing methods, the method of manufacturing is responsible for any differences in strength. Both ABS and Nylon 12 performed better when they were created using PIM. The average tensile strengths of ABS were 6310 psi and 5572.2 psi for PIM and RP respectively, and the averages for Nylon 12 were 7953 psi and 7367.4 psi for PIM and RP respectively. The average elongation of ABS using PIM was 3.998% and 2.219% using RP. Nylon 12 had an average elongation of 275.292% for PIM and 7.741 for RP. The average elongation at break for ABS was 13.003% using PIM and 3.71% using RP, and the results for Nylon 12 were 249.536% using PIM and 16.533% using RP. Analyzing the data using ANOVA, ABS had a p-value of 0.002 and Nylon 12 had a p-value of 0.000 confirming that there is a significant difference between the two manufacturing methods for both ABS and Nylon 12. Even though statistical analysis confirms that PIM performed better than RP, it is worth noting that the RP method provided more consistent results than the PIM method. The higher standard deviation of the PIM results may be caused by one, or more, of the many factors that go into creating a part using PIM. In this experiment, these factors include mold design, temperature of the molten plastics, temperature of the mold, recycled plastics, air pressure used to control entry speed, and air bubbles in the finished product. The takeaway from this experiment is that a product that may experience any kind of force, should be produced using PIM. Even more critically, if a finished product will have forces exerted on it from multiple directions it should not be created using RP because there is such a dramatic difference in strength depending on build orientation. While many factors can have an effect on the strength of a part created using PIM, the direction of a force being exerted on the product should not matter.

If a product will be used outdoors or any environment that it will get wet, it is important to understand how it moisture interacts with the product. In this experiment, the parts created using RP have an anisotropic structure while the PIM parts have an isotropic structure. Because of this structure, there are cavities in the parts created using RP that allow water to be absorbed and trapped. The weight of the ABS test specimen created using PIM increased by 0.35583% and the test specimen created using RP increased by 11.273%. The weight of the Nylon 12 test specimen created using PIM increased by 0.22143% and the test specimen created using RP increased by 1.46997%. Statistical analysis using ANOVA returns a p-value of 0.006 for ABS and 0.015 for Nylon 12 confirming that there is a significant difference between PIM and RP. If a finished product will be in a moist environment or needs to provide any kind of protection from water, PIM should be used.

The final experiment tested the hardness of the test specimen created using both PIM and RP. The Shore hardness D-scale was used to evaluate the hardness of these parts and a higher score indicates a harder surface. The average Shore hardness score of the ABS test specimen created using PIM was 75.5 and the RP test specimen was 78.42. The average Shore hardness score of the Nylon 12 test specimen created using PIM was 70.17 and the RP part was 77.17. Unfortunately, ANOVA cannot be used to analyze this data because the data points from Liu's research were not available, but the averages indicate that the RP parts performed better than the PIM parts. The standard deviations for PIM were 1.19 for ABS, 3.412 for Nylon 12, and 2.832 for Polystyrene. The standard deviations for parts created using RP were 2.109 for ABS, and 1.75 for Nylon 12. These standard deviations were relatively high and since the tool used to measure Shore hardness is manually operated device, the results could differ from user to user. Also, the materials used for PIM were recycled several times since the initial mold was redesigned and the parts had to be recreated. Theoretically, thermoplastics can be melted and solidified over and over without losing strength, but it is possible that recycling the thermoplastics had an effect on its performance.

Overall, the PIM process, using a Mini-Jector Model 45, outperformed the RP process of the EOS Formiga P100 and the Stratasys Dimension Elite 3D Printer. The better results of test specimen crated using PIM signifies that RP needs to be improved before it transitions to RM. A summary of all the results can be found in Table 25. Due to the anisotropic structure of a part created using RP, the mechanical properties may never be equivalent to those of a par created using PIM. However, when looking at the results of the Nylon 12 parts and ABS parts you can see that the difference in average tensile strength between the ABS parts is 737.8 psi and only 585.6 psi for the Nylon 12 parts. This difference can be attributed to the different processes of RP (FDM vs SLS) used for each material. With advances in these processes, specifically trying to achieve a structure that is more isotropic than anisotropic, the RP process might get closer to performing at the same level of the PIM parts. One improvement that must be addressed before RP can switch over to RM is the ability to consistently meet the dimensional requirements of the design. In most manufacturing the ability to work within tight tolerances is vital and RP is not capable of this right now. If the dimensional accuracy, strength, elongation (including at break), or water absorption are important factors in product design, then PIM should be used instead of RM for final production.

Table 25 - Summary of Results

Results Summary								
Manufacturing Method	Material	Dimensional Accuracy		Tensile Properties			Water Absorption (%)	Shore Hardness (D Scale)
		Average (%)	Standard Deviation	Tensile Strength (psi)	Elongation (%)	Elongation at Break (%)		
Plastic Injection Molding	ABS	1.049	0.03691	6310	3.998	13.003	0.35586	75.5
	Nylon 12	2.955	0.06127	7953	275.292	249.536	0.22143	70.17
Rapid Prototyping	ABS	1.1025	0.9519	5572.2	2.219	3.71	11.27315	78.42
	Nylon 12	0.5093	0.6335	7367.4	7.741	16.533	1.46997	77.17

5.2 Future Work

The primary need in the RP field is improvement in the current processes. For RP to begin its transition to RM, the performance of products created by RP must be at the same level of products made by current manufacturing methods. To improve RP, there still needs to be a better understanding of what needs to be improved. Below is a list of research areas that need to be understood before improving RP.

1. Mechanical properties of dynamic parts
    - This thesis tested the mechanical properties on a single axis of the test specimen. Most products, especially those that are load bearing, have forces acting on multiple axes. Figure 47 shows an L shaped part and the internal lines suggest the orientation that it was built by a rapid prototyping system. From Liu's research, we know that this part will be much stronger along the x-axis because of the build orientation. Research is needed to assess how these dynamic parts created by RP compare to traditional manufacturing methods.

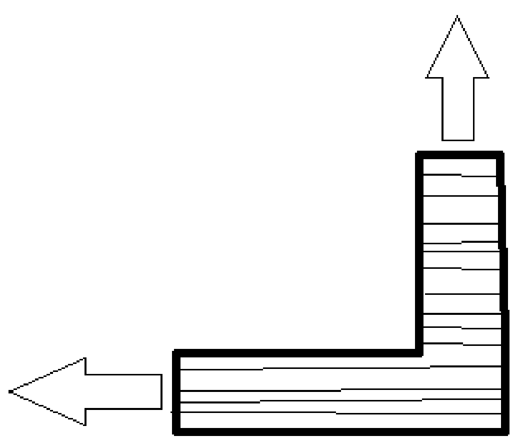


Figure 47 - Part for Dynamic Testing

2. Multi-axis extruders and print heads
    - CNC mills that have more than 3 axes are able to make more complex parts. Adding an axis to RP will not improve its ability to create complex geometries, but it could allow a single product to be built in different orientations. This could be a solution to creating stronger dynamic parts.
3. Improved fusion between layers
    - In this thesis, the gap between the tensile strength and water absorption of the Nylon 12 parts was smaller than the gap between ABS parts. If you look at the magnified images from Liu's thesis (Table 5) you can see that the gaps between the layers of the Nylon 12 part are much smaller than the ABS part. Reducing the void space between layers may improve the mechanical properties of RP.
4. Extruder head shape in FDM
    - The layers created by FDM technology are tubular and this is the cause of the larger gaps between layers. The extrusion heads are circular and this creates the tubular layers. It is possible that a rectangular extruder head might reduce the gaps between layers.
5. Best practices and methodology
    - Most RP technology has predetermined settings and very few settings can be customized. Traditional manufacturing methods

have well defined best practices and this needs to be defined for RP before it can transition to RM.

6. Production speed (reduced cost)
    - One of the biggest challenges RM will face is the cost to manufacture finished goods. The current RP technologies are very slow compared to traditional methods. Reducing the production times will be critical for the transition from RP to RM. Both SLS and SLA technologies should explore multiple lasers and projection technologies to create layers faster. PolyJet technologies, found in Objet printers, should explore the similar advances in 2D printers such as laser printers.
7. Dimensional precision control
    - Manufacturing relies on the manufacturing method's ability to make precise products. Current RP machines need to improve their ability to consistently make accurate parts. The variation in dimensional accuracy was much higher in RP than PIM. This could require improvements in both hardware and software.

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