2012-07-11

A Comparative Study of Strength and Stiffness of Thin-Walled Specimens Fabricated By FDM and 3D Printing Technologies

Miranda Rodrigo
Brigham Young University - Provo

A Comparative Study of Strength and Stiffness of Thin-Walled Specimens Fabricated by FDM and 3D Printing Technologies

Rodrigo Miranda

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Master of Science

Alan J. Boardman, Chair
Perry W. Carter
Michael P. Miles
Charles R. Harrell

School of Technology

Brigham Young University

August 2012

ABSTRACT

A Comparative Study of Strength and Stiffness of
Thin-Walled Specimens Fabricated with FDM
and 3D Printing Technologies

Rodrigo Miranda
School of Technology, BYU
Master of Science

Rapid Prototyped part failure constitutes a major issue for both RP providers and customers. When parts fail the reputation of the vendor is heavily deteriorated, customer dissatisfaction increase and replacement of the broken parts is often necessary to avoid the loss of future business. Product design teams often run into situations where Rapid Prototyped parts are not able to withstand shipping and handling and delivered broken or while demonstrating and examining the parts. When done in the face of customers this builds a perception of poor quality and lack of aptitude on the design group as well as the RP processes. The rapid advance of the RP industry and technology has led users to employ RP parts for structural applications where the need to understand in great detail and accuracy the mechanical behaviorof the product and its individual components is greater than ever.

Models built on Rapid Prototyping (RP) equipment are most often made from polymers which frequently have mechanical properties that are inferior to those manufactured by traditional methods such as thermoforming or injection molding. Not only are the mechanical properties of RP models typically low, they are usually, at least in thin sections, directly dependent on the section or wall thickness of the models. This dependence of strength on wall thickness makes it difficult to predict a proper wall thickness for RP models, even when nominal values of material strength are known.

The purpose of this work is to present and compare measured values of tensile strength and stiffness as a function of wall thickness for three RP processes and materials. These properties will assist designers estimating adequate minimum wall thicknesses for models built by the three processes. The three RP technologies included in the scope of this research are: Z Corporation (powder with polymer binder layup), Fuse Deposition Modeling and PolyJet Layup (Objet). The findings of this study establish that tensile strength and stiffness values are dependent upon wall thickness, building orientation and direction of the applied force of specimens created with the methods in consideration. It was also determined that the correlation between thickness and strength for all procesess is non-linear.

Due to these results a single tensile strength and modulus value for each material and all wall thicknesses do not accurately represent their bevior. However, these results will allow a designer to understand the relationship between the wall thickness and using the data provided in this work be able to model and then fabricate adequate 3D prototypes.

Keywords: Rodrigo Miranda, rapid prototyping, tensile strength, stiffness, thin-walled features, mechanical properties, wall thickness

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 INTRODUCTION

Models built on Rapid Prototyping (RP) equipment are most often made from polymers which frequently have mechanical properties that are inferior to those produced by traditional plastics processes such as thermoforming or injection molding. Not only are the mechanical properties of RP models typically low, they are usually, at least in thin sections, dependent upon section thickness or wall thickness of the models. Such behavior is attributed to the layered processing characteristic of RP systems and the non-uniform bonding existing between layers. This makes it difficult to predict an adequate wall thickness for RP models, even when nominal values of material strength are known.

Rapid Prototype part failure constitutes a major issue for both RP providers and designers. Whe parts fail t he reputation of the vendor is heavily deteriorated, customer dissatisfaction increase and replacement of the broken parts is often necessary to avoid the loss of future business. Product design teams often run into situations where Rapid Prototyped parts are not able to withstand shipping and handling and are delivered broken or easily break when being handled and examined. This adversely affecting design review and project deadlines as well as diminishes the good perception and trust that customers have of RP processes. Due to the need for understanding in great detail and accuracy of the mechanical behavior for structural applications, RP parts have become the standard practice for designers and engineers. A good understanding of the physical design criteria for the individual RP processes and their mechanical properties for various geometries and dimensions will greatly improve the confidence of designers in the RP technologies and contribute to its further development. The result will be shortend product development times, monetary savings, development of new systems and increased reliability of existing RP.

The objective of this work is to present measured values of tensile strength and stiffness as a function of wall thickness for three RP processes and materials. These properties will assist designers estimating adequate minimum wall thicknesses for models built byeach of these three processes. The results of this work will be validated by using the data gathered and applied through a design case study of a simple part fabricated by each process and material. This will illustrate the use of the data in estimating safe wall thickness.

1.1 Background

Rapid Prototyping (RP) is a technology developed in the 1980s in the United States. RP converts a Computer Aided Design (CAD) file into a solid physical object in a matter of hours. The lead time to create high-complexity functional prototypes that can be tested for visualization, form and fit, function or even for tooling has been dramatically reduced. This has lead to decreased costs related to product design and development. Rafiq Noorani (PhD) in his work "Rapid Prototyping Principles and Applications" (2006) provides a summary of the RP process:

1. Create a CAD solid model of the design.
2. Convert the CAD model to stereolithography (STL) file format.
3. Slice or divide the STL file into two-dimensional (2d) cross-sectional layers.
4. Grow or 3D-print the model.
5. Clean and finish the model.

The contributions of rapid prototyping to the field of product design and development have been significant, and keep expanding. During the 1990's RP was mainly used to create prototypes, today its applications have gone beyond simple visualization. Rapid tooling and manufacturing have been included within the capabilities of this technology (Noorani 2006). The development of different technologies within the rapid prototyping industry has caused users and developers to come up with different terms to emphasize the distinctive characteristics of RP. Some of these terms include: desktop manufacturing, direct CAD manufacturing, instant manufacturing, layered manufacturing, material deposit manufacturing and material addition manufacturing, solid freeform fabrication and solid freeform manufacturing, which emphasizes the ability of RP to produce solid objects with complex shapes of any form (Noorani 2006).

1.2 Nature of the Problem

The usefulness and capabilities of RP are commonly constrained by the poor mechanical properties present in parts created using standard RP technologies. A common example of mechanical failure is observed in the easy damaging of thin-walled features. Thin-walled sections or features are prone to collapse during part handling or when the support material is being removed. This situation causes loss to the rapid prototyping provider (scrap and rework mainly), since the customer will never accept a broken part. To avoid this situation, RP providers often established, based on their own experience, minimum part wall thickness values when accepting contracts, which usually leads to "thicker than necessary" features that increase costs. Having analyzed this situation, we arrived to the following question: **What are recommended thicknesses for RP thin-walled features that will withstand specified loads?** Naturally, the answer to this question will depend upon the machine technology and material used.

1.3 Purpose of the Research

The purpose of this research is to determine and present thin-wall mechanical properties for three RP processes. These properties will help designers predict the effects of loads applied to parts made by these processes. These loads can occur during finishing operations or during the intended use of the part.

1.4 RP Categorization and Project Delimitations

Rapid prototyping technologies have been categorized according to the initial state of the raw material used to produce a model. This material can be solid-based, liquid-based or powder-based (Noorani 2006). For this study, a representative system from each category has been selected, each of which will be analyzed and compared with the other two. Table 1.4.1 summarizes the materials and RP technologies that have been analyzed and compared in this project. A more detailed analysis of the features, advantages and disadvantages, and building or printing process of each technology has been extracted from the vendor's website and different literature. This information is included below.

Table 1.4.1 Materials and RP Technologies Analyzed and Compared in This Project

RP Technology	Model	Material	Raw Material Category
PolyJet 3D Printer	Objet Alaris30	Photopolymer	Liquid-Based
Fused Deposition Modeling (FDM)	Stratasys' Prodigy Plus	ABS P400	Solid-Based
Z Corp. 3D Printer	Spectrum Z510	Powdered Material (ZP-131)	Powder- Based

1.5 RP Systems Background Information

1.5.1 Z Corporation's 3D Printing System

The Z Corporation 3D printing process has been recognized as the fastest RP process available. As shown in Table 1.4.1 above, the Spectrum Z510 (see Figure 1.5.1a) is the model utilized for this study. Compared with the other two RP technologies, the Z printer provides lowest operating costs. Another advantage of this process is that it is not necessary to remove any support material after the model has been formed, since the powder surrounding the model provides a "built-in" support as the model is fabricated. A major drawback of this machine is the poor mechanical properties present in models made with it. It is necessary to impregnate these parts with additives (such as epoxy resin) to enhance their properties. Doing this can turn a fragile model (that could get broken during the printing process) into a model strong enough to be used as a sand casting pattern. Large tolerances and poor surface finish are common outcomes of this process (Carter 2002).

Spectrum Z510 Printing Process

The process used to produce models on the Z510 machine is as follows:

1. A CAD model is imported to the Z printer software and divided into layers of a specific thickness.
2. Powder material is evenly distributed across the machine building area.
3. The moving (top) head of the machine applies liquid binder onto the powder surface using ink-jet technology, which rapidly bonds the powder together to form the first layer of the model, and provides support for the next layers.

4. This operation is repeated for each consecutive layer, where binder solution is sprayed onto the loose powder on top of the previously formed layer.
5. When the model is complete, it is removed from the loose powder and "blown clean" (Noorani 2006).

1.5.2 Stratasys' FDM (Fused Deposition Modeling) Prodigy Plus

The Prodigy Plus was introduced by Stratasys Inc. on March 7th, 2002 (See Fig. 1.5.1b). Stratasys is the company that created the FDM technology. This specific process is capable of creating strong and light ABS parts of different colors and better mechanical properties than the Spectrum Z510 (in its green state). These properties include: Impact strength, tensile strength, heat and chemical resistance, and hardness (Noorani 2006). Some of the disadvantages of this process occur because of the filament deposition nature of this technology. Disadvantages include low density, brittleness, unsuitability for direct tooling, and poor finish on angled segments. The use of support material is also necessary in this process, which then needs to be broken away or dissolved (Carter 2002).

The FDM Process

1. A CAD file (usually STL format) is imported to the Stratasys' software and it is sliced or divided into horizontal layers, which determine the path of the nozzle. The Stratasys' software will automatically calculate and add separate support material where needed.
2. Thermoplastic ABS material of about .07" diameter is fed into the machine (heating chamber) where it is heated, and then extruded through the nozzle in diminutive filaments (0.007", 0.010" or 0.013" diameter), which are deposited onto the XY plane

of the machine. In this planar orientation, the deposited filaments are called "roads". Roads define the resolution of the machine.

3. As layers of extruded thermoplastic are applied on top of each other, the model grows in the Z direction. Each subsequent layer of material adheres to the previous one as it cools down.
4. Once the part is complete, it is taken from the machine and the support material is removed (Noorani 2006). Newer Stratasys' models utilize a water-based solution to automatically dissolve temporary support structures from the finished model.

1.5.3 Objet Alaris30 3D Printer

According to the equipment manufacturer, Objet "was the first company to successfully jet photopolymer material" (Objet 2010). The PolyJet system is a new technology that was introduced in early 2000. The specific model that has been used for this study is the Alaris30 3D printer (See Fig. 1.5.1c), which, compared with the other two systems (the Spectrum Z510 and the FDM Prodigy Plus) offers a series of advantages such as: higher ultimate strength, toughness, accuracy or tighter tolerances (.1 mm), thinner walls can be created (.6 mm) and better surface finish. Two major drawbacks of this system are the high cost per part and its building or printing speed, which is shaded by the faster Prodigy Plus and the much faster and economical Z printer. Another disadvantage of the Objet is the finishing operation required to remove the support material, which is automatically applied to the part where needed.

The PolyJet Printing Process

1. Similar to the processes previously described, the Objet machine software divides the solid model imported from a CAD system into ultra-thin layers (up to 16 microns), which represent the layers that the physical model will be made of.
2. The machine head moves along the X axis and deposits one layer of material at a time onto the machine build tray (the photopolymer material is deposited as a fine jet of liquid).
3. Instantly, UV light is emitted onto the recently added layer to immediately cure and harden it.
4. As each layer is deposited, the machine tray moves down to allow for the next layer to be placed on top of the previous one. This depositing and curing process is repeated until the part is complete.
5. After extracting the finished part from the machine, the support material has to be removed, either by scraping it off the part or water jetting it (Objet 2010).

Table 1.4.2 Machine Models and Technologies Comparison

Model/ Supplier	Support material	Curing Method	Use of Binders	Building Speed	Operating Costs	Part Strength
Objet Alaris30	Yes	UV Light	N/A	Low	High	Good
Stratasys' Prodigy Plus	Yes	N/A	N/A	Medium	Medium	Intermediate
Spectrum Z510	N/A	N/A	Yes	High	Low	Poor

Figure 1.5.1 RP Machine Models Utilized in This Research Project, Spectrum Z510 (a), Objet Alaris30 (b) and Stratasys' Prodigy Plus (c)

1.6 Methodology

This research will first determine the strength and stiffness of thin-wall sections for each of the three rapid-prototyping methods described above. Strength and stiffness measurements will be determined by creating slender, three-point loaded beams (beams resting on two supports and centrally loaded) of varying thicknesses by each of the rapid-prototyping processes and loading each of the beams to failure while recording load and deflection for each. From the load and deflection data values of ultimate strength and stiffness will be calculated using known equations. Anticipating that these mechanical properties will vary somewhat with section thickness, plots of strength and stiffness versus thickness will be made for each of the processes. These values will then be used to predict failure in walls of rapid-prototyped models under common loading or handling methods.

In order to test the strength of the beams a special tool will be built to exert downward force onto the RP specimens, which will be placed on a custom base onto the tensile testing machine. Data from the experiment will be obtained through different load cells to which the pushing tool will be attached. Readings from the load cells will be automatically recorded and plotted by special software. Figure 3.2 in Chapter 3 of this document shows the testing method that will be employed in this experiment.

Project Variables

- Technology
  - PolyJet (Objet Alaris30)
  - FDM (Stratasys' Prodigy Plus)
  - Z-corporation (Spectrum Z510)
- Material
  - Objet proprietary photopolymer
  - ABS P400

- ➢ Z-Corp proprietary ZP-131 Powder material, which is a mixture of calcium sulfate and silica.
- Specimen thickness

Instrumentation

- PolyJet (Objet Alaris30)
- FDM (Stratasys' Prodigy Plus)
- Z-corporation (Spectrum Z510)
- CAD/CAM systems
- Tensile-testing machine
- Rapid prototyping finishing instruments
- Load Cells with capacities of 5.6, 22, 112 and 1000 lbs.

1.7 Glossary

Acrylonitrile butadiene styrene (ABS) - This material is a terpolymer of acrylonitrile, butadiene and styrene. Usual compositions are about half styrene with the balance divided between butadiene and acrylonitrile. Considerable variation is, of course, possible resulting in many different grades of acrylonitrile butadiene styrene with a wide range of features and applications (IDES n.d.) .

Instron machine (Tensile -testing machine) - Instron manufactures testing machines used to test the mechanical properties and performance of various materials, components and structures in a wide array of environments (Illinois Tool Works Inc. 2011).

Layer - Once an STL file has been imported into RP software, it is sliced or divided into ultra-thin sections or layers, which represent the amount of material that will be placed at a time on the machine work surface to produce a model. Layers are placed on top of each other to build up the final product.

Photopolymer - It is a liquid base material that solidifies or cures when exposed to electromagnetic radiation with a specific wave length including X-rays, UV, visible light, and infrared. Radiation technology today uses electron-beam and UV curing of photopolymers as the most common commercial applications (Noorani 2006).

ZP 131 Powder material - Calcium Sulfate powder with silica utilized by solid-based RP technologies as building material.

Road - In the FDM process, it is the deposited filament of extruded material used to build a layer on the XY plane of the machine.

Stereolithography (STL) - It is the de-facto standard file format for model building in the RP industry.

2 LITERATURE REVIEW

2.1 Introduction

Since 1980's, when the first modern RP system was developed, many studies have been performed on the various applications of RP which have demonstrated the usefulness of this technology. Much work has also been put into the research and development of new and more versatile RP technologies, which has resulted in the development of over 30 different RP systems. Due to the rapid development of the RP industry, much work still needs to be done to establish standard procedures or design rules when working with the many RP processes. In an attempt to achieve this, and to communicate new findings and knowledge obtained through research and experimentation, different journals containing information relevant to this industry have been created. Some of these publications include:

- Rapid Prototyping Journal
- Society of Manufacturing Engineers Technical Papers
- Journal of Industrial and Engineering Management

Experts in the industry have also developed important documents containing background information and general knowledge of the RP industry, such information can be classified into the categories of RP history, materials, technologies, processes and applications.

In order to provide a background for this thesis project and to communicate the results of studies performed on thin-walled features strength and failure mechanisims, a summary of the most relevant documents (according to the researcher) pertaining to this matter are included below. This synopsis has been categorized into three main subjects: 1) technologies, processes and applications, 2) experimental studies and 3) Design aids.

2.2 Technologies, Processes and Applications

Perry Carter, an associate professor in the school of technology of Brigham Young University, Utah, in his technical paper "Advances in rapid prototyping and rapid manufacturing" (Carter 2002) provided a description of the capabilities and limitations of the most popular RP systems in 2002, as well as an overview of the processes they follow to build or print a model. This article has been helpful in providing a summary of the advantages and disadvantages of the technologies utilized for this thesis project. This article has also served as a base to select the most common applications of RP models, which are:

- Visualization: Prototypes which are merely used to communicate product concepts and ideas through an actual representation which can be held and touched. This is primarily used in marketing operations. It does not provide any type of mechanical or physical properties examination but mere conception.
- Form and Fit: RP models which can be assembled and to reveal any issues such as interferences that are hard to detect by simply analyzing a CAD model or drawing.
- Product Test: Prototypes that enable and speed up the creation of first-article parts. Product development time and costs are decreased, and nearly fully functional pieces are possible to build without molding, machining or forming operations.
- “Bridge” Tooling: RP models that are capable of withstanding the forces of production processes such as the pressures and processes casting patterns and molds are subjected to.

Naturally RP models will not offer the durability of a tool steel mold, but they can be used as a “bridge” tool, which means that they will be used temporally until a permanent tool becomes available.

- End-use parts: Modern RP technologies are now capable of producing fully functional parts made out of metal, ceramics or plastics for various industries in which low volume and a high variety of parts are typical (such as the medical and aerospace industries).

The work of Rafiq Noorani has been another valuable source of RP background information, in his book "Rapid Protoyping, Principles and Applications" (Noorani 2006) he presents an overview of the basic principles behind RP. Background information of rapid prototyping in general has been commonly extracted from this work. The information covered in this book includes a very detailed description and story line of the history and important events of the RP industry. It also provides an extensive record of different RP technologies as well as their suppliers, materials, advantages and disadvantages, and applications. Specifically, Chapters 1 and 3-5 have been very useful to this thesis project. They provide a detailed explanation of how each RP technology works, making reference to specific machine parts and processes. The subjects covered in these chapters provided solid background information to this project.

The documents cited above provided useful information regarding applications, technologies, process and history of RP, but they contain little information regarding materials and testing methods. Ali K. Kamrani and Abouel Emad N. in the first chapter of their work "Rapid Prototyping: Theory and Practice" (Kamrani and Abouel 2005) provide specific and concise information about RP materials and their properties, as well as a variety of mechanical tests that can be performed on RP models to determine their properties. Their work provides a classification of materials according to their structure, crystalline or amorphous. It also provides the engineering classification: metals, ceramics and glass, polymers and composites.

The next section of this chapter gives a description of different mechanical tests that can be performed to determine different properties of RP models. These tests include: uniaxial tensile test, toughness, hardness, flexure and creep tests, some of which will be useful in quantifying the mechanical behavior of models created for this thesis project. Other tests described in Chapter 1 of this work include: engineering stress and strain, ductility, and true stress and strain, among others.

2.3 Experimental Studies

The study performed by a group of researchers of the Poznan University of Technology (POLAND) on the creation of thin-walled RP products (Filip Górski 2010) supports the need of the current thesis project. The purpose of this study was to create an algorithm that would serve as a guide to users in selecting the RP technology that will provide optimal results when building thin-walled products. For this project, three RP technologies were analyzed: 3D printing, Fused deposition modeling (FDM) and Vacuum casting (VC). The thin-walled criterion of this project was set as "anything below 6 mm", which is actually too large for this thesis project, but the methodology they followed will be useful to the purposes of this work. Parts were built with each of these technologies, and categorized as following:

- Group 1: Visual prototypes. No specific mechanical properties were required. These parts were merely utilized for visualization, surface finish, dimensioning and coloring.
- Group 2: Functional prototypes. Mechanical properties were required, but not at the same level of the next group, Group 3. Properties such as flexural, tensile and impact strength and hardness were examined in this group.

- Group 3. Fully functional prototypes. Durable and machinable prototypes were expected. Besides the mechanical properties required in Group 2, incombustibility, humidity and atmospheric-hazards resistance were also taken into account.

The results were as following:

- 3D Printing technology was only good for parts belonging to group 1.
- FDM was good for parts belonging to groups 1 and 2.
- Vacuum casting is suitable to create parts for group 3.

This study will be useful to the purposes of this thesis project in that two of these RP technologies will be analyzed and studied. It also provides a good starting point for designers wishing to obtain a general idea of characteristics offered by different RP processes. Once a designer has selected a specific technology, the findings of the current research will provide further information regarding specific loads that models built by such technology are expected to withstand.

A technical paper on thin-walled features published by the Society of Manufacturing Engineers (Lyons, et al. 2008), presents the results obtained from a study on the dimensional variability that exists in thin walled features of RP models fabricated with FDM and 3D printing technologies. This document describes a project similar in purpose to this thesis project. Both of the technologies they used to perform their experiments are included within the technologies that will be analyzed in the current study. The findings of this technical paper suggest that the minimum wall thickness that will allow predictability of mechanical properties is of two millimeters, for both of the methods in consideration. As it is mentioned above, the results of this article are similar in purpose to this thesis project, but they do not provide any material properties, which is precisely one of the purposes of this work. They also failed in giving information about loads, and specific tests which their parts were subjected to. This document will also be helpful to the current research because it employs an excellent way to present findings, describe the technologies and materials utilized, and include all the processes information needed to be helpful to other people looking for information on this matter. It is important to mention that the minimum wall thickness that will be analyzed in the current research is of one millimeter. By doing this, Lyons work will be supported and consistency will be maintained across all three RP methods that will be studied, since Lyons did not include PolyJet technology in his research.

Another study that points out the importance of careful design when dealing with thin-walled features was performed by an engineering team of the University of Oxford, whose purpose was to build scaffold moulds using a 3D printing technology (C.Z. Liu 2007). What is relevant to this thesis project about this article is the relationship they defined between wall height, length and thickness. The following table presents the variation of failure rate of thin walled features, with length of feature and printing orientation. Printing orientation is classified as perpendicular or parallel to the axis of the machine. Height and length of the testing specimens are given in increments of 2 and 5 millimeters respectively.

Table 2.3.1 Variation of Failure Rate of Thin Walled Features

		Length (mm)				
Orientation	Height (mm)	1	5	10	15	20
Parallel	2	0/3	0/3	0/3	0/3	0/3
	4	3/3	2/3	1/3	1/3	1/3
	6	3/3	3/3	3/3	2/3	2/3
	8	3/3	3/3	3/3	3/3	3/3
Perpendicular	2	0/3	0/3	0/3	0/3	0/3
	4	3/3	1/3	0/3	0/3	0/3
	6	3/3	3/3	2/3	2/3	1/3
	8	3/3	3/3	3/3	3/3	3/3

Note: With fixed width of 1 mm

Note that in the table above, digits on the left of the slash correspond to the number of specimens that experienced failure during the printing process. Digits to the right of the slash indicate the total number of specimens printed at the specified height and length. Width was maintained constant throughout the experiment (1 mm).

This table provides a good idea of what type of results should be expected from the Z-corporation machine. It is important to mention that failure of these parts occurred during the printing process. A minimum wall thickness of 2 mm was defined as the safe thickness at any length, for features perpendicular to the axis of the machine. This is a good starting point for the current research; a thickness of 2 mm will be expected to resist the printing process. From there, specific failure loads and displacement values for different thicknesses will be obtained. For consistency purposes, the minimum wall thickness that will be analyzed for all three RP technologies in this research is of 1 millimeter. This is due to the fact that studies presenting information about mechanical properties and dimensional accuracy of 1 millimeter PolyJet specimens have not been found.

In addition to the articles above, the Society of Manufacturing Engineers published the findings of another study whose purpose was to develop a mathematical model to quantify the effect of road width and raster angle on the strength of parts built by FDM technology. Parts made with different FDM strategies and raster angles were analyzed and tested for tensile strength (Suslia and Arunachalam 2005). The material used for this study (ABS P301), is a material similar to the one that will be used in the current project for the FDM system. In this experiment, two different strategies of road filling were analyzed and compared: raster filling and contour filling. Figure 2.3.1 illustrates the concepts of raster angle and contour filling techniques. The results of this experiment suggested that the raster angle approach will provide minimum and maximum strengths at 45^0 and 90^0 angles respectively, whereas the contour filling strategy produced the strongest specimens of all.

An important assumption made in this study is that void formation (which reaches its maximum at a raster angle of 45^o) is inversely proportional to model strength. Contour filling produced the least amount of voids. Figures 2.3.2, 2.3.3 show the relationship between raster angle, void volume, contour filling and strength found in this study. Note that in this research layer thickness and road width values were maintained constant for all specimens. All specimens were built with the following dimensions: 150 X 12.5 X 5 mm. Figure 2.3.4 below illustrates the building direction that was used in this project.

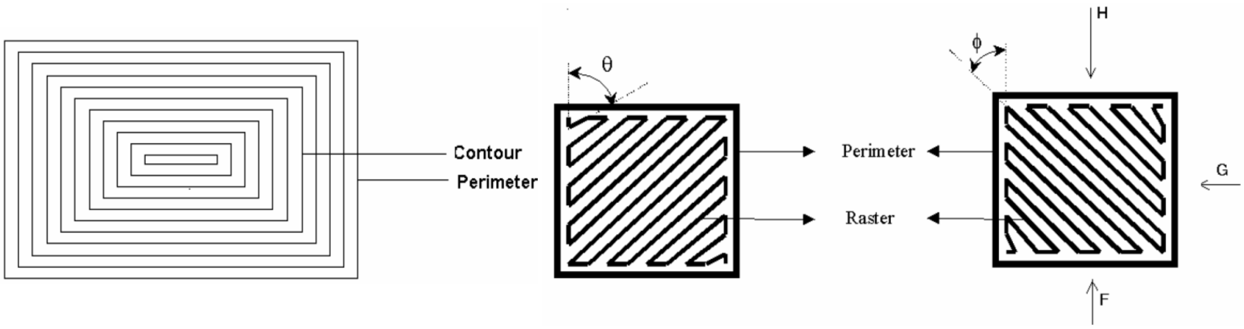


Figure 2.3.1 Contour Filling and Raster Angle Techniques

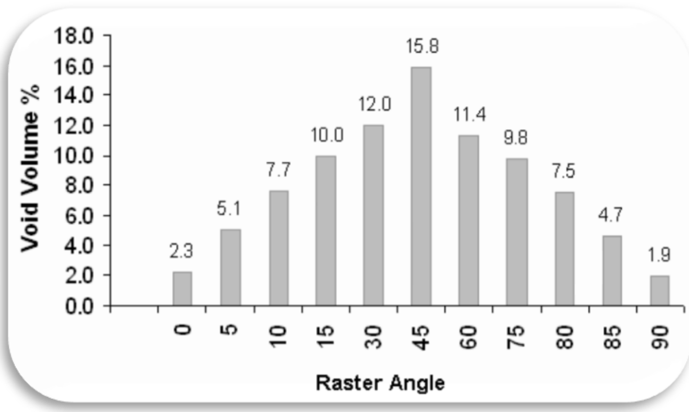


Figure 2.3.2 Void Volume vs. Raster Angle

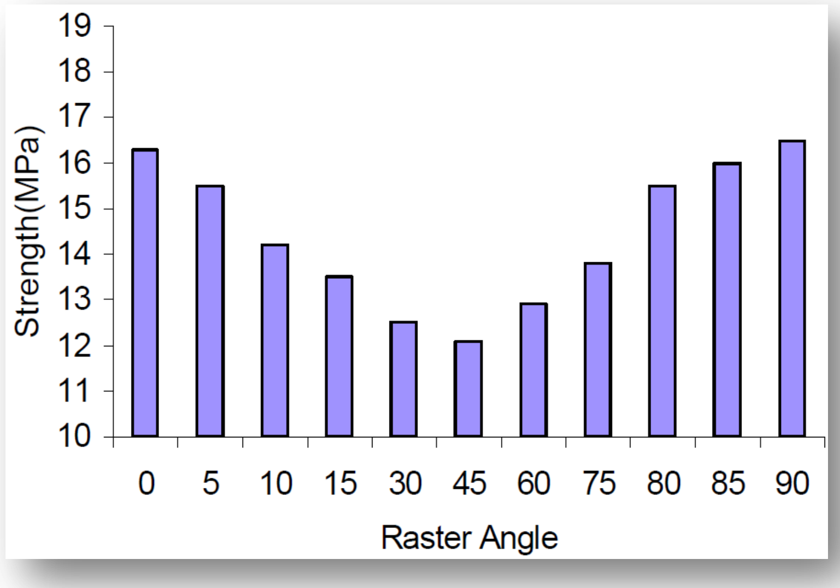


Figure 2.3.3 Strength vs. Raster Angle

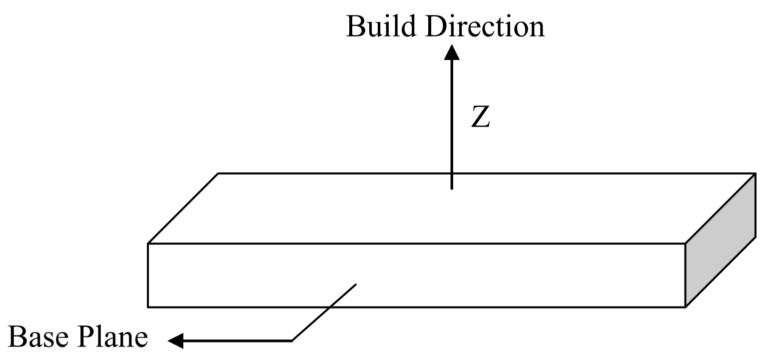


Figure 2.3.4 Specimens Build Direction

Figure 2.3.3 shows that the tensile strength resulting from a raster angle of 45^{o} is equal to 12.1 Mpa for parts created with ABS P301. It is expected that higher strength values will be obtained in the current research, since the material being tested is ABS P400, whose base material tensile strength is higher than that of ABS P301 (Suslia and Arunachalam 2005). FDM testing specimens for the current thesis project will be produced in the same building direction as the specified in the study presented above. Even though the previous study suggests that the contour angle technique produces stronger parts due to a lower amount of voids (21.4 N/mm2 vs. 12.1 N/mm2), the current project will employ the raster angle technique at 45^{o} degrees to observe standard practices of the RP provider.

A similar research was performed on ring-shaped specimens made by an experimental 3D printing machine, with the purpose of defining how mechanical properties of RP parts are affected by different parameters and settings such as layer thickness, binder volume per layer, type of binder and temperature (Ramos-Grez 2010). The powder material used in this experiment was zp® 131, which is the same material being used in the current research. A 2^4 design of experiment (DOE) was conducted to quantify and analyze the effects of the different variables. Table 2.3.2 below presents the factors and range of values tested in this experiment.

Table 2.3.2 DOE Factors and Range of Values

Factors	Range of Values (Low and High)
Layer Thickness (mm)	0.15-0.3
Amount of binder per layer (g)	0.0760-0.1016
Type of binder	Demineralized water - zb® 60
Temperature (^{o}C)	15-35

All samples were destructively tested for tensile strength. The results of this study suggests that layer thickness is the factor with the greatest effect on apparent density, fracture strength and hardness of the specimens, the smaller the layer thickness the higher the density, which is directly proportional to the force supported by the specimen (Figure 2.3.5). Temperature was the variable with the least impact on the properties of the specimens.

All factors used in this experiment will be maintained constant for all specimens built for the current study.

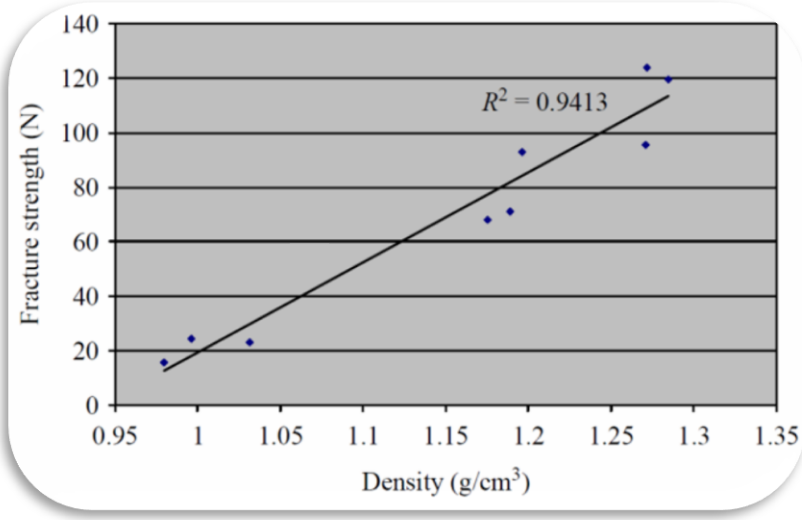


Figure 2.3.5 Fracture Strength vs. Density for 3-D Printing Specimens

2.4 Design Aids

Design is commonly known as the systematic interplay between synthesis (creation) and analysis (evaluation). Synthesis is "the combination of ideas to form a system". Analysis is "the detailed examination of the elements or structure of something". A designer evaluates different materials, methods, existing solutions and processes to find or create a solution for a given problem. Pahl and Beitz (2007) state that the design process consists of four main phases: Planning and task clarification, conceptual design, embodiment design and detail design (Gerhard, et al. 2007). Naturally, these stages are usually customized to accommodate the requirements of a specific industry or project.

During phase one (planning and task clarification), the design team is organized, individual responsibilities are assigned, the problem is exposed, all tasks are clarified and a preliminary schedule is created. Naturally, no solid models or prototypes of any type are built.

In phase two (conceptual design), customer requirements are defined and documented, similar products or systems are explored, existing solutions are studied, numerous design concepts are created, and technical and economical aspects are evaluated. During this phase sketches of possible solutions are created, but a solid physical structure has not been defined.

During the embodiment design phase, the preliminary form design is developed, which in turn originates the first set of drawings and solid models. In this phase engineering analysis, manufacturing process selection, geometry, FEA tests and material evaluations are performed. The outcome of this stage is the product preliminary layout.

In the last phase of the product design process, all the previous aspects are refined and improved. Process and product qualifications are executed, process and product FMEA are performed, costs are minimized and production and assembly documents are prepared. The product definitive layout is the result of this stage.   Figure 2.4.1 below summarizes the product design process as defined in this work.

The research findings that will be provided in this document are meant to be used mainly in the third stage of the product design process, where the structure of the construction is developed, the preliminary form design is defined and material selection and calculations are performed.

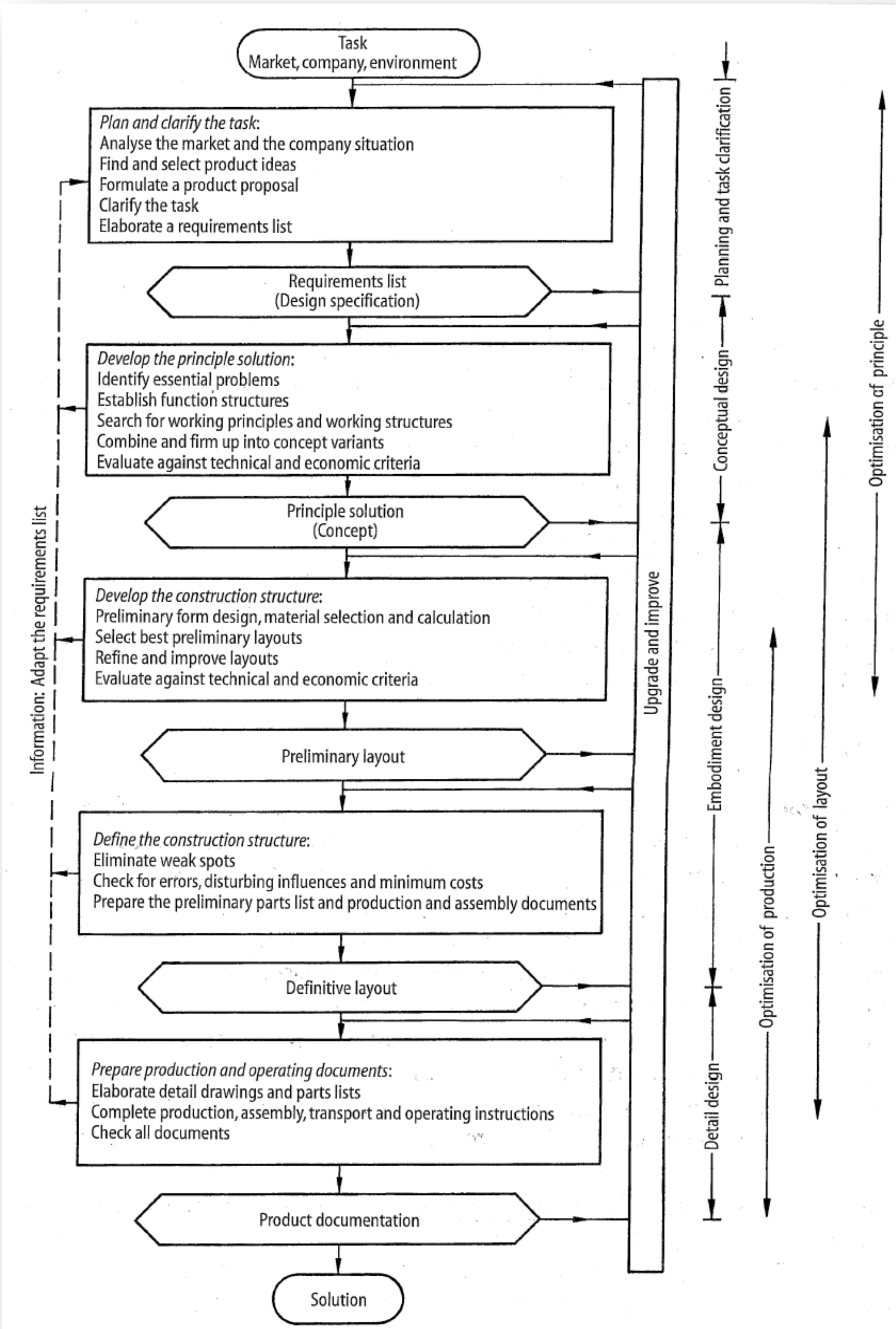


Figure 2.4.1 Product Design Process

2.5 Summary of Literature Review

Much work has been performed to increase and solidify current knowledge of the RP industry, and there is still a lot of room for new discoveries. The great variety of RP emerging technologies provides a large field for research, standardization and development. As it has been mentioned above, the purpose of this thesis project is to provide mechanical properties for three RP processes that will allow designers to predict the behavior of parts made by these processes when subject to simple loads. Such objective will be achieved by building upon the work of different teams of researchers that have studied similar issues.

One of such studies performed at the University of Michigan defined the minimum wall thickness, which would present predictable mechanical properties, as 2mm for models created with FDM and 3D printing processes (Lyons, et al. 2008). A comparable project conducted by researchers of the Universities of Oxford and Jilin, China, presented similar results which suggested that the minimum acceptable (that will survive the printing process) thickness for parts created with a 3D printing system is 2mm (C.Z. Liu 2007).

Other investigations have attempted to define and predict part strength in relation to parameters such as: building orientation, layer and road dimensions, material deposition strategies, additives and binders. All of these studies have contributed valuable knowledge to the RP industry, but a study demonstrating specific loads at which RP parts built with PolyJet, FDM and Z- Corporation printing technologies will fracture has not been completed yet. Such study is the purpose of this thesis project.

3 METHODOLOGY

3.1 Introduction

The objective of this work is to present measured values of tensile strength and stiffness as a function of wall thickness for three RP processes and materials. These properties will assist designers estimating safe minimum wall thicknesses for models built by these three processes. Ninety thin-walled specimens will be created, thirty each from the three RP technologies (PolyJet, FDM and Z Corp.). These specimens will be tested for strength and stiffness in a three-point bend test. All the parts will be tested under similar conditions. Loads and deflections will be used to obtain measured values of tensile strength and stiffness as a function of wall thickness for the three RP processes and materials in consideration.

A custom made tool, which will be secured to several load cells of different capacities, will be built to exert downward force onto the RP specimens, which will be laid horizontally and supported by a fixed base (see Figure 3.2). Readings from the load cells will be automatically recorded and plotted by special software (Lab View).

3.1.1 Project Variables

As it was mentioned in the introduction of this work, three RP technologies will be analyzed and compared: PolyJet (Objet Alaris30), FDM (Stratasys' Prodigy Plus) and Z-corporation (Spectrum Z510). The PolyJet system is available in the rapid prototyping facility of the Brigham Young University, Provo, Utah. FDM and Z-corporation specimens have been outsourced from a local Rapid Prototyping provider.

The materials of which the testing specimens will be made are the standard manufacturer recommendations for each machine, which is limited to: Objet Photopolymer, ABS (P400) and powder material (ZP- 131) respectively.

Other sources of variation such as road width, layer thickness, raster angles, orientation with respect to the machine axis (FDM), and type and amount of additives if any, will be kept constant. The most important variable from specimen to specimen will be thickness. All specimens will be built laying flat onto the machine stage or build tray (see Figure 2.5 in the previous chapter).

3.1.2 Additional Resources

Besides the RP equipment mentioned above, the following additional resources will be employed to perform the proposed experiment.

- CAD/CAM systems
- Statistical software (Lab View)
- Customized base
- Custom-made tool with nose radius of 0.125 inch.
- Tensile-testing machine (Instron machine)
- Load Cells of different capacities
- RP finishing instruments

3.2 Experimental Design

Per the information above, this is a quantitative research project. A total of 90 thin-walled specimens will be designed, built and tested for strength and stiffness.

3.2.1 Specimen Design

Three sets of ten specimens will be built for each technology, a total of thirty for each. Each set of ten specimens will include thicknesses ranging from 1 to 10 mm in increments of one mm., All specimens will be 70 mm in length and 15 mm in width. Each individual specimen will be built and placed on a custom-made base, which will be secured to the tensile-testing machine platform. In order to ensure that loads will be applied exactly on the same location in each test a three-point aligning tool will be used. Figure 3.1 below shows the basic design of the testing specimens and aligning tool.

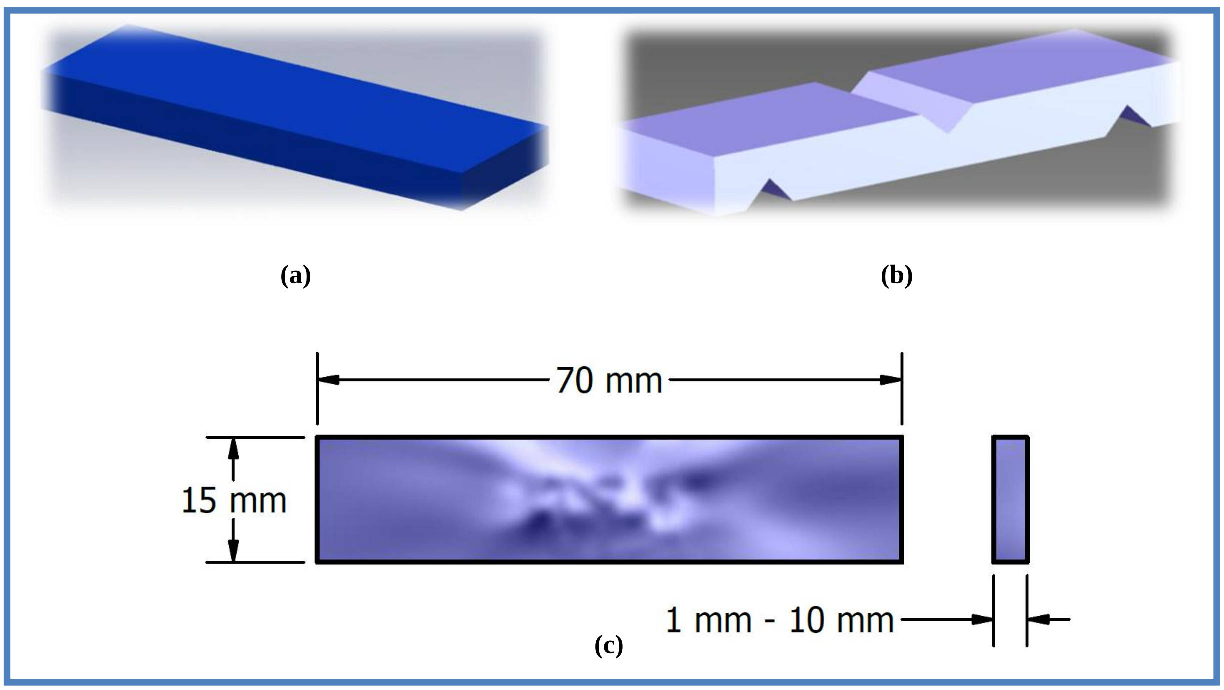


Figure 3.1 Testing Specimen (a), Aligning Tool (b) and Testing Specimen with Dimensions (c)

3.2.2 FDM Specimens Specifics

The FDM parts that will be tested and analyzed in this project will be built flat with respect to the machine stage or build tray. ABS P400 plastic material will be employed and 45^o Raster angles will be utilized with a layer thickness of 0.010 inches.

3.2.3 Z Corporation Specimens Specifics

The Z Corporation specimens that will be built for this research project will be made using Z Corp.'s proprietary powder material (ZP-131) and impregnated by brushing with a two part epoxy resin: Proset 117 and 226. Z Corp. specimens will have a layer thickness of 0.004 inches and will be built flat with respect to the machine stage.

3.2.4 PolyJet Specimens Specifics

Objet specimens that will be utilized for this project will also be built flat with respect to the machine building tray. Standard Objet materials and procedures will be employed to print the specimens. No additives of any type will be used to enhance the properties of the parts. Layer thickness will be set to 0.002 inches.

3.3 Experimental Procedure and Data Collection Methods

Each specimen will be located on the base, which will be secured to the tensile testing machine platform. The machine will send the data of the experiment directly to statistical software which will allow the values to be automatically recorded and plotted. As the tool exerts downward force onto the specimens, the tensile testing machine will register an increase of force (through a load cell) until the specimen fails; such readings will be sent to and automatically recorded by the software (see section 4.3.1). This procedure will provide the information needed to determine the load at which each part failed and corresponding displacement values. The same procedure will be repeated with each specimen. Each thin-walled specimen will be treated and analyzed as a three-point-loaded beam, which will accurately represent the type and direction of forces to which RP parts are exposed in typical applications. Figure 3.2 below illustrates the testing system previously described.

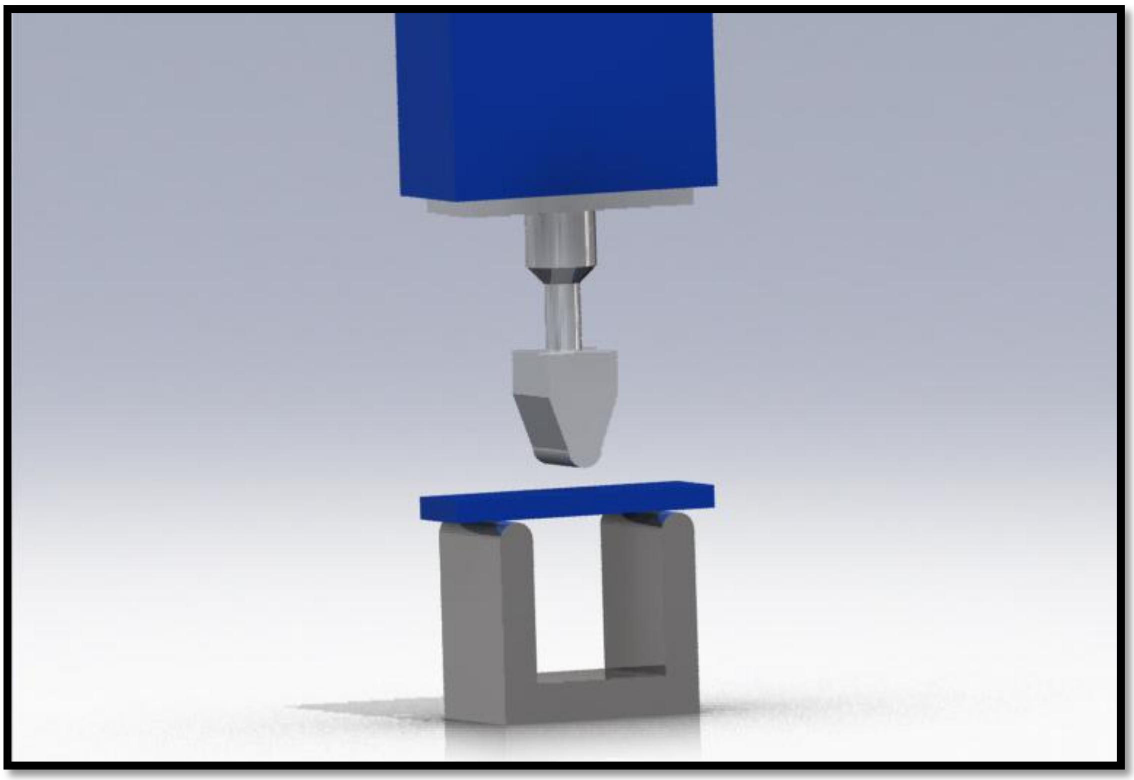


Figure 3.2 Testing System with Thin-Walled Specimen

3.4 Data Analysis Methods

After recording the data points from the different specimens, all the values will be plotted and tabulated. Doing so will allow us to have a visual understanding of the mechanical behavior of the specimens, as well as help us to identify any patterns and outliers in the data. The following formulas will be employed to obtain numerical values of the mechanical properties in consideration for each specimen.

Tensile Strength

$$\boldsymbol{\sigma = \frac{MC}{I} = \frac{F}{2} \cdot \frac{L}{2} \cdot \frac{h}{2} \cdot \frac{12}{bh^3} = \frac{3FL}{2bh^2}} \tag{3.4.1}$$

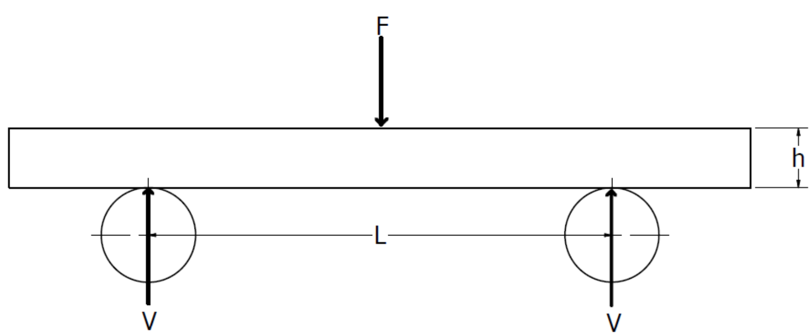
Maximum Deflection

$$Y = \frac{FL^3}{48EI} \tag{3.4.2}$$

Young's Modulus

$$E = \frac{FL^3}{48YI} = \frac{FL^3 12}{48Ybh^3} = \frac{FL^3}{4Ybh^3} \tag{3.4.3}$$

Where:



F = Load

L = Base length

E = Young's modulus of beam

I = Area moment of inertia of beam

Y = Maximum deflection

h = Thickness of beam

b = Width of beam

4 RESULTS AND ANALYSIS

4.1 Introduction

During this research project, ninety (90) RP thin-walled specimens fabricated with three different technologies and materials were destructively tested for tensile strength and stiffness. A detailed description of the experiment methodology is included in the previous chapter of this document, and it is depicted in Figure 4.1 below, which shows a four-millimeter-thick FDM specimen (ABS P400) being tested to tensile failure. Quantitative data has been divided into three main sections, each corresponding to the RP technology utilized to fabricate the set of specimens whose data are being presented. Each main section contains a summary of the data obtained through destructive testing and the corresponding calculated values for tensile strength (σ_{max}), and young's modulus (E).

The actual fabricated width and thickness of each specimen were measured prior to being placed on the tensile testing machine, thus, actual part dimensions were substituted into the equations and utilized to calculate the mechanical properties of the materials in consideration. To eliminate allocation bias, specimens were randomly selected prior to being destructive tested.

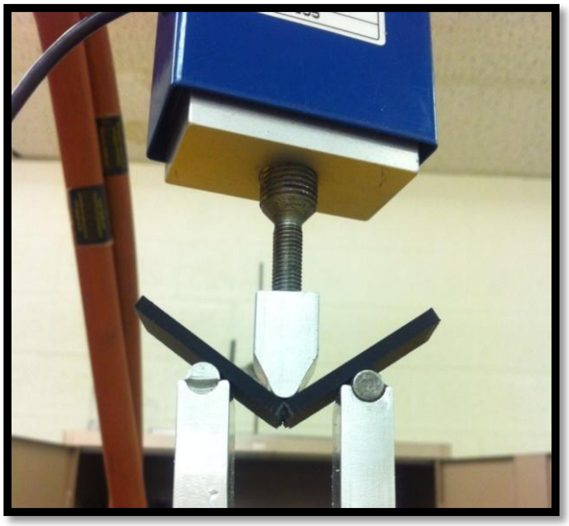


Figure 4.1.1 Testing System

4.2 Tensile Stress and Stiffness Values

FDM specimen number 15 has been randomly selected to be used as an example to illustrate the procedures followed to determine tensile stress and stiffness values for the materials in consideration.

Table 4.2.1 Testing System Data

Part No.	Thickness (mm)	Width (mm)	Load at failure (grams)	Displacement (mm)	Base Length (mm)
15 FDM	5.11	15.01	36058.132	2.110	31.25

Table 4.2.1 above presents the raw data as it was obtained from the tensile testing machine software and critical testing system dimenisons . The graph below shows the raw values for force and displacement. Figures 4.2.2 and 4.2.3 present the steps to calculate tensile strength and stiffness.

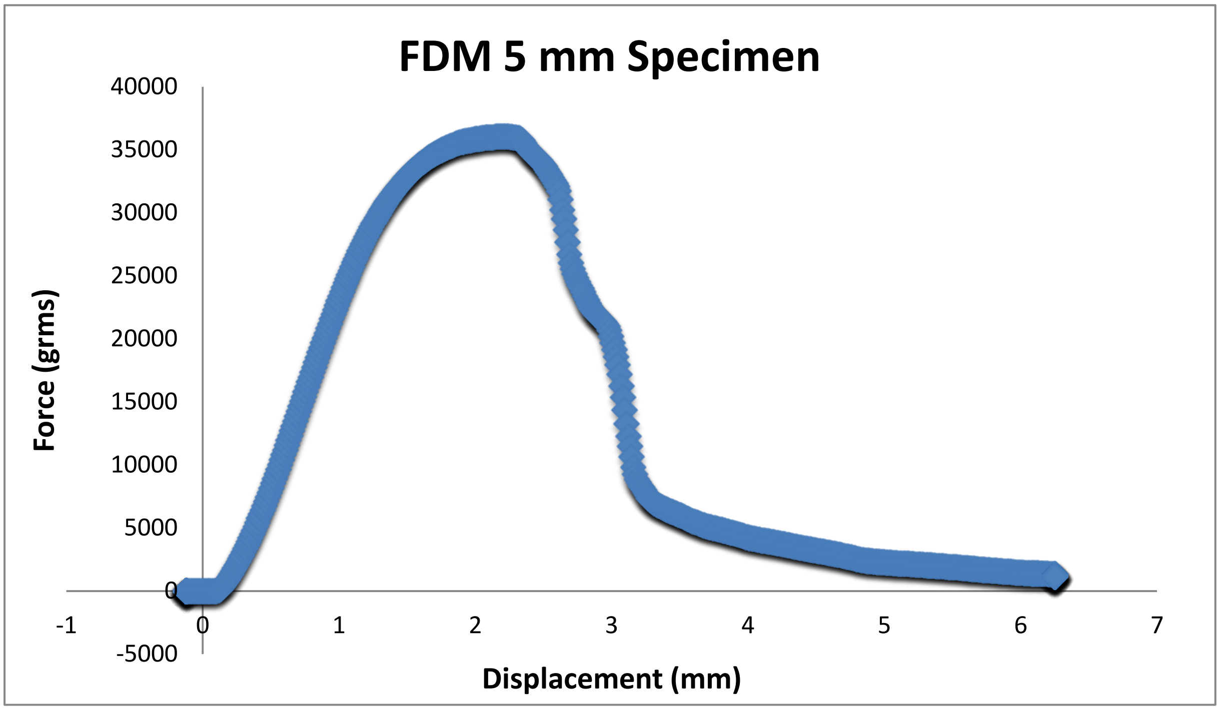


Figure 4.2.1 FDM 5 mm- Thick Specimen Force vs. Displacement Graph

Substituting the data from table 4.2.1 into the tensile stress equation (3.4.1):

$$\sigma = \frac{3FL}{2bh^2}$$

$$\sigma = \frac{3(36058.132)(31.25)}{2(15.01)(5.11)^2}$$

$$\sigma = 4312.43\, {}^{gm}/_{mm^2}$$

Converting to Mega Pascals:

$$\sigma = \frac{4312.43}{100}$$

$$\sigma = 43.124 \text{ Mpa}$$

Figure 4.2.2 Calculating Tensile Strength for FDM 5 mm-Thick Specimen

Young's Modulus (Stiffness):

$$E = \frac{FL^3}{4Ybh^3}$$

$$E = \frac{(36058.132)(31.25)^3}{4(2.110)(15.01)(5.11)}$$

$$E = 65097.971 \, {}^{gm}/_{mm^2}$$

Converting to Mega Pascals:

$$E = \frac{65097.971}{100}$$

E= 650.979 Mpa

Figure 4.2.3 Calculating Young's Modulus for FDM 5 mm-Thick Specimen

4.3 Sources of Error

Even though precautions such as randomization, locating fixtures, custom made tools, single build direction and orientation, and consistent width and length dimensions were employed to minimize the amount of error, three observable sources of error were identified during the course of this thesis project.

4.3.1 Load Cell Resolution.

Load cells of different load capacities were employed to transduce the force exerted on the testing specimens by the tensile testing machine. The lowest possible capacity load cell would be utilized to break the specimens whose failure load would fall within the range of that cell, if a testing specimen was found to be "stronger" than a load cell, the next higher capacity load cell would be utilized. Load cell resolution varies depending upon force capacity as follows (See Table 4.3.1):

Table 4.3.1 Load Cells Capacity and Resolution

Load Cell Capacity (Pounds)	Resolution (Grams)
5.6	± 0.03
22	± 0.1
112	± 0.5
1000	± 20

Please note that values for load cell capacities are given in pounds, whereas resolution values are given in grams, which constitutes an error percentage of less than 0.5 % for the greatest value.

4.3.2 Changing Support Length

For the three point tests performed for this thesis project, specimens were placed onto a base with an "L" value of 31.25 millimeters, and loads were applied onto the beams at the center of the support (see Figure 4.3.2.1). As loads are applied to the specimen and elastic or plastic deformation occurs (depending on the specimen), the beam tends to slide inward thus changing the "L" value. The supporting base features that interface with the specimens have a radius of 3.175 mm (0.125"), which results on a theoretical "L” reduction that ranges from 1.25 to approximately 29.6 mm for specimens breaking at a 15 degree angle with the horizontal. This represents about a 5 % reduction in the L dimension which represents a direct 5% increase in the calculated tensile strength and an approximate reduction of 15% in Young’s Modulus. The only specimens to exceed this angle were the 1 mm thick Objet specimens but even in their case the peak load was seen at less than a 15 degree angle.

Because of these small effects and the difficulty of accurately measuring the deflection angle of the specimens at failure, changes in the "L" value were not contemplated in calculating mechanical properties of the materials in consideration.

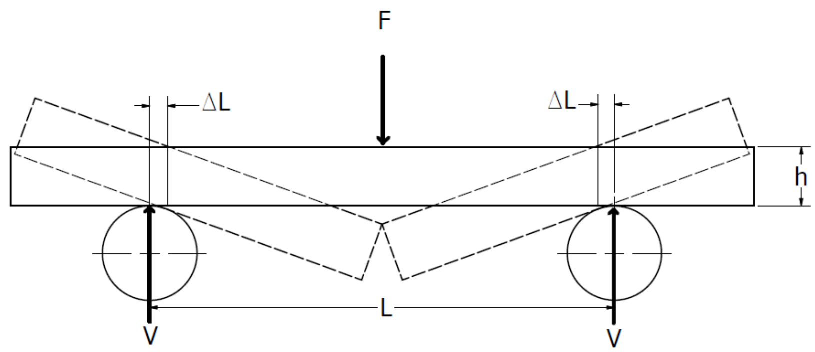


Figure 4.3.2.1 Testing System Change in Length

4.3.3 Unbreakable Specimens

Finally, the last source of error encountered during the development of this project was attributed to the one (1) millimeter thick Objet specimens, whose elastic properties surpassed those of all other specimens (see Figure 4.3.3.1). A more detailed explanation of the behavior of these parts is provided in the following section.

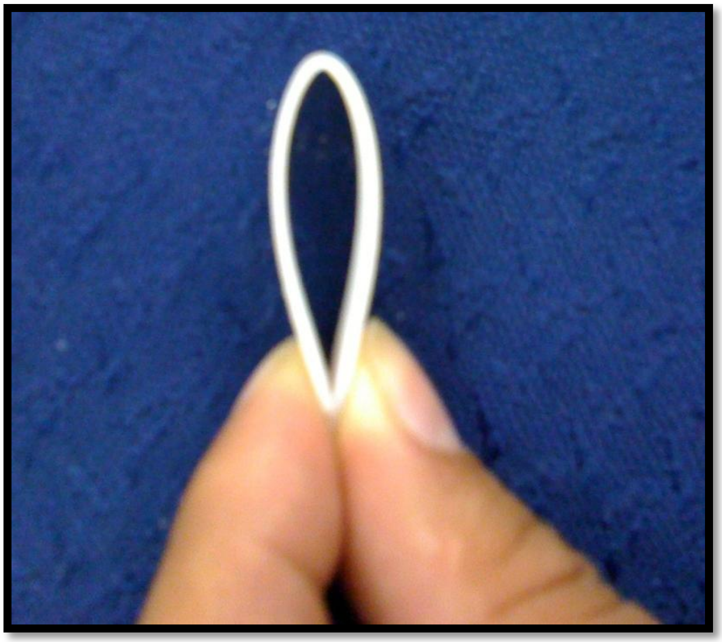


Figure 4.3.3.1 One (1) Millimeter Objet Specimen (Unbreakable)

4.4 Quantitative Data and Results

4.4.1 PolyJet Results

System: Objet Alaris30 3D Printer

Technology: PolyJet

Material: Proprietary Photopolymer

Based on quantitative data summarized in Table 4.4.1 below, specimens created by the Objet Alaris30 3D Printer presented substantial higher strength than those produced by the other two methods. The thinnest PolyJet specimens (~1mm) presented greater flexibility and displacement values than specimens of the other two processes, which prevented them from reaching a true fracture point (see Figure 4.3.3.1). Figure 4.4.1 below graphically summarizes and compares the results obtained from specimens numbers 2 and 4, with a thickness of 1.09 and 2.09 mm respectively.

Table 4.4.1 PolyJet Test Results Summarized

Objet Alaris30 3D Printer (PolyJet Technology)						
Part No.	Thickness (h mm)	Width (b mm)	Load at Failure (gms)	Displacement Y (mm)	Tensile Strength (σ_{max}) MPa	Modulus (E), MPa
1	3.7	15.15	41940.978	3.300	94.790	1263.563
2	1.09	14.96	2168.512	7.214	57.190	1183.829
3	6.02	15.17	108459.493	2.641	92.476	946.704
4	2.09	15.15	11729.154	4.471	83.081	1447.107
5	4.71	15.21	72962.327	2.809	101.361	1246.939
6	5.76	15.11	106785.566	2.640	99.849	1068.727
7	3.44	14.88	30313.327	4.075	80.697	937.045
8	2.13	15.04	11946.537	4.256	82.068	1473.479
9	3.32	15.01	30776.249	3.580	87.197	1194.065
10	3.75	15.31	40835.910	3.260	88.909	1183.711
11	3.86	15.2	41808.854	3.236	86.535	1127.572
12	1.05	15.05	2203.199	7.100	62.241	1358.880
13	3.29	15.02	30265.505	3.420	87.262	1262.276
14	5.95	15.11	109490.411	2.487	95.944	1055.298
15	4.72	15.09	71639.024	2.579	99.889	1335.574
16	4.71	15.11	72132.565	2.834	100.871	1230.057
17	2.11	14.99	11614.645	4.548	81.579	1383.651
18	1.19	15.04	2121.634	7.114	46.695	897.818
19	9.88	15.01	339219.452	2.456	108.524	728.021
20	9.85	15.01	324411.301	2.479	104.420	696.046
21	7.89	14.99	200945.852	2.322	100.940	896.949
22	9.85	15.01	320936.442	2.340	103.302	729.339
23	6.76	15.00	148763.566	2.477	101.731	988.927
24	7.83	15.16	192653.017	2.412	97.162	837.240
25	6.82	14.98	143918.564	2.515	96.823	918.727
26	8.86	14.98	250453.683	2.450	99.837	748.611
27	7.77	15.27	189853.921	2.475	96.534	816.887
28	6.73	15.12	138974.121	2.374	95.125	969.009
29	8.78	14.98	245532.139	2.299	99.666	803.785
30	8.85	15.01	245817.977	2.449	98.014	736.195

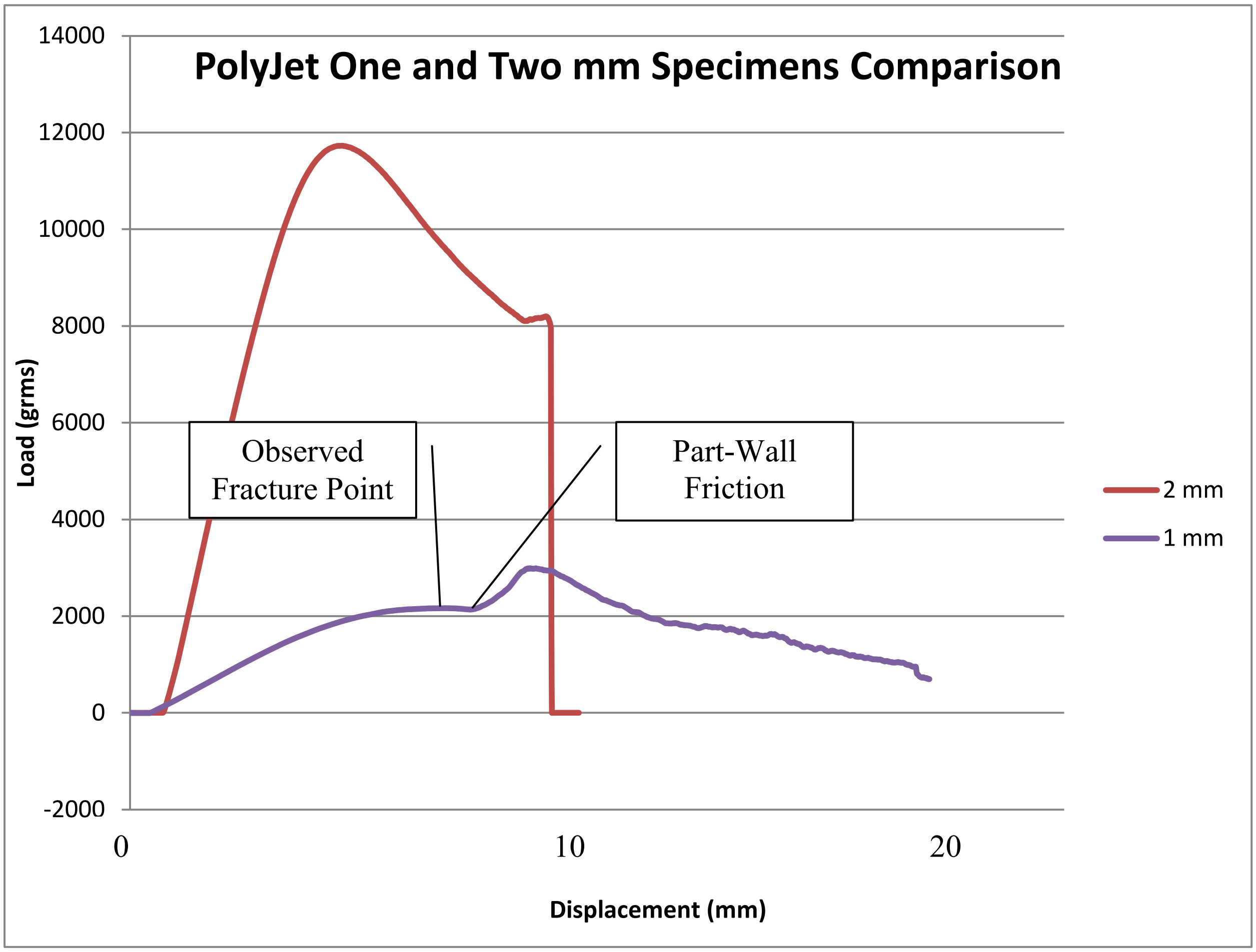


Figure 4.4.1 PolyJet One (1) and Two (2) Millimeter Specimens Comparison

Figure 4.4.1 illustrates the significant difference in strength and displacement, which results in greater toughness, which exists between one and two millimeter thick Objet specimens. The observed fracture point (labeled in the graph), represents the point at which one-millimeter specimens stopped resisting the downward force exerted on them by the load cell and plastically yielded. As it can be observed, a second and more prominent force peak was produced, which was the result of the friction generated between the specimen and fixture inner walls, as the part was forced down by the load cell. The one millimeter thick PolyJet specimens were the only parts that exhibited this behavior. Figure 4.4.2 illustrates the large flexibility present in the one millimeter PolyJet specimens.   All other specimens presented patterns similar to the two millimeter thick specimens.

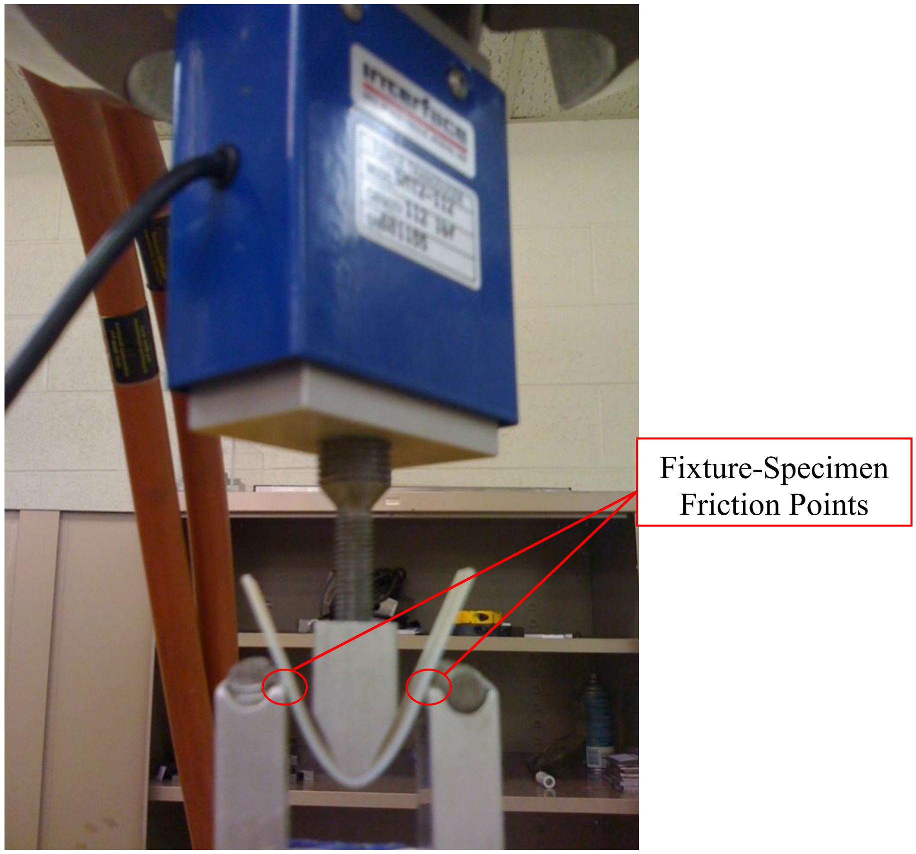


Figure 4.4.2 One (1) mm Objet Specimen-to-Base Friction

Figure 4.4.3 below, summarizes in graphical form the results for tensile strength obtained for all PolyJet specimens. The data suggest that the tensile strength of photopolymer material lies within 80 and 108 MPa for specimens greater than 1 mm thickness. Although the 1 mm specimens quit resisting load at the stress values shown they did not actually fracture. This suggests that wall thicknesses less than 2 mm might be used for PolyJet models where elastic deflections can be tolerated.

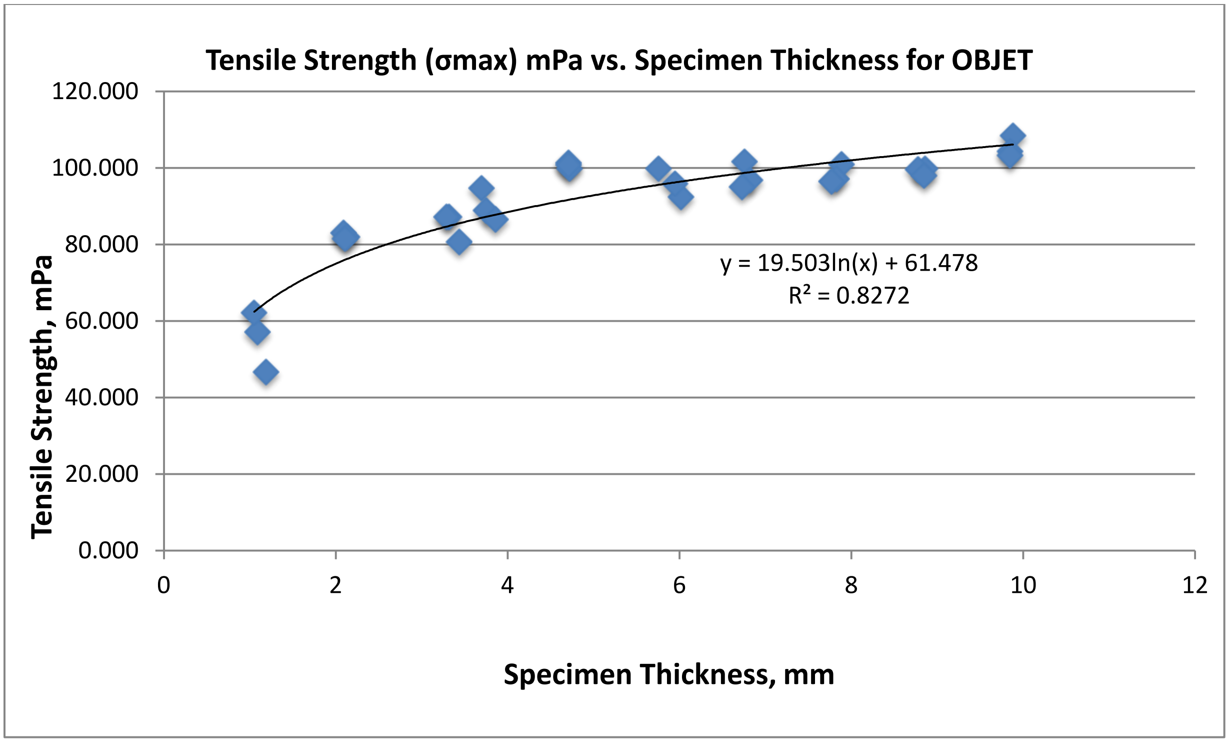


Figure 4.4.3 Tensile Strength vs. Specimen Thickness (Objet system)

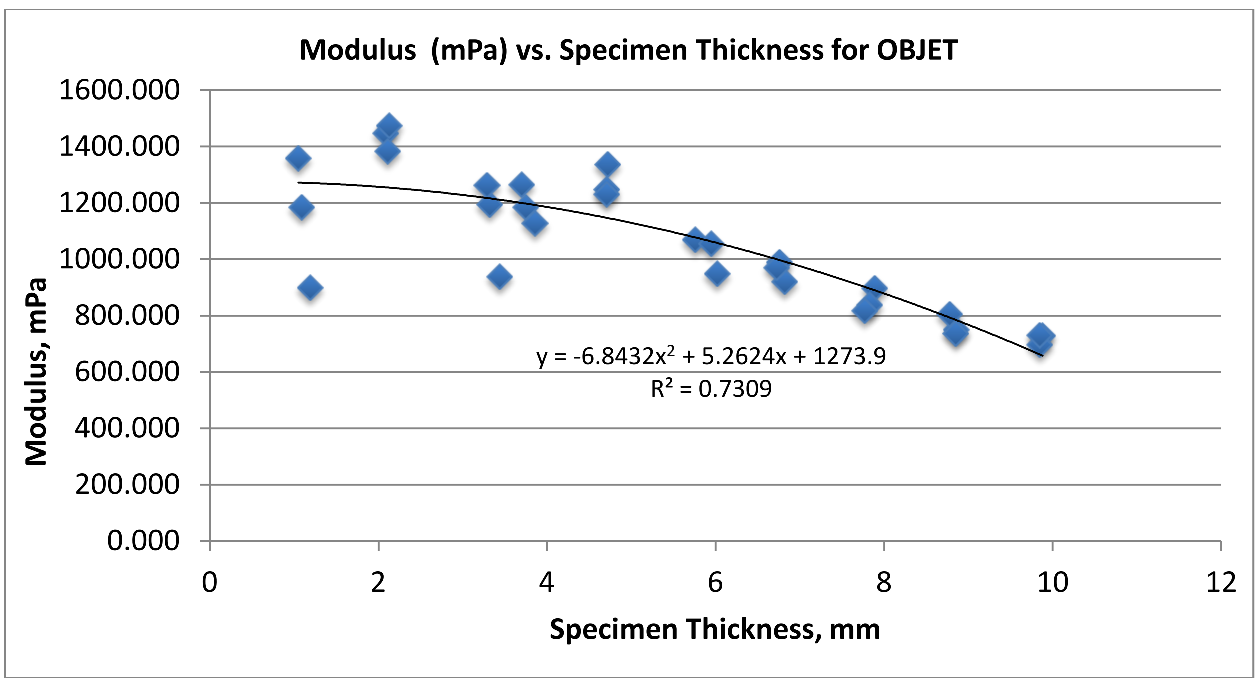


Figure 4.4.4 Modulus vs. Specimen Thickness (Objet System)

4.4.2 FDM Results

System: Stratasys' Prodigy Plus

Technology: FDM

Material: ABS P400

Based on quantitative data obtained through destructive testing summarized in Table 4.4.2 below, parts created in the Stratasys' Prodigy Plus Machine presented, intermediate tensile strength compared to the other two methods in consideration. Tensile strength values for FDM specimens presented significantly less dimensional variation, compared to the Objet and Z Corporation samples. As it can be observed in Figure 4.4.5below, the range of values for FDM parts tensile strength lies within 33 and 49 MPa.

As in the case of Photopolymer specimens, ABS P400 one millimeter samples presented a different behavior that the rest of the FDM specimens. In this case, ABS specimens did not present as much displacement as their photopolymer counterparts, but their tensile strength values fall around 34 MPa, while all other samples are equal or above 40.7 MPa with a max of 49.8 MPa. This range corresponds to the known ABS Thermoplastic range of values for tensile strength, which is 40 to 51 MPa at failure. The commonly used tensile strength value for ABS thermoplastic is 41.4 MPa (Strong 2006).

Table 4.4.2 Stratasys' Prodigy Plus (FDM) Results Summarized

Stratasys' Prodigy Plus (FDM Technology)						
Part No.	Thickness (h mm)	Width (b mm)	Load at Failure (gms)	Displacement Y (mm)	Tensile Strength (σmax) MPa	Modulus (E), MPa
1	1.06	15.15	1257.777	5.554	34.635	957.542
2	1.07	14.99	1258.393	5.780	34.371	904.536
3	1.08	15.01	1255.143	6.050	33.605	837.097
4	2.05	15.01	5556.981	4.560	41.294	718.988
5	2.05	15.03	5634.232	4.420	41.813	751.073
6	2.07	15.05	5668.058	4.505	41.200	719.088
7	3.07	15.01	12306.980	3.060	40.779	706.520
8	3.07	15.04	12964.949	2.810	42.873	808.894
9	3.09	14.96	12817.616	3.214	42.063	689.357
10	4.08	15.01	22867.204	2.450	42.900	698.515
11	4.1	15.01	23006.014	2.545	42.740	666.671
12	4.09	14.95	23196.085	2.495	43.478	693.463
13	5.08	15.12	37116.336	1.980	44.589	721.518
14	5.11	14.98	37001.037	2.030	44.341	695.718
15	5.11	15.01	36058.132	2.110	43.124	650.980
16	6.14	15.01	50396.940	1.690	41.747	654.820
17	6.15	15.01	52186.861	1.827	43.090	624.175
18	6.18	15.02	51435.214	1.830	42.030	604.873
19	9.18	14.89	133468.687	1.670	49.859	529.398
20	8.18	14.9	104395.558	1.594	49.083	612.839
21	9.22	14.88	128322.163	1.869	47.553	449.217
22	8.21	14.88	103549.661	1.870	48.395	513.029
23	9.21	14.88	129572.799	1.634	48.121	520.599
24	7.15	14.94	79855.034	1.921	49.010	580.669
25	10.17	14.93	160832.595	1.695	48.822	461.078
26	10.18	14.93	157830.664	1.691	47.816	452.047
27	10.14	14.96	160422.855	1.584	48.888	495.337
28	7.19	14.91	74195.897	1.755	45.122	581.908
29	8.16	14.83	102540.181	1.630	48.676	595.605
30	7.19	14.95	76908.919	1.885	46.646	560.180

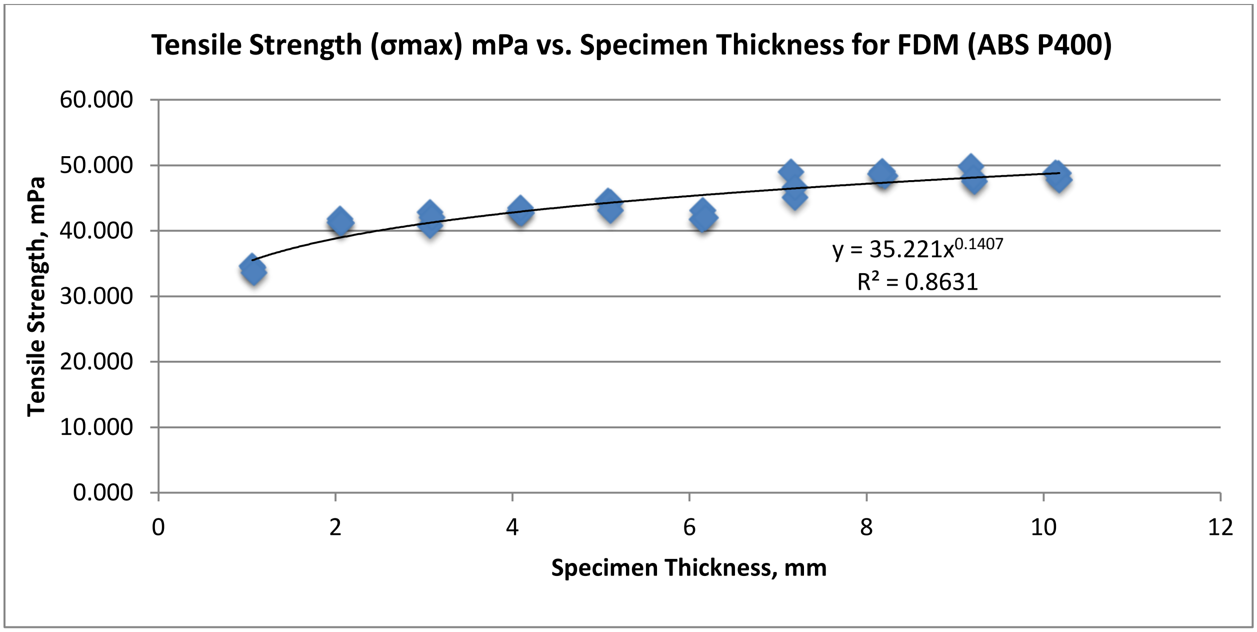


Figure 4.4.5 Tensile Strength vs. Specimen Thickness (Stratasys' System)

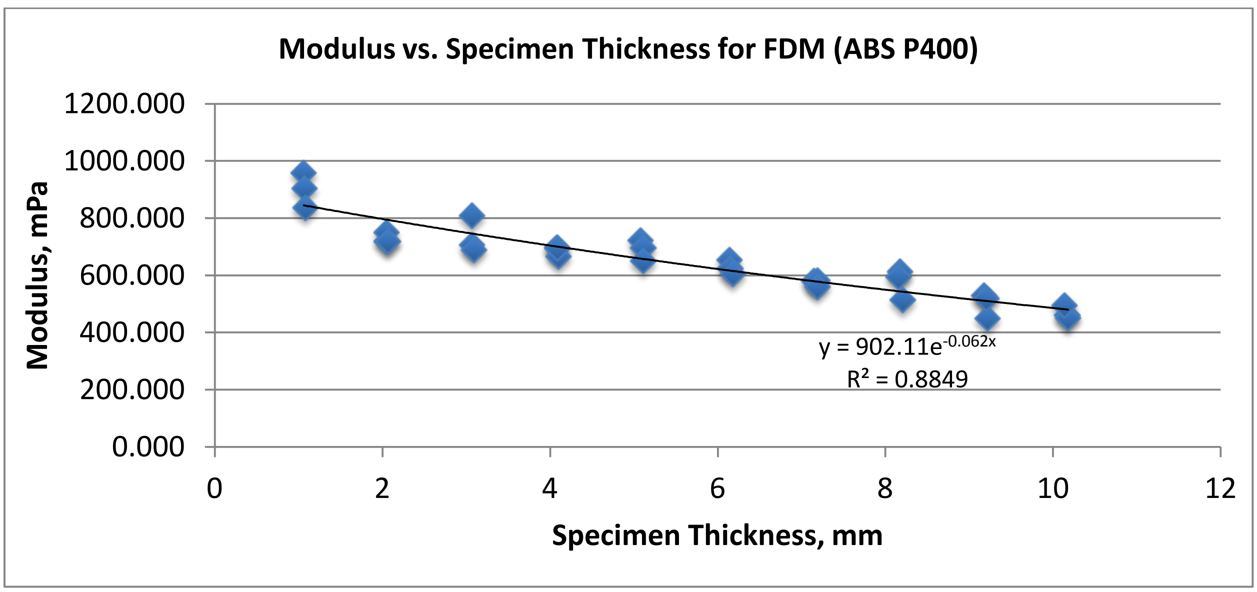


Figure 4.4.6 Modulus vs. Specimen Thickness (Stratasys' System)

4.4.3 Z Corporation Results

System: Spectrum Z510

Technology: Z Corporation

Material: Proprietary Powder Material (ZP-131)

Based on quantitative data obtained through destructive testing summarized in Table 4.4.3 below, parts created in the Spectrum Z510 machine presented lower tensile strength values compared to the other methods in consideration. As it can be observed in Figure 4.4.7 below, the range of values for Z Corp. parts tensile strength lies within 18.9 and 45.8 MPa.

Table 4.4.3 Z Corp. Results Summarized

Spectrum Z510 (Z Corp. 3D Printing Technology)						
Part No.	Thickness (h mm)	Width (b mm)	Load at Failure (gms)	Displacement Y (mm)	Tensile Strength (σmax) MPa	Modulus (E), MPa
1	9.14	15.15	51141.620	0.508465	18.941	663.365
2	6.21	15.14	31225.327	0.489082	25.069	1343.429
3	4.81	15.15	22074.917	0.402462	29.521	2482.084
4	9.15	15.15	62142.339	0.482182	22.965	847.209
5	4.85	15.15	20405.350	0.420207	26.840	2143.547
6	4.18	15.17	12767.655	0.401848	22.579	2187.888
7	6.69	15.15	38339.738	0.389704	26.505	1654.678
8	3.17	15.15	9993.956	0.435912	30.771	3624.418
9	3.18	15.15	8545.641	0.429955	26.147	3112.560
10	1.2	15.15	1884.370	1.116462	40.489	4918.764
11	2.2	15.15	4519.537	0.485941	28.892	4398.655
12	10.35	15.16	72657.936	0.4706	20.972	700.811
13	8.08	15.15	56105.892	0.396342	26.590	1351.393
14	6.67	15.15	32760.802	0.403985	22.784	1376.224
15	10.26	15.16	82673.85	0.455823	24.284	845.125
16	10.2	15.15	65161.440	0.406933	19.378	759.879
17	8.06	15.15	55514.125	0.347123	26.440	1538.128
18	1.2	15.16	2133.2736	1.166297	45.806	5327.023
19	1.19	15.15	2071.382	1.126079	45.258	5497.027
20	8.07	14.76	47367.482	0.327597	23.099	1422.078
21	4.22	15.16	16089.239	0.410785	27.935	2622.856
22	3.2	15.14	9588.515515	0.391874	28.991	3762.870
23	6.17	15.15	23572.947	0.335758	19.159	1505.253
24	6.2	14.72	29124.751	0.3768500	24.128	1680.741
25	2.16	15.15	6106.617	0.593737	40.497	5139.523
26	7.14	15.15	44559.406	0.514728	27.044	1197.690
27	4.82	14.7	22730.46	0.388442	31.199	2712.150
28	2.11	15.15	6036.896	0.597461	41.954	5416.694
29	4.2	15.15	16140.483	0.409781	28.310	2677.283
30	9.15	15.15	60908.73	0.4	22.510	1000.999

As it was observed in the results obtained from the previous methods (FDM and PolyJet), the one (1) mm Z Corporation specimens presented a different behavior than the rest of the specimens printed by the same system (see Figures 4.4.7 and 4.4.8). In this case, the one millimeter specimens exhibited higher tensile strength values than thicker specimens, which is contrary to the results we observed in the other methods in consideration, whose thinner specimens presented lower tensile strength values. This behavior has been attributed to the presence of additives use to harden the Z Corporation parts. As it was mentioned in the previous chapter, Z Corp. parts were impregnated with a two part epoxy resin (Proset 117 and 226), which was manually applied to all external surfaces of the parts after they were printed. Once the resin has been applied, it penetrates about 1.5 millimeters into the part, which causes thinner specimens to acquire a strong bond across their entire thickness. Thicker specimens obtain strong bonds only in their periphery, leaving unbonded powder material in the center. This results in the thinner-wall specimens achieving a higher tensile strength and stiffness than the thicker-wall specimens. Figure 4.4.9 below illustrates this concept.

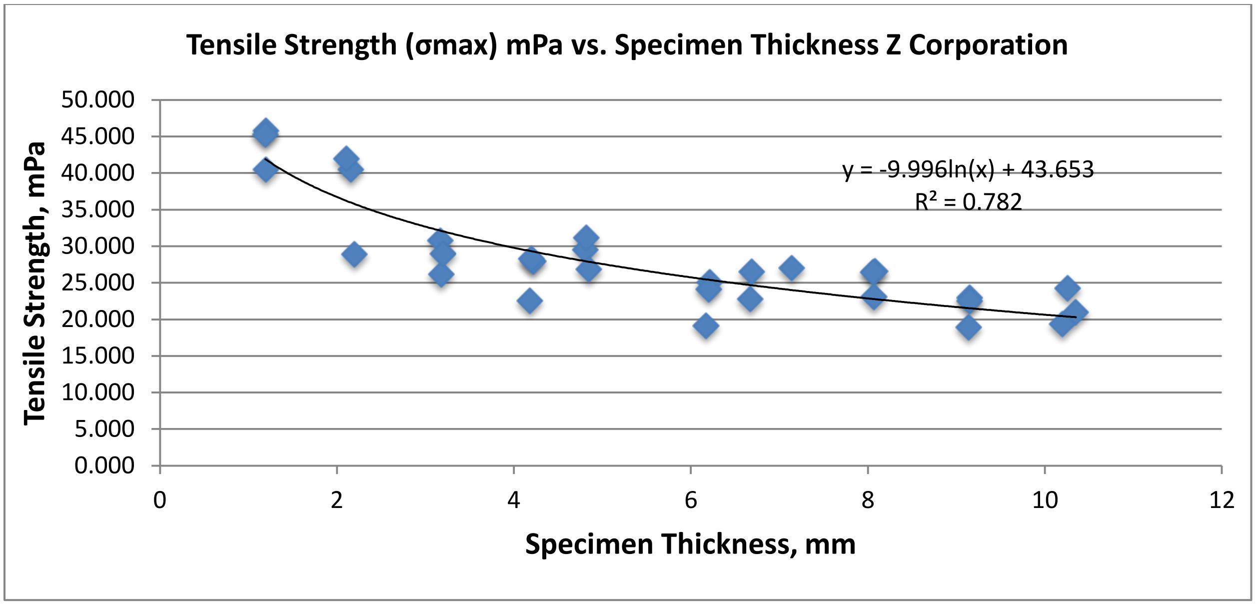


Figure 4.4.7 Tensile Strength vs. Specimen Thickness (Z Corp. System)

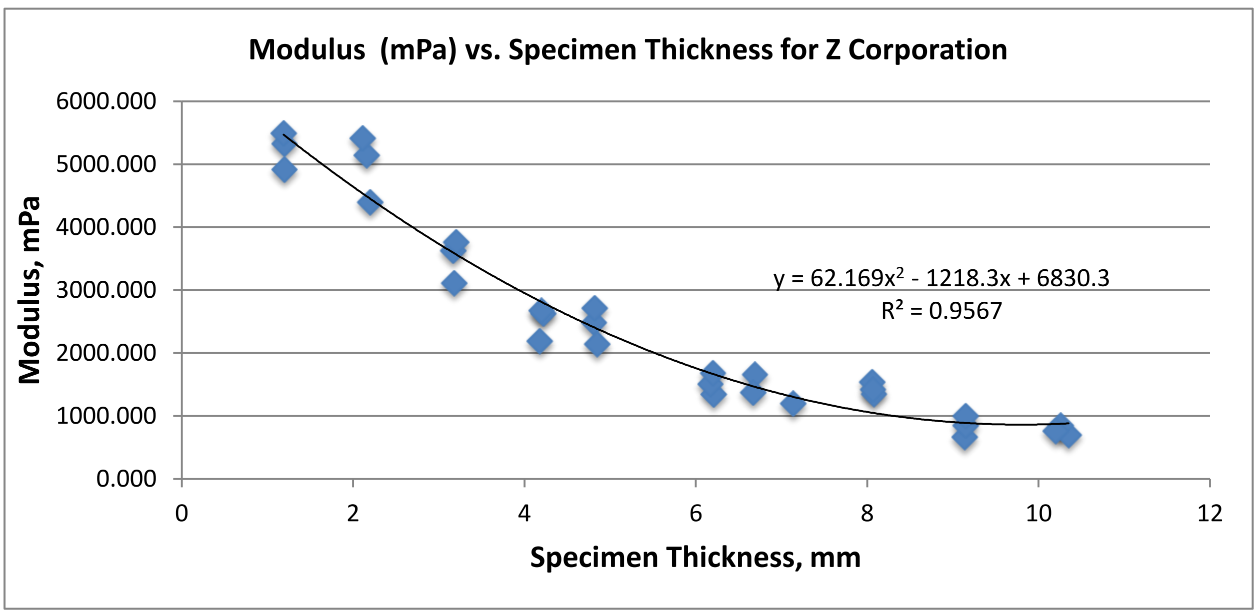


Figure 4.4.8 Modulus vs. Specimen Thickness (Z Corp. System)

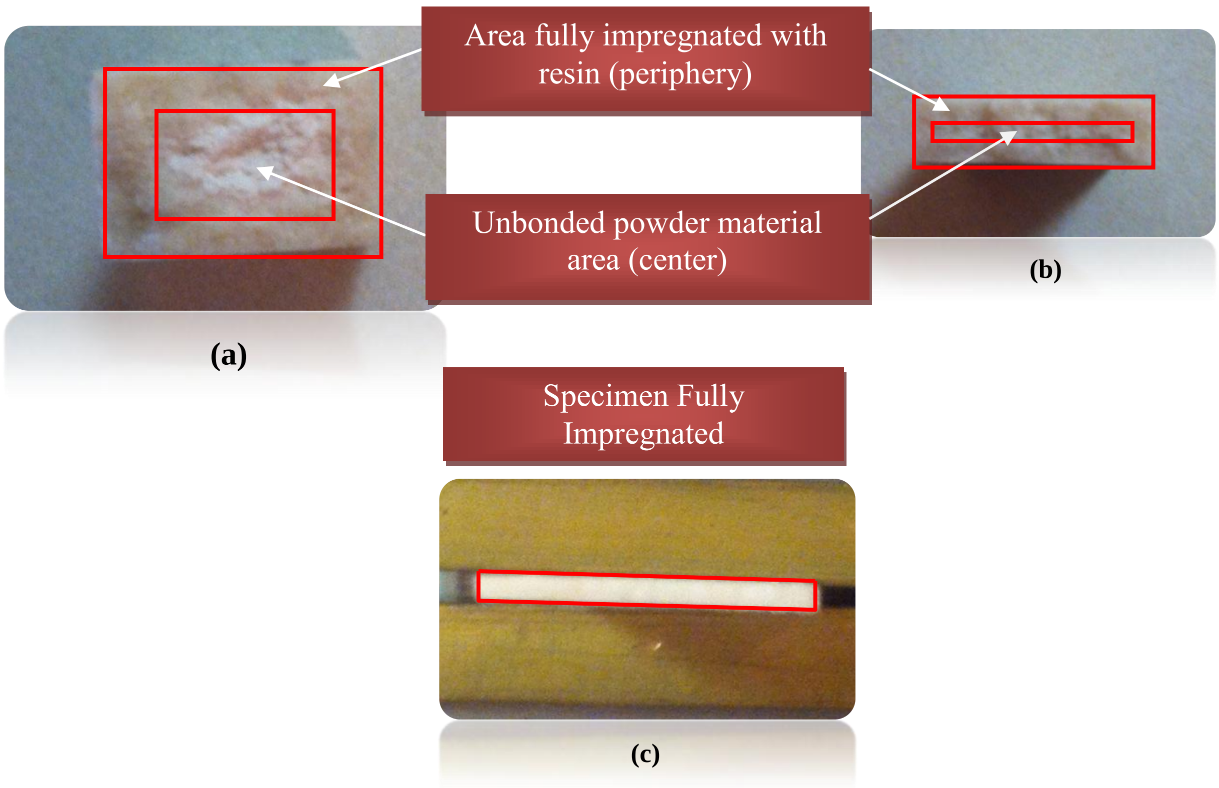


Figure 4.4.9 Z Corp. 10 mm-Thick Specimen (a), Z Corp. 4 mm-Thick Specimen (b), and Z Corp. 1mm-Thick Specimen (c)

5 CASE STUDY

5.1 Design of Plastic Enclosures for "X" Application

The following case study has been included to provide a guide in the use and application of the findings of this thesis project.

1. It is desired to build a simple 25 x 25 x 19 mm cubic enclosure that is hollow and open on one of the 19 mm faces (see Figure 5.1.1) that will withstand a load of 50 pounds (22,679.62 grams) at the center of one of the open edges and a deflection of less than 0.5 mm. Your chosen process, for equipment availability and economic reasons, is the ZCorporation process. How thick should the walls be?

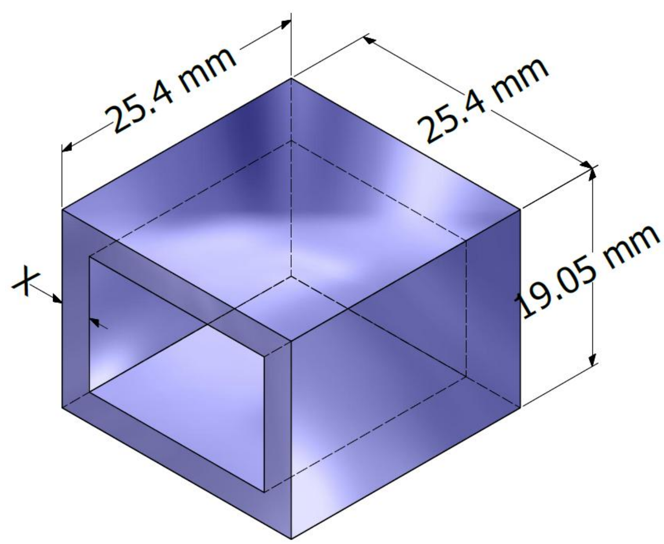
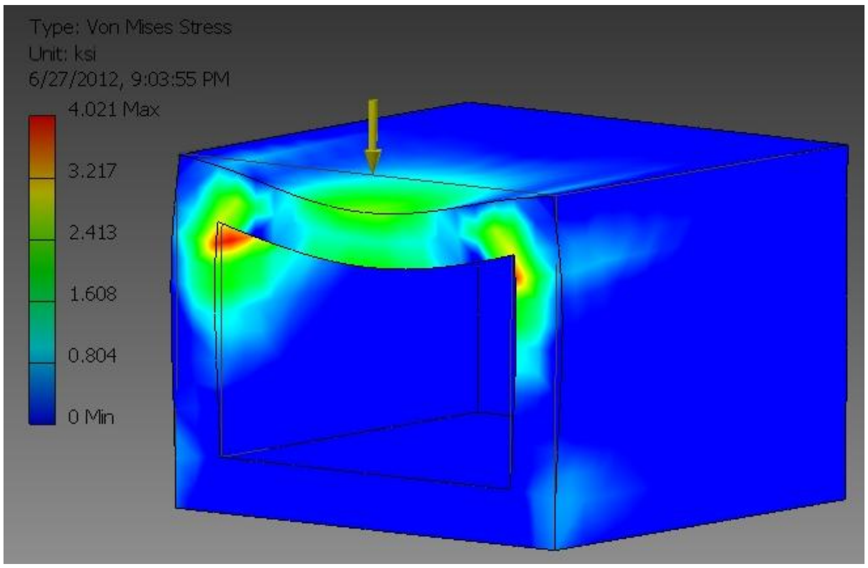


Figure 5.1.1 Cubic Enclosure

2. To answer the problem query, start by creating a CAD model with a 1 mm thick wall. Provide the mechanical properties of tensile strength and modulus shown for the 1 mm specimens in Figures 4.4.7 and 4.4.8 in Chapter 4.
3. Apply a point load of 50 pounds and, using FEA analysis, determine the resulting maximum stress and deflection.
4. Compare these FEA values with the design specifications of no fracture and less- than or equal to 0.5 mm deflection.
5. If the specifications are met continue with the 1 mm wall design. If they are exceeded repeat the process with a 2 mm wall thickness to see if the additional strength will allow the specifications to be met (increments of 0.5 mm can be applied using interpolation).
6. If the specifications are still not met continue the iterations until a sufficient wall thickness is found.
7. To confirm the analysis, once a sufficient wall thickness is found, build a sample cube of the acceptable wall thickness and test it at the specified load. It should just meet the desired specifications.

The case study could be set up reversely by first assuming a required wall thickness and then using FEA to establish the maximum allowable force that can be supported without failure.

Given the above requirements, a FEA study showed that a 1.0 mm-thick ZCorp. specimen would reach failure stress of Fig. 4.4.7 and deflect 0.8 mm when a load of 10 pounds (4530 grams) is applied on it. A 2.0 mm-thick cubic specimen would reach failure stress and deflect 0.32 mm when a force of 38 pounds is applied on it. A 3 mm-thick specimen would reach failure stress under a point load of 55 lbs (24,915 grams) with a maximum displacement of 0.22 mm; therefore, based on the results of the FEA study, it is recommended that a cubic enclosure with a wall thickness of no less than 3 mm should be chosen for the desired application. As shown in Figure 5.1.2 below, the resulting stress of the 55 lb. applied load is 4.021 ksi (27.7 Mpa), with a corresponding deflection of 0.0086 in (0.22 mm).



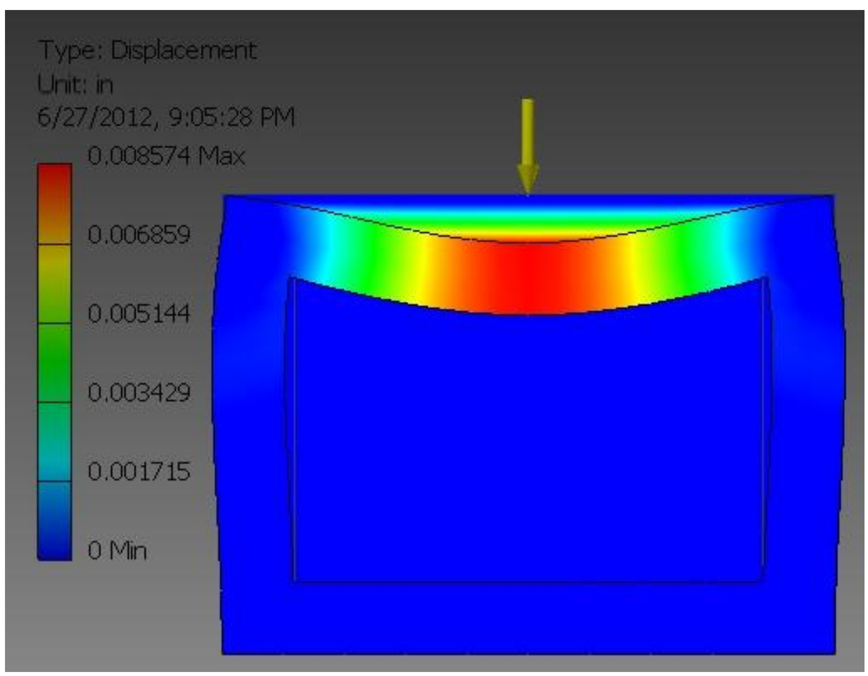


Figure 5.1.2 FEA Performed on 3 mm-Thick Z Corporation Specimen (55 Lb Load).

For this study, a set of three ZCorporation cubes were fabricated (using the methods and parameters previously described for such system) and tested to failure (see Figure 5.1.3). A load cell with a resolution of ± 20 grams was employed to perform these tests.

Figure 5.1.3 Z Corp. Cubic Specimen Being Tested to Failure

The actual average load at which failure occurred for the three Z Corp. cubic specimens was equal to 51.02 pounds (23,112.06), with an average deflection of 0.31 mm. It is important to mention that one specimen failed at a registered load of 46.3 pounds (20,973.9 grams). The other two cubic specimens failed when the force surpassed 50 pounds; all specimens experienced a deflection of less than 0.5 mm (see Table 5.1.1).

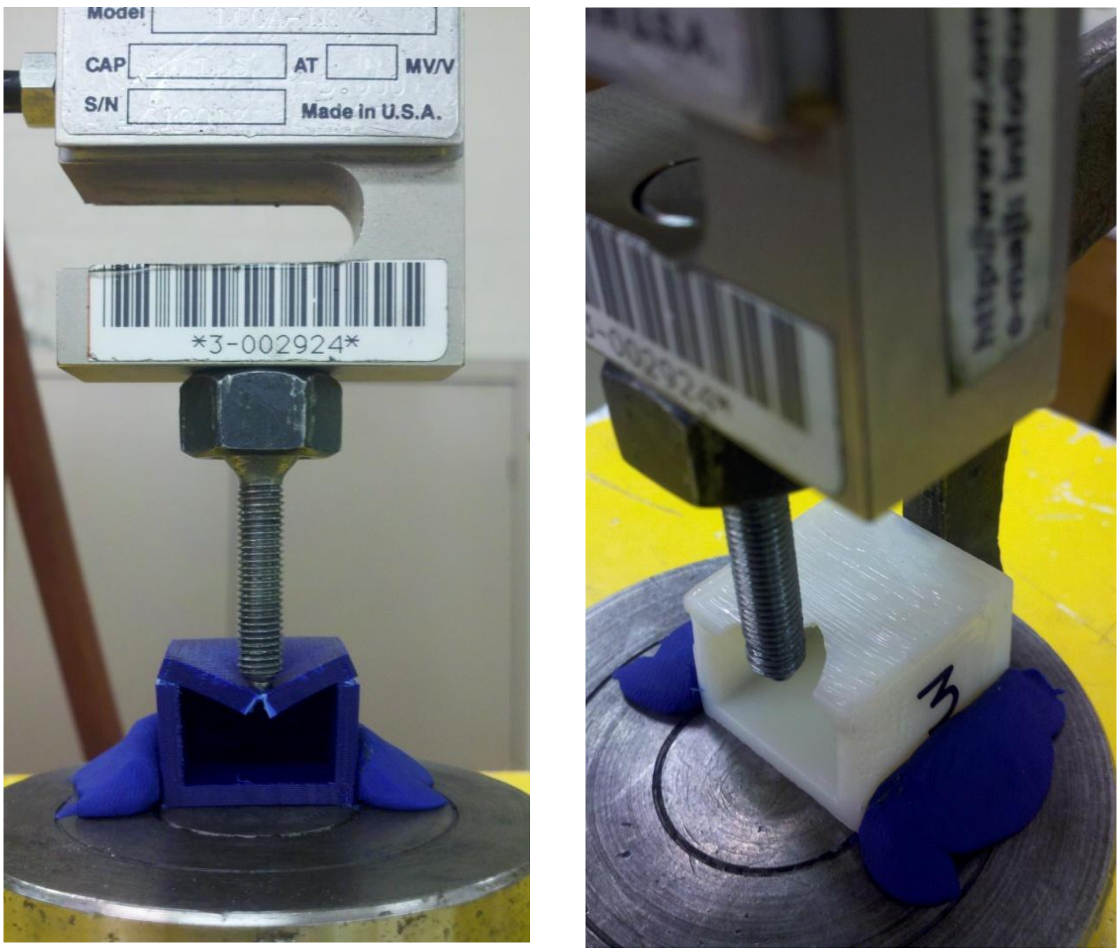
Table 5.1.1 Case Study Results for Z Corp., FDM and PolyJet Cubic Specimens

RP System	Strength Required	Deflection Required	FEA force at failure	FEA max. deflection	Actual failure load	Actual max. deflection
Z Corp.	50 lbs	< 0.5 mm	55 lbs	0.22 mm	55.6 lbs	0.30 mm
					51.2 lbs	0.30 mm
					46.3 lbs	0.33 mm
FDM	55 lbs	< 2.0 mm	85 lbs	1.46 mm	51.7 lbs	1.85 mm
					58.2 lbs	1.5 mm
					58.7 lbs	2.0 mm
PolyJet	75 lbs	< 5.0 mm	168 lbs	1.81 mm	70.7 lbs	3.9 mm
					76.0 lbs	4.9 mm
					79.8 lbs	4.1 mm
Note. All specimens were built with a wall thickness of 3 mm.						

Similar tests were conducted with FDM and Objet cubic specimens (see Figure 5.1.4). The FEA outputs for these specimens were not as representative as the results obtained for the ZCorp. specimens (see Table 5.1.1). It was determined that FEA fails to properly simulate the behavior of the FDM and Objet cubic specimens built for this experiment. As seen in the Figures below, for both of the systems, fracture occurs in different regions from those observed in the finite element analysis. Figure 5.1.2 above, shows maximum stress concentrations occurring at the front-upper-inner corners of the cube, while actual fracture occurred at the center of the front edge (below the pushing tool) and the outside edge of the front-upper corners for the Objet and FDM specimens respectively.

This behaviorcan be attributed to the building orientation of the parts. Both the FDM and Objet specimens were built flat with respect to the machine stage or building tray, which means that the direction of the force exerted by the pushing tool is perpendicular to the layers of material, provoking a premature separation of the top face from the side walls of the specimens.

This behavior is not observed in parts built with the ZCorporation process, due to the impregnant applied to Z Corp specimens. Since ZCorp. specimens are impregnated with an external binder, in this case epoxy resin (Proset 117 and 226),which soaks more-or-less uniformly through the walls up to a certain depth, the effect of bonded layers is reduced, contributing to a more solid-like behavior. Therefore, it is suggested that tensile strength and stiffness of FDM and Objet specimens are more dependent upon building orientation and direction of the applied force than wall thickness.



(a) **(b)**

Figure 5.1.4 Cubic FDM (a) and Objet (b) Specimens Being Tested to Failure

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Overview

As stated in Chapter 1, the primary purpose of this study was to present measured values of tensile strength and stiffness as a function of wall thickness for three RP processes and materials. Such values would assist designers estimating adequate minimum wall thicknesses for models built by these three processes. The query presented in Chapter 1 and whose answer is the outcome of this study was:

What are recommended thicknesses for RP thin-walled features that will withstand specified loads?

Ninety RP specimens were fabricated with three different technologies and materials. All specimens were tested under similar conditions (three point test) until failure loads and displacement values were determined. Tensile strength and stiffness (young's modulus) values were established and used to predict failure loads and displacement values as part of a case study where hollowed cubic enclosures were designed, built (with the systems in consideration) and tested to verify the findings of this study.

The results of this study not only established a firm foundation for designers to predict failure loads based on wall thickness of Z Corp parts, but also provided a method to anticipate displacement values that RP models will experience when exposed to specific loads.

6.2 Important Findings

Below is a list of the important findings from this study.

Z Corporation Technology- Spectrum Z510 System- Powdered Material (ZP-131)

1. Due to the strong bonds created by the application of impregnants used to harden and strengthen the specimens and the penetration of such, tensile strength and modulus values decrease as thickness increases, which suggests that:
2. For the Z Corporation powder material and additives in consideration, neither single tensile strength nor unique modulus values can be defined. These properties vary with the wall thickness of the specimens.
3. Due to the application of additives, Z Corp specimens present a more solid-like behavior than specimens built by the other technologies in consideration, which contributes to better mechanical behavior predictability.
4. Based on the results of this study, the use of Z Corporation technology is recommended when moderate strength and stiffness are acceptable.

PolyJet Technology - Objet Alaris30 System- Photopolymer Material

5. Thinner Specimens present mechanical properties similar to those of molded polymer parts, where increased ductility is observed in thinner features.
6. Contrary to the powder material (ZP-131), tensile strength of photopolymer specimens is directly proportional to thickness.
7. Tensile strength and modulus values fall within a narrower range than the observed in Z Corporation's results.

8. Strenght and stiffness of Objet specimens are more dependent upon building orientation and direction of the applied force than wall thickness.
9. Based on the results of this study and considering that thinner features exhibit higher ductility, it is suggested that photopolymer material be used for high strength and ductility applications.

Fused Deposition Modeling Technology- Stratasys' Prodigy Plus System- ABS P400 Material

10. ABS specimens created with FDM technology exhibited tensile strength values similar to those of conventional ABS thermoplastic, which further validates the testing system employed in this research.
11. Tensile strength and modulus values for FDM specimens presented the least amount of variation, which suggests that mechanical behavior of simple shapes created by the Stratasys' Prodigy Plus System can be predicted with high accuracy.
12. Based on the results of this study, it is recommended that FDM technology be used when dimensional accuracy, medium strength and ductility are required.

6.3 Contributions

First, Filip Gorski (2010) reported that parts created with 3D printing technology (Z Corporation), were only good for visualization, surface finish, dimensioning and coloring. This statement was made based on poor mechanical properties, mainly excessive brittleness. This study also presented recommendations for the use and application of parts created with FDM technology, which exhibited higher strength and ductility than 3D printed parts, and are recommended to be used as functional prototypes.

Although, Gorski did not establish specific mechanical values for the materials in consideration, the current study supports his findings and adds to his work. While Gorski focused on identifying the proper use and applications of parts created with FDM, 3D Printing and Vacuum Casting Technologies, this research provides specific tensile strength and modulus values for such RP methods, excluding Vacuum Casting, which is out of the scope of the current project. Gorkis findings and this research conclude that FDM technology produces stronger and more ductile specimens than Z Corporation.

Second, Lyons (2008) determined that mechanical properties of Z Corporation and FDM parts built with a wall thickness of less than 2 mm will be hardly predictable. He based this statement on the results obtained in his study, which established that dimensional variation of parts built with such RP technologies will affect their mechanical behavior. Lyons did not perform mechanical experiments on this study; his recommendations are based on dimensional accuracy of the processes in consideration.

Although, the current project does not suggest that tensile strength and modulus values calculated for the1 mm specimens are null, it has been stated that parts with a wall thickness of less than 2 mm exhibit different behavior than thicker specimens, which supports Lyons findings. Although dimensional accuracy is out of the scope of the current research, by comparing the thickness and width values of Tables 4.4.2 and 4.4.3, it can be observed that FDM specimens built for this project possess higher dimensional accuracy than their Z Corp. counterparts, which also supports Lyons work. Tensile strength and modulus values calculated for FDM specimens, also presented less variability.

Third, this research provides a body of work which presents comparative specific loads and displacement values for specimens built with the thre most common RP systems and methods. This research is thus providing documented results and numerical values for the failure points of the vaiours samples per the RP processes, which will now allow for adequate design of RP models, which has today not been readly published or available .

6.4 Summary and Recommendations for Further Study

The findings of this research project are therefore presented as reliable means to calculate and predict mechanical behavior of RP parts fabricated with the Spectrum Z510 system. It has also been established that tensile failure of parts created with Stratasys' Prodigy Plus and Objet Alaris30 systems and their corresponding proprietary materials, are largely dependent upon building orientation and direction of the force applied. It has also been demonstrated that tensile strength and stiffness values of specimens created with the Spectrum Z510 system are dependent upon wall thickness; therefore, tensile strength and modulus are presented as a range of values.

Further experimentation is recommended to determine how different building orientations would affect mechanical properties of RP materials. For FDM (ABS P400) specimens, understanding the impact of raster angles combined with different layer thicknesses and road widths on ultimate tensile strength and modulus would also constitute a project worth of pursuing.

Another area of further experimentation applies to the understanding of how different additives, use to harden powder materials, impact mechanical properties of Z Corporation specimens.

The last area of recommended future experimentation applies to FE analyses. A study that reflects the actual road and layer structure of FDM specimens would provide accurate data to perform accurate FD analyses.

REFERENCES

Liu, C.Z., Sachlos, E., Wahl, D.A., Han, Z.W. and Czernuszka, J.T. "Manufacturability of scaffold mould using a 3D printing technology." *Rapid Prototyping Journal*, 2007: 163-174.

Perry, C. "Advances in rapid prototyping and rapid manufacturing ." Update, Provo, 2002.

Dilip, I., Abhaykumar, K. "Coding system for rapid prototyping industry." *Rapid Prototyping*, 2008: 1-13.

Filip, G., Wiesław, K., Radosław, W., Adam, D. "Choosing optimal rapid manufacturing process for thin-walled products using expert algorithm." *Journal of Industrial Engineering and Management*, 2010: 1-13.

Fretag, D., Wohler, T. and Philippi, T. *Rapid Prototyping: State of the Art.* special, Chicago: Manufacturing Technology Information Analysis Center, 2003.

Gerhard, P., Beitz, W., Jorg, F. and Karl, H.G. *Engineering Design A Systematic Approach.* Berlin: Springer, 2007.

IDES. *IDES The Plastic WEB.* http://www.ides.com/info/generics/1/Acrylonitrile-Butadiene-Styrene-ABS (accessed 2011 йил 20-April).

Illinois Tool Works Inc. *Instron, The difference is measurable.* 2011. http://www.instron.us/wa/corporate/profile.aspx (accessed 2011 йил 20-April).

Javier, M., Joaquim, D.C. and Carles, R. "Pursuing successful rapid manufacturing." *Rapid Prototyping Journal*, 2008: 173-179.

Ali, K. and Abouel, E. *Rapid Prototyping: Theory and Practice.* Houston: Springer Science, Inc., 2005.

Lyons, B., Saito, E., Hollister, S. and Beiber, K. *Inspection of Thin Wall and Fine Features from 3DP and FDM Processes.* Technical Paper, Lake Buena Vista,: Society of Manufacturing Engineers, 2008, 1-11.

Rafiq, N. *Rapid Protyping, Principles and Aplications.* Los Angeles: John Wiley & Sons, INC, 2006.

Objet. "PolyJet Technology." *Objet Web site.* January 2010. www.objet.com (accessed March 22, 2011).

Guillermo, Z.A. and Jorge, R.G. "Characterization of the mechanical properties of samples fabricated by an experimental SGM device." *Rapid Prototyping Journal*, 2010: 356-364.

Brent, S. *Plastics Materials and Processing.* Upper Saddle River, New Jersey: Pearson Education, Inc., 2006.

Suslia, B. and Arunachalam, S. *Evaluating the Strength of Prototype Components Produced by FDM Using Mathematical Model.* Technical Paper, Dearborn: Society of Manufacturing Engineers, 2005.