HEATING APPARATUS THAT AIDS IN THE PREVENTION OF DELAMINAITON IN BIG AREA ADDITIVE MANUFACTURING APPLICATIONS

by

Teng Lee

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STATEMENT OF COMMITTEE APPROVAL

Dr. Raji Sundararajan, Chair

School of Engineering Technology

Professor Paul McPherson

School of Engineering Technology

Dr. Hachao Mao

School of Engineering Technology

Approved by:

Dr. Duane D. Dunlap

To my Mother, Father, and Brother

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LIST OF ABBREVIATIONS

AM	Additive Manufacturing
BAAM	Big Area Additive Manufacturing
FDM	Fused Deposition Modeling
PLA	Poly Lactic Acid
PETG	Polyethylene terephthalate glycol
IR	Infrared

GLOSSARY

Additive Manufacturing (AM)	“The process of using a digital 3D model to produce an object without the use of tools or patterns of conventional manufacturing” (DeGarmo, Black, Kohser, & DeGarmo, 2012, p. 267).
Allowance	"The intentional, desired difference between the dimension of two mating parts" (DeGarmo, Black, Kohser, & DeGarmo, 2012, p. 964)
Big Area Additive Manufacturing	Using additive manufacturing process to make large products (Li et al., 2019)
Delamination	The splitting of the 3D printed layers (Li et al., 2019).
Fused Deposition Modeling (FDM)	The process of melting thermoplastic filament and then extruding the melted plastic onto a bed by gradually building layers until a 3D object is produced (Akhoundi et al., 2020).
Glass Transition Temperature	“Glass transition temperature is described as the temperature at which 30–50 carbon chains start to move. At the glass transition temperature, the amorphous regions experience transition from rigid state to more flexible state making the temperature at the border of the solid state to rubbery state.” (Shrivastava, 2018)
Heated Bed	The platform component of FDM 3D printers which incorporates a heating system to warm the layers of prints. It is generally used to prevent heat-related issues that arise from changing temperatures during an FDM 3D print. (Li et al., 2019)
Layer Adhesion	The concept of how well the plastic layers bond to one another during the printing process (Li et al., 2019).
Millimeter	The metric system of length measurement and is one-thousandths of a meter.
Printer head	The assembly which houses the heating element to melt the thermoplastic and the mechanism to extrude the melted thermoplastic onto the bed.
Thermoplastic	"A plastic that can be heated to be formed into products” (DeGarmo, Black, Kohser, & DeGarmo, 2012, p. 210)

Warping	A phenomenon, which occurs when a material's latitude and longitude axis cools at different rates, which caused the material to distort the shape. (DeGarmo, Black, Kohser, & DeGarmo, 2012, p. 210)

ABSTRACT

Fused Deposition Modeling (FDM) uses thermoplastic filament to produce 3D objects by depositing melted plastic onto a platform in layers until a full object is made. However, the FDM process has an inherent problem: The constant cycles of heating and cooling the plastic experience during the printing process caused by the presence of a heating elements. The FDM process uses the heating element to melt the filament and then extrude the melted plastic onto a bed, gradually building up the layers to create a 3D object. The heating element essentially places warm melted plastic on top of already cooled plastic material which causes the buildup internal stresses leading to improper layer adhesion. Which can then lead to delamination or warping. Traditional prevention methods focus on the heating apparatus. Having a heated bed integrated into the printer itself, only helps in the first few beginning layers. Printers used for Big Area Additive Manufacturing (BAAM) do not have built-in measures to ensure the printed layers cool at the same rate or stay at a constant temperature. The study tested the viability of an external heating system integrated into a 3D printer to prevent warping or delamination at all layer levels. The engineering design process was used to test various heating methods and materials and develop a test of concept heating system for BAAM applications, which will prevent or mitigate delamination or warping while not impeding the overall functionality of the printer. A functional heating system was developed through trial and error of the engineering design process, which prevented delamination and mitigated the warping of FDM prints. The success of the external heating system as a concept for FDM prints is intended to serve as a steppingstone for research in the BAAM industry and prevent print failures during the additive manufacturing process.

CHAPTER 1. INTRODUCTION

1.1 Background

Recently, 3D printers have become increasingly common and affordable, this technology has become commonplace in the industrial and personal markets since making these machines have become increasingly cheaper. The average American consumer can buy an FDM 3D printer off the internet for $250 and be ready to start printing with minor setup. Fused Deposition Modeling printers utilize polymer materials such as Polylactic Acid (PLA), that are melted and then extruded onto a platform, where layers will be gradually built up over time until a fully completed part is made.

FDM 3D printers appeared in the 1980s and were developed by S. Scott Crump (*"Fused Deposition Modeling: Everything You Need To Know About FDM 3D Printing | 3DSourced,"* 2019). Then in 2009, when the life on the patent on FDM printers expired, these printers became more common. It was during this time that more Do It Yourself 3D printers became more widespread now that 3D printer enthusiasts were able to design and develop their own 3D printers without the worry of legal repercussions due to patent laws.

1.2 Advantages FDM

FDM does have advantages, over the more mainstream manufacturing techniques used in the industry such as subtractive manufacturing or injection molding when wanting to prototype a new product or general production. One benefit of 3D printers is creating complex geometries or structures with less complicated tools and machinery. ((Wickramasinghe et al., 2020). Traditional methods, such as subtractive manufacturing and injection molding, have issues making more complex or unique geometries compared to what is possible with FDM printing. A possible example can be a hollow box with 3mm thick walls. Subtractive manufacturing techniques cannot create the box easily due to the tooling being unable to hollow out the box without harming the surface of the box. Using the FDM process the hollow box can be easily made by laying the layers of plastic on top of each other until the part is made.

In addition, the material requirements for subtractive manufacturing are more than that compared to FDM printing. (Wickramasinghe et al., 2020). Subtractive manufacturing starts with stock material and then gradually chips away the material until the part is made. At the end of the process there is a lot of scrap material in the form of chips or bits of material. While additive manufacturing, there is relatively little waste due only the material required to produce the actual part will be used. The capability of being able to produce complex geometries in conjunction with less material waste FDM is ideal for prototyping new products.

Another traditional manufacturing process which FDM shines over is injection molding, where melted plastic would be injected into a mold. For injection molding unique two-part molds must be made for each design and can be expensive to produce and maintain. In contrast with 3D printing, no initial setup of a mold is required. Industrial injection molding, requires the production line to be built around a specific mold design, where there needs to be a hydraulic or pneumatic system to run the machine, either injecting the plastic into the mold with a piston or opening and shutting the two mold pieces (Wickramasinghe et al., 2020). This can make it hard to quickly switch mold designs as the production line has to be shut down to replace the molds if they need to be replaced for a new design or removed for maintenance. This is FDM’s advantage over injection molding. A new design can be easily changed by uploading a new file onto the software that manages the 3D print. This makes additive manufacturing more versatile in nature, allowing manufacturers to change the design without changing the shop floor's layout to accommodate a new design the company wants to produce.

1.3 Problem

Two common failures in experienced during 3D printing are phenomenon called delamination and warping. Delamination is caused when two connected layers cools at different rates due to thermal expansion coefficient of extruded plastic. As the plastic layers cool the material contracts pulling on surrounding connected layers. Layers at different temperatures can contract at different rates causing layers to split apart or the plastic at the base of the print to lift off of the printing platform. Delamination and warping are often caused by the lack of supplemental heat from an external source during the heating process. Without supplemental heat to ensure that the layers stay at the same temperature leads to the undesirable delamination and warping in FDM prints.

In addition to having supplemental heat to prevent deformations during the printing process, heat is important during the initial stages of the print. The first filament lines being extruded onto the bed is one of the most important stages of a 3D print (*"Fused Deposition Modeling: Everything You Need To Know About FDM 3D Printing | 3DSourced,"* 2019). If the temperature is not warm enough, the print may shift in later stages of the print, causing the filament to be extruded in the wrong place leading to unusable part.

1.4 Significance

The research was aimed to test the concept of an external heating system that can be easily integrated and without interfering with the functionality of a 3D printer. If an external heating system can be integrated with the small-scale additive manufacturing printers to prevent delamination and warping, then a similar concept can be applied to BAAM printers. This heating system will reduce the need to reprint a part which can cost the user a lot of money in terms of time, material, and electricity cost. According to Jason King, the cost of running a desktop 3D printer can build over time when having prints fail multiple times (King, 2017). Bad prints result in wasted material, electricity, and wear on the machine. For example, a kilogram of Polylactic Acid (PLA) filament, the most common filament used in 3D printers, can cost between $25 to $60 (King, 2017). This may seem cheap for a hobby printer; however, if a Polylactic Acid (PLA) print fails, the print must be thrown away. This is because PLA cannot be easily recycled in house to create new filament like other polymers that can be used in 3D printers due to PLA being made of plant matter (*"Fused Deposition Modeling: Everything You Need To Know About FDM 3D Printing | 3DSourced,"* 2019). When scaled to BAAM may become being several thousands of dollars of wasted material. A study was done by the Manufacturing Systems Research Group and the Deposition, Science, and Technology Group showed that a single FDM successful print of 93 in^3 of material could cost up to $31,368 (Post et al., 2016) This cost encompasses preprocess, material, processing, and post-processing. If this part were to fail and the company had to reprint the part, the cost could total over $60,000 and many hours of wasted time. For a small company, these costs cannot be afforded.

1.5 Purpose

The purpose of this project was to design and validate a heating system for fused deposition modeling that will mitigate the problem of non-uniform cooling that results in poor layer adhesion that can lead to bad prints. During the 3D printing process, especially in fused deposition modeling, the plastic prints go through constant heating and cooling cycles, which "causes non-uniform temperature gradients," which results in shape distortions (*"Fused Deposition Modeling: Everything You Need To Know About FDM 3D Printing | 3DSourced,"* 2019). These shape distortions often lead to layer splitting or warping of the plastic prints, which are undesirable defects in 3D printing.

One of the current methods to prevent delamination is to apply the proper amount of heat to the polymer to prevent premature cooling. In a typical 3D printer, the way that heat is applied to the extruded polymer is through the extruder or the heated bed (Emma Pollock, 2019). However, this sometimes is not high enough to ensure good layer adhesion because the temperature is not high enough or aids the initial lays of the print The correct temperature for a good layer adhesion is right at the polymer's glass transition temperature in question (Aitchison & Wang, 2019). So, the problem addressed by this study is preventing failed prints caused by improper layer adhesion due to a lack of properly applied heat during the 3D printing process. Therefore, this project's purpose will be designing a physical attachment mounted to the moving head of an FDM 3D printer. This study's deliverable will be a functioning prototype that will prevent poor layer adhesion and distortion due to differential cooling by applying additional heat to a 3D printed part throughout the printing process.

1.6 Research Questions

The research questions being addressed by this study.

1. Can an external heater be developed for a 3D printer without interfering with core functions?
2. Will the heater in question prevent or mitigate the effects of warping or Delamination?
3. How can the design be applied for BAAM applications?

1.7 Assumptions

Prior to development and testing of the heating system the researcher made the following assumptions to drive the design process.

1. The room temperature would be constant at 20C°.

2. Little vibration from the environment is present.
3. There would be no power outages during the printing process.
4. The bed would be level during the entire printing process.
5. The printer setting would remain constant during the printing process.
6. No unauthorized personnel would interact with the printer during the printing process.

1.8 Limitations

When designing and testing the heating system the researcher had the following limitations:

1. The design of the heating system is limited to the Ender 3 Pro design.
2. The design of the heating could not interfere with prior functions and parts of the printer.
3. Using a 3D printer to produce the housing parts of the heating system.
4. The design is unable to be tested on a full-sized BAAM printer.

1.9 Delimitations

During the design and testing of the heating system the researcher did not consider the following:

1. Potential for printer bed misalignment.
2. Possible debris on the printing bed.
3. Possible fluctuations in room air current due to movement of bodies.
4. Adapting the design to other types of FDM 3D printers.
5. The flatness of the printing bed

CHAPTER 2. REVIEW OF LITERATURE

2.1 Introduction

Chapter Two discussed how the FDM printing process operates in practice and importance of the heated bed. In addition, the material, PLA, is discussed in this section describing the properties as well the pros and cons of material. To conclude this chapter prior research done to solve the issue of interlayer bonding in FDM 3D printing using post processing methods or supplemental heating apparatuses will be discussed.

2.2 How FDM 3D Printers Function

FDM printers work by feeding filament into a heated nozzle, called the extruder, where the material will melt to a semiliquid consistency. Once the material is melted, it would be extruded onto a platform or bed in the X, Y, or Z-axis. Gradually layers will be laid on top of each other until a full 3D object has been created. The 3D printer movement when the filament is being laid out depends on the design of the printer itself. Some printers will control the bed in only the Z-axis, and the extruder nozzle will move in the X and Y-axis. Whereas others may have the bed move exclusively on the Y-axis while the heater will move in the X and Y-axis.

FDM printers models such as the, Creality Ender and MakerBot Replicator, have a heating element such a heated bed to aid in the printing process. The purpose of the heated bed is to ensure that all the layers of printed plastic remain relatively the same temperature. If two layers were of different temperatures while cooling, the layers can pull away from each other due the contraction of the plastic as it cools. This pulling away from each other leads to the layer deformations known as delamination and warping. The heated bed is integrated into the printer to provide a building platform while ensuring the layers of the print are the same temperature. However, some printers do not have this feature built into the core design. Without this added heat, delamination and warping is more likely to occur during the print.

However, the presence of heated bed can be a detriment, especially for larger print sizes. The typical print size is 220mm x 220mm x 250mm in dimension. Say a heated bed is set at 60°C, the layers that are 245mm from the bed are not receiving the same amount of heat that layers only 1mm. The radiant heat is cooling as heat rises to higher levels of the print which can cause delamination due to the temperature difference between layers cause the lower layers are warmer than the upper layers.

2.3 Polylactic Acid in the FDM Process

The filament used in FDM printers can be a variety of materials, typically a thermoplastic material, such as Polylactic acid ((*PLA (Polyactic Acid) Biodegrable Filament*, n.d.). These thermoplastics can be tailored to a specific application, where one thermoplastic property is more desirable than another. One of the most common filaments used is Polylactic Acid. This material is made from cornstarch (Goldschmidt, 2020). This makes this material readily available and cost-effective, where a kilogram spool can cost only $20 (Liu et al., 2019). Also, since PLA is made of biodegradable cornstarch, it is more environmentally friendly than traditional petrol-based plastics (Li et al., 2019). However, the properties are less than desirable for more rugged applications. PLA has material strength with a tensile strength of 59 megapascal. PLA is brittle in nature, where it can easily break and not be very heat resistant.

PLA melts at lower temperatures. With a “glass transition temperature in the range of 65–70°C and melting temperature around 160–170°C” (Rafie et al., 2020). If PLA is exposed to excessive amounts of heat it will warp. Even leaving a PLA printed part in a car during the summer can cause significant deformation. There have been studies as well that certain colors have worse mechanical properties than others. A study was done by Wittbrodt shown that natural color PLA has better tensile properties compared to PLA with color additives (Wittbrodt & Pearce, 2015). His study showed that natural color PLA had a higher tensile strength of at least 3 megapascals over a “black, grey, blue, and white filament” (Wittbrodt & Pearce, 2015).

While PLA is not ideal for practical used, PLA is great for rapid prototyping. PLA is ideal to see if parts will fit together when assembled or if cosmetically is appealing to customers. There two core reasons why PLA is ideal for rapid prototyping. The first reason why PLA is ideal for this rapid prototyping is because the material doesn’t require 3D printers capable of high printing temperatures. Compared to materials such as, Acrylonitrile Butadiene Styrene (ABS), Polyetheretherketone Polymer (PEEK), and Nylon, PLA is printed at a lower temperature of 180°C and doesn’t require a heated bed. Allowing the material to printed on inexpensive 3D printers and saving users cost in machinery. The second reason is that PLA is made of cornstarch, a biodegradable material. While the material cannot be recycled, the users of PLA do not have to worry about thrown away PLA parts impacting the environment like conventional petroleum-based polymer materials.

2.4 Other Thermoplastics used in FDM

There are other variants of thermoplastic besides the previously mentioned PLA that are commonly used in FDM printing. Some of the other materials include Acrylonitrile Butadiene Styrene (ABS), Polyetheretherketone Polymer (PEEK), and Nylon. These materials all have different properties compared to PLA. Materials like PEEK and Nylon have better durability in terms of mechanical strength than PLA (Liu et al., 2019). These materials are more chemical resistant than PLA making these filaments more desirable for medical applications. However, these materials require more care during the printing process, where the heat must be carefully maintained. This is because is because Acrylonitrile Butadiene Styrene (ABS), Polyetheretherketone Polymer (PEEK), and Nylon are more susceptible to delamination caused by heat differences. While having better mechanical, chemical, and thermal properties these thermoplastics cost users more monetarily.

2.5 Prior Attempts to solve the Problem

In the past two decades, there have been several attempts to solve this issue. These typically involve pre- or post-processing treatments to mitigate the issue defects caused by the differential cooling (Li et al., 2019). One of the solutions currently being explored is using a laser to warm or melt the print layers as the printer moves. One example is the experiment done by researchers from Nazarbayev University. The researchers utilized a CO2 laser to melt the layers as the printer head moves(Sabyrov et al., 2020). However, systems like these are quite complex and can be expensive. As noted in the researchers' study at Nazarbayev University, they had to create a relatively complex mounting rig to mount the laser. The Nazarbayev researchers set up the laser to only affected the Y-axis of the 3D printed part. . Making the use of a laser less optimal for frames that don’t have the capability to mount laser. . In addition, the researchers noted that the laser would gradually degrade the plastic print at higher power levels.

An experiment done by Andrew Aitchison and Qing Wang from the United Kingdom had a much more cost-effective and less complex method using hot air as the heating method (Aitchison & Wang, 2019). Their goal was to make FDM printing's mechanical properties in line with that of other manufacturing processes. However, the researchers wanted a simpler method of enhancing interlayer bonding. Using an attachment to the printer's head would blow warm air onto the layers, ensuring that the 3D printed parts did not go under the constant heating and cooling fluctuations. This process has shown some success in improving interlayer bonding. However, the researchers' goal was unable to achieve their goal to make FDM in line with conventional methods. The improvements in mechanical properties, such as Young's Modulus, were not improved to the values the researchers would have hoped for. This research did improve interlayer bonding. However, the one drawback in Aitchison and Wang design is that they could not change the temperature output of their system. The two researchers only output a constant 100°C since a heat gun with no variable temperature setting was utilized during experimentation.

CHAPTER 3. RESEARCH METHODOLOGY

3.1 Introduction

Chapter three will cover the design process of the heating system and the testing of the designed system. The process of designing and testing was broken into three steps. The first step was designing the heating element that would be used to generate and propel heat onto the prints. The second step is making the housing that would contain the heating element and be attached to the Ender 3 Pro. Then the last step is testing is the combination of heating element and housing to prevent or mitigate the occurrence of delamination or warping.

3.2 Equipment Used

Ender 3 Pro Printer

A Fused Deposition Modeling 3D Printer used for hobby and commercial projects, made and sold by the Creality company. The printing area the Ender 3 Pro is 220mm x 220mm x 250mm. Using G Code from a slicer program, 1.75mm thermoplastic filament is fed into an extruder assembly and deposited onto a heated bed.

Soldering Iron

A simple soldering iron was used to solder wires together, particularly connections for the power supplies.

Flat Head and Philips Screw Drivers

A typical hand tool used to screw in mechanical fasteners.

Box Cutter

The box cutter was a utility tool to cut excess plastic or aid in the soldering process.

Wire Stripper

The wire stripper incorporated a wire cutter while also being able to remove the plastic covering on wires. The tool was used to expose the copper wires so connections with ports or other wires can be made.

FLIR E30BX Thermo Camera

The E30BX is an Infrared handheld camera used to visually see heat levels on objects. For the experiment, the E30BX was used to view the heat distribution of warm air on the print.

Digital Hand Caliper

A hand measuring tool used for "width measurement using two parallel blades" that would be placed in between two surfaces to determine length. The corresponding length would be displayed on digital screen.

3.3 Software Used

Autodesk Inventor

Autodesk Inventor is a general-purpose Computer-Aided Design program created by the Autodesk company. The program was used to design the heating system's housing assembly as well as the test part.

Cura

Cura is a slicer program that converts 3D files into G Code which is used by the printer to make the 3D part. The program is a free downloadable program made by Ultimaker, and the program is commonly used for a variety of FDM printers. The program can set the temperature, layer height, support, and infill settings before printing.

3.4 Materials Used

Black Polylactic Acid Filament

The filament used during the testing process was Hatch Box Poly Lactic Acid filament. Polylactic acid or PLA is a plastic polymer made from either corn or beets(*What Is PLA*

(Polylactic Acid)? | HATCHBOX – HATCHBOX 3D, n.d.). The PLA material is ideal for lower-temperature printing. For this reason, PLA is an ideal material for printers without heated beds. The reason why black filament was chosen over other colors is because the goal of the project is to cause delamination in the FDM process. Pigmented PLA filaments will have more chances of delamination than natural colored PLA since the layer adhesion of pigmented PLA is less than that of natural colored PLA.

Black Polyethylene terephthalate glycol Modified (PETG) Filament

The filament Polyethylene Terephthalate glycol or PETG was purchased from Overture's brand of 3D printer filament and was used to make the housing of the heating system. Polyethylene Terephthalate glycol is a polymer material made from a mix of cyclohexane dim ethanol with phthalic acid (*What Is PETG? | HATCHBOX – HATCHBOX 3D*, n.d.). In addition, compared to PLA, PETG has a higher heat tolerance with a glass transition 85°C compared to PLA's 60°C.

Nichrome Wire

The nichrome wire used was the Nichrome 80 28-gauge wire. Nichrome is an alloy material encompassing 80% Nickel, 19.5% Chromium, 1.45% Silicon, and 0.05% miscellaneous metals, typically used in heating systems. Due to the alloy combination, Nichrome possesses a resistance of 0.635Ω and has a maximum operating temperature of 1180°C, making the wire an ideal material for heating applications. Heat is generated by flowing electric current through the wire, which the high resistance causes a buildup of heat.

Polyimide Heater

Polyimide Heaters are a type of heater using a film "comprising of a 25μm thick 100Ω resistor layer and 25μm thick dielectric layer" to produce heat (Rapolu et al., 2018).When electric current flows through the film the resistance of the heater will produce heat up to 240°C for aerospace, medical, and electronic applications.

Space Heater

The space heater is a self-contained heater incorporating a small fan and heating mechanism similar to a hair dryer. The system would provide a constant flow of warm air at a constant temperature while avoiding the possibility of a fire hazard. The fan and the heater are powered by two separate power supplies. The fan was powered by a 12-volt power supply, while the heating mechanism is powered by a 12-volt 150 Watt power supply. The space heater was purchased from the Fdit company on Amazon.

Electronic Thermostat Controller

The electronic thermostat controller from Drok is used to control the amount of current through the heating system. The controller works by setting the desired heating temperature along with a tolerance using the buttons on the interface. Then the accompanying thermocouple will measure the temperature. If the measured temperature is below the set temperature, the thermo-controller will continue to power the heating element. Once the thermocouple reads a temperature that exceeds the set temperature, power to the heating element will cease. The controller will cycle the power through the heating element, ensuring the temperature remains relatively constant.

Super Glue

The super glue used was a thicker variant with a viscosity was 1500 CPS. The thicker viscosity helps to bridge gaps that are commonly found in FDM parts due to layer lines. The glue was used during the assembly process of the heater housing.

¼” Neodymium Magnets

The Neodymium Magnets were used in the attachment mechanism of the heater to the extruder housing. The magnets would allow for easy installation and removal of the heating system to the extruder.

J-B Weld High Heat High Strength Automotive Epoxy Putty

A two-part putty that is hand mixed and then applied to surfaces. When mixed the putty is resistant to continuous exposure of 232°C (*HighHeat Stick Safety Data Sheet*, 2019). The putty was used to seal any gaps during assembly and was used to cover areas inside the housing that would be exposed to the constant warm air.

18-gauge wire

The 18-gauge wire has used connectors and extensions for the power supplies, which were too short to be of practical use.

Lead Fee Solder

The solder was used to connect wires together permanently.

Soldering Flux

The flux was used to clean the soldering iron and prevent oxidation.

DC 12 Volt 150-Watt Power Supply

This power supply was used to power the heating element of the combined fan and heater assembly.

DC 12 Volt 14-Watt Power Supply

This power supply was used to power the Electric Thermostat Controller.

DC 12 Volt 6-Watt Power Supply

This power supply was used to power the fan of the combined fan and heater element.

3.5 Design Methodology

Section 3.5 details how the researcher designed the heating system. The researcher used the engineering design process to design the heating system where trial and error would be used until the proper combination of heating element and monitoring system was found. To narrow the down the design three constraints, need to be made before any designing or testing was done. The first constraint was that the overall design must designed around the Ender 3 Pro FDM printer. The second constraint is that the designed heating system cannot interfere with any prior functions of the Ender 3 Pro. What this constraint means when the heater is installed the Ender 3 Pro will function like the heater wasn't on the frame. The heater cannot prevent the movement of parts on the chassis, the blocking of switches, and inhibiting the capabilities of the motors on the printer. The last constraint is that the heat applied to the printing part will be warm air propelled by a small fan. The constant flow of warm air at a constant temperature should prevent the plastic from cooling at different rates, thus preventing delamination.

3.5.1 Ender 3 Pro

The 3D printer used for experimentation was the Ender 3 Pro from Creality, a budget FDM 3D printer used in hobby applications. This printer was selected because of the open fame chassis which allows more freedom of design for the heater housing. Therefore, the design of the heating system must be built around the Ender 3 Pro structure. To begin the design of the heater attachment, the researcher used digital hand calipers were to take the dimensions of the extruder assembly housing. The housing ended up measuring 40mm x 56.693mm x 50.8mm. After the dimensions were taken, a box was made in Autodesk Inventor, which would be used as a template to build the heating system around. In addition to the base dimensions, the location of the extruder's cooling fan dimensions had to be measured. Any obstructions of the fan will stop the circulation of cool air to prevent the extruder from overheating resulting in damage. Once the researcher measured all initial dimensions and features the next step was to design a functioning heating system.

3.5.2 Design Iteration 1: Nichrome Wire and PID Thermo-Controller

The first idea was to use nichrome wire as the heating element. The researcher hooked up nichrome wire to a PID thermal controller and a solid-state relay shown in Figure 3.1. The combination of the PID thermal controller and solid-state relay would control the flow of electricity flowing through the nichrome wire and therefore maintaining the temperature. The PID Controller essentially will supply power through the wire, and the resistance of the nichrome will produce heat. Attached to the controller is a thermocouple which will detect the heat of the nichrome. Once the thermocouple detects the set temperature ha has exceeded the set value, the PID Controller will shut off the supply of power to the wire. After the supply of electricity ceases, the nichrome will stop producing heat and start to cool. Once the thermocouple detects the temperature is below the set temperature, the PID controller will supply power to the wire, again producing heat. This process will cycle continuously to where the electricity will be flickering through the wire, maintaining a constant temperature.

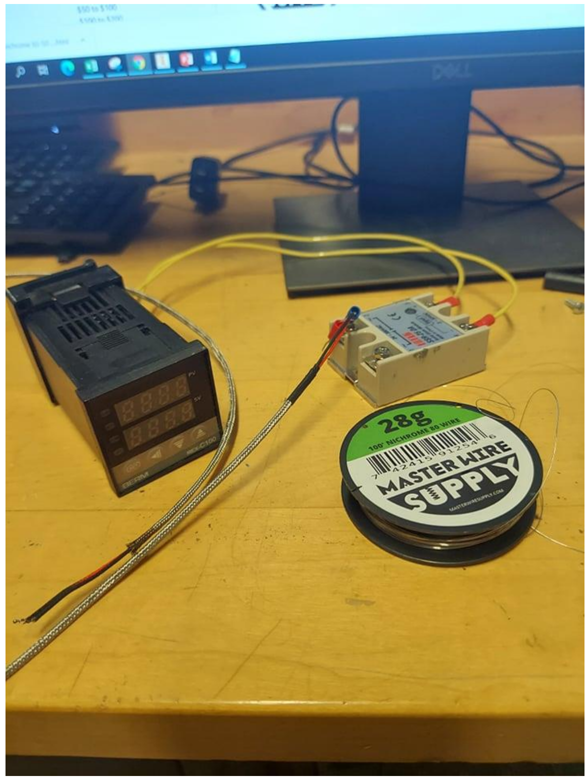

Figure 3.1 Nichrome Wire and PID Temperature Controller

During testing of nichrome wire for functionality, a major issue was encountered. Once power was supplied to the system and the designated temperature reached, the temperature continued to climb. The PID temperature controller did not stop the flow of current through the wire as expected once the thermocouple read the actual temperature surpassed the set value. The temperature would exceed double the set value without signs of the rise in temperature stopping. The cause for this constant rise is a result of the nichrome heated faster than the PID could react. The continuous rise of temperature in the nichrome proved to be a possible fire hazard, which is not desirable. Another monitoring system would need to be found. In addition, the researcher uncovered a problem with the nichrome wire which will be discussed in the next section.

3.5.3 Design Iteration 2: Polyimide Heater and DROK Thermo-controller

Since the nichrome wire and PID thermo-controller failed to prove fruitful for the heating system design the researcher had to find a new heating element and controller. A new heating control system had to be determined since it was the key component of the system, even more so than the heating element itself. This is due to the controller regulating the heat output of the heating element. If the heating element warms the print too much the print can become deformed or worse a fire can occur. While researching heat controllers, the Electronic Thermostat Controller from DROK was discovered. The DROK thermo-controller functions similarly to the PID temperature controller by using a thermocouple to read temperatures and regulating current of the connected heating element. The thermo-controller was tested with the nichrome wire to see if the controller could maintain a constant temperature. This controller reacted more quickly than the PID temperature controller. As soon as the temperature exceeded the set temperature the controller would shut off the supply of current. The DROK thermo-controller kept the tested nichrome wire at a constant temperature, meaning a useful temperature controller was found. With the monitoring system finalized, the next step was to test the functionality of the nichrome wire.

While testing the nichrome wire with the DROK thermo-controller it was discovered that the nichrome was not effective enough to be used in the heating system. The nichrome by itself did provide heat, however not in significant amounts. When testing the temperature output when the nichrome wire was under the influence of a computer fan, the temperature output was severely lacking. This test was determined by placing a thermocouple on a flat surface and then suspending the nichrome wire 40 mm from the thermocouple. Then the researcher held a computer box fan 25mm above the nichrome wire. The nichrome was set to radiate 60°C, but the read temperature of the wire and fan combination was closer to 30°C. The fan was strong enough to cool the wire to the point of being ineffective for the heating system. Now knowing that the nichrome would not produce the heat required, a new type of heating element had to be found.

After researching other types of heaters that could be used, the researcher found the polyamide heaters. The polyimide heater is the same type of heater used in heated beds of the Ender 3 Pro. The researcher purchased a pack of 45mm x 100mm polyimide heaters.The polyimide heaters came as flat strips with adhesive backings and wires that would connect to the thermo-controller. The flat adhesive proved to be a hindrance for air flow when under the influences of a fan, so carefully using a hobby knife, the adhesive back was cut away from the heating elements, leaving only the heating film. During testing, the heaters proved to be more successful in supplying heat than the nichrome wire even when the fan was on. The Polyimide heater was able to maintain the desired 60°C temperature while the nichrome was not able to.

To ensure the polyamide system can withstand constant usage for hours at time the polyimide was left to run for an hour. The purpose was to see if the temperature of the polyimide heater can be maintained for long periods of time and see if there was any chance of a possible fire hazard. At the end of the test, the researcher noticed a burning odor coming from the heater. Figure 3.2 shows polyimide heater at the end of the test. Looking at the polyimide heater, burn marks could be seen on the surface along with the cut-away adhesive to allow air flow. Seeing the brown discoloration was a sign of a possible fire hazard. And a new heating system had to be discovered again.

Figure 3.2 Burnt Polymide Heater

3.5.4 Design Iteration 3: Self Contained Heater and DROK Thermo-controller

Instead of using a custom-made heating element with a fan, a fully assembled heating system would be used shown in Figure 3.3 On the left in Figure 3.3 is the DROK Thermo-controller and on the right is the Small Space Heater. The researcher found the small space heater on Amazon, which incorporated a design similar to hair dryers found a household’s bathroom, utilizing a high electrical resistant alloy which produces the heat and a compact box fan that propels the heat generated as warm air. The dimensions of the heater measured to be 60 mm x 60 mm x 40 mm. Knowing this dimension is key when designing the housing.

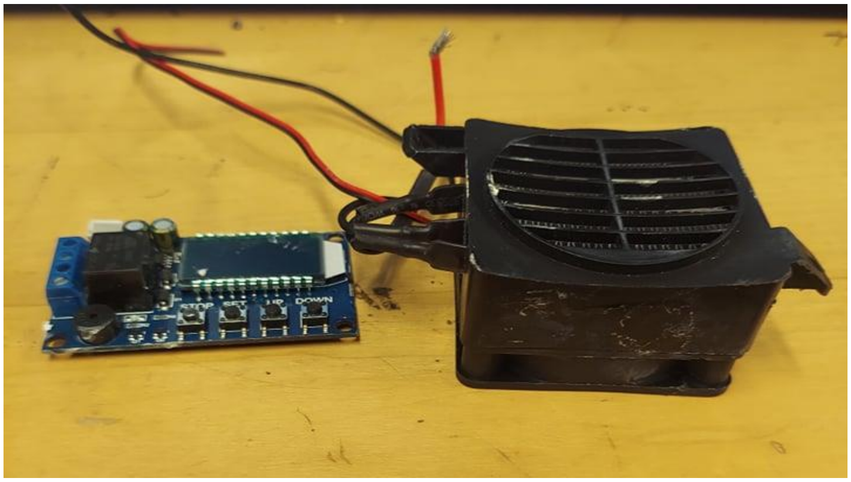

Figure 3.3 Drok Thermo-controller and Small Space Heater

Just like polyimide heater the small space heater was tested for an hour to see if the heater can withstand continual usage. The goal was to see if the heating system was able to endure and maintain temperature during long periods of time without possible signs of failing or causing a fire. At the end of the hour trial the heater successfully passed. The next step was to design the housing that would contain the heater and attach itself to the Ender 3 Pro.

3.5.5 Housing

With the heating element finalized the design for the housing can be made. The housing design must be able to accommodate both for the heater and extruder. Templates were created in Inventor in the exact dimensions of the heater and extruder. These templates were used to ensure that the final design can accommodate for the heater and can fit on the extruder. Using Autodesk Inventor, the housing would designed as separate parts which can be assembled together. Fig. 3.4 shows the images of the various parts of the assembly.

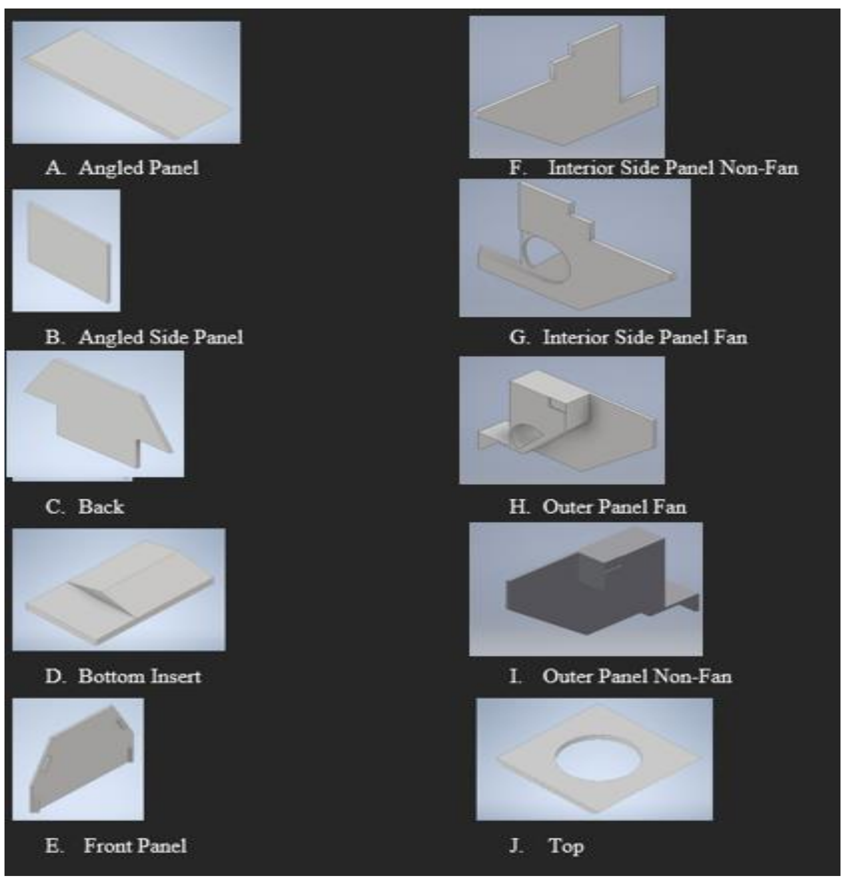

Figure 3.4 CAD Images

After all the parts were made in Inventor, a wooden mockup, Figure 3.5, was made using balsa wood and pins. The wood mock was made with pins and balsa wood to the dimensions of the CAD drawings. The researcher made a mockup to determine if the size of the housing were correct, and that the heating system could fit inside. Once the mockup was done, a dry fit was done onto the printer. The mock up was to ensure that there were proper clearances for microswitches, wires, and the bed of the printer. Once a successful dry fit was complete, the next step was to produce the housing. Due to equipment and material constraints, the housing would be 3D printed. A proper filament needed to be found.

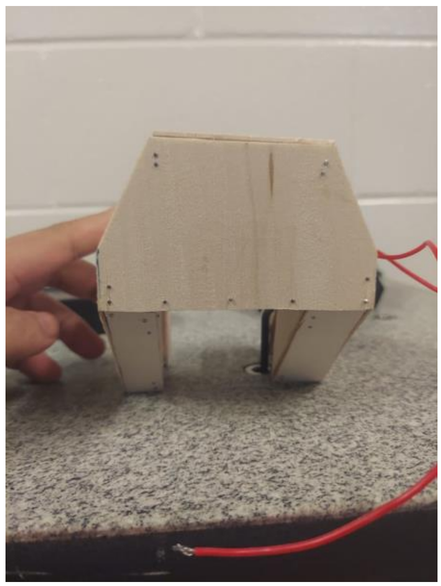

Figure 3.5 Wooden Mockup

Out of the readily available materials on hand, Polyethylene terephthalate glycol or PETG was a good choice. Using PLA would not be ideal due to the heater expelling heat close to the glass transition temperature, which would cause structural integrity issues. PETG’s glass transition temperature is close to 80°C compared to PLA’s 60°C, making PETG the optimal material for the housing. Over the course of four days, the Ender 3 Pro would print out each part using the PETG filament. After printing all the components, the parts was assembled and glued using super thick glue. As a precaution to prevent layer splitting during the testing process, a heat-resistant polymer putty was applied to key areas. The putty would then be set to cure for 24 hours and would be sanded using medium-grit sandpaper.

After letting the putty cure and sanding, the polyimide heater, thermo-controller, and fan would be installed into the housing. Once all the parts were installed, the space heater was wired to the thermo-controller and power supply. The fan would be connected to its own separate power supply. The final design can be seen in Figure 3.6 which shows various views of the heater integrated into the Ender 3 Pro. The heater was attached to the metal housing of the extruder using neodymium magnets which were glued to the housing of the heater. The magnets provided enough magnetism to ensure the heater would not fall off the extruder during travel. The wiring is connected to independent power supplies, which would supply power to the temperature controller, fan, and heater. The thermocouple that would measure temperature would be placed at the bottom of the heater closest to the exit point of the warm air while not interfering with the printing process.

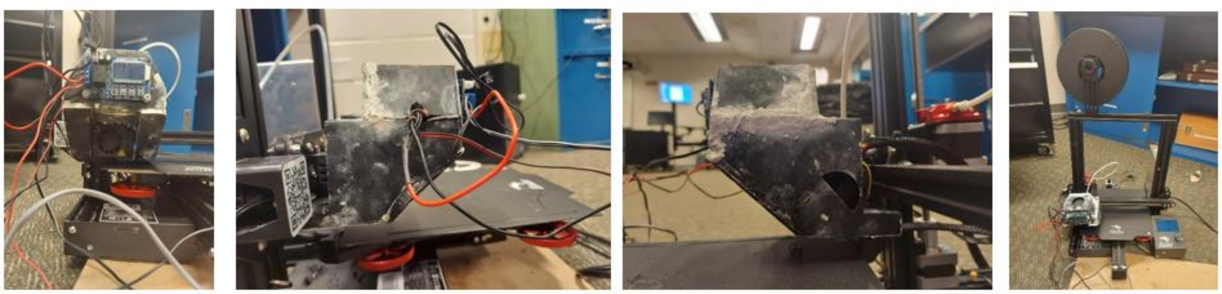

Figure 3.5 A Figure 3.5 B Figure 3.5 C Figure 3.5 D

Figure 3.6 Heater Integrated into Ender 3 Pro

Once the new heating system was integrated into the housing, a one-hour test run was performed to test for signs of fire hazard and functionality where the heater would be left on and monitored for any signs of failure or fire hazard from the design. After the one-hour trial run without any issues found the system was ready for experimentation.

3.6 Developing the Testing Procedure

The following sections covers how the system would be tested if the heating system can mitigate or prevent delamination and warping. The development of the testing procedure was broken into three steps. The first step of testing would be establishing a testing sample that can be used to test the functionality of the heating system. The second step would be determining the settings that the heater and printer would use during the testing process. The last step was developing the methods to measure delamination and warping. Once the sample was designed, settings established, and method of data collecting testing could begin.

3.6.1 Test Part Design and Printing

Section 3.6.1 describes how the heating element and housing would be tested. Due to being unable to test the heating system on a BAAM FDM Printer, a smaller scale test sample had to be made. In order to simulate a BAAM part the test sample must prevent the heating system from being able to cover all areas of the print at once. Essentially the design of the printing part causes the heater to neglect areas during printing process. To achieve this effect blocks forming a U-shaped object was created. Figure 3.7 shows the test print in Cura. The full-sized part was scaled to reach the outer edges of the printing bed to maximize the amount of time it takes the heater to move from one side of the test print to the other. The total size of the print measured to be 189.4194 mm X 189.4193 mm x 26.1658 mm.

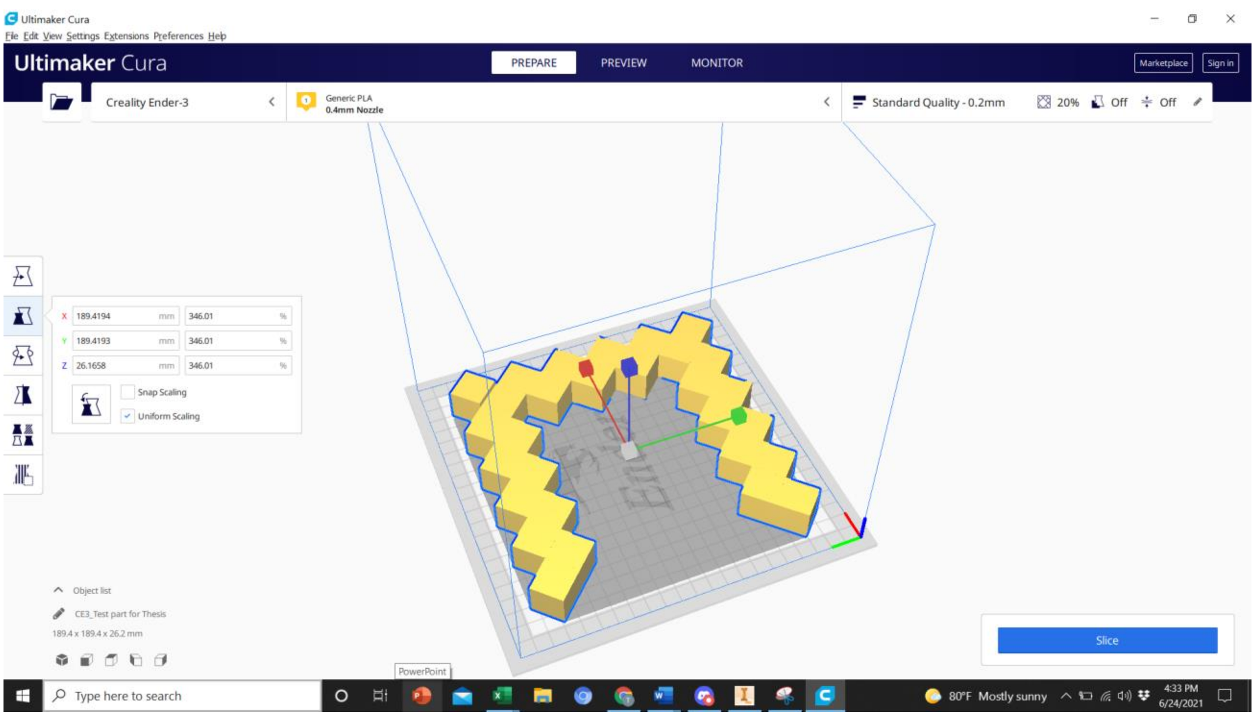

Figure 3.7 Test Sample in Cura

Since the goal of the project was to design a system that prevented delamination, the proper setting required to cause delamination had to be found. The Ender 3 Pro's setting would be adjusted until a proper setting for experimentation could be found. The manufacturer suggests the minimum the extruder temperature setting should be set at 180°C and 60°C for the bed temperature. However, since BAAM 3D printers have no heated bed, the bed temperature had to be set to 0°C in the software. In Cura setting the bed temperature to 0°C would turn off the heated bed. Therefore, the only thermal setting being changed was the extruder's temperature. Now that the lowest setting was determined, the maximum temperature needs to be found. The highest recommended extruder setting for PLA is 200°C. Therefore, during testing the temperature of the extruder would between 180°C and 200°C.

Other settings can influence the occurrence delamination besides temperature, mainly layer height—the taller the layer higher the chance for print to fail due to delamination. Layer heights are typically done at least 80% of the nozzle diameter (Dwamena, 2021). Since the nozzle used in experimentation is 0.40mm, the maximum layer height is 0.32 mm. Prior experience using the Ender 3 Pro has shown that prints at 0.28mm can still produce parts without signs of delamination. Therefore, layer heights will need to be above 0.28 mm. A final setting that would need to be considered is the infill setting. The infill setting would be set at the lowest setting possible. The reason for using a lower infill is because delamination is more likely to less point of contact for the plastic to adhere to while providing enough structural stability for the print. From past experiences, 2% infill would provide stability during the printing process while having the possibility for delamination due to there fewer points of contact for the plastic layers to adhere to. The next steps were to find a combination of extruder temperature and layer height while having an infill setting of 2%. The constraints for determining the proper setting for delamination will be a minimum extruder temperature of 180°C and maximum of 195°C. The layer setting would be between 0.3 mm and 0.32mm while having the infill setting at 2%. The table of the settings can be seen below in Table 3.1. The combination would be printed in descending order until a part can be made where delamination would occur and without the print failing completely. A completely failed print is defined as a part that would not be able to finish the printing process at any point. At the end of the testing procedure, the proper setting for experimentation would be combination four, who's settings include 195°C, 0.30mm, and 2% infill.

Table 3.1 Experimentation Test Settings

Combination	Extruder Temperature	Layer Height	Infill %	Bed Temperature
1	195°C	0.32	2	30°C
2	195°C	0.3	2	30°C
3	190°C	0.32	2	30°C
4	190°C	0.3	2	30°C
5	185°C	0.32	2	30°C
6	185°C	0.3	2	30°C
7	180°C	0.32	2	30°C
8	180°C	0.3	2	30°C

3.6.2 Heater and Printer Settings

Since the printer setting combination was discovered, a test range for the designed heater had to be determined. The heating system would be set at four different temperatures. The first temperature would be with the heating system off. Essentially the prints would be made at the temperature of the room which was 20°C. Then three different temperature settings were used to test if the heating system has any valuable effect on the prints. The three temperature setting out of the heater would be 60°C, 65°C, and 70°C. The reason for choosing the temperature range 60°C, 65°C, and 70°C is because this is the manufacturer's recommended heated bed settings. In total 12 samples would be printed over the course of experimentation.

Table 3.2 represents the full settings set in Cura for samples where the heater would be on. The values were determined from the previous section. Using the Cura software, the key settings were adjusted to the core printer setting. Such setting changes were the setting the extruder temperature to 195°C, layer height to 0.3 mm, and the infill to 2.0%. The test parts would be made three times at each temperature setting. To view screen shots of how the setting were done in Cura reference Appendix C for Figures C.61 through Figure C.65.

Table 3.2 Heat Treated Settings

Heat Treated Settings	
Parameter	Value
Layer Height	0.30 mm
Initial Layer Height	0.20 mm
Line Width	0.4 mm
Wall Line Width	0.4 mm
Infill	2.00%
Infill Layer Thickness	0.30 mm
Infill Line Distance	4.0 mm
Print Head Temperature	190°C
Print Bed Temperature	Off
Print Speed	60 mm/s

The full settings for Non-Heat-Treated Parts or test where the prints would be done at 20°C can be seen in table 3.3. The key difference the heat treated, and non-heat-treated settings was that the heated bed would be turned on. The Bed was turned to 30°C to allow the print to stick to the printing bed. Without any heat, during the 20°C test, the bed would become easily knocked off the bed. The 30°C allows for layer adhesion to the bed while not applying enough heat to impact the test.

Table 3.3 Non-Heat-Treated Settings

Non-Heat-Treated Settings	
Parameter	Value
Layer Height	.30 mm
Initial Layer Height	.20 mm
Line Width	0.4 mm
Wall Line Width	0.4 mm
Infill	2.00%
Infill Layer Thickness	.16 mm
Infill Line Distance	4.0 mm
Print Head Temperature	190°C
Print Bed Temperature	30°C
Print Speed	60 m/s

3.6.3 Methods for Inspection

Two label keys were made to record the deformities. Figure 3.8 shows the locations for delamination measurement starting at the side indicated and moving in a clockwise direction, each side was assigned a number from 1 up to 58. Each point labeled are areas that can be measured for delamination and will correspond to a location in the data collection Excel sheet.

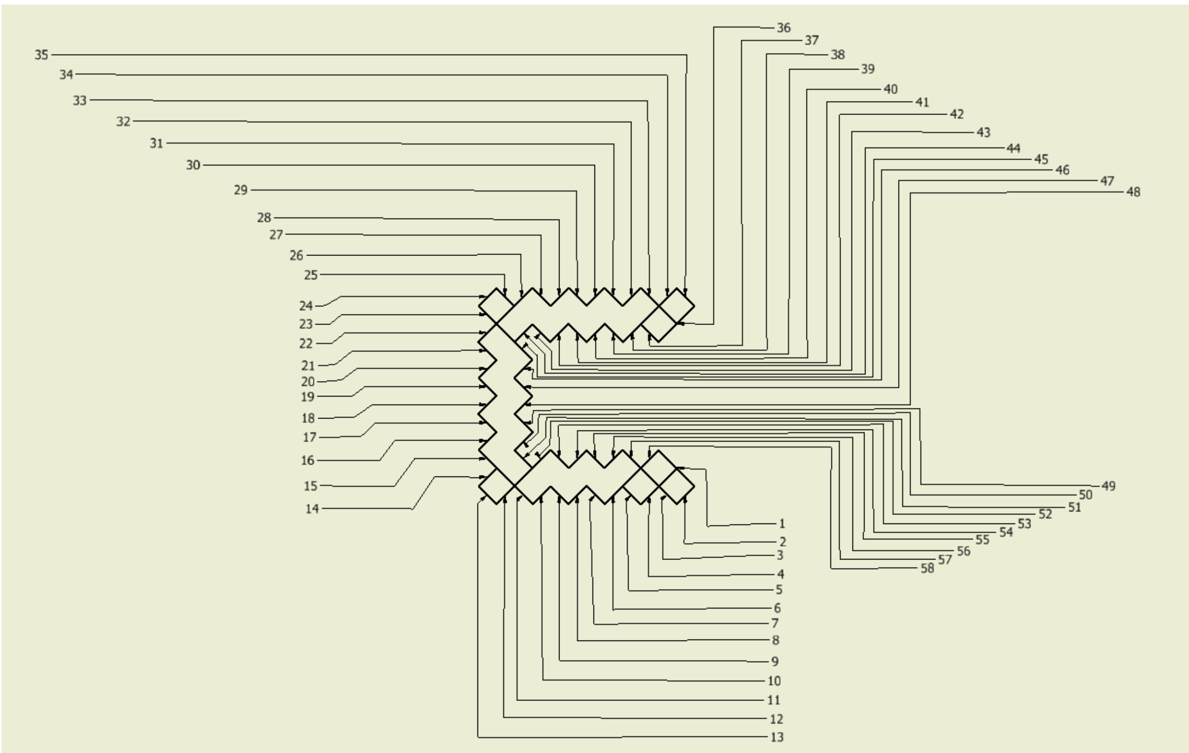

Figure 3.8 Delamination Location Points

When looking for delamination, a .25mm diameter pin was to probe areas of interest. If an area was suspected of delamination, the pin would be gently inserted into a possible split within the layers. If the pin slid into the slit easily without the requirement of additional applied force, then delamination occurred and would be measured with the dial caliper. Careful attention would be used when measuring. The reason for caution was to prevent the delamination from getting worse when using the calipers.

Similarly, warping points were assigned a location maker for measurements. However, rather than the sides being the markers, the outer corners were locations of interest. Starting at point 1 in Figure 3.9 and moving in a clockwise fashion, each point was assigned a number up to

31. The reason for choosing corners compared to reusing the locations used for delamination is due to warping occurring more severely at corners or sharp edges at the base of FDM prints.

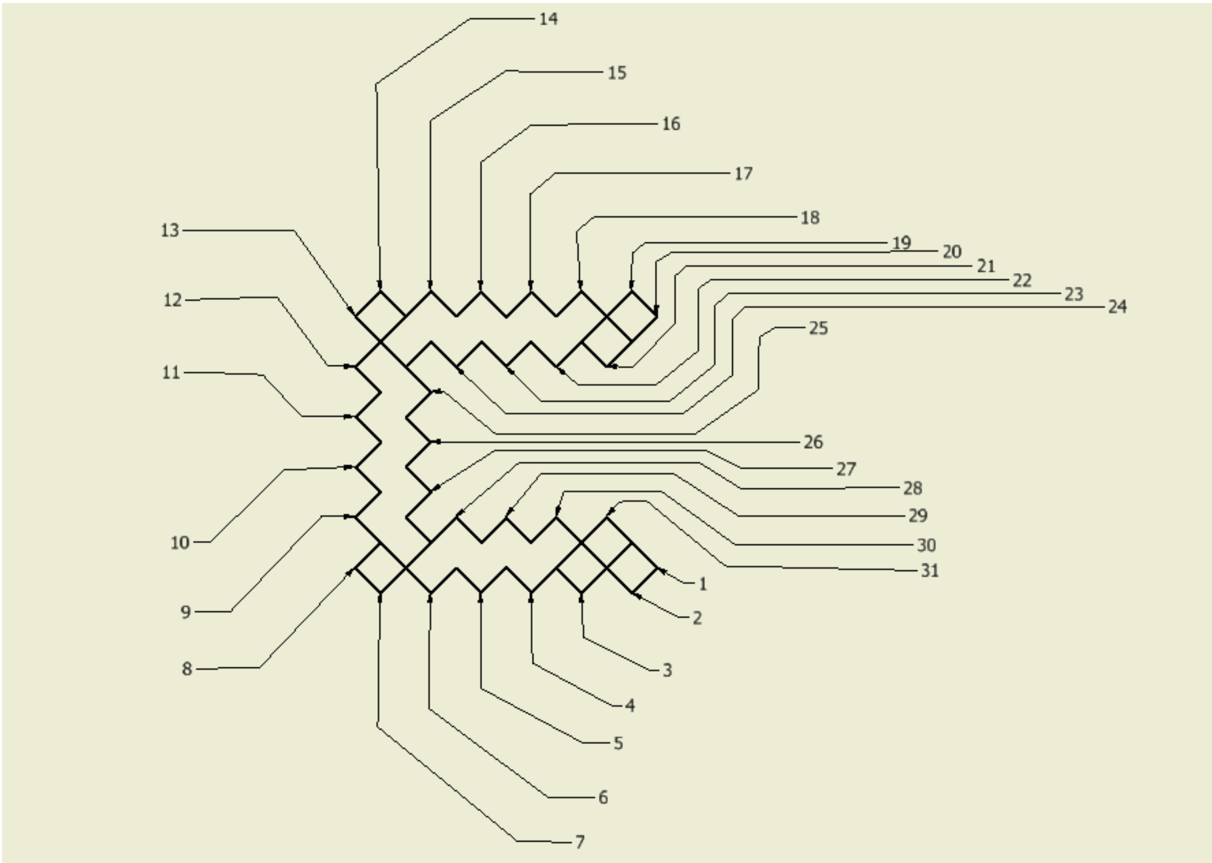

Figure 3.9 Warping Location Points

When determining if any warping occurred, the part would be placed on a flat granite surface, and the edges would analyze for any raised formations. If area were raised off the flat surface, the area would be measured with the dial caliper.

Each assigned side or point from Figure 3.8 and 3.9 would be measured three times, and then an average was taken to ensure that a proper measurement was recorded. The measuring tool used was a dial caliper measuring in millimeters. Once all areas of interest of each part are measured and recoded into Excel data tables, the data would go under standard statistical analysis such as mean, median, mode, and standard deviation.

Each test print setting would be measured three times to provide enough sample data to come to a full conclusion of the effectiveness of the novel heating system. If a print were to fail, the sample would be included in the data pool, and any possible measurements would be taken.

The labeling convention for each sample would be the temperature of the heating element followed by the test number. For example, the third test done at 60°C would be "60°C 3".

After all data collection for each test set was done, the researcher preformed a general analysis of the sample population. The statistical data in conjunction with an ANOVA test was used to see if the novel heating system would prevent or mitigate the deformities of FDM print, such as delamination and warping.

CHAPTER 4. RESULTS

4.1 Introduction

This chapter covers the analysis of the data gathered during testing. Using Microsoft Excel 365, the data was easily analyzed to see the impact of the heater on delamination and warping. The analysis process was broken up into two sections. The first analysis would be on delamination and secondly warping for each test print made during experimentation. Once analysis for delamination and warping concluded the viability of the designed external heating system could be determined.

4.2 Delamination Analysis

Section 4.2 covers data analysis for delamination results. After all points of delamination were recorded into Excel, the data would undergo statistical and partial ANOVA analysis to see if the novel heating system were capable to prevent or mitigate delamination. In addition, the average delamination of each point, of prints made at a similar setting, would be compared into a line graph to see any correlation between location and delamination.

4.2.1 Delamination General Analysis

Table 4.1 of delamination has the readings for 20°C 1, as 0.000 mm on the measured data. This was due to two factors that occurred during the print. During the process, severe deformation in the form of delamination or warping occurred. Since the heated bed was set at a low temperature of 30°C, the bottom layer adhesion to the bed was not ideal; in addition, the layers cooling at different rates caused the print to get knocked off the printer bed.

Table 4.1 Delamination 20°C 1

Point	Delamination, mm	Delamination, mm	Delamination, mm	Average, mm	Standard Deviation, mm
1	0.000	0.000	0.000	0.000	0.000
2	0.000	0.000	0.000	0.000	0.000
3	0.000	0.000	0.000	0.000	0.000
4	0.000	0.000	0.000	0.000	0.000
5	0.000	0.000	0.000	0.000	0.000
6	0.000	0.000	0.000	0.000	0.000
7	0.000	0.000	0.000	0.000	0.000
8	0.000	0.000	0.000	0.000	0.000
9	0.000	0.000	0.000	0.000	0.000
10	0.000	0.000	0.000	0.000	0.000
11	0.000	0.000	0.000	0.000	0.000
12	0.000	0.000	0.000	0.000	0.000
13	0.000	0.000	0.000	0.000	0.000
14	0.000	0.000	0.000	0.000	0.000
15	0.000	0.000	0.000	0.000	0.000
16	0.000	0.000	0.000	0.000	0.000
17	0.000	0.000	0.000	0.000	0.000
18	0.000	0.000	0.000	0.000	0.000
19	0.000	0.000	0.000	0.000	0.000
20	0.000	0.000	0.000	0.000	0.000
21	0.000	0.000	0.000	0.000	0.000
22	0.000	0.000	0.000	0.000	0.000
23	0.000	0.000	0.000	0.000	0.000
24	0.000	0.000	0.000	0.000	0.000
25	0.000	0.000	0.000	0.000	0.000
26	0.000	0.000	0.000	0.000	0.000
27	0.000	0.000	0.000	0.000	0.000
28	0.000	0.000	0.000	0.000	0.000
29	0.000	0.000	0.000	0.000	0.000
30	0.000	0.000	0.000	0.000	0.000
31	0.000	0.000	0.000	0.000	0.000
32	0.000	0.000	0.000	0.000	0.000
33	0.000	0.000	0.000	0.000	0.000
34	0.000	0.000	0.000	0.000	0.000
35	0.000	0.000	0.000	0.000	0.000
36	0.000	0.000	0.000	0.000	0.000
37	0.000	0.000	0.000	0.000	0.000
38	0.000	0.000	0.000	0.000	0.000
39	0.000	0.000	0.000	0.000	0.000
40	0.000	0.000	0.000	0.000	0.000
41	0.000	0.000	0.000	0.000	0.000
42	0.000	0.000	0.000	0.000	0.000
43	0.000	0.000	0.000	0.000	0.000
44	0.000	0.000	0.000	0.000	0.000
45	0.000	0.000	0.000	0.000	0.000
46	0.000	0.000	0.000	0.000	0.000
47	0.000	0.000	0.000	0.000	0.000
48	0.000	0.000	0.000	0.000	0.000
49	0.000	0.000	0.000	0.000	0.000
50	0.000	0.000	0.000	0.000	0.000
51	0.000	0.000	0.000	0.000	0.000
52	0.000	0.000	0.000	0.000	0.000
53	0.000	0.000	0.000	0.000	0.000
54	0.000	0.000	0.000	0.000	0.000
55	0.000	0.000	0.000	0.000	0.000
56	0.000	0.000	0.000	0.000	0.000
57	0.000	0.000	0.000	0.000	0.000
58	0.000	0.000	0.000	0.000	0.000

Figure 4.1 shows the picture of the 20°C Test print. Where around the sixteenth layer, the delamination occurred. Severe warping occurred around the edges producing a U-shaped part due to nothing preventing the layers from cooling at different rates. The raised plastic, due to delamination or warping, got caught or ran into the extruder, and then the part proceeded to get knocked off the bed, causing the print to become incomplete. When probing the completed layers seen in Figure 4.1, no signs of delamination were found. Since no concrete measurement of delamination was able to be obtained, data in Table 4.1 appeared as 0.0 mm.

Figure 4.1 20°C 1 Print

The prints 20°C 2 and 20°C 3 proved more successful in providing concrete delamination data. Figure 4.2 shows examples of delamination from tests 20°C 2 and 20°C 3. The example shown in the 20°C 2 test shows delamination occurring at the top of the print. While in 20°C 3 shows delamination occurring towards the bottom.

Figure 4.2 A 20°C 2 Delamination

Figure 4.2 B 20°C 3 Delamination

Figure 4.2 Delamination Examples from 20°C 2 and 20°C 3

All test parts of 60°C, 65°C, and 70°C batches did not show signs of delamination at any point of the test parts. For this reason, tables for the three heat-treated samples have zeros in their respective data tables. To see results of the heat treat parts refer to Appendix A for Table A.4 through Table A.12. Because there were no signs of delamination in the layers of the heat-treated parts, the heating system conceptionally is viable to prevent delamination in FDM 3D printed parts.

Table 4.2 reveals the statistical data from 20°C 1, 20°C 2, and 20°C 3. Table 4.2 shows the average, standard deviation, median, mode, and the highest and lowest measurements of delamination. The majority of the areas of the prints would have a 0.0 mm reading; therefore, when using Excel, only non-zero values were used during the statistical analysis of delamination.

While the average delamination is very small at .095 mm, there were incidents of larger delamination values present, such as the 1.223 mm reading.

Table 4.2 Delamination 20°C Analysis

Statistic	Value, mm
Average	0.095
Standard Deviation	0.252
median	0.700
mode	0.663
Highest	1.223
Lowest	0.177

Figure 4.2 is for the tests where the heater was "0°C". "0°C 1" was omitted from this analysis since the delamination halfway through the print caused the part to get knocked off due to improper bed to layer adhesion, and no delamination on the lower layers was found. The error bar represents the standard deviation ranges. Figure 4.2 shows "0°C 2" and "0°C 3" did exhibit delamination but appear to be sporadic in value and location. Only points three and fourteen appeared to suffer delamination in the same spot but are not conclusive enough to determine direct causation between no heat and delamination in these areas.

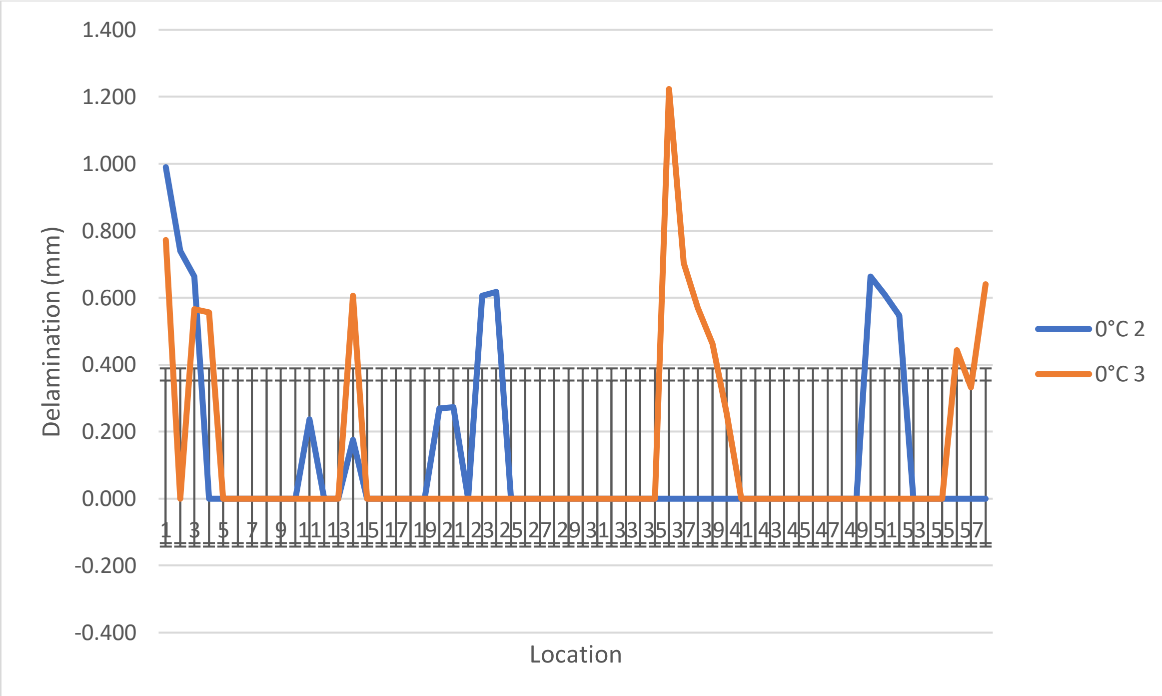

Figure 4.3 Delamination Measurement 20°C 2 vs. 20°C 3

A similar analysis to find delamination was performed on the 60°C, 65°C, and 70°C tests. However, no delamination was found in these samples thus no graph was created due the data showing up as all 0.0 mm.

4.2.2 Setting's Impact on Delamination

To visually see the data a partial ANOVA test was done in Excel to generate tables and graphs to see the impact of the heating system on the 3D prints. Taking the average delamination measurement for mm in each test and Table 4.3 was made. The Test number is the batch of samples that had the same setting. Test 1 had the heater on at 60°C, layer height of 0.30mm, and the bed off. Since there was no delamination experienced in Tests 1 through 3 the raw data reads as 0.0 mm. When the heater was off for Test 4 delamination was experienced and therefore has usable values. The first Test 4 reads as 1.0 mm since halfway through the print delamination occurred and the part got knocked off the bed preventing a complete print. To represent the worst delamination value the raw data will be represented as the 1.0 mm entry. After a grand mean was determined deviation from the mean was calculated and then squared to generate a deviation squared value to calculate variance.

Table 4.3 Delamination Average Data

Test	Heater Temp	Layer Height, mm	Bed	Raw Data, mm	Deviation from the Mean, mm	Deviation Squared, mm
1	60°C	.30	off	0.000	-0.100	0.010
1	60°C	.30	off	0.000	-0.100	0.010
1	60°C	.30	off	0.000	-0.100	0.010
2	65°C	.30	off	0.000	-0.100	0.010
2	65°C	.30	off	0.000	-0.100	0.010
2	65°C	.30	off	0.000	-0.100	0.010
3	70°C	.30	off	0.000	-0.100	0.010
3	70°C	.30	off	0.000	-0.100	0.010
3	70°C	.30	off	0.000	-0.100	0.010
4	20°C	.30	on	1.000	0.900	0.809
4	20°C	.30	on	0.124	0.024	0.001
4	20°C	.30	on	0.081	-0.020	0.000
			Grand Mean:	0.100	0.000	0.901

From here a Means at High and Lows table was made and can be seen in Table 4.4. The values in Table 4.4 are calculated by taking the average of the respective Test setting from Table 4.2. Since Tests with 60°C, 65°C, and 70°C values were all 0 mm the average would be 0 mm. While 20°C experienced delamination which resulted in an average of 0.402 mm. The Bed settings values were calculated similarly by taking averages of the respective settings.

Table 4.4 Delamination Means at High and Low Levels

Means at high and low levels

Heater Temp, °C				Bed	
60°C	65°C	70°C	20°C	Off	On
0.000	0.000	0.000	0.402	0.000	0.402

Figure 4.3 was made using data from Table 4.4 and shows the impact a setting has on delamination. Steeper the rate of change for the line, means that a more pronounced effect happened during a particular setting. In the 60°C, 65°C, and 70°C setting the line is flat and at 0

mm. This means that delamination was nonexistent, while a jump in rate of change can be seen between 70°C and 0°C. The jump from 0 mm to around 0.4 mm shows that turning off the heating system had a significant impact on the print. The bed being "off" showed the same result showing that added heat is needed to prevent delamination in 3D printed parts.

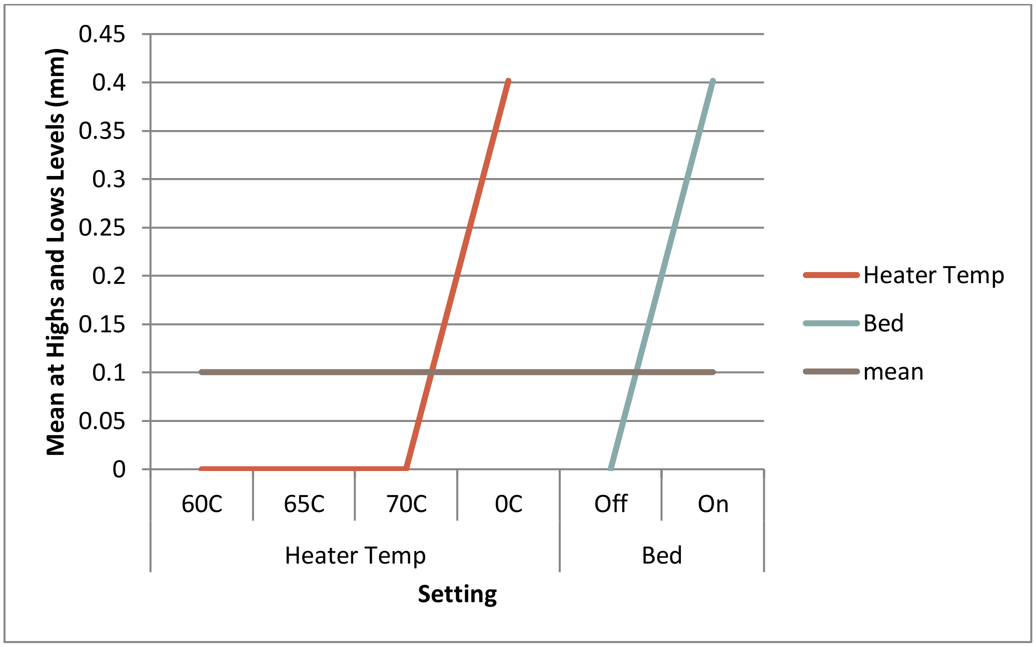

Figure 4.4 Setting's Impact on Delamination

<u>4.2.3 Setting's Interaction on Delamination</u>

A heater vs. bed analysis was done. From here Table 4.5 that would be used to create a graph which would show how combinations of setting of the heater and bed impacted delamination. Table 4.5 was made by taking the averages of respective setting combinations of the heater being on and the heated bed being Off and vice versa from Table 4.3. The Ideal is meant to represent the ideal measurement of where 0mm of delamination.

Table 4.5 Setting Combination Interaction on Delamination

	B (Off)	B(On)
H(on)	0	
H(Off)		0.401688
Ideal	0	0

Figure 4.5 was made by taking the respective setting combinations from Table 4.5. For the heater being on and the bed being off and average of Tests 1 through 3 were taken. While for the bed being on and the heater being off an average was taken from Test 4.The y axis on Figure 4.5 represents the average delamination in mm, and the goal is to have 0 mm of delamination, which is represented by the red line labeled ideal. In Figure 4.5, H represents the status of the heater and B represents the status of the heated bed. H(On) means the heater was on and B(Off) means the heated bed was off. When the heater was on, and the bed was off the delamination was 0 mm. During tests where the heater was off, and the bed was on delamination occurred. Figure 4.5 visually shows that having the heater on prevents delamination.

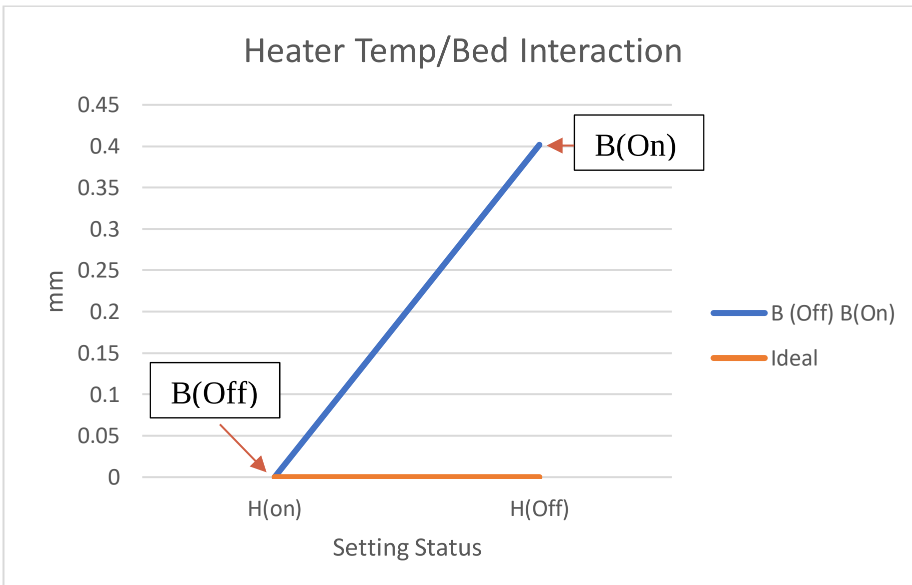

Figure 4.5 Delamination Heat Temp/ Bed Interaction

4.3 Warping Analysis

Sections 4.3 covers the data analysis for warping. Although delamination did not occur within any of the heat-treated parts, warping was a rampant issue throughout all tests. All samples suffered warping at all points of the part. However, the untreated parts exhibited significantly graver warping compared to the heat-treated parts. The same data analysis done for delamination was performed on the warping results.

4.3.1 Warping General Analysis

Table 4.6 shows the statistical results of the 60°C tests. The average data for the 60°C trials can be seen in Table 4.6 A. The average warping across all three parts was 1.107 mm with the highest recoded warping being 2.563 mm and the lowest 0.470 mm. The standard deviation for all the readings across all three parts was .446 mm. Table 4.6 B. represents the statistical analysis for 65°C during the warping analysis. The highest measured warping out all three tests was 2.780mm and the lowest being 0.423mm. Compared to the 60°C trials the 65°C had the lowest warping reading. However, the 65°C had a higher standard deviation with a value of 0.496 mm to 60°C standard deviation value of 0.446 mm which shows that 65°C had more deviations from the mean compared to the 60°C tests. The 70°C tests showed the worst warping out of all the heat-treated parts. Table 4.6 C. displays the statistical values of the 70°C tests. The average warping was 1.647 mm. 0.6 mm and 0.54 mm higher to the 65°C and 60°C tests, respectively. The highest warping recorded out of the heat treaded parts also came out of the 70°C tests with a value of 3.180 mm.

Table 4.6 Statistical Data for Heat Treated Parts

Table 4.6 A. Warping 60°C Statistics

Statistic	Value, mm
Average	1.107
Standard Deviation	0.446
median	0.953
mode	0.813
Highest	2.563
Lowest	0.470

Table 4.6 B. Warping 65°C Statistics

Statistic	Value, mm
Average	1.647
Standard Deviation	0.641
median	1.610
mode	1.040
Highest	3.180
Lowest	0.590

Table 4.6 C. Warping 70°C Statistics

Statistic	Value, mm
Average	1.047
Standard Deviation	0.496
median	0.947
mode	0.733
Highest	2.780
Lowest	0.423

Table 4.7 reveals the determinants of not having a heating element to ensure the layers cool at a similar rate. Compared to the heat-treated parts the 20°C tests had the highest average warping, highest value recorded, and highest median. Even the lowest warping measured during the 20°C test was higher compared to all the heat-treated parts. Within the non-treated samples, the worst warping value was 18.70 mm which occurred during the “0°C 1” print run. The same print run which failed to print completely. Compared to the heat-treated parts the most severe warping was 3.180 mm which occurred in 70°C 2. Raw data for the warping values can be seen

in appendix. Between most severe points of warping, the heat-treated parts experienced warping 1/6th that of non-treated parts.

Table 4.7 Warping 20°C Statistics

Overall	Value, mm
Average	3.609
Standard Deviation	3.262
median	2.413
mode	2.763
Highest	18.700
Lowest	0.710

When comparing warping distances between the heat-treated trials, the 70°C had the highest warping distances out of the three heat settings. The 70°C average warping was 1.647 mm. While for 60°C and 70°C warping were 1.107 mm and 1.047 mm, respectively. The reason for this due to the temperature of the room experimentation took place. The average temperature of the room was 20°C while the temperature of the heater was 70°C. The 50°C temperature difference compared to 45°C or 40°C could have caused the higher warping values in the 70°C tests.

To supplement seeing the significance of warping another analysis was completed to see if warping regularly occurred in specific areas of a part. Data for Figure 4.6 was taken from Tables A.26 in Appendix A to see the severity of warping for 60°C samples. The error bars represent the standard deviation of 0.446 mm.

In Figure 4.6 locations five through nine show a similar phenomenon where the warping would suddenly spike in the region. Referring to Figure 3.8 in Chapter 3 this is the back left corner of the part. Then between points 19 and 20 is the front right corner of the part. The measurement in this area seems to be around the same measurement for the three tests at 60°C.

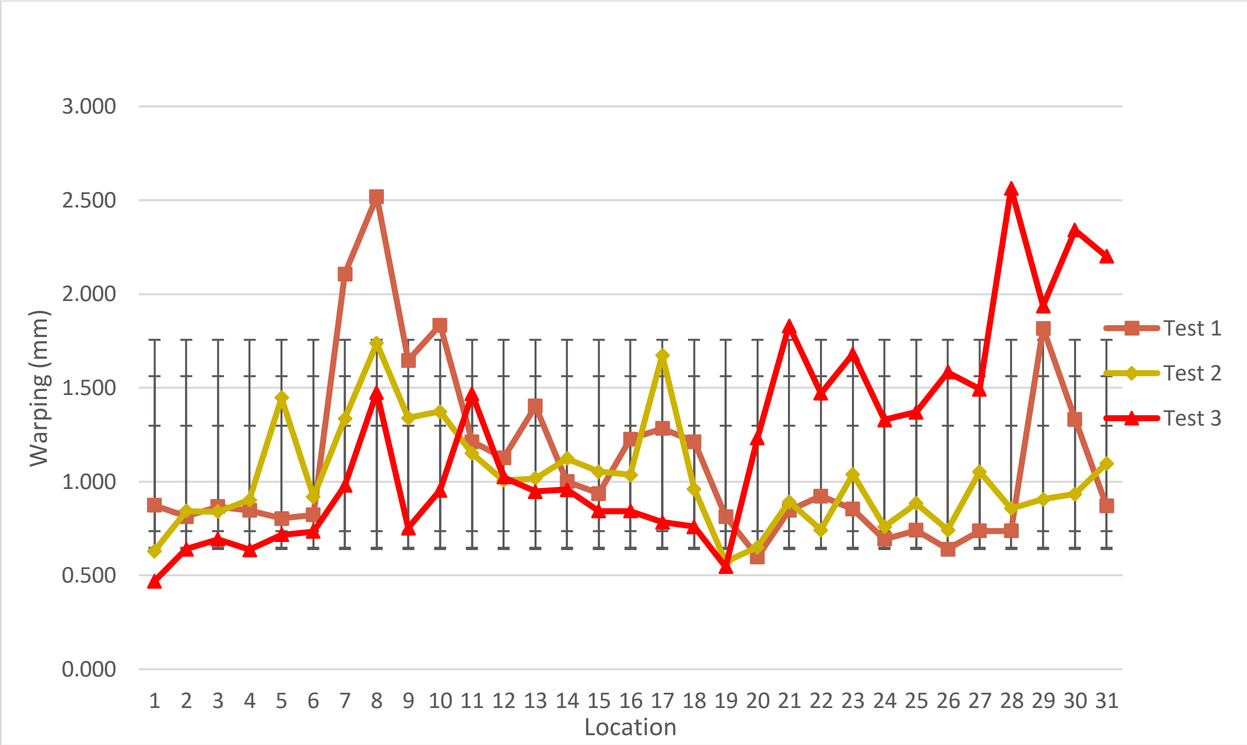

Figure 4.6 60°C Warping: Test 1 vs. Test 2 vs. Test 3

Figure 4.7, shows the analysis for 65°C. Data for Figure 4.6 was taken from Table A.27 in Appendix A. Similarly, to the 60°C graph there was a spike in around measurements at point 5. Tests 2 and 3 had warping spikes in this area similarly to the 60°C graph. There was an anomaly with test 1 in this area. Where the warping was minor compared to the latter two prints. There are a few factors that could cause these results such as environmental factors outside of the tester’s control. Tests 2 and 3 were printed on the same day while Test 1 was printed the day before. So, an environmental change is possible for the abnormality of between the tests. Another abnormality between Test 1, 2, and 3 during the 65°C prints was that a massive warping occurred at point 25 in test 1 while in Test 2 and 3 the warping was milder. The error bars represent the .496 mm standard deviation.

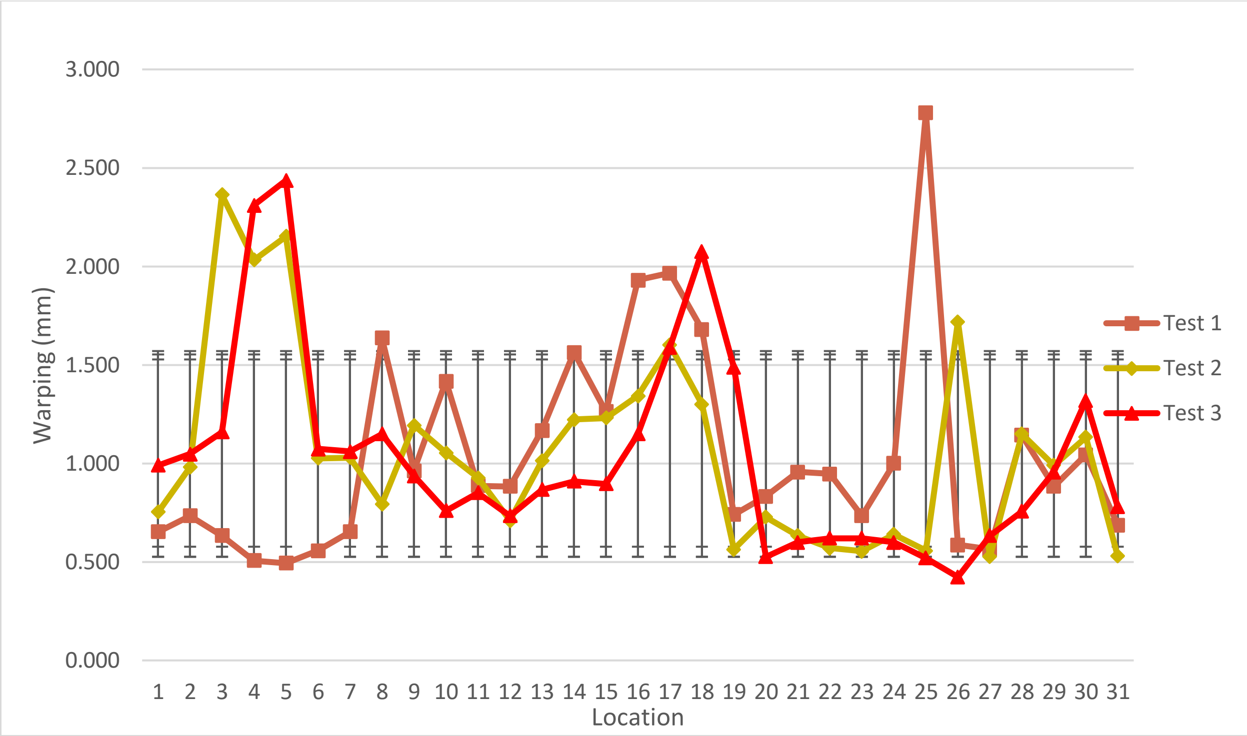

Figure 4.7 65°C Warping: Test 1 vs. Test 2 vs. Test 3

The next graph, Figure 4.8, is for last heat-treated samples of the 70°C test. Values for the graph can be seen in Table A.28 in Appendix A and the error bars represents the 0.641 standard deviation. The warping in the 70°C Test sample seems to be more in line with each other. Where all three lines followed a similar pattern. The warping seems to occur primarily in between location points 6 through 20. Referencing Figure 3.7, these points lie along the left, back, and right sides of the part. Points between 21 and 27 seem to be very mild in warping and these points lie within inner perimeter of the print. Compared to the tests of 60°C and 65°C the warping values are higher most likely due to the temperature difference between the heater the 20°C ambient temperature of the room. In conjunction of the printing bed not retaining heat expelled from the heating system.

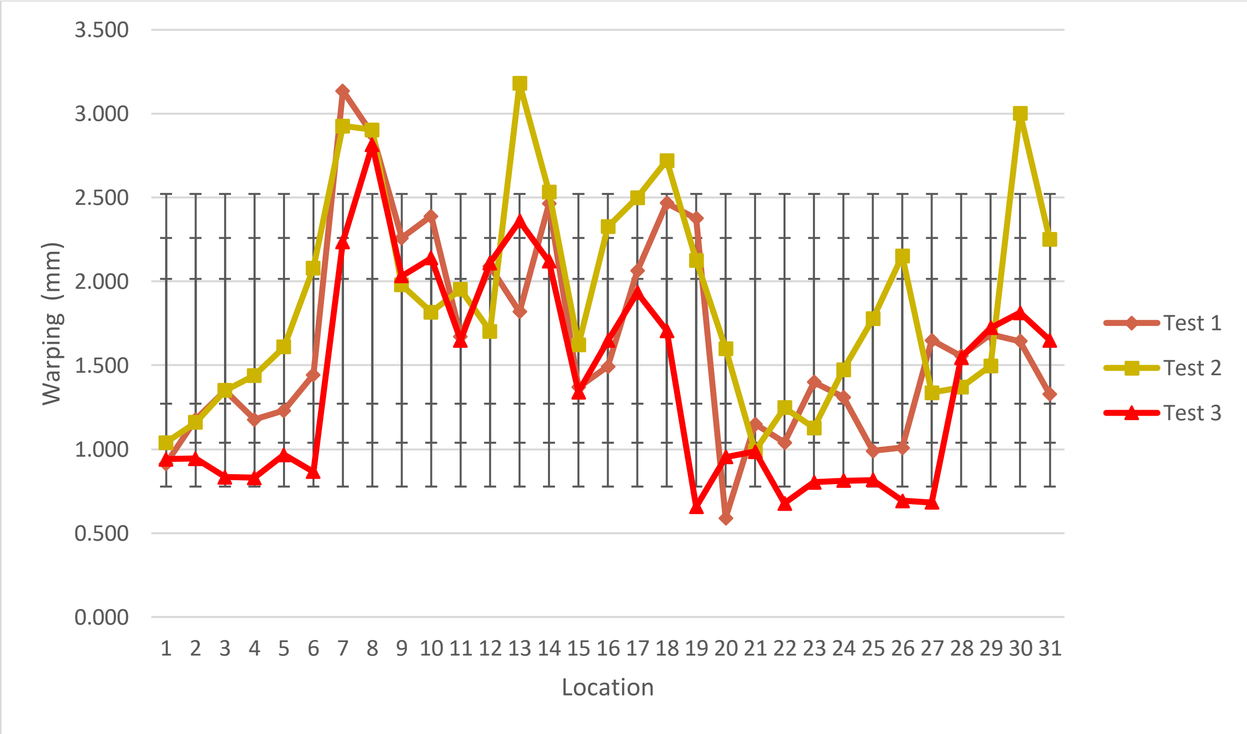

Figure 4.8 70°C Warping: Test 1 vs. Test 2 vs. Test 3

The last graph, Figure 4.9, reveals the average warping for the 20°C test samples. Values used in Figure 4.8 can be found in Table A.29 from Appendix A. This test reveals no real observable relationship between warping and location. However, areas where the most significant warping occurred were the furthest corners of the prints. Revealing that the outer most corners and edges are the most susceptible to warping.

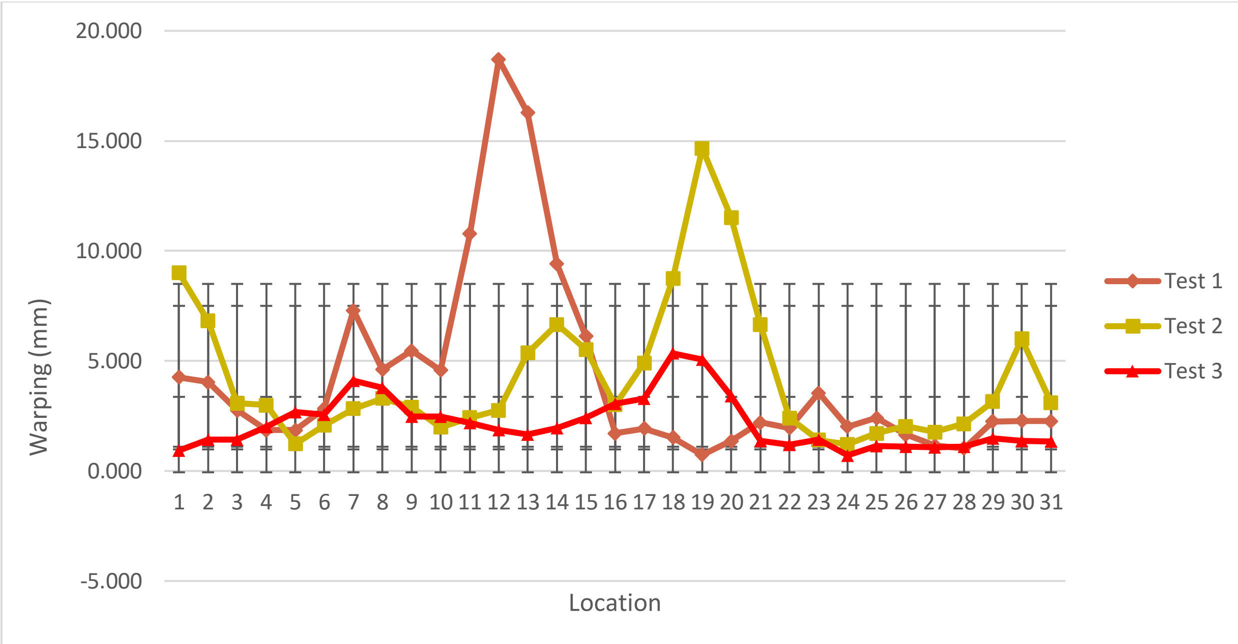

Figure 4.9 Warping 20°C: Test 1 vs. Test 2 vs. Test 3

4.3.2 Setting's Impact on Warping

A partial ANOVA test was performed in Excel by taking the average warping across all test samples to see the influence of the heating system. Table 4.8 shows the test sample number, the temperature of the heater the layer height, if the bed was on or off, and finally the average warping. Line one would represent test one where the heater temperature was 60°C, layer height .3mm, the bed was off. Lastly the raw data would represent the average warping value across the entire part which was 1.101 mm. Data from all the other test samples would be entered into Table 4.8. After completing Table 4.8 a grand mean was generated over all test samples, which resulted in a value of 1.841 mm. To supplement the grand mean value deviation from the mean, deviation squared, variance and standard deviation was also calculated from the data set.

Table 4.8 Warping Average Data

Test sample	Heater Temp, °C	Layer Height, mm	Bed	raw data, mm	deviation from the mean, mm	deviation squared, mm
1	60	30	off	1.101	-0.740	0.548
2	60	30	off	1.017	-0.825	0.680
3	60	30	off	1.202	-0.640	0.409
4	65	30	off	1.048	-0.794	0.630
5	65	30	off	1.065	-0.776	0.603
6	65	30	off	1.027	-0.814	0.663
7	70	30	off	1.649	-0.192	0.037
8	70	30	off	1.897	0.055	0.003
9	70	30	off	1.396	-0.445	0.198
10	0	30	on	4.220	2.378	5.657
11	0	30	on	4.302	2.460	6.053
12	0	30	on	2.174	0.332	0.110
		Grand Mean:		1.84143	0.00000	15.5911143

The values from Table 4.8 were used as a comparison value to see how impactful certain settings are on warping via a graph. By comparing the different setting combinations, the following Table 4.9 was generated which compared the means of the highest and lowest levels of the various settings. The values were calculated by taking the average value of each test sample with a similar setting from Table 4.9. The value for 60°C under the Heater Temp column was the average of all the 60°C tests. The 65°C, 70°C, and 20°C were calculated in the same manner. Bed Temperature values were calculated by taking the average of the test, where the Bed was On or Off.

Table 4.9 Warping Means at High and Low Levels

Means at high and low levels

Heater Temp				Bed	
60°C	65°C	70°C	0°C	Off	On
1.107	1.047	1.647	3.565	1.267	3.565

Using the results of Table 4.9 was then used to generate Figure 4.10. To interpret Figure 4.10 the slope of the graph shows how pronounced a setting affects the 3D print prints. The steeper the slope the more significant effect the setting has on the 3D printing process. The 60°C, 65°C, and 70°C have milder slope inclines while the 20°C has a very steep incline. Essentially, turning off the heater had a significant impact on the prints due the steeper slope. Turning off the heater had higher warping values which then resulted in the steeper slop. Showing that the heating system being on does aid in mitigating warping.

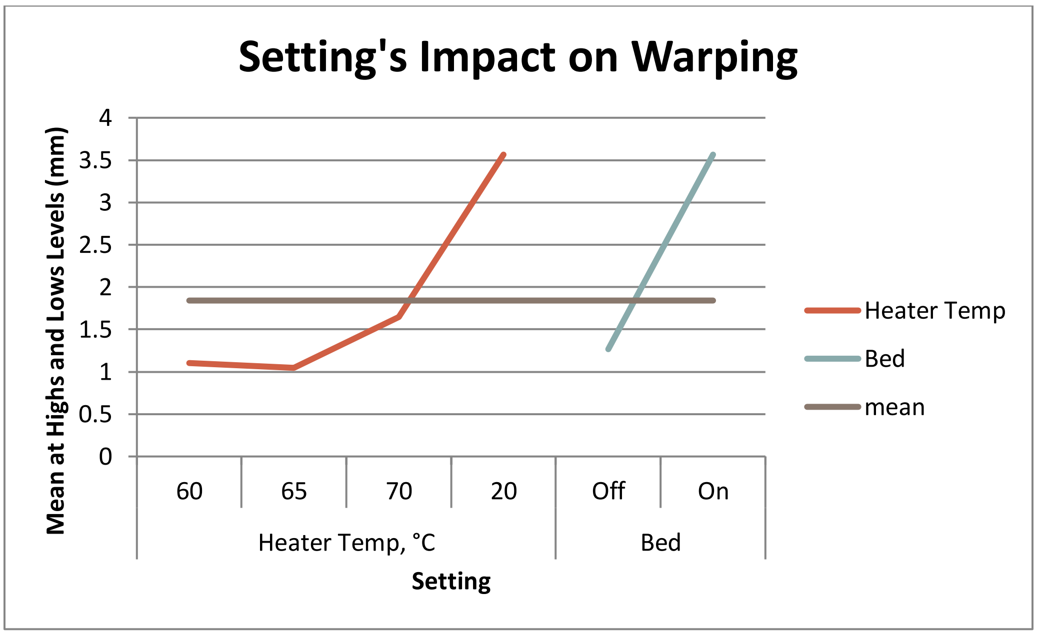

Figure 4.10 Setting’s Impact on Warping

4.3.3 Setting’s Interaction on Warping

Table 4.10 which is used to create a visible graph of how the combination of the heater and heated bed affects the FDM prints. Just like Figure 4.3, H represents the status of the heater and B represents the status of the heated bed. Therefore, H(On) means the heater was off and B(Off) means the heated bed was off during testing. Values were calculated by taking the average of the respective setting combinations from Table 4.8. Ideally the mm measurement should be 0 mm because it means there was no warping during testing.

Table 4.10 Setting Combination Interaction on Warping

	B (Off)	B(On)
H(on)	1.266878	
H(Off)		3.56509
Ideal	0	0

Figure 4.11 was determined by taking the average of relevant setting combinations from Table 4.10. Figure 4.11 represents the interaction between the heater being on/off and the bed being off/on. The red line represents the ideal while the blue shows the actual and the interaction the Heater and Bed has on the prints. When the heater is on, H(On), and the bed is off, B(Off), the warping was lower. While when the bed was on and the heater the opposite occurred. More warping occurred when the bed was on, and the heater was off. Causation for this is that the heater was producing heat closer to the glass transition temperature of the PLA. While the bed only produced heat at 30°C just enough to ensure that print adheres to the bed. 30°C is half of what is recommended for 60°C bed temperature for PLA. Since the bed was at a lower temperature compared to the heater the bed would be worse at preventing warping.

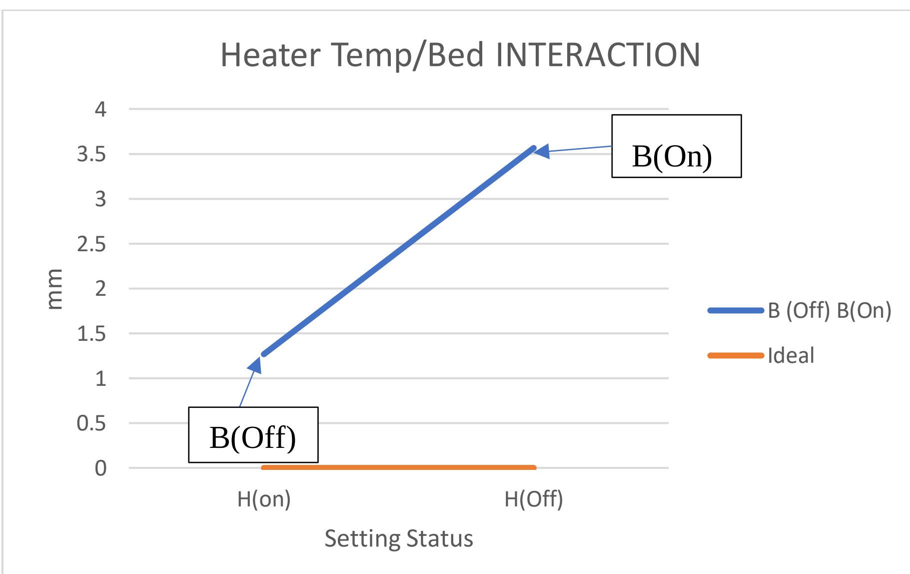

Figure 4.11 Setting Impact on Warping

CHAPTER 5. SUMMARY, CONCLUSIONS, AND RECOMENDATIONS

5.1 Summary

The design created did accomplish the intended goal of preventing and mitigating delamination and warping. However, the design took multiple iterations of testing and redesign to achieve the final product. This is expected in the engineering design process. After three iterations of design which took a total of five weeks to complete and a total of 72 hours of printing time for testing a fully functional design was accomplished.

5.2 Conclusion

The results of design and experimentation for a novel external heating system proved fruitful in preventing delamination and mitigating warping in FDM 3D prints. The data proves that an added heating system can prevent delamination and mitigate the effects of warping. When a part had any heat, treatment applied from the heating system no delamination occurred, while in the non-heat-treated parts delamination occurred due to the layers not cooling at the same rate. One of the non-treated parts suffered a catastrophic delamination where the print was knocked off the bed by the moving extruder due the raised layers. When comparing the warping values between treated and non-treated parts the treated prints suffered less significant warping compared to non-treated prints. Between the two highest points of warping the nontreated parts was the measurement was six times that of heat-treated parts. The results showing that no delamination occurred, and that warping was less significant in heat treated parts, proves an external heating system can aid in preventing failed or mitigating deformities of Fused Deposition Modeling Prints.

5.3 Recommendations

Section 5.3 covers the designs edits for the heater if research was to be continued. All recommendations are meant to either improve effectiveness or structural durability of the heating system.

5.3.1 Alternate Heat Distribution

Although the experimentation proved promising there are recommendations or modification that should be made in future iteration of this project. For future iterations of the heating system a wider coverage of the warm air is desired. Looking at the following thermal picture the air is only distributed along the sides and towards the nozzle of the heater. Figure 5.1 shows the heat distribution from the heating system using the FLIR E30bx thermo camera. The red and purple colors in white box shows distribution of heat from the system. The origin of the red and purple colorations in the figure is the heat expelled the nozzles of heater and the radiant heat from the extruder. Ideally, having full coverage of an area is desired, however due to design of the Ender 3 Pro extruder and frame full coverage of an area by the heater could not be achieved with the current heating system. Implementing a halo style applicator, air can be evenly disturbed over the printing area.

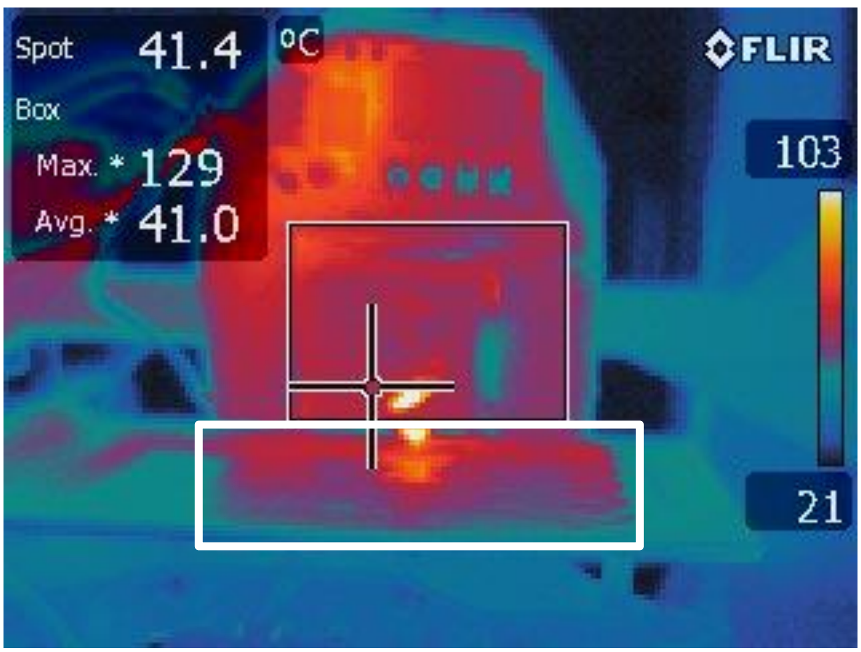

Figure 5.1 Thermal Image of Heater

To further explain the need for a new distribution system, Figure 5.2 shows the shape of the heat distribution outputted by the current heating system. The brown dot represents the extruder, and the black circles and ovals represents areas directly affected by the warm air or radiant heat. In Figure 5.2 the H shaped distribution and how neglected areas can occur during the printing process. Which may explain for significant warping along the outer corners and edges of the print.

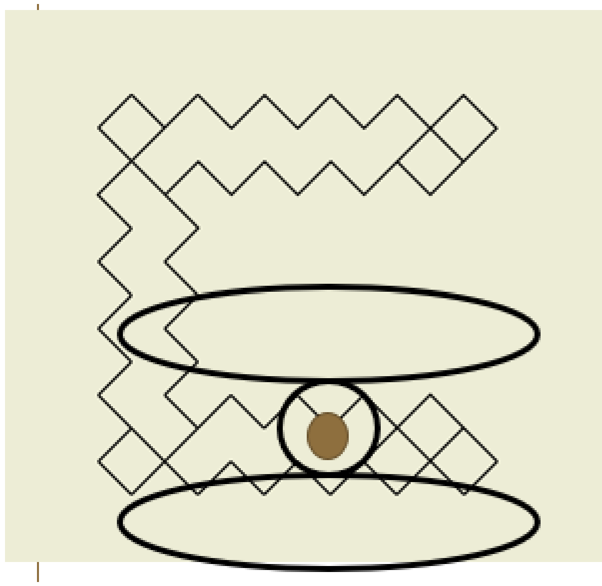

Figure 5.2 Current Heat Distribution Diagram

To ensure a proper full coverage of the printing area a halo like ring system to distribute the warm air in a circle like shape compared to a “H” is more desirable. Figure 5.3 shows the circular ideal distribution. With the circle distribution areas will not be neglected while the heating system is an area of a print.

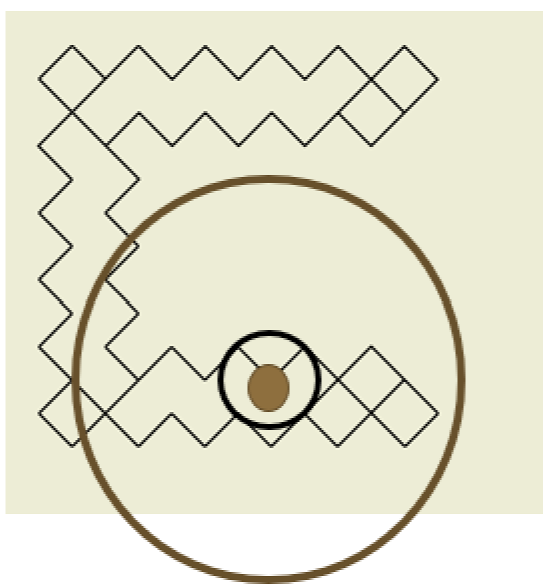

Figure 5.3 Ideal Heating Distribution Diagram

The while the “H” styled distribution sufficed for a trial run prototype, the location of the applied heat from the currently designed heater may explain some of the irregularities in the warping data. Significant warping appears along the left and right sides and corners. An example can be seen in Figure 4.6 which shows warping for the 60°C tests. The Test 1 line in the graph shows and incident of warping signifyingly higher at point 8 and 29. Point 8 and 29 are in areas that during the printing process are parallel to the longest sides of the heater. As the printer head moves a certain direction, specific areas may be neglected by the designed heating system. To be more specific areas parallel to long side of the nozzle. Designing a heat distribution system where all areas within a desired area can receive equal amount of heat may improve the effectiveness of an external heating system. A circular distribution would provide more even coverage compared to the H like distribution of the current system.

5.3.2 Material Selection

If the current design was to be made for the actual BAAM 3D printer other materials will be needed. The frame should be made of a strong and light weight material that has significant heat resistance at least two times higher than the glass transition temperature of the printing material. The current design utilized PETG 3D filament for the housing structure. Since the PETG is a thermoplastic, the constant applied heat can soften the material’s rigidity. PETG has a glass transition temperature of 80°C which is over the temperatures being tested of 60°C, 65°C, and 70°C. However, the constant application of heat caused the plastic to deform significantly during the 6-hour print runs. To mitigate the possibility of deformation due to heat, the reseacher used a heat-resistant putty applied to the surface where heat will be in contact with the plastic. However, parts of the housing started to deform during testing while under constant applied heat. An example of this can be seen in Figure 5.4 where the supporting tab that rests on top of the extruder housing deformed significantly. There was leak in the seal where the plastic putty cracked and got removed from the body of the housing and allowed some warm air to escape. The absence of putty is represented by the white box in Figure 5.4 shows where the warp air escaped. The escaping warm air softened the material to the point where the weight of the housing and heater caused the tab to deform due the weight of the heater.

Figure 5.4 Warped Tab

A material that can maintain structural integrity while under constant heat is ideal for the full scaled version of the heating system. Such types of materials suggested are heat resistant lightweight alloys or composite materials. An aluminum alloy will be ideal for the redesigned prototype or full-sized heating system. Aluminum can withstand the constant applied heat and having enough structural integrity, in addition to being lightweight enough to not impair the motors used in 3d printers.

5.3.3 Making the System in Less Parts

Due to the limitation of the available manufacturing equipment the housing had to be printed in individual panels and parts. Multiple parts requiring assembly creates opportunity of misalignment during the assembly process. The housing had a total of 13 Parts**,** however several of the subassemblies such as the nozzle areas could have been printed together to ensure greater overall structural integrity.

5.3.4 Attaching System

The current design utilizes neodymium rare earth magnets as the attachment mechanism for the heating system. For future iterations of the design an actual mechanical bond should be utilized using pins or screws that securely attaches the housing to the extruder. During initial testing of the system sudden jerks of the printer's head or the movement of the power brick for the power supplies caused the housing to fall off the extruder. This movement caused damage to the housing itself. Utilizing mechanical fasteners that will permanently attach the system ensure a secure bond to the printer and no jostling to prevent damage.

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APPENDIX A: DATA TABLES

Table A. 1 Delamination 20°C 1

Point	Delamination, mm	Delamination, mm	Delamination, mm	Average, mm
1	0.000	0.000	0.000	0.000
2	0.000	0.000	0.000	0.000
3	0.000	0.000	0.000	0.000
4	0.000	0.000	0.000	0.000
5	0.000	0.000	0.000	0.000
6	0.000	0.000	0.000	0.000
7	0.000	0.000	0.000	0.000
8	0.000	0.000	0.000	0.000
9	0.000	0.000	0.000	0.000
10	0.000	0.000	0.000	0.000
11	0.000	0.000	0.000	0.000
12	0.000	0.000	0.000	0.000
13	0.000	0.000	0.000	0.000
14	0.000	0.000	0.000	0.000
15	0.000	0.000	0.000	0.000
16	0.000	0.000	0.000	0.000
17	0.000	0.000	0.000	0.000
18	0.000	0.000	0.000	0.000
19	0.000	0.000	0.000	0.000
20	0.000	0.000	0.000	0.000
21	0.000	0.000	0.000	0.000
22	0.000	0.000	0.000	0.000
23	0.000	0.000	0.000	0.000
24	0.000	0.000	0.000	0.000
25	0.000	0.000	0.000	0.000
26	0.000	0.000	0.000	0.000
27	0.000	0.000	0.000	0.000
28	0.000	0.000	0.000	0.000
29	0.000	0.000	0.000	0.000
30	0.000	0.000	0.000	0.000
31	0.000	0.000	0.000	0.000
32	0.000	0.000	0.000	0.000
33	0.000	0.000	0.000	0.000
34	0.000	0.000	0.000	0.000
35	0.000	0.000	0.000	0.000
36	0.000	0.000	0.000	0.000
37	0.000	0.000	0.000	0.000

38	0.000	0.000	0.000	0.000
39	0.000	0.000	0.000	0.000
40	0.000	0.000	0.000	0.000
41	0.000	0.000	0.000	0.000
42	0.000	0.000	0.000	0.000
43	0.000	0.000	0.000	0.000
44	0.000	0.000	0.000	0.000
45	0.000	0.000	0.000	0.000
46	0.000	0.000	0.000	0.000
47	0.000	0.000	0.000	0.000
48	0.000	0.000	0.000	0.000
49	0.000	0.000	0.000	0.000
50	0.000	0.000	0.000	0.000
51	0.000	0.000	0.000	0.000
52	0.000	0.000	0.000	0.000
53	0.000	0.000	0.000	0.000
54	0.000	0.000	0.000	0.000
55	0.000	0.000	0.000	0.000
56	0.000	0.000	0.000	0.000
57	0.000	0.000	0.000	0.000
58	0.000	0.000	0.000	0.000

Table A. 2 Delamination 20°C 2

Point	Delamination, mm	Delamination, mm	Delamination, mm	Average, mm
1	0.940	1.000	1.030	0.990
2	0.740	0.750	0.730	0.740
3	0.660	0.660	0.670	0.663
4	0.000	0.000	0.000	0.000
5	0.000	0.000	0.000	0.000
6	0.000	0.000	0.000	0.000
7	0.000	0.000	0.000	0.000
8	0.000	0.000	0.000	0.000
9	0.000	0.000	0.000	0.000
10	0.000	0.000	0.000	0.000
11	0.710	0.710	0.710	0.710
12	0.000	0.000	0.000	0.000
13	0.000	0.000	0.000	0.000
14	0.510	0.530	0.520	0.520
15	0.000	0.000	0.000	0.000
16	0.000	0.000	0.000	0.000
17	0.000	0.000	0.000	0.000

18	0.000	0.000	0.000	0.000
19	0.000	0.000	0.000	0.000
20	0.000	0.000	0.810	0.270
21	0.000	0.000	0.820	0.273
22	0.000	0.000	0.000	0.000
23	0.600	0.620	0.600	0.607
24	0.610	0.620	0.620	0.617
25	0.000	0.000	0.000	0.000
26	0.000	0.000	0.000	0.000
27	0.000	0.000	0.000	0.000
28	0.000	0.000	0.000	0.000
29	0.000	0.000	0.000	0.000
30	0.000	0.000	0.000	0.000
31	0.000	0.000	0.000	0.000
32	0.000	0.000	0.000	0.000
33	0.000	0.000	0.000	0.000
34	0.000	0.000	0.000	0.000
35	0.000	0.000	0.000	0.000
36	0.000	0.000	0.000	0.000
37	0.000	0.000	0.000	0.000
38	0.000	0.000	0.000	0.000
39	0.000	0.000	0.000	0.000
40	0.000	0.000	0.000	0.000
41	0.000	0.000	0.000	0.000
42	0.000	0.000	0.000	0.000
43	0.000	0.000	0.000	0.000
44	0.000	0.000	0.000	0.000
45	0.000	0.000	0.000	0.000
46	0.000	0.000	0.000	0.000
47	0.000	0.000	0.000	0.000
48	0.000	0.000	0.000	0.000
49	0.000	0.000	0.000	0.000
50	0.670	0.670	0.650	0.663
51	0.610	0.600	0.620	0.610
52	0.540	0.530	0.570	0.547
53	0.000	0.000	0.000	0.000
54	0.000	0.000	0.000	0.000
55	0.000	0.000	0.000	0.000
56	0.000	0.000	0.000	0.000
57	0.000	0.000	0.000	0.000
58	0.000	0.000	0.000	0.000

Table A. 3 Delamination 20°C 3

Point	Delamination, mm	Delamination, mm	Delamination, mm	Average, mm
1	0.770	0.780	0.770	0.773
2	0.000	0.000	0.000	0.000
3	0.570	0.560	0.570	0.567
4	0.560	0.550	0.560	0.557
5	0.000	0.000	0.000	0.000
6	0.000	0.000	0.000	0.000
7	0.000	0.000	0.000	0.000
8	0.000	0.000	0.000	0.000
9	0.000	0.000	0.000	0.000
10	0.000	0.000	0.000	0.000
11	0.000	0.000	0.000	0.000
12	0.000	0.000	0.000	0.000
13	0.000	0.000	0.000	0.000
14	0.600	0.630	0.590	0.607
15	0.000	0.000	0.000	0.000
16	0.000	0.000	0.000	0.000
17	0.000	0.000	0.000	0.000
18	0.000	0.000	0.000	0.000
19	0.000	0.000	0.000	0.000
20	0.000	0.000	0.000	0.000
21	0.000	0.000	0.000	0.000
22	0.000	0.000	0.000	0.000
23	0.000	0.000	0.000	0.000
24	0.000	0.000	0.000	0.000
25	0.000	0.000	0.000	0.000
26	0.000	0.000	0.000	0.000
27	0.000	0.000	0.000	0.000
28	0.000	0.000	0.000	0.000
29	0.000	0.000	0.000	0.000
30	0.000	0.000	0.000	0.000
31	0.000	0.000	0.000	0.000
32	0.000	0.000	0.000	0.000
33	0.000	0.000	0.000	0.000
34	0.000	0.000	0.000	0.000
35	0.000	0.000	0.000	0.000
36	1.220	1.240	1.210	1.223
37	0.700	0.700	0.710	0.703
38	0.580	0.570	0.560	0.570
39	0.470	0.460	0.460	0.463
40	0.260	0.270	0.240	0.257
41	0.000	0.000	0.000	0.000
42	0.000	0.000	0.000	0.000

43	0.000	0.000	0.000	0.000
44	0.000	0.000	0.000	0.000
45	0.000	0.000	0.000	0.000
46	0.000	0.000	0.000	0.000
47	0.000	0.000	0.000	0.000
48	0.000	0.000	0.000	0.000
49	0.000	0.000	0.000	0.000
50	0.000	0.000	0.000	0.000
51	0.000	0.000	0.000	0.000
52	0.000	0.000	0.000	0.000
53	0.000	0.000	0.000	0.000
54	0.000	0.000	0.000	0.000
55	0.000	0.000	0.000	0.000
56	0.440	0.450	0.440	0.443
57	0.330	0.340	0.330	0.333
58	0.640	0.630	0.650	0.640

Table A. 4 Delamination 60°C 1

Point	Delamination, mm	Delamination, mm	Delamination, mm	Average, mm
1	0.000	0.000	0.000	0.000
2	0.000	0.000	0.000	0.000
3	0.000	0.000	0.000	0.000
4	0.000	0.000	0.000	0.000
5	0.000	0.000	0.000	0.000
6	0.000	0.000	0.000	0.000
7	0.000	0.000	0.000	0.000
8	0.000	0.000	0.000	0.000
9	0.000	0.000	0.000	0.000
10	0.000	0.000	0.000	0.000
11	0.000	0.000	0.000	0.000
12	0.000	0.000	0.000	0.000
13	0.000	0.000	0.000	0.000
14	0.000	0.000	0.000	0.000
15	0.000	0.000	0.000	0.000
16	0.000	0.000	0.000	0.000
17	0.000	0.000	0.000	0.000
18	0.000	0.000	0.000	0.000
19	0.000	0.000	0.000	0.000
20	0.000	0.000	0.000	0.000
21	0.000	0.000	0.000	0.000
22	0.000	0.000	0.000	0.000

23	0.000	0.000	0.000	0.000
24	0.000	0.000	0.000	0.000
25	0.000	0.000	0.000	0.000
26	0.000	0.000	0.000	0.000
27	0.000	0.000	0.000	0.000
28	0.000	0.000	0.000	0.000
29	0.000	0.000	0.000	0.000
30	0.000	0.000	0.000	0.000
31	0.000	0.000	0.000	0.000
32	0.000	0.000	0.000	0.000
33	0.000	0.000	0.000	0.000
34	0.000	0.000	0.000	0.000
35	0.000	0.000	0.000	0.000
36	0.000	0.000	0.000	0.000
37	0.000	0.000	0.000	0.000
38	0.000	0.000	0.000	0.000
39	0.000	0.000	0.000	0.000
40	0.000	0.000	0.000	0.000
41	0.000	0.000	0.000	0.000
42	0.000	0.000	0.000	0.000
43	0.000	0.000	0.000	0.000
44	0.000	0.000	0.000	0.000
45	0.000	0.000	0.000	0.000
46	0.000	0.000	0.000	0.000
47	0.000	0.000	0.000	0.000
48	0.000	0.000	0.000	0.000
49	0.000	0.000	0.000	0.000
50	0.000	0.000	0.000	0.000
51	0.000	0.000	0.000	0.000
52	0.000	0.000	0.000	0.000
53	0.000	0.000	0.000	0.000
54	0.000	0.000	0.000	0.000
55	0.000	0.000	0.000	0.000
56	0.000	0.000	0.000	0.000
57	0.000	0.000	0.000	0.000
58	0.000	0.000	0.000	0.000

Table A. 5 Delamination 60°C 2

Point	Delamination, mm	Delamination, mm	Delamination, mm	Average, mm
1	0.000	0.000	0.000	0.000
2	0.000	0.000	0.000	0.000

3	0.000	0.000	0.000	0.000
4	0.000	0.000	0.000	0.000
5	0.000	0.000	0.000	0.000
6	0.000	0.000	0.000	0.000
7	0.000	0.000	0.000	0.000
8	0.000	0.000	0.000	0.000
9	0.000	0.000	0.000	0.000
10	0.000	0.000	0.000	0.000
11	0.000	0.000	0.000	0.000
12	0.000	0.000	0.000	0.000
13	0.000	0.000	0.000	0.000
14	0.000	0.000	0.000	0.000
15	0.000	0.000	0.000	0.000
16	0.000	0.000	0.000	0.000
17	0.000	0.000	0.000	0.000
18	0.000	0.000	0.000	0.000
19	0.000	0.000	0.000	0.000
20	0.000	0.000	0.000	0.000
21	0.000	0.000	0.000	0.000
22	0.000	0.000	0.000	0.000
23	0.000	0.000	0.000	0.000
24	0.000	0.000	0.000	0.000
25	0.000	0.000	0.000	0.000
26	0.000	0.000	0.000	0.000
27	0.000	0.000	0.000	0.000
28	0.000	0.000	0.000	0.000
29	0.000	0.000	0.000	0.000
30	0.000	0.000	0.000	0.000
31	0.000	0.000	0.000	0.000
32	0.000	0.000	0.000	0.000
33	0.000	0.000	0.000	0.000
34	0.000	0.000	0.000	0.000
35	0.000	0.000	0.000	0.000
36	0.000	0.000	0.000	0.000
37	0.000	0.000	0.000	0.000
38	0.000	0.000	0.000	0.000
39	0.000	0.000	0.000	0.000
40	0.000	0.000	0.000	0.000
41	0.000	0.000	0.000	0.000
42	0.000	0.000	0.000	0.000
43	0.000	0.000	0.000	0.000
44	0.000	0.000	0.000	0.000
45	0.000	0.000	0.000	0.000
46	0.000	0.000	0.000	0.000
47	0.000	0.000	0.000	0.000

48	0.000	0.000	0.000	0.000
49	0.000	0.000	0.000	0.000
50	0.000	0.000	0.000	0.000
51	0.000	0.000	0.000	0.000
52	0.000	0.000	0.000	0.000
53	0.000	0.000	0.000	0.000
54	0.000	0.000	0.000	0.000
55	0.000	0.000	0.000	0.000
56	0.000	0.000	0.000	0.000
57	0.000	0.000	0.000	0.000
58	0.000	0.000	0.000	0.000

Table A. 6 Delamination 60°C 3

Point	Delamination, mm	Delamination, mm	Delamination, mm	Average, mm
1	0.000	0.000	0.000	0.000
2	0.000	0.000	0.000	0.000
3	0.000	0.000	0.000	0.000
4	0.000	0.000	0.000	0.000
5	0.000	0.000	0.000	0.000
6	0.000	0.000	0.000	0.000
7	0.000	0.000	0.000	0.000
8	0.000	0.000	0.000	0.000
9	0.000	0.000	0.000	0.000
10	0.000	0.000	0.000	0.000
11	0.000	0.000	0.000	0.000
12	0.000	0.000	0.000	0.000
13	0.000	0.000	0.000	0.000
14	0.000	0.000	0.000	0.000
15	0.000	0.000	0.000	0.000
16	0.000	0.000	0.000	0.000
17	0.000	0.000	0.000	0.000
18	0.000	0.000	0.000	0.000
19	0.000	0.000	0.000	0.000
20	0.000	0.000	0.000	0.000
21	0.000	0.000	0.000	0.000
22	0.000	0.000	0.000	0.000
23	0.000	0.000	0.000	0.000
24	0.000	0.000	0.000	0.000
25	0.000	0.000	0.000	0.000
26	0.000	0.000	0.000	0.000
27	0.000	0.000	0.000	0.000

28	0.000	0.000	0.000	0.000
29	0.000	0.000	0.000	0.000
30	0.000	0.000	0.000	0.000
31	0.000	0.000	0.000	0.000
32	0.000	0.000	0.000	0.000
33	0.000	0.000	0.000	0.000
34	0.000	0.000	0.000	0.000
35	0.000	0.000	0.000	0.000
36	0.000	0.000	0.000	0.000
37	0.000	0.000	0.000	0.000
38	0.000	0.000	0.000	0.000
39	0.000	0.000	0.000	0.000
40	0.000	0.000	0.000	0.000
41	0.000	0.000	0.000	0.000
42	0.000	0.000	0.000	0.000
43	0.000	0.000	0.000	0.000
44	0.000	0.000	0.000	0.000
45	0.000	0.000	0.000	0.000
46	0.000	0.000	0.000	0.000
47	0.000	0.000	0.000	0.000
48	0.000	0.000	0.000	0.000
49	0.000	0.000	0.000	0.000
50	0.000	0.000	0.000	0.000
51	0.000	0.000	0.000	0.000
52	0.000	0.000	0.000	0.000
53	0.000	0.000	0.000	0.000
54	0.000	0.000	0.000	0.000
55	0.000	0.000	0.000	0.000
56	0.000	0.000	0.000	0.000
57	0.000	0.000	0.000	0.000
58	0.000	0.000	0.000	0.000

Table A. 7 Delamination 65°C 1

Point	Delamination, mm	Delamination, mm	Delamination, mm	Average, mm
1	0.000	0.000	0.000	0.000
2	0.000	0.000	0.000	0.000
3	0.000	0.000	0.000	0.000
4	0.000	0.000	0.000	0.000
5	0.000	0.000	0.000	0.000
6	0.000	0.000	0.000	0.000
7	0.000	0.000	0.000	0.000

8	0.000	0.000	0.000	0.000
9	0.000	0.000	0.000	0.000
10	0.000	0.000	0.000	0.000
11	0.000	0.000	0.000	0.000
12	0.000	0.000	0.000	0.000
13	0.000	0.000	0.000	0.000
14	0.000	0.000	0.000	0.000
15	0.000	0.000	0.000	0.000
16	0.000	0.000	0.000	0.000
17	0.000	0.000	0.000	0.000
18	0.000	0.000	0.000	0.000
19	0.000	0.000	0.000	0.000
20	0.000	0.000	0.000	0.000
21	0.000	0.000	0.000	0.000
22	0.000	0.000	0.000	0.000
23	0.000	0.000	0.000	0.000
24	0.000	0.000	0.000	0.000
25	0.000	0.000	0.000	0.000
26	0.000	0.000	0.000	0.000
27	0.000	0.000	0.000	0.000
28	0.000	0.000	0.000	0.000
29	0.000	0.000	0.000	0.000
30	0.000	0.000	0.000	0.000
31	0.000	0.000	0.000	0.000
32	0.000	0.000	0.000	0.000
33	0.000	0.000	0.000	0.000
34	0.000	0.000	0.000	0.000
35	0.000	0.000	0.000	0.000
36	0.000	0.000	0.000	0.000
37	0.000	0.000	0.000	0.000
38	0.000	0.000	0.000	0.000
39	0.000	0.000	0.000	0.000
40	0.000	0.000	0.000	0.000
41	0.000	0.000	0.000	0.000
42	0.000	0.000	0.000	0.000
43	0.000	0.000	0.000	0.000
44	0.000	0.000	0.000	0.000
45	0.000	0.000	0.000	0.000
46	0.000	0.000	0.000	0.000
47	0.000	0.000	0.000	0.000
48	0.000	0.000	0.000	0.000
49	0.000	0.000	0.000	0.000
50	0.000	0.000	0.000	0.000
51	0.000	0.000	0.000	0.000
52	0.000	0.000	0.000	0.000

53	0.000	0.000	0.000	0.000
54	0.000	0.000	0.000	0.000
55	0.000	0.000	0.000	0.000
56	0.000	0.000	0.000	0.000
57	0.000	0.000	0.000	0.000
58	0.000	0.000	0.000	0.000

Table A. 8 Delamination 65°C 2

Point	Delamination, mm	Delamination, mm	Delamination, mm	Average, mm
1	0.000	0.000	0.000	0.000
2	0.000	0.000	0.000	0.000
3	0.000	0.000	0.000	0.000
4	0.000	0.000	0.000	0.000
5	0.000	0.000	0.000	0.000
6	0.000	0.000	0.000	0.000
7	0.000	0.000	0.000	0.000
8	0.000	0.000	0.000	0.000
9	0.000	0.000	0.000	0.000
10	0.000	0.000	0.000	0.000
11	0.000	0.000	0.000	0.000
12	0.000	0.000	0.000	0.000
13	0.000	0.000	0.000	0.000
14	0.000	0.000	0.000	0.000
15	0.000	0.000	0.000	0.000
16	0.000	0.000	0.000	0.000
17	0.000	0.000	0.000	0.000
18	0.000	0.000	0.000	0.000
19	0.000	0.000	0.000	0.000
20	0.000	0.000	0.000	0.000
21	0.000	0.000	0.000	0.000
22	0.000	0.000	0.000	0.000
23	0.000	0.000	0.000	0.000
24	0.000	0.000	0.000	0.000
25	0.000	0.000	0.000	0.000
26	0.000	0.000	0.000	0.000
27	0.000	0.000	0.000	0.000
28	0.000	0.000	0.000	0.000
29	0.000	0.000	0.000	0.000
30	0.000	0.000	0.000	0.000
31	0.000	0.000	0.000	0.000
32	0.000	0.000	0.000	0.000

33	0.000	0.000	0.000	0.000
34	0.000	0.000	0.000	0.000
35	0.000	0.000	0.000	0.000
36	0.000	0.000	0.000	0.000
37	0.000	0.000	0.000	0.000
38	0.000	0.000	0.000	0.000
39	0.000	0.000	0.000	0.000
40	0.000	0.000	0.000	0.000
41	0.000	0.000	0.000	0.000
42	0.000	0.000	0.000	0.000
43	0.000	0.000	0.000	0.000
44	0.000	0.000	0.000	0.000
45	0.000	0.000	0.000	0.000
46	0.000	0.000	0.000	0.000
47	0.000	0.000	0.000	0.000
48	0.000	0.000	0.000	0.000
49	0.000	0.000	0.000	0.000
50	0.000	0.000	0.000	0.000
51	0.000	0.000	0.000	0.000
52	0.000	0.000	0.000	0.000
53	0.000	0.000	0.000	0.000
54	0.000	0.000	0.000	0.000
55	0.000	0.000	0.000	0.000
56	0.000	0.000	0.000	0.000
57	0.000	0.000	0.000	0.000
58	0.000	0.000	0.000	0.000

Table A. 9 Delamination 65°C 3

Point	Delamination, mm	Delamination, mm	Delamination, mm	Average, mm
1	0.000	0.000	0.000	0.000
2	0.000	0.000	0.000	0.000
3	0.000	0.000	0.000	0.000
4	0.000	0.000	0.000	0.000
5	0.000	0.000	0.000	0.000
6	0.000	0.000	0.000	0.000
7	0.000	0.000	0.000	0.000
8	0.000	0.000	0.000	0.000
9	0.000	0.000	0.000	0.000
10	0.000	0.000	0.000	0.000
11	0.000	0.000	0.000	0.000
12	0.000	0.000	0.000	0.000

13	0.000	0.000	0.000	0.000
14	0.000	0.000	0.000	0.000
15	0.000	0.000	0.000	0.000
16	0.000	0.000	0.000	0.000
17	0.000	0.000	0.000	0.000
18	0.000	0.000	0.000	0.000
19	0.000	0.000	0.000	0.000
20	0.000	0.000	0.000	0.000
21	0.000	0.000	0.000	0.000
22	0.000	0.000	0.000	0.000
23	0.000	0.000	0.000	0.000
24	0.000	0.000	0.000	0.000
25	0.000	0.000	0.000	0.000
26	0.000	0.000	0.000	0.000
27	0.000	0.000	0.000	0.000
28	0.000	0.000	0.000	0.000
29	0.000	0.000	0.000	0.000
30	0.000	0.000	0.000	0.000
31	0.000	0.000	0.000	0.000
32	0.000	0.000	0.000	0.000
33	0.000	0.000	0.000	0.000
34	0.000	0.000	0.000	0.000
35	0.000	0.000	0.000	0.000
36	0.000	0.000	0.000	0.000
37	0.000	0.000	0.000	0.000
38	0.000	0.000	0.000	0.000
39	0.000	0.000	0.000	0.000
40	0.000	0.000	0.000	0.000
41	0.000	0.000	0.000	0.000
42	0.000	0.000	0.000	0.000
43	0.000	0.000	0.000	0.000
44	0.000	0.000	0.000	0.000
45	0.000	0.000	0.000	0.000
46	0.000	0.000	0.000	0.000
47	0.000	0.000	0.000	0.000
48	0.000	0.000	0.000	0.000
49	0.000	0.000	0.000	0.000
50	0.000	0.000	0.000	0.000
51	0.000	0.000	0.000	0.000
52	0.000	0.000	0.000	0.000
53	0.000	0.000	0.000	0.000
54	0.000	0.000	0.000	0.000
55	0.000	0.000	0.000	0.000
56	0.000	0.000	0.000	0.000
57	0.000	0.000	0.000	0.000

58	0.000	0.000	0.000	0.000

Table A. 10 Delamination 70°C 1

Point	Delamination, mm	Delamination, mm	Delamination, mm	Average, mm
1	0.000	0.000	0.000	0.000
2	0.000	0.000	0.000	0.000
3	0.000	0.000	0.000	0.000
4	0.000	0.000	0.000	0.000
5	0.000	0.000	0.000	0.000
6	0.000	0.000	0.000	0.000
7	0.000	0.000	0.000	0.000
8	0.000	0.000	0.000	0.000
9	0.000	0.000	0.000	0.000
10	0.000	0.000	0.000	0.000
11	0.000	0.000	0.000	0.000
12	0.000	0.000	0.000	0.000
13	0.000	0.000	0.000	0.000
14	0.000	0.000	0.000	0.000
15	0.000	0.000	0.000	0.000
16	0.000	0.000	0.000	0.000
17	0.000	0.000	0.000	0.000
18	0.000	0.000	0.000	0.000
19	0.000	0.000	0.000	0.000
20	0.000	0.000	0.000	0.000
21	0.000	0.000	0.000	0.000
22	0.000	0.000	0.000	0.000
23	0.000	0.000	0.000	0.000
24	0.000	0.000	0.000	0.000
25	0.000	0.000	0.000	0.000
26	0.000	0.000	0.000	0.000
27	0.000	0.000	0.000	0.000
28	0.000	0.000	0.000	0.000
29	0.000	0.000	0.000	0.000
30	0.000	0.000	0.000	0.000
31	0.000	0.000	0.000	0.000
32	0.000	0.000	0.000	0.000
33	0.000	0.000	0.000	0.000
34	0.000	0.000	0.000	0.000
35	0.000	0.000	0.000	0.000
36	0.000	0.000	0.000	0.000
37	0.000	0.000	0.000	0.000

38	0.000	0.000	0.000	0.000
39	0.000	0.000	0.000	0.000
40	0.000	0.000	0.000	0.000
41	0.000	0.000	0.000	0.000
42	0.000	0.000	0.000	0.000
43	0.000	0.000	0.000	0.000
44	0.000	0.000	0.000	0.000
45	0.000	0.000	0.000	0.000
46	0.000	0.000	0.000	0.000
47	0.000	0.000	0.000	0.000
48	0.000	0.000	0.000	0.000
49	0.000	0.000	0.000	0.000
50	0.000	0.000	0.000	0.000
51	0.000	0.000	0.000	0.000
52	0.000	0.000	0.000	0.000
53	0.000	0.000	0.000	0.000
54	0.000	0.000	0.000	0.000
55	0.000	0.000	0.000	0.000
56	0.000	0.000	0.000	0.000
57	0.000	0.000	0.000	0.000
58	0.000	0.000	0.000	0.000

Table A. 11 Delamination 70°C 2

Point	Delamination, mm	Delamination, mm	Delamination, mm	Average, mm
1	0.000	0.000	0.000	0.000
2	0.000	0.000	0.000	0.000
3	0.000	0.000	0.000	0.000
4	0.000	0.000	0.000	0.000
5	0.000	0.000	0.000	0.000
6	0.000	0.000	0.000	0.000
7	0.000	0.000	0.000	0.000
8	0.000	0.000	0.000	0.000
9	0.000	0.000	0.000	0.000
10	0.000	0.000	0.000	0.000
11	0.000	0.000	0.000	0.000
12	0.000	0.000	0.000	0.000
13	0.000	0.000	0.000	0.000
14	0.000	0.000	0.000	0.000
15	0.000	0.000	0.000	0.000
16	0.000	0.000	0.000	0.000
17	0.000	0.000	0.000	0.000

18	0.000	0.000	0.000	0.000
19	0.000	0.000	0.000	0.000
20	0.000	0.000	0.000	0.000
21	0.000	0.000	0.000	0.000
22	0.000	0.000	0.000	0.000
23	0.000	0.000	0.000	0.000
24	0.000	0.000	0.000	0.000
25	0.000	0.000	0.000	0.000
26	0.000	0.000	0.000	0.000
27	0.000	0.000	0.000	0.000
28	0.000	0.000	0.000	0.000
29	0.000	0.000	0.000	0.000
30	0.000	0.000	0.000	0.000
31	0.000	0.000	0.000	0.000
32	0.000	0.000	0.000	0.000
33	0.000	0.000	0.000	0.000
34	0.000	0.000	0.000	0.000
35	0.000	0.000	0.000	0.000
36	0.000	0.000	0.000	0.000
37	0.000	0.000	0.000	0.000
38	0.000	0.000	0.000	0.000
39	0.000	0.000	0.000	0.000
40	0.000	0.000	0.000	0.000
41	0.000	0.000	0.000	0.000
42	0.000	0.000	0.000	0.000
43	0.000	0.000	0.000	0.000
44	0.000	0.000	0.000	0.000
45	0.000	0.000	0.000	0.000
46	0.000	0.000	0.000	0.000
47	0.000	0.000	0.000	0.000
48	0.000	0.000	0.000	0.000
49	0.000	0.000	0.000	0.000
50	0.000	0.000	0.000	0.000
51	0.000	0.000	0.000	0.000
52	0.000	0.000	0.000	0.000
53	0.000	0.000	0.000	0.000
54	0.000	0.000	0.000	0.000
55	0.000	0.000	0.000	0.000
56	0.000	0.000	0.000	0.000
57	0.000	0.000	0.000	0.000
58	0.000	0.000	0.000	0.000

Table A. 12 Delamination 70°C 3

Point	Delamination, mm	Delamination, mm	Delamination, mm	Average, mm
1	0.000	0.000	0.000	0.000
2	0.000	0.000	0.000	0.000
3	0.000	0.000	0.000	0.000
4	0.000	0.000	0.000	0.000
5	0.000	0.000	0.000	0.000
6	0.000	0.000	0.000	0.000
7	0.000	0.000	0.000	0.000
8	0.000	0.000	0.000	0.000
9	0.000	0.000	0.000	0.000
10	0.000	0.000	0.000	0.000
11	0.000	0.000	0.000	0.000
12	0.000	0.000	0.000	0.000
13	0.000	0.000	0.000	0.000
14	0.000	0.000	0.000	0.000
15	0.000	0.000	0.000	0.000
16	0.000	0.000	0.000	0.000
17	0.000	0.000	0.000	0.000
18	0.000	0.000	0.000	0.000
19	0.000	0.000	0.000	0.000
20	0.000	0.000	0.000	0.000
21	0.000	0.000	0.000	0.000
22	0.000	0.000	0.000	0.000
23	0.000	0.000	0.000	0.000
24	0.000	0.000	0.000	0.000
25	0.000	0.000	0.000	0.000
26	0.000	0.000	0.000	0.000
27	0.000	0.000	0.000	0.000
28	0.000	0.000	0.000	0.000
29	0.000	0.000	0.000	0.000
30	0.000	0.000	0.000	0.000
31	0.000	0.000	0.000	0.000
32	0.000	0.000	0.000	0.000
33	0.000	0.000	0.000	0.000
34	0.000	0.000	0.000	0.000
35	0.000	0.000	0.000	0.000
36	0.000	0.000	0.000	0.000
37	0.000	0.000	0.000	0.000
38	0.000	0.000	0.000	0.000
39	0.000	0.000	0.000	0.000
40	0.000	0.000	0.000	0.000
41	0.000	0.000	0.000	0.000
42	0.000	0.000	0.000	0.000

43	0.000	0.000	0.000	0.000
44	0.000	0.000	0.000	0.000
45	0.000	0.000	0.000	0.000
46	0.000	0.000	0.000	0.000
47	0.000	0.000	0.000	0.000
48	0.000	0.000	0.000	0.000
49	0.000	0.000	0.000	0.000
50	0.000	0.000	0.000	0.000
51	0.000	0.000	0.000	0.000
52	0.000	0.000	0.000	0.000
53	0.000	0.000	0.000	0.000
54	0.000	0.000	0.000	0.000
55	0.000	0.000	0.000	0.000
56	0.000	0.000	0.000	0.000
57	0.000	0.000	0.000	0.000
58	0.000	0.000	0.000	0.000

Table A. 13 Table Delamination 20°C Analysis

Point	T1, mm	T2, mm	T3, mm	Average, mm
1	n/a	0.990	0.773	0.882
2	n/a	0.740	0.000	0.370
3	n/a	0.663	0.567	0.615
4	n/a	0.000	0.557	0.278
5	n/a	0.000	0.000	0.000
6	n/a	0.000	0.000	0.000
7	n/a	0.000	0.000	0.000
8	n/a	0.000	0.000	0.000
9	n/a	0.000	0.000	0.000
10	n/a	0.000	0.000	0.000
11	n/a	0.237	0.000	0.118
12	n/a	0.000	0.000	0.000
13	n/a	0.000	0.000	0.000
14	n/a	0.177	0.607	0.392
15	n/a	0.000	0.000	0.000
16	n/a	0.000	0.000	0.000
17	n/a	0.000	0.000	0.000

18	n/a	0.000	0.000	0.000
19	n/a	0.000	0.000	0.000
20	n/a	0.270	0.000	0.135
21	n/a	0.273	0.000	0.137
22	n/a	0.000	0.000	0.000
23	n/a	0.607	0.000	0.303
24	n/a	0.617	0.000	0.308
25	n/a	0.000	0.000	0.000
26	n/a	0.000	0.000	0.000
27	n/a	0.000	0.000	0.000
28	n/a	0.000	0.000	0.000
29	n/a	0.000	0.000	0.000
30	n/a	0.000	0.000	0.000
31	n/a	0.000	0.000	0.000
32	n/a	0.000	0.000	0.000
33	n/a	0.000	0.000	0.000
34	n/a	0.000	0.000	0.000
35	n/a	0.000	0.000	0.000
36	n/a	0.000	1.223	0.612
37	n/a	0.000	0.703	0.352
38	n/a	0.000	0.570	0.285
39	n/a	0.000	0.463	0.232
40	n/a	0.000	0.257	0.128
41	n/a	0.000	0.000	0.000
42	n/a	0.000	0.000	0.000
43	n/a	0.000	0.000	0.000
44	n/a	0.000	0.000	0.000
45	n/a	0.000	0.000	0.000
46	n/a	0.000	0.000	0.000
47	n/a	0.000	0.000	0.000
48	n/a	0.000	0.000	0.000
49	n/a	0.000	0.000	0.000
50	n/a	0.663	0.000	0.332
51	n/a	0.610	0.000	0.305
52	n/a	0.547	0.000	0.273
53	n/a	0.000	0.000	0.000
54	n/a	0.000	0.000	0.000
55	n/a	0.000	0.000	0.000
56	n/a	0.000	0.443	0.222
57	n/a	0.000	0.333	0.167
58	n/a	0.000	0.640	0.320

Table A. 14 Warping 60°C 1

Point	Warping, mm	Warping, mm	Warping, mm	Average, mm
1	0.850	0.890	0.880	0.873
2	0.810	0.810	0.820	0.813
3	0.870	0.860	0.870	0.867
4	0.880	0.830	0.830	0.847
5	0.840	0.780	0.790	0.803
6	0.850	0.820	0.800	0.823
7	2.100	2.100	2.120	2.107
8	2.540	2.530	2.490	2.520
9	1.620	1.670	1.650	1.647
10	1.820	1.860	1.820	1.833
11	1.250	1.190	1.200	1.213
12	1.140	1.150	1.090	1.127
13	1.410	1.440	1.360	1.403
14	0.960	0.950	1.090	1.000
15	0.870	0.960	0.980	0.937
16	1.220	1.250	1.210	1.227
17	1.280	1.270	1.300	1.283
18	1.200	1.180	1.260	1.213
19	0.830	0.820	0.790	0.813
20	0.640	0.570	0.590	0.600
21	0.870	0.820	0.850	0.847
22	0.920	0.910	0.940	0.923
23	0.880	0.820	0.860	0.853
24	0.680	0.710	0.690	0.693
25	0.740	0.750	0.730	0.740
26	0.640	0.660	0.620	0.640
27	0.780	0.710	0.720	0.737
28	0.770	0.720	0.720	0.737
29	1.820	1.810	1.820	1.817
30	1.380	1.310	1.310	1.333
31	0.850	0.870	0.890	0.870

Table A. 15 Warping 60°C 2

Point	Warping, mm	Warping, mm	Warping, mm	Average, mm
1	0.660	0.610	0.620	0.630
2	0.860	0.840	0.830	0.843
3	0.840	0.850	0.830	0.840
4	0.870	0.920	0.920	0.903
5	1.460	1.420	1.460	1.447
6	0.930	0.920	0.910	0.920

7	1.310	1.350	1.350	1.337
8	1.750	1.720	1.740	1.737
9	1.310	1.310	1.400	1.340
10	1.370	1.380	1.370	1.373
11	1.190	1.130	1.130	1.150
12	1.020	0.930	1.070	1.007
13	1.100	0.950	1.000	1.017
14	1.110	1.117	1.140	1.122
15	1.080	0.990	1.090	1.053
16	1.010	1.040	1.060	1.037
17	1.780	1.580	1.660	1.673
18	0.980	0.960	0.940	0.960
19	0.590	0.620	0.510	0.573
20	0.680	0.640	0.630	0.650
21	0.950	0.870	0.860	0.893
22	0.800	0.700	0.730	0.743
23	1.030	1.110	0.980	1.040
24	0.760	0.750	0.770	0.760
25	0.890	0.890	0.870	0.883
26	0.770	0.710	0.750	0.743
27	1.100	0.970	1.090	1.053
28	0.860	0.870	0.840	0.857
29	0.930	0.890	0.900	0.907
30	0.920	0.950	0.930	0.933
31	1.110	1.140	1.040	1.097

Table A. 16 Warping 60°C3

Point	Warping, mm	Warping, mm	Warping, mm	Average, mm
1	0.430	0.470	0.510	0.470
2	0.640	0.600	0.680	0.640
3	0.700	0.710	0.670	0.693
4	0.670	0.620	0.620	0.637
5	0.740	0.710	0.700	0.717
6	0.710	0.730	0.760	0.733
7	0.960	0.970	1.010	0.980
8	1.470	1.440	1.520	1.477
9	0.740	0.760	0.760	0.753
10	0.960	0.920	0.980	0.953
11	1.410	1.440	1.550	1.467
12	0.950	1.090	1.030	1.023
13	0.960	0.920	0.960	0.947

14	0.960	0.960	0.950	0.957
15	0.820	0.870	0.840	0.843
16	0.850	0.870	0.810	0.843
17	0.790	0.800	0.760	0.783
18	0.750	0.770	0.760	0.760
19	0.520	0.460	0.660	0.547
20	1.230	1.260	1.210	1.233
21	1.800	1.860	1.830	1.830
22	1.440	1.500	1.470	1.470
23	1.770	1.600	1.670	1.680
24	1.380	1.280	1.330	1.330
25	1.390	1.370	1.350	1.370
26	1.600	1.550	1.600	1.583
27	1.500	1.490	1.490	1.493
28	2.580	2.540	2.570	2.563
29	1.980	1.920	1.910	1.937
30	2.310	2.350	2.360	2.340
31	2.220	2.150	2.230	2.200

Table A. 17 Warping 65°C1

Point	Warping, mm	Warping, mm	Warping, mm	Average, mm
1	0.640	0.660	0.660	0.653
2	0.780	0.710	0.710	0.733
3	0.610	0.640	0.650	0.633
4	0.510	0.500	0.510	0.507
5	0.510	0.480	0.490	0.493
6	0.540	0.550	0.580	0.557
7	0.690	0.610	0.660	0.653
8	1.620	1.640	1.650	1.637
9	0.960	1.010	0.920	0.963
10	1.340	1.440	1.470	1.417
11	0.890	0.890	0.880	0.887
12	0.910	0.880	0.860	0.883
13	1.200	1.130	1.170	1.167
14	1.520	1.580	1.590	1.563
15	1.290	1.270	1.230	1.263
16	1.930	1.920	1.940	1.930
17	1.970	1.970	1.960	1.967
18	1.690	1.670	1.680	1.680
19	0.740	0.740	0.750	0.743
20	0.830	0.840	0.830	0.833

21	0.960	0.960	0.950	0.957
22	0.950	0.940	0.950	0.947
23	0.730	0.730	0.740	0.733
24	1.000	0.990	1.010	1.000
25	2.780	2.790	2.770	2.780
26	0.590	0.580	0.590	0.587
27	0.560	0.570	0.560	0.563
28	1.140	1.150	1.140	1.143
29	0.880	0.890	0.880	0.883
30	1.050	1.040	1.040	1.043
31	0.690	0.690	0.680	0.687

Table A. 18 Warping 65°C2

Point	Warping, mm	Warping, mm	Warping, mm	Average, mm
1	0.740	0.760	0.760	0.753
2	0.990	0.980	0.970	0.980
3	2.370	2.360	2.360	2.363
4	2.030	2.030	2.040	2.033
5	2.160	2.150	2.150	2.153
6	1.030	1.020	1.030	1.027
7	1.040	1.030	1.020	1.030
8	0.790	0.800	0.790	0.793
9	1.190	1.190	1.200	1.193
10	1.050	1.060	1.050	1.053
11	0.930	0.940	0.910	0.927
12	0.700	0.710	0.720	0.710
13	1.020	1.010	1.010	1.013
14	1.210	1.230	1.230	1.223
15	1.230	1.240	1.220	1.230
16	1.340	1.350	1.340	1.343
17	1.600	1.590	1.610	1.600
18	1.290	1.310	1.300	1.300
19	0.570	0.560	0.560	0.563
20	0.730	0.740	0.710	0.727
21	0.630	0.620	0.650	0.633
22	0.570	0.560	0.580	0.570
23	0.560	0.560	0.540	0.553
24	0.640	0.640	0.640	0.640
25	0.560	0.560	0.550	0.557
26	1.730	1.720	1.710	1.720
27	0.520	0.530	0.530	0.527

28	1.160	1.130	1.160	1.150
29	1.000	0.980	0.990	0.990
30	1.140	1.130	1.130	1.133
31	0.540	0.520	0.530	0.530

Table A. 19 Warping 65°C3

Point	Warping, mm	Warping, mm	Warping, mm	Average, mm
1	1.000	0.980	0.990	0.990
2	1.050	1.050	1.040	1.047
3	1.160	1.160	1.160	1.160
4	2.310	2.320	2.300	2.310
5	2.430	2.430	2.450	2.437
6	1.080	1.070	1.070	1.073
7	1.060	1.060	1.060	1.060
8	1.150	1.150	1.150	1.150
9	0.930	0.940	0.940	0.937
10	0.770	0.750	0.760	0.760
11	0.850	0.850	0.850	0.850
12	0.730	0.730	0.740	0.733
13	0.880	0.860	0.860	0.867
14	0.910	0.890	0.930	0.910
15	0.890	0.900	0.900	0.897
16	1.150	1.160	1.140	1.150
17	1.590	1.590	1.590	1.590
18	2.080	2.080	2.070	2.077
19	1.500	1.490	1.470	1.487
20	0.520	0.530	0.530	0.527
21	0.600	0.600	0.600	0.600
22	0.610	0.620	0.630	0.620
23	0.620	0.620	0.620	0.620
24	0.600	0.600	0.600	0.600
25	0.520	0.520	0.520	0.520
26	0.420	0.420	0.430	0.423
27	0.650	0.640	0.610	0.633
28	0.750	0.760	0.760	0.757
29	0.950	0.960	0.960	0.957
30	1.320	1.320	1.320	1.320
31	0.780	0.780	0.780	0.780

Table A. 20 Warping 70°C1

Point	Warping, mm	Warping, mm	Warping, mm	Average, mm
1	1.000	0.980	0.990	0.990
2	1.050	1.050	1.040	1.047
3	1.160	1.160	1.160	1.160
4	2.310	2.320	2.300	2.310
5	2.430	2.430	2.450	2.437
6	1.080	1.070	1.070	1.073
7	1.060	1.060	1.060	1.060
8	1.150	1.150	1.150	1.150
9	0.930	0.940	0.940	0.937
10	0.770	0.750	0.760	0.760
11	0.850	0.850	0.850	0.850
12	0.730	0.730	0.740	0.733
13	0.880	0.860	0.860	0.867
14	0.910	0.890	0.930	0.910
15	0.890	0.900	0.900	0.897
16	1.150	1.160	1.140	1.150
17	1.590	1.590	1.590	1.590
18	2.080	2.080	2.070	2.077
19	1.500	1.490	1.470	1.487
20	0.520	0.530	0.530	0.527
21	0.600	0.600	0.600	0.600
22	0.610	0.620	0.630	0.620
23	0.620	0.620	0.620	0.620
24	0.600	0.600	0.600	0.600
25	0.520	0.520	0.520	0.520
26	0.420	0.420	0.430	0.423
27	0.650	0.640	0.610	0.633
28	0.750	0.760	0.760	0.757
29	0.950	0.960	0.960	0.957
30	1.320	1.320	1.320	1.320
31	0.780	0.780	0.780	0.780

Table A. 21 Warping 70°C2

Point	Warping, mm	Warping, mm	Warping, mm	Average, mm
1	1.050	1.040	1.030	1.040
2	1.160	1.150	1.170	1.160
3	1.350	1.350	1.350	1.350
4	1.440	1.430	1.450	1.440

5	1.600	1.600	1.630	1.610
6	2.090	2.040	2.110	2.080
7	2.950	2.920	2.910	2.927
8	2.910	2.860	2.940	2.903
9	1.980	2.000	1.960	1.980
10	1.820	1.820	1.810	1.817
11	1.970	1.930	1.960	1.953
12	1.700	1.680	1.730	1.703
13	3.180	3.150	3.210	3.180
14	2.510	2.520	2.570	2.533
15	1.640	1.630	1.590	1.620
16	2.310	2.340	2.330	2.327
17	2.500	2.520	2.480	2.500
18	2.740	2.710	2.710	2.720
19	2.140	2.130	2.110	2.127
20	1.600	1.580	1.620	1.600
21	0.990	1.000	0.980	0.990
22	1.250	1.230	1.260	1.247
23	1.130	1.110	1.140	1.127
24	1.480	1.480	1.460	1.473
25	1.780	1.790	1.760	1.777
26	2.160	2.130	2.170	2.153
27	1.340	1.350	1.320	1.337
28	1.370	1.380	1.360	1.370
29	1.500	1.490	1.500	1.497
30	3.010	3.010	2.990	3.003
31	2.260	2.250	2.240	2.250

Table A. 22 Warping 70°C3

Point	Warping, mm	Warping, mm	Warping, mm	Average, mm
1	0.950	0.940	0.930	0.940
2	0.940	0.940	0.950	0.943
3	0.820	0.830	0.850	0.833
4	0.830	0.820	0.840	0.830
5	0.980	0.950	0.970	0.967
6	0.870	0.850	0.880	0.867
7	2.230	2.240	2.240	2.237
8	2.810	2.820	2.810	2.813
9	2.030	2.020	2.050	2.033
10	2.110	2.180	2.130	2.140
11	1.660	1.650	1.640	1.650

12	2.110	2.120	2.100	2.110
13	2.380	2.340	2.360	2.360
14	2.100	2.110	2.150	2.120
15	1.330	1.310	1.380	1.340
16	1.670	1.640	1.630	1.647
17	1.960	1.940	1.900	1.933
18	1.720	1.710	1.690	1.707
19	0.660	0.680	0.630	0.657
20	0.970	0.950	0.940	0.953
21	1.000	0.990	0.970	0.987
22	0.680	0.690	0.660	0.677
23	0.780	0.820	0.810	0.803
24	0.820	0.810	0.810	0.813
25	0.820	0.810	0.820	0.817
26	0.690	0.700	0.690	0.693
27	0.690	0.680	0.680	0.683
28	1.550	1.580	1.510	1.547
29	1.730	1.740	1.700	1.723
30	1.810	1.790	1.840	1.813
31	1.690	1.650	1.610	1.650

Table A. 23 Warping 0°C1

Point	Warping, mm	Warping, mm	Warping, mm	Average, mm
1	4.260	4.250	4.250	4.253
2	4.040	4.040	4.050	4.043
3	2.740	2.780	2.770	2.763
4	1.860	1.810	1.890	1.853
5	1.870	1.870	1.840	1.860
6	2.860	2.830	2.820	2.837
7	7.300	7.320	7.270	7.297
8	4.600	4.580	4.640	4.607
9	5.470	5.470	5.450	5.463
10	4.580	4.590	4.560	4.577
11	10.780	10.730	10.800	10.770
12	18.680	18.700	18.720	18.700
13	16.280	16.290	16.250	16.273
14	9.400	9.390	9.440	9.410
15	6.140	6.120	6.110	6.123
16	1.700	1.670	1.740	1.703
17	1.930	1.950	1.910	1.930
18	1.540	1.520	1.510	1.523

19	0.740	0.750	0.700	0.730
20	1.340	1.360	1.370	1.357
21	2.220	2.210	2.180	2.203
22	1.950	1.940	1.960	1.950
23	3.540	3.570	3.520	3.543
24	2.010	2.020	2.000	2.010
25	2.400	2.410	2.430	2.413
26	1.670	1.650	1.650	1.657
27	1.130	1.200	1.150	1.160
28	1.010	1.030	1.050	1.030
29	2.260	2.270	2.220	2.250
30	2.270	2.280	2.260	2.270
31	2.260	2.270	2.240	2.257

Table A. 24 Warping 0°C2

Point	Warping, mm	Warping, mm	Warping, mm	Average, mm
1	8.990	9.000	9.000	8.997
2	6.800	6.850	6.820	6.823
3	3.080	3.090	3.070	3.080
4	3.010	3.000	2.960	2.990
5	1.210	1.260	1.200	1.223
6	2.090	2.050	2.100	2.080
7	2.830	2.840	2.830	2.833
8	3.290	3.280	3.300	3.290
9	2.890	2.900	2.930	2.907
10	2.000	1.970	1.980	1.983
11	2.410	2.420	2.440	2.423
12	2.440	2.440	3.410	2.763
13	5.360	5.370	5.350	5.360
14	6.670	6.650	6.640	6.653
15	5.520	5.520	5.530	5.523
16	3.000	3.010	3.000	3.003
17	4.920	4.890	4.940	4.917
18	8.750	8.760	8.720	8.743
19	14.660	14.670	14.640	14.657
20	11.540	11.530	11.490	11.520
21	6.650	6.650	6.640	6.647
22	2.410	2.410	2.390	2.403
23	1.400	1.400	1.400	1.400
24	1.200	1.210	1.220	1.210
25	1.710	1.690	1.730	1.710

26	2.060	2.010	2.040	2.037
27	1.750	1.780	1.760	1.763
28	2.160	2.160	2.100	2.140
29	3.160	3.150	3.160	3.157
30	6.000	6.000	6.010	6.003
31	3.110	3.110	3.120	3.113

Table A. 25 Warping 0°C3

Point	Warping, mm	Warping, mm	Warping, mm	Average, mm
1	0.92	0.900	0.960	0.927
2	1.44	1.420	1.430	1.430
3	1.43	1.470	1.410	1.437
4	1.99	2.030	1.980	2.000
5	2.68	2.670	2.680	2.677
6	2.55	2.570	2.540	2.553
7	4.1	4.070	4.120	4.097
8	3.8	3.770	3.820	3.797
9	2.48	2.470	2.500	2.483
10	2.49	2.480	2.470	2.480
11	2.16	2.180	2.180	2.173
12	1.87	1.890	1.860	1.873
13	1.66	1.640	1.700	1.667
14	1.94	1.960	1.910	1.937
15	2.39	2.430	2.410	2.410
16	3.07	3.060	3.050	3.060
17	3.28	3.280	3.280	3.280
18	5.34	5.330	5.360	5.343
19	5.1	5.100	5.000	5.067
20	3.39	3.390	3.410	3.397
21	1.34	1.350	1.370	1.353
22	1.19	1.200	1.170	1.187
23	1.42	1.430	1.410	1.420
24	0.71	0.740	0.680	0.710
25	1.14	1.110	1.150	1.133
26	1.11	1.160	1.010	1.093
27	1.1	1.090	1.080	1.090
28	1.1	1.100	1.150	1.117
29	1.49	1.490	1.500	1.493
30	1.37	1.390	1.350	1.370
31	1.34	1.320	1.330	1.330

Warping Data Summary

Table A. 26 Warping 60C Analysis

Point	T1, mm	T2, mm	T3, mm	Average, mm	Standard Deviation, mm
1	0.873	0.630	0.470	0.658	0.203
2	0.813	0.843	0.640	0.766	0.110
3	0.867	0.840	0.693	0.800	0.093
4	0.847	0.903	0.637	0.796	0.140
5	0.803	1.447	0.717	0.989	0.399
6	0.823	0.920	0.733	0.826	0.093
7	2.107	1.337	0.980	1.474	0.576
8	2.520	1.737	1.477	1.911	0.543
9	1.647	1.340	0.753	1.247	0.454
10	1.833	1.373	0.953	1.387	0.440
11	1.213	1.150	1.467	1.277	0.168
12	1.127	1.007	1.023	1.052	0.065
13	1.403	1.017	0.947	1.122	0.246
14	1.000	1.122	0.957	1.026	0.086
15	0.937	1.053	0.843	0.944	0.105
16	1.227	1.037	0.843	1.036	0.192
17	1.283	1.673	0.783	1.247	0.446
18	1.213	0.960	0.760	0.978	0.227
19	0.813	0.573	0.547	0.644	0.147
20	0.600	0.650	1.233	0.828	0.352
21	0.847	0.893	1.830	1.190	0.555
22	0.923	0.743	1.470	1.046	0.378
23	0.853	1.040	1.680	1.191	0.434
24	0.693	0.760	1.330	0.928	0.350
25	0.740	0.883	1.370	0.998	0.330
26	0.640	0.743	1.583	0.989	0.517
27	0.737	1.053	1.493	1.094	0.380
28	0.737	0.857	2.563	1.386	1.022
29	1.817	0.907	1.937	1.553	0.563
30	1.333	0.933	2.340	1.536	0.725
31	0.870	1.097	2.200	1.389	0.712

Table A. 27 Warping 65°C Analysis

Point	T1, mm	T2, mm	T3, mm	Average, mm	Standard Deviation, mm
1	0.653	0.753	0.990	0.799	0.173
2	0.733	0.980	1.047	0.920	0.165
3	0.633	2.363	1.160	1.386	0.887
4	0.507	2.033	2.310	1.617	0.971
5	0.493	2.153	2.437	1.694	1.050
6	0.557	1.027	1.073	0.886	0.286
7	0.653	1.030	1.060	0.914	0.227
8	1.637	0.793	1.150	1.193	0.423
9	0.963	1.193	0.937	1.031	0.141
10	1.417	1.053	0.760	1.077	0.329
11	0.887	0.927	0.850	0.888	0.038
12	0.883	0.710	0.733	0.776	0.094
13	1.167	1.013	0.867	1.016	0.150
14	1.563	1.223	0.910	1.232	0.327
15	1.263	1.230	0.897	1.130	0.203
16	1.930	1.343	1.150	1.474	0.406
17	1.967	1.600	1.590	1.719	0.215
18	1.680	1.300	2.077	1.686	0.388
19	0.740	0.563	1.487	0.930	0.490
20	0.833	0.727	0.527	0.696	0.156
21	0.957	0.633	0.600	0.730	0.197
22	0.947	0.570	0.620	0.712	0.205
23	0.733	0.553	0.620	0.636	0.091
24	1.000	0.640	0.600	0.747	0.220
25	2.780	0.557	0.520	1.286	1.294
26	0.587	1.720	0.423	0.910	0.706
27	0.563	0.527	0.633	0.574	0.054
28	1.143	1.150	0.757	1.017	0.225
29	0.883	0.990	0.957	0.943	0.055
30	1.043	1.133	1.320	1.166	0.141
31	0.687	0.530	0.780	0.666	0.126

Table A. 28 Warping 70°C Analysis

Point	T1, mm	T2, mm	T3, mm	Average, mm	Standard Deviation, mm
1	0.913	1.040	0.940	0.964	0.067
2	1.177	1.160	0.943	1.093	0.130
3	1.350	1.350	0.833	1.178	0.298
4	1.177	1.440	0.830	1.149	0.306
5	1.230	1.610	0.967	1.269	0.323
6	1.443	2.080	0.867	1.463	0.607

7	3.137	2.927	2.237	2.767	0.471
8	2.877	2.903	2.813	2.864	0.046
9	2.260	1.980	2.033	2.091	0.149
10	2.390	1.817	2.140	2.116	0.287
11	1.673	1.953	1.650	1.759	0.169
12	2.090	1.703	2.110	1.968	0.229
13	1.820	3.180	2.360	2.453	0.685
14	2.463	2.533	2.120	2.372	0.221
15	1.370	1.620	1.340	1.443	0.154
16	1.493	2.327	1.647	1.822	0.444
17	2.063	2.500	1.933	2.166	0.297
18	2.467	2.720	1.707	2.298	0.527
19	2.377	2.127	0.657	1.720	0.929
20	0.590	1.600	0.953	1.048	0.512
21	1.150	0.990	0.987	1.042	0.093
22	1.040	1.247	0.677	0.988	0.289
23	1.400	1.127	0.803	1.110	0.299
24	1.310	1.473	0.813	1.199	0.344
25	0.990	1.777	0.817	1.194	0.512
26	1.010	2.153	0.693	1.286	0.768
27	1.650	1.337	0.683	1.223	0.493
28	1.557	1.370	1.547	1.491	0.105
29	1.683	1.497	1.723	1.634	0.121
30	1.643	3.003	1.813	2.153	0.741
31	1.327	2.250	1.650	1.742	0.469

Table A. 29 Warping 20°C Analysis

Point	T1, mm	T2, mm	T3, mm	Average, mm	Standard Deviation, mm
1	4.253	8.997	0.927	4.726	4.056
2	4.043	6.823	1.430	4.099	2.697
3	2.763	3.080	1.437	2.427	0.872
4	1.853	2.990	2.000	2.281	0.618
5	1.860	1.223	2.677	1.920	0.729
6	2.837	2.080	2.553	2.490	0.382
7	7.297	2.833	4.097	4.742	2.301
8	4.607	3.290	3.797	3.898	0.664
9	5.463	2.907	2.483	3.618	1.612
10	4.577	1.983	2.480	3.013	1.376
11	10.770	2.423	2.173	5.122	4.893
12	18.700	2.763	1.873	7.779	9.468
13	16.273	5.360	1.667	7.767	7.595

14	9.410	6.653	1.937	6.000	3.779
15	6.123	5.523	2.410	4.686	1.993
16	1.703	3.003	3.060	2.589	0.767
17	1.930	4.917	3.280	3.376	1.496
18	1.523	8.743	5.343	5.203	3.612
19	0.730	14.657	5.067	6.818	7.127
20	1.357	11.520	3.397	5.424	5.377
21	2.203	6.647	1.353	3.401	2.843
22	1.950	2.403	1.187	1.847	0.615
23	3.543	1.400	1.420	2.121	1.232
24	2.010	1.210	0.710	1.310	0.656
25	2.413	1.710	1.133	1.752	0.641
26	1.657	2.037	1.093	1.596	0.475
27	1.160	1.763	1.090	1.338	0.370
28	1.030	2.140	1.117	1.429	0.617
29	2.250	3.157	1.493	2.300	0.833
30	2.270	6.003	1.370	3.214	2.457
31	2.257	3.113	1.330	2.233	0.892

APPENDIX B: CAD FILES

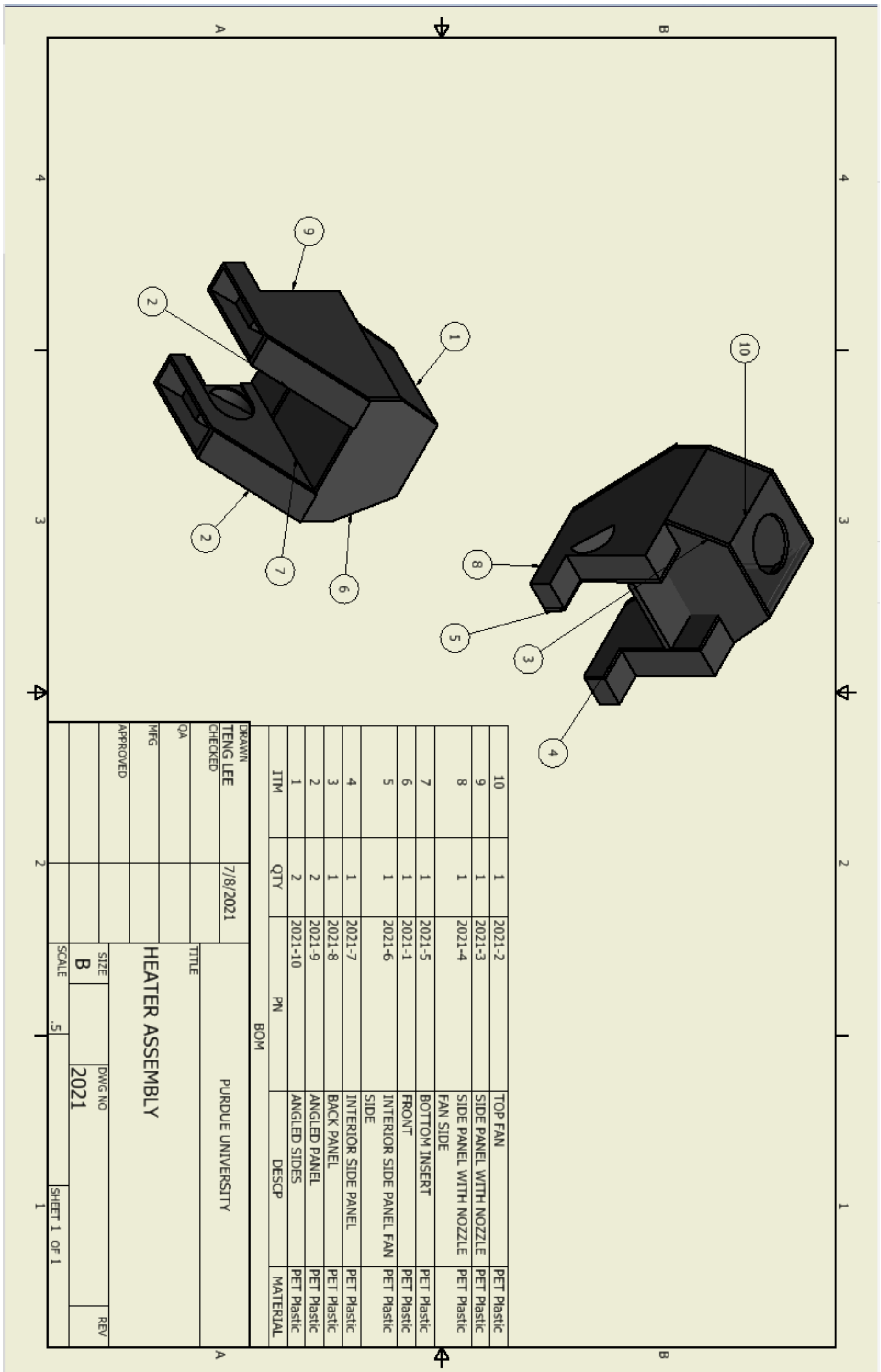

Figure B.1 Heater Assembly

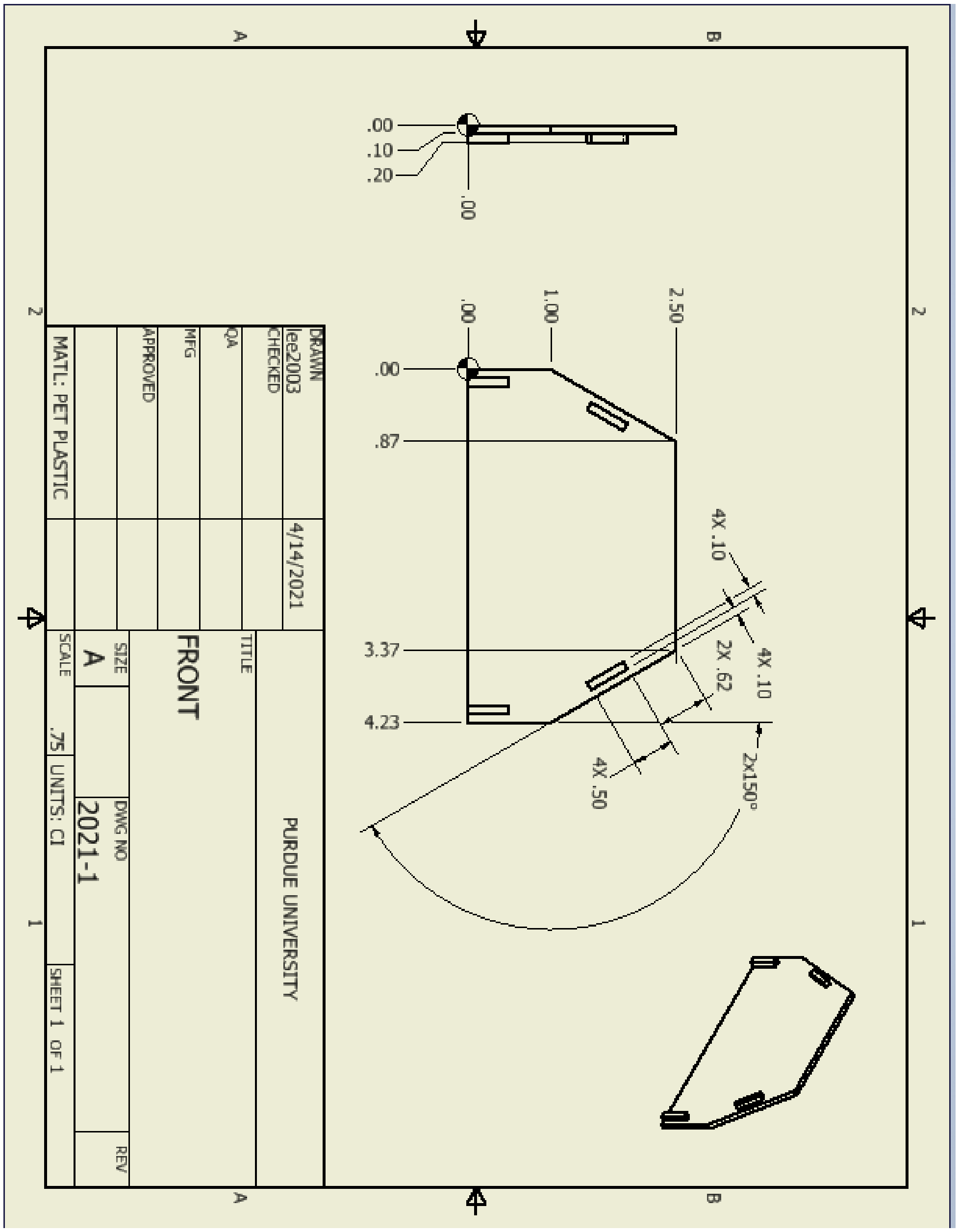

Figure B.2 Front

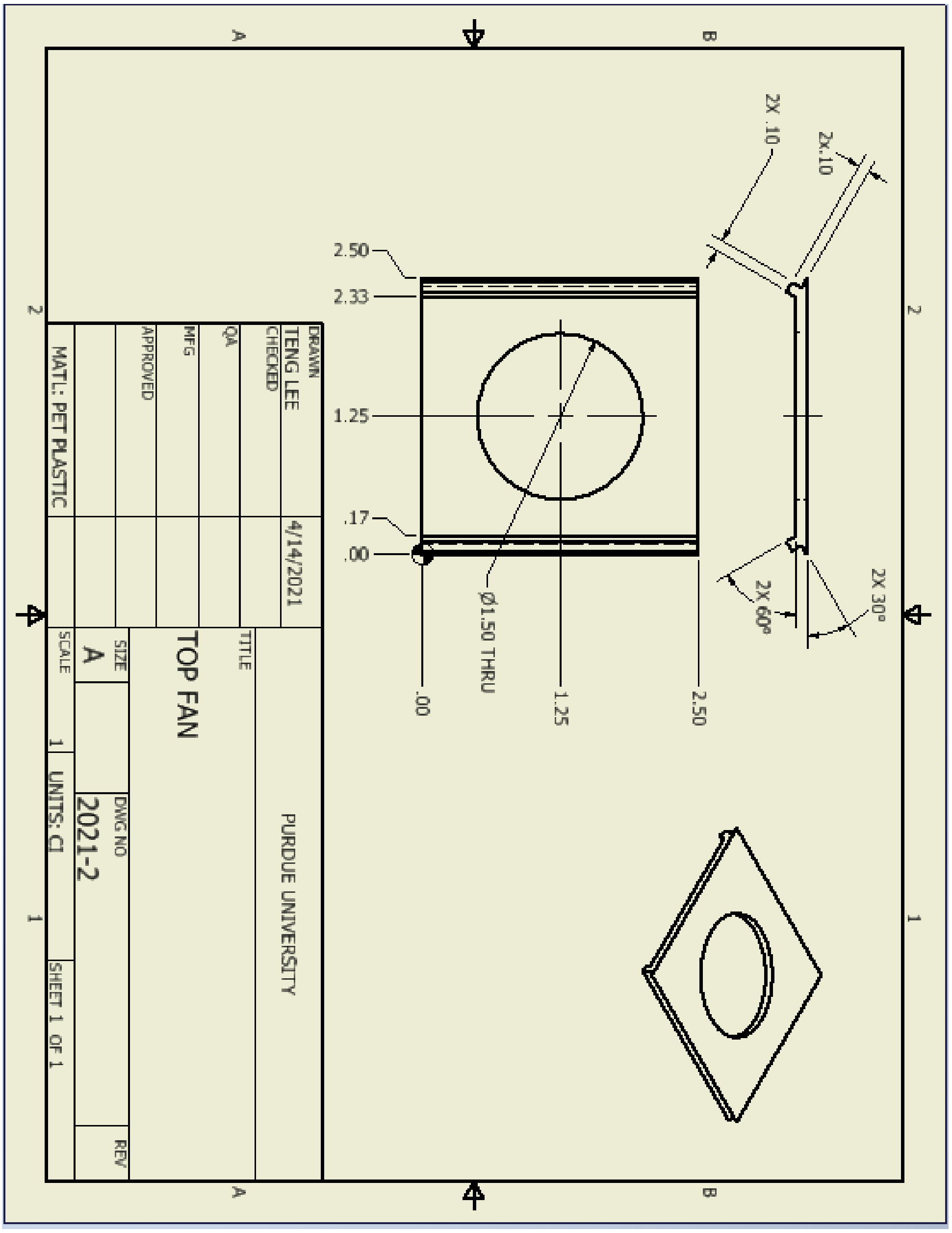

Figure B.3 Top Fan

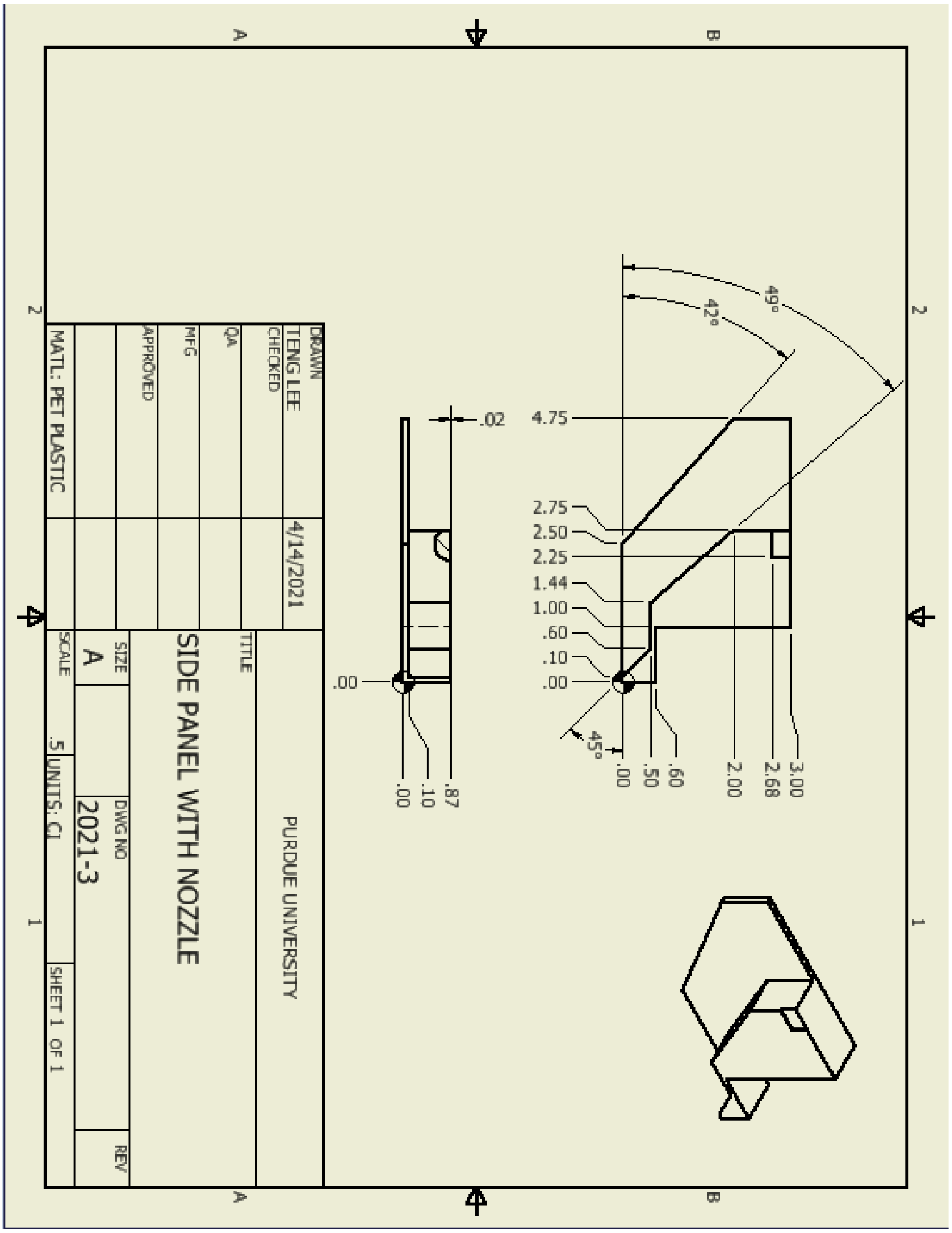

Figure B.4 Side Panel with Nozzle

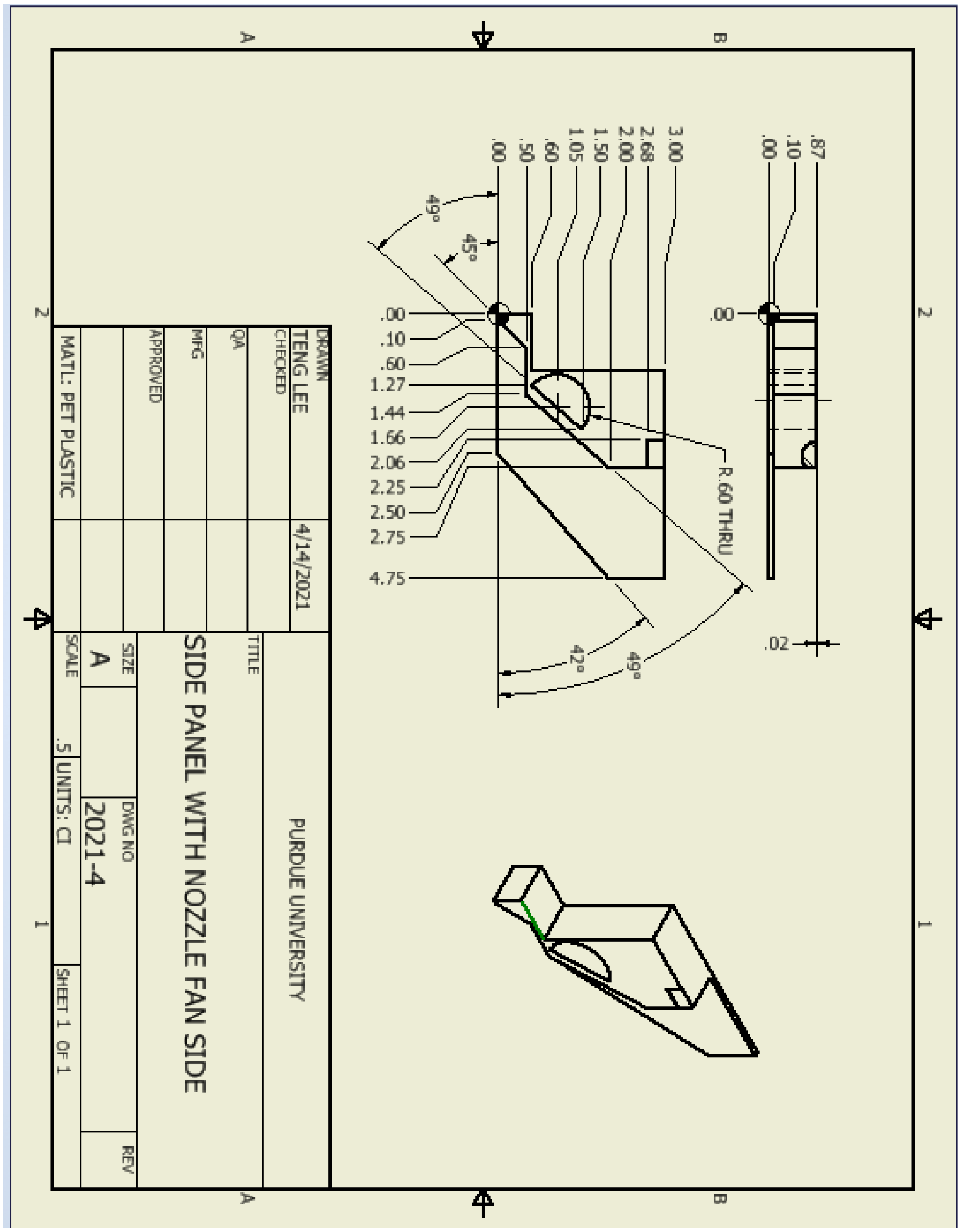

Figure B.5 Side Panel With Nozzle Fan Side

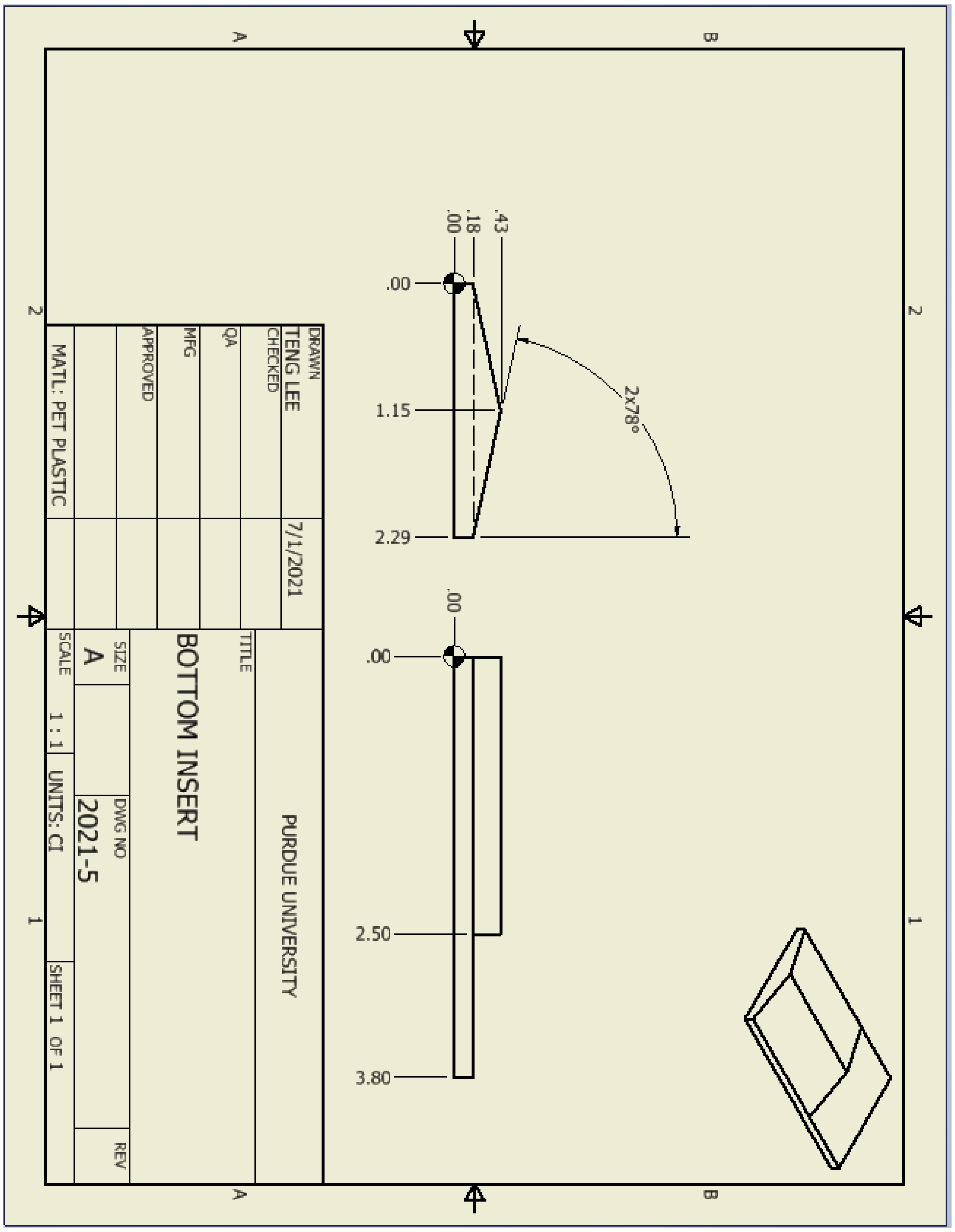

Figure B.6 Bottom Insert

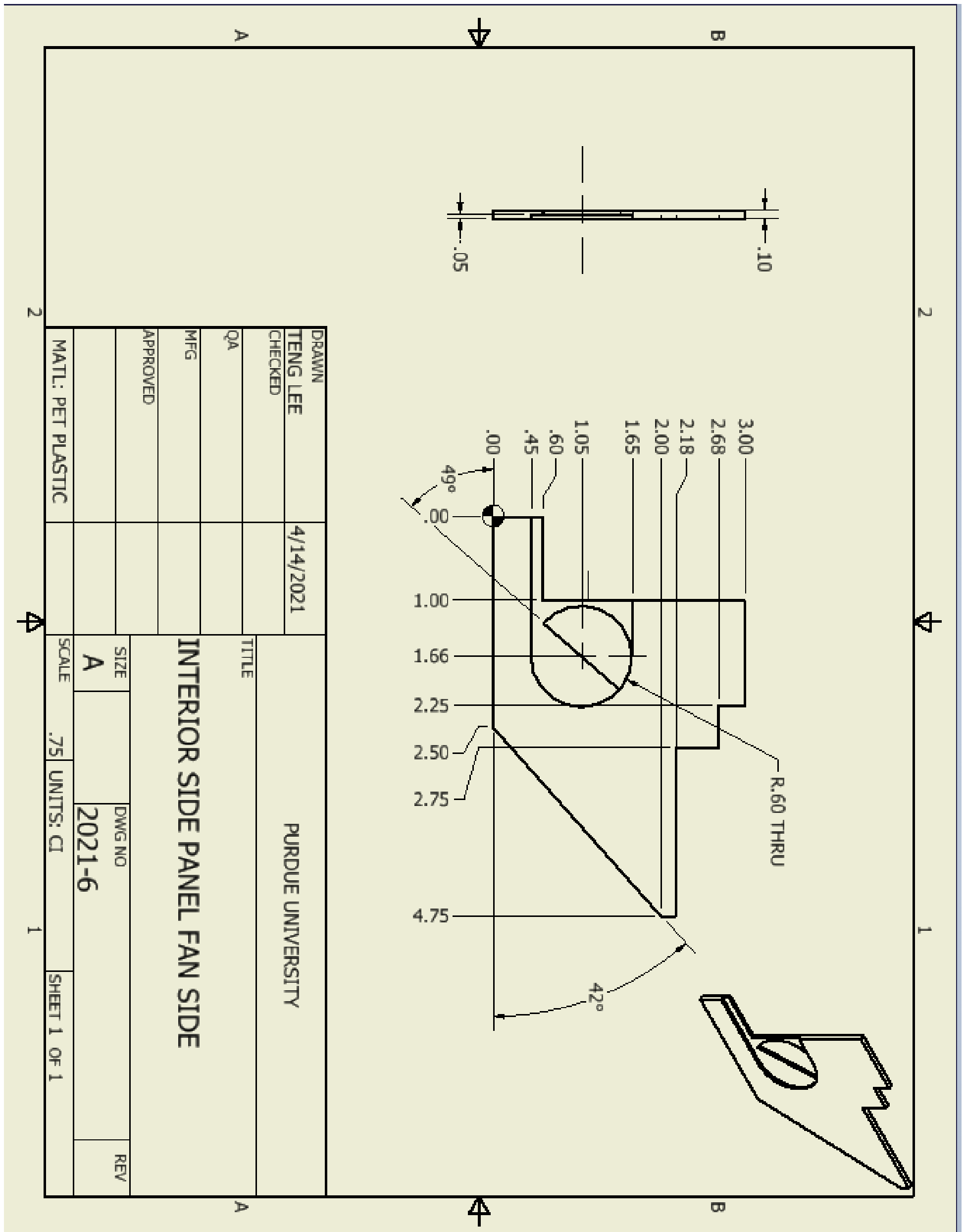

Figure B.7 Interior Side Panel Fan Side

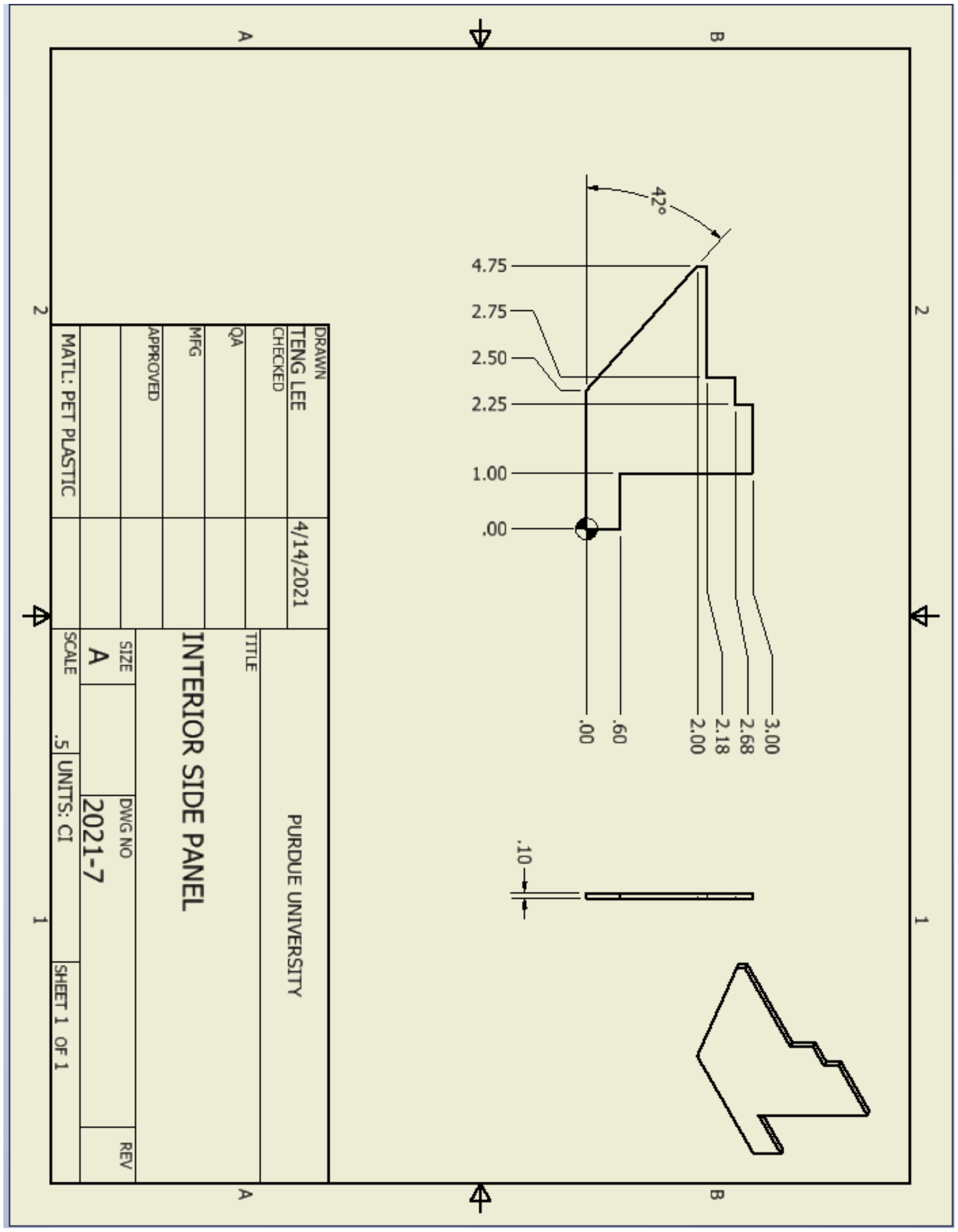

Figure B.8 Interior Side Panel

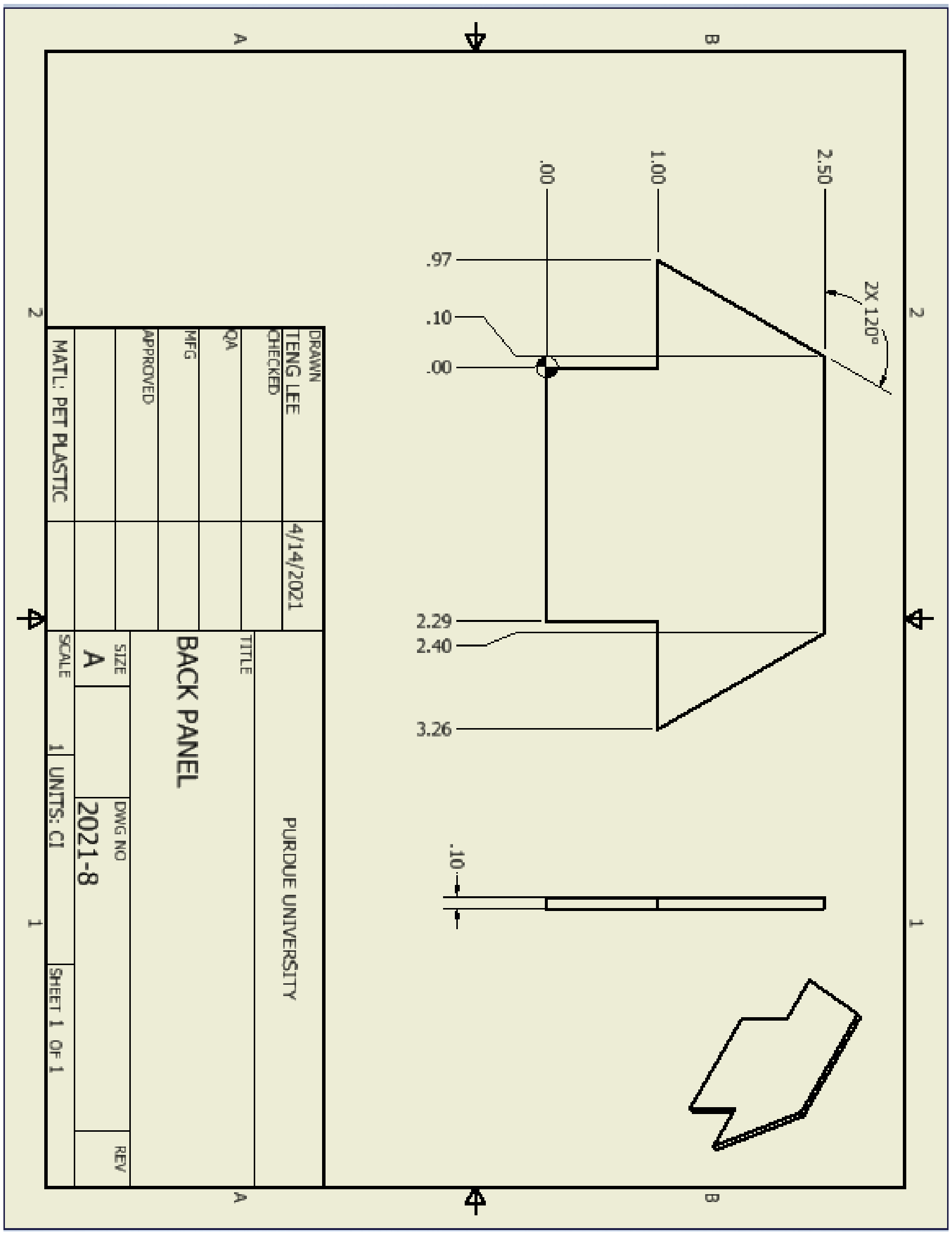

Figure B.9 Back Panel

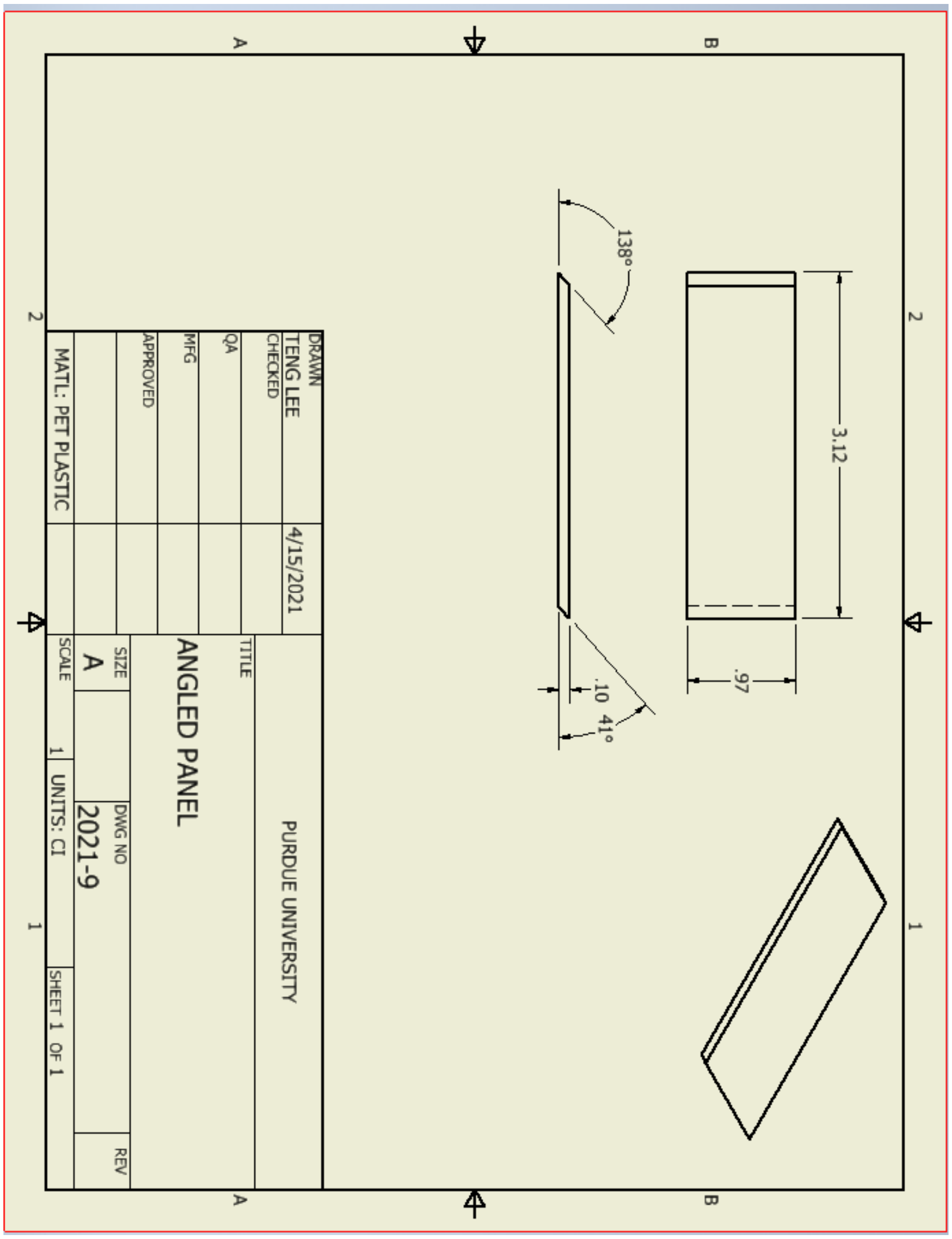

Figure B.10 Angled Panel

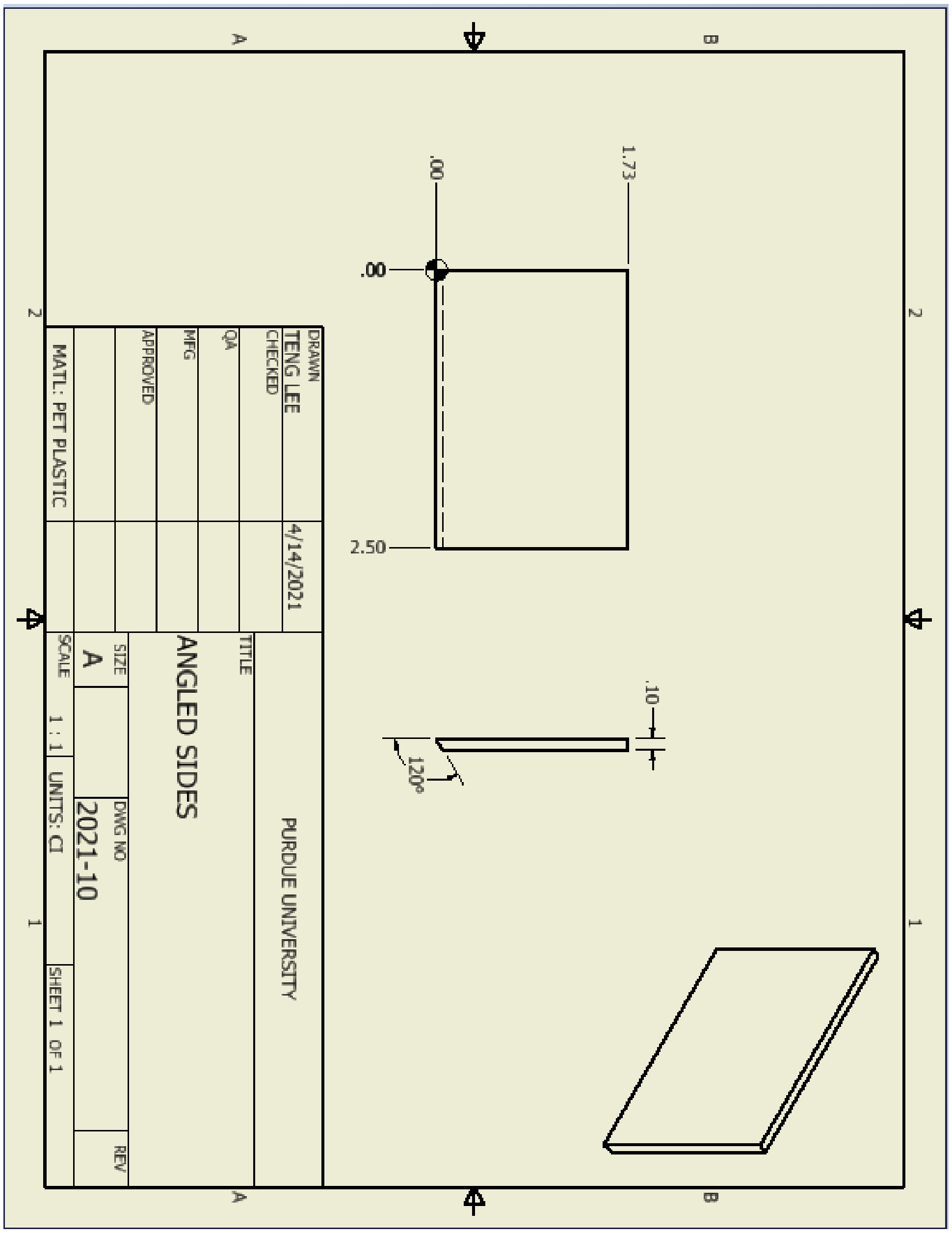

Figure B.11 Angled Sides

APPENDIX C: PHOTOS

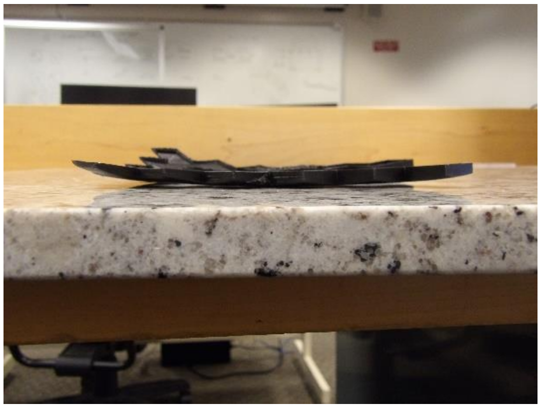

Figure C. 1 20°C 1 Right View

Figure C. 2 20°C 1 Back View

Figure C. 3 20°C 1 Left View

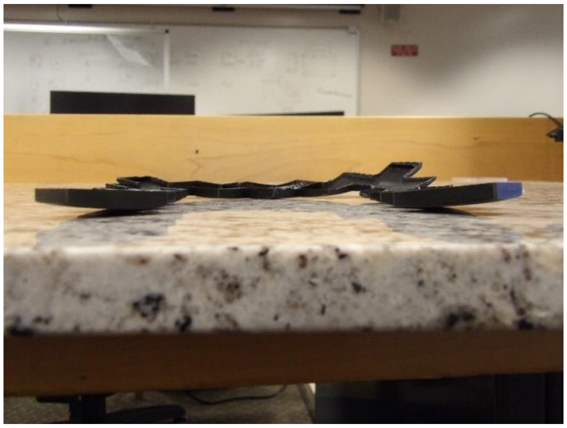

Figure C. 4 20°C 1 Front View

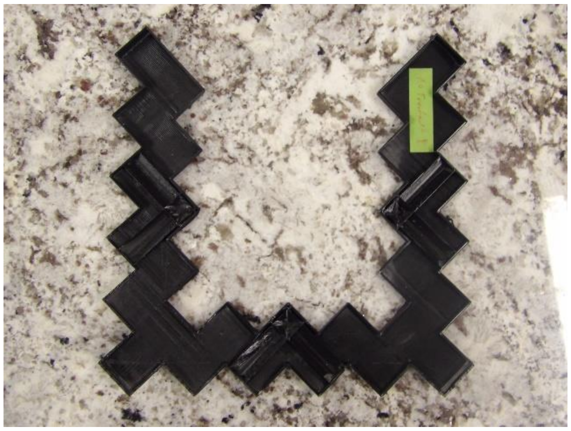

Figure C. 5 20°C 1 Top View

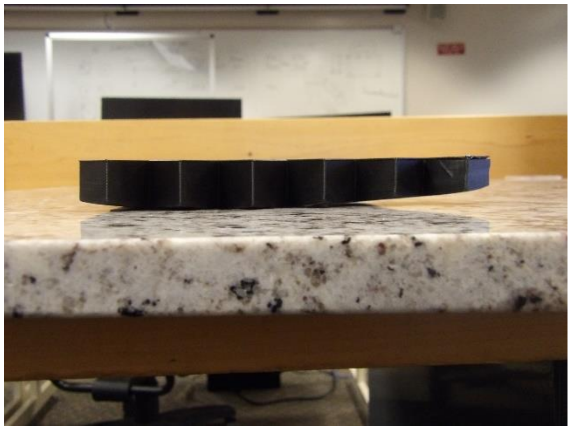

Figure C. 6 20°C 2 Right View

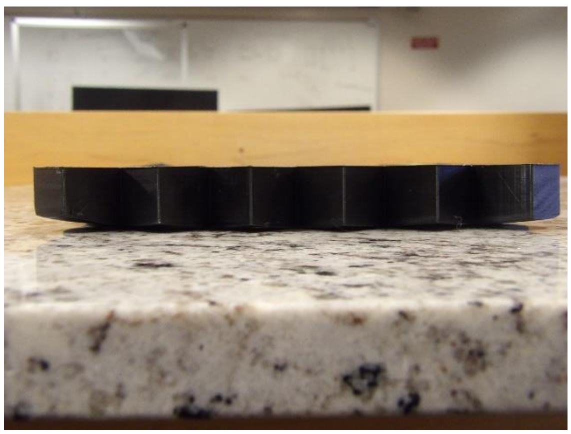

Figure C. 7 20°C 2 Back View

Figure C. 8 20°C 2 Left View

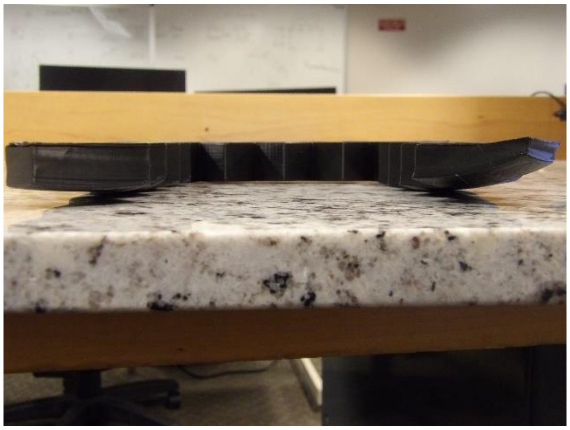

Figure C. 9 20°C 2 Front View

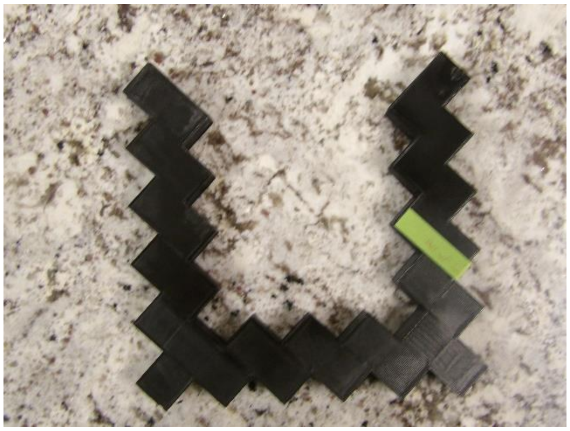

Figure C. 10 20°C 2 Top View

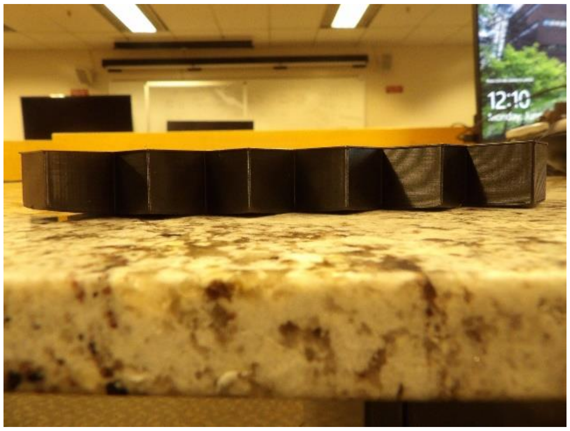

Figure C. 11 20°C 3 Right View

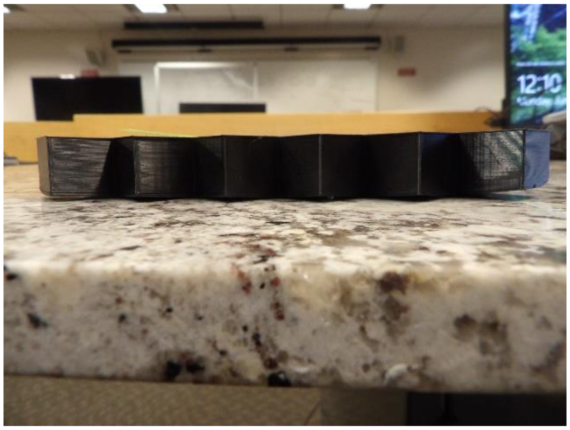

Figure C. 12 20°C 3 Back View

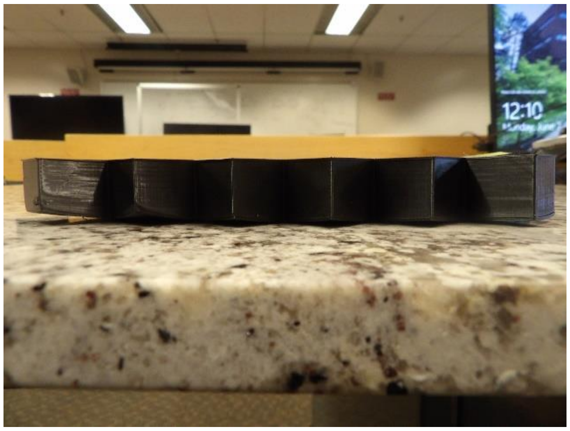

Figure C. 13 20°C Left View

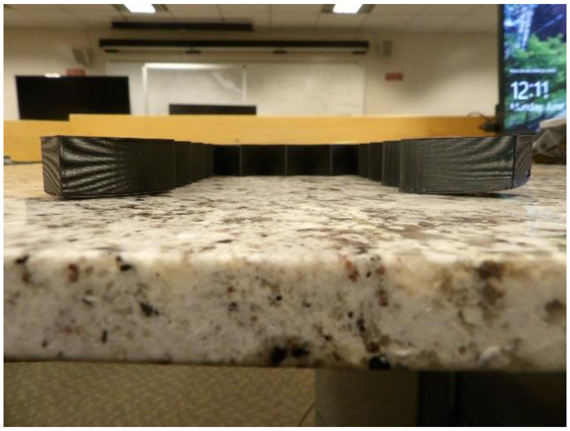

Figure C. 14 20°C Front View

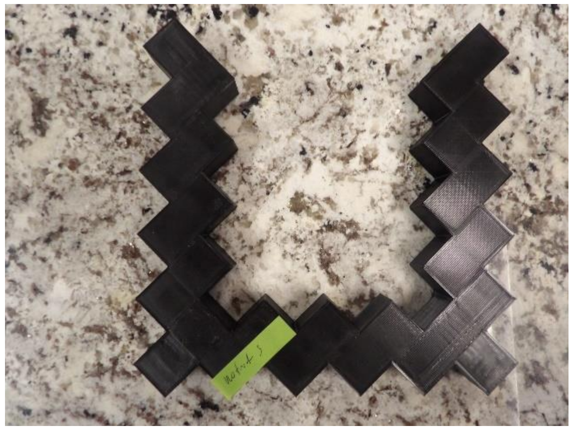

Figure C. 15 20°C 3 Top View

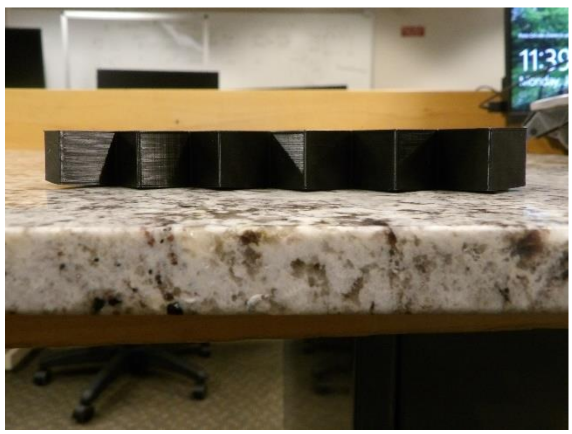

Figure C. 16 60°C 1 Right View

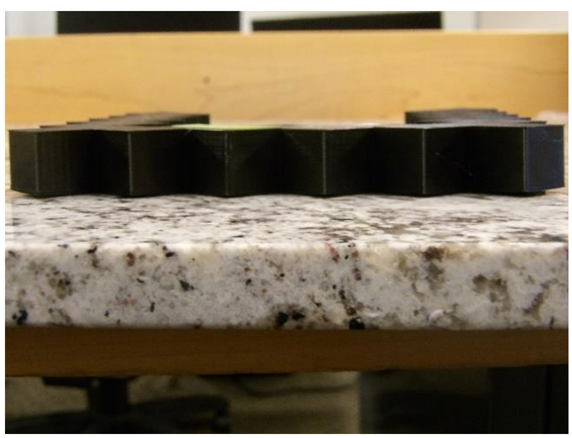

Figure C. 17 60°C 1 Back View

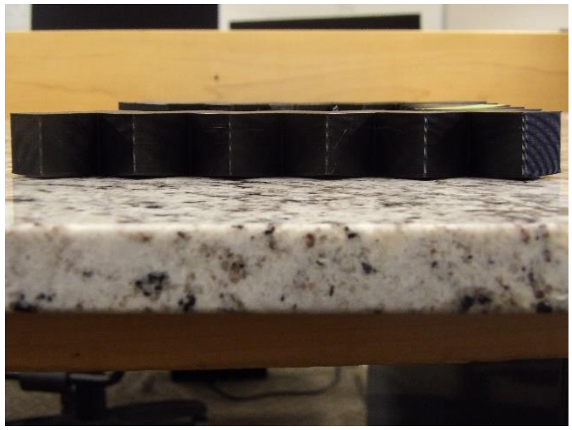

Figure C. 18 60°C 1 Left View

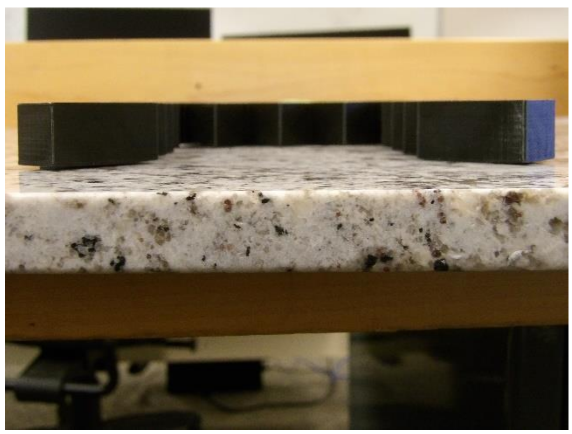

Figure C. 19 60°C 1 Front View

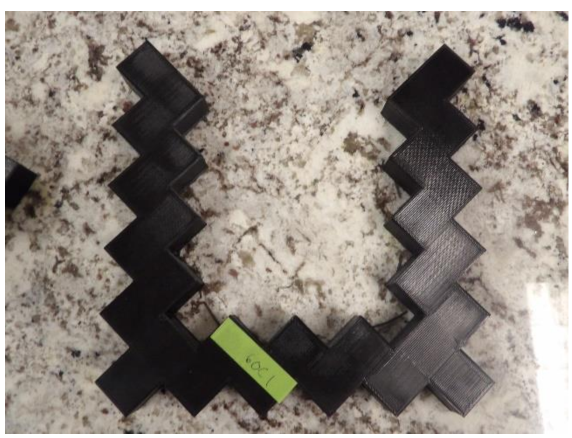

Figure C. 20 60°C 1 Top View

Figure C. 21 60°C 2 Right View

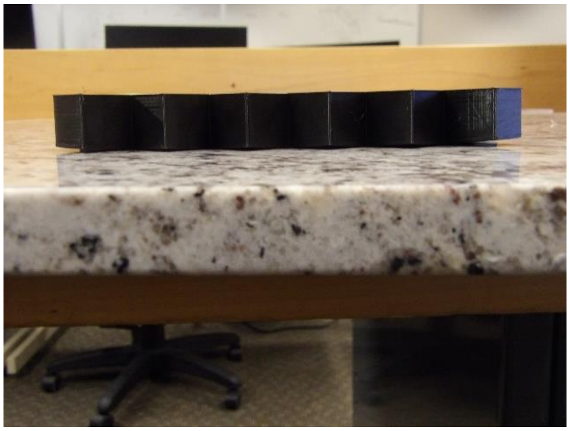

Figure C. 22 60°C 2 Back View

Figure C. 23 60°C 2 Left View

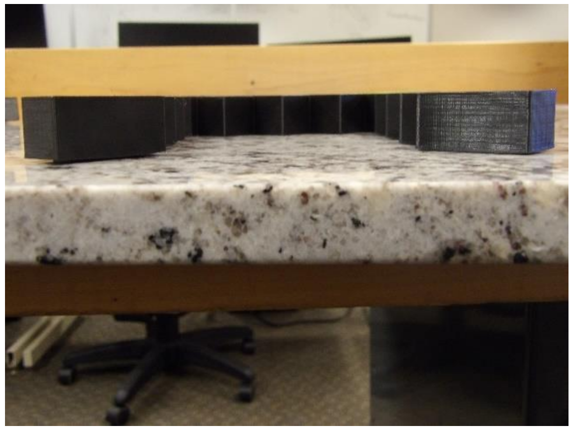

Figure C. 24 60°C 2 Front View

Figure C. 25 60°C 2 Top View

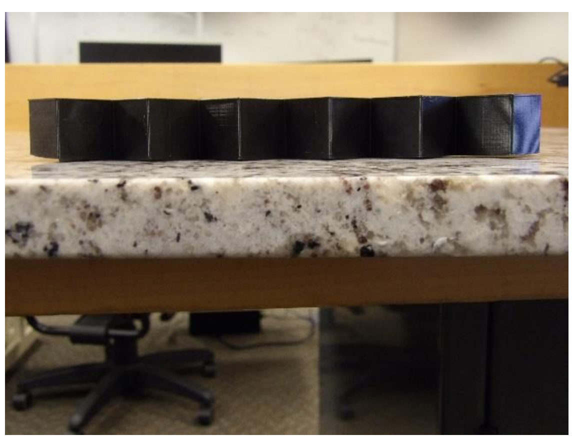

Figure C. 26 60°C 3 Right View

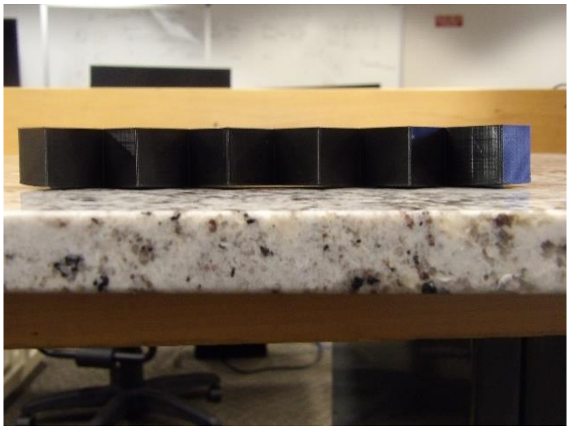

Figure C. 27 60°C 3 Back View

Figure C. 28 60°C 3 Left View

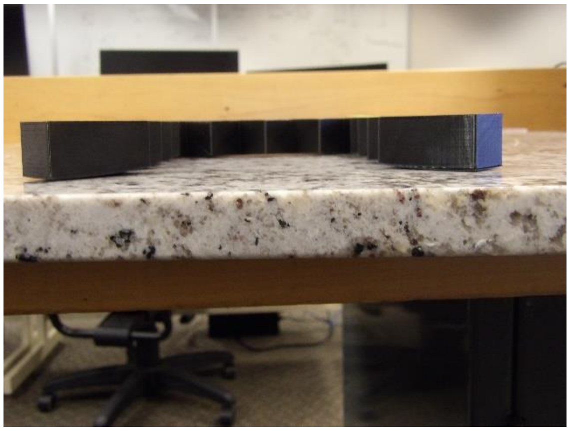

Figure C. 29 60°C 3 Front View

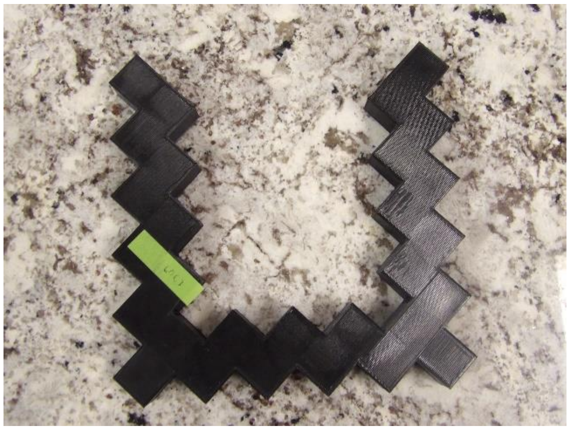

Figure C. 30 60°C 3 Top View

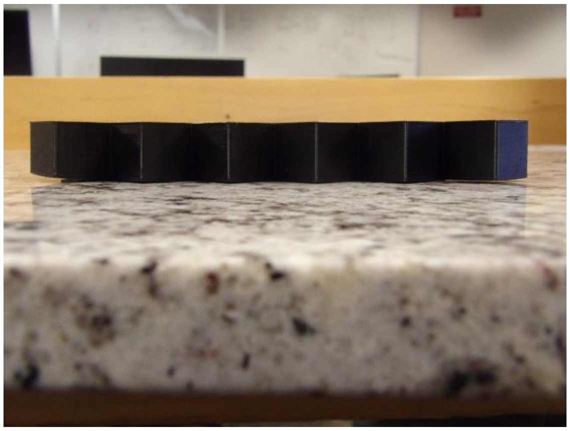

Figure C. 31 65°C 1 Right View

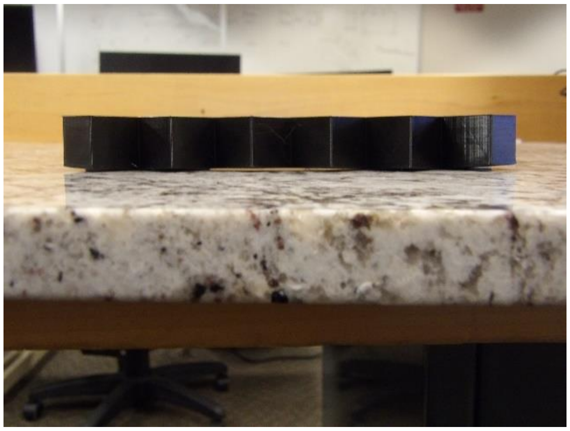

Figure C. 32 65°C 1 Back View

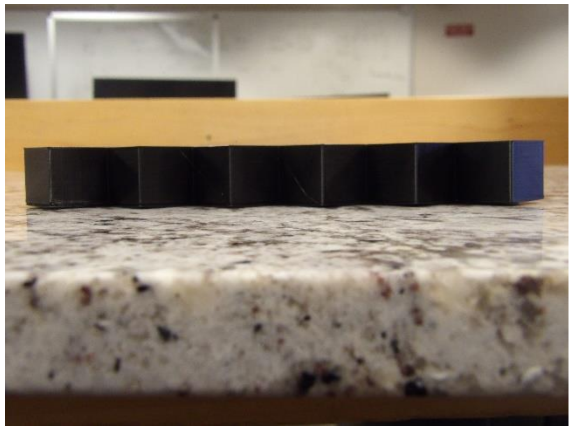

Figure C. 33 65°C 1 Left View

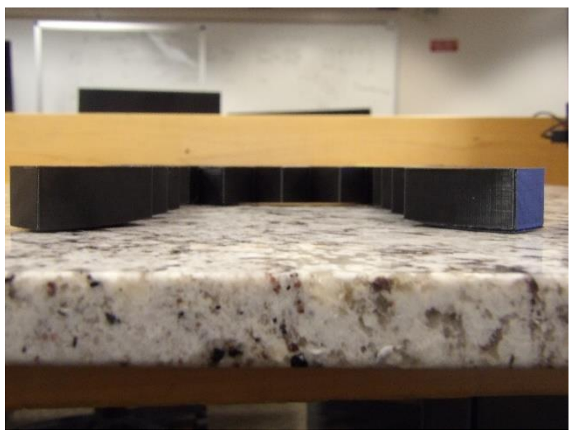

Figure C. 34 65°C 1 Front View

Figure C. 35 65°C 1 Top View

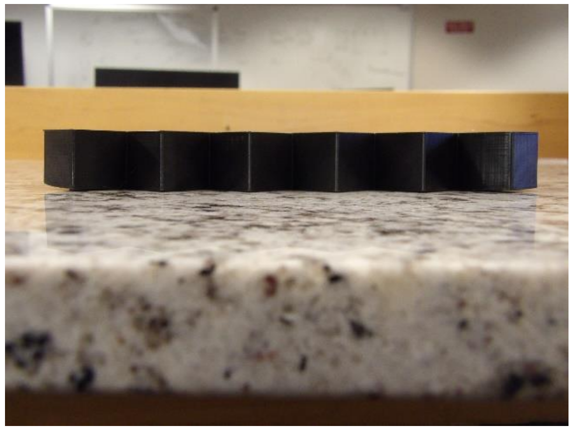

Figure C. 36 65°C 2 Right View

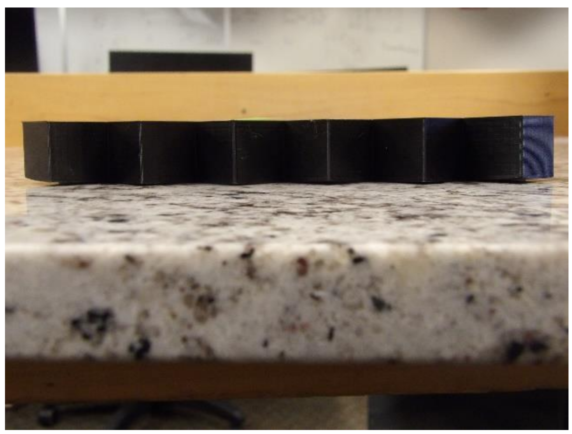

Figure C. 37 65°C 2 Back View

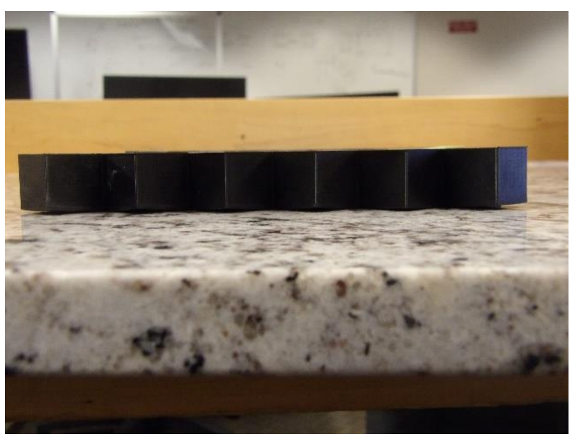

Figure C. 38 65°C 2 Left View

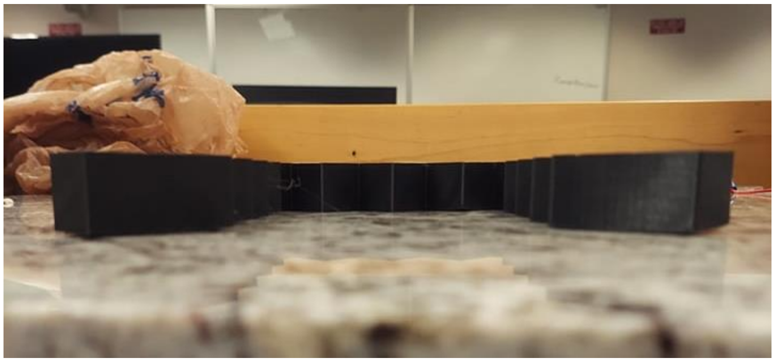

Figure C. 39 65°C 2 Front View

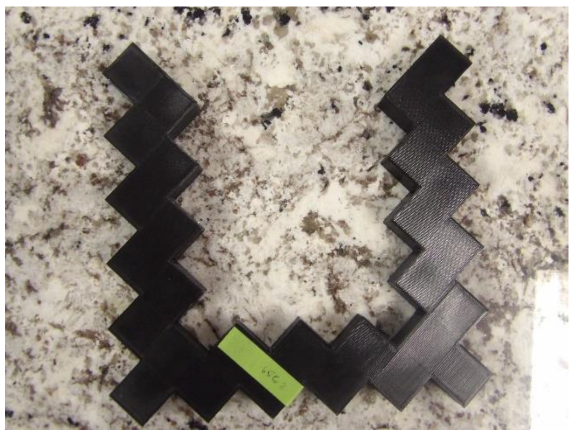

Figure C. 40 65°C 2 Top View

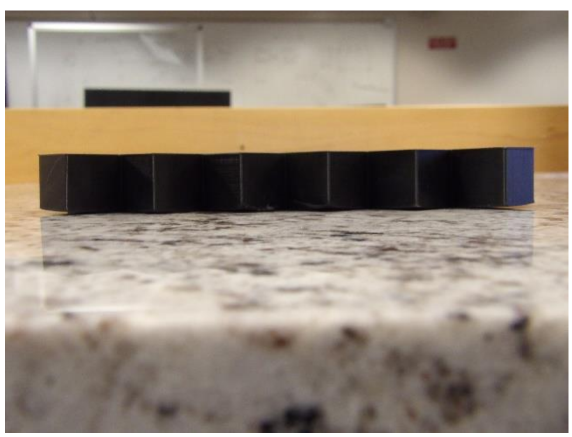

Figure C. 41 65°C 3 Right View

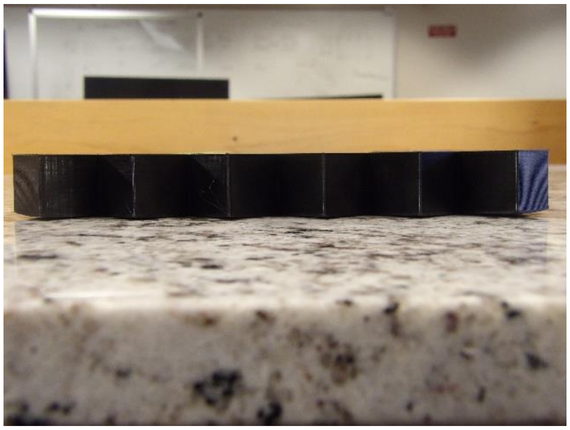

Figure C. 42 65°C 3 Back View

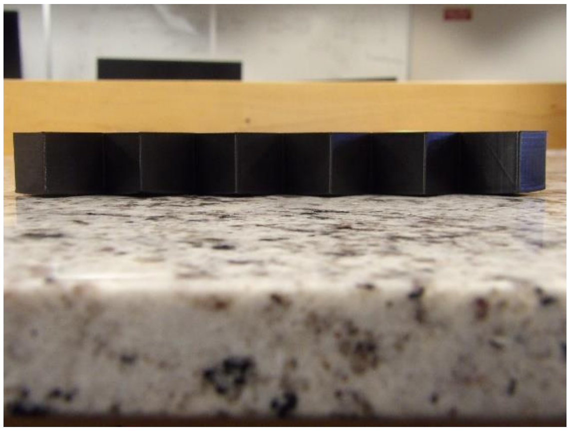

Figure C. 43 65°C 3 Left View

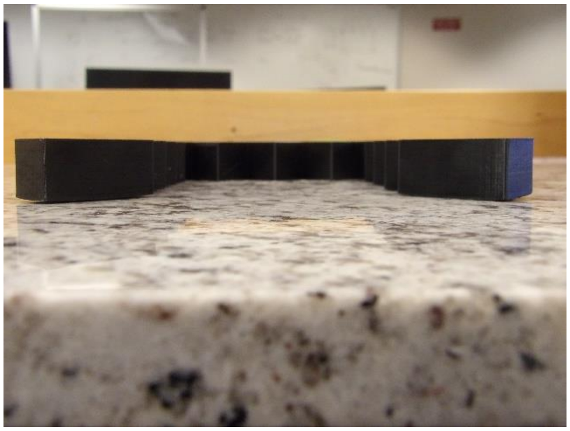

Figure C. 44 65°C 3 Front View

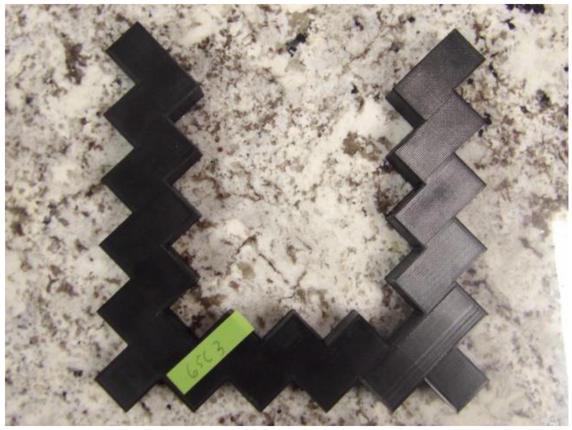

Figure C. 45 65°C 3 Top View

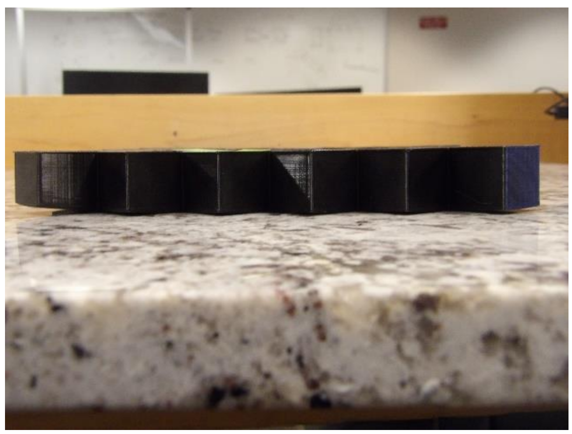

Figure C. 46 70°C 1 Right View

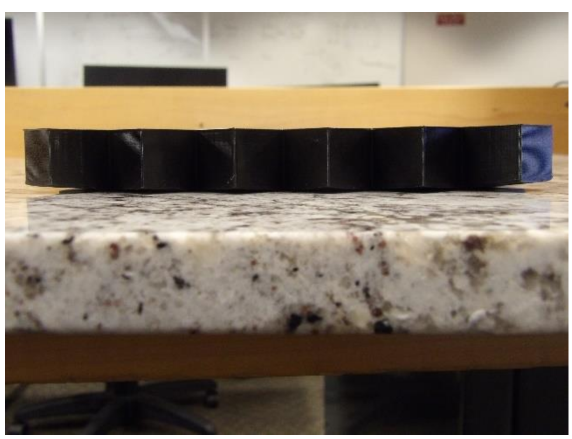

Figure C. 47 70°C 1 Back View

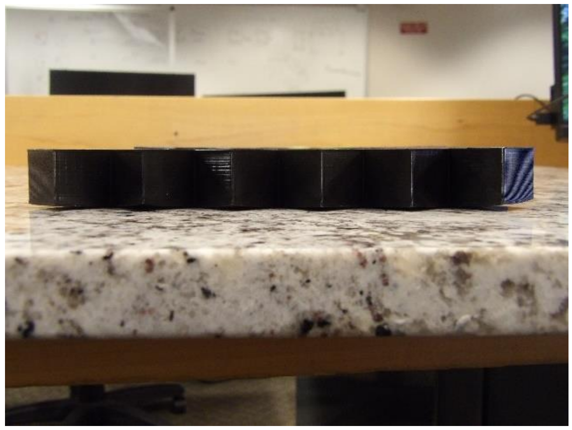

Figure C. 48 70°C 1 Left View

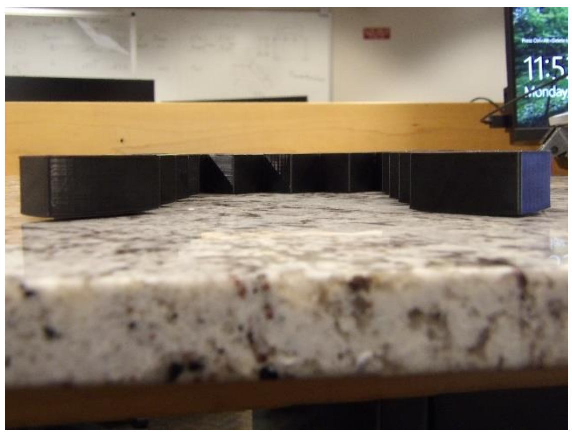

Figure C. 49 70°C 1 Front View

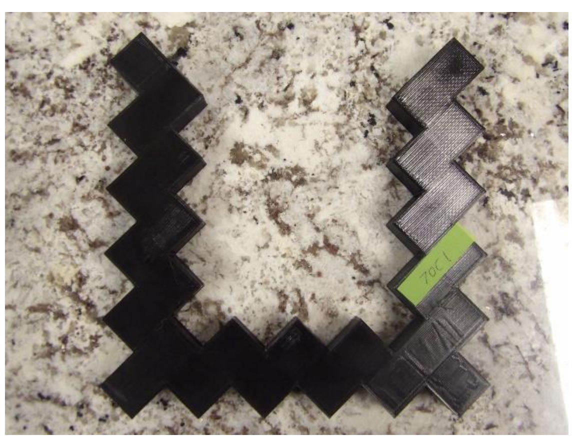

Figure C. 50 70°C 1 Top View

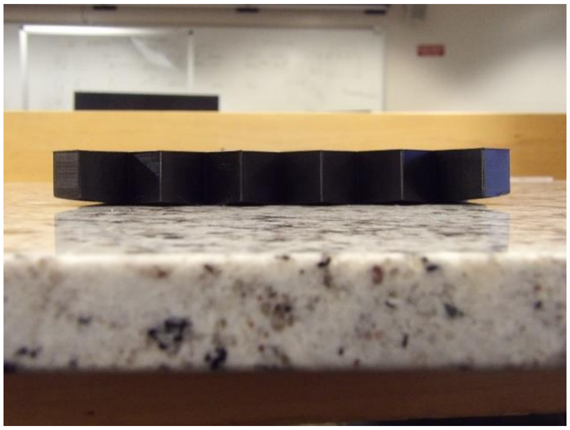

Figure C. 51 70°C 2 Right View

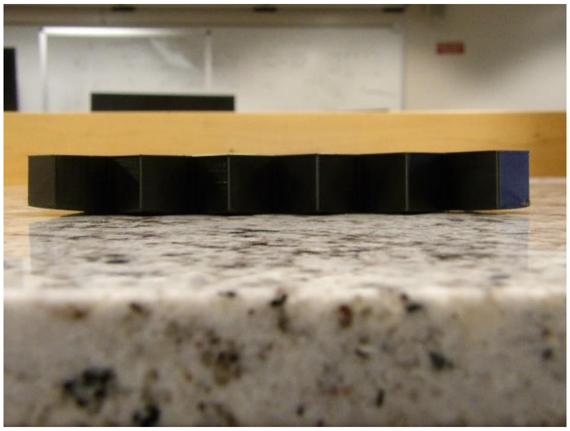

Figure C. 52 70°C 2 Back View

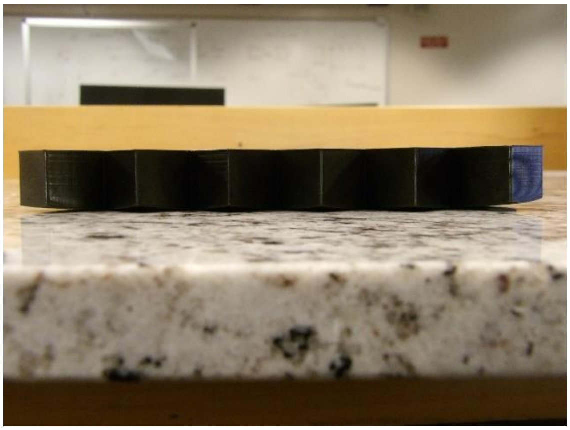

Figure C. 53 70°C 2 Left View

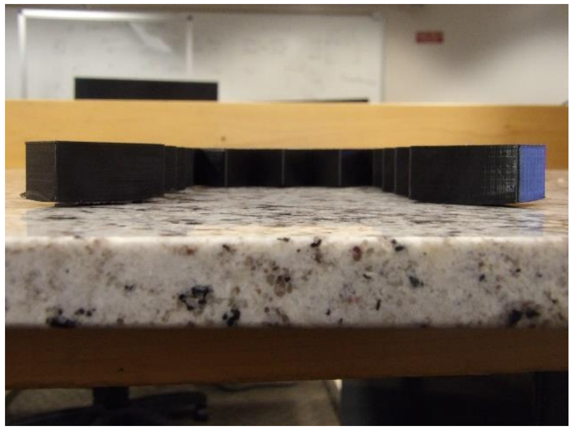

Figure C. 54 70°C 2 Front View

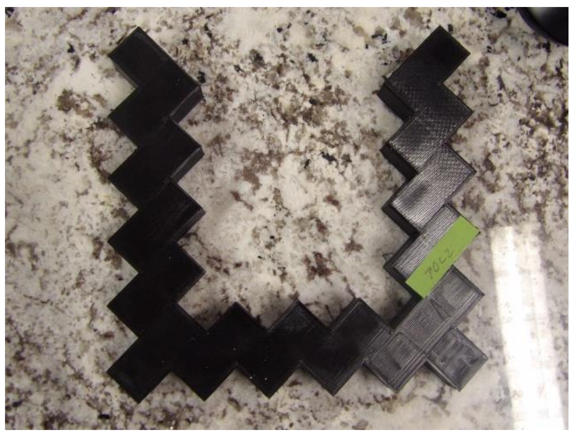

Figure C. 55 70°C 2 Top View

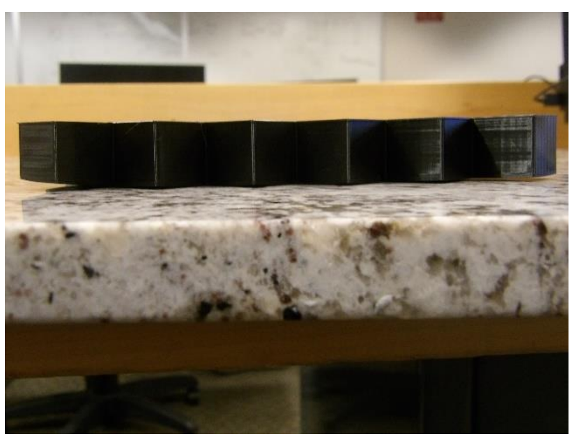

Figure C. 56 70°C 3 Right View

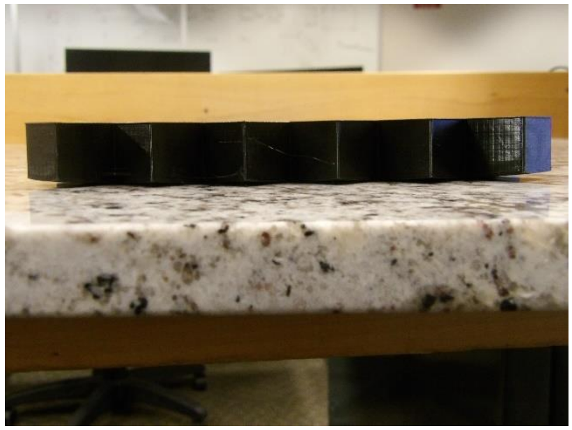

Figure C. 57 70°C 3 Back View

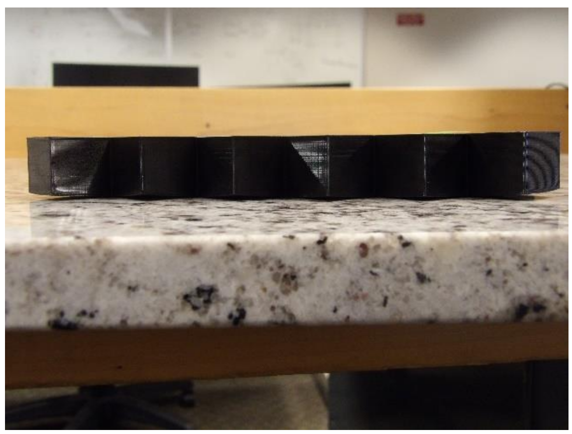

Figure C. 58 70°C 3 Left View

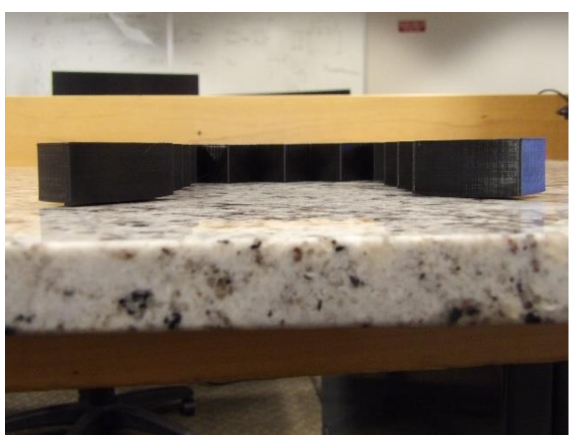

Figure C. 59 70°C 3 Front View

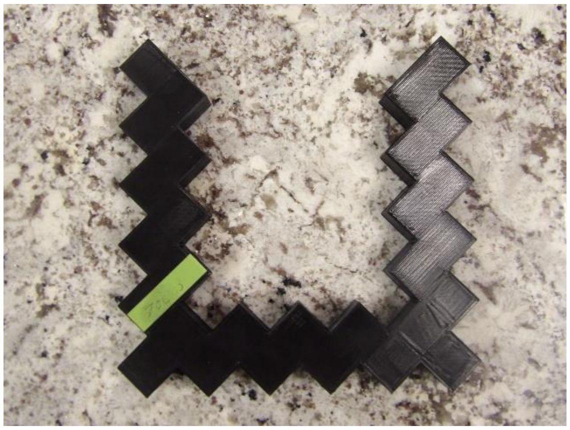

Figure C. 60 70°C 3 Top View

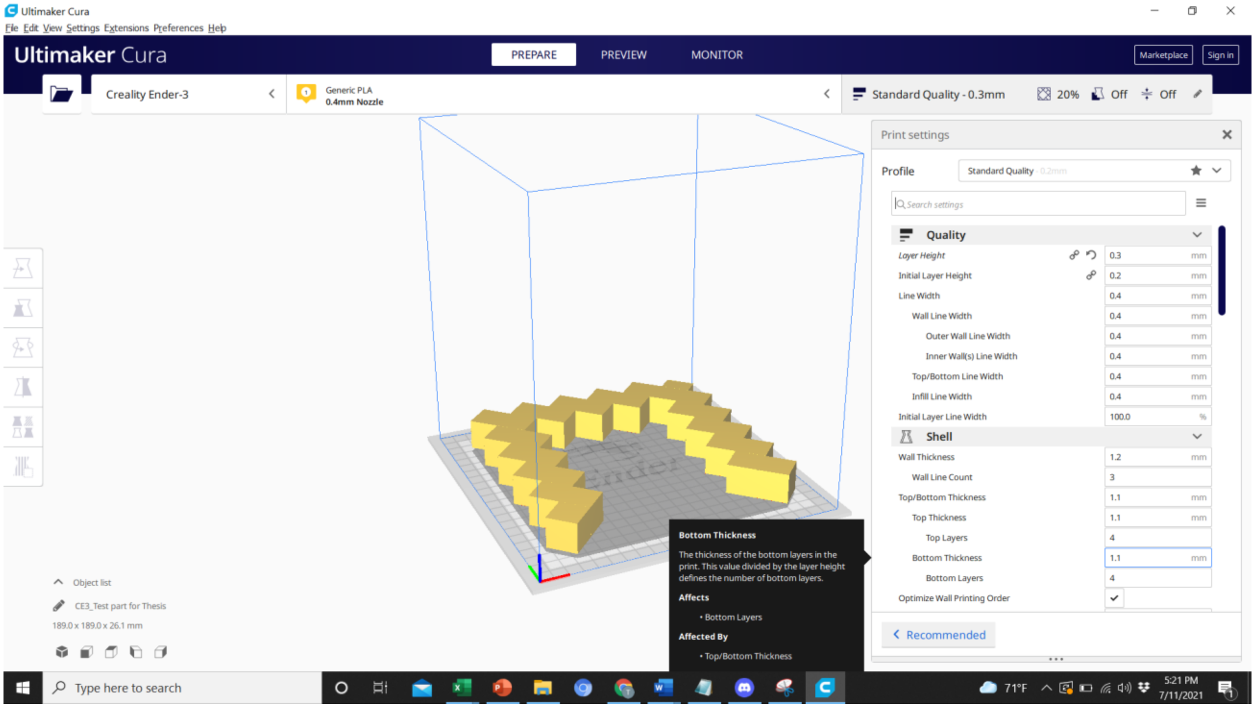

Figure C. 61 Cura Settings 1

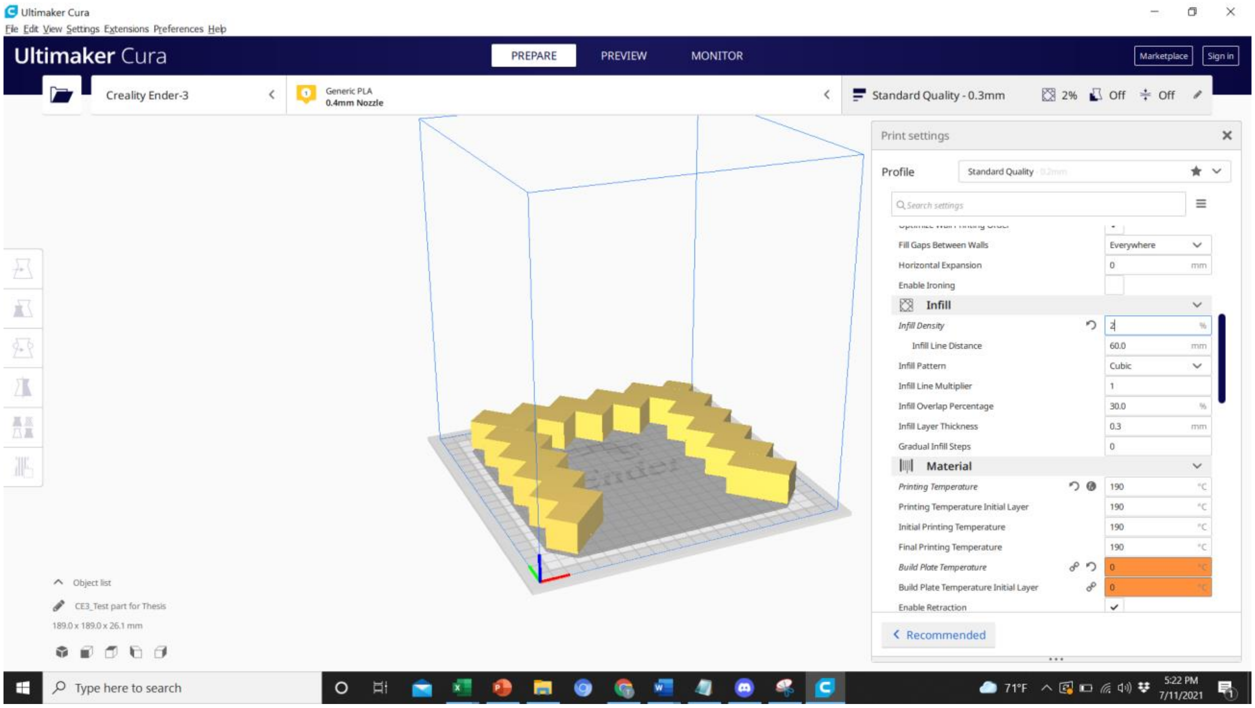

Figure C. 62 Cura Settings 2

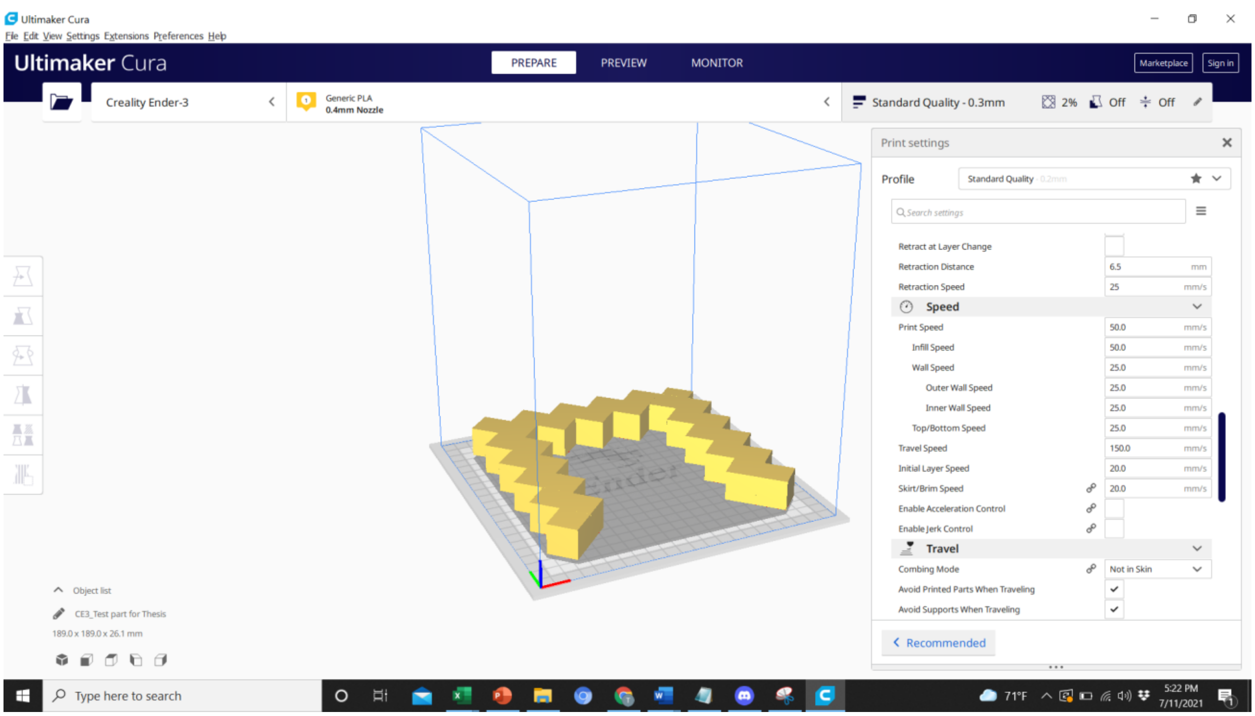

Figure C. 63 Cura Settings 3

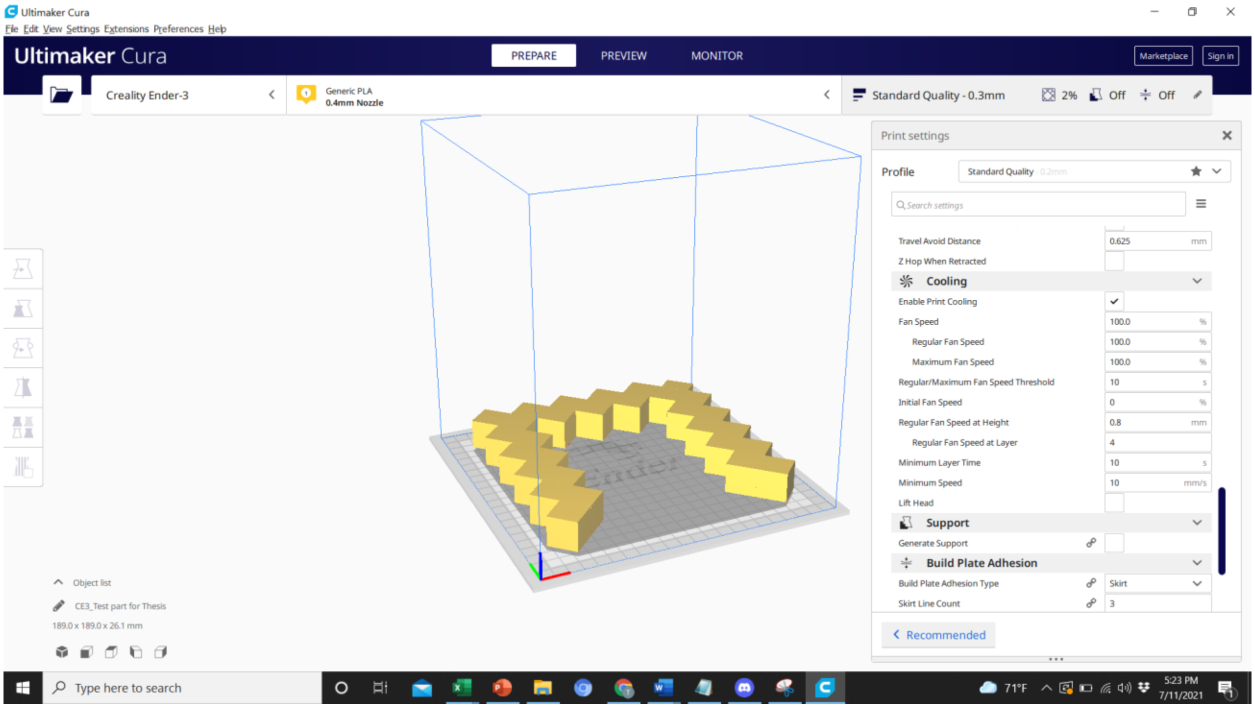

Figure C. 64 Cura Settings 4

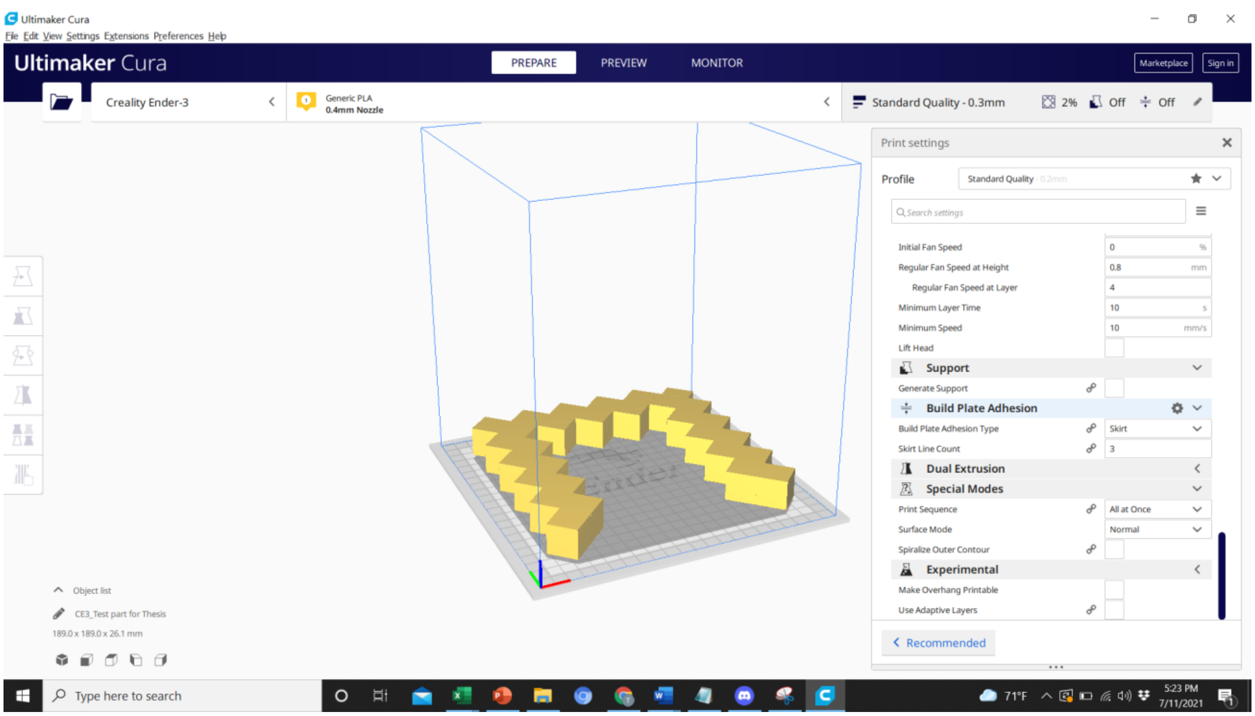

Figure C. 65 Cura Settings 5