

Improving the Mechanical Performance of 3D Printed Parts Using
Fused Filament Fabrication

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Abstract

The 3D printing industry has seen rapid growth in the last 10 years and has been called the next industrial revolution. There are several different processes used in 3D printing, but the most popular process is called Fused Filament Fabrication (FFF) or Fused Deposition Modeling (FDM). This is the process where (most commonly) plastic filament enters a nozzle, is heated to a semi-liquid state, and then deposited into a pattern to create a print. One major drawback to this process is that the prints are anisotropic. This means that the strength of the part varies on the orientation that it was created. This project experimented to determine if a proposed post processing method would decrease the anisotropy in the FFF process. The proposed process involved using a high intensity lamp to flash the print after each layer is printed. The theory was that this would decrease the gap between deposited filaments and from research this was a proven way to make prints stronger.

For this project, a Xenon Sinteron 2000 was used as the high intensity lamp and a Printbot Simple Metal Plus was used as the 3D printer. Three experiments were done to determine if the Sinteron would be successful in reducing the gap between deposited filaments. The first experiment was done by flashing the surface of completed prints and then using a portable microscope to measure the height of the surface layer and necking between deposited filaments. The data were analyzed using a two-way ANOVA and the results did not conclude that the Sinteron was successful in reducing the gap. The second experiment was analyzed visually using an optical microscope and revealed that Sinteron might be able to reduce the gap on parts that are solid. The third experiment was analyzed using an optical microscope and the area of the gaps were measured using ImageJ software. The results concluded that the Sinteron was not successful in reducing the gap.

The quantitative data from these experiments suggest that the proposed processing method would not be successful in reducing the anisotropy of 3D printed parts created by the FFF process. The recommendation is to investigate post processing methods such as a heat gun that would apply heat evenly across a layer.

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1. Introduction

Type in 3D printing on google and click on the news tab. You will be amazed at the amount of creativity and innovation being done currently using this technology. From printing houses [1] to guns [2], 3D printing allows user to create anything they can imagine and model. In the past few years, the industry has grown tremendously. Crowdfunding has increased the number of desktop printers owned by hobbyists and continues to push the boundaries on the affordability and capability of these machines.

The most popular process for desktop printing is Fused Filament Fabrication (FFF) or Fused Deposition Modeling (FDM). This is the process where filament is heated and then deposited side by side then layer by layer. The advantages to FFF/FDM vary depending on what process it is compared to, but overall these machines have good resolution, are inexpensive, and material changeover is done easily. The disadvantages to FFF/FDM include the surface finish, the consistency between prints, and the biggest disadvantage which is mechanical performance. Surface finish can be resolved with exterior finishing techniques, and the consistency issue can be fixed by properly calibrating the machine. Mechanical performance however, still does not have a clear solution.

So how is mechanical performance an issue in the FFF/FDM process? The process creates prints that are anisotropic, so the strength varies on the direction of the print. This can be better explained using wood as an example. Wood is anisotropic because it is easier to cause a failure if you apply a force against the grain versus along the grain. Similar to wood, 3D prints have individual deposited fibers called rasters. An illustration of the FFF/FDM process can be seen below (Figure 1). As explained previously, filament is extruded side by side and the process is repeated layer by layer.

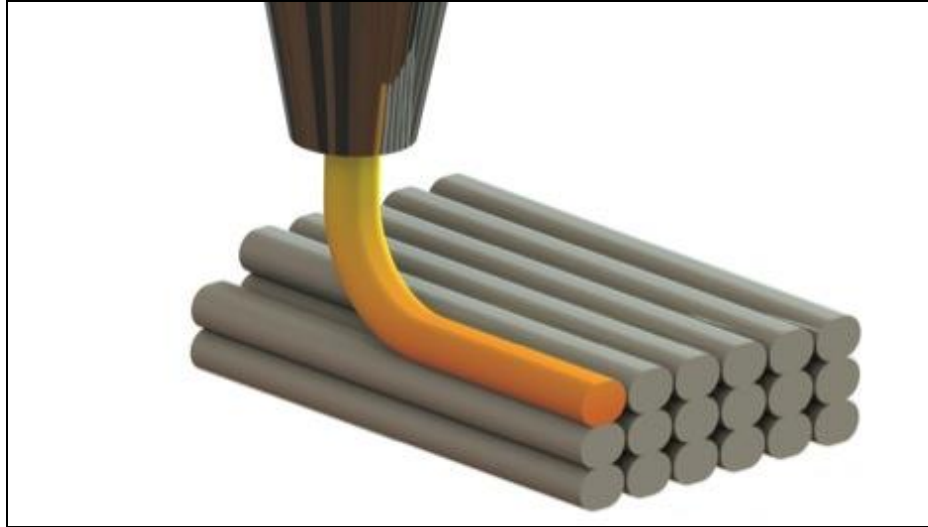


Figure 1: FFF/FDM process with nozzle extruding material onto print. (Source: www.3devo.eu)

Similar to the wood analogy, parts produced using the FFF/FDM process are anisotropic. The anisotropy is not as extreme as in the wood example, but industry and researchers agree that it is present. For example, Shaffer et al. (2014) write that the mechanical performance is limited due to the anisotropic properties of the process. The anisotropy occurs because of the way the parts are created. The process requires filament to be fed into a nozzle, heated, and then extruded and deposited onto a print. The material that is extruded is thin and “deposited in a criss-cross manner resulting in direction dependent, or anisotropic, material properties” (Ahn et al. 2002).

Loading along the raster is fairly strong but loading perpendicular to the raster (across the joints) will cause a part to fail much earlier. This is because the strength of the joint is weaker than the strength along the filament. Another issue is that “an FDM part can be considered as laminated composite structure with vertically stacked layers of bonded fibres” (Casavola et al, 2015). What this means is that the layers are stacked above one another. First one entire layer is printed, then the nozzle is moved up, and then another layer is printed. This process repeats until the print is finished. The issue with this is that the bond in between layers is very weak.

Researchers have investigated the issues and currently there are two distinct solutions. The first solution is optimization of the printing parameters. These parameters include raster angle, nozzle temperature, air gap, build orientation, material, layer height, and many other factors (Lanzotti, Sood, Sung-Hoon Ahn, Bagsik). Most researchers have

found that certain factors are more significant than others, but mechanical performance is still limited and lacking when compared to other manufacturing methods such as injection molding (Sung-Hoon Ahn et al, 2002). This has resulted in industry turning to post processing to address this issue.

Post processing is a method of adding a process after the part is printed to improve the mechanical performance. One post processing method is resin infiltration. In this process, the surface of the part is coated with a resin. The resin infiltrates the part and hardens to create a part that is stronger. Some even submerge the entire print in a resin bath to make it stronger [3]. Resin infiltration is the most accepted post processing method used in industry but is time consuming. The curing time is dependent on the size of the part but is often longer than the time required to print the part.

Another post processing method developed by researchers is using fill compositing (Belter et al, 2014). In this method, the parts are printed with intentional voids. These voids are then later injected with a resin to strengthen them. This method was able to improve the part strength up to 45%.

Hobbyists often submerge the part in an acetone bath to improve the surface finish, and it is also believed that this method increases the strength of the part. Research was very limited until 2015, when Rao et al, investigated the effects of post processing with acetone and methyl ethyl ketone (MEK) on the tensile strength. The results concluded that there was an increase on the tensile strength due to post processing with these chemicals.

All of these post processing methods might seem very different from each other but they are similar in one important aspect. The reason why these methods work is because what they are effectively doing is filling in gaps between rasters and layers. The resin infiltration method fills in these gaps, and then hardens similar to glue. Fill compositing does the same thing but the gaps are filled in where the voids are intentionally made. The acetone and MEK method works by eating away at the surface of the part and leaving a smooth surface finish. This surface finish is smooth and the adhesion between rasters is stronger.

These methods have the ability to improve the mechanical performance, but it should be noted that these methods also increase the processing time for each part. In order to make 3D printing a technology that is used to manufacture on a larger scale, a solution needs to be produced that will improve the mechanical performance while also minimizing the total process time. Due to these requirements demanded by industry, this paper is focused on experimenting with a new post processing method to improve the mechanical performance of 3D printed parts.

My interest in 3D printing and experimentation is what led me to this project. The idea for this project was introduced to me by Dr. Xuan Wang. Dr. Wang previously experimented with a high intensity lamp to see the effects that it would have on a part that was created with ABS. The result of his experiment concluded that the lamp did have enough energy to melt the surface of an ABS part.

This new processing technique will involve exposing layers to a high intensity lamp. This high intensity lamp will melt each layer to form a stronger bond between adjacent rasters and layers. This would hopefully create layers that are homogenous and reduce the anisotropic properties of the FFF/FDM process.

2. Background

There are several different technologies used in 3D Printing. An overview of some of the technologies is given below

- Fused Deposition Modeling (FDM) or Fused Filament Fabrication (FFF) is the process where filament is heated, then deposited side by side and layer by layer. This is the most popular printer technology among hobbyists because of its affordability. There are two names for this technology because of a trademark on FDM by Stratasys, a large 3D printer manufacturer. For this report FFF and FDM will be used interchangeably.
- Selective Layer Sintering (SLS) is the process of using a high power laser to fuse powders together. Powder is laid across a bed and the laser draws a pattern on the bed. The powders fuse together and then the bed is lowered. A new layer of powder covers the print and the process is repeated.
- Laminate object manufacturing (LOM) is a process where sheets of paper with glue on one side are cut and then stacked layer by layer. These cuts are made wither by knife or laser.
- PolyJet is a process similar to inkjet printing. In the 3D printing process though, the inkhead jets a resin and UV light is used to instantly cure the resin.

There are just some of the 3D printing technologies being used in industry today. The scope of this project will focus on FFF/FDM technology. Specifically, this project will be using a Printrbot Simple Metal with a heated bed. A picture of this machine is shown below (Figure 2)

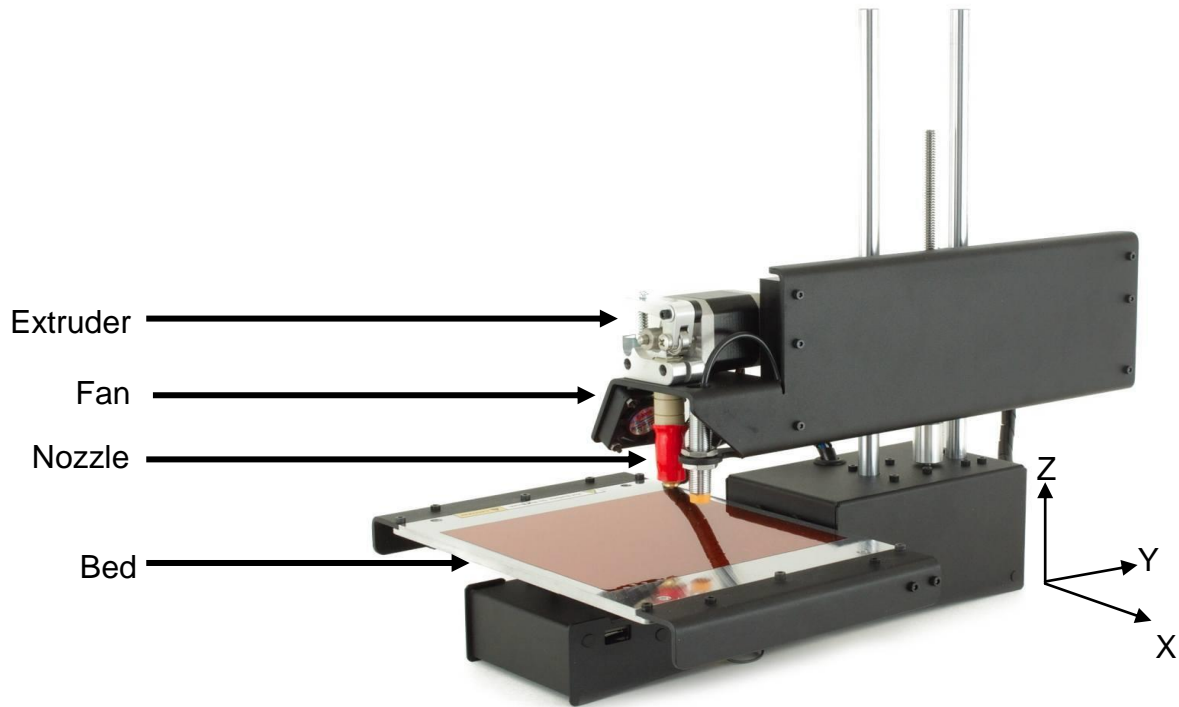


Figure 2: Printrbot Simple Metal with heated bed. (Source: www.primtrbot.com)

The image above (Figure 2) outlines the important features and components that make up the printer. The extruder motor is responsible for feeding the filament into the nozzle. The fan is used to cool down the material as it is deposited onto the print. The bed is the surface that the first layer adheres to. There are stepper motors for each axis of the printer. The X-axis motor is responsible for the movement of the bed. The Y-axis motor is responsible for the movement of the nozzle. The Z-axis is responsible for the height of the nozzle.

2.1 Vocabulary

An explanation of technical terms is given below.

- Anisotropic: Having varying properties depending on direction.
- Layer thickness: Also referred to as filament height, bead height, or raster height. This is the height of the filament when it is extruded onto a print.
- Raster: The filament that occupies the internal space of a part.
- Raster width: Thickness of the filament that occupies the internal space of a part.

- Raster angle: Also referred to as infill orientation. This is the angle the raster is laid down in respect to an axis.
- Shell: The filament that makes up the perimeter or outline of the part. The difference between raster and shell is that the shell looks like the outline of the part.
- Air gap: Usually refers to the raster-to-raster air gap. This is the distance in between two adjacent rasters.
- Shell width: Width of the shell. Similar to raster width.
- Perimeter-to-raster air gap: Distance between the shell and the raster.

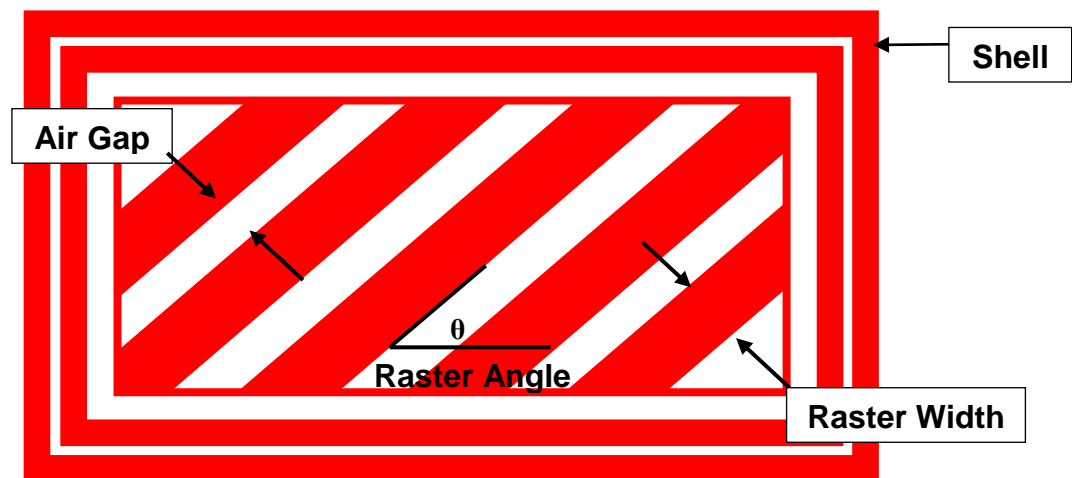


Figure 3: Single layer of a part created by the FFF process.

3. Literature Review

Researchers agree that the shortcomings of FFF include the lack of strength. In one research paper Shaffer et al. (2014) write that “FFF 3D printing is increasingly becoming a vital tool in many industries for its ability to produce a wide range of physical parts quickly, but the quality of the printed parts are lacking the strength, toughness, and reliability of parts manufactured through injection molding or milling”. Researchers across the world recognize that this is an issue and there are numerous experiments that have been conducted to learn about what parameters affect the mechanical performance of these parts.

Lanzotti et al. (2015) researched the impact of process parameters on the mechanical properties of PLA parts printed by an open-source 3D printer. A FFF desktop printer was used in this experiment to investigate the effects of layer thickness, raster angle, and shell perimeters on the Ultimate Tensile Strength (UTS). The experiment concluded that all three factors had a significant effect on the UTS. Analysis revealed that UTS increased when; raster angle decreased (parallel to loading line), number of shells increased, and layer thickness increased up to 20mm. Optimization was done and the parameter settings to maximize UTS for layer thickness, raster angle, and shell perimeters are 0.20mm, 0.00° (parallel to loading line), and 2.645 shells.

Raster angle is one of the parameters that significantly affects the mechanical performance. The optimization result for raster angle obtained by Lanzotti et al, (2015), agrees with the research done by Sood et al. (2011). In this experiment, the effects of orientation, layer thickness, raster angle, raster width and air gap were investigated on the compressive strength. The results concluded that raster width does not have a significant effect on the compressive strength. The remaining factors had interactions with one another so the main effects could not be interpreted. Optimization was done using Particle Swarm Optimization (PSO). The maximum compressive strength is achieved with setting layer thickness, orientation, raster angle, raster width, and air gap as 0.254mm, 0.036 °, 59.44°, 0.422mm, and 0.00026mm respectively.

Sung-Hoon Ahn et al. (2002) investigated the effects that process parameters have on the anisotropic properties. An experiment was conducted to test the effects of air gap, raster

width, nozzle temperature, ABS color, and raster angle on the tensile strength. Results concluded that air gap and raster angle are the only factors that significantly affect the tensile strength. All other factors were removed and focus was shifted to air gap and raster angle. The raster angle that resulted in the highest tensile strength regardless of the air gap setting was 0° (parallel to loading line). The raster angle setting that had the lowest tensile strength was 90° (perpendicular to the loading line). This is intuitive because the tensile load in these specimens only need to overcome the joint between filaments which is weak. Decreasing the air gap to -0.003inch (overlap) increased the tensile strength across all raster angle settings. However, it is important to note that a negative air gap can result in imperfections. This is due to the overlap of material causing raised heights on the layer surface. Another consideration is that the results of this experiment only valid for air gap between 0.000inch and -0.0003inch. The results should not be extended beyond this range.

Bagsik et al. examined the effects of raster angle, raster width, raster to raster air gap, perimeter to raster air gap, and build orientation on the tensile strength. The material used in this experiment was Polyetherimide. The experiment concluded that the maximum tensile strength was achieved using a negative air raster air gap. One major drawback to this experiment is that statistical analysis was not performed with the data. The analysis was performed by plotting points on a radar chart. Therefore the only conclusion that will be drawn from this experiment is that build direction plays a significant effect on the tensile strength.

Dawoud et al. (2015) investigated the effect of printing parameters on the mechanical behavior of virgin ABS. Part samples were made either by an injection molding (IM) process or FDM process. The density, tensile strength, flexural strength, impact strength, and dimensional accuracy were compared between these processes. In addition some printing parameters were varied for different tests. When density was compared between the processes, it was concluded that using a FDM process with negative airgap (-0.05m) resulted in a density that 98% of the maximum IM density. FDM parts produced with a positive air gap resulted in the lowest density.

Research has been done all over the globe on the printing parameters and most researchers will agree that raster angle and air gap are the most important parameters that affect the mechanical performance. In 2002, Ahn et al. were the early researchers who investigated the anisotropic properties of FDM printed parts. Their experimentation led them to develop build rules for designing FDM parts. These build rules said to “build parts such that the tensile loads will be carried axially along the fibers” and to “use a negative air gap to increase both strength and stiffness”. Both of these statements have been fully supported by research done in the 3D-Printing industry. All of the literature review concluded that air gap is one of the most critical parameters to creating strong prints. Prints that were created with smaller air gaps outperformed those that were created with larger gaps.

4. Proposed Post Processing Method

This project will be investigating a new post processing method to improve the mechanical performance of 3D-Printed parts. This method would use a high intensity lamp to sinter each layer after printing. After sintering, we expect each layer to be homogeneous and a reduction in the anisotropic properties of the FDM process. The illustration below shows the step by step process of how this new process would work.

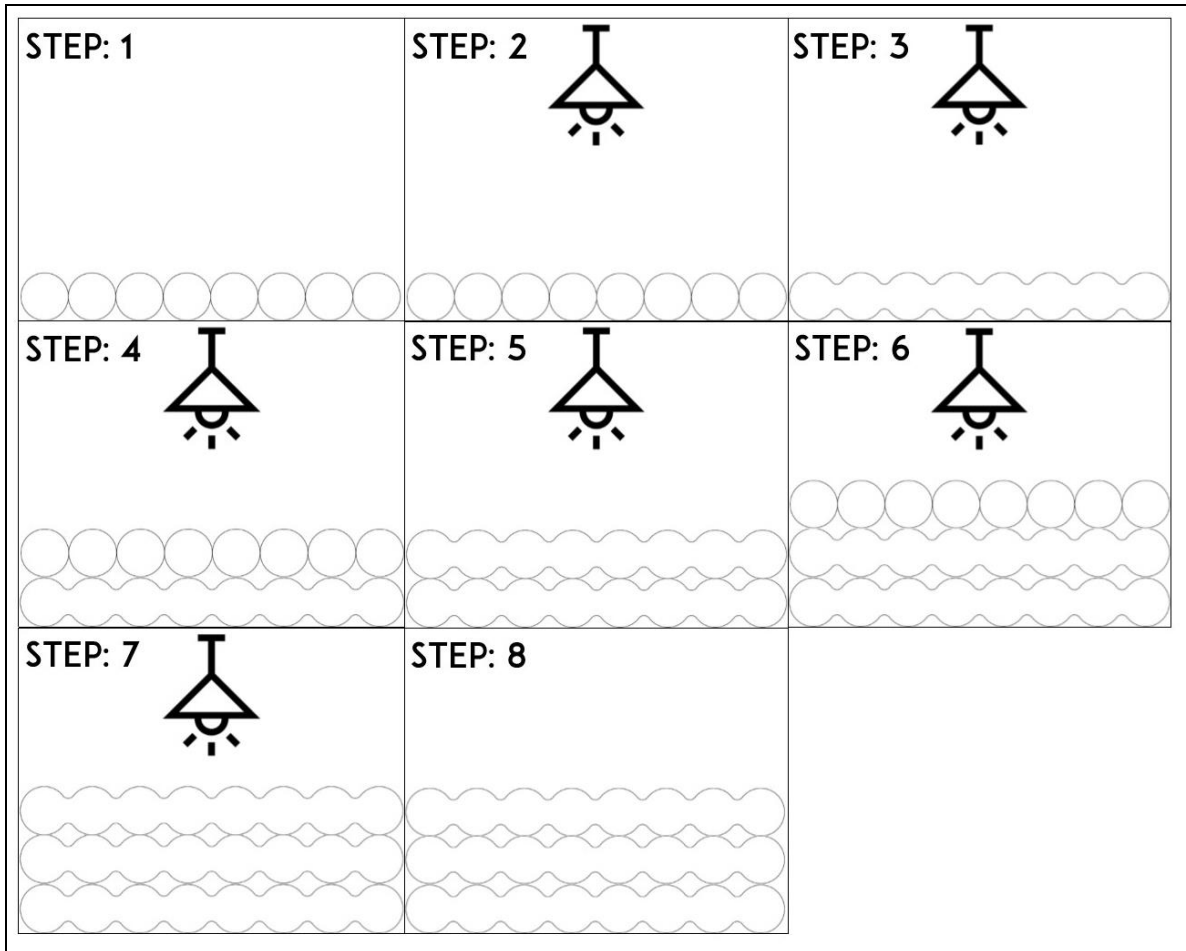


Figure 4: Step by step breakdown of proposed manufacturing process

In step 1, we see the cross section of the 1st (or bottom) layer of a print. This print would be exposed to a high intensity lamp as shown in step 2. After exposure, we expect the layer to be more homogenous as shown in step 3. In step 4 we print a new layer on top of the first layer. In step 5, the layer is exposed to the high intensity lamp. In step 6 we print another layer on top of the second layer. In step 7 we expose the top layer to the lamp. Step 8 would be the finished product. The step by step process detailed above only

demonstrates a 3 layer part. This new post processing method could be used for any number of layers.

5. Theory

Resin infiltration is a successful for improving the mechanical performance because the resin fills gaps between rasters and layers. A detailed explanation is given in the illustrations below.

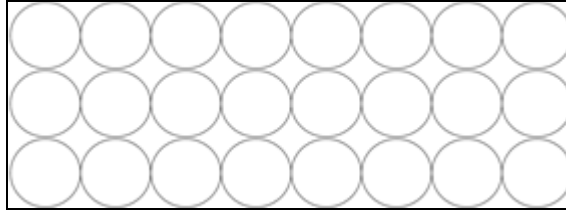


Figure 5: Illustration of a cross section for a part created using the FFF process. Post processing has not been done to this part.

Notice the gaps between rasters and layers in Figure 5. The circles represent raster. The white space between each raster and layer represent empty space. These gaps are present in parts that do not undergo any post processing. Failures are caused by applying enough force to break apart these bonds.

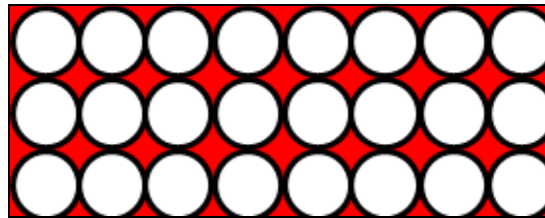


Figure 6: Illustration of a cross section for a part created using the FFF process. Post processing has been done to this part.

Figure 6 illustrates a part that has undergone resin infiltration. The gaps are now filled with resin and the part is much stronger. The red coloring in this illustration represents the resin. The resin fills in the empty space between rasters and layers, strengthening the part. This project used a different approach to improve the mechanical performance.

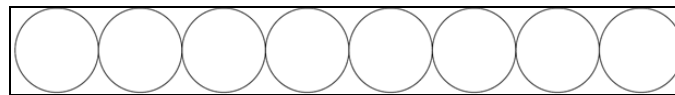


Figure 7: Cross section of a single layer.

As mentioned previously, parts that are not post processed have gaps between rasters. This is illustrated for a single layer in Figure 7. It is believed that the high intensity lamp will sinter the layer, creating a better bond between rasters and layers. The single layer is expected to look like Figure 8 after being sintered.

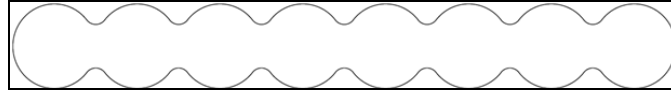


Figure 8: Layer after being exposed to high intensity lamp.

There might still be a gap from layer to layer adhesion, but if this post processing methods works, it will greatly reduce the gap.

6. Experimentation

Three experiments were conducted and a breakdown of each experiment is listed in the respected section. A trial experiment was first conducted to find the operating window for the factors. There are several different input factors that could be changed for these experiments. In order to avoid scope creep, four factors were originally planned for the experiments. These factors are exposure time, exposure height, exposure voltage and number of pulses.

6.1 Trial Experiment

Since this method has not been tested before, a screening experiment was conducted to determine the operating window for the various factors.

This experiment was done with the help of Samuel Vierra, who volunteered to help in exchange for credit in another class. After reading documentation on the machine, it was determined that the exposure time was fixed and could not be changed. A decision to fix the exposure distance to 1.5 inches was also made because changing the exposure distance requires significant time. This left 2 factors to experiment with; voltage and number of pulses. The machine had a low voltage setting at 1600V and a high voltage at 3600V. The number of pulses was manually controlled so there was no limit to this factor.

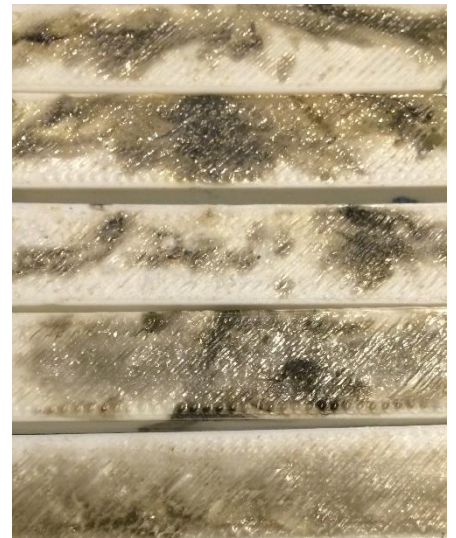


Figure 9: Test specimens from the screening experiment

Test specimens used for the trial experiment were older parts that were printed for an earlier experiment. Voltage and number of pulses were varied until there was a visual effect on the surface of the print. This screening experiment was very beneficial to understanding the process and all of the variables that could affect our results. The following are the key takeaways from the screening experiment.

- Contamination of oils and ink on the part surface increases the likelihood of a burn occurring.
- High voltage causes burns on the surface.
- High number of pulses combined with a low voltage creates a smooth surface.

The screening experiment gave us valuable information for the final experiment. Figure 9 is a picture of the specimens used in the screening experiment. Factor levels were raised until a burn occurred to determine the appropriate levels for the factors.

6.2 Experiment 1

Final design of the experiment resulted in two factors and four levels for each of those factors. The two factors chosen for the experiment were voltage and number of pulses. This resulted in 16 treatments. The response for this experiment was layer height and neck height. This would be measured using an optical microscope. We chose a sample size of 2 for this experiment. The decision to use two replicates instead of just one was made because the process was not stable and very sensitive to contamination. Using one replicate could give us results that are not representative of the process. Using JMP the runs were completely randomized. The decision to use four factors was a result of the screening experiment. This led us to believe that the window was actually somewhere between our low and high point.

Table 1: Factors and respective levels for experiment 1.

		Number of Pulses			
		10	13	17	20
Voltage (v)	1600	Treatment 1	Treatment 5	Treatment 9	Treatment 13
	1850	Treatment 2	Treatment 6	Treatment 10	Treatment 14
	2100	Treatment 3	Treatment 7	Treatment 11	Treatment 15
	2350	Treatment 4	Treatment 8	Treatment 12	Treatment 16

6.2.1 Manufacturing

All of the test samples were created on the same day. Lots of 16 samples were printed each time. To prevent contamination, gloves were used when handling each sample. After each lot was printed, they were cooled and then removed from the bed. They went into a plastic bag to prevent contamination during handling. An image of the manufacturing process is shown in the appendix (Figure A)

6.2.2 Exposure

Due to the burns observed on screening test samples, care was taken prevent contamination from oils and inks. Throughout the experiment, gloves were worn and only one experimenter ever handled the test samples pre-flash. Samuel handled all of the samples. Samuel loaded each sample onto the test bed and placed it under the lamp. Samuel then positioned himself at the door away from the test flashing. This allowed him to turn off the overhead lights during the flashing process and to prevent anyone else from walking in during the flash testing. Inderpreet adjusted the voltage and number of pulses for each sample. Upon confirmation of the test, Inderpreet would pull the test bed out of the machine while Samuel prepared an envelope marked with the voltage and number of pulses. The samples were cooled and Samuel would place it in the envelope with his right hand and tape it with his left hand. This was to ensure that the hand exposed to tape adhesive never touched the samples directly. An image of the Sinteron can be seen in the appendix (Figure B)

6.2.3 Measurement

The envelopes were shuffled and measurements were taken with a portable microscope. Gloves were worn during this process to make sure that contamination did not affect the results. The following is the procedure for measurement

1. Remove sample from envelope
2. Use scalpel to cut sample perpendicular to filament direction (Figure 14)
3. Place sample with cross section exposed up
4. Place microscope on top of cross section
5. Focus microscope to get clear image
6. Capture image and get measurements
7. Record measurement in computer

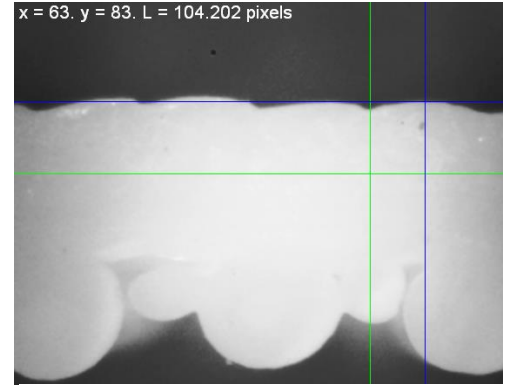


Figure 10: Layer height measurement from a sample.

6.2.4 Discussion

During the measurement process a major flaw was discovered in our experiment. The microscope that was used did not have the capability to tell the user what the exact magnification was at a specific time. This was very crucial to our experiment because measurements could not be compared to other measurements if we did not know the magnification. The microscope manufacturer was contacted about this issue and they confirmed this was an issue that most people had. They recommended purchasing a new tool that would solve this issue. Due to the time limitations, we had to determine another response that could be used.

As discussed in the earlier sections, the response was going to be layer height and neck height. Due to the issue with the microscope capabilities, we decided to change the response to be the neck height divided by the layer height. In the optimal case we would want the layer height and the neck height to be equal or a value of 1 for the response. This would result in a homogenous level layer. Samples can now be compared regardless of magnification

6.2.5 Analysis

ANOVA test will be used for this experimental analysis. Assumption for ANOVA were validated and the results are in the appendix (Figure C,D,&E). Normal quantile plot of the residuals revealed that the residuals do not appear to be normally distributed.

ANOVA is very robust so analysis will continue with all data points. Scatterplot of residuals did not reveal any trend. Independence was assumed. Residuals by predicted graph did not reveal any violations to the assumption for constant variance. The RSquared value was 0.07 indicating that the model was not very useful.

Table 2: ANOVA for the entire model.

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	3	0.00878737	0.002929	0.7040
Error	28	0.11649917	0.004161	Prob > F
C. Total	31	0.12528654		0.5576

From Table 2 above, the p value is greater 0.05. This indicates that the model is not significant. The parameters will still be analyzed.

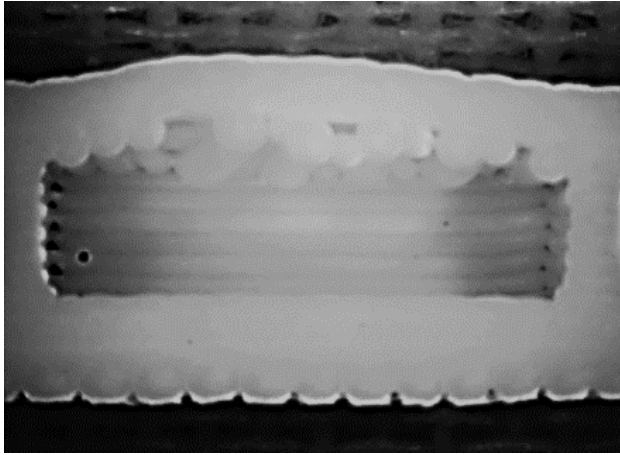
Table 3: Effects of each factor.

Source	DF	Sum of Squares	F Ratio	Prob > F
Voltage	1	0.00806690	1.9388	0.1748
# Pulses	1	0.00043997	0.1057	0.7475
Interaction	1	0.00028050	0.0674	0.7970

Table 3 above reveals that none of the factors seems to be significant. The p values are greater than 0.05

6.2.6 Results

The analysis revealed that none of the factors were significant. This was not the result that we were expecting, but do believe that with a different response we could get a result that is more useful. The measurement of the current response was not as accurate as we hoped and this was due to the limitation of the microscope. There was not a statistical significance on the response, but there was a physical response on the test specimens. The



treatment with both factors on the high setting caused buckling on the surface of the part. This is illustrated in Figure 11 which is a zoomed in photograph of the cross section. The top surface was exposed to the lamp. Notice the buckling that occurred. This was also noticeable in the second replicate.

Figure 11: Cross section of part treated with high setting of factors.

6.2.7 Scanning Electron Microscope Analysis

The previous experiment was revisited and in order to increase the resolution of the image, a Scanning Electron Microscope (SEM) was used to look at the cross section of the part. The SEM had advantages over the previous microscope that was used, including higher magnification and the ability to see depth of field. Dr. Richard Savage was contacted from the Biomedical Engineering department. Dr. Savage assisted with the operation of the machinery and gave suggestions for the experiment.

One major difference from the last experiment was that it was not be possible to look at each of the 32 samples with the SEM. This was due to a constraint in time and resources. It was decided to first look at a single control sample (no treatment applied) under the SEM and then determine if it is worth the resources to look at other samples. Since the SEM only works with conductive materials, a sputtering machine was used to deposit a

thin gold layer on the cross section of the part. The sputtering machine is seen below in Figure 12.



Figure 12: Sputtering Machine used to deposit gold on the surface of the print. This is done so that the SEM can be used in this experiment.

Once the thin layer was deposited on the part, we were able to insert the sample into the SEM and look at the cross section. Below is a screen shot of the control sample under the SEM.

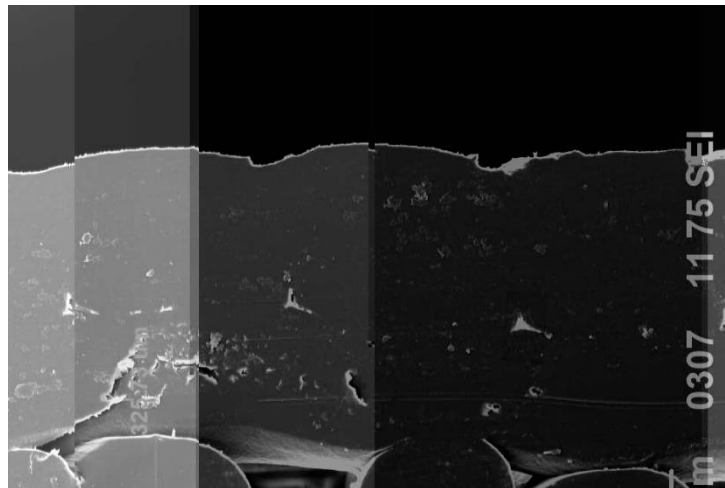


Figure 13: Screenshot from the SEM. This is the control sample at 70X magnification. The lighting on the image is corrupted but is still useful for examination.

After looking at the control sample, it was determined that the SEM would be appropriate for this experiment. The following week, four more samples were brought in to the lab for examination, resulting in a total of five samples (including the control sample from the previous week). Preparation and setup of each sample for the SEM took over an hour. Therefore, looking at all 32 samples from the experiment would not be feasible. Below is a table with information about each sample.

Table 4. Detailed information about each sample.

Sample Number	Number of Pulses	Voltage (V)
1	Control (Not Exposed)	Control (Not Exposed)
2	10	1600
3	13	1850
4	17	2100
5	20	2350

The samples were brought into the lab and then cut to expose the cross section. Many different cutting applications were thought of, but the one that worked best was using a medical grade scalpel. This resulted in the cleanest cut and did not leave any burrs on the sample. The illustration below (Figure 14) shows how the cuts were made for each sample. The samples were 3mm squares and had a height of about 15 layers. The cut made on each sample was perpendicular to the direction of the raster. Once cut, the inner layers were exposed for examination.

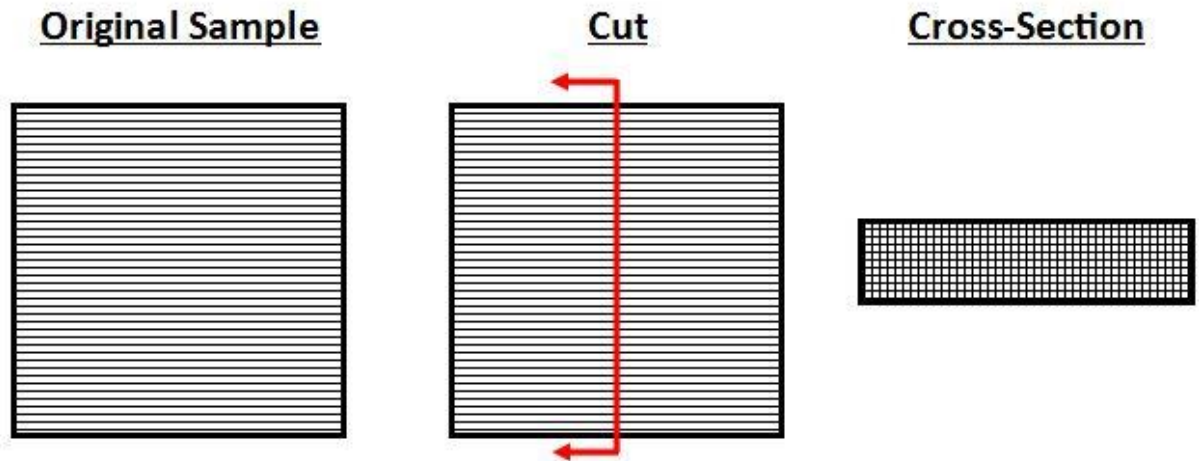


Figure 14: Visual representation to illustrate how each sample was cut.

After all four samples were cut, they were transferred to the sputtering machine so that they could become conductive. The sputtering machine used for these samples was much larger. An image of two samples is shown below.



Figure 15: Gold coating applied to the cross section of the sample.

After the samples were coated with gold, they were transferred to the SEM for imaging. Three images were taken for each sample. This was the left, middle, and right side. The

comparisons for all samples are shown below. The top layer is the one that was exposed to the Sinteron, so we want to examine and determine if the top layer differs from sample to sample.

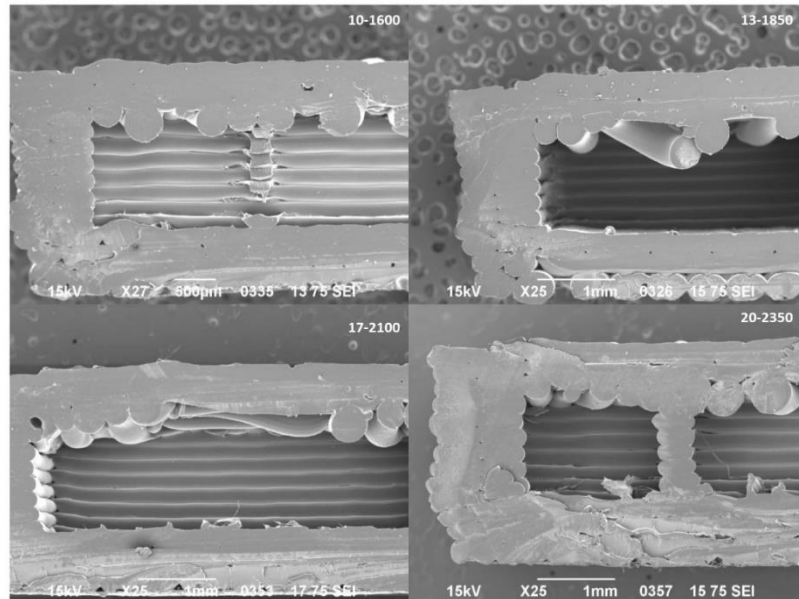


Figure 16: Cross section of the sample. The top layer was exposed to the Sinteron. Numbering on top right of each photograph corresponds to number of pulses and voltage. This is the image for the left side of each sample at 25-27 magnification.

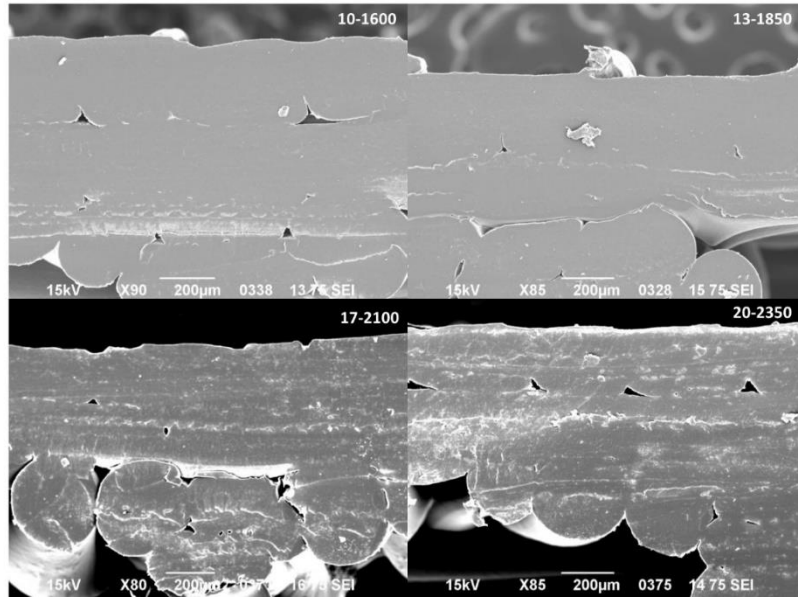


Figure 17: Cross section of the sample. The top layer was exposed to the Sinteron. Numbering on top right of each photograph corresponds to number of pulses and voltage. This is the image for the middle of each sample at 80-90 magnification.

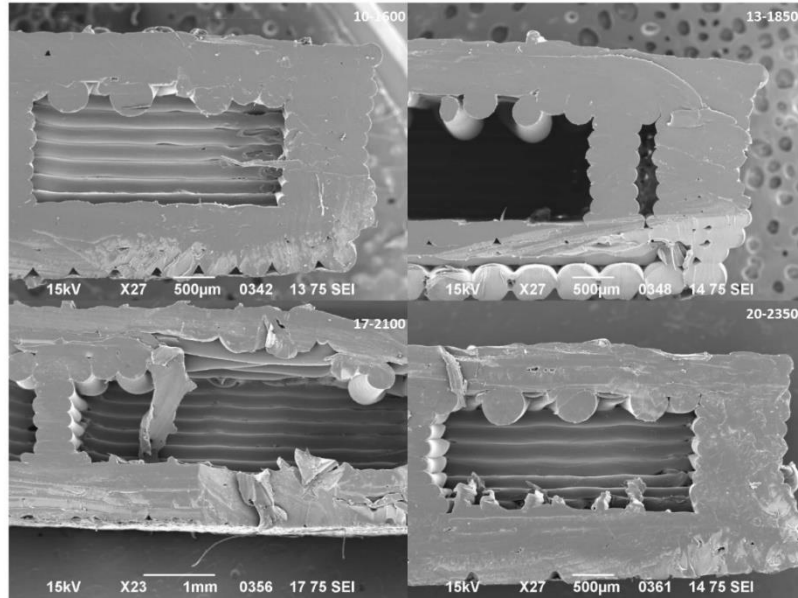


Figure 18: Cross section of the sample. The top layer was exposed to the Sinteron. Numbering on top right of each photograph corresponds to number of pulses and voltage. This is the image for the right side of each sample at 23-27 magnification.

The results from this experiment visually revealed that there was not a significant effect on the top layer due to the Sinteron. Air gap was still visible in all of the images and was not reduced with any of the exposures. However, something that was of interest is that if we look at the “13-1850” sample in the photos above, we can see that the bottom most layer is very distinct. The rasters are very well formed and the adhesion from the top layer is visible. At this point all of the evidence for the project supported that the Sinteron is not successful in reducing the air gap between layers. To ensure that this was in fact true, another experiment was conducted. This was to investigate the effect of the Sinteron on all of the layers.

6.3 Experiment 2

In this experiment, Dr. Wang and I decided to print three samples with 100% infill (solid). Since our previous experiments had no significant effect on a single layer, it was decided to print a sample with only three layers. One of these sample would be the control sample (no treatment) and the other two samples would be treated with the high treatment (20-2350).

6.3.1 Manufacturing

The dimensions for these samples were kept similar to the previous experiment. The length and width were 20mm and the height was changed to 0.7mm so that only three layers would print.

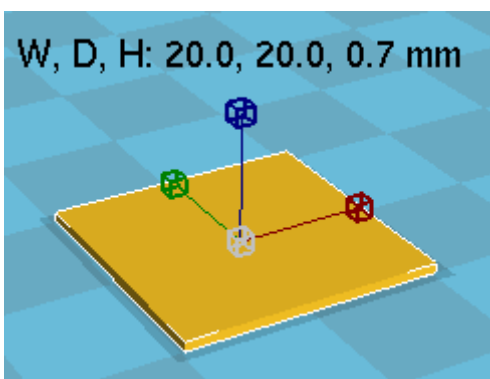


Figure 19: Visual representation of the sample created.

The samples were printed individually at the sample location and not simultaneously. This was done so that the location of where the sample was created on the print bed would not have an effect on the experiment. Simply put, this was to reduce noise in the experiment due to the manufacturing properties of the printer. Gloves were also worn during the manufacturing procedure to prevent contamination.

6.3.2 Exposure

Two samples were exposed with the number of pulses set at 20 and the voltage at 2350V. This setting was chosen because if the results of this experiment shows no effect, than it would be highly unlikely that a lower setting would cause an effect. The first sample was exposed to the Sinteron and a burn mark appeared on the surface of the print. Along with this, the print was no longer sitting flat on the bed. It was warped in a concave up position. Note of this was taken and a photograph was taken for the next sample. The photograph can be seen below.

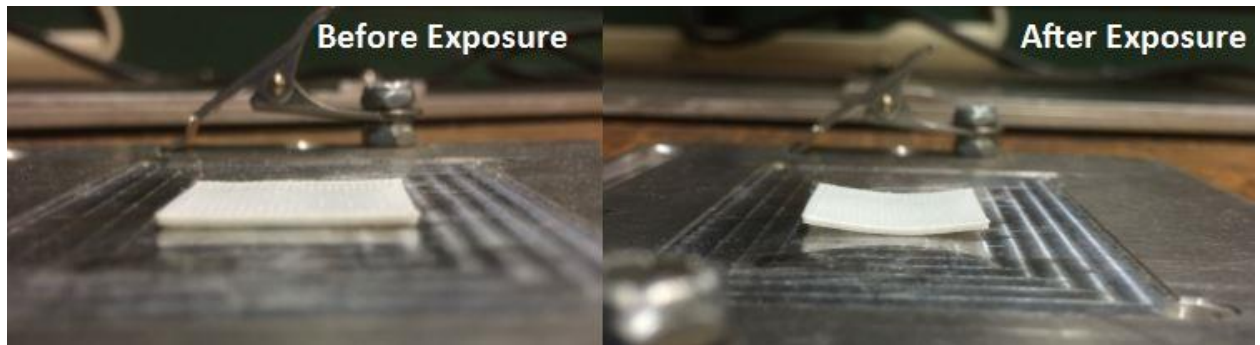


Figure 20: Photograph taken before exposure and after exposure. Notice the warping that occurred due to the treatment.

Further research was done to determine why this warping occurred. An article [4] was found online where Colin Hindle, Polymer Technology Lecturer at Napier University, speaks about warping of ABS. Hindle says that the thermal expansion and contraction of polymers is very high. As the print is heated it expands, but as cooling occurs, the polymers contract and this is what causes the warping. The layers beneath are cooler than the top and so the Sinteron will heat up the layer but the contraction pulls the side by side rasters together.

6.3.3 Measurement

The samples were brought into the Material Engineering lab and the optical microscope was used to examine the cross section. This was done with the help of Eric Beaton, Materials Engineering Support Technician. The sample with a burn mark was not examined because of potential noise it could add to the experiment. The parts were cut with a scalpel perpendicular to the filament direction like the previous experiment.

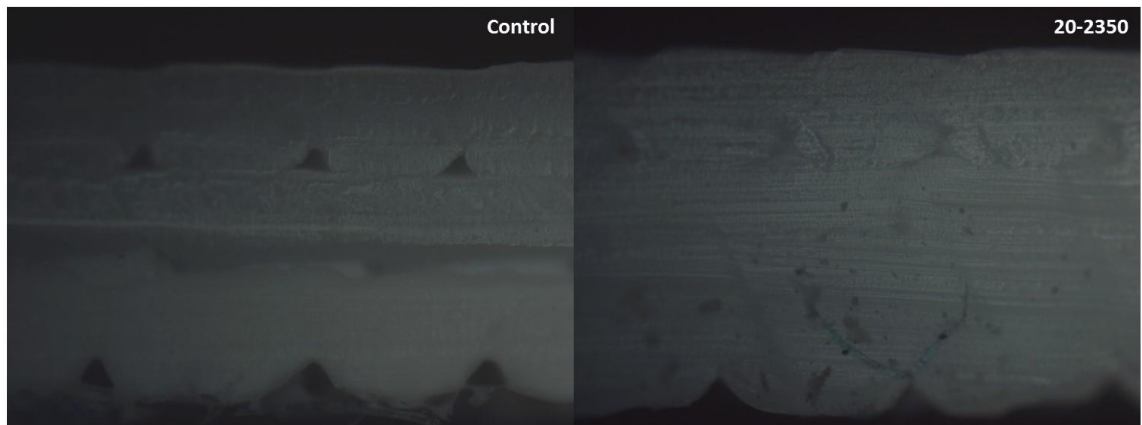


Figure 21: Image taken from the optical microscope. The control sample is on the left and the exposed sample is on the right.

6.3.4 Results

The image comparison might look as if the air gap was eliminated, but you can still see the distinction between side by side rasters. Technical Advisor, Dr. Xuan Wang was contacted and his recommendation was to try and sand or polish the sample and get another image. The exposed sample was brought into the lab the following week and was sanded down. The image revealed that the cross section was very smooth. This was not due to the exposure, but the sanding procedure actually smoothed the surface of the cross section. A polisher was then used on the surface of the cross section. The sample was examined in the microscope and an image was captured. This is shown below.

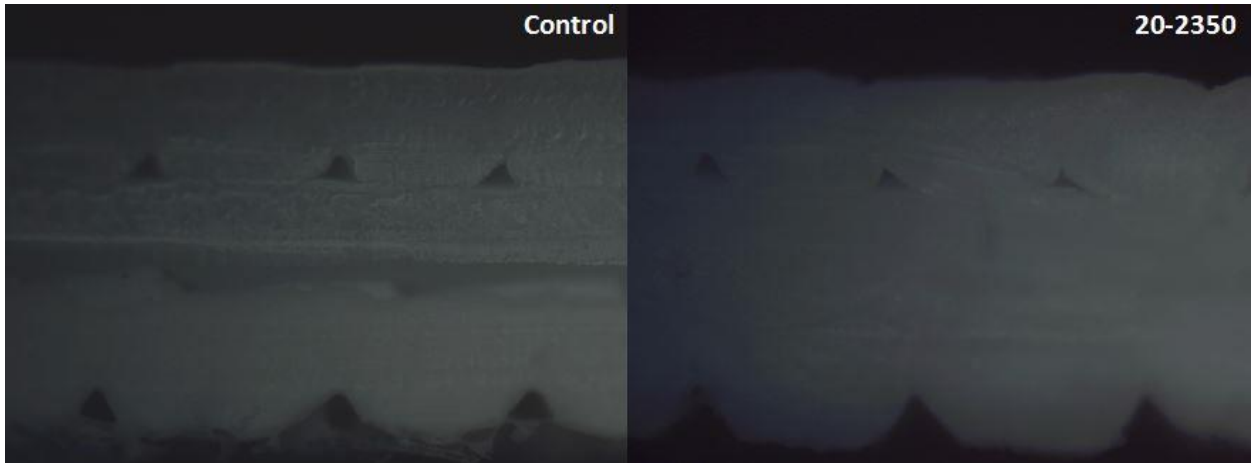


Figure 22: Side by side comparison of control sample and exposed sample. Exposed sample was polished.

The image above shows that the air gap due to the treatment was not eliminated. There is also not a visual significant effect on any other layer. Comparing the two images, it does seem that the gap in the treatment sample is smaller.

6.4 Experiment 3

In order to get a quantifiable conclusion, additional samples were printed and then the area of the gap was measured using ImageJ software. Two sample groups were compared, one control group and one treatment group. The levels for the treatment group were set to 20 pulses and 2350V. The sample size was 7.

6.4.1 Manufacturing

The dimensions of the sample for this print were kept the same as experiment 2. Gloves were used throughout the entire manufacturing and exposure process. Prints were made one at a time and all prints were put into a plastic bag after manufacturing.

6.4.2 Exposure

Similar to experiment 2, the samples in this experiment also had warping issues. All samples that were manufactured were randomly mixed in a bag. Seven samples were removed and one by one they were exposed to the Sinteron. Gloves were worn during the entire process.

6.4.3 Measurement

The samples were cut perpendicular to the raster direction to expose the cross section (Figure 14). An optical microscope was used to look at the cross section. A photograph of the setup is shown in the appendix (Figure F&G). All 14 samples were examined under the microscope and an image was taken with the scale. The images were then analyzed in ImageJ. The area of each gap was measured in ImageJ and recorded.

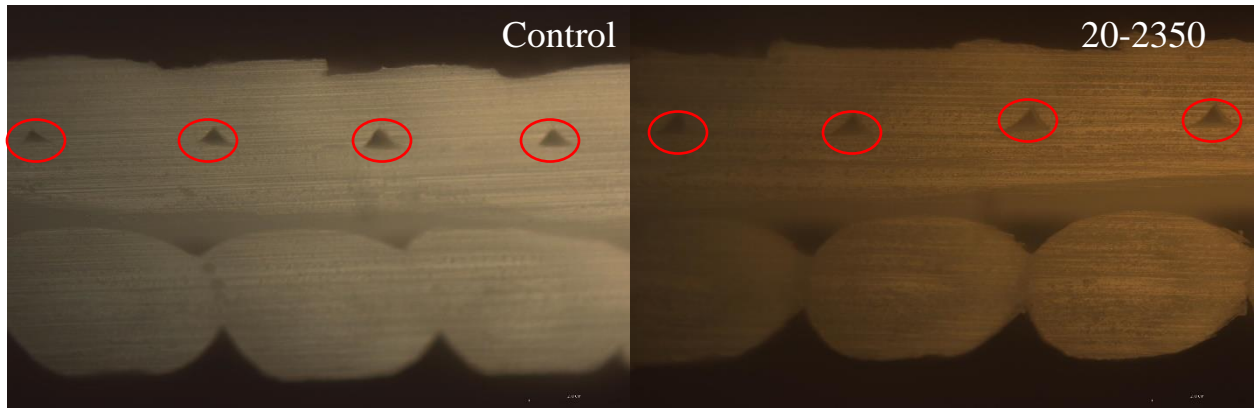


Figure 23: Control sample compared to sample with treatment. Red callouts are areas that were measure for experiment.

The image above is one comparison of a control sample and a treatment sample. The gaps are indicated by red circles in the image. The areas of these gaps were measured for all 14 samples. The data were then analyzed in JMP.

6.4.4 Analysis

Since we are only investigating one factor with two levels in this experiment, we can use a One Way ANOVA. This test will be able to tell us if the sample groups are statistically different from one another.

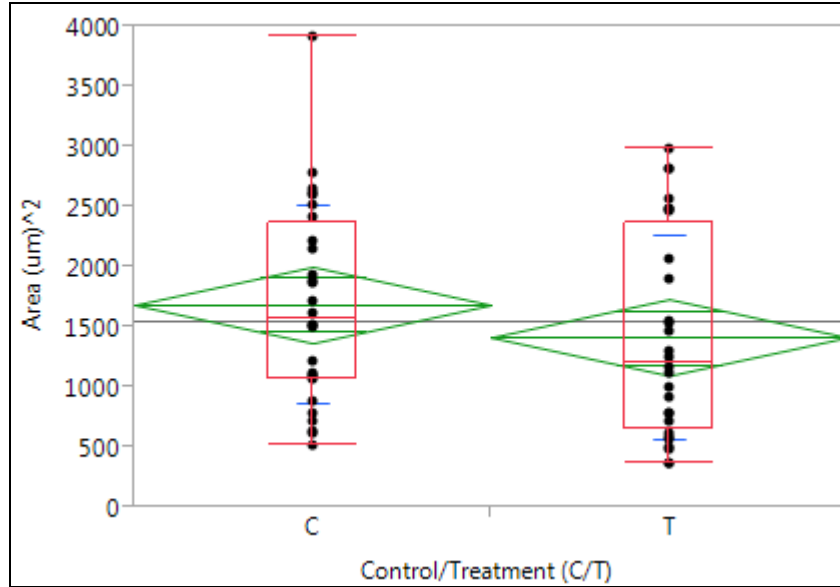


Figure 24: Boxplot and mean diamond for both sample groups.

The boxplot above illustrates the data visually. From the box plot we can see that the variation was similar for both sample groups (outlier excluded). The treatment sample group does have a mean area that is smaller, but it does not seem significantly different.

Table 5: ANOVA table comparing control and treatment sample.

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Control/Treatment (C/T)	1	1020879	1020879	1.4540	0.2331
Error	54	37914322	702117		
C. Total	55	38935201			

The ANOVA table above has a P-Value greater than 0.05. From this analysis, we cannot conclude that the control sample and the treatment sample are statistically significant.

This concluded that using the Sinteron does not have a significant effect on reducing side by side or layer to layer air gap.

7. Conclusion

This project aimed to experiment and determine if a proposed post processing method would decrease the anisotropy in the FFF/FDM process. The proposed process involved using a high intensity lamp to flash the print after each layer is printed. The theory was that this would decrease the gap between deposited filament and from research this was a proven way to make prints stronger.

For this project, a Xenon Sinteron 2000 was used as the high intensity lamp and a Printbot Simple Metal Plus was used as the 3D printer. Three experiments were done to determine if the Sinteron would be successful in reducing the gap between deposited filaments. The first experiment was done by flashing the surface of completed prints and then using a portable microscope to measure the height of the surface layer and necking between deposited filaments. The data were analyzed using a two-way ANOVA and the results did not conclude that the Sinteron was successful in reducing the gap. The second experiment was analyzed visually using an optical microscope and revealed that Sinteron might be able to reduce the gap on parts that are solid. The third experiment was analyzed using an optical microscope and the area of the gaps were measured using ImageJ software. The results concluded that the Sinteron was not successful in reducing the gap.

The quantitative data from these experiments suggest that the proposed processing method would not be successful in reducing the anisotropy of 3D printed parts created by the fused filament process. The theory of the proposed project seemed as though it would work, but one major shortcoming is that the Sinteron is not able to evenly apply its intensity. The recommendation is to investigate post processing methods such as a heat gun that would apply heat evenly across a layer.

The findings of this experiment cannot be discarded though. As Engineers, investigations to improve products or systems are always ongoing, and most experiments give us results that are not desirable. The experimental process for this project was followed and the experiments grew as the results from previous experiments were analyzed.

If this project was successful, it would have had a significant social impact. The social impact would be revolutionizing how we buy certain products. Instead of waiting for things to be

mailed to us, we could download files and print products inside of our homes. Lead times would have been drastically reduced and entire supply chains would have been changed. Common households across the world could build parts with strengths acceptable for their application and this would have been a contender for the injection molding process.

This project was done using a step by step method as mentioned previously. Since this project was mainly involved with research of a new post processing method, the only change that I could have done was involving either a different response or different sample specimens. Instead of using imaging as a response, structural tests could have been done to get quantifiable results. This response though, would require much more time since samples would have to have been much larger and the testing procedure would take longer as well. Physical dimensions of the samples could have also been changed for the experiments. Instead of going from large to small dimensions, I could have went from small sample dimensions to get a result and then work on to larger samples dimensions.

This entire project has been a learning experience. Prior to this project, I had little knowledge about 3D printing. I learned about the different processes in 3D printing and got very well versed in what the advantages and downfalls to FDM printing were. My senior project was able to identify a problem, investigate a possible solution to the problem, and then use my engineering background to experiment and determine if this solution worked. This project lived up to the Cal Poly motto of “Learn By Doing”.

8. References

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9. Appendix

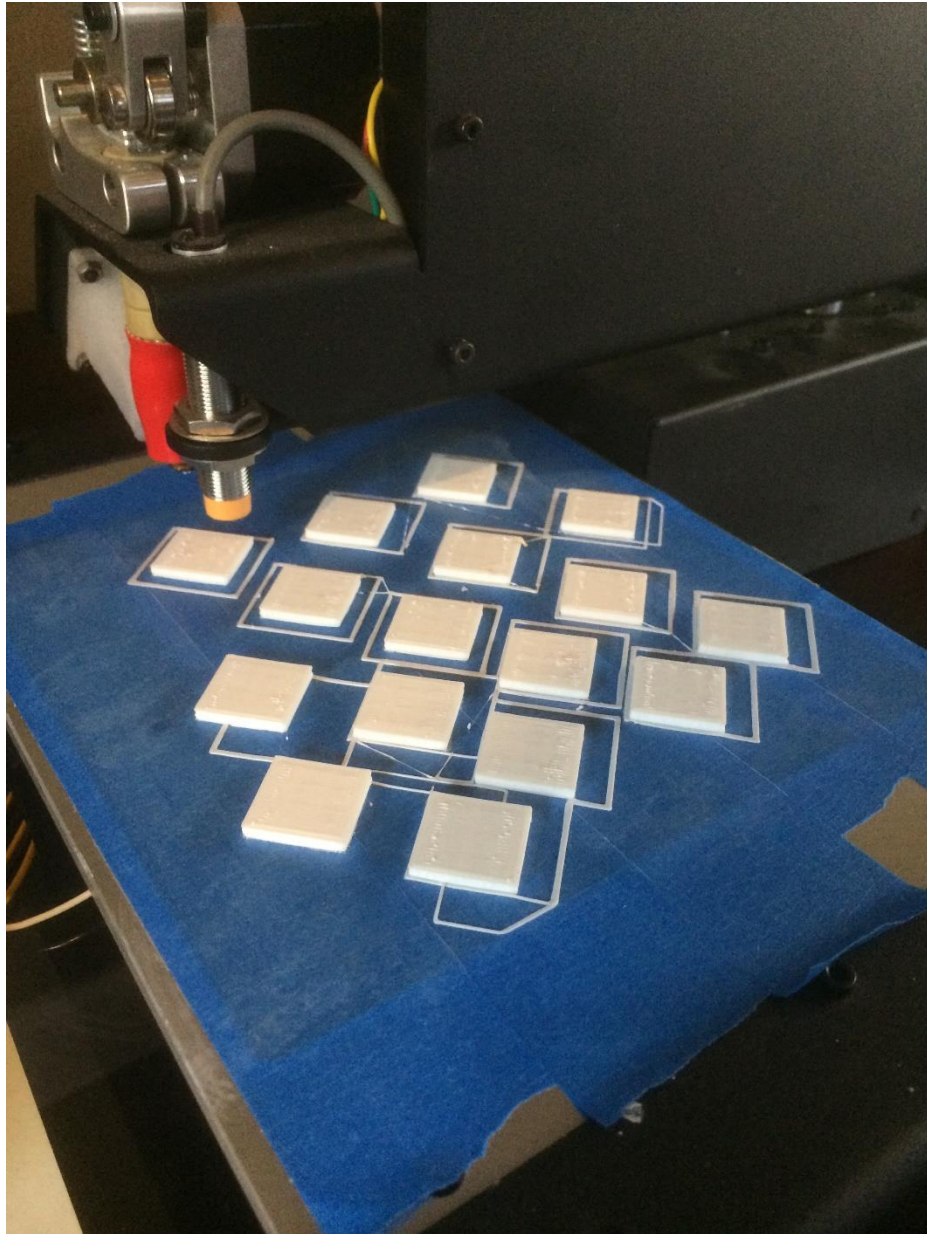


Figure A: Manufacturing Process for experiment 1.

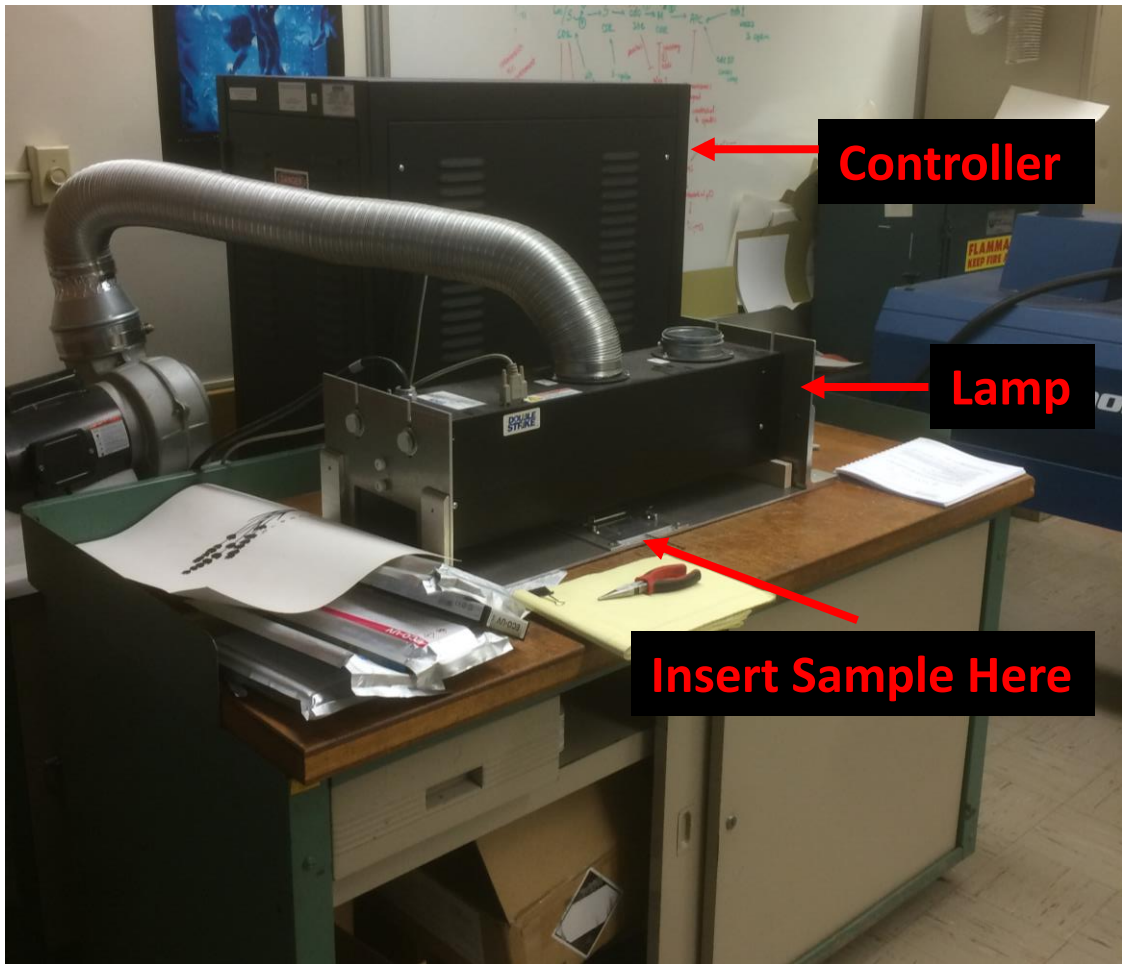


Figure B: Sinteron machine used in all experiments.

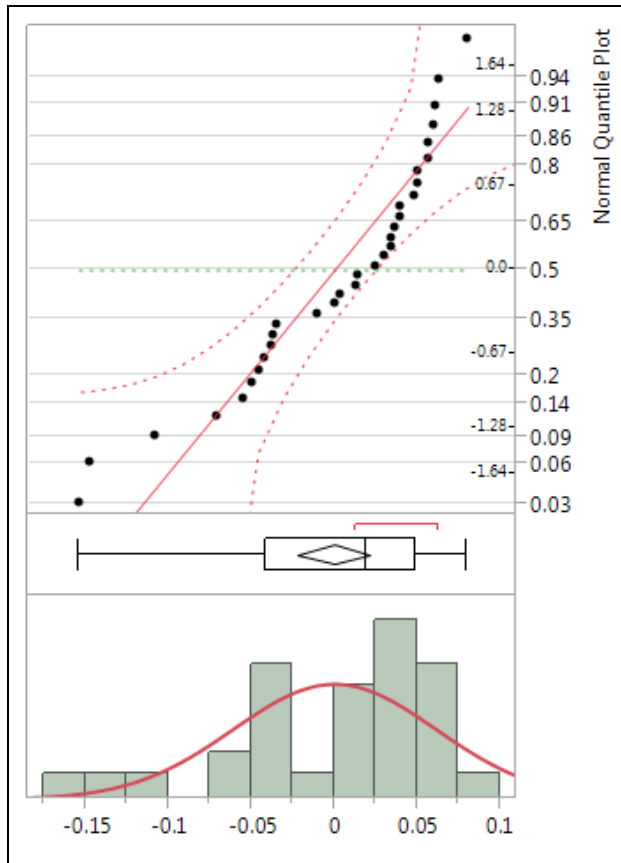


Figure C: Testing for normality of residual for experiment 1 using the portable microscope. Data seems to be a bit skewed.

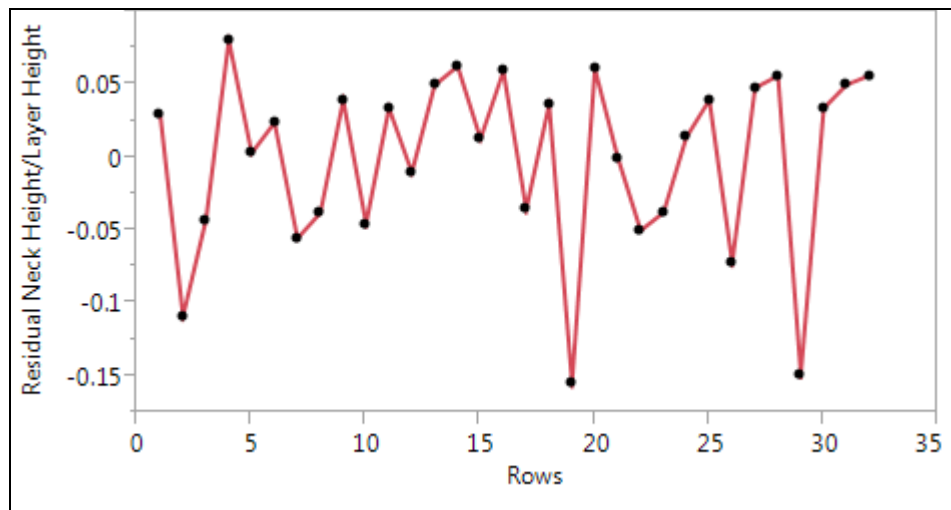


Figure D: Independence test for experiment 1 using the portable microscope. There does not appear to be a trend.

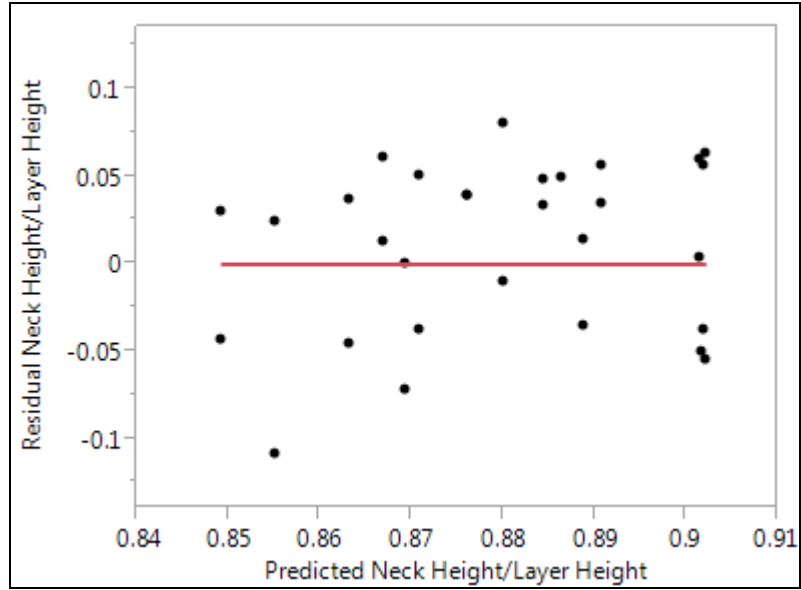


Figure E: Constant variance test for experiment 1 using a portable microscope.

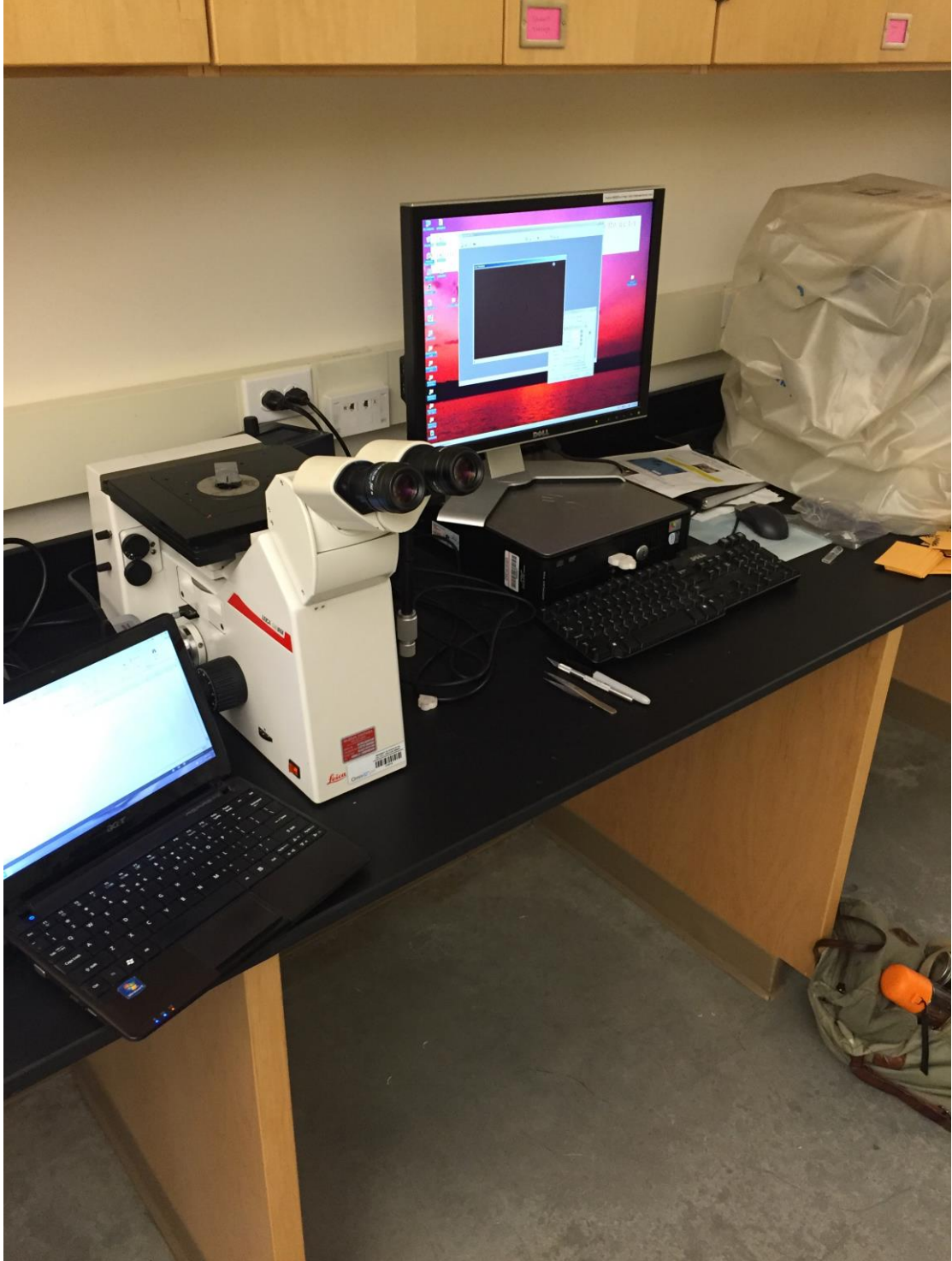


Figure F: Optical microscope used for experiment 2 and 3.

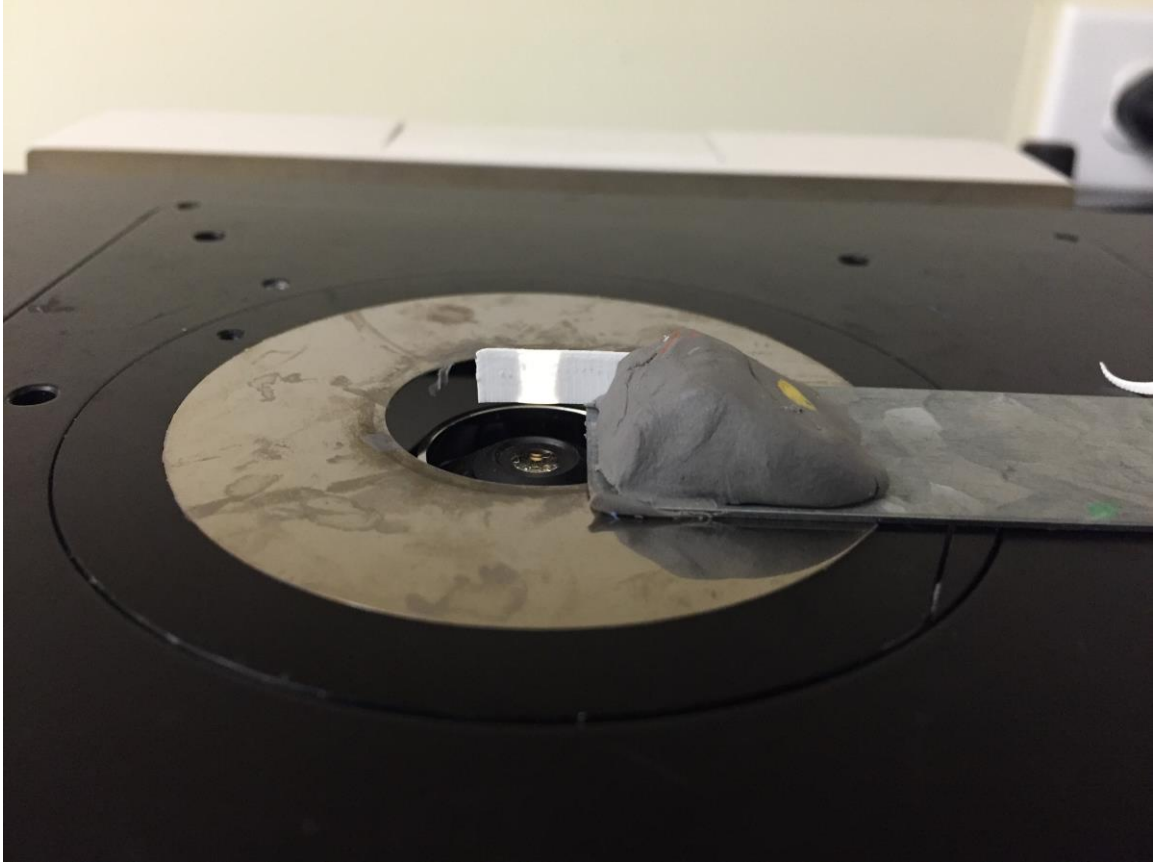


Figure G: Mounting setup for experiment 2 and 3.

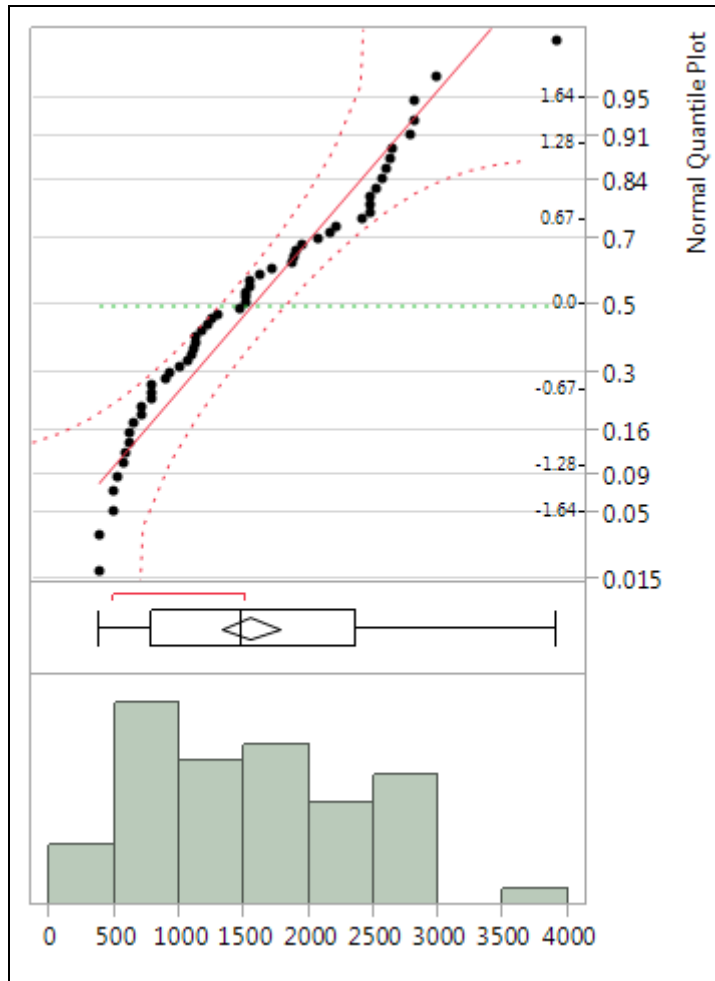


Figure H: Normal Quantile Plot for Experiment 3.

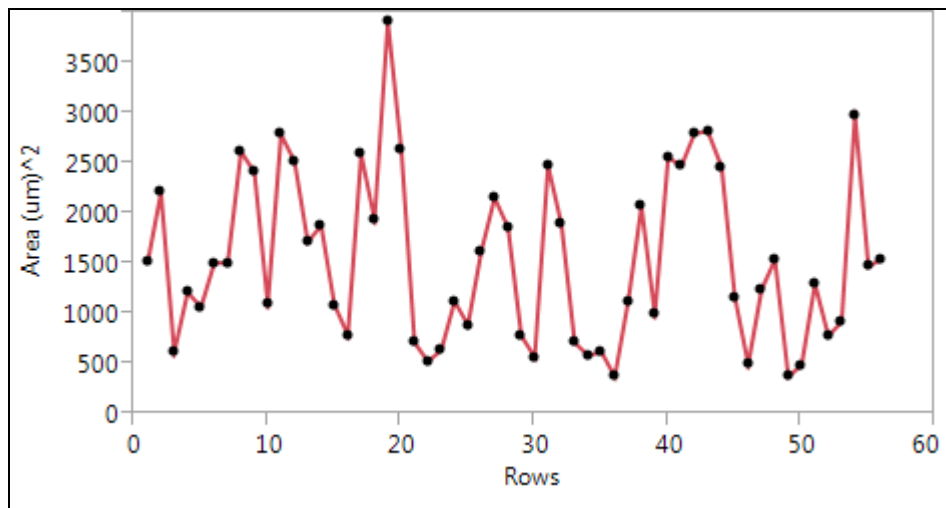


Figure I: Independence test for experiment 3.

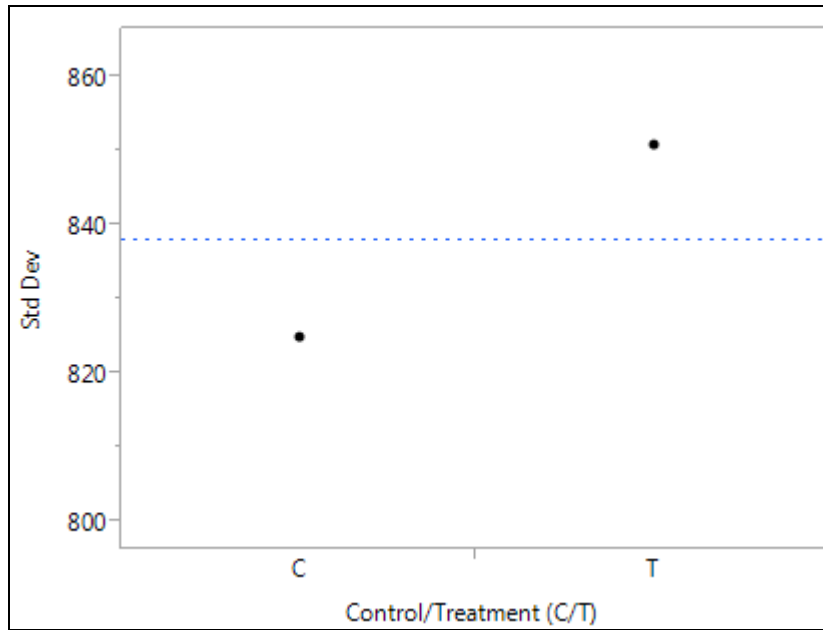


Figure J: Equal variance test for experiment 3.