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Effects of Process Parameters on the Dimensional Accuracy of Fused Deposition Modeled Parts

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by

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Effects of process parameters on dimensional accuracy of fused deposition modeled parts.

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Fused deposition modelling (FDM) is one of the most common additive manufacturing techniques used with applications ranging from rapid prototyping at a professional scale to simple part creation at a hobbyist scale. FDM printing has very little in terms of information based on how accurate printed parts can be. This issue, which is common amongst many different types of additive manufacturing techniques, is something that has not been studied in FDM printed parts in high volumes. Research based on the effects of process parameters on mechanical properties has been conducted in high proportions. This study focused on FDM machines using polylactic acid (PLA) filament as the main material being deposited. Three process parameters were tested: print speed, layer height, and bed temperature. Each of these parameters were tested at three different setting values. Using the different settings, twenty-seven trials were conducted using a part designed for the experiment. These test parts were then measured to analyze the dimensional inaccuracies created in all three axes by comparing the actual value to the values provided by the respective geometry. Once the printing process was complete, the parts were analyzed in both qualitative and quantitative methods. The parts were observed for any defects created in the printing process. The measured data was analyzed using both the analysis of variance (ANOVA) and Tukey tests as a way to calculate the statistically significant parameter values.

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Dedication

This research is dedicated to my family, without their constant support I would not be where I am today. To my grandparents who have supported me in every endeavor I have pursued, to my parents who have been nothing but supportive and encouraging throughout this entire process, thank you all.

Most importantly, this research is dedicated to my mother. Without her own relentless push for education, never quitting attitude, and love and care, I know that I would not be where I am today with that same thirst for knowledge. I love you mom.

Chapter 1: Introduction

Since its creation almost 40 years ago, additive manufacturing has been utilized for rapid prototyping and select manufacturing. While for the majority of that 40 year period most types of additive manufacturing have remained too expensive for common commercial and hobbyist applications. The origin of most cost friendly additive manufacturing machines started in 2004, where the company RepRap began looking into ways to create and sell machines for under $5,000 USD. [1] In the almost 20 years since their start, the price has dramatically decreased for these machines. There is still a price for this decrease in cost, namely the quality of the final product. This is mainly due to the cheaper machines lacking many automatic features, requiring the operator to control areas of the machine without a very high amount of accuracy.

The initial additive manufacturing machines used stereolithography (SLA) to create a chemical reaction that would ultimately produce a 3 dimensional object. [2] While many modern machines still operate stereolithography, there are many other kinds of additive manufacturing machines. Another type of additive manufacturing that is commonly used is fused deposition modeling (FDM), a layer-by-layer approach to printing patented by Scott Crump in 1989. [3] This type of machine has gained popularity due to the relatively low costs associated with it. While both SLA and FDM machines operate differently, both types of machines are commonly referred to as 3D Printers. The main difference between the two kinds of printers is in their method of creating 3-dimensional objects. While SLA uses light and chemical reactions, FDM printers extrude material to build up the object. Other differences include the materials each printer uses, with SLA

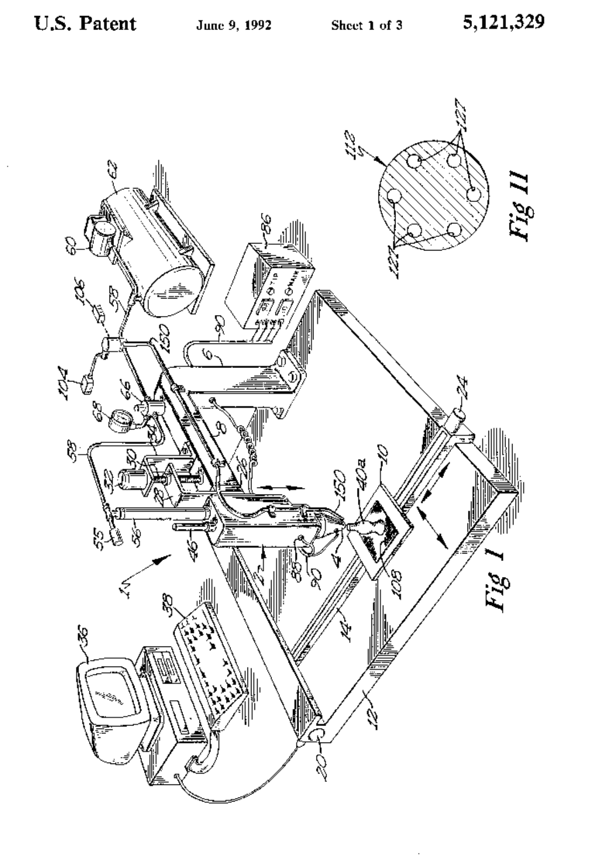


Figure 1: Scott Crump's Design [3]

commonly using resin and FDM commonly using polylactic acid (PLA). Although PLA is the most commonly used material filament, FDM printers have a wide variety of material options including Acrylonitrile Butadiene Styrene (ABS), a plastic that is commonly used in injection molding.

Although FDM printers have many different configurations that can be tailored to a specific need, all FDM printers share two key components. These two components are the extrusion device and the build plate. Extrusion systems in FDM printers move filament from outside of the machine, traditionally on a spool, into the heating element and then out of the hot end nozzle. These systems traditionally use drive gears to move the filament via a Bowden tube to the heating element. The nozzle at the end of the heating element is an important part of the printer as the diameter of the exit affects not only the filament that can be used in it but also the layer thickness of the 3D object. Nozzle's also have a variety of material compositions, with the most common being brass. While brass can become weak and easily worn down under use of specialized filaments such as carbon fiber or wood infused, it has shown to have a large durability when extruding PLA. The build plate, commonly called the bed of a printer, has the ability to move in one degree of freedom which is used to help the extrusion system build complex geometries. Printer beds normally feature a heating element to help the molten filament adhere to the bed more effectively. There are also many types of materials that print beds can be made from, with the two most common being glass and select types of thermoplastics embedded with magnetic parts. The material used in the bed can create issues when printing select plastics, such as the aforementioned ABS which is known to have issues with magnetic beds. Print beds also have an effect on the quality of the print due to their subtle differences in adhesion abilities. Although both parts are common amongst all FDM printers, the included controls for some aspects of the parts are dependent on the individual printer. The extrusion system will almost always be controlled by an external source, traditionally with an onboard computer system. With print beds, the level of autonomous control varies depending on the price of the printer. The variation of control can create issues due to the bed needing to be “level” with the nozzle in order to create a uniform surface. This optimal leveling of the nozzle is found when the extruder is at its base level of the Z-axis as dictated by the printer.

Figure 2: Examples of Bed Leveling

Most printers at and below $200 USD do not include an onboard leveling system and instead require the user to manually do the process. This can create large amounts of error due to the less than exact methods commonly used. The overall quality of the object can be affected by how close or far the bed is from the nozzle, creating a smushing or gap in the layers of filament as seen in figure 2.

While the physical components of the printer can have a large impact on the total quality of the printed object, there are other internal printer settings that can affect the overall quality. These settings do affect how the printer’s physical components operate while printing, they are controlled entirely by the onboard control system. Three setting types that are more commonly used to control the quality of a print include: Temperature, Print Speed, and Layer Height. These settings are edited in specialized software, commonly called slicers, that work to convert the 3D object into a usable process for the printer to follow. Some printers include their own proprietary slicers, while others recommend the use of freely available slicers such as Ultimaker Cura.

Due to the nature of FDM printers, the temperature applied to the filament is a crucial element for the success of a print. With most PLA filaments, a temperature range of 190-220 $°C$ is recommended as the optimal temperature range to melt the filament. This seemingly mundane temperature choice can have large consequences due to external effects to the print. One common concern is the affects of HVAC on prints as it can cause the filament to cool down too quickly and thus affect the overall print. Factors such as this should be considered when deciding what temperature should be chosen. However, the maximum temperature given in the range should also be clearly understood as going beyond the maximum optimal temperature can cause the filament to burn and crystalize which can lead to the printer's nozzle becoming clogged. Physical damage to the machine can also be caused by attempting to print at a lower temperature than the minimum optimal temperature. At a lower temperature, the filament may not melt properly which can stall the drive gears that move the filament from its source to the extruder. This stalling can cause the gears to wear down which will reduce their ability to move the filament at the speed required for the print.

Print speed is another commonly used setting that can not only affect the object being printed but also the area surrounding the printer. Print speed, unlike temperature, is mainly based on the geometries of the 3D object, with printer properties and material properties still influencing the speed by some capacity. The pre-set print speed in Ultimaker Cura for numerous printers is 60 mm/s. [4] While this is the case for many printers, the overall size and construction type of the individual printer is where the speed may need to vary. Larger and more bare printers such as the Creality CR-10, are traditionally run at lower speeds due to their increased chances of not only shaking the printed object off of the bed but also shaking the surface the printer is on which may cause more issues with the final print. More compact printers, such as the Voron0, have set speed records by printing test objects at speeds from 450-500 mm/s. While the ability to print at much higher speeds is rather remarkable accomplishment, the overall quality of the quickly printed parts was rather poor in comparison to slower print runs of the same object. The geometry of the object being printed plays a key role in what speed can be achieved. Objects with very simplistic designs such as the well known calibration cube can be printed at higher speeds due to the overall movement required to produce the object. Parts that contain complex geometries or are much taller than they are wide can create problems at higher speeds for different reasons. Complex geometries can cause the printer to move too fast around the part and not allow for the extruding filament to fully leave the nozzle before moving onto the next area. Taller prints can easily fail at higher speeds due to the motions produced by the machine affecting the object and causing it to detach from the build plate.

Slicing software such as the aforementioned Ultimaker Cura convert 3D models into “.gcode” files, allowing them to be easily read by the printer and then physically replicated. This process sees the slicer splitting the object into layers that when combined together build the overall object. The layer height selected is almost completely influenced by the size of the 3D model being sliced. Models with smaller and more intricate features should be accommodated with an overall decrease in layer height, while models with larger and less intricate features can handle larger layer heights. Changing the layer height affects the quality of a print by controlling how many layers of plastic is printed in a select area. Areas with a thickness of 0.25mm would only receive one layer of plastic with a 0.2mm layer height, making the part almost see-through, while using a layer height of 0.1mm creates a second layer which can increase the overall strength of the object. While the layer height affects the quality of the final product, it also effects how long the object will need to be printed. Increasing the layer height will decrease the overall print time as it will require a lower number of layers to finish printing, while the opposite is true for decreasing the layer height of a print.

The final quality of a 3D printed part can also be influenced by the setup of the print and the maintenance of the printer itself. Although most 3D slicing programs have a large library of pre-set settings that have been shown to be optimal for either the selected printer or material, they do still lack many beneficial qualities. One of the largest visible issues that can be caused by an improper setup of the part is layer lines. These lines are visible protrusions on a print that greatly affect the initial quality of a print. While most layer lines can be easily removed through post-processing tools such as sandpaper, many instances can be easily avoided by understanding the print orientation of the part. Understanding and utilizing a proper print orientation is vital for the not only the success of a print but also the functionality of the print once it is complete. For parts that may receive some amount of force in a certain area, print direction can be used to have the part printed in a direction that allows for the individual layers to be orthogonal to the force applied. This will stop the part from being split into smaller pieces from the load applied to it. Determining the location of the part on the print bed is also an important setup step. While the location will most likely not affect the overall quality of the print, it can affect the success of it. In most slicing software, the 3D model can be moved and rotated by all 6 degrees of freedom. This ability to maneuver the part into optimal areas can help negate any previously known issues in the print bed such as a heat warped base. One of the most common ways for FDM printers to "move" is with pulley systems. While these systems can create extremely precise movement, they also require an adequate amount of maintenance to maintain optimal motion. Over time the wheels used to move the pulleys can collect dust, which can cause the wheels to slip and potential cause the print to fail. The pulleys can also be affected by extensive use by wearing down and stretching, which can cause the printer to not be as precise in its motion. Both of these common needs for maintenance are easily fixed by either applying specific maintenance procedures onto the areas, cleaning the areas around the wheels or tightening the existing pulley cord, or by replacing the parts causing problems.

Many different aspects that affect the overall quality of a print share one common attribute, that they also affect the time needed for the machine to finish printing the 3D object. Most of the different features discussed are changed independently from one another due to the user's experiences with printing. However due to the fact that they all affect the overall quality of the build, there are many ways to determine how effective the techniques are at increasing the quality of a print. A key aspect of 3D printing is the difference between a successful print and a quality print, although both use physical measurements and observations to determine the success of the print. A successfully printed object is typically seen as any object that was printed completely with no fails during the printing process. These successful parts may still lack the standards to be considered a quality print,

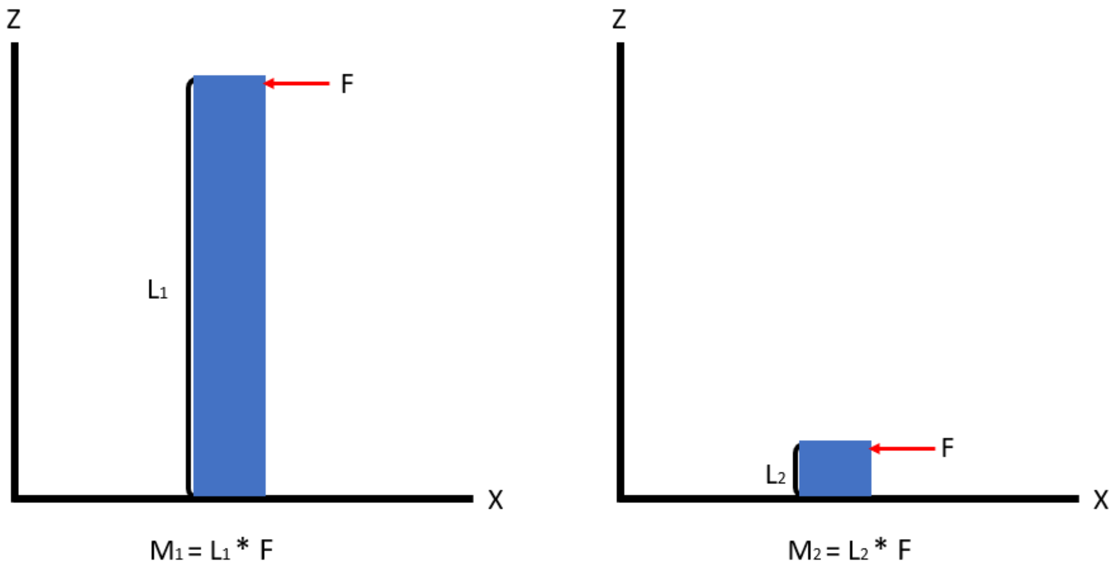


Figure 3: Bending Moment Applied to Varied Heights

with the largest issues being conformance to tolerances and layer lines. Due to the numerous variables that can affect a 3D print, something modeled out to be perfectly centered or at a certain angle may not actually be. This may be caused by shrinkage from the material filament or even a lack of printed supports. Layer lines not only influenced by the initial setup of the print, but also by the external environment. If the printer is too close to an HVAC vent or creating motion that is shaking the surface it is resting on it can also cause these shifts in the layers. Although layer lines can be removed through post-processing, it does cause the final product to require more time and resources to be completed.

Large portions of print quality are controlled by the individual printer; however, the characteristics of the selected 3D object can also have an effect on the overall quality of the print. While 3D printers have the ability to print complex geometries, the features creating the complexity can create issues when printing. The two contributors to the complexity of an object are the overall size of the object as well as overhangs and other extrusions. The overall size of an object plays a large role in all aspects of 3D printing, as a large object can increase print time, material used, and potential to fail. The size of a print can be scaled in three different axes: X, Y, and Z. The X and Y axis affect the thickness and length of a 3D print while the Z axis affects the height. The height of a print can greatly affects the success of a print, which can be seen by viewing the static forces on the print. In a layer-by-layer process, such as FDM, the new layer placed onto the part applies a small but important amount of force on the object. Figure 3 shows a simplified 2 dimensional example where the forces applied to both parts are equal, while the length of the first part (L_1) and the second part (L_2) are different, with L_1 being larger than L_2. Using the bending moment equation, it can be seen that the moment being applied to the first part (M_1) is greater than the moment applied to the second part (M_2). The moment applied to the part can create issues and complexity for printing due to the printed part having a higher chance to delaminate and disconnect from the print bed. The common practice to avoid failure of this kind is to print the object on its side, rotating the part 90 degrees to allow it to be printed mainly on the X and Y axis. However due to the variability in the 3D printed object, this solution is not always valid. Printing mainly in the X and Y axes also can create issues, with the largest being warping caused by the heated bed. Another set of characteristics of a 3D object that can create complexity in the printing process are overhangs and extrusions. Extrusions from the core section of the 3D object can create varied complexity depending on the angle the extrusion is at. This complexity comes in the form of supports needed for printing. Supports are a structure used in 3D printing to allow for parts with overhangs to be printed without issue. The need for support structures comes from the nature of 3D printing, which is traditionally a layer-by-layer process, as overhangs need some kind of surface to be built upon. Although supports can be a vital part of successfully printing an object, there are ways to negate the need for them. Depending on the angle the overhang is projected at affects the need for supports. This practice, often referred to as the “45 Degree Rule”, states that if the angle of an overhang is less than or within 35-55 degrees the area will most likely not need support material which can be seen below in figure 4. While 55 degree overhangs under this rule can be printed without supports, due to the way support structures are added to 3D objects they typically receive support structures. The generation and use of supports is another feature of slicing programs, such as the aforementioned Ultimaker Cura. Slicing programs give the user the option to select at what overhang angle support structures should be generated for, however the default angle is 45 degrees. Support structures, while necessary for some objects, do have positives and negatives to their use. The largest positive attribute to using support structures comes in the ability to fully print an object in one piece, rather than having to split it apart and attach the overhang to the base object after printing. Other attributes of supports can be accredited to the different types, with the ability

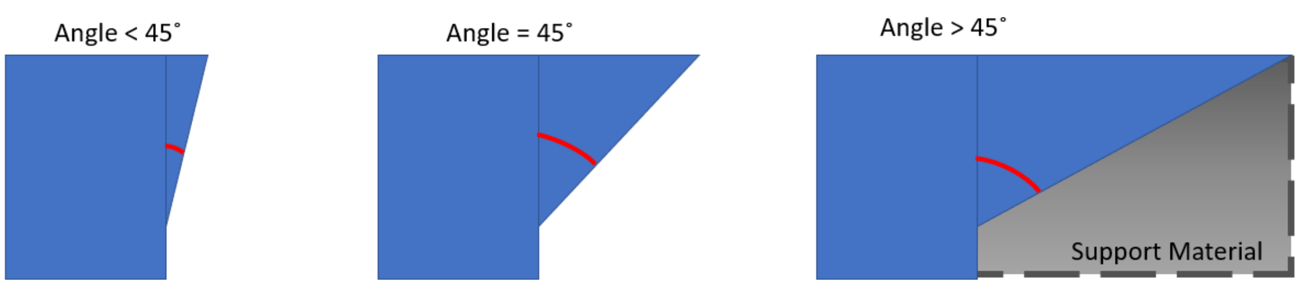


Figure 4: 45 Degree Rule

to choose between more rectangular supports for heavy support or more fluid and “tree-like” supports for small areas. While the type of supports needed and when to use them can vary from one 3D object to another, most of the negative attributes associated with supports are common regardless of the type. Areas that are printed onto supports typically still have some number of defects, which can range from the initial few layers printed not properly combining together to the entire region failing to be built. This is commonly caused by the chosen air gap between the 3D object and the support structure. If the gap is too far apart, the layers begin to sag and not fully make the intended design. While if the gap is too close, the support structure can be welded to the 3D object. Print quality in areas that use support structures is important, however that is not the only major flaw with using supports. Another important negative attribute to using support structures is the amount of material wasted on them. Support structures, depending on the type, can cause a large amount of the material used in a 3D print to be thrown away. Although there are commercial products that can be used to recycle support material, the range of cost for the machines required is anywhere from $6,000-16,000 USD. With such a high price to own the proper machinery for recycling the material waste, most support material is thrown away after the print is completed.

With such a variety of influential factors, efforts to rationalize the effectiveness of those parameters has begun. Many of the existing studies have focused on two main parameters, raster angle and temperature. The raster angle is the angle the printer takes when placing the initial layer of filament onto the bed. This initial layer is crucial for the success of all layers following it. Studies have shown that both raster angle and temperature are key parameters for increasing the quality of the surface of the part. [5] Other important variables such as object height, print bed temperature and print speed have not been equally researched for their individual impacts on the final quality of a 3D printed object.

This lack of thorough research can be accredited to the large variety of components and settings that can be used in the printing process. This lack of studied variability has led to most 3D printer operators to print with what they have empirically found to work for them. At Florida Tech's L3Harris Student Design Center (L3HSDC), an entire room is dedicated to additive manufacturing, with a primary focus on FDM printing. Due to the nature of most printed objects coming out of the L3HSDC being for prototyping the common settings used reflect that. The temperatures used for the print bed and the nozzle are 60 $°C$ and 215 $°C$, respectively.[6] While the print speed is broken down into two subcategories that are dependent on what area of the object the printer is making, with a range of 40-60 mm/s for the outer perimeter of the part and a range of 100-200 mm/s for the infill. The layer height for all prints is set to 0.2 mm unless the student or faculty member specifies otherwise. Another key variable that is left a variable at the

Figure 5: Galactic Armory's Print Farm [7]

L3HSDC is the percent infill of the part, which is varied depending on the specifications and application of the request print. Although percent infill is allowed to vary, all of the other variables are set at the discussed values due to experimental success with previously printed parts or due to specifications from the manufacturer of the specific FDM printer in use. While the L3HSDC focuses primarily on prototyping with the 9 FDM printers available, other organizations and companies have constructed large “print farms” to produce printed products at a higher quantity. One such company, Galactic Armory, utilizes a print farm of 80 printers, figure 5, to produce their final product. Galactic Armory sells a various array of science fiction based build at home kits, which requires the printed parts to be a high quality before the orders can be processed and distributed to the buyer. The need for a higher quality product compared to standard prototyping can be seen with the variation in the settings used when compared to those used by Florida Tech's L3HSDC. While both Galactic Armory and the L3HSDC use the same print value for the bed, at 60 $°C$, all other settings vary to some amount. Galactic Armory sets all of the printers to a nozzle temperature of 210 $°C$, layer height of 0.3 mm, a constant percent infill of 10%, and a constant print speed of 50 mm/s. [7] Comparatively, most settings are close with the exception of percent infill and print speed. While percent infill is allowed to vary at the L3HSDC due to the overall variety of print requests made to the center, it is held constant for Galactic Armory because it is what the company says it is what has been found to work the best for the types of printing performed. Similarly, to the constant infill used, the constant print speed is another setting that was chosen due to it being what has been found to work the best. 50 mm/s when compared to the settings at the L3HSDC is a rather interesting value to settle on, as it is in the midpoint of the perimeter range used yet it is anywhere from one half of the speed to a quarter of the speed used for printing the infill of the object.

While FDM printing has some unique aspects, any 3D printed part is susceptible to failure mechanisms. These mechanisms can be seen throughout the printing process as well as after. Many failure mechanisms are shared between 3D printed and traditionally manufactured parts, however some are unique to 3D printing. One such failure mechanism is layer shifts. These failures can be caused by the part being printed as well as defects in the machine itself. Like most defects in 3D printing, some layer shifting defects can be easily removed due to post processing, however this is not always the case. Layer shifting can happen on its own, however in many cases other defects can be observed at the same time. For example, in figure 6 both layer shifting and stringing can be seen. The shifted layers show that during the printing process the layers moved almost an inch in one

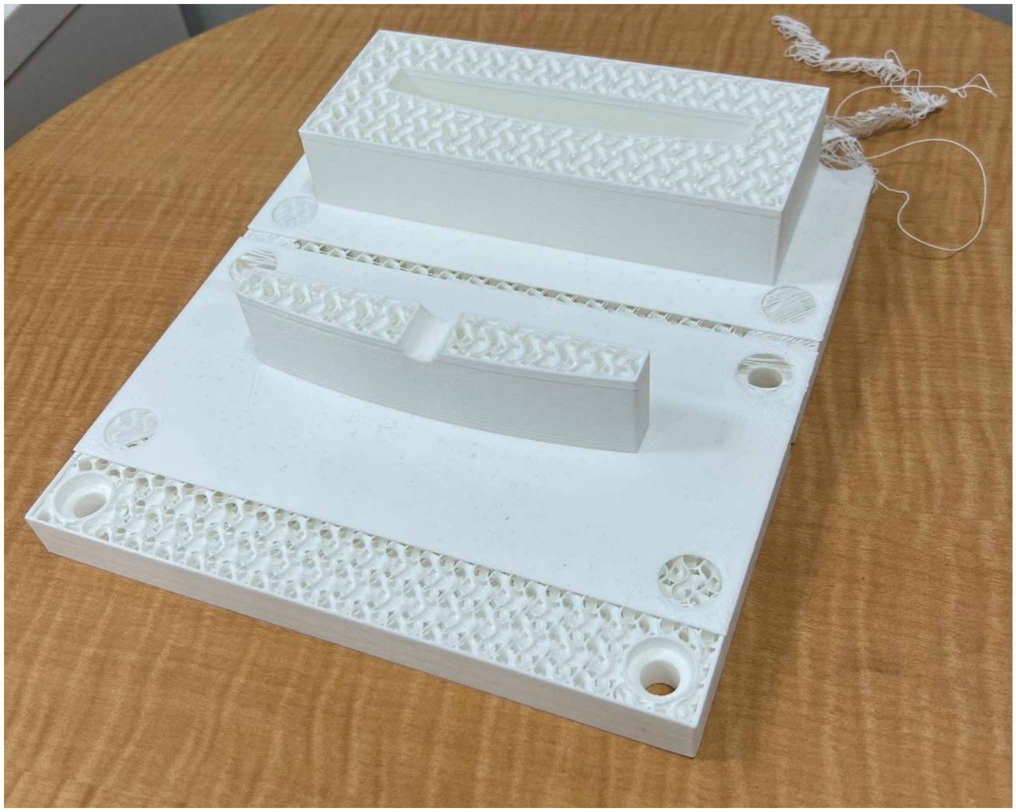


Figure 6: Failed Part with Layer Shifting and Stringing

direction. This print was promptly cancelled once the layer shift was observed, however the causation of the shift created an interesting debate. While in most cases layer shifting is caused when the part becomes disconnected from the build plate, this was not the case. The base pieces were still perfectly adhered to the build plate, meaning that the shift was caused by the actual 3D printer used. Another very common failure mechanism seen in 3D printed parts is stringing. Similar to layer shifts, stringing can have varying degrees of failure. Unlike layer shifts, stringing is primarily caused by issues with the printer itself. The causes for stringing can come from incorrect printer settings to other larger defects. Many 3D printed parts feature a small amount of stringing, which can typically be removed during the post-processing process. Stringing defects can cause varying levels of issues during post-processing. More commonly, any observed stringing can be easily removed by hand as it is comprised of only small strands. In other cases, like in figure 7,

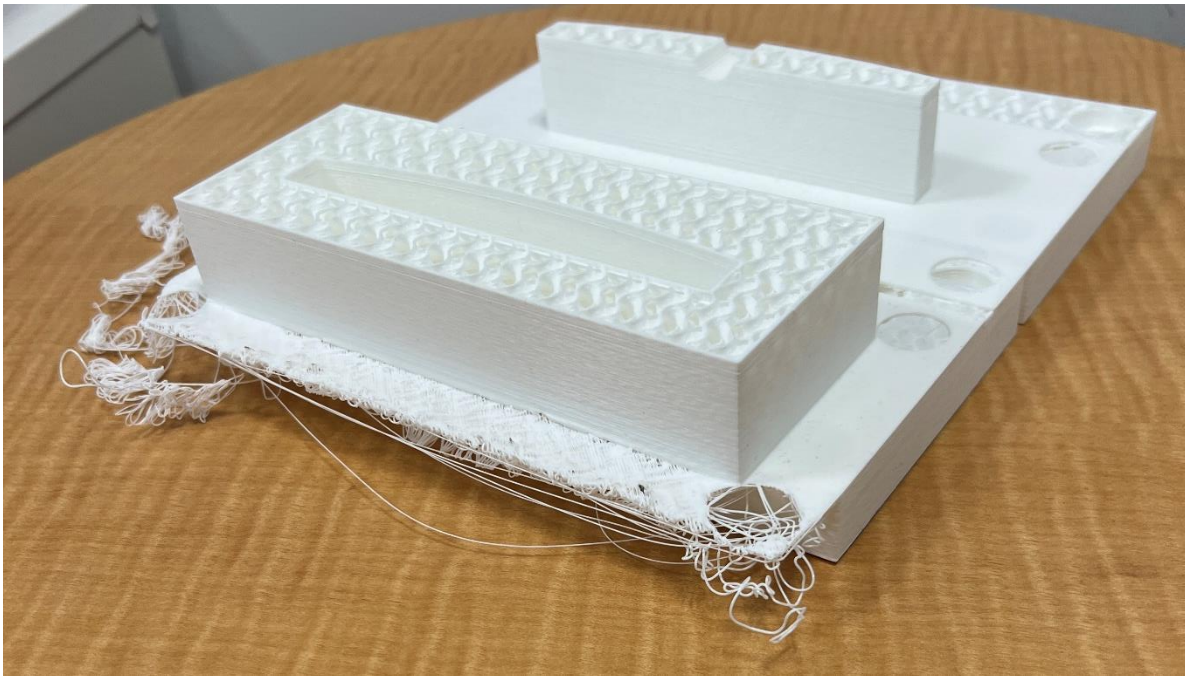


Figure 7: Failed Print with Severe Stringing

stringing cannot be fixed by simple post-processing. In many observations where a part needs to be reprinted, the stringing is more severe. This is caused due to the nature of FDM printers, as they cannot detect print failures. This lack of ability to detect a failure during printing can cause the machine to continuously deposit material in areas that are not a part of the base model. In some observations where severe stringing occurs, the affect area will still be printed. The area printed will typically have major defects that do not allow it to be easily fixed with post-processing.

The 3D printing process, and more specifically FDM printing process, includes a large number of variables that can ultimately affect the overall quality of the 3D printed object. While many of the variables are used as constant values due to individual user experiences, this way of operation has created a less than satisfactory pool of general knowledge for 3D printing. This lack of generalized knowledge can also cause issues when operating an assortment of 3D printers from different manufacturers. This variation of information can be confusing to anyone working with 3D printers, regardless of if it is their first time or if they have years of experience. More research into how the variables affect the quality of a FDM printed part could greatly benefit numerous areas from research to commercial use. In terms of the overall quality of the 3D printed object, a key area of focus is the dimensional accuracy of the part. This accuracy is in comparison to the existing CAD model's dimensions. While some information is known about the differences between CAD models and the final printed part, such as the practice of adding 0.2mm onto a diameter on a given object, for many applications it is not known. The focus of this experiment is to test, analyze, and record the affects different process parameters have on the dimensional accuracy of an FDM printed part.

Chapter 2: Literature Review

Quality control and the observation of the effects of different variables on the overall quality of 3D printed parts have been studied numerous times, however most research has been conducted in specific fields rather than for an overall observation. A large majority of the existing research was conducted for medical applications, utilizing different types of 3D printing types. A study conducted by Mika Salmi, helped to outline where the different types of printing were utilized in the medical and dental fields; with SLA, FDM and powder bed fusion metal printing (PBF) considered the three most established processes used.[8] It was also found that these three processes were chosen due to their common use as well as because of the material variety. The material needed for the certain application, (i.e., implants, tools, or models) was found to be a key reason why the specific printing process was chosen. The study also outlined certain observations in relation to different areas of application, such as using additive manufacturing to create more accurate, cost efficient, and personalized orthopedics.[8] Further on in the same study, the applications available for FDM printing were discussed along with the types of filament the process requires. Of the six application areas (medical models, implants, tools for medical devices, medical aids, and biomanufacturing) FDM was shown to be able to utilize PLA as the printing filament, along with select other plastics such as ABS and nylon.[8] Along with labeling difference processes on their current medical and dental application, the study also made comments on where the future of medical applications and studies could come from. Other research for the medical field has included comparing different processes for their dimensional accuracies. One study compared FDM printing to PolyJet printing, a process similar to SLA printing. To compare the two additive manufacturing types, the study printed models of different human internal parts; normal aortic anatomy, coronary artery anatomy, aortic aneurysm, and aortic dissection. [9] To validate the two processes, the parts printed were measured for accurate wall thickness, as well as conformity to the original 3D model. The 35 models that were printed, 20 FDM and 15 PolyJet, were measured using a CT scan. [9] The study concluded that both printing processes are viable, however each type displayed some flaws. One issue that was found in all 35 models was a relative increase in wall thickness by 5%, when compared to the original 3D model's STL file.[9] The FDM printed parts were found to have a mean surface deviation as low as +90μm while the Polyjet printed parts were found to have a +150μm mean surface deviation, both of which are within the current additive manufacturing recommendations for accuracy.[9] The technical differences between FDM and PolyJet were also found. With FDM being unable to produce parts as the complexity of the part increased, and PolyJet being a more expensive process for both the printer and the materials used. [9]

Although a majority of the existing research for FDM printers focuses on its applications in the medical field and how certain processes can be performed to reduce the dimensional inaccuracies, other studies have begun to into observing other areas of the process that affect the inaccuracies of the finished product. One such study reviewed a previous work and tested how three different variables affect the accuracy of the part. These three factors were raster angle, air gap, and raster width. [10] Uniquely, the study tested using FDM printed ABS parts instead of the more common PLA.[10] The use and removal of support material is also discussed, however the models used in testing are not presented. The study used a

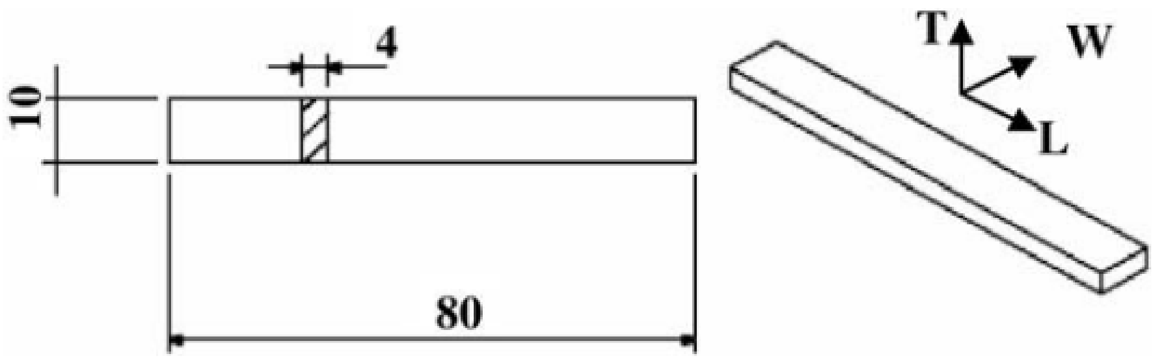


Figure 8: Test Part [11]

combination of response surface methodology (RSM) and composite desirability function (CFD) to conclude that of the three tested variables, it was the raster angle that influenced the dimensional accuracy by a significant amount. The tests performed in the experiment were to test the variation in the measured length, width, and thickness when compared to the CAD model.[10] The same setup was used for calculating the difference, which was done by subtracting the physical variable (length, width, or thickness) by the value on the CAD model and then dividing it by the value given by the CAD Model (Equation 1). To test variations in the test variables, the three values were given three levels to be tested at. These three levels (labeled -1, 0, and 1) were then tested in 20 different tests where the values for each varied between: $0°C$, $30°C$, and $60°C$ for raster angle, -0.004mm, 0mm, and 0.004mm for air gap, and 0.4064mm, 0.4564mm, and 0.5064mm for raster width.

A similar study was conducted to determine the relationship between layer thickness, orientation, raster angle, raster width, and air gap in terms of the printed

$$\Delta X = \frac{X - X_{CAD}}{X_{CAD}}$$

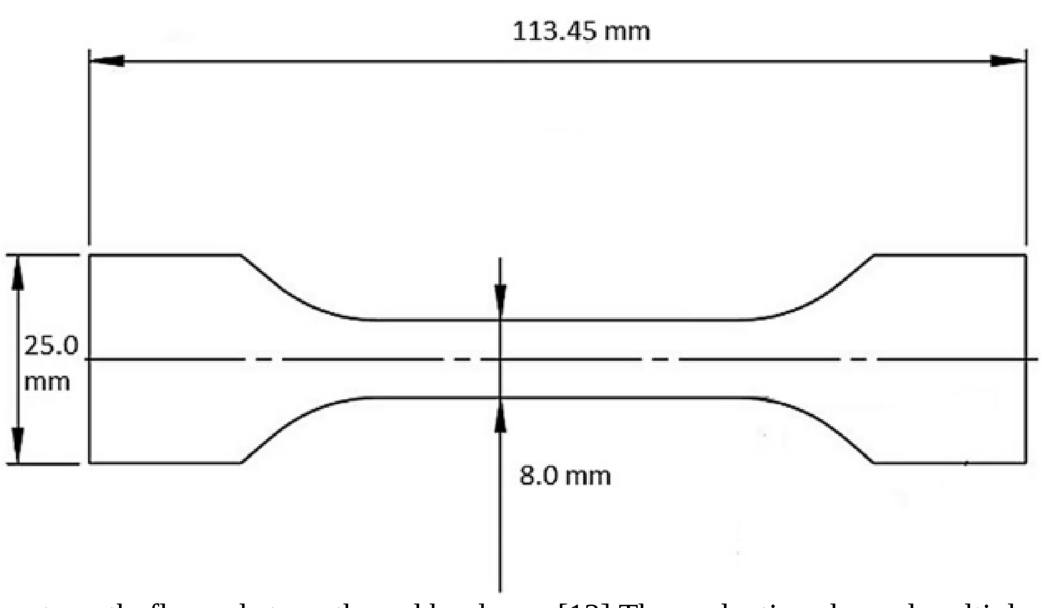
Equation 1: Relative change in dimension [10]

part's dimensional accuracy. Unlike the aforementioned, the researchers used gray Taguchi method to analyze the tested data, which showed the estimated values that were found to improve the overall dimensional accuracy. The five variables studied were: minimum layer thickness, part orientation, air gap, raster width and raster angle. Like the previous study, this study also used ABS plastic as the print material, a three level comparison system, and a similar change in dimension equation.[11] The study also showed a sketch of the test part for the experiment, which was shown to be a 80x10x4mm rectangular prism, shown in figure 8. Using the test part, 27 tests were performed with the data being collected and then analyzed. The study used both gray Taguchi method as well as signal to noise to determine the cause and variation in the test parts.[11] The study concluded that the optimal values to use when considering dimensional accuracy were: minimum layer thickness of 0.178 mm, part orientation of 0°, air gap of 0.008 mm, raster width of 0.4564 mm, and a raster angle of 0°.[11] Another consideration found by the study shows that the variation in thickness is influenced by the part orientation, which further explains the conclusion of using a 0° print orientation when compared to the 15° and 30° that were also tested.[11] The study also discussed issues with the FDM process, mainly in terms of heat distribution and stresses applied. It was discussed that due to the melting and rapid cooling process, as well as the deposition process. With the melting process, the uneven heat distribution is caused by the material being forced to liquidity and then quickly solidify onto the already printed plastic, which can be accredited as to why the part may not retain its original dimensions.[11] The deposition process discussed mainly focused on print speed, but also included when the nozzle stops depositing filament. It was noted that both the speed and technique would affect the heat distribution in the part, which would influence the dimensional accuracy of the printed part.[11] The stress accumulated in the print was also discussed as being caused by the uneven heat distribution. With the two main factors being the pattern used in printing as well as the size of the part, which were both accredited with affecting the required heat needed to be put into the filament.[11]

Another similar study also looked at how the infill pattern affected different mechanical attributes of the printed parts. The study used four parameters (layer thickness, travel speed of extruder, infill ratio, and infill pattern) at three different levels to see how each affected the compressive, flexural, and tensile strength of the printed parts.[12] The levels tested the layer thicknesses of 0.1 mm, 0.2 mm, and 0.3 mm.[12] With speeds varying from 35 mm/min, 40 mm/min, and 45 mm/min.[12] As well as the infill ratio differing from 60%, 80%, and 100% with a change in the infill pattern between linear, diamond, and hexagonal.[12] The parts used in the three tests varied in, with a bone shaped design for the tensile test, a rectangular prism design for the compression test, and a flat thin rectangular prism for the flexural test. As an additional measure to test the accuracy of the experiment, the researchers also tested the three different part types using FEM analysis. The FEM analysis performed was found to provide needed information on how the specimen would perform, but did not find the relationship between the breaking point of the parts and the infill pattern used.[12] When comparing the experimental and simulated results, a variance in the expected outcome was found with the simulated results being on average 40% larger than the experimental outcome. [12] The study concluded that all of the test parameters had a significant effect on the overall quality and mechanical properties of the test parts.

Other studies used the existing research to better define parameters and show gaps within the current understanding of FDM printers. While the gap of information is quite diverse, one study analyzed and reported that the current major issues were inaccurate dimensions of the part produced, poor surface finish, and poor mechanical properties. [13] To evaluate these issues, the study suggested the use of seven quality tools: check sheets, histograms, pareto diagrams, stratification, graphs, Ishikawa cause and effect diagrams, and stock diagrams.[13] The study also categorized multiple different studies on their research goal, parameters, and methodology used. The experiment performed saw the testing of 32 test parts. The study also utilized a single type of printer and printed the experimental part at two different levels, with the variation between levels being the infill ratio, layer thickness, print speed, nozzle temperature, bed temperature, and shell thickness.[13] The test part, shown in figure 9, was also shown to have a shape similar to an I-beam or bone and was printed using PLA.[13] The design was chosen to allow for the printed part to be evaluated using four different tests. The four areas of evaluation focused on the ultimate tensile strength, compressive

Figure 9: I-Beam Test Part [13]



strength, flexural strength, and hardness. [13] The evaluation showed multiple relationships between the six variables and the four evaluations parameters. Of the multiple relationships discussed, it was found that bed temperature played a significant role in the ultimate tensile strength of the part; while print speed only affected the flexural strength of the part.[13] It was also observed that the infill ratio influenced all four paramters. [13] For printing the test parts, the printer's settings were provided: print speed at 25-150 mm/s, bed temperature at 60°C, and nozzle temperature at 210°C.[13] Interestingly, the values used in printing the parts were justified only by being labeled the recommended settings, with no other justification in their use.

Another similar test was performed to see how the initial layer thickness, bed temperature and infill pattern affected mechanical properties of the 3D printed specimens. Two different sample designs were used, with the first (a) being for the tensile testing and the second (b) being for the flexural testing. [14] The first specimen was similar to previously discussed designs, with a slight indent near the center of the part. The other specimen was nearly identical to a previously discussed designs; however, it was the standard rectangular shape. Both designs can be seen below in figure 10. The designs were based on two different testing standards, ASTM D638 and ASTM D790.[14] The designs were printed out of PLA, with three different values for each of the tested parameters. The primary layer thickness ranged from 0.150 mm to 0.200 mm with each value changing by 0.025 mm. [14] Similarly the bed temperature values also changed by a uniform amount, from 40°C

to 80°C with the value changing by 20 °C. [14] Due to the nature of infill patterns, the change in design was not uniform and was chosen to vary between: grid,

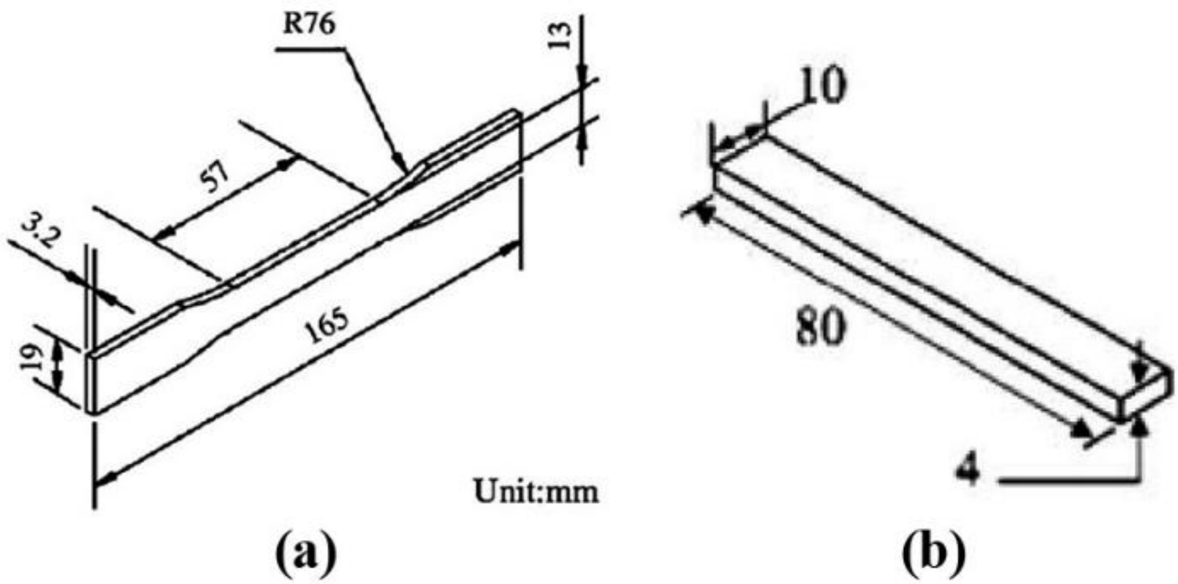


Figure 10: Test Parts a and b [14]

triangular, and honeycomb. [14] Other process values were chosen but kept constant throughout the printing process. Some of these values included an infill percentage of 50% and a nozzle temperature of $220°C$.[14] The printing process was performed 27 times, to allow for all the varied process parameters to be used. The study found that there was no singular set of parameter values that produced the best overall outcome. In the case of tensile strength in relation to bed temperature, the higher temperatures lowered the tensile strength of the triangular and grid patterned parts, however it was found to increase for the honeycomb pattern. [14] For tests based on the flexural strength of the specimen, it was found that as the primary layer thickness increased, the flexural strength increased for all three pattern types. The same cannot be said for the change in bed temperature, as it was found that the overall increase in temperature only improved the grid pattern's flexural strength. A unique trend was observed in the triangular and honeycomb pattern's, as the bed temperature increased the flexural strength increased and then began to decrease.[14] The study concluded that of the three infill patterns, both triangular and honeycomb were better suited for tensile loads as well as flexural loads. [14]

While understanding the current research that is tailored to the research performed in this experiment is important, it is equally as important to understand the overall additive manufacturing industry and how it has evolved. While numerous websites and databases due catalog different aspects of the additive manufacturing industry they are still heavily disconnected. Groups such as the Wohlers Associates have created documents describing the state of the additive manufacturing industry. Wohlers' report documents not only the updates in materials and processes used, but also how the industry has been changed globally. The report also includes reports of recent research developments as well as a grounded prediction for the future of the industry moving forward into the next year.

The report begins by discussing the current misconceptions with additive manufacturing. One such misconception is that additive manufacturing will replace traditional manufacturing, which the report claims is not the case. Additive manufacturing, although it is becoming more affordable, will still stay relatively expensive for low-value products. [15] While additive manufacturing may not replace traditional manufacturing, it can be used in combination with it. This provides the possibility for designers and machinists to create complex geometries that would otherwise be expensive or impossible to produce in a traditional sense. This ability to adapt to complex geometries would allow for users to create affordable custom parts that would otherwise be impossible to produce. [15] While the ability to produce complex geometries is a very important differentiation for additive manufacturing, this complexity does come with its own set of challenges. The complexity of the additively manufactured part comes with a higher cost in producing the model, as creating the complexity creates complexity in itself. [15] While this complexity can cause issues in the development of the design, it can allow for the design to be optimized in ways only available for additive manufacturing. The most prominent three ways of AM exclusive optimization are part consolidation, topographical refinement, and lattice structure implementation.

[15] Another common misconception is that additive manufacturing is a simple process that can be performed at the push of a button. This is the farthest from the truth. From creation to completion, additive manufacturing requires a level of planning at all stages. [15] In the creation stages of a design, parameters such as build orientation, locations of support material, and how post-processing will be performed should all be planned out as the model is made. Regardless of the type of process, this planning is traditionally performed by a user that is not a regulated machine, the same can be said for post-processing. [15] Post processing requires the user to be skilled in tasks such as removing support material. While these myths may have people thinking incorrectly about additive manufacturing, as the technology expands so will the general knowledge of the different processes.

The repot discussed in what avenues are additive manufacturing being considered, used, or refined for. These avenues were split into five overall categories, with some having at least one subcategory. These five being prototyping, tooling, final part production, education/research, and other. [15] The subcategories created included two for prototyping, three for tooling, and one for final part production. The data collected on these applications was collected using a survey sent to 124 additive manufacturing service providers. [15] These providers were spread out around the world, and provided a stable idea of what the industry currently looks like. The data collected showed that almost 79% of all services

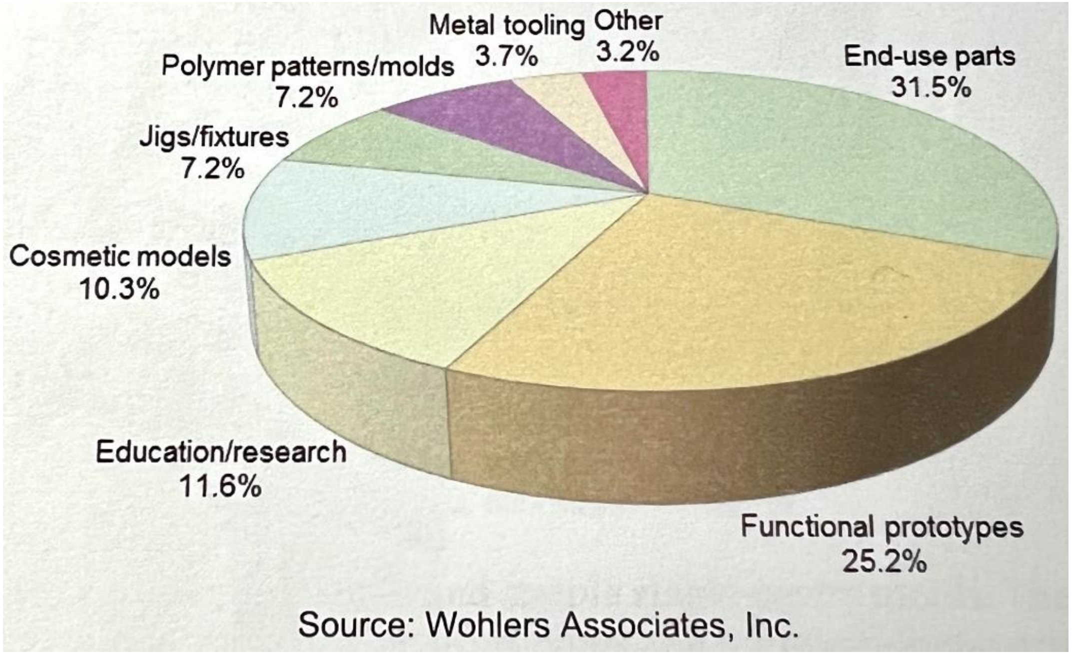


Figure 11: Industrial Applications of Additive Manufacturing [15]

provided could be classified in one of four categories. Those being cosmetic models (10.3%), education/research (11.6%), functional prototypes (25.2%), and end-use parts (31.5%). [15] This classification of the different types of additive manufacturing shows an interesting application that is not assumed to be in the position it was found to be in. Most discussions of additive manufacturing have it classified and used primarily for functional prototyping, however the data collected shows that the information provided as common knowledge is not backed up by the actual data. Another key point that was made about the data was that most functional prototypes were also used in other categories such as cosmetic models. [15] With the importance of prototyping in the design process, the ability to create functional prototypes that also fit other purposes is both effective and resourceful.

The data collected from the 124 services encompassed more than the areas for which the service providers classified their work in. The survey also asked the companies to provide what industry they operate in and the estimated percentage of revenue their production creates. [15] Of the 124 service providers, nearly half of them fall under one of three categories. Those being automotive (16%), aerospace

(15.9%) and academics (14.4%). [15] The full breakdown, provided below in figure 12, shows that of the 124 service providers they all fall into 9 categories. This

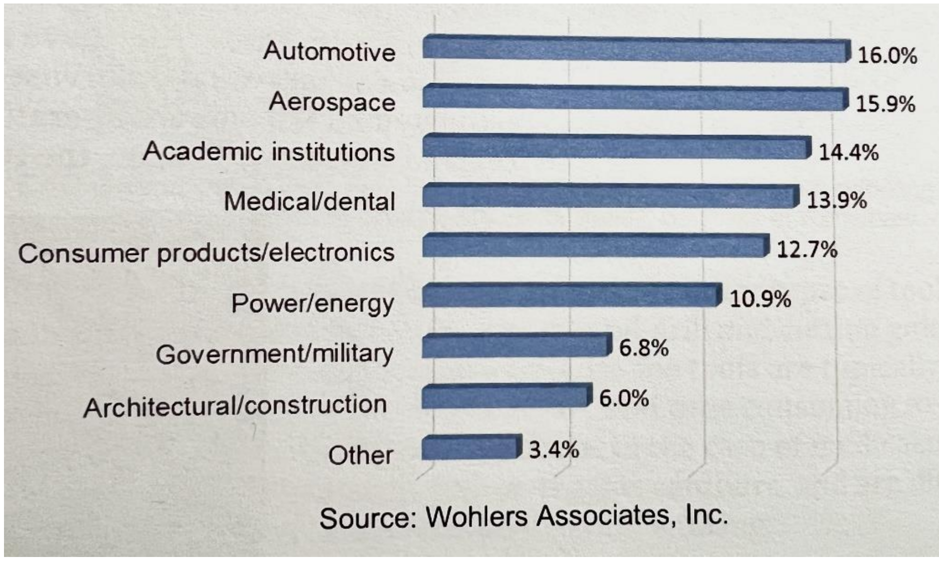


Figure 12: Industry Breakdown [15]

shows that the current implementation, while high in some areas, is still proving to be a niche market. It also outlines what was previously discussed in terms of additive manufacturing's place in the production world, with it taking a more complementary approach to traditional manufacturing instead of replacing it. With the automotive industry being the largest surveyed section for the implementation of additive manufacturing technologies, the diversity it has been implemented shows the widespread reach additive manufacturing has. While the majority of additive manufacturing implementations uses different types of metal manufacturing, there are also some cases where plastic is being utilized. Regardless of the material makeup of the implantation, the unique techniques of additive manufacturing have also been applied. Lattice structures have been implemented into the Bugatti Bolide hyper car, specifically in the vehicle's front suspension. The pushrod, made from titanium, was manufactured with a variable wall thickness and an internal lattice structure. This allows the rod to weight 100 grams (0.22 lbs), while being able to withstand a break force of 3,700 kg (8,157 lbs). [15] As for plastic implementation, Jaguar Land Rover has created a flexible safety device for their assembly line. This safety device uses a lattice structure to allow for flexibility while also creating support to help reduce muscle fatigue. [15] The glove was created to assist people working with fitting clips and fasteners to the vehicle's chassis. While the main focus in the automotive industry for additive manufacturing is with metal applications for vehicles, the implementation of an additive manufactured design for those assembly the vehicles is unique.

The automotive industry is not the only industry that has begun applying additive manufacturing techniques to their products. The aerospace industry has implemented additively manufactured parts in non-structural based parts since the mid-1990s. [15] Since their initial applications in the 1990s, the use and implementation of additive manufactured parts has become widespread throughout the aerospace industry. With many applications being to conserve weight, the choice to apply additive methods into aerospace designs fits together. Similar to the

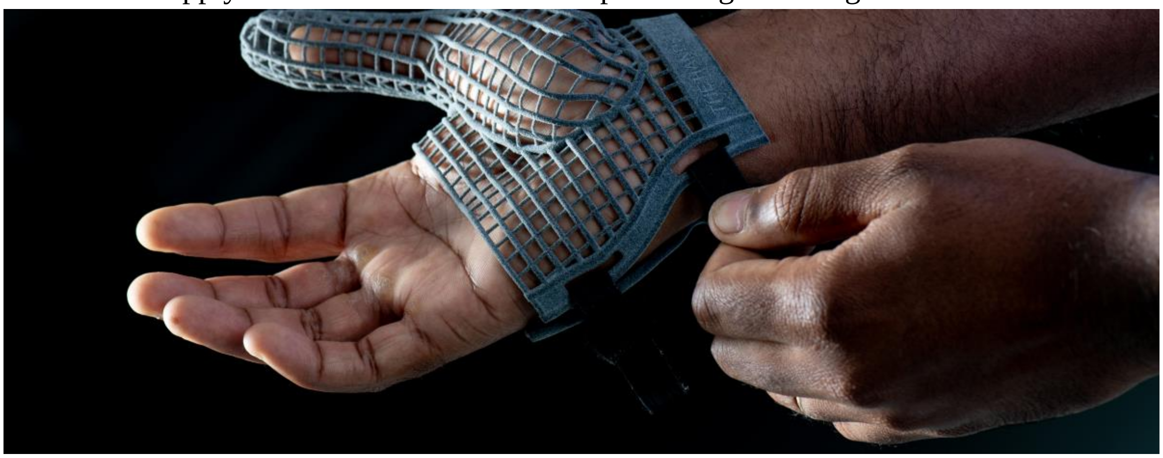


Figure 13: Jaguar Land Rover's 3D Printed Glove [15]

automotive industry, the majority of the push for additive manufactured parts comes from metal usage. However, the use of additively manufactured plastic parts has remained a constant part of the aerospace industry in the last 30 years. Boeing has been a major contributor to aerospace applications, with the company being one of the first to use additively manufactured parts in finalized part production. While the company initially implemented polymer based parts, they have begun including metal based parts since 2017. [15] There is an estimated 70,000 additively manufactured parts on Boeing's aircrafts, including both commercial and military. [15] In addition to the applications used by Boeing, the company is also working on developing more process controls for structural parts made of aluminum and titanium, through powder bed fusion.

In the realm of academia, additive manufacturing serves many different purposes. While in higher education it is mainly used in research and problem solving, the manufacturing style can also be used in other educational applications. During the COVID-19 pandemic, many academic institutes used additive manufacturing to help in making face shields for students, staff, and faculty. [15] While many academic institutes use additive manufacturing for research, the use of different tools is not universally practiced. Many different levels of education are working on applying additive manufacturing to their curriculum in terms of problem solving and hands on approaches, however this is not a universal push. [15]

Desktop 3D printers were defined by any additive manufacturing machine that sells for less than $5,000 USD.[15] These printers are split up into two

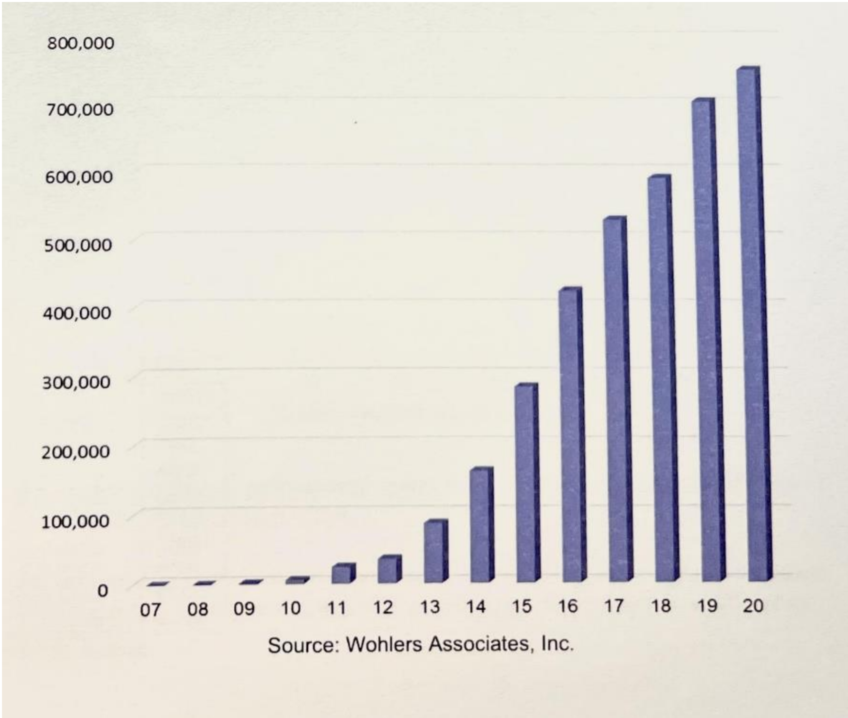


Figure 14: Estimated Sales of Desktop Printers from 2007-2020 [15]

different types, material extrusion and vat photopolymerization. For sales data of desktop 3D printers, it was noted that the method of distribution for sales is untraditional and in some areas is difficult to track. This untraditional nature was credited to the diversity in the market, from companies selling parts, kits, and assemblies using online retailers like Amazon and eBay.[15] While this lack of hard data was considered an issue on some respects, the data found provided results that included the following graph. Regardless of the uncertainty in the sales an estimated 753,211 printers were sold in 2020, seeing an increase in sales by 6.7%. Although the classification of “desktop 3D printer” may seem to denote this category of machines as bad for commercial use, the opposite is true. Numerous types of printers that fit under the provided explanation are used in the design process, from prototyping to some reports of them being used in final part manufacturing. An even more cost effective category of desktop 3D printers is also discussed, those in the price range between $150-500 USD. The majority of printers sold in that price range are produced in areas with a lower manufacturing cost, and due to the differences in the sales system in those areas makes it harder to track how many are sold. It is estimated that Chinese based companies, such as Creality, sold more than 1 million 3D printers in 2020, all with prices under $1,000 USD. [15] However, due to these estimates not having any concrete backing, the printer sales were omitted from figure 14.

While the process performed by the printer is a feature of specific types of printers, the material used can vary between printers. For example, two different printers that use SLA processes can operate with different materials with one using resin and the other using an onyx-carbon fiber powder. In 2020, sales of additive manufacturing materials was estimated to be around $2.1 billion USD, a 9.9% increase from previous year. [15] While this $2.1 billion encompasses all materials used under the umbrella of additive manufacturing, there are four types of materials

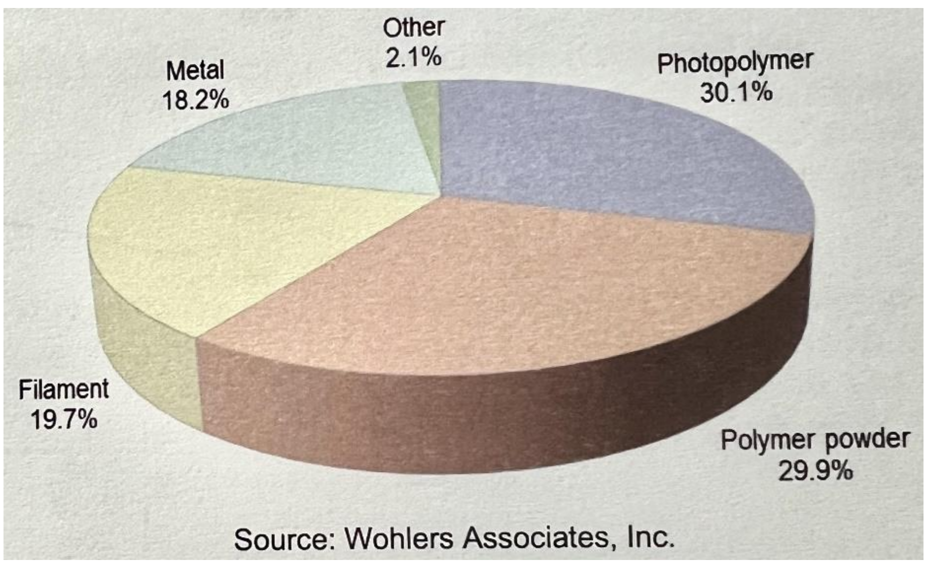


Figure 15: Sales of Additive Manufacturing Materials

that make up a majority of sales. These four being: photopolymers (30.1%), polymer powder (29.9%), filament (19.7%), and metal (18.2%). [15] It is also predicted that in the upcoming years that photopolymers will be overtaken by polymer powder materials. Figure 15 shows the percentage of each material type in terms of sales, with the other category representing wax and ceramic. Figure 15 shows that filament based printers make up the third largest material type sold, however it is closely followed by metal which may overtake it in the future in the same way that polymer powder is predicted to overtake. Although filament makes up only 19.7% of the sales for additive manufacturing materials, it is still a large contributor, especially in the desktop 3D printer market. This is mainly due to the accessibility of desktop printers, which allows them to use non-first party materials for printing. This has allowed smaller third party companies to produce a wide range of filament types that are compatible with most desktop 3D printers. Sales of all filament types grew by 5% in 2020, resulting in an estimated yearly sale of $414.1 million USD. [15]

Engineering standards are a common section in any area of the engineering field, with many companies devoted to creating standards. Of the standards introduced in 2020, they focused on six to seven overall goals for the standard. Those being test methods, design, materials and processes, environmental health

Figure 16: Distribution of AM Material Sales by Material Type [15]

and safety, terminology, and quality. [15] Wohler's chose to focus on two specific organizations that focus on standards in their report: ASTM Committee F42 and ISO/TC 261. These two organizations introduced a total of 35 standards that focused on additive manufacturing, shown in tables in Appendix A. ASTM introduced a total of 28 standards, with the majority of them focused on different processes for metal manufacturing. While ASTM did very little in terms of plastic FDM standards, it was reported that the organization was working on developing standards for feedstock specifications and a guide for design material extrusion processes. [15] ISO/TC261 introduced a total of seven additive manufacturing based standards in 2020, with the primary focus of them relating to metal additive manufacturing. However, they did release one standard that focused on plastic as a joint standard with ISO/TC 61/SC9.[15] The standard categorized as JWG11 focused on the qualification and classification of part properties for polymer parts. [15]

Chapter 3: Methodology

Process Parameters

The goal of this study is to analyze different process parameters to determine if they affect the dimensional accuracy of a 3D printed object. Due to the nature of FDM printing, the shear amount of process parameters involved in the printing process are too much for a singular study to conclude on their effectiveness in dimensional accuracy. From the research discussed in the literature review, three process parameters were chosen to be the main focus of the experiment. The three variables being Print Speed, Bed Temperature, and Layer Height. These three parameters were not the only ones in consideration, however due to numerous different reasons the other parameters were neglected. While there currently is little research performed on how the ambient temperature in the room where the FDM printer is printing affects the printed part in any way, the choice to neglect that for data collection purposes was chosen due to the complexity of controlling it. Another factor that was considered was the physical height of the printed part. This idea was rejected not because of its complexity but instead because of its lack of uniformity amongst all FDM printed parts. The height of the part is a function controlled by the part and the part designer, rather than a function of the parameters built into the FDM printers. Other more prevalent process parameters were also rejected due to the abundance of existing information about the parameter. While multiple were rejected for this reason, the biggest parameter was nozzle temperature. The optimal nozzle temperature was found to not only affect the dimensional accuracy of a printed part, but also the physical properties of the part such as tensile and compressive strength. Dimensional accuracy was also not the only area affected by the parameters that was considered, with print time being another large contributor. Print time was ultimately rejected for numerous reasons including the situational nature of needing to control print times, as well as current breakthroughs in FDM technology that are actively reducing the amount of time required. While the larger plastic additive manufacturing companies have not adapted to this faster new technology, companies such as Bambu Labs and Voron are adapting and building onto this technology. Youtubers 247printing and Fail

Figure 17: 3DBenchy Model Render [15]

Fast! have both demonstrated this new technology using Voron printers, reducing the print time for a standard “Benchy” from an estimated 2 hours to 3 minutes 27 seconds and 2 minutes 43 seconds respectively. While print speeds for a “Benchy” may seem as a rather obscure measurement, the model of a small boat that has been coined a “Benchy” is commonly used in lower levels of production to test FDM printers’ basic capabilities. [16] Another potential parameter that was excluded due to new technology being released was bed height. Bed height, as previously discussed, is a major part of the setup process for FDM printing. While in the past economically priced FDM printers, such as the Creality CR-10, lacked an automated system for bed leveling, the inclusion of bed leveling technologies have become a near standard occurrence in newer printers. In addition to the bed leveling technology being included in the newer printers, companies have begun production on additional parts for older printers that allow for the printer to level itself.

The first process parameter to be examined in the study is Print Speed. Print Speed can be easily varied using slicer software, such as Cura Ultimaker, and can be made nonconstant during the printing process. As previously discussed, the L3HSDC print room uses a varied print speed for their standard printing process. It was noted that the print room uses 40-60mm/s for the outer layers of the part and a considerably faster 100-200mm/s for the infill of the part. [6] From the interview with the staff member running the print room, the reason for the varied print speed

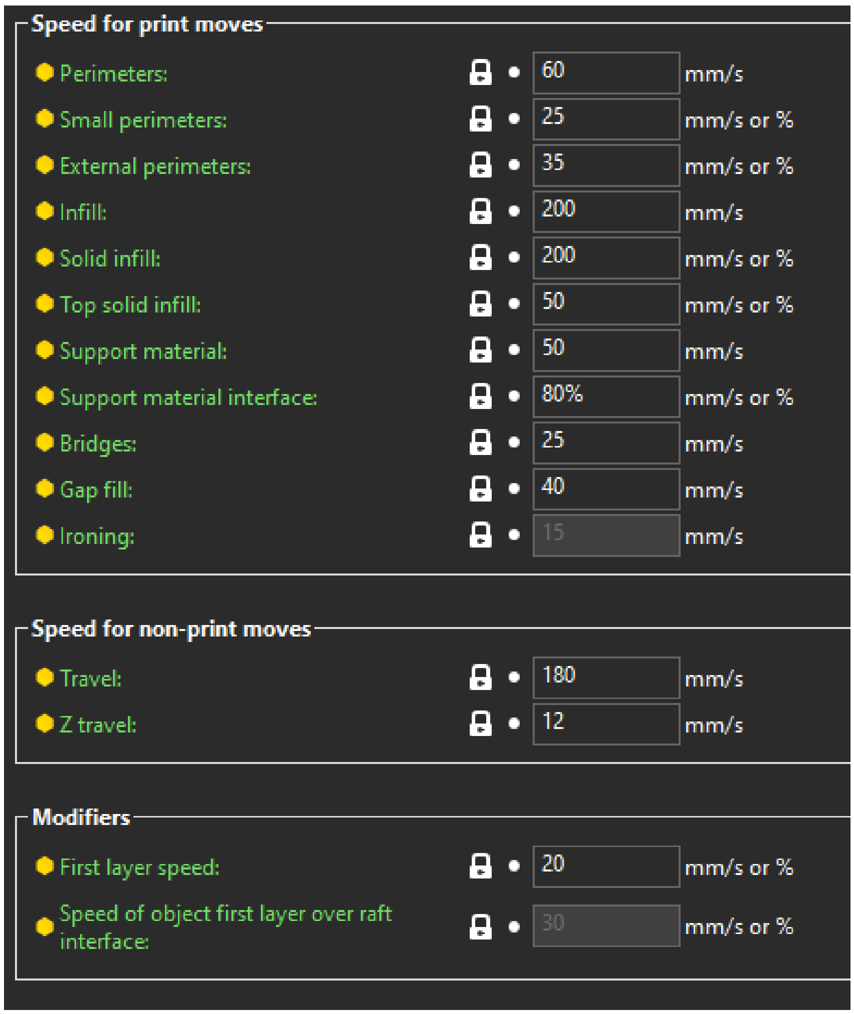


Figure 18: Print Speed Settings on Prusa Slicer

was to allow for an acceptable outer finish, while reducing the amount of time needed to print the part. Studies have also shown this variation in speed, with one study reporting a usage range of 25-150mm/s. [13] However this study did not specify if the print speed was a constant or varied parameter. Due to the substantial difference between the high and low end of the print speed it can be assumed that the experiment used a varied print speed. Selecting the test speed range was a two part process. The first, and much more intense decision making was in consolidating the information shown from the found research. This included looking at where the different speeds intersected as well as where the outlier speeds were. It also included the consideration of using a constant or varied speed for the printing process. The other section of the decision making process was based on the

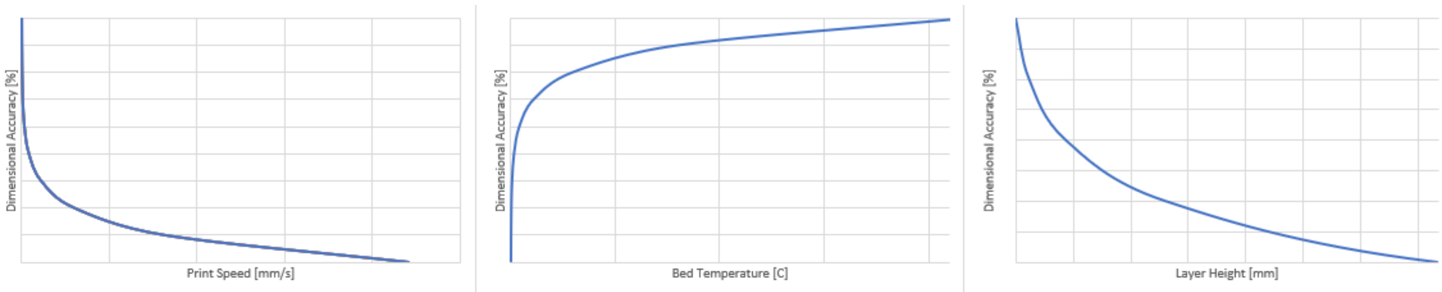


Figure 19: Predicted Behavior of Dimensional Accuracy

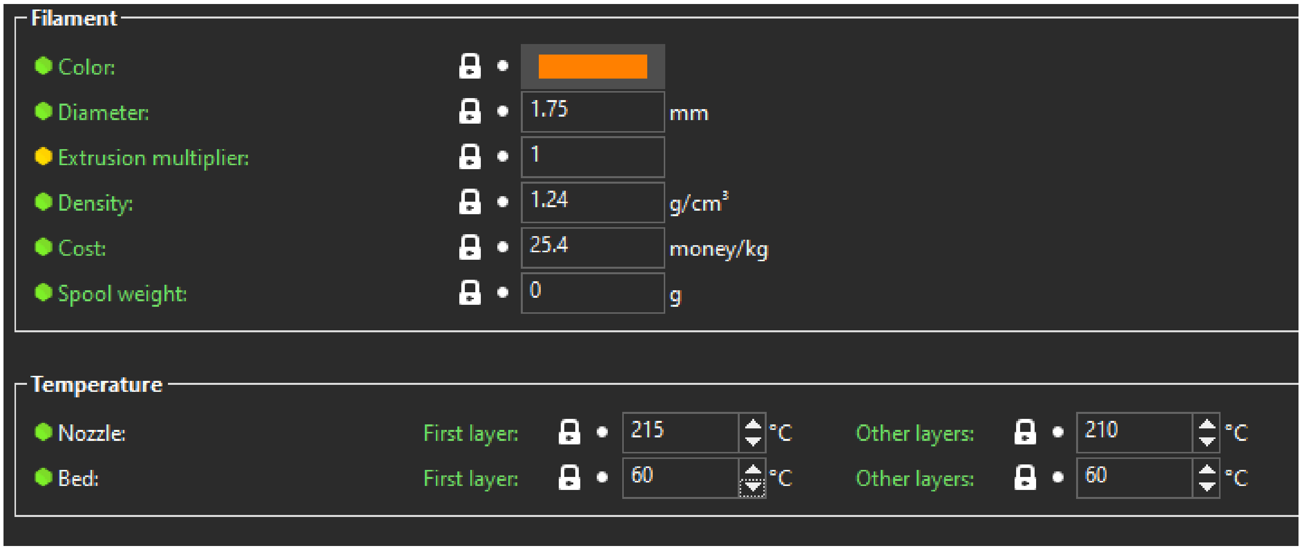
current technology available. This limitation affected the decision process due to some speeds being too fast for the printer that will be used to conduct the experiment. Using the information discussed, it was decided that the print speed will be constant throughout each print and have an operation range between 25, 50, and 100 mm/s. Other speeds were considered, including 175 and 200 mm/s, however due to the discussed technical limitations the two speeds were removed from the range. The speeds in the range will be used to demonstrate how print speed affects the overall dimensional accuracy of the printed part. It is currently theorized, through research and background experience, that the increase in print speed will greatly reduce the dimensional accuracy. With the largest drop in accuracy being in the 100 mm/s constant print speed.

The second of the three process parameters to be examined in the study is bed temperature. Bed temperature, unlike print speed, can be controlled from the user interface on the printer and does not require any software such as Cura

Ultimaker to be changed. However, some newer printers allow the user to input the temperature setting from the g-code generated by the slicing software. Although there are different ways to control the bed temperature, regardless of which process is chosen the results are still the same. Bed temperature can be a vital part of the printing process, as a heated bed allows for better adhesion from the extruded filament to the build plate surface. The temperature of the bed is not the only part of the set up process that is used for better build plate adhesion, leveling the bed is another crucial part of the process. For this reason, it is assumed that the bed being used in the experiment is level with the nozzle. This is also assured by the technology used in the printer. Unlike print speed, bed temperature is kept at a constant temperature for the entirety of the printing process. This temperature is kept constant until the printing process is finished, where then most printers activate an auto-cooling process that allows for the bed to cool down to near room

Figure 20: Temperature Settings on Prusa Slicer

temperature. Like print speed, the variation between bed temperatures used that was found in the research created a large range. The largest range discussed was between 40$°C$ and 80$°C$, with a variation between each test of 20$°C$. [14] This range of temperatures was originally chosen to be tested; however, this range was not chosen due to how broad the range was. Unlike print speed, there were no technical limitations when choosing the bed temperature with the selected printer being able to handle temperatures beyond 80$°C$. The temperature range chosen for the experiment was slightly closer than the previously discussed range, with the range of 50$°C$ to 70$°C$ with a 10$°C$ interval. This closer range, centered at 60 $°C$, provides a more precise look into the effects of the changing temperature. The choice to center the range around 60 $°C$ was also an idea provided during my interview with Zac Gross. Where it was noted that most of his personal success with printed parts was using print bed temperatures at or close to 60 $°C$.[6] Temperature consideration is a very important component of FDM printing, specifically due to the use of plastic. Plastics have a variety of reactions to



temperature, specifically heat. While PLA is not directly affected by temperatures in the range being observed in the experiment, the effects of the temperature can cause issues. The largest of these is warping, which can be caused by a multitude of temperature related situations. The most relevant to the experiment is warping due to when the parts are removed from the print bed. This concern will be primarily disregarded as the procedure for printing will require the parts be removed from the print bed only after the bed has returned to the base temperature, which is typically around room temperature. Another relevant concern to the experiment is the lower, or initial, layers of the parts warping while the parts are being printed. While this concern is made even more prominent due to the shape of the test part, the range chosen should attempt to negate any warping at higher temperatures. These concerns and the understanding behind them ultimately lead to the proposed behavior that is being tested. That the higher bed temperatures will lead to a slightly more "compressed" part due to the temperatures allowing for the parts to stay at a higher temperature for longer, which could cause the parts to shrink by melting together. This shrinking process will in turn cause inaccuracies in the height of the printed parts.

The final of the three process parameters to be observed in the study is layer height. Similarly, to print speed, layer height is another parameter set by the slicing program. The layer height described means the physical height of each layer of deposited material in the print. The variation in this can cause numerous things in a print. These variations also come with positives and negatives to them. Smaller layer heights are seen as ways to increase the resolution of the sliced model, as the model is split up into smaller layers which allows them to better describe the model. However, one of the major issues with decreasing layer height is the amount of time needed to finish the print increases. This is caused by the printer having to incorporate more layers into the process. Other issues with smaller layer heights include heating and cooling issues due to the layers being exposed to more heat from the nozzle, which can cause the final part to compress or warp. Increasing the layer height creates the expected opposite outcome from decreasing it. An increased layer height allows for the manufacturing process to be performed faster, at the cost of assumed accuracy. The size of the part that will be printed is also important when deciding layer height. Larger parts, like prototype rocket nozzles, typically benefit from a larger layer height. While smaller parts benefit from a smaller layer height. This is due to the layer height dictating how many times the nozzle passes over certain areas of a print. If a printed part has an overall thickness of 0.4 mm and a layer height of 0.2 mm, then the areas with that thickness will only be covered by two layers of deposited filament. While a part of the same thickness but with a layer height of 0.1 mm will have four layers of deposited filament in that area. The range of usable layer heights is dictated by the nozzle, as the range of sizes it extrudes directly affects the layer height. Due to this, the range for testing layer height is relatively smaller than the ranges for both print speed and bed temperature. The variation between layer heights is 0.1 mm, with the smallest layer height being 0.1mm and the largest being 0.3 mm. This variation may seem small, but as previously stated it controls how many layers are placed for a given thickness. Using the range chosen, an area with a thickness of 0.6 mm would

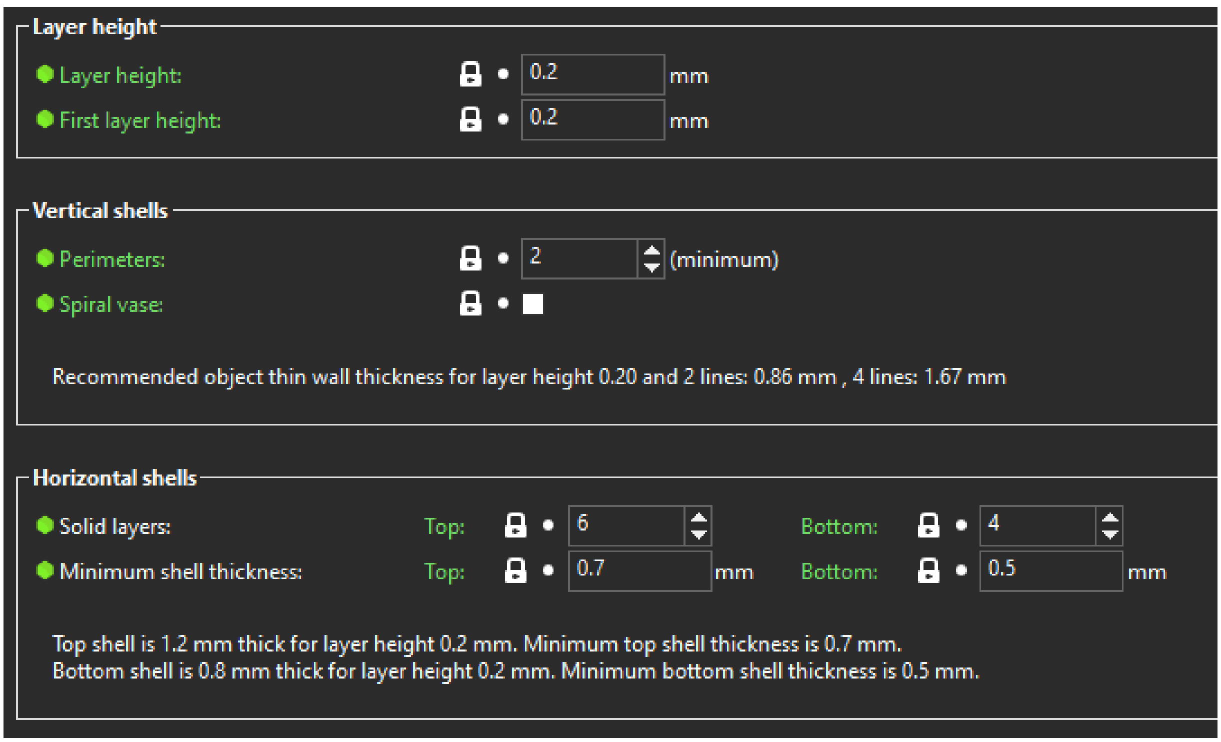


Figure 21: Layer Height Settings on Prusa Slicer

receive either 6, 3, or 2 layers depending on the settings chosen. Layer height in relation to dimensional accuracy of a 3D print is typically assumed to increase as the height decreases, and while that is an expected outcome other possibility may appear. Due to the higher resolution provided by a layer height of 0.1, it is predicted that that layer height will provide the best accuracy for the test part. This will be an interesting contrast, as Florida Tech's L3HSDC operates at a standard 0.2 mm layer height. This is most likely because of the increase in print time that a standard 0.1 mm layer height would create.

3D Model Design

To properly analyze the aforementioned process parameters in regard to their effect on the dimensional accuracy of a FDM printed object, a sample design was required. While there are organizational standards for what a sample design should be designed with, they all focus on analyzing the material properties of the print instead of the accuracy of it. One of the previously mentioned papers, A. Chadha, M. Ul Haq, A Raina, R. Singh, N. Penumarti, and M. Bishnoi, used two of those standards. A. Chadha et al, used both ASTM standards D638 and D790 for creating the test design. Due to the nature of the analysis, two different models were required. This caused A. Chadha et al, to create a design reminiscent of a bone, and another that was a standard rectangular prism. [14] In the experiment, the bone design was used to conduct tensile testing under ASTM D638. While the rectangular design was used to conduct flexural testing under ASTM D790. Due to the large amount of data reviewed focusing on the tensile, compressive, and flexural strength of FDM printed parts, the large majority of test part models used resorted to a similar design.

With most existing data focusing on the material strengths of FDM printed parts and not the dimensional accuracy of the parts, a new design was created for testing. The design created, shown below in figure 22, showed similar features to

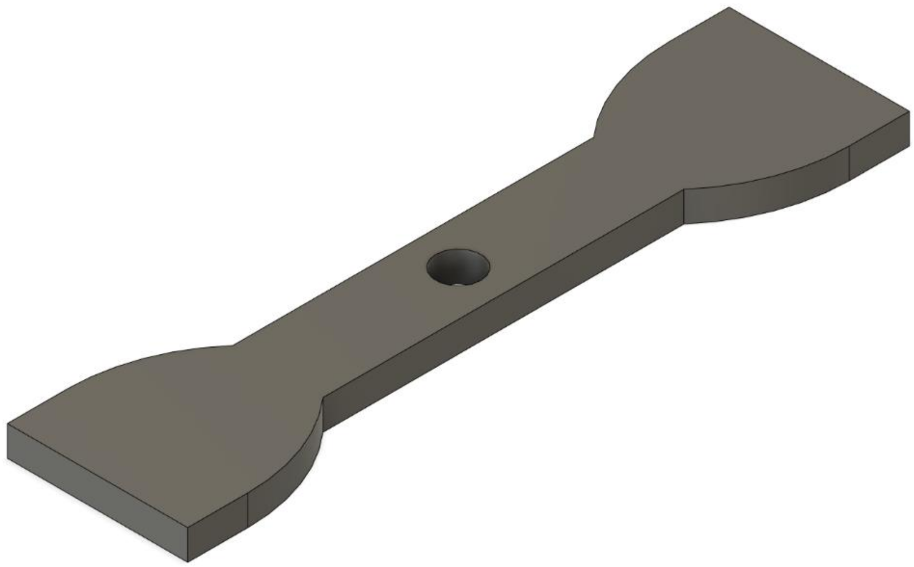


Figure 22: Initial Test Part Design

the test parts used under ASTM D638 with some unique differences. The two largest differences from the ASTM D638 were the rounded areas and the central hole. The outer rounded edges were chosen as a way to create some basic complexity in the design, as well as to reduce the amount of plastic used in printing the part. The central hole was created in the design to allow for an additional measurement to be taken, the inner diameter of the hole. This design choice would also allow for the test part to be differentiated from previous experiments. Another key difference between the design used for tensile testing and the new one was in the size of the part. When compared to the tensile part, the new design was larger in width and thickness, but smaller in height. The design, shown below in figure 23, featured a width of 30 mm, a thickness of 5 mm, and the inner diameter of the centralized hole was 7.5 mm. Before testing began, further research on the validity of the design of the test part was performed, and it was found that a certain area needed to be addressed. The feature that required some changing was the centralized hole. This change was brought to light when validating the usefulness of the hole. The research explained that due to the nature of FDM printing, the complexity of creating narrow holes with close tolerances typically causes some

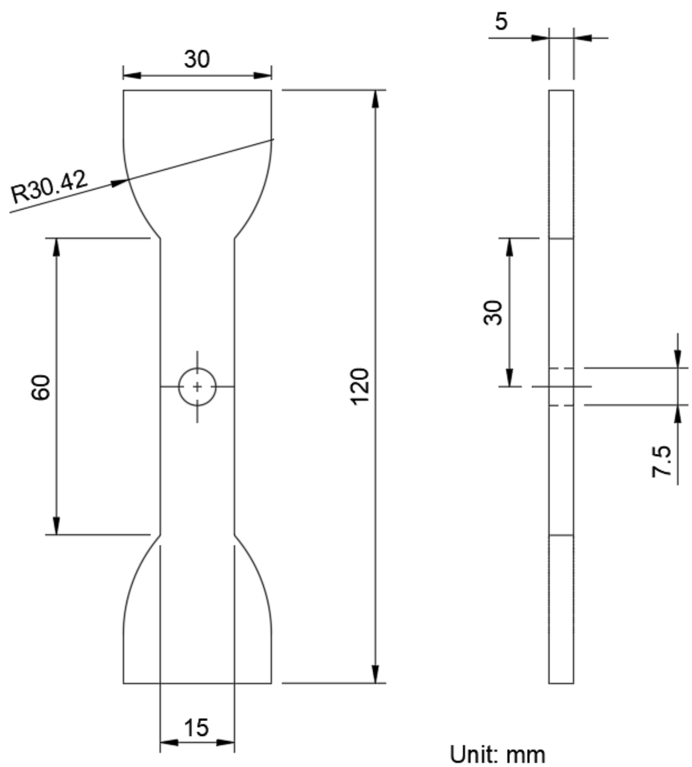


Figure 23: Initial Design Dimensions

amount of distortion in the final print. [17] The research further explained how to deal with narrow holes in 3D printed parts, with the main way to resolve any issues being to print the part in question in the orientation where the hole was vertically aligned. Due to this discovery, the decision was made to remove the central hole. The main reason for removal being that the part was already being printed in the suggested orientation. The finalized design for the printed part would be identical to the earlier design but with a solid middle area. The finalized test part design, shown below in figure 24, was further validated using the same research that invalidated the original design. The largest validation of the model occurred when discussing where to measure the width of the part. Many different areas were

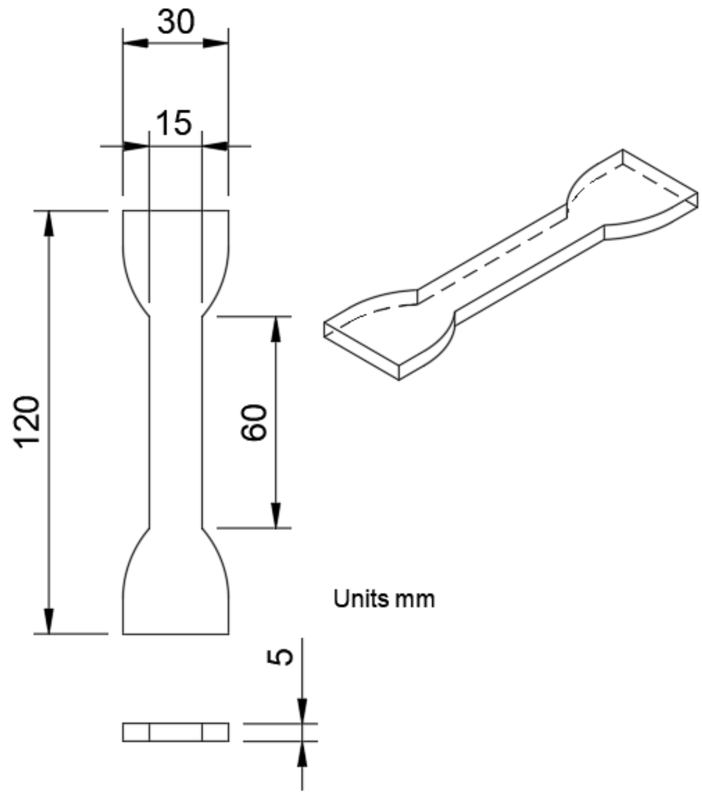


Figure 24: Final Part Dimensions

considered; however, a final area was chosen due to the research. The research noted that sharp corners and internal edges are more dependent on the radius of the nozzle and are not typically the exact 90° angle that the model is shown as. [17] With this in consideration, the area to measure the width of the part was determined to be between the inner area of the part. This area provides the flat surface needed for measuring while also allowing the printer to follow the original design more accurately because of the wider arc the nozzle will travel. Further analysis of the final part will be discussed in the part analysis section.

Printing Process

The printing process was performed at Florida Tech's L3HSDC, by select employees. These select employees were chosen in an effort to negate adding more errors into the trials. The printer used for the experiment was sectioned off by the L3HSDC staff. The printer, named "Power", is a Prusa i3 MK3 which was

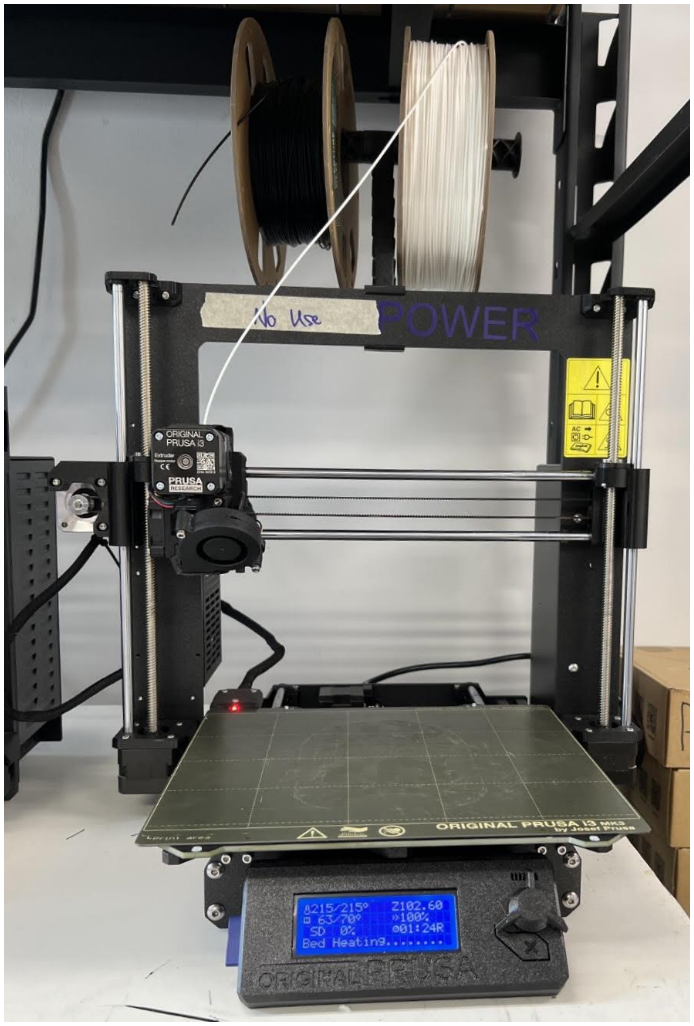


Figure 25: Prusa i3 MK3 "Power"

sectioned off from the rest of the print farm. This caused the printer to only be printing the test parts. The test part discussed above was printed four times per trial. As previously stated, the three varying parameters included the print speed in mm/s, bed temperature in $°C$, and layer height in mm. Each parameter had three chosen numeric settings. Print speed was allowed to vary between 25, 50, and 100 mm/s. Bed temperature was set at temperatures 50, 60, and 70 $°C$. Finally, layer height was varied between 0.1, 0.2, and 0.3 mm. These additional parameters were chosen after a discussion with the L3HSDC staff about their current printing standards. For temperature-based parameters there was only one constant, the nozzle temperature which was held at a constant $215°C$. For the actual printed parts, the percent infill as well as the infill pattern were kept constant throughout at 10% and grid respectively. Other settings held constant included the speed of the nozzle during the initial layer and the top and bottom thickness of the part. Another effort to negate error was in the filament choice. After a discussion with the staff, it was decided that all of the test parts would be printed in white filament. While it is normally negligible, the small differences between filaments of different colors were considered a factor that could cause error. In addition to filament color, different roles of filament of the same type could also have small differences that would affect the printed parts. While this was a concern, all trials were able to be performed using a singular roll of white PLA filament. To accommodate all the unique setups for the three variable parameters, a total of 27 trial prints were performed. The 27 trials performed all of the different parameter values, shown below in table 1, to be properly examined.

Table 1: Process Parameter Values

	Lower (-1)	Mid (0)	Upper (1)
Print Speed	25	50	100
Bed Temp	50	60	70
Layer Height	0.1	0.2	0.3

Another precaution that was performed during the printing process was the amount of prints each trial would include. Each trial was given a singular print, with four of the test models being printed per. No additional printing was performed for any of the 27 trials. While in most applications, if a 3D printed part fails during the printing process the print is stopped and restarted. However, due to the nature of the experiment, none of the printing processes that featured a failure in the printing process were stopped. This was to allow for uniformity in the data creation process as all trials were given the same number of trials. These qualitative defects in the printing process will be discussed later in the results section of the paper.

Part Analysis

Once the printing process for all 27 trials was completed, analysis of the printed parts was performed. Each part was measured physically using a VINCA DCLA-605 digital caliper. The caliper used provided a measuring distance of

Figure 26: VINCA Digital Calipers

150mm/ 6 inches, which allowed for all measurements of the test parts to be measured. The caliper also had a measurement accuracy of $\pm 0.03mm\ /\ 0.001\ inches$. The parts were measured in three distinct areas, with the areas measured for the length width, and thickness of the part. The approximate locations for all the measurements can be seen below in figure 26. Using the information discussed previously, the area for the width measurement (a) was chosen to be the inner distance of the part. This was chosen due to the way FDM printers deposit material, which causes for sharp corners to be dictated by the nozzle instead of the actual angle of the part. The area chosen for the length measurement (b) spans the length of the entire part. An assumption was made about the walls used to measure the length value. This assumption was that the walls were parallel to each other as well as perpendicular to the bottom face of the part. The area measured for the thickness (c) was chosen to be on the inside of the part. While the thickness measurement was chosen to be in the same section on all of the test parts, it was assumed that the thickness was constant throughout the part. Once all 108 test parts were printed, the measuring process to find the data was performed. Each trial of four test parts took an estimated 10 minutes to fully record all the required data. The data for all four test parts was then averaged. Once all 108 test parts were averaged into a data set of 27, the data was then compared to the original CAD model. The equation that was originally planned to be used for comparing the 27 trial measurements with the original CAD model was found during the research process. The equation used, equation 1, was used by Sood, A. K., Ohdar, R. K., and Mahapatra. In their study, the dimensional accuracy of an FDM printed test part was also measured. However, the parameters chosen in the study were different from the three observed. The 27 measurements for each of the three variables were compared to their respective original CAD measurements. However, the equation was changed to only include the averaged value of all four measurements and the

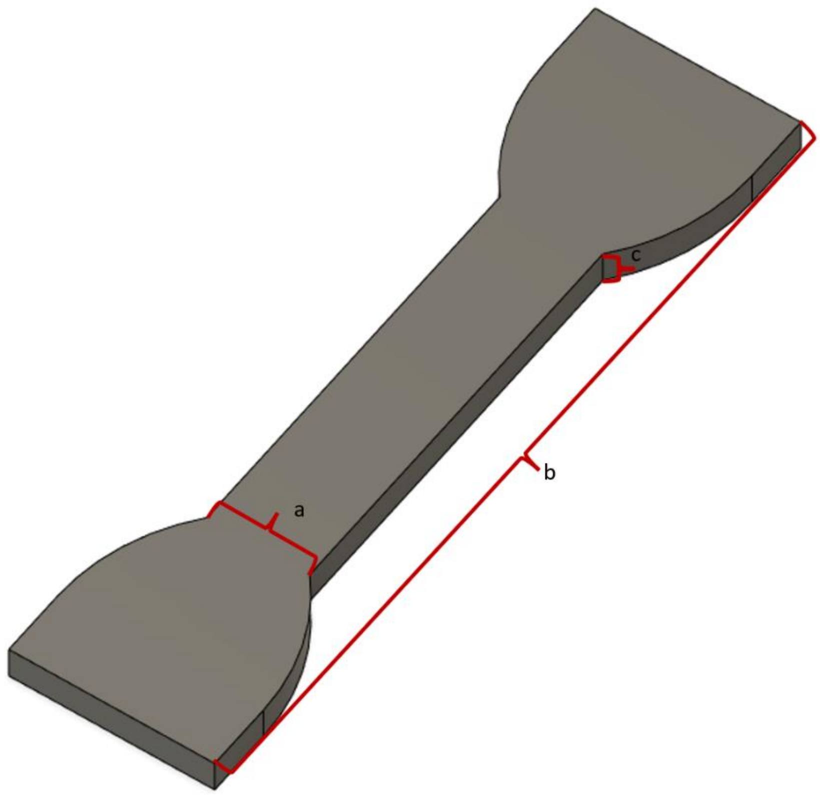


Figure 27: Measured Areas on Printed Part

respective CAD model. After all 81 trials were compared, the final value found was the variance between the CAD and each trial.

$$X_{Var} = X_{Avg} - X_{CAD}$$

Equation 2: Average Variance Equation

Once the variance of each trial was found, an analysis of the variance (ANOVA) was performed. Due to the parameters tested, a three-way ANOVA was required to properly analyze the interactions between each parameter. This analysis is used to generate an ANOVA table, which shows the significance of each of the analyzed variances. This analysis was performed by a program, IBM SPSS Statistics. Each variance was observed independently of each other, while still being compared to the 27 trial settings. This allowed for the observation of any significant trends both within and between the three process parameters and their effect on the dimensional accuracy of either of the three measured values.

Chapter 4: Results

Qualitative Observations

While every trial was observed using the ANOVA statistics table, physical attributes of the test parts were observed in the printing process. Some of the test parts that shared similarities in certain values for test parameters showed unique trends. One such example that was found in certain test parts was an uneven final printing surface. These final surfaces showed many different defects. Some test parts featured bumps or ridges at the ends of a string of melted filament. This has many causes, one of which could be the top part was allowed to cool too quickly. Other potential reasons this happened can be due to the printer moving too fast for the filament to be successfully planted onto the layer underneath it. Other issues seen in the test parts included holes in the final layer. These holes were most likely

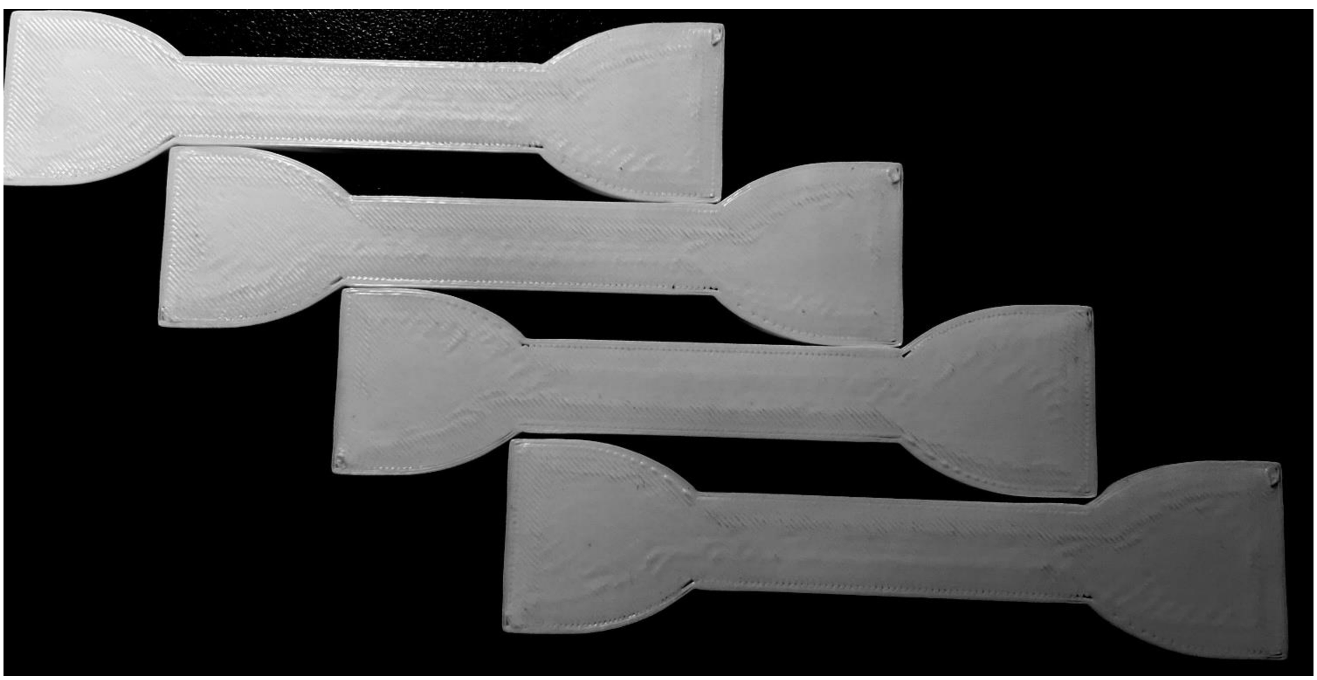


Figure 28: Trial 1 Test Parts

caused again by the printer's speed. In the printing process, if the extruder was moved too quickly past certain areas, then the layer would not be able to "close off" the layer underneath it. These hole defects were primarily found in the corners of the print, as well as in areas where the particular layer strand would be quickly forced to end. The opposite can be said for the other side of the layers in question. Other areas featured a small buildup of filament where the extruder began

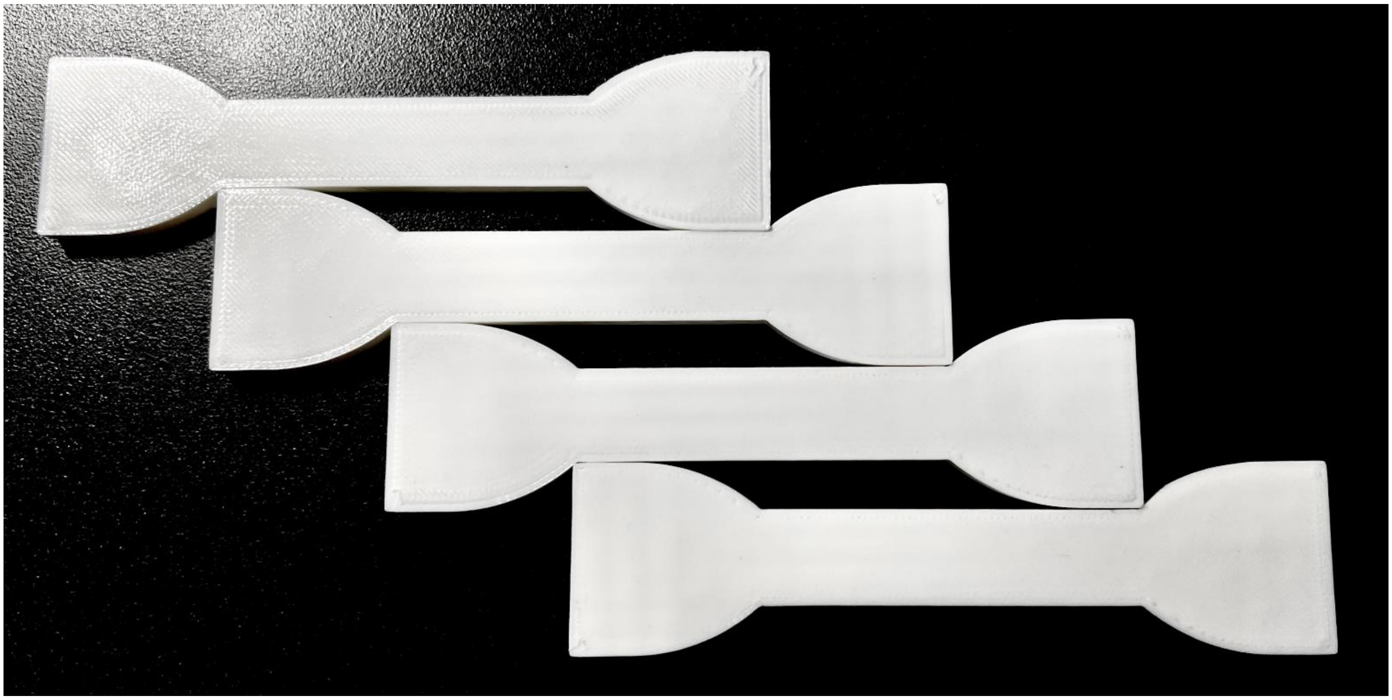


Figure 29: Trial 17 Test Parts

depositing the hot filament. All three of the aforementioned defects were observed in earlier trials, which all featured a print speed of 100 mm/s. Some of these defects can be seen in figure 29. After the initial observation of the discussed defects, other trial test parts were viewed. The nine trials that used a print speed of 50 mm/s were analyzed first. These nine trials' test parts showed almost no holes or ridges amongst them. Of the 36 test parts analyzed, only 3 of them featured minimal ridges on one side of the exterior face. While some of the test parts did still show some ridges, none of the 36 test parts featured any holes in the outer layer. For this analysis, only the exterior face that was printed last was observed. This is because of how the printing process of the test parts goes layer by layer. This layer by layer process seals off the exterior face of the test part that was printed directly onto the build plate.

Small ridges and holes were not the only defects observed on the parts after the printing process. Some of the test parts experienced varying levels of stringing.

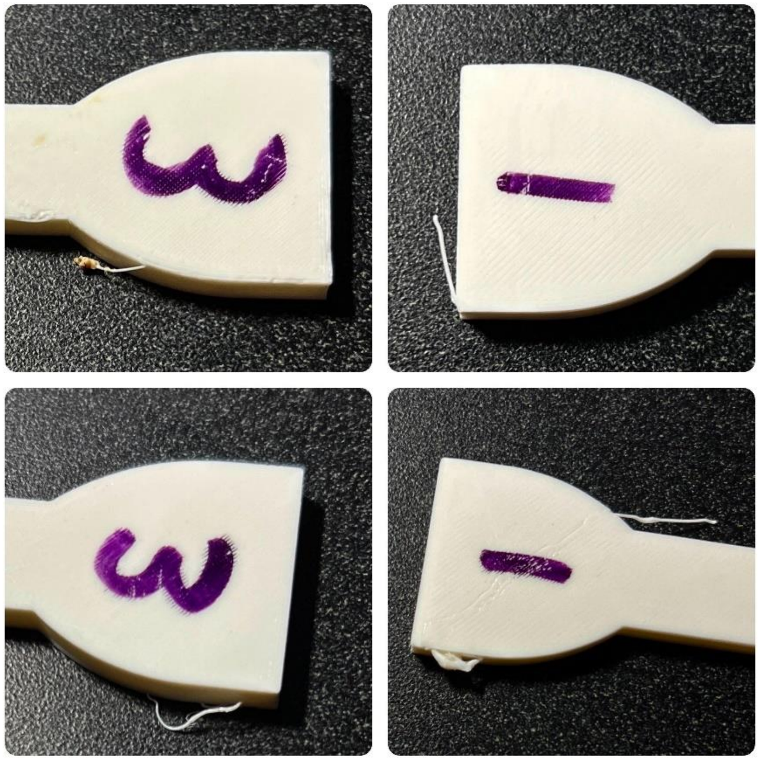


Figure 30: Observed Stringing from Test Parts

While similarly to the ridges and holes that were observed in some parts, the stringing defects found are small. However, they still indicate issues in control during the printing process. While the exact reason of the stringing defects in each of the observed cases is not known, it can be assumed that it was caused by the speed at which the printer was depositing the filament. Unlike the previous defects, which were only observed in trials using one of the three speed states, the stringing was observed in two different speed stages. Of the 108 test parts, four experienced some amount of stringing. Of these four, two of them were printed using a print speed of 100 mm/s, while the other two were printed using a print speed of 50 mm/s. Three of the four trials that experienced stringing also shared another variable in common, layer height. Three of the four trials were operating under a layer height of 0.1 mm, while the fourth trial used 0.2 mm as the layer height.

These stringing defects were observed across all three temperature states for bed temperature, thus ruling it out as a possible cause for it. Bed temperature can also be ignored due to how the stringing would be created during the printing process. The actual test part can also be ignored as a reason for the stringing. This is primarily due to the stringing occurring at different areas on the four test parts.

There was another group of smaller defects that was observed after the printing process. These defects being the shifted layers. While there were some test parts that experienced some layer shifting, the number of them was smaller than those affected by ridges and holes. However, the number of test parts that experienced some layer shifting equaled the amount of test parts that experienced stringing. Many of the observed layer shifts were caused by another much larger observed issue. This smaller defect was most likely caused by the initial layers of the part, as they did not properly adhere to the printer bed. Of the 108 test parts, a total of four experienced layer shifting. Of the four that were printed, two were from the same trial, while the other two were from another trial that was also shared by both of the remaining parts. Interestingly all four parts that experienced shifting shared two of the three process parameter values. This shifting was seen in trial 25 and 26, sharing both print speed and bed temperature. The print speed of the two was set to the slowest setting, at 25 mm/s. Bed temperature was also set to the lowest setting, at $50°C$. Of the four test parts, only one of them would be generally considered a successful print. While this “successful” test part did have layer shifting, it was minor enough that most applications would see the end-user performing post-processing on it. For minor layer shifts such as this one, simply sanding down the area would allow for the test part to be seen as a successful print. The test part also only experienced shifting on of the sides of the face, while the other remained in the correct area. Another of the four could also be considered successful after post-processing. Similarly, to the least affected, sanding and trimming the affected area would allow it to be considered of decent quality. This cannot be said for the other two test parts. However, of the two test parts they both experienced different levels of layer shift. The lesser of the two featured a layer

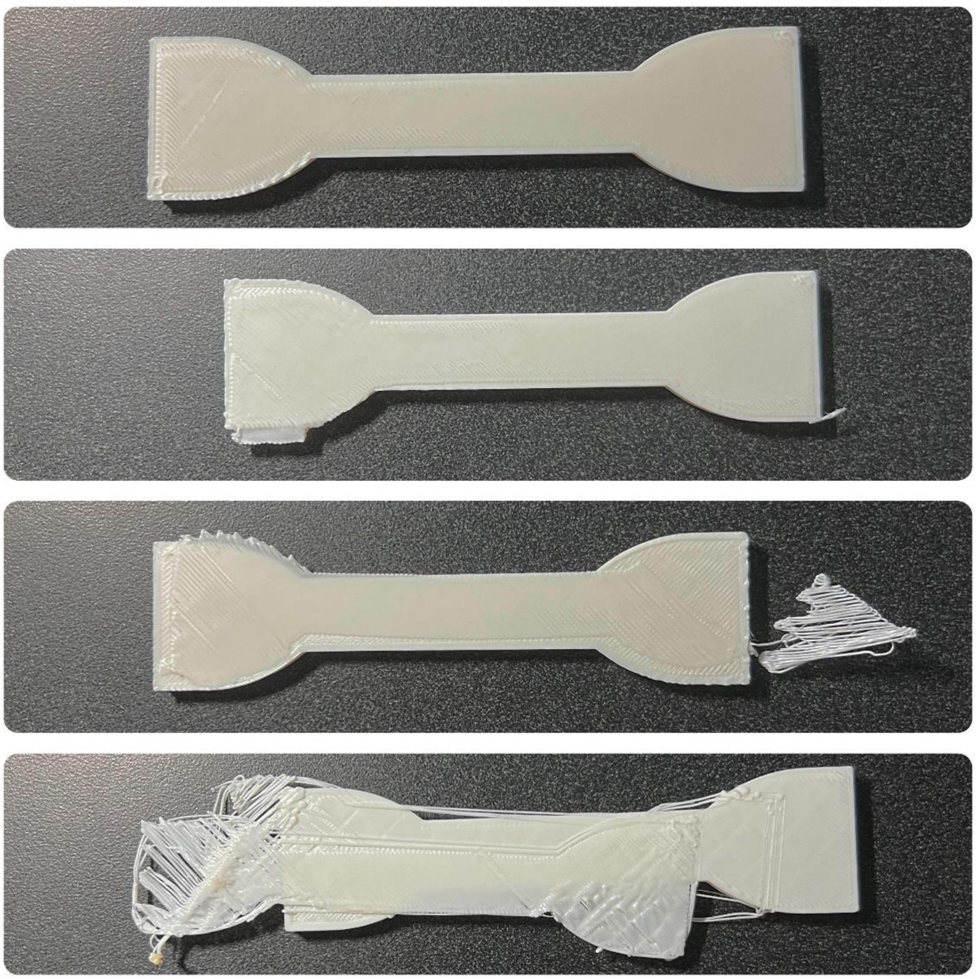


Figure 31: Test Parts with Increasing Amounts of Layer Shifting

shift only on the final layers of the part. While this is enough to consider the part a failure, the condition of it would allow for it to be salvaged as a usable part if reprinting it was not an option. The lesser of the two more severely shifted test parts also featured some stringing, however this stringing was attributed to the layer shift and not caused by the same issues that caused the stringing observed in the other parts. Both of the parts that experienced smaller amounts of layer shifting were both pairs to the two test parts that experienced a larger amount of layer shift. The layer shifting observed in the last observed test part from would be considered a complete failure. While the first few shifted layers remained on the test part in some amount, the following layers did not. This caused the part to “grow” out of the area defined for the part. The layer shifting of the least affected could have been caused by numerous issues. However, the cause of the defect can be assumed to be due to the issue that occurred for the other shifted test part. The other two test parts affected by layer shifting were caused by the same reason. This causation was due to the test parts becoming loose and shifting on the print bed while the printing process was still being performed.

The lack of print bed adhesion caused other issues as well. The other defects created by this could be considered a greater issue than that of layer shifting. Of the 108 test parts, a total of six test parts could be considered a failure. This is due to all six of the test parts becoming loose on the print bed during the

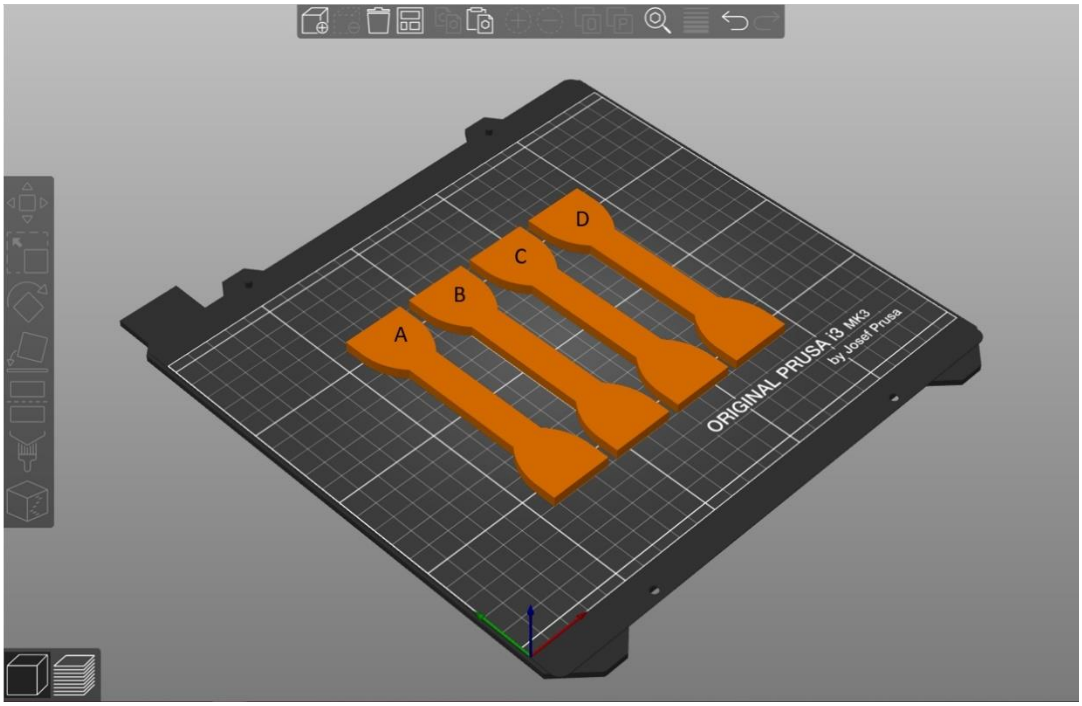


Figure 32: Part Placement on Build Plate

printing process. The six test parts occurred during five trials, with the final trial featuring two test parts that came off of the bed. All five trials shared a single parameter value, while the other two parameters varied between each. The test parameter that all five trials shared was the bed temperature. The bed temperature in all five trials was kept at the lowest tested value, at $50°C$. This commonality points to the bed temperature being the only cause for the test parts coming off of the bed prematurely. Interestingly, not all nine trials were observed to have bed adhesion issues. While the assumption that the bed temperature was the primary cause for the failed prints seems plausible, there is another option to explain this. This other reason for the failed prints is that they were caused by the printer used to print them. This reasoning comes from the location where each of the failed prints were located. Of the six test parts, five of them were located on the inner left side (B) of the print bed, with the sixth being located on the inner right side of the print bed (C). These locations can be seen in figure 32. However, the plausibility that it was a fault of the printer used can be negated for one simple reason, that the other 22 trials did not feature any kind of issues in those areas. This holds the assumption

Figure 33: Failed Print with the Smallest Thickness Value

that the variance created was caused by the printer settings and not the actual hardware of the printer. Interestingly, the final thickness of the failed parts was almost entirely in the 4 mm range. Of the six test parts, five of them featured a thickness between 4.18-4.98 mm, the smallest of which can be seen in figure 33. The singular outlier had a thickness of 5.18 mm.

Quantitative Observations

Once the 108 test parts were measured, the data was logged and analyzed.

Table 2: Measured Data

Trial Number	Print Speed	Bed Temperature	Layer Height	Change in Length (mm)	Change in Width (mm)	Change in Thickness (mm)
1	1	1	1	-0.09	0.12	0.1275
2	1	1	0	-0.1225	0.025	0
3	1	1	-1	-0.06	0.01	0.035
4	1	0	1	-0.0125	0.045	0.08
5	1	0	0	-0.0925	-0.01	0.0375
6	1	0	-1	-0.165	0.12	0.0375
7	1	-1	1	-0.0675	0.0775	0.205
8	1	-1	0	0.0225	0.065	0.02
9	1	-1	-1	-0.07	0.16	-0.06
10	0	1	1	-0.1575	0.065	0.16
11	0	1	0	-0.22	0.03	0.005
12	0	1	-1	-0.2525	0.125	-0.01
13	0	0	1	-0.1075	0.0375	0.1675
14	0	0	0	-0.1675	-0.015	0.04
15	0	0	-1	-0.2275	0.0525	0.02
16	0	-1	1	-0.0925	0.0875	0.145
17	0	-1	0	-0.145	0.09	0.025
18	0	-1	-1	-0.12	0.2725	-0.1075
19	-1	1	1	-0.165	0.0575	0.12
20	-1	1	0	-0.0675	-0.0125	0.005
21	-1	1	-1	-0.275	0.0325	-0.01
22	-1	0	1	-0.1175	0.1	0.025
23	-1	0	0	-0.1075	0.045	0.025
24	-1	0	-1	-0.1975	-2.4425	0.005
25	-1	-1	1	0.025	0.19	0.05
26	-1	-1	0	-0.065	0.4475	0.09
27	-1	-1	-1	0.2	0.2625	-0.2025

Each test part was measured for three variables: length, width, and thickness. The average of the four measurements was taken for each variable, which was used as the respective data point for that trial. Once the averages for all three measurements were found, they were then compared to their respective CAD measurement. This was done by using equation 2, which simply subtracts the CAD measurement from the average measurement. The data collected can be seen in table 2, with the values for the process parameters located in table 1.

Once the data was measured and collected, it was statistically analyzed. The program used was IBM SPSS Statistic. The nature of the experiment led to the conclusion to use ANOVA as the main process for analysis. The first step in an ANOVA is to make sure the data is normally distributed and homogenous. Numerous tests were conducted to validate the data, including the Shapiro-Wilk test. These tests showed that the data for all three dependent variables were both normally distributed and homogenous. To properly analyze the data, all three dependent variables were analyzed separately. This allowed for all independent variables to be properly analyzed when compared to only one dependent variable at a time. For each of the three dependent variables, a three-way ANOVA was planned to be performed. However, due to a technical issue with SPSS, three variations of the three-way ANOVA were not performed. While three trials of the three-way ANOVAs were not performed, a solution was found using two-way ANOVA. This tripled the number of tests needed to be certain about the data, however using two-way ANOVA could still be utilized to show how two independent variables affected the dependent variable as well as each other. Each dependent variable had three two-way ANOVAs performed. The three analyses saw the use of: Print Speed*Layer Height, Print Speed*Bed Temperature, and Layer Height*Bed Temperature. To observe any significance in creating variance, a 95% confidence interval was used for all tests. For the first dependent variable, length, the ANOVAs showed significance in both the Print Speed*Bed Temperature and Layer Height*Bed Temperature tests, shown in table 3. The significance shown in these tests were for the print speed and bed temperature

Table 3: Two-Way ANOVA Significance for Change in Length

Tests of Between-Subjects Effects

Dependent Variable: ChangeInL

	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	.151[a]	8	.019	3.576	.012
ɔt	.315	1	.315	59.653	.000
eed	.045	2	.023	4.289	.030
np	.075	2	.038	7.112	.005
PrintSpeed * BedTemp	.031	4	.008	1.450	.258
	.095	18	.005		
	.562	27			
Corrected Total	.246	26			

a. R Squared = .614 (Adjusted R Squared = .442)

Tests of Between-Subjects Effects

Dependent Variable: ChangeInL

	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	.110[a]	8	.014	1.823	.138
ɔt	.315	1	.315	41.707	.000
eight	.008	2	.004	.538	.593
np	.075	2	.038	4.972	.019
LayerHeight * BedTemp	.027	4	.007	.891	.490
	.136	18	.008		
	.562	27			
Corrected Total	.246	26			

a. R Squared = .448 (Adjusted R Squared = .202)

independently for the first observation, and only bed temperature for the second observation. For the second dependent variable, width, no significance was found.

For the final dependent variable, thickness, two tests showed some amount of significance. These tests were Print Speed*Layer Height and Layer Height*Bed

Table 4: Two-Way ANOVA Significance for Change in Thickness

Tests of Between-Subjects Effects

Dependent Variable: ChangeInThickness

	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	.129[a]	8	.016	4.831	.003
ɔt	.040	1	.040	11.865	.003
eed	.009	2	.005	1.417	.268
eight	.106	2	.053	15.885	.000
PrintSpeed * LayerHeight	.014	4	.003	1.011	.428
	.060	18	.003		
	.229	27			
Corrected Total	.189	26			

a. R Squared = .682 (Adjusted R Squared = .541)

Tests of Between-Subjects Effects

Dependent Variable: ChangeInThickness

	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	.150[a]	8	.019	8.664	.000
ɔt	.040	1	.040	18.286	.000
eight	.106	2	.053	24.482	.000
np	.005	2	.003	1.245	.312
LayerHeight * BedTemp	.039	4	.010	4.464	.011
	.039	18	.002		
	.229	27			
Corrected Total	.189	26			

a. R Squared = .794 (Adjusted R Squared = .702)

Temperature, shown in table 4. In the first of the two observations, only layer height was significant, while in the second observation layer height and the relationship of layer height and bed temperature were significant. All nine ANOVA observation tables can be seen in appendix C.

ANOVA tests were not the only statistical test performed; Tukey tests were also conducted to allow for the observation of the significance of the individual parameter values. Similarly, to the two-way ANOVA tests, three Tukey tests were performed per dependent variable. These nine tests, in appendix C, showed some significance in all three independent variables. For interpreting the Tukey tests, the significance of a variable showed a significant amount of variation from the original value. Of the nine tests performed, five relationships were shown to have the least significance, and thus the least significance. Along with the significance of the variables, the Tukey test also provided the mean difference between the independent variables. This information was then used to find that five relationships could be considered for the least variation causing. Of the five, two sets of two were duplicates seen amongst the different tests. These duplicates were the relationships between the highest and middle setting of the bed temperature, as well as the lowest and the middle setting for layer height. The fifth relationship was between the highest and lowest value of the print speed. Of the first four, additional observations were used in deciding which variables could be considered the least variation causing. These additional observations included comparing the mean difference values as well as the average variance in the analyzed data. For the fifth relationship, another approach was taken to find the optimal setting. This additional consultation was performed by observing the physical test parts, as many with the same setting value experienced major defects that would not have been considered from just a statistical approach.

Chapter 5: Conclusion

The purpose of this study was to observe, document, and analyze how different process parameters affect the dimensional accuracy of FDM printed parts. This was done by varying three independent variables: print speed, bed

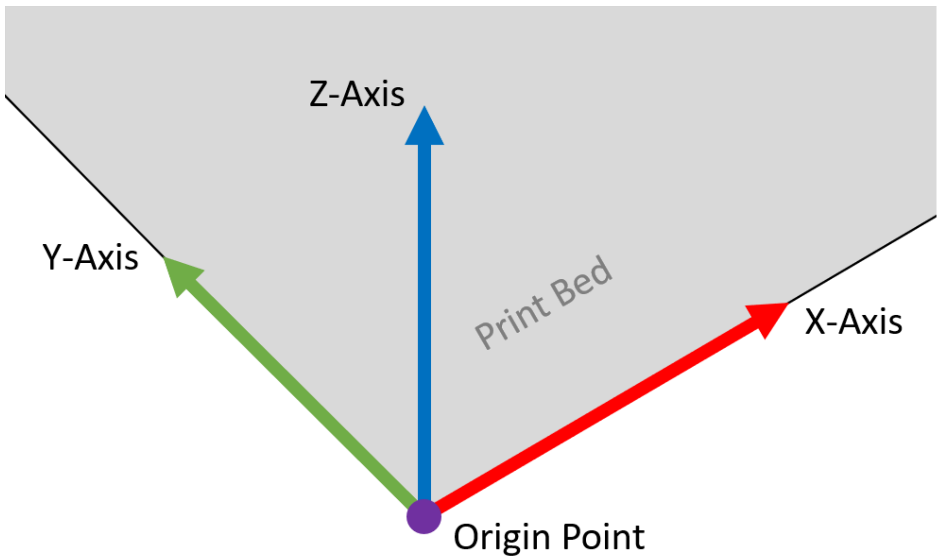


Figure 34: Axial Directions from Print Bed Origin

temperature, and layer height. Using a literature review, three hypotheses were formed to explain the expected outcomes of each independent variable on the dependent variable. A test part was modeled following research found during the literature review that was later used in the experiment. When varying the three variables, test trials were performed where four identical test parts were printed. A total of 27 trials were conducted, resulting in 108 printed test parts. Once the printing process was concluded, all 108 parts were measured by hand. The measurements taken included the length, width, and thickness of the part. These three measurements were representative of accuracy in the X, Y, and Z-axis. The four values for each of the three dependent variables were then averaged together and then compared to the original value provided by the CAD model of the test part. The remaining values, the variation between the test part and the CAD model, were uploaded into IBM SPSS Statistics for further analysis. Multiple tests were performed in the program, including Shapiro-Wilk normality test, analysis of variance (ANOVA), and Tukey test. Along with the statistical tests performed, observations of the overall physical quality of the printed parts were also conducted. Both the statistic and physical observations concluded with an output of potential variables that could lead to less variance in the printing process. The following variables, in table 5, were found to create the least variance in the printing process. The three variables were a print speed of 100 mm/s, a bed temperature of 70°C, and a layer height of 0.2 mm. All three concluded values go against the hypothesized behaviors discussed. While the layer height was hypothesized to be the most accurate at 0.1 instead of 0.2, it is the closest prediction of the three. Both print speed and temperature were hypothesized to be the least accurate at their largest observed values of 100 mms/ and 70°C. The most interesting of this observation is the bed temperature, which was observed as a significant parameter in almost every test that involved it. With such a relatively high temperature, the material is close to the glassing temperature of an estimated 80°C. As for the 100 mm/s, while this does seem like a relatively high speed in terms of the parameter values tested on, there have been recent breakthroughs in technology such as the ones described that have allowed FDM printers to operate at print speeds of 700 mm/s.

The experiment also faced some limitations, as well as potential future suggestions were observed. One of the biggest limitations was with the printer that was used. The Prusa i3 MK3 that was used for printing operated on a build plate that was 250 mm x 210 mm x 210 mm. This limited the amount of test parts that could be printed in a single trial. As a recommendation, a similar test could be

Table 5: Optimal Settings for Dimensional Accuracy

	Print Speed (mm/s)	Bed Temperature (C)	Layer Height (mm)
Value	100	70	0.2

performed with a larger sample size, which would further validate the information. A similar recommendation can be made, which would be increasing the trial size so each group of three process parameters has numerous iterations to be averaged with. The process parameter values could also be another potential area that could see some success, as with newer technology the bounds of what FDM printers can operate under is vastly changing. Another limitation caused by the printer itself is the potential error found within it. While the experiment did validate the assumption that the printer was not a cause of error in the experiment, the printer itself was used for an extended period of time before the printing process of the 27 trials. Another test that included a brand new printer could show if the printer itself did create any variance in the printed parts. This would most likely be caused by fatigue on parts such as the belts used to move the extruder. Another potential recommendation would be to do similar tests with different materials such as ABS. Due to the materials behaving differently, it is not currently possible to draw any conclusions that link the two materials together without further testing. The lack of testing with other materials could be seen as another limitation, as the L3HSDC print room does not currently support any non-PLA based filaments.

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Appendices

Appendix A: Additive Manufacturing Standards

ASTM Committee F42 Standards

Table 6: ASTM AM Standards Introduced in 2020 [15]

Standard	Title/description
F2924-14	Standard specification for additive manufacturing titanium-6 aluminum-4 vanadium with powder bed fusion
F2971-13	Standard practice for reporting data for test specimens prepared by additive manufacturing
F3001-14	Standard specification for additive manufacturing titanium-6 aluminum-4 vanadium ELI (extra low interstitial) with powder bed fusion
F3049-14	Standard guide for characterizing properties of metal powders used for additive manufacturing processes
F3055-14a	Standard specification for additive manufacturing nickel alloy (UNS N07718) with powder bed fusion
F3056-14e1	Standard specification for additive manufacturing nickel alloy (UNS N06625) with powder bed fusion
F3091/F3091M-14	Standard specification for powder bed fusion of plastic materials
F3122-14	Standard guide for evaluating mechanical properties of metal materials made via additive manufacturing processes
F3184-16	Standard specification for additive manufacturing stainless steel alloy (UNS S31603) with powder bed fusion
F3187-16	Standard guide for directed energy deposition of metals
F3213-17	Standard for additive manufacturing - Finished part properties - Standard specification for cobalt-28 chromium-6 molybdenum via powder bed fusion
F3301-18a	Standard for additive manufacturing - Post processing methods - Standard specification for thermal post-processing metal parts made via powder bed fusion
F3302-18	Standard for additive manufacturing - Finished part properties - Standard specification for titanium alloys via powder bed fusion
F3318-18	Standard for additive manufacturing - Finished part properties - Specification for AlSi10Mg with powder bed fusion - Laser beam
F3413-19	Guide for additive manufacturing - Design - Directed energy deposition

F3434-10	Guide for additive manufacturing - Installation/operation and performance qualification (IQ/OQ/PQ) of laser-beam powder bed fusion equipment for production manufacturing
ISO/ASTM52900-15	Standard terminology for additive manufacturing - General principles - Terminology (Process terms and definitions from this standard have been fully adopted in the *Wohlers Report*.)
ISO/ASTM52915-16	Standard specification for additive manufacturing file format (AMF) version 1.2
ISO/ASTM52901-16	Standard guide for additive manufacturing - General principles - Requirements for purchased AM parts
ISO/ASTM52910-18	Additive manufacturing - Design - Requirements, guidelines and recommendations
ISO/ASTM52902-19	Additive manufacturing - Test artifacts - Geometric capability assessment of additive manufacturing systems
ISO/ASTM52907-19	Additive manufacturing - Feedstock materials - Methods to characterize metallic powders
ISO/ASTM52901-19	Additive manufacturing - Process characteristics and performance - Practice for metal powder bed process to meet critical applications
ISO/ASTM52921-13 (2019)	Standard terminology for additive manufacturing - Coordinate systems and test methodologies
ISO/ASTM52903-20	Additive manufacturing - Material extrusion-based additive manufacturing of plastic materials - Part 1: Feedstock materials
ISO/ASTM52915-20	Specification for additive manufacturing file format (AMF) version 1.2
ISO/ASTM52942-20	Additive manufacturing -Qualification principles - Qualifying machine operators of laser metal powder bed fusion machines and equipment used in aerospace applications
ISO/ASTM52941-20	Additive manufacturing - System performance and reliability - Acceptance tests for laser metal powder bed fusion machines for metallic materials for aerospace applications

ISO/TC 261 Standards:

Table 7: ISO/TC 261 AM Standards introduced in 2020. [15]

Reference	**Focus**	**Example Projects**
WG 1	Terminology	ISO/ASTM52900-15, Additive manufacturing - General principles
WG 2	Methods, process, and materials	ISO/ASTM52907-19, Additive manufacturing - Feedstock materials - Methods to characterize metal powders
WG 3	Test methods and quality specifications	ISO/ASTM52902-19, Additive manufacturing - Test artifacts - Geometric capability assessment of additive manufacturing systems
WG 4	Data and design	ISO/ASTM52911-1-19 Additive manufacturing - Design - Part 1: Laser-based powder bed fusion of metals
WG 6	Environment, health, and safety	ISO/ASTM AWI 52931, Additive manufacturing - Environmental health and safety - Standard guideline for the use of metallic materials
JWG 10	Additive manufacturing in aerospace applications - joint with ISO/TC 44/SC 14	ISO/ASTM DIS 52941, Additive manufacturing - System performance and reliability - Standard test method for acceptance of powder bed fusion machines for metallic materials for aerospace application
JWG 11	Additive manufacturing for plastics - joint with ISO/TC 61/SC9	ISO/ASTM CD 52924, Additive manufacturing - Qualification principles - Classification of part properties for additive manufacturing of polymer parts

Appendix B: Test Part Images

Below are images of all test parts for each of the 27 trials.

Figure 35: Trial 1

Figure 36: Trial 2

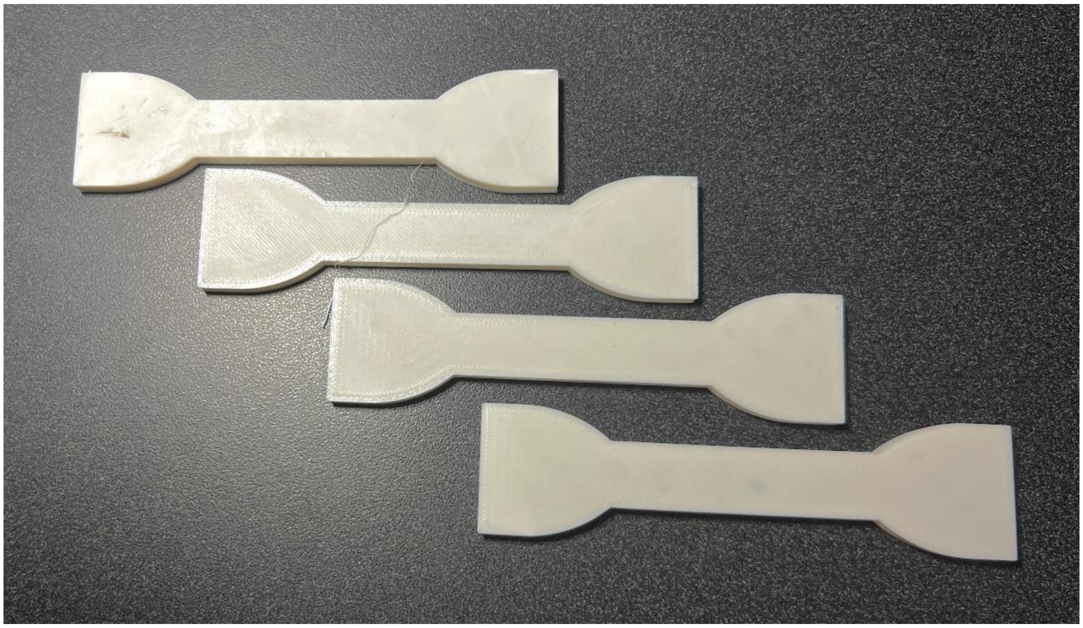
Figure 37: Trial 3


Figure 38: Trial 4

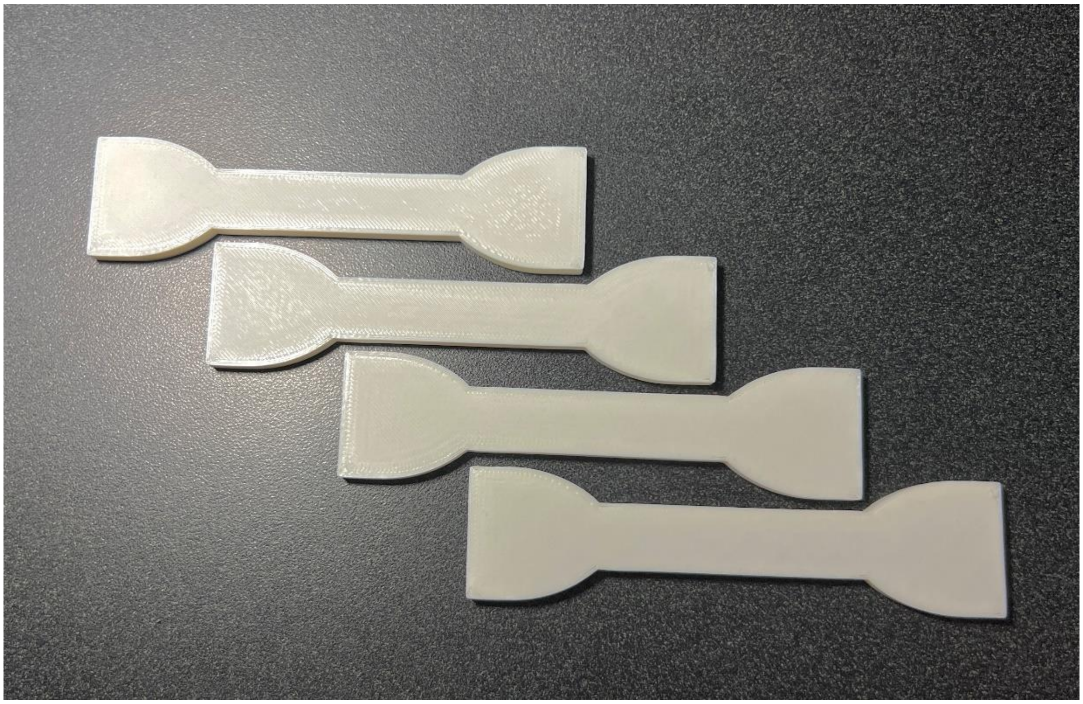

Figure 39: Trial 5

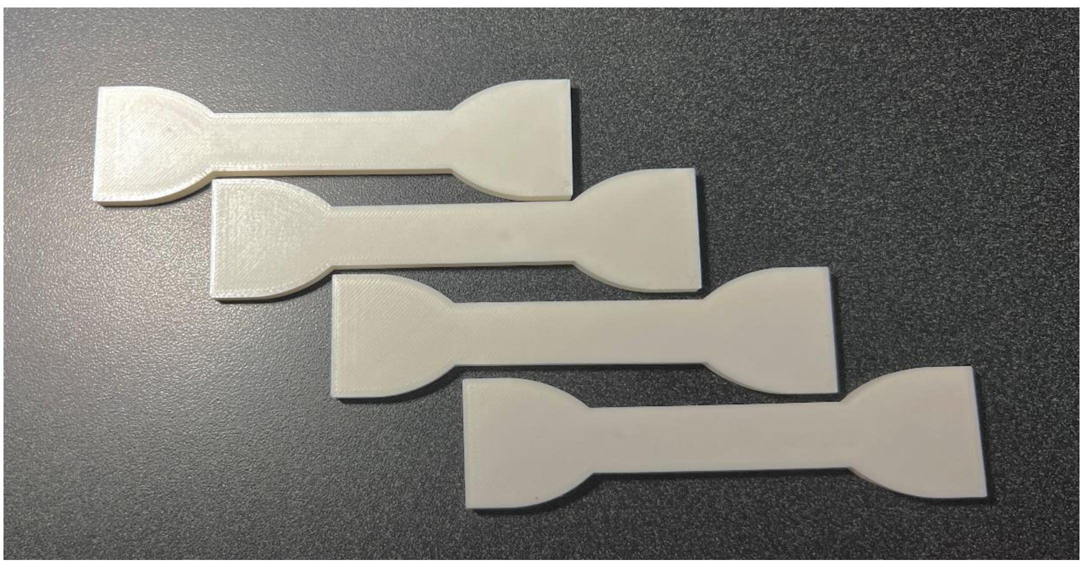

Figure 40: Trial 6

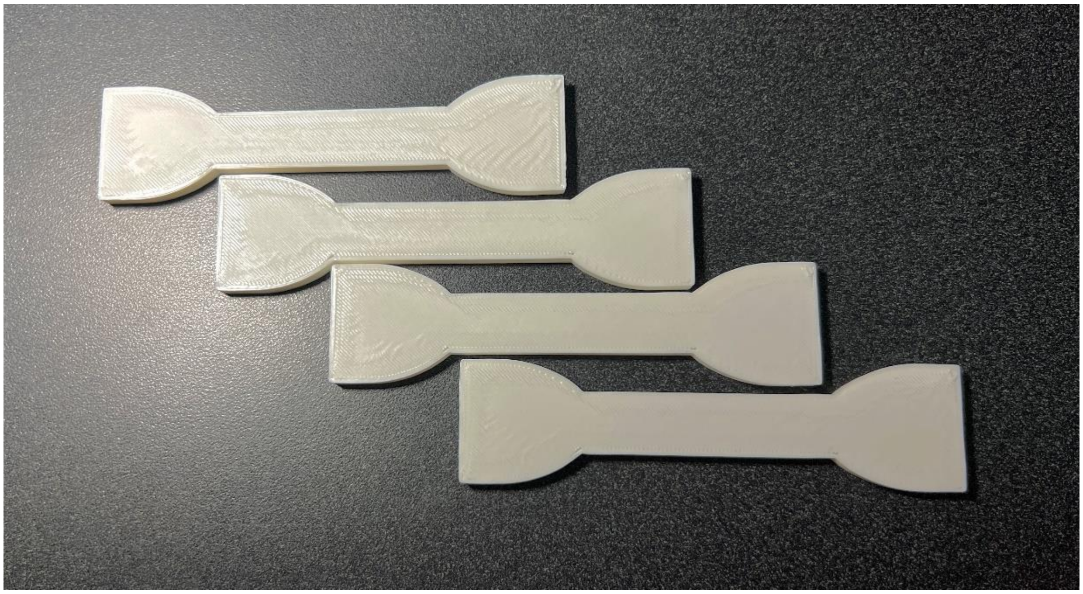

Figure 41: Trial 7

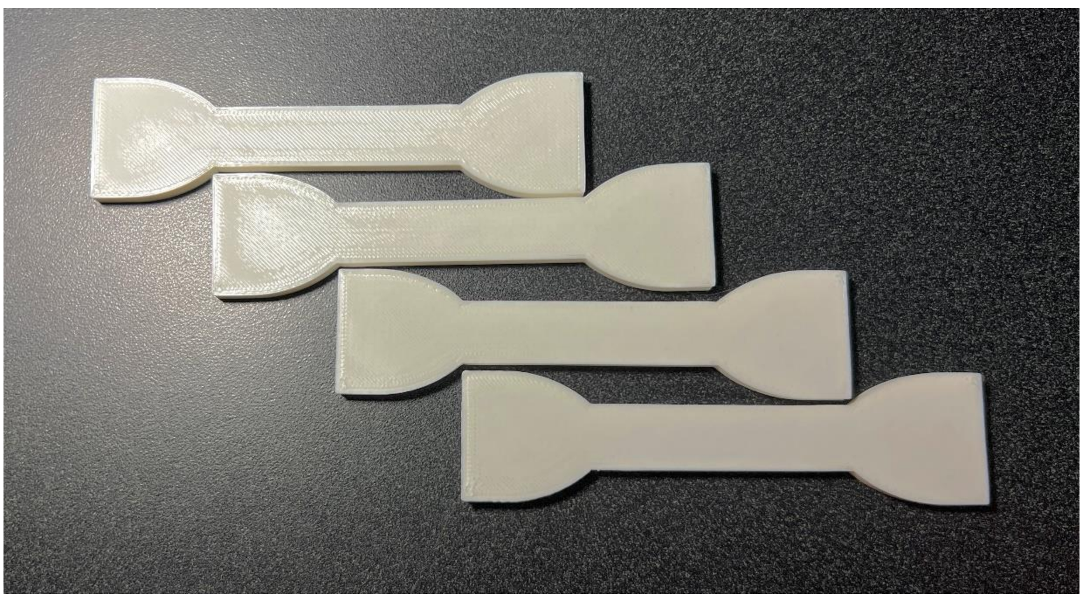

Figure 42: Trial 8

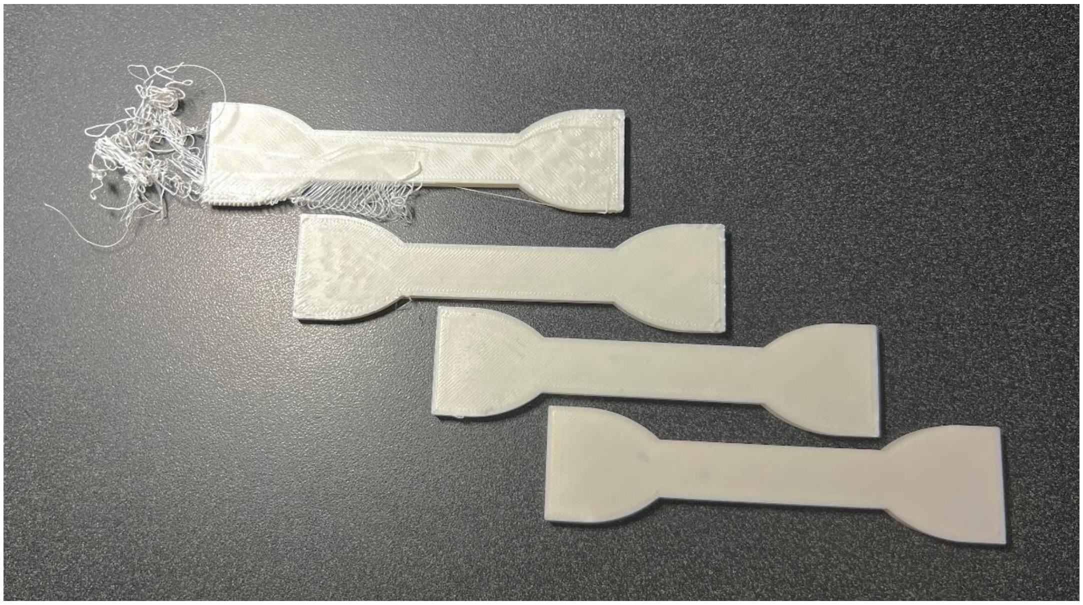

Figure 43: Trial 9

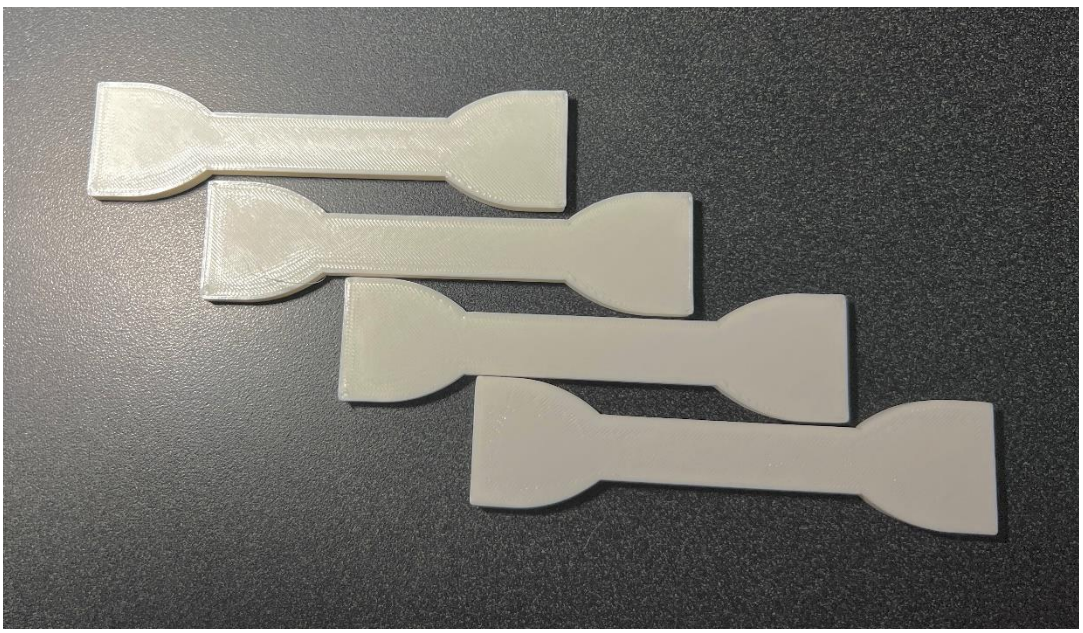

Figure 44: Trial 10

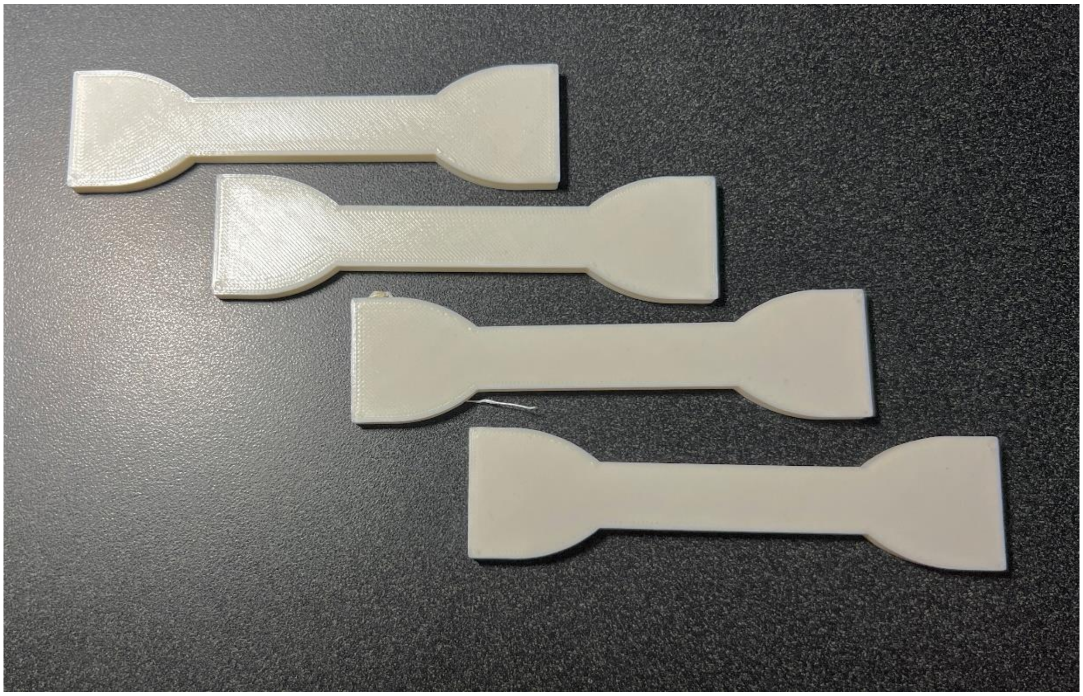

Figure 45: Trial 11

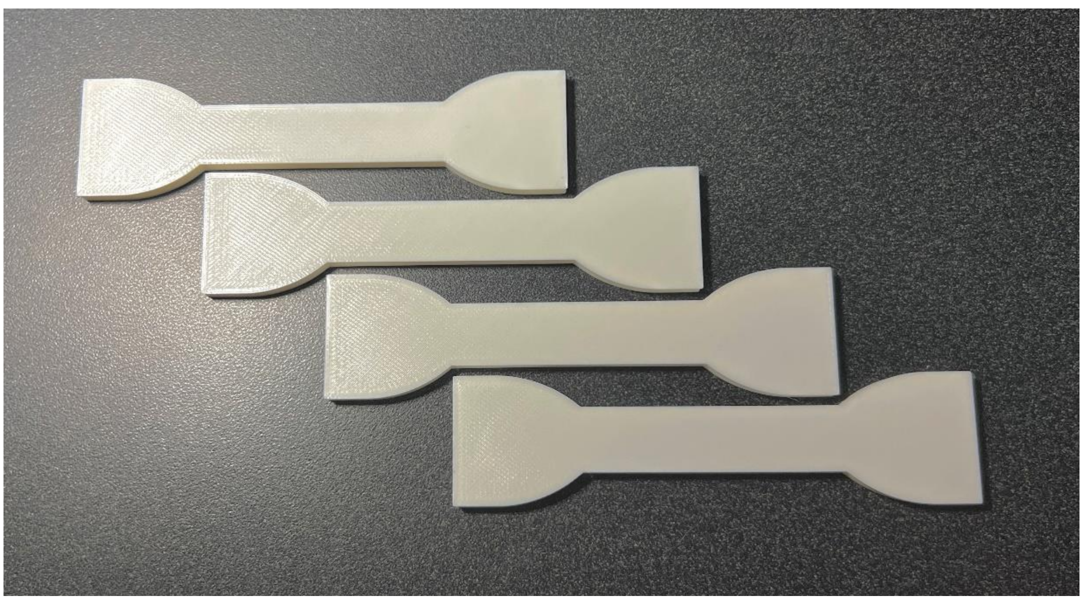

Figure 46: Trial 12

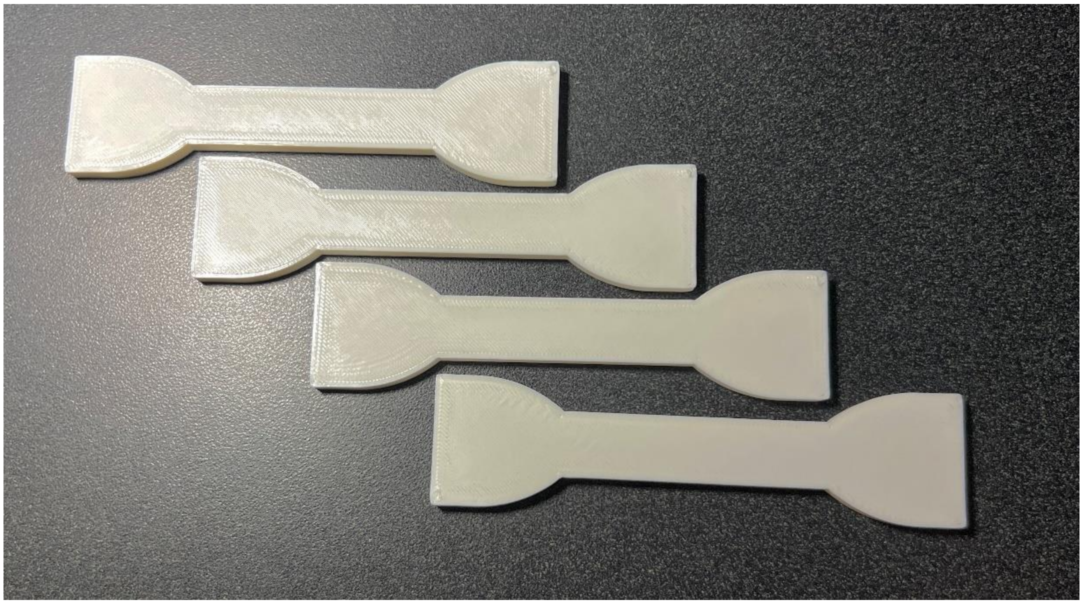

Figure 47: Trial 13

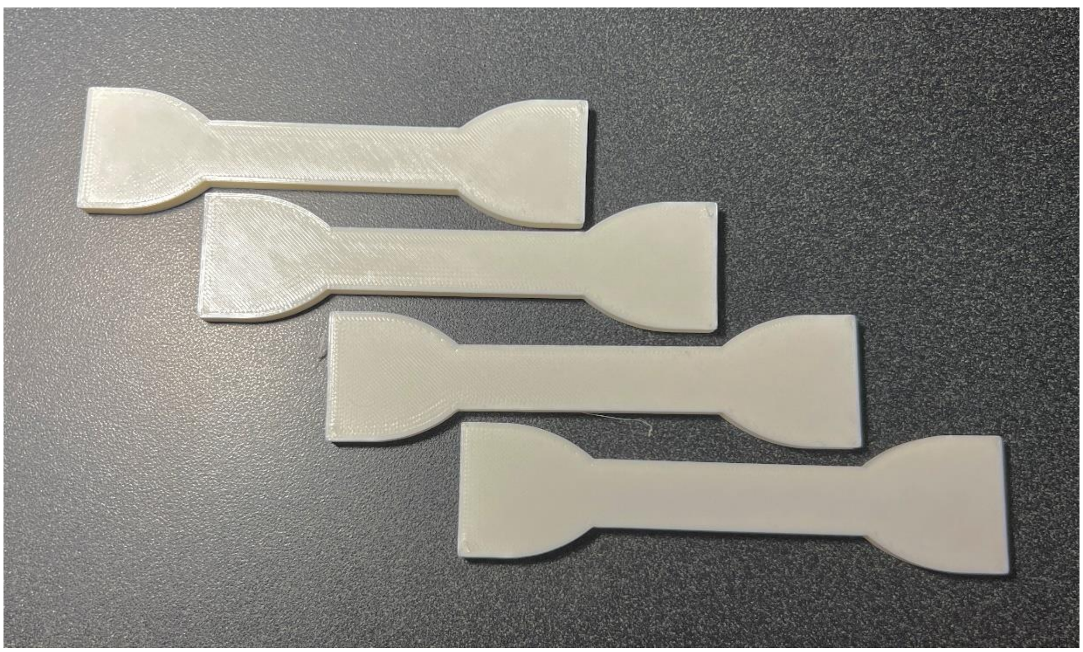

Figure 48: Trial 14

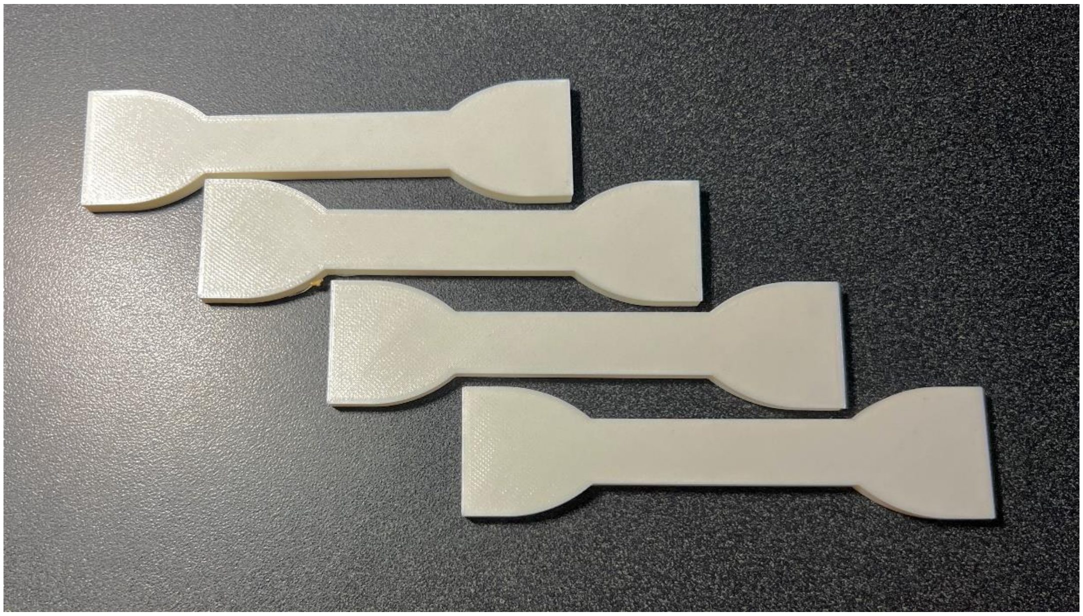

Figure 49: Trial 15

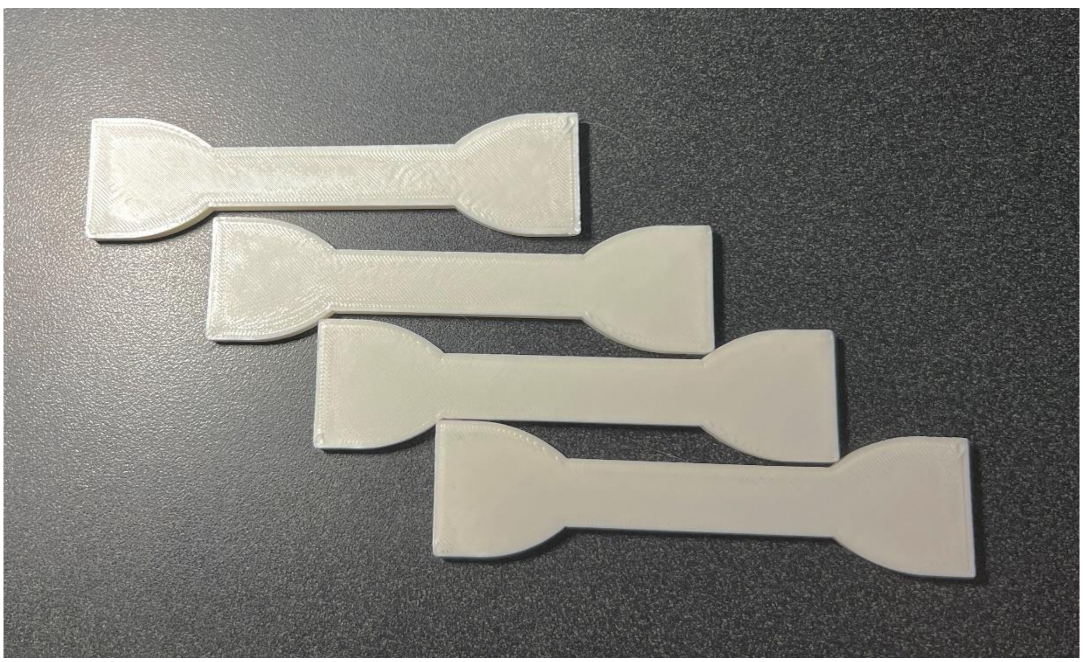

Figure 50: Trial 16

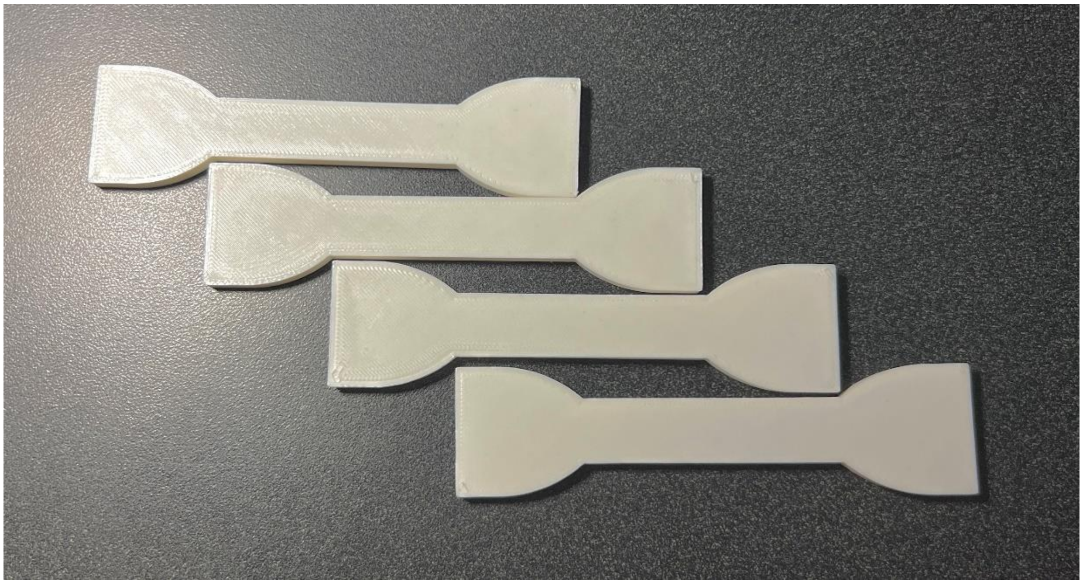

Figure 51: Trial 17

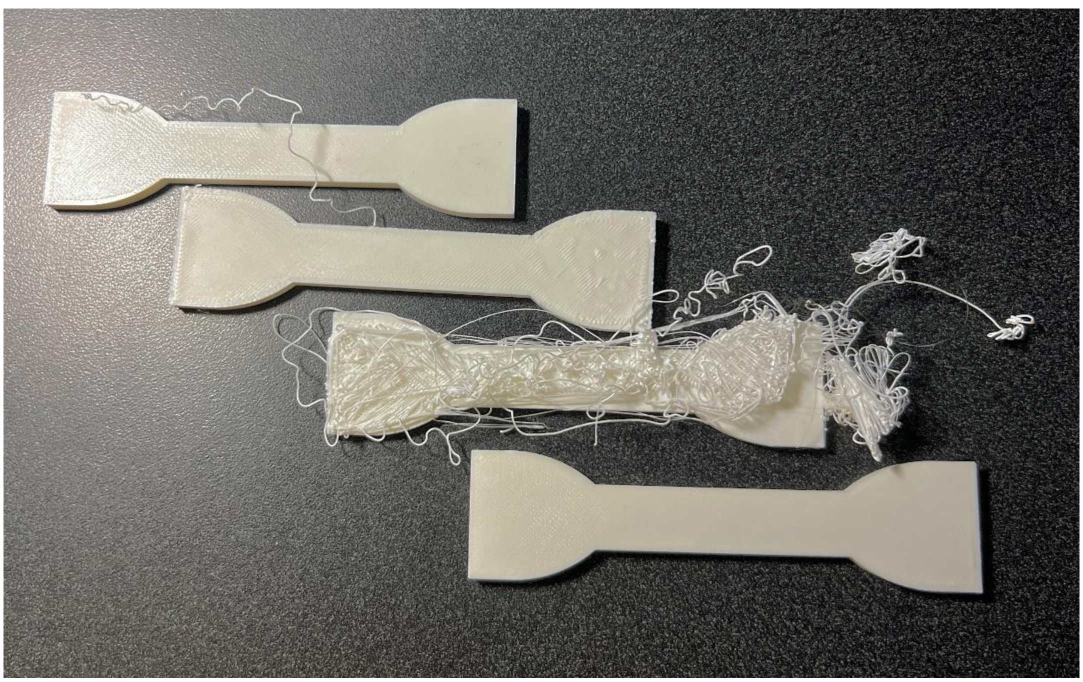

Figure 52: Trial 18

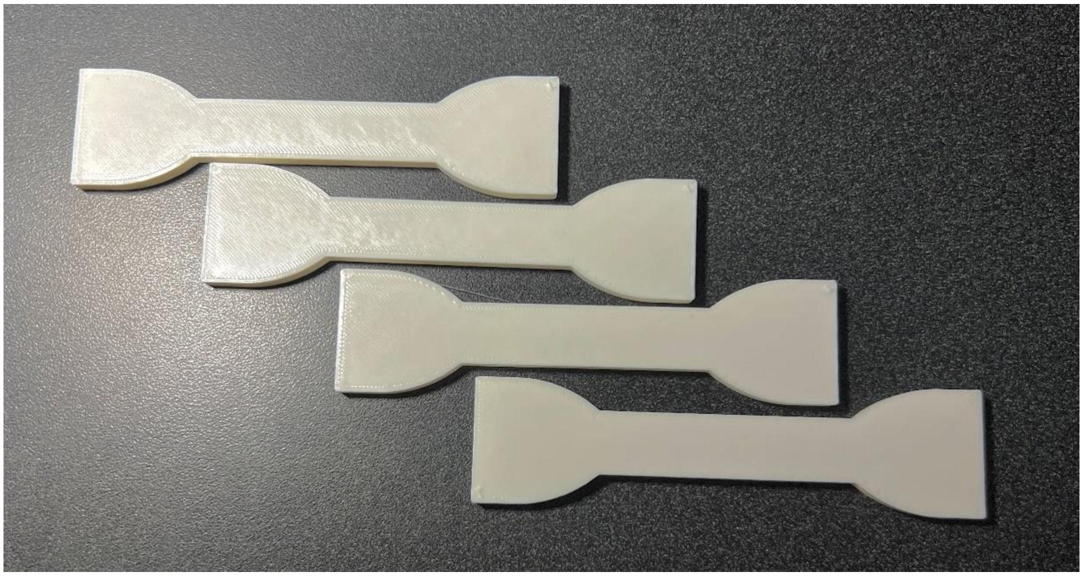

Figure 53: Trial 19

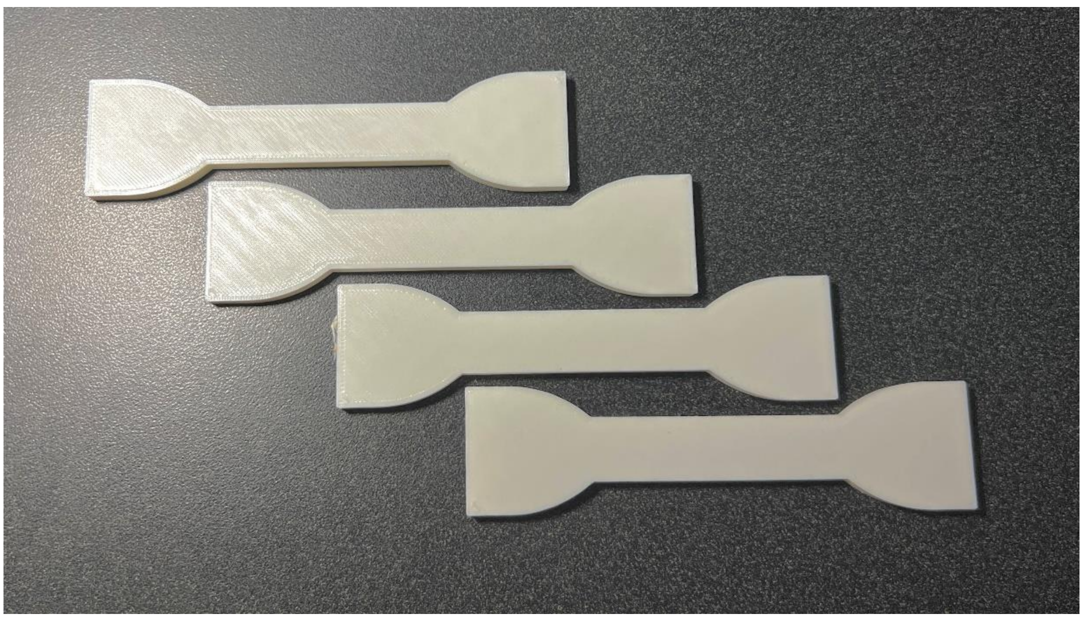

Figure 54: Trial 20

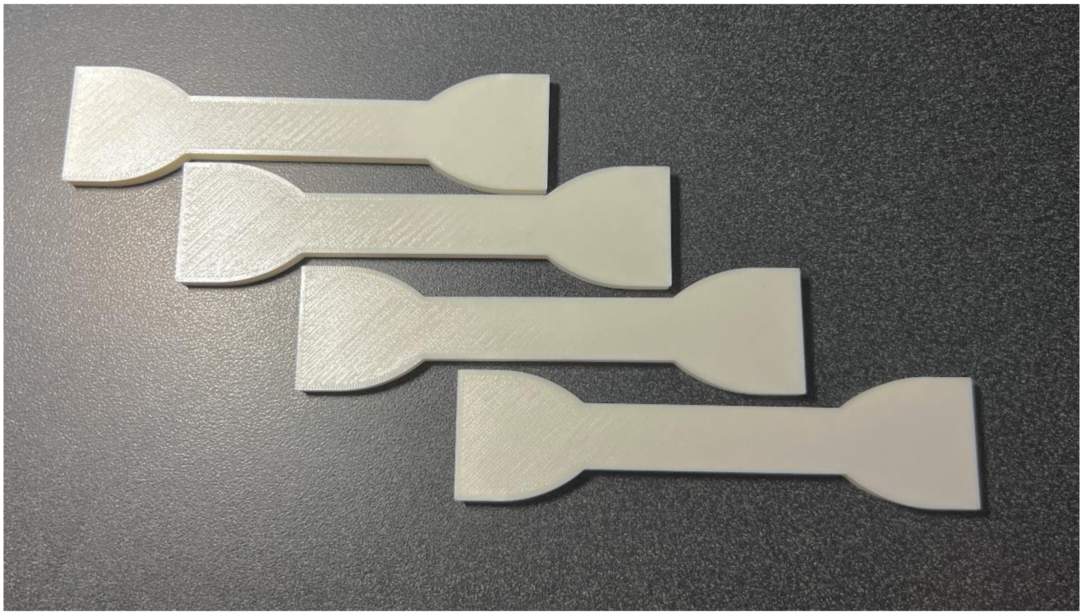

Figure 55: Trial 21

Figure 56: Trial 22

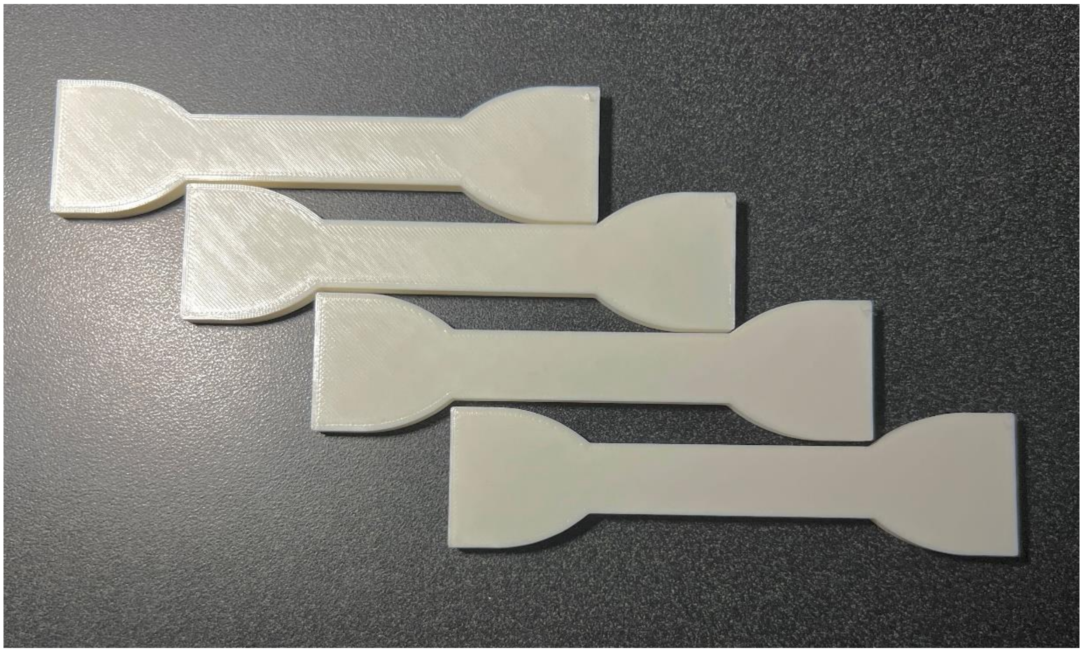

Figure 57: Trial 23

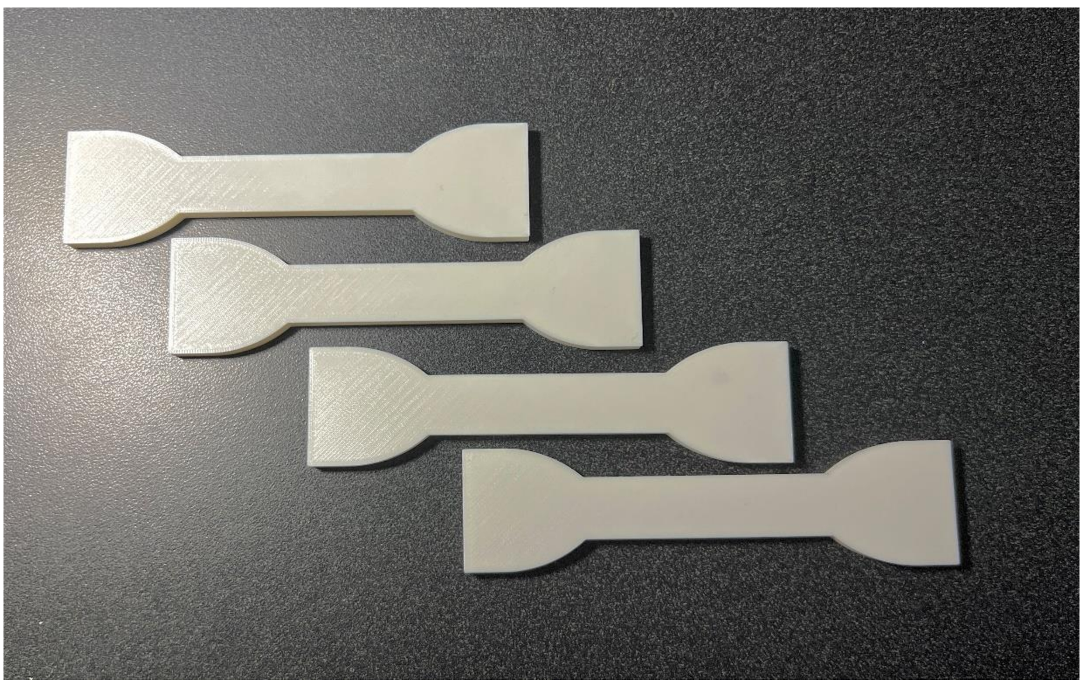

Figure 58: Trial 24

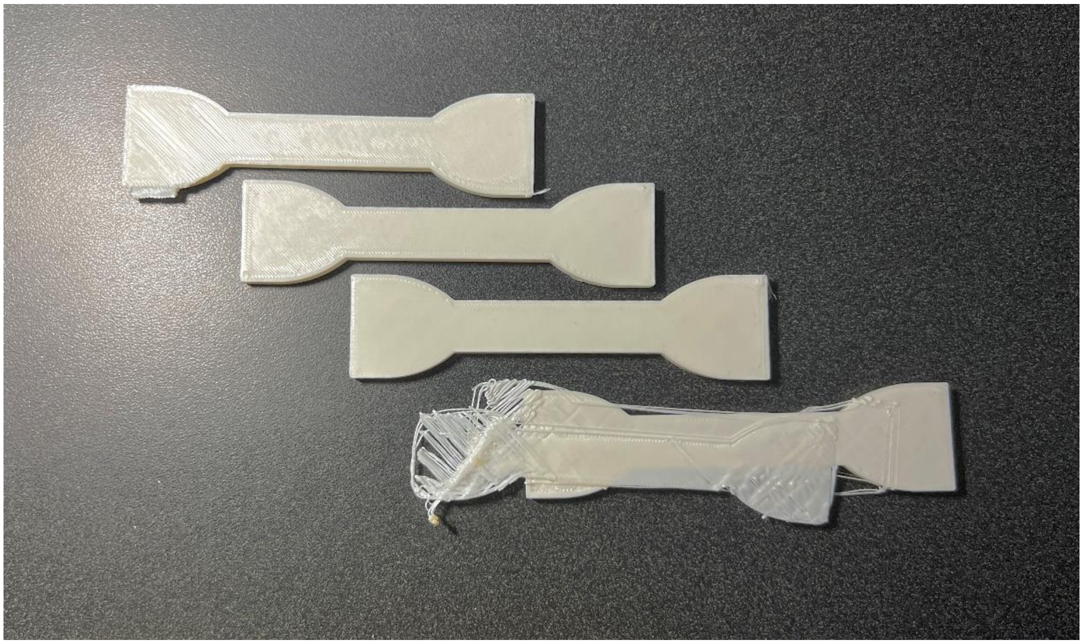

Figure 59: Trial 25

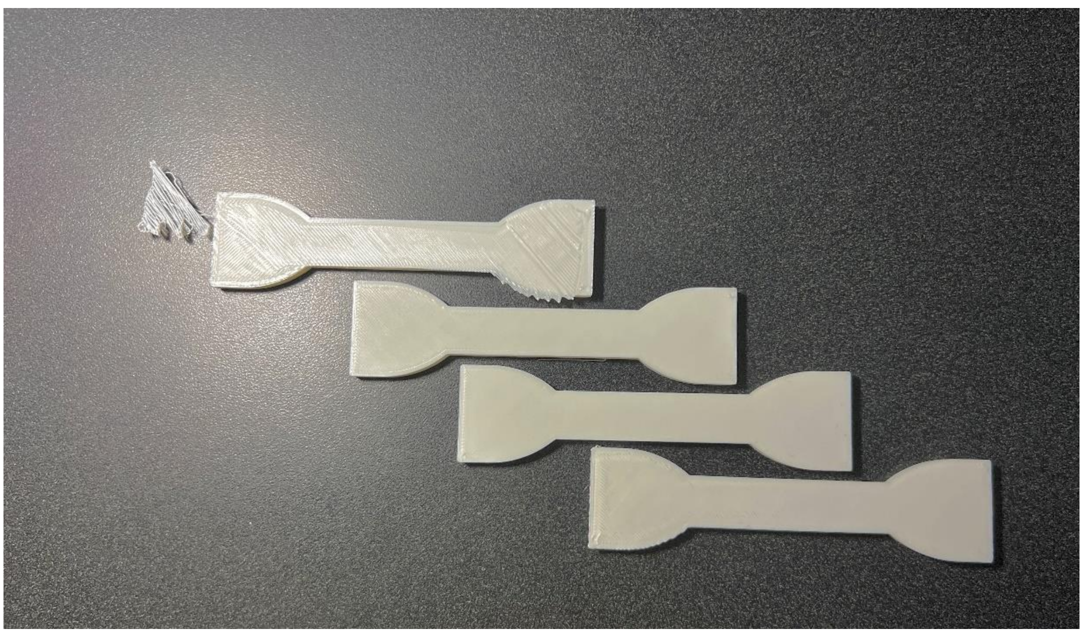

Figure 60: Trial 26

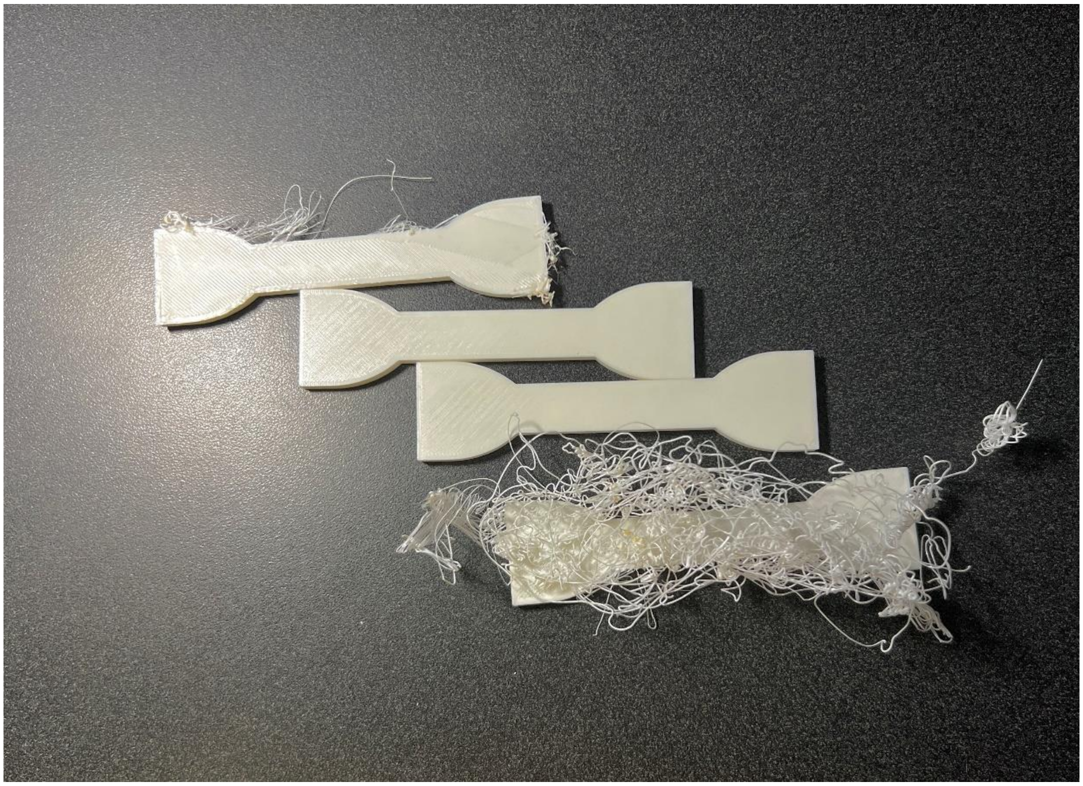

Figure 61: Trial 27

Appendix C: Statistical Analysis Tables

Change in Length Tables

Below are all data tables created in the analysis process, the first set of three tables are the outputs from the two-way ANOVA tests. After the first three tables, the remaining tables are the outputs from the Tukey tests.

Table 8: Change in Length ANOVA Table 1

Tests of Between-Subjects Effects

Dependent Variable: ChangeInL

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	.059[a]	8	.007	.707	.682	.239
Intercept	.315	1	.315	30.284	.000	.627
PrintSpeed	.045	2	.023	2.178	.142	.195
LayerHeight	.008	2	.004	.391	.682	.042
PrintSpeed * LayerHeight	.005	4	.001	.131	.969	.028
Error	.187	18	.010			
Total	.562	27				
Corrected Total	.246	26				

a. R Squared = .239 (Adjusted R Squared = -.099)

Table 9: Change in Length ANOVA Table 2

Tests of Between-Subjects Effects

Dependent Variable: ChangeInL

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	.151[a]	8	.019	3.576	.012	.614
Intercept	.315	1	.315	59.653	.000	.768
PrintSpeed	.045	2	.023	4.289	.030	.323
BedTemp	.075	2	.038	7.112	.005	.441
PrintSpeed * BedTemp	.031	4	.008	1.450	.258	.244
Error	.095	18	.005			
Total	.562	27				
Corrected Total	.246	26				

a. R Squared = .614 (Adjusted R Squared = .442)

Table 10: Change in Length ANOVA Table 3

Tests of Between-Subjects Effects

Dependent Variable: ChangeInL

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	.110[a]	8	.014	1.823	.138	.448
Intercept	.315	1	.315	41.707	.000	.699
LayerHeight	.008	2	.004	.538	.593	.056
BedTemp	.075	2	.038	4.972	.019	.356
LayerHeight * BedTemp	.027	4	.007	.891	.490	.165
Error	.136	18	.008			
Total	.562	27				
Corrected Total	.246	26				

a. R Squared = .448 (Adjusted R Squared = .202)

Table 11: Change in Length Tukey Test 1

Multiple Comparisons

Dependent Variable: ChangeInL

Tukey HSD

(I) PrintSpeed	(J) PrintSpeed	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
-1.00	.00	.080000	.0480965	.246	-.042750	.202750
	1.00	-.012500	.0480965	.964	-.135250	.110250
.00	-1.00	-.080000	.0480965	.246	-.202750	.042750
	1.00	-.092500	.0480965	.161	-.215250	.030250
1.00	-1.00	.012500	.0480965	.964	-.110250	.135250
	.00	.092500	.0480965	.161	-.030250	.215250

Based on observed means.
The error term is Mean Square(Error) = .010.

Multiple Comparisons

Dependent Variable: ChangeInL

Tukey HSD

(I) LayerHeight	(J) LayerHeight	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
-1.00	.00	-.022500	.0480965	.887	-.145250	.100250
	1.00	-.042500	.0480965	.657	-.165250	.080250
.00	-1.00	.022500	.0480965	.887	-.100250	.145250
	1.00	-.020000	.0480965	.910	-.142750	.102750
1.00	-1.00	.042500	.0480965	.657	-.080250	.165250

	.00	.020000	.0480965	.910	-.102750	.142750

Based on observed means.
The error term is Mean Square(Error) = .010.

Table 12: Change in Length Tukey Test 2

Multiple Comparisons

Dependent Variable: ChangeInL

Tukey HSD

(I) PrintSpeed	(J) PrintSpeed	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	Upper Bound
-1.00	.00	.080000	.0342693	.076	-.007461	.167461
	1.00	-.012500	.0342693	.930	-.099961	.074961
.00	-1.00	-.080000	.0342693	.076	-.167461	.007461
	1.00	-.092500*	.0342693	.037	-.179961	-.005039
1.00	-1.00	.012500	.0342693	.930	-.074961	.099961
	.00	.092500*	.0342693	.037	.005039	.179961

Based on observed means.
The error term is Mean Square(Error) = .005.
*. The mean difference is significant at the .05 level.

Multiple Comparisons

Dependent Variable: ChangeInL

Tukey HSD

(I) BedTemp	(J) BedTemp	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	Upper Bound
-1.00	.00	.098056*	.0342693	.027	.010595	.185516
	1.00	.121944*	.0342693	.006	.034484	.209405
.00	-1.00	-.098056*	.0342693	.027	-.185516	-.010595
	1.00	.023889	.0342693	.768	-.063572	.111350
1.00	-1.00	-.121944*	.0342693	.006	-.209405	-.034484
	.00	-.023889	.0342693	.768	-.111350	.063572

Based on observed means.
The error term is Mean Square(Error) = .005.
*. The mean difference is significant at the .05 level.

Table 13: Change in Length Tukey Test 3

Multiple Comparisons

Dependent Variable: ChangeInL

Tukey HSD

(I) LayerHeight	(J) LayerHeight	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	Upper Bound
-1.00	.00	-.022500	.0409845	.848	-.127099	.082099
	1.00	-.042500	.0409845	.564	-.147099	.062099
.00	-1.00	.022500	.0409845	.848	-.082099	.127099
	1.00	-.020000	.0409845	.878	-.124599	.084599
1.00	-1.00	.042500	.0409845	.564	-.062099	.147099
	.00	.020000	.0409845	.878	-.084599	.124599

Based on observed means.
The error term is Mean Square(Error) = .008.

Multiple Comparisons

Dependent Variable: ChangeInL

Tukey HSD

(I) BedTemp	(J) BedTemp	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	Upper Bound
-1.00	.00	.098056	.0409845	.068	-.006544	.202655
	1.00	.121944*	.0409845	.021	.017345	.226544
.00	-1.00	-.098056	.0409845	.068	-.202655	.006544
	1.00	.023889	.0409845	.831	-.080710	.128488
1.00	-1.00	-.121944*	.0409845	.021	-.226544	-.017345
	.00	-.023889	.0409845	.831	-.128488	.080710

Based on observed means.
The error term is Mean Square(Error) = .008.
*. The mean difference is significant at the .05 level.

Change in Width Tables

Table 14: Change in Width ANOVA Table 1

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1.787[a]	8	.223	.859	.567
Intercept	5.208E-5	1	5.208E-5	.000	.989
PrintSpeed	.297	2	.148	.571	.575
LayerHeight	.337	2	.168	.647	.535
PrintSpeed * LayerHeight	1.154	4	.288	1.108	.383
Error	4.683	18	.260		

Total	6.470	27			
Corrected Total	6.470	26			

Table 15: Change in Width ANOVA Table 2

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	2.163[a]	8	.270	1.130	.390
Intercept	5.208E-5	1	5.208E-5	.000	.988
PrintSpeed	.297	2	.148	.620	.549
BedTemp	.801	2	.401	1.674	.215
PrintSpeed * BedTemp	1.066	4	.266	1.113	.381
Error	4.307	18	.239		
Total	6.470	27			
Corrected Total	6.470	26			

Table 16: Change in Width ANOVA Table 3

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	2.082[a]	8	.260	1.068	.426
Intercept	5.208E-5	1	5.208E-5	.000	.988
LayerHeight	.337	2	.168	.691	.514
BedTemp	.801	2	.401	1.643	.221
LayerHeight * BedTemp	.945	4	.236	.969	.449
Error	4.388	18	.244		
Total	6.470	27			
Corrected Total	6.470	26			

Table 17: Change in Width Tukey Test 1

Multiple Comparisons

Dependent Variable: ChangeinW

Tukey HSD

(I) PrintSpeed	(J) PrintSpeed	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
-1.00	.00	-.229444	.2404462	.614	-.843102	.384213
	1.00	-.214722	.2404462	.651	-.828380	.398936
.00	-1.00	.229444	.2404462	.614	-.384213	.843102
	1.00	.014722	.2404462	.998	-.598936	.628380

1.00	-1.00	.214722	.2404462	.651	-.398936	.828380
	.00	-.014722	.2404462	.998	-.628380	.598936

Based on observed means.
The error term is Mean Square(Error) = .260.

Multiple Comparisons

Dependent Variable: ChangeinW

Tukey HSD

(I) LayerHeight	(J) LayerHeight	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	Upper Bound
-1.00	.00	-.230278	.2404462	.612	-.843936	.383380
	1.00	-.243056	.2404462	.580	-.856713	.370602
.00	-1.00	.230278	.2404462	.612	-.383380	.843936
	1.00	-.012778	.2404462	.998	-.626436	.600880
1.00	-1.00	.243056	.2404462	.580	-.370602	.856713
	.00	.012778	.2404462	.998	-.600880	.626436

Based on observed means.
The error term is Mean Square(Error) = .260.

Table 18: Change in Width Tukey Test 2

Multiple Comparisons

Dependent Variable: ChangeinW

Tukey HSD

(I) PrintSpeed	(J) PrintSpeed	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	Upper Bound
-1.00	.00	-.229444	.2305847	.589	-.817934	.359045
	1.00	-.214722	.2305847	.628	-.803212	.373767
.00	-1.00	.229444	.2305847	.589	-.359045	.817934
	1.00	.014722	.2305847	.998	-.573767	.603212
1.00	-1.00	.214722	.2305847	.628	-.373767	.803212
	.00	-.014722	.2305847	.998	-.603212	.573767

Based on observed means.
The error term is Mean Square(Error) = .239.

Multiple Comparisons

Dependent Variable: ChangeinW

Tukey HSD

(I) BedTemp	(J) BedTemp	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	Upper Bound
-1.00	.00	.413333	.2305847	.200	-.175156	1.001823
	1.00	.133333	.2305847	.833	-.455156	.721823
.00	-1.00	-.413333	.2305847	.200	-1.001823	.175156

	1.00	-.280000	.2305847	.460	-.868490	.308490
1.00	-1.00	-.133333	.2305847	.833	-.721823	.455156
	.00	.280000	.2305847	.460	-.308490	.868490

Based on observed means.
The error term is Mean Square(Error) = .239.

Table 19: Change in Width Tukey Test 3

Multiple Comparisons

Dependent Variable: ChangeinW

Tukey HSD

(I) LayerHeight	(J) LayerHeight	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
-1.00	.00	-.230278	.2327453	.593	-.824282	.363726
	1.00	-.243056	.2327453	.560	-.837060	.350948
.00	-1.00	.230278	.2327453	.593	-.363726	.824282
	1.00	-.012778	.2327453	.998	-.606782	.581226
1.00	-1.00	.243056	.2327453	.560	-.350948	.837060
	.00	.012778	.2327453	.998	-.581226	.606782

Based on observed means.
The error term is Mean Square(Error) = .244.

Multiple Comparisons

Dependent Variable: ChangeinW

Tukey HSD

(I) BedTemp	(J) BedTemp	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
-1.00	.00	.413333	.2327453	.206	-.180671	1.007337
	1.00	.133333	.2327453	.836	-.460671	.727337
.00	-1.00	-.413333	.2327453	.206	-1.007337	.180671
	1.00	-.280000	.2327453	.467	-.874004	.314004
1.00	-1.00	-.133333	.2327453	.836	-.727337	.460671
	.00	.280000	.2327453	.467	-.314004	.874004

Based on observed means.
The error term is Mean Square(Error) = .244.

Change in Thickness Tables

Table 20: Change in Thickness ANOVA Table 1

Tests of Between-Subjects Effects

Dependent Variable: ChangeInThickness

Source	Type III Sum of Squares	df	Mean Square	F	Sig.

Corrected Model	.129[a]	8	.016	4.831	.003
Intercept	.040	1	.040	11.865	.003
PrintSpeed	.009	2	.005	1.417	.268
LayerHeight	.106	2	.053	15.885	.000
PrintSpeed * LayerHeight	.014	4	.003	1.011	.428
Error	.060	18	.003		
Total	.229	27			
Corrected Total	.189	26			

a. R Squared = .682 (Adjusted R Squared = .541)

Table 21: Change in Thickness ANOVA Table 2

Tests of Between-Subjects Effects

Dependent Variable: ChangeInThickness

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	.019[a]	8	.002	.258	.972
Intercept	.040	1	.040	4.202	.055
PrintSpeed	.009	2	.005	.502	.614
BedTemp	.005	2	.003	.286	.755
PrintSpeed * BedTemp	.005	4	.001	.122	.973
Error	.170	18	.009		
Total	.229	27			
Corrected Total	.189	26			

a. R Squared = .103 (Adjusted R Squared = -.296)

Table 22: Change in Thickness ANOVA Table 3

Tests of Between-Subjects Effects

Dependent Variable: ChangeInThickness

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	.150[a]	8	.019	8.664	.000
Intercept	.040	1	.040	18.286	.000
LayerHeight	.106	2	.053	24.482	.000
BedTemp	.005	2	.003	1.245	.312
LayerHeight * BedTemp	.039	4	.010	4.464	.011
Error	.039	18	.002		
Total	.229	27			

Corrected Total	.189	26			

a. R Squared = .794 (Adjusted R Squared = .702)

Table 23: Change in Thickness Tukey Test 1

Multiple Comparisons

Dependent Variable: ChangeInThickness

Tukey HSD

(I) PrintSpeed	(J) PrintSpeed	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	Upper Bound
-1.00	.00	-.037500	.0272600	.374	-.107072	.032072
	1.00	-.041667	.0272600	.302	-.111239	.027905
.00	-1.00	.037500	.0272600	.374	-.032072	.107072
	1.00	-.004167	.0272600	.987	-.073739	.065405
1.00	-1.00	.041667	.0272600	.302	-.027905	.111239
	.00	.004167	.0272600	.987	-.065405	.073739

Based on observed means.
The error term is Mean Square(Error) = .003.

Multiple Comparisons

Dependent Variable: ChangeInThickness

Tukey HSD

(I) LayerHeight	(J) LayerHeight	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	Upper Bound
-1.00	.00	-.060000	.0272600	.098	-.129572	.009572
	1.00	-.152500*	.0272600	.000	-.222072	-.082928
.00	-1.00	.060000	.0272600	.098	-.009572	.129572
	1.00	-.092500*	.0272600	.009	-.162072	-.022928
1.00	-1.00	.152500*	.0272600	.000	.082928	.222072
	.00	.092500*	.0272600	.009	.022928	.162072

Based on observed means.
The error term is Mean Square(Error) = .003.
*. The mean difference is significant at the .05 level.

Table 24: Change in Thickness Tukey Test 2

Multiple Comparisons

Dependent Variable: ChangeInThickness

Tukey HSD

(I) PrintSpeed	(J) PrintSpeed	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	Upper Bound

-1.00	.00	-.037500	.0458050	.697	-.154402	.079402
	1.00	-.041667	.0458050	.641	-.158568	.075235
.00	-1.00	.037500	.0458050	.697	-.079402	.154402
	1.00	-.004167	.0458050	.995	-.121068	.112735
1.00	-1.00	.041667	.0458050	.641	-.075235	.158568
	.00	.004167	.0458050	.995	-.112735	.121068

Based on observed means.
The error term is Mean Square(Error) = .009.
Multiple Comparisons

Multiple Comparisons

Dependent Variable: ChangeInThickness

Tukey HSD

(I) BedTemp	(J) BedTemp	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	Upper Bound
-1.00	.00	-.030278	.0458050	.789	-.147180	.086624
	1.00	-.029722	.0458050	.795	-.146624	.087180
.00	-1.00	.030278	.0458050	.789	-.086624	.147180
	1.00	.000556	.0458050	1.000	-.116346	.117457
1.00	-1.00	.029722	.0458050	.795	-.087180	.146624
	.00	-.000556	.0458050	1.000	-.117457	.116346

Based on observed means.
The error term is Mean Square(Error) = .009.

Table 25: Change in Thickness Tukey Test 3

Multiple Comparisons

Dependent Variable: ChangeInThickness

Tukey HSD

(I) LayerHeight	(J) LayerHeight	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	Upper Bound
-1.00	.00	-.060000*	.0219579	.035	-.116040	-.003960
	1.00	-.152500*	.0219579	.000	-.208540	-.096460
.00	-1.00	.060000*	.0219579	.035	.003960	.116040
	1.00	-.092500*	.0219579	.001	-.148540	-.036460
1.00	-1.00	.152500*	.0219579	.000	.096460	.208540
	.00	.092500*	.0219579	.001	.036460	.148540

Based on observed means.
The error term is Mean Square(Error) = .002.
*. The mean difference is significant at the .05 level.

Multiple Comparisons

Dependent Variable: ChangeInThickness

Tukey HSD

(I) BedTemp	(J) BedTemp	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
-1.00	.00	-.030278	.0219579	.372	-.086318	.025762
	1.00	-.029722	.0219579	.385	-.085762	.026318
.00	-1.00	.030278	.0219579	.372	-.025762	.086318
	1.00	.000556	.0219579	1.000	-.055485	.056596
1.00	-1.00	.029722	.0219579	.385	-.026318	.085762
	.00	-.000556	.0219579	1.000	-.056596	.055485

Based on observed means.
The error term is Mean Square(Error) = .002.