ADDITIVE MANUFACTURING, SLICING & LOW COST FDM STUDY

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INTRODUCTION

Although Additive Manufacturing (AM) technology is continually making headlines in a variety of media, and showing significant trends of adoption within custom based industries such as aerospace and biomedical, rifts of AM adoption, or even consideration, are beginning to appear. For example, AM application hotspots typically include highly industrialized, metropolitan regions, where enterprise level companies can afford and implement expensive equipment. However, regions not showing AM growth or even considering AM applications in general are regions where significant manufacturing exists, but local companies are generally smaller, based on contract manufacturing for larger enterprises, and are less likely to consider incurring significant expense for AM application exploration. Manufacturing entities set in rural regions where labor costs are typically lower, are especially prone to such limitations or management mental blocks, even though they are often already employing forms of advanced conventional manufacturing systems.

This project incorporated a two-fold research/case-study approach. The one objective was to evaluate the cost savings and payoff potential of using smaller desktop AM machines (typical FDM/FFF systems) for the purpose of rapid production of custom tooling, equipment, and jigs for internal maintenance/repair, production, and quality control use. Such effective use could then be a justification for AM resistive companies to consider some form of AM integration, and thus pave the way toward their own preparations for more robust AM applications.

The other objective was to evaluate the product and performance of items produced with such low-cost, desktop AM systems, but where additional techniques are applied to enhance the product performance or optimize it. Such techniques included the use of custom slicing/coding software and additional post processing techniques such as annealing.

Essentially both objectives focused on the demonstration that low cost AM desktop systems and techniques can be used to effectively produce, practical, custom tools and parts for internal manufacturing operations. Thereby saving time, money, and improving operational efficiency for those companies that embrace the technology on the small scale.

Positive results from this project, through presentations and dissemination, could then lead to an increase of AM process adoption within rural or more remote manufacturing regions, and thus lead managers to consider other and more advanced AM applications within their own operations.

EXISTING RESEARCH

Searches were made for any existing research along the lines of annealing parts made via fused deposition modeling (FDM). Unfortunately, other than general videos found on Youtube.com by enthusiasts, only two brief sources were located during the search. One of these sources was a single page document found to be provided by an undergraduate team from Arizona State University (ASU), but their results were quite brief and limited in quantitative results. The other was a brief website posting with even less information. There were however, several published articles found regarding annealing metal AM product work, but both FDM and fused filament fabrication (FFF), another term for the target format of production, were lacking.

However, the research provided by the ASU team suggestions that parts produced by typical desktop AM systems with typical thermoplastics, such as Polylatic Acid based plastic, may be subject to performance improvement due to annealing (Sevenson, 2014). As this concept was obviously still new and with little research and documentation being present, proceeding with this objective was considered appropriate, even if to only collect more quantifiable data.

Other initial searches were made regarding the other objectives for this project involving maintenance based AM integration, and the slicing related goals of this project, but no publications were found using the search parameters.

<u>OBJECTIVE 1</u>

The primary goal was to explore methods in which low cost FDM produced parts could be enhanced and optimized for practical applications. Specifically, enhancement through annealing and optimization through production settings using third party slicing software.

For reference, the term "slicing" is a common AM reference to the process of automated g-code generation that will provide the overall tool path instructions to the equipment to produce physical versions of a 3D computer model. The concept of slicing is based on the fact that the software essentially "slices" a model in layers and generates the tool path g-code for each layer. These instructions include motor speeds, temperatures, distances, X,Y,Z coordinate locations, etc. The g-code language is decades old and typically the same commands as those used for modern CNC equipment.

```
G26 ; clear probe fail condition
M140 S[bed0_temperature] ; start heating bed
M104 S170 ; start heating extruder
G28 XY ; home X and Y
G1 X-19 Y258 F1000 ; move to safe homing position
M109 S170 ; soften filament for Z homing
G28 Z ; home Z
G92 E0 ; zero extruder
G1 E-12 F100 ; retract 12mm filament
G1 X-15 Y100 F3000 ; move above wiper pad
G1 Z1 ; push nozzle into wiper
G1 X-17 Y95 F1000 ; slow wipe
G1 X-17 Y90 F1000 ; slow wipe
G1 X-17 Y85 F1000 ; slow wipe
G1 X-15 Y90 F1000 ; slow wipe
G1 X-17 Y80 F1000 ; slow wipe
G1 X-15 Y95 F1000 ; slow wipe
G1 X-17 Y75 F2000 ; fast wipe
G1 X-15 Y65 F2000 ; fast wipe
G1 X-17 Y70 F2000 ; fast wipe
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Figure 1: Example of FDM g-code

What is incredibly unique about AM versus subtractive manufacturing is the ability to control the slicing settings such that internal structures of parts can be modified to be hollow, honeycombed, diaphragmed, etc. Likewise, part wall thicknesses, bottom layers, and top layers can be thickened or thinned based on design or operational parameters. AM also allows for complex internal part designs as well as one-run multi part batches, a concept that is nearly impossible for conventional subtractive manufacturing.

For this study, a slicing software known as Simplify3D (S3D) was used to evaluate the impact on part performance given specific slicing parameters. S3D was selected due to its low cost, approximately $150 for 2 seats of the software, significant amount of optimizing setting controls, and its near universal compatibility for most main stream low cost FDM machines. The software also provides an extremely useful simulation mode for visualization of the fabrication process and for evaluation. This feature greatly helps to catch mistakes or make programming changes prior to the machine executing the g-code. A screen capture of the simulation has been provided below.

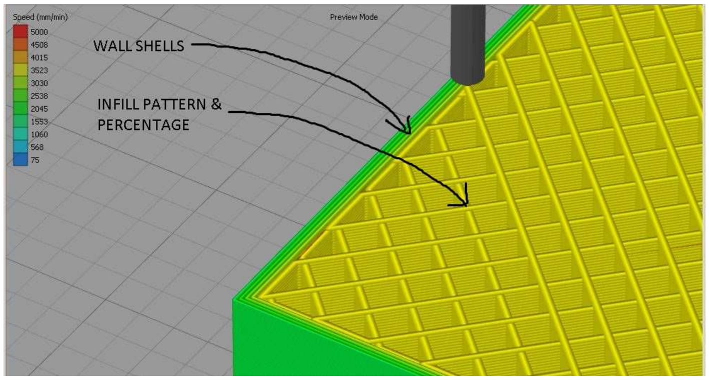


Figure 2: Example of S3D simulation

The primary FDM machine selected for this study was the Ultimaker 2 (U2), a widely accepted FDM machine with a price range of approximately $2,500 to $3,000. The U2 is known for its reliability and quality, and is internationally accessible for purchase. A backup machine, the Lulzbot TAZ 6 (TAZ) was used for the final two batches due a minor mechanical issue on the U2.

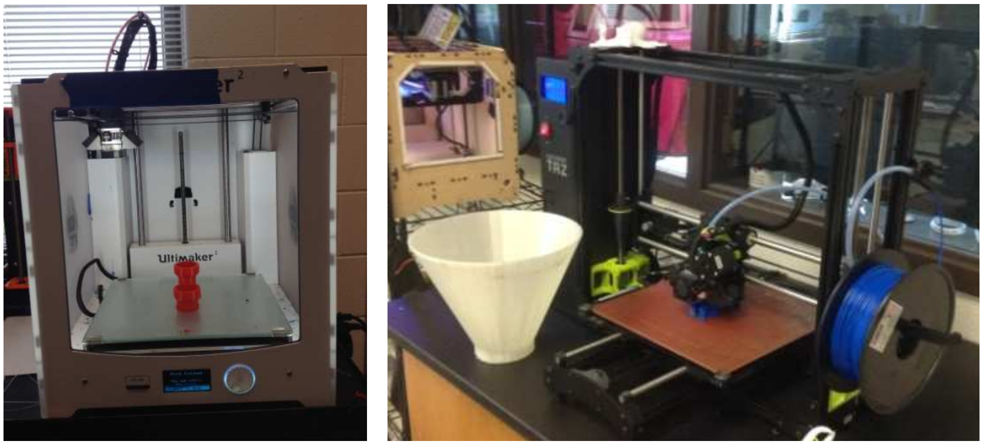


Figure 3: Pictures of U2 (left) and TAZ (right)

The test filament for this study was a single roll of Polylactic acid or Polylactide (PLA) thermoplastic, polymer filament, approximately 1kg, with a filament diameter of 3mm with +/- of 0.05mm. This particular FDM filament is commonly considered a “bioplastic” as it is derived from renewable resources such as corn starch, tapioca roots, or sugarcane depending on international region, and is quite biodegradable. The cost of the filament also was relatively low, with a typical purchasing cost of $18 per kg with shipping included in this price. Granted this is a significantly higher material cost per unit mass than pellet extrusion systems, but given the current nature of most low cost FDM machines, pellet usage is not an option at this time. The filament density was sampled, and determined to be 1.23 kg/cm^3.

Figure 4: Picture of PLA filament used for testing

Unfortunately, due to lack of budgetary options, the testing equipment used for the majority of this project was of low quality, including a typical household toaster oven, a 5 pound weight from the campus gym, a steel ruler, and a luggage load cell. Initially, a wooden testing fixture was used, until the campus welding/fabrication department was able to provide a steel testing fixture.

Figure 5: Pictures of initial testing equipment and break test procedure

Given the limited testing equipment, the desire was to keep the testing processes as simple and linear as possible. Therefore, the testing procedure would progress in the following stages:

1. Establish the desired slicing settings per batch
2. Batch FDM fabricate all of the test parts, one batch group at a time
3. Perform the deflection tests on that batch, in cantilever condition
4. Break test one or two parts at most of that batch, in cantilever condition
5. Anneal the remaining unbroken parts in the batch
6. Perform the deflection test on the annealed batch, in cantilever condition
7. Break test one or two parts at most of the annealed batch, in cantilever condition
8. Repeat with the next batch

Slicing Settings

A variety of slicing settings were applied to each batch of test parts, and a portion of the primary settings associated with each batch are provided below.

Batch #	Infil %	Layer Height	S. Shell Count	Top/Bottom Shell Count	Average Speed mm/min	Batch Quantaty
1	20%	.1500mm	2	3	3600	9
2	20%	.1500mm	3	3	3600	7
3	20%	.1500mm	1	3	3600	7
4	20%	.1500mm	4	3	3200	7
5	20%				3200	7
6	20%	.1500mm	2	2	3200	7
7	10%	.2000mm	1	2	2800	7
8	10%	.2000mm	2	3	2600	8
9	30%	0.15	4	4	2400	8

Figure 6: Primary batch slicing settings

The setting differences for the batches included mainly layer heights, infill values, and shell counts. Although speed factors were also adjusted, the maximum range for these adjustments were only 20 mm/sec, with the majority only being roughly 7mm/sec of system travel, therefore, speed considerations and their impact overall were initially assumed to not likely provide that much of a contributing factor.

To understand the concepts of wall shells, versus top and bottom shells, see the sketch below regarding Batch 4 and Batch 6 (B4 and 6 respectively). Though, their infill settings were of equal 20% values, the sidewalls of Batch 4 were roughly 0.16mm thick with top and bottom wall thicknesses of 0.12mm, whereas Batch 6 had equivalent values of 0.8mm and 0.8mm. To further explain, most slicing softwares address walls as being perpendicular to the build plate, while top/bottom walls are parallel. In all the cases of this study the parts were printed in their sides, therefore, the testing load would be applied parallel to what the slicing software would consider the top/bottom, if viewed from the front of the machine.

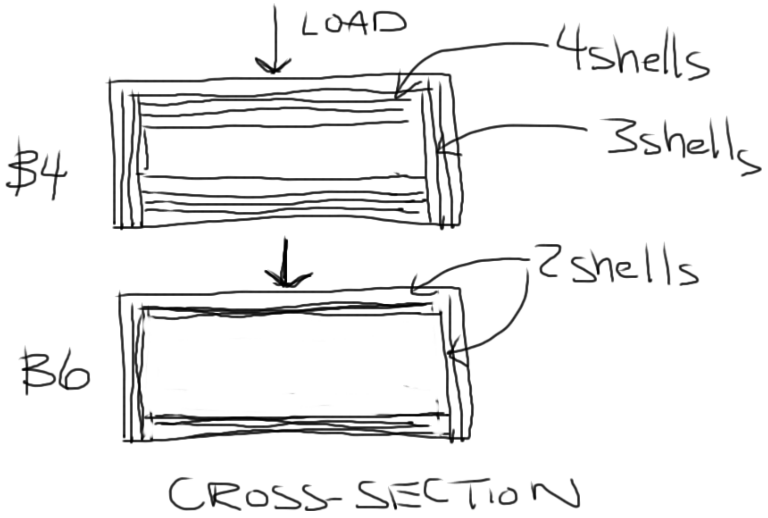


Figure 7: Sketch of part cross section showing shell counts

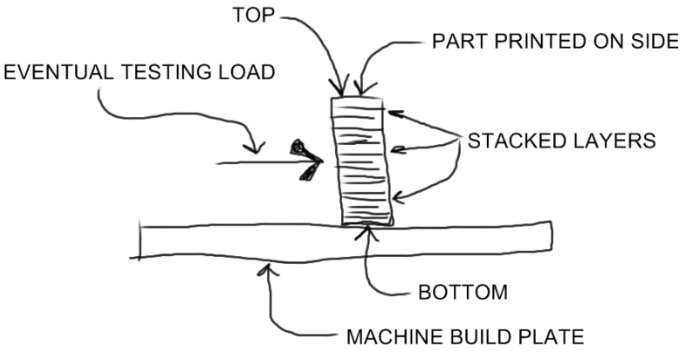


Figure 8: Sketch of part if viewed from the front of the machine

With this printing orientation, part layers were stacked perpendicular to the direction of the force that would be applied by the weight during testing. The theory was that the test would primarily involve flexural stresses, therefore, the layers were run parallel to that internal tensile and compressive stress direction and act more in a fiber-like form. The cross sectional sketch below visually describes this approach.

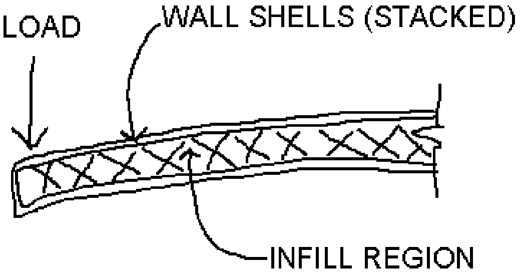


Figure 9: Conceptual cross section related to load and layer orientation

Additionally, to better understand layer height, it is essentially the distance (height) of the extruder nozzle above the previously layer, see below.

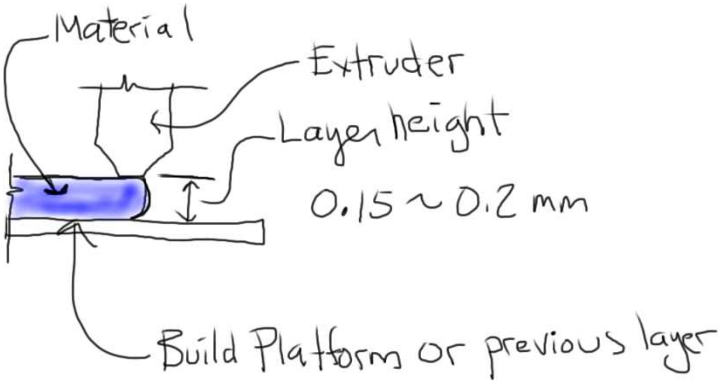


Figure 10: Conceptual sketch of FDM process layer height

In most FDM applications, speed is sacrificed when higher number of shells, increased infill values, or decreased layer heights are used. And although layer height does not contribute to increased wall thickness or significant part volume change, it does affect surface finish and possibly layer to layer adhesion.

For this study not only were multiple settings altered, but so was the design model. For example, B1-4 were designed on an angle design model for convenience of setup and testing. However, it became apparent early in the testing that the angle design was not a good design for testing of this nature. Although relatively easy to set up and prepare a fixture for this scenario, the settings could not be truly evaluated due to the stress concentrations of the load and the non-homogeneous nature of the AM created parts. Although comparisons could still be made for the annealing tests, a better design was needed for slicing selections. Therefore, a redesign was performed such that B5-9 were designed simply as a flat bar plate, with an opening to facilitate the connection of the load bearing wire, as well as hole for connecting it to the testing fixture.

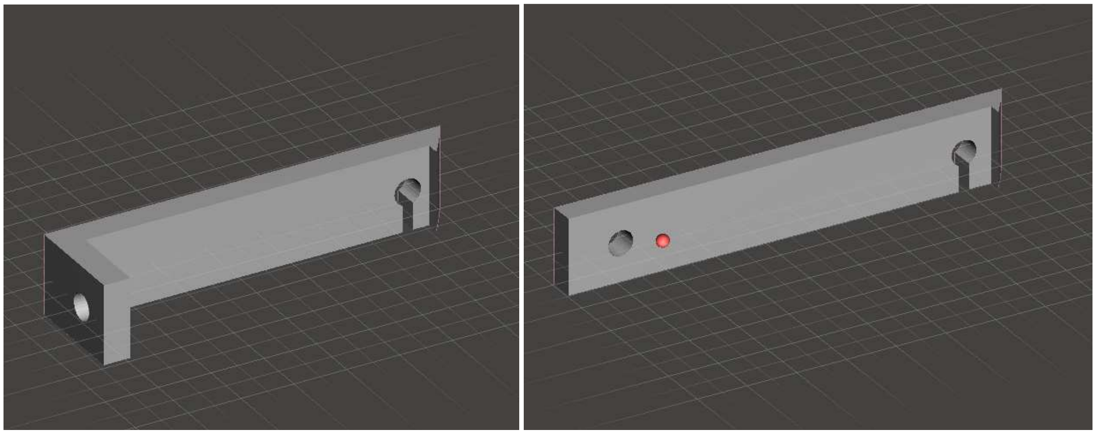


Figure 11: 3D models of B1-4 shape (left) and B5-9 shape (right)

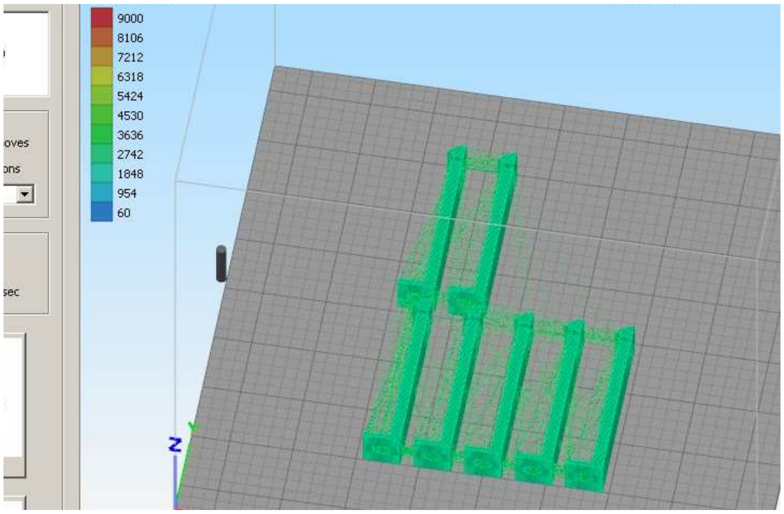


Figure 12: S3D simulation preview mode of B3 prior to printing

As shown in the previous figure of slicing settings, there was an issue with data recording on B5 in that one specific screen capture of the typical 11 image group showing all of the options and settings per batch was lost. And unfortunately this missing image was not discovered until after the testing of that batch had been completed. Therefore, the results were added to the study, but with the knowledge that the layer heights and shell counts would not be determinable. However, it is most likely that B5 layer height at least was 0.15mm, as that was the primary setting for the majority of the prints. Likewise, it was assumed that B5 had shell count settings to close to that of B9 based on the recorded mass values.

Slicing Setting Results

Although there was also an issue with Batch 3, that being an inability to determine the breaking point using the video recording, overall there was very unique data to be observed. For example, the different design and settings resulted in a wide range of untreated (un-annealed) part performances in terms of deflection.

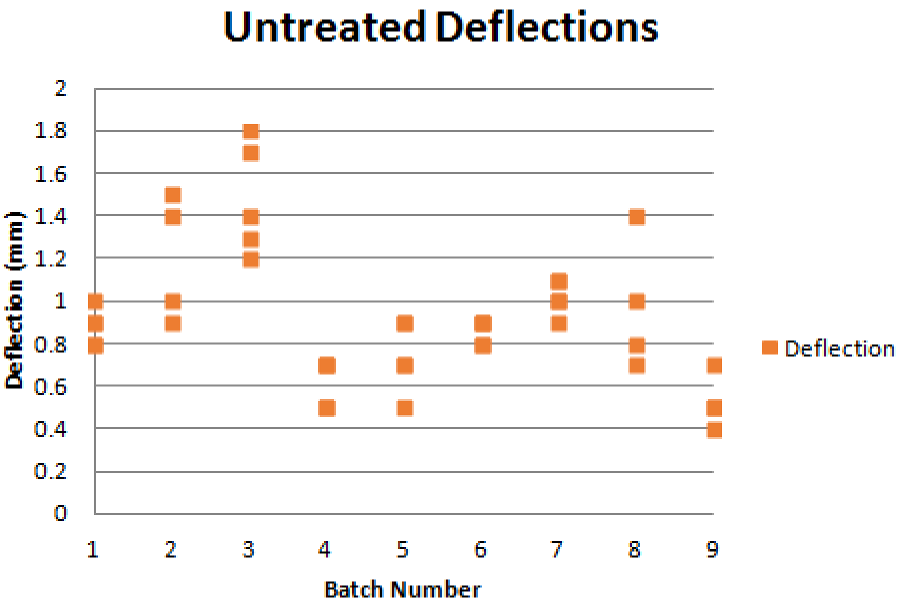


Figure 13: Results of test deflection values for parts prior to annealing

Again noting that B1-4 were of the angle design and B5-9 were of the rectangular bar/plate design, there were obviously significance performance changes achieved by the simple manipulation of slicing settings.

After changing the design to a typical plate for B5-9, settings could be better evaluated, although again B5 shell settings were lost, B6-9 gave good comparisons. Of interesting note was the differences in deflection and break loads between B6 and 7. The given the change of one less wall shell, 0.05mm layer height difference, and a 10% infill difference a significant deflection value was observed. Which in most line of thought makes sense, less material in critical moment of inertia regions would yield a greater deflection. And the setting changes from B6 to B7 resulted in physical material volume reduction of about 32%. However, the change in break load capacity was unproportionally more significant, resulting in an ultimate strength reduction of nearly 50%, or roughly half of its ultimate load capacity.

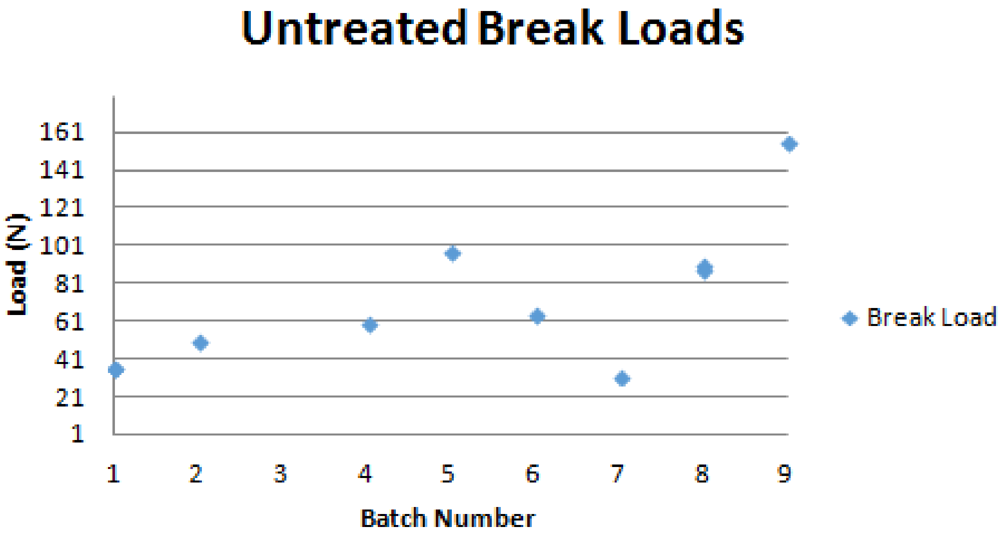


Figure 14: Results of break test values for parts prior to annealing

Likewise it was noted that B6 had roughly 15% more material compared to B8 but faired significantly worse in break tests, achieving roughly a 38% lower value, with setting changes only to the infill percentage and top/bottom shell count in slicing settings. Although of note, unfortunately B8 was printed using the TAZ by necessity and B6 the U2, therefore, a new variable was introduced in the comparison. However, the units do not vary that greatly in mechanical process, and it is likely that the equipment differential is not that dramatic. Surprisingly though, the B8 deflections were observed to be both better and worse than B6 in terms of range, and at this point, the reasons are uncertain.

B9 had the highest amount of material consumed in production and resulted in the obvious best deflection resistance and ultimate capacity. However, material consumption from B8 to B9 was roughly increased 60%, but ultimate capacity increased 74% and average deflection was only reduced by roughly 46%.

Therefore, one consideration that can be established very early is that there is a significant amount of performance control and time/material savings represented in the slicing controls related to the internal structure of a component. However, it is much more complex that considerations for products made through conventional manufacturing where the materials are much more homogenous in structure. Component orientation during layering and the distinction between wall shells versus top/bottom shells is paramount. Likewise, it would appear the interaction of infill density to the part deformation and failure modes clearly is just as complex.

Annealing

To establish a target annealing temperature, several tests were performed on existing FDM parts that were produced for other projects. The goal was to determine what approximate temperature and time would be appropriate for the annealing process without resulting in deformation of the part. The determined values resulted in roughly 173 degrees F (78.3C) for a time period of 15 minutes, and an unassisted cool down period to room temperature. The idea of quenching the parts immediately after annealing was considered, but was discarded given the number of variables already present and again lack of proper laboratory equipment and conditions. Additionally, it was also feared that quenching could result in warping due residual stress. Given the variable controls of this typical toaster oven, a thermal camera was used to determined what the actual temperature was being achieved per the control setting, and this setting was not changed for the duration of the study. However, it is possible due to an equipment error, B1 may have had a slightly higher annealing temperature, possibly closer to 190 degrees F, though no deformations were observed. Reaching temperatures over 180 degrees F are always a concern due to the fact that PLA typically begins to become too malleable and deforms under its own weight, especially when dealing with uncolored PLA. Coloring agents typically modify the mechanical properties of PLA, including thermal deformation resistance.

Figure 15: Pictures of annealing oven temperature tests and sample parts that deformed during annealing due to higher temperatures

Figure 16: Example of test parts being annealed

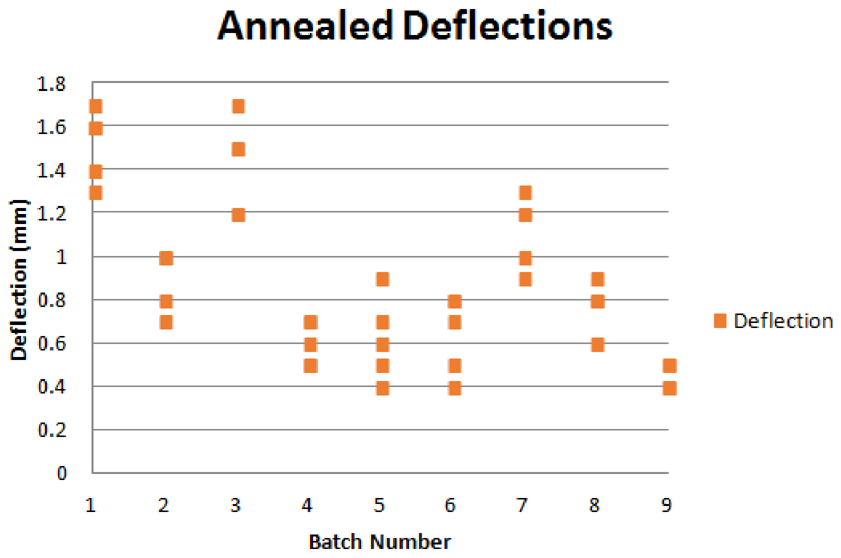
Each of the part batches would be annealed after an initial deflection test was provided of the part. All of the parts of each batch would be annealed at the same time, and allowed to cool passively before the second deflection tests were performed, as well as the break tests.

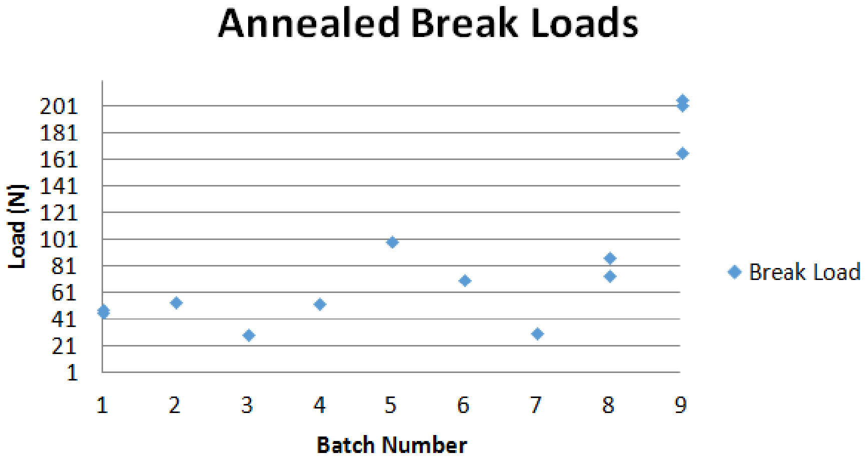
It is to be noted that moisture content of the filament was not evaluated as part of this study, and could somewhat play a factor in fabrication performance. However, from experience it is anticipated that unless under extremely moist environments, it would not be a significant issue for this project.

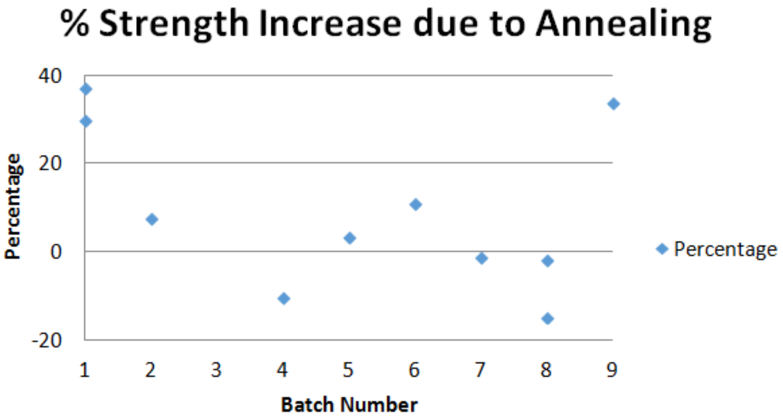
Annealing Results

As can be seen from the data below, the annealing process provided a mixture of unanticipated results. The working theory was that annealing FDM parts would have similar results to that of conventional part annealing results, and that ultimate strength would increase compared to its original state, and ductility would likely increase. It was also anticipated that the annealing results would be comparatively uniform across the batches regardless of the slicing settings involved in their production or the part’s shape.

However, this was not the case as there were a variety of results, both anticipated and unanticipated. The resulting data has been provided below.


Annealed Deflections


Annealed Break Loads


% Strength Increase due to Annealing

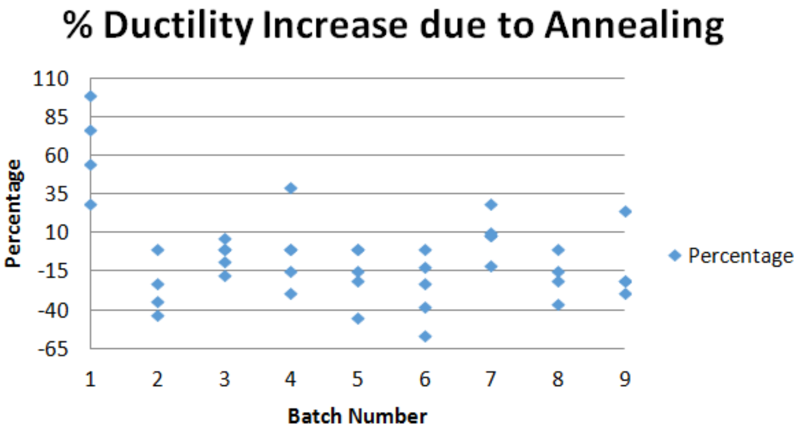


Figure 17: Results of parts after being annealed

For the most part, the data reflected the fact that annealing did increase the ultimate strength of the parts, however, the percentage of improvement was widely varied. B9 which was likely the strongest of the parts with the largest concentration of infill and shells had a significantly higher increase in strength in break testing. However, B1 had settings similar to B6 and significantly outperformed B6 in terms of annealing strength increase. Granted, B1 and 6 were shaped differently but this comparison is based on batch break tests for the same shape, therefore, it would be anticipated that performance would be similar. It was noted that the only differences in settings between B1 and 6 was that B1 had a slightly higher print speed and a top/bottom shell count of 3 versus 2 in the B6 settings.

Likewise B6 and 8 were similar in slicing settings except for a 10% decrease in infill and a top/bottom shell count of 3 for B8, but yet B6 had a significantly positive annealing result whereas B8 actually had a strength decrease from annealing. B8 was noted to also have been running around 10mm/s slower in print speed from B6 as well. The mass difference between B6 and B8 individual parts was roughly 1.2g which was roughly a 20% mass reduction from B6 to B8 parts, but obviously something was significant in the difference between the two.

For the majority of the parts, the annealing did increase the ultimate strength of the part, but there were some unique instances even in that situation. For the bar design, both B7 and 8 had an actual reduction in tested strength, and though B8's shell counts were not that abnormal, both B7 and 8 had only 10% infill and a layer height of 0.2mm, the only batches in the project of the bar design to use those settings. This generated the question regarding the impact of larger layer heights in terms of annealing recyrstallization, and whether or not the distance between layers possibly inhibited this process, especially on the extreme perimeters of the parts.

Also of note was the fact that B9 parts, being the group with the most rigid settings of shells and infill, deformed slightly in the direction perpendicular to their long dimension during annealing. As far as is known, no annealing settings were altered, so the deformation was unexpected. It is possible that B9 was cooled too fast and unevenly due to the toaster oven door being opened prematurely after annealing and the residual stresses resulted in warping. And although the change in shape was perpendicular to the direction of testing deflection, it did likely impact the deflection and break tests at least to a small degree.

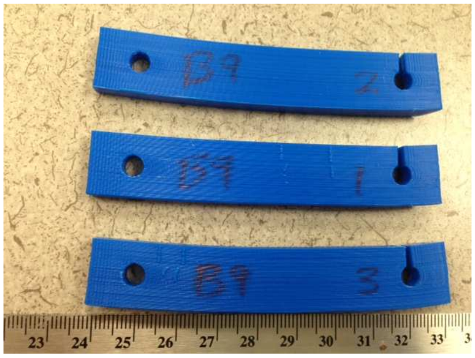


Figure 18: Picture of B9 parts curling after annealing

The ductility changes were even more unanticipated as the results were quite surprising. Many of the batches suffered from a loss in ductility instead of an improvement. B1 and 9 both of which benefitted from annealing in strength, did not both significantly benefit in ductility. All of B1's parts showed significant ductility improvement, but B9 actually had both positive and negative ductility changes. Most of the samples for all the batches were below 10% ductility increase, with a combined batch average of 29% decrease in ductility from annealing. Again, granted the testing equipment was rudimentary, but the general numbers of the results were most surprising.

Also of interest was that the ASU team document stated that their results loosely demonstrated that annealing resulted in stiffer PLA parts, which was actually reflected more so by more than half of this project's subjects (Sevenson, 2014).

Additionally, a comparison was made between the actual mass of the individual parts and the annealing ductility/strength results in hopes that there was some correlation between the amount of actual PLA material present and the effect of the annealing process on each part. However, no obvious patterns emerged. As can be seen on the previous % Strength Increase due to Annealing chart and the chart below, B2 and 5 had comparatively higher mass than B1 and 6, yet were below both B1 and 6 in terms of percentage of strength increase.

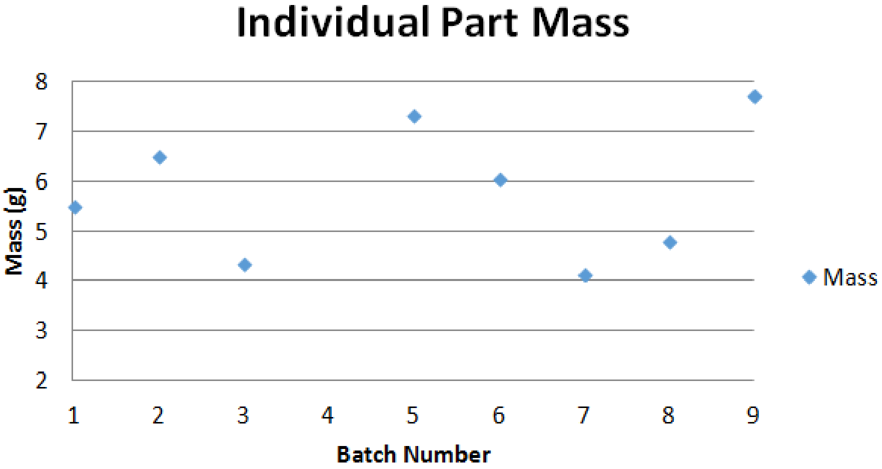


Figure 19: Individual part mass per batch

Also of note was the fact that the B1 group, which possibly was annealed at a slightly higher temperature, had positive results in increased ductility and strength while being of average settings and mass.

Granted that the testing equipment was subpar to typical laboratory standards, the results were still significant enough that that lack of precision equipment could not have been the only cause of the varied results. The combinations of varied slicing setting changes and annealing definitely had results that created new questions on performance.

Difficulties in the Testing

As mentioned, the testing equipment was less than precise, and the breaking tests specifically were most precarious. Using the low-cost digital, luggage scale was challenging due to its lack of locking or retaining maximum values on the screen. Therefore, the break tests were video recorded to allow the maximum value to be essentially caught on tape, and determined later. A screen capture of one of the videos right before the breaking point can be seen below. In the case of untreated B3 break test sample, the value in the video imagery simply could not be determined, and this was not discovered until after the Batch 3 group had been annealed.

Figure 20: Screen capture of break test video recording

Likewise in the B9 untreated group, the part was capable of withstanding the average range of break loads previously experienced and one of the individuals could simply not pull down enough in his seated position to create the expected breaking load. This part could not be re-tested as in the test it was partially damaged and would not provide accurate results if reused.

Attempts were made to use campus microscopes to more closely evaluate the structural breaks and make comparisons, however, the microscopes in question were not designed for these applications, and images that were generated from the process were not useful. The Appendix contains an example of the best image that was able to be obtained.

OBJECTIVE 2

The primary goal was to demonstrate that low-cost FDM desktop units could effectively be used within existing manufacturing/production industries to enhance their existing operations or generate cost savings. Initially, the goal was to include at least two companies in this study, however, one of the two companies was unable to participate in the time span allotted for this work, therefore only results from the one participating company, Hearthside Food Solutions (HFS), located in London, KY has been provided.

The HFS work included two categories, one was the primary goal of creating AM parts for their maintenance operations, including both small repair/replacement parts and fixture mounting parts. The other category was more specifically related to a funnel-like part used on 16 of their systems within their operations. The funnel component specifically would represent the most significant cost savings potential of the study project, as this particular part is very expensive, and is replaced 8 times year at minimum. This funnel part can also be responsible for a significant amount of failed product batches of foodstuffs as it begins to degrade due regular service life. According to HFS, an ideal situation would be that this part be replaced as an item of a regular maintenance plan which could be as many as 24 times a year. However, the current cost of the conventionally manufactured part makes that impossible given their operational budget.

HFS Small Parts

During the study, HFS provided several component designs of their own making for AM fabrication. It is to be noted that none of these components were for production or sales applications, only for internal maintenance testing purposes. The components were designed by HFS using a typical computer aided design (CAD) package, and stereo lithography (STL) files were exported and emailed for the purpose of this work. It is important to note that although CAD skills are typically required for AM integration, the level of CAD skill does not necessarily need to be that significant. For the HFS work, the CAD package used was a fairly low-level 3D modeling application, not even parametric, and was quite sufficient to produce the necessary work. In fact, a training course of less than six modules, or perhaps three weeks, would be sufficient to generate enough introductory CAD skill to fulfill the basic need for industries where CAD is not a part of their workforce applications. Images of some of the part models provided for this study can be seen below. The parts ranged from small sizes of 50x12mm to larger sizes of 260x50mm.

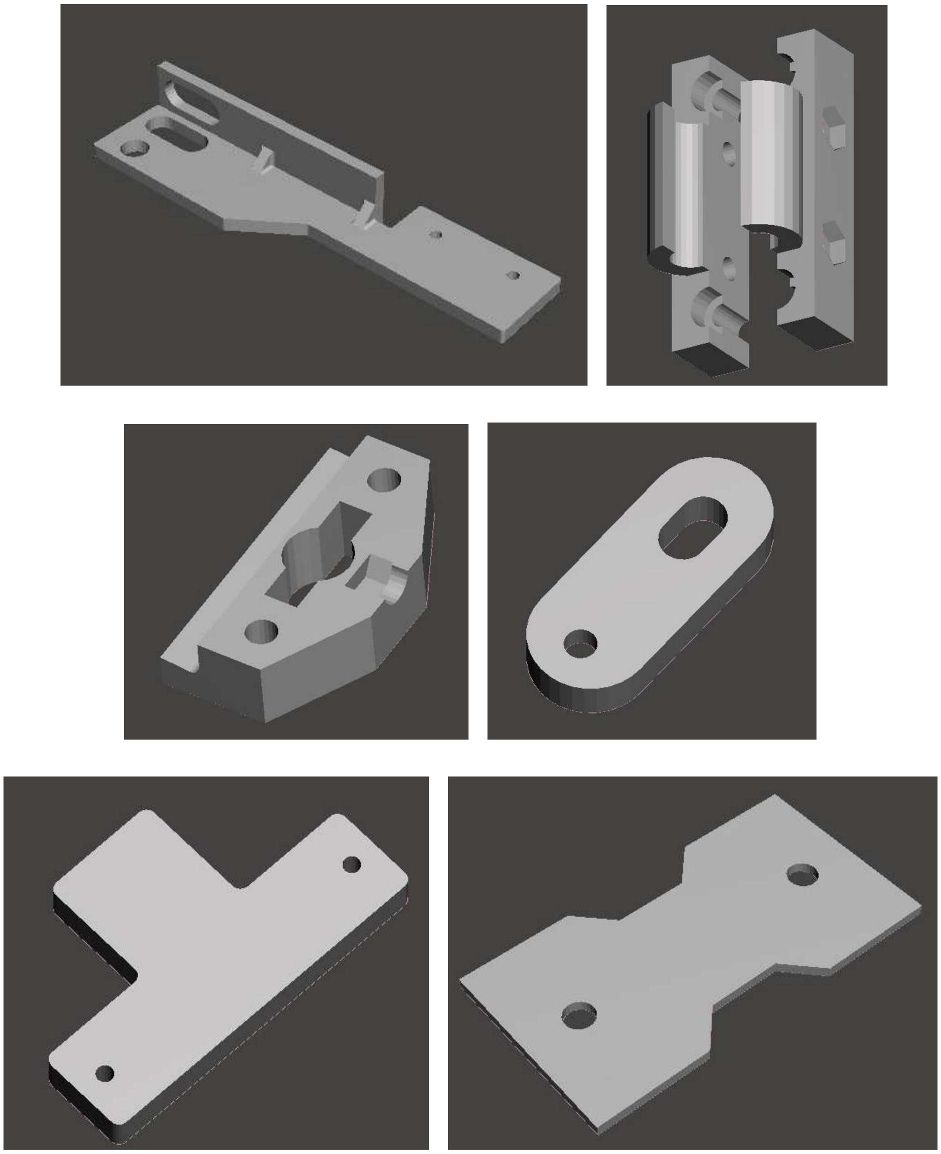


Figure 21: 3D models of HFS small parts

The HFS files were typically then sliced and the g-code generated for FDM part production. As the goal was to generate parts that were to be more durable that just example models, the slicing settings included a higher number of shells and infill values. For the majority of such parts, the wall, top, and bottom shell counts were set at 3, with an infill percentage of 30%. Where multiples of parts were required, the parts in question were batch printed, typically overnight, to optimize time and equipment usage, below is a screen capture of a batch of Dorner Photoeye Brackets being batch sliced for overnight fabrication.

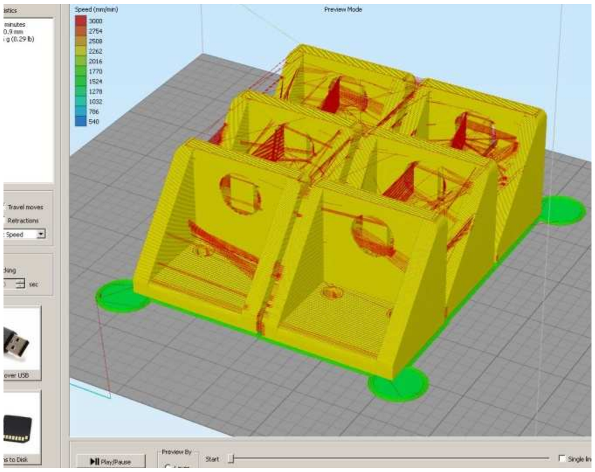


Figure 22: S3D batch print of HFS small parts

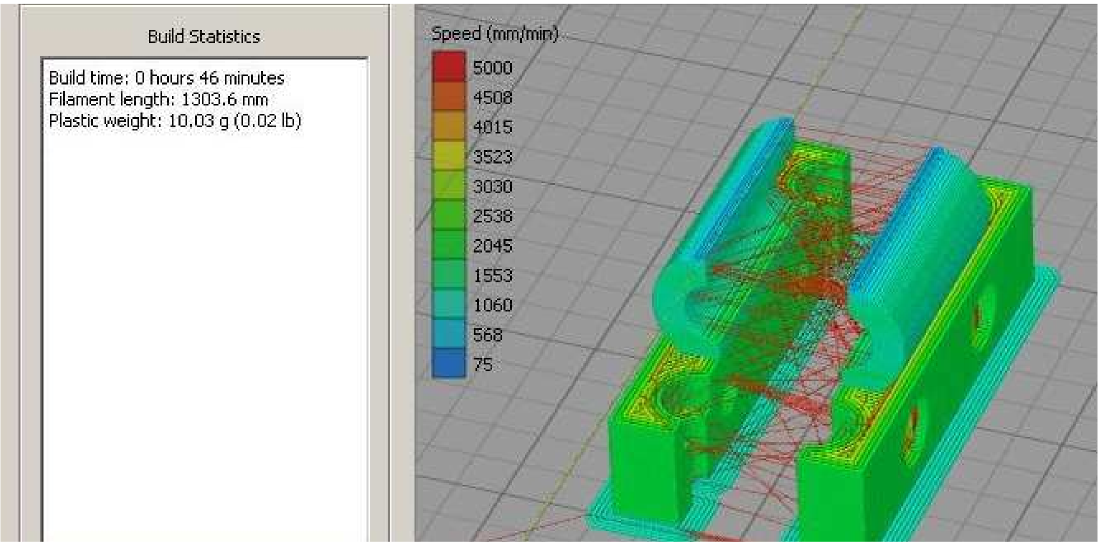
PLA was the only material used for these parts, however, the suppliers varied, as well as the filament size, therefore, no specific information has been provided in that regard. Likewise, several different FDM machines were used for these particular HFS parts. The machines included were the U2, Original Prusa I3 Mk2, and a more custom built, large format FDM system that is a joint project with another company. It is to be noted that this large format FDM system does not qualify as a low cost example; however, it was used due the size of a particular set of HFS files for convenience. All of these specific parts could have been produced on the TAZ, however that system had not arrived by the time small part production was scheduled to begin.

Figure 23: Pictures of Prusa I3 Mk2 (left) and custom large format FDM (right)

Other than removal of support material, no post processing work or finishing was performed on these parts. They were essentially placed into immediate service testing.

Cost Comparison

For simple comparative cost analysis, all FDM produced parts were based on a simple material cost plus a predetermine rate factor. As most desktop FDM units operate on power supplies similar to those in capacity to desktop computers, typically 600 watts or less, electrical costs were nearly negligible, however a cost factor per hour can easily account for such usage. Likewise maintenance costs of the FDM machines as a unit cost factor were also not included due to the fact that such costs are typically very low, and necessary part replacement is rare for the active FDM machines used in this project. Therefore, a value of 30 cents per hour was used to account for FDM energy consumption and possible other operational costs, a FDM material cost of 0.018$/g was used which is the equivalent unit cost of a roll of common filament ($18 per kg) used for this project, which does include shipping costs.

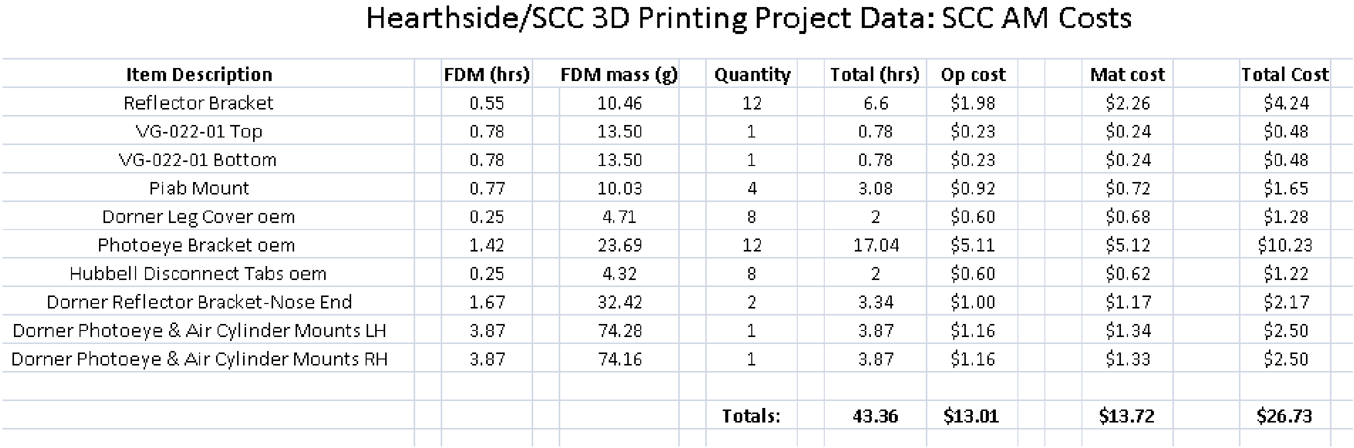


```
Build time: 0 hours 46 minutes
Filament length: 1303.6 mm
Plastic weight: 10.03 g (0.02 lb)
```

Figure 24: S3D data used FDM for cost estimates

HFS provided their own cost estimates for the parts associated with this work based on their own previous experiences and internal data. HFS noted that they used the most minimum costs possible for this comparison where parts were conventionally fabricated by their own technicians, and that such parts are most likely to be higher than what was listed. Parts that are purchased by HFS are simply the actual documented cost.

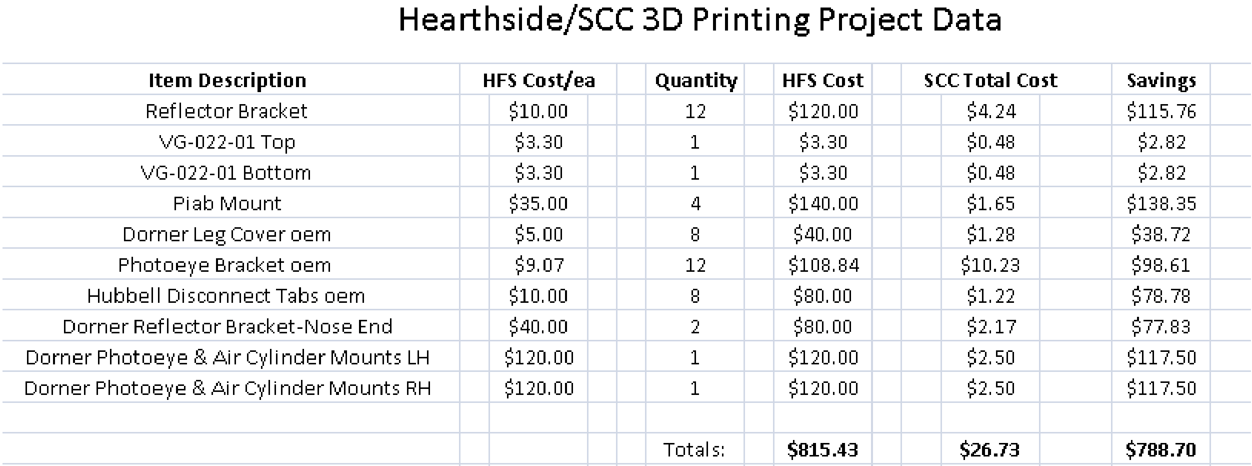
Cost comparisons are provided below.



Hearthside/SCC 3D Printing Project Data: SCC AM Costs

Item Description	FDM (hrs)	FDM mass (g)	Quantity	Total (hrs)	Op cost	Mat cost	Total Cost
Reflector Bracket	0.55	10.46	12	6.6	$1.98	$2.26	$4.24
VG-022-01 Top	0.78	13.50	1	0.78	$0.23	$0.24	$0.48
VG-022-01 Bottom	0.78	13.50	1	0.78	$0.23	$0.24	$0.48
Piab Mount	0.77	10.03	4	3.08	$0.92	$0.72	$1.65
Dorner Leg Cover oem	0.25	4.71	8	2	$0.60	$0.68	$1.28
Photoeye Bracket oem	1.42	23.69	12	17.04	$5.11	$5.12	$10.23
Hubbell Disconnect Tabs oem	0.25	4.32	8	2	$0.60	$0.62	$1.22
Dorner Reflector Bracket-Nose End	1.67	32.42	2	3.34	$1.00	$1.17	$2.17
Dorner Photoeye & Air Cylinder Mounts LH	3.87	74.28	1	3.87	$1.16	$1.34	$2.50
Dorner Photoeye & Air Cylinder Mounts RH	3.87	74.16	1	3.87	$1.16	$1.33	$2.50
			Totals:	**43.36**	**$13.01**	**$13.72**	**$26.73**

Figure 25: FDM cost data for HFS small parts



Hearthside/SCC 3D Printing Project Data

Item Description	HFS Cost/ea	Quantity	HFS Cost	SCC Total Cost	Savings
Reflector Bracket	$10.00	12	$120.00	$4.24	$115.76
VG-022-01 Top	$3.30	1	$3.30	$0.48	$2.82
VG-022-01 Bottom	$3.30	1	$3.30	$0.48	$2.82
Piab Mount	$35.00	4	$140.00	$1.65	$138.35
Dorner Leg Cover oem	$5.00	8	$40.00	$1.28	$38.72
Photoeye Bracket oem	$9.07	12	$108.84	$10.23	$98.61
Hubbell Disconnect Tabs oem	$10.00	8	$80.00	$1.22	$78.78
Dorner Reflector Bracket-Nose End	$40.00	2	$80.00	$2.17	$77.83
Dorner Photoeye & Air Cylinder Mounts LH	$120.00	1	$120.00	$2.50	$117.50
Dorner Photoeye & Air Cylinder Mounts RH	$120.00	1	$120.00	$2.50	$117.50
		Totals:	**$815.43**	**$26.73**	**$788.70**

Figure 26: Cost comparisons between conventional costs and FDM costs for HFS small parts

As can been seen, the difference of FDM costs of production versus conventional are exceptionally dramatic. Especially when considering that HFS did not account for shipping costs for materials for conventional fabrication or when parts could be purchased from vendors. However, the FDM produced parts did account for shipping in the material costs, and included a 30 cent/hr equipment operational cost. Therefore, the savings are likely to be even greater than what is calculated by a significant margin. This is of additional consideration when noting that the majority of the FDM machines that can be used to produce these FDM parts all cost less than $2,600. The Prusa I3 MK2 kit specifically only costs $805 with shipping included, and the fully assembled version only $1200, with shipping included. And the majority of the HFS parts for this work could be produced by the Prusa.

What is not considered is the lifespan of FDM parts and potential part replacement in comparison to equal parts produced by conventional means and may be capable of providing a longer operational life cycle. If the FDM parts fail or need to be replaced sooner, those are cost factors potentially associated with down time and technician labor. However, counter to this would be an integration of regular maintenance scheduling and FDM part replacement. Especially considering the extremely low cost nature of the FDM produced parts, making their actual production cost nearly a negligible factor even if replaced several times over a reasonable amount of time.

Also not considered as a cost factor for this project were the shipping costs of sending FDM parts to HFS, approximately 35 miles from the FDM production location. This was omitted due to the understanding that this project was based on the idea of FDM integration, therefore, eventually HFS would have its own FDM unit to provide this work and obviously no shipping costs would thereby be incurred, other than FDM material shipping which is already included in the material cost.

Regardless, the results clearly show that low cost FDM desktop equipment has a significant potential for existing operational cost savings and optimization. And further benefits include the 24-7 operational profile of FDM units. Granted the equipment must be maintained and occasionally monitored, but with a knowledgeable technician and a good understanding of initial calibration techniques, these machines can run multiple days without flaws. Yielding a low cost production machine that can be located virtually anywhere within a facility and be associated with nearly negligible overhead or labor costs. Likewise, if the parts are well designed with minimum support material included, then post processing work can be of only minor significance.

As an interesting side note, both the Prusa and TAZ unit used for this project, have a significant number of their own manufactured parts produced by matching FDM units. The Prusa especially is composed of over 50% of structural FDM produced parts, and those parts are produced by the same model of Prusa, note the orange parts in the previous picture of the Prusa. To explain in a more general way, 50% of the structural Prusa unit is produced by its siblings so to speak. This essentially means that the manufacturer is using low cost FDM units to manufacturer a significant portion of low cost FDM units. Which is of great benefit because both the Prusa and TAZ are capable of re-producing their own FDM replacement parts in advance should the need arise. Or as the Prusa manufacturer issues updates or design changes, these units are capable of producing their own updating or upgrading parts, a fascinating concept that likewise could be considered for further study.

A separate concern in this study was the source of the files that were provided by HFS, and potential copyright infringement. To the best of my knowledge, the files did come directly from HFS and were their own CAD creation, and not based on some form of copyrighted part model. Given the nature of the part designs, it is considered unlikely that this would be the case, and furthermore, HFS would obviously not be reselling the productions, and therefore not violating or infringing on any copyright or patent. Such protection does not cover internal fabrication for private use. But given the ease at which these parts can be fabricated using a low cost FDM unit, it does raise the question of this issue for future consideration.

HFS Funnels

This objective also included a separate project of great interest to HFS. The goal that HFS had in mind was to use FDM machines to produce a specific part that is a crucial component within their quality control process, specifically their metal detection process. Essentially, a large funnel component is used to vertically funnel baked goods through a metal detector system designed to inhibit any shillings or metal machine fragments possibly being packaged up with the baked goods. A sketch of the system is provided below. The funnel therefore, must be made of a polymer, in this case a form of Federal Drug Administration (FDA) approved Nylon, to facilitate this process. The funnel shape is fairly simple, but approximately 280mm wide and 220mm tall, and costs HFS approximately $800 to replace, plus shipping.

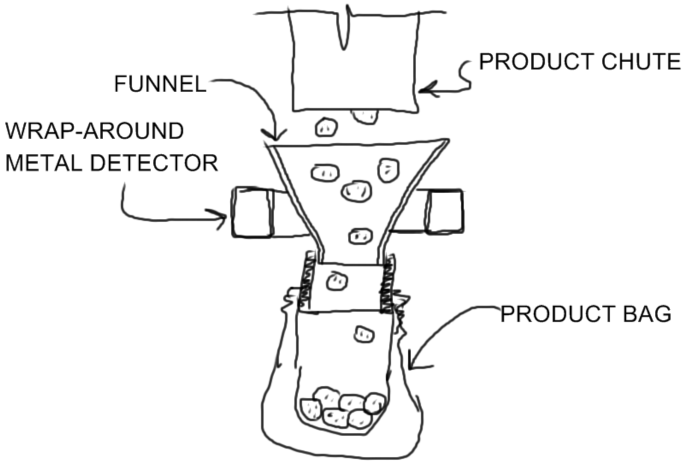
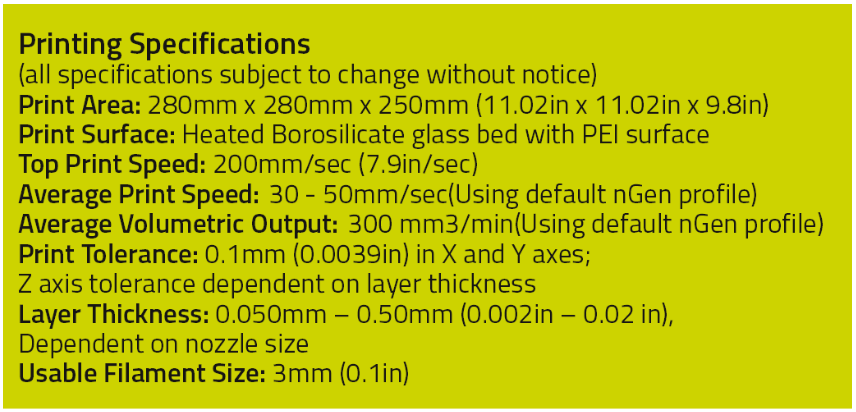


Figure 27: Conceptual sketch of the HFS funnel and metal detection system

As mentioned previously, HFS has 16 machines that incorporate this funnel and at minimum, must replace at least 8 of them per year due to wear. Resulting in a minimum annual cost of $6,400 plus shipping for a part that is generic in shape, protected by no application of patent or copyright, and currently fabricated by combination of milling multiple parts, and assembly via plastic welding. HFS has also noted that the cost of this part typically goes up approximately $75 every year as well.

Therefore, if HFS could produce this part internally and at lower cost, then they would be able to optimize foodstuff production by producing 24 of these funnels annually and reducing the number of failed foodstuff batches. With this in mind, HFS was very interested in determining if the part could be fabricated using a low cost FDM system given the significant potential cost savings. To explore this possibility, HFS purchased two, single extruder Lulzbot TAZ 6, machines with a typical unit cost of approximately $2,500 each. The operating specifications for the equipment are provided below.



Printing Specifications
(all specifications subject to change without notice)
Print Area: 280mm x 280mm x 250mm (11.02in x 11.02in x 9.8in)
Print Surface: Heated Borosilicate glass bed with PEI surface
Top Print Speed: 200mm/sec (7.9in/sec)
Average Print Speed: 30 - 50mm/sec(Using default nGen profile)
Average Volumetric Output: 300 mm3/min(Using default nGen profile)
Print Tolerance: 0.1mm (0.0039in) in X and Y axes;
Z axis tolerance dependent on layer thickness
Layer Thickness: 0.050mm – 0.50mm (0.002in – 0.02 in),
Dependent on nozzle size
Usable Filament Size: 3mm (0.1in)

Figure 28: TAZ FDM unit specifications

This selection was based on the machine's build volume capacity, reliability rating as provided by various online sources, its heated build platform, extruder thermal capacities, and its approval for various acceptable filaments, including various grades of Nylon.

Unfortunately, the testing of the machines could not begin as early as desired, as it took several months for the various agreements and purchasing approvals to make it through HFS administration system. And as a result the first machine arrived so late that only about 3 to 4 weeks of experimentation, calibration, and testing could be achieved. However, after initial calibration periods the optimized slicing settings, using S3D slicing software, were determined using PLA filament. Then the Nylon filament was ordered and testing began on producing the actual funnel in desired material.

Suited for Advanced Users

Sale: Nylon 618 by Taulman 3D

3 mm , 1lb reel

Flexibility meets strength with 618 nylon from Taulman 3D. Not only is 618 nylon stronger than PLA and ABS, it's more chemically resistant and has a lower coefficient of friction. Since objects printed in 618 nylon are so strong, sturdy, and flexible you can replace existing components. Custom washers, wearing surfaces, and weight-bearing surfaces work well when printed. 618 nylon 3D printed parts will change the way you look at breakdowns and upgrades on the job.

Printing Specifications

Special Tool Head Requirements: LulzBot Hexagon Hot End recommended

Hot End Temperature Range: 238°C

Print Surface: PEI film is recommended with a glue stick (such as UHU® brand) applied to the print surface prior to powering on your LulzBot 3D printer. Maintain the print surface by powering off your LulzBot and cleaning the glue stick residue with a soft cloth and water.

Print Surface Temperature: 110°C

Figure 29: Initial filament used for funnel production

The process went surprisingly quickly and it only took a few small funnel prints to get the TAZ calibrated and set up for a full sized Nylon funnel.

Figure 30: Test FDM Nylon parts

One consideration with the funnel design was the fact that STL files that were generated using HFS's simple CAD 3D software package resulted in a slightly more angularly-edged funnel versus a typical rounded curvature. This issue was solved by remodeling the same funnel design with a more advanced CAD parametric software package. Although the design model parameters and dimensions were identical, the exported STL no longer resulted in a multi-edged polygon curvature and was more circular. At this time, the only theory regarding this problem is based on the exportation/triangulation method of the simple CAD package versus the more advanced parametric package.

Figure 31: Test funnel showing angular-edged issue, due to original CAD model

Another issue in the equipment setup was the need to add extra "hold-down" pads to the design in the slicer software. These pads are typical cylinders that are approximately 175mm in diameter and 0.4mm thick. They were modeled parametrically and imported as separate STL files within the slicing software. These pads simply serve as adhesion footpads to help hold an object down as residual thermal stresses in the first several layers of fabrication typically cause those first layers to curl off of the build plate. This is a common problem in many AM systems, particularly FDM systems. The pads however are designed to be very thin and can easily be cut away from the final part, typically with a pair of scissors. Likewise their addition to the model does not affect the model design as they merge with the initial model design.

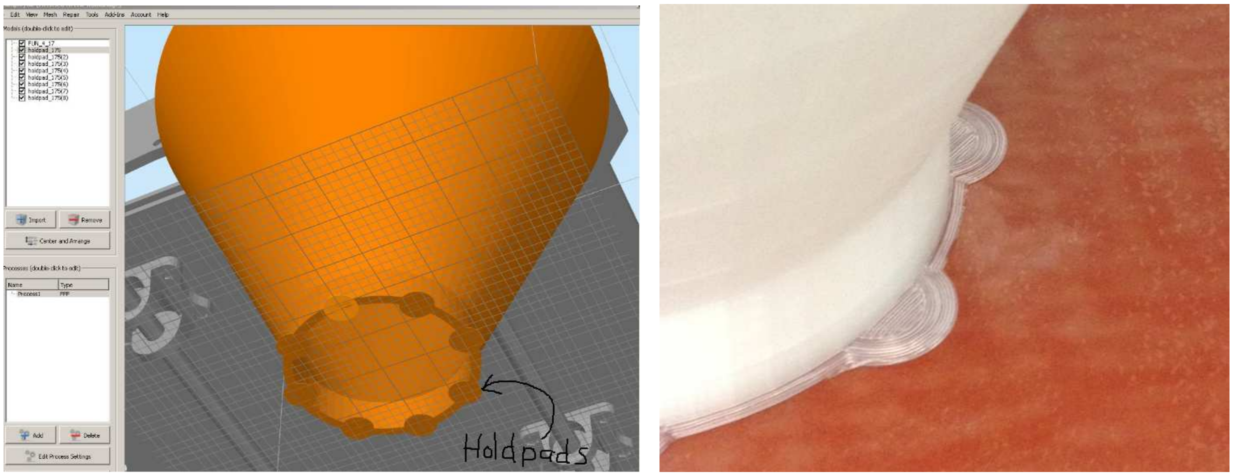
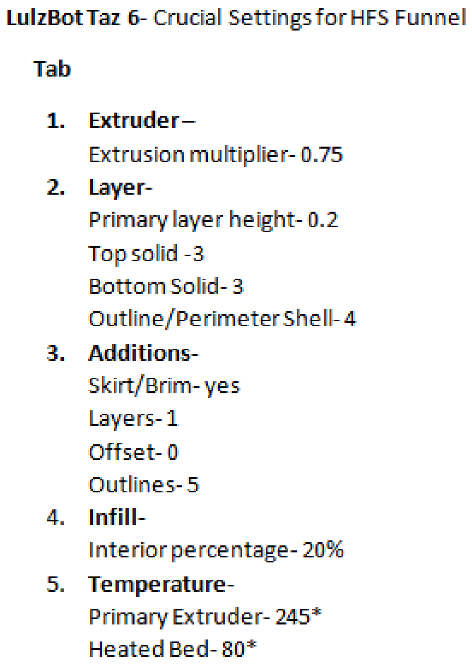


Figure 32: Hold pad applications on HFS funnel

It is to be noted, however, that even though first layer curling is a common problem in FDM systems, some shapes, such as cylinders in this case do not suffer as greatly during production due to the nature of their shape, compared to more rectangular designs. Although, there is some edge lifting from the build plate, it is typically uniform across the part and the part remains stationary.

To also increase first layer adhesion, a small amount of typical common adhesive, in the form of a glue stick, was applied in a circular pattern across the building plate prior to fabrication to improve adhesion. This is a common desktop FDM technique as well, and probably could be eliminated with a few more adjustments; however, in the interest of time it was applied for funnel production.

The first full size funnel production was initialized and estimated to last approximately 36 hours. It was monitored during normal business hours and ran quite smoothly. The settings for the first full size production are provided below.



LulzBot Taz 6- Crucial Settings for HFS Funnel

Tab

1. **Extruder –**
   Extrusion multiplier- 0.75
2. **Layer-**
   Primary layer height- 0.2
   Top solid -3
   Bottom Solid- 3
   Outline/Perimeter Shell- 4
3. **Additions-**
   Skirt/Brim- yes
   Layers- 1
   Offset- 0
   Outlines- 5
4. **Infill-**
   Interior percentage- 20%
5. **Temperature-**
   Primary Extruder- 245*
   Heated Bed- 80*

Figure 33: S3D slicing settings for initial Nylon funnel

There was however an issue due to human error, in that there was not enough Nylon filament left on the roll to complete the part. Since only one roll was ordered, and several test runs had been performed prior to the full production, the funnel only reach approximately 82% of completion. This was an error that could have been avoided had records of the amount of mass of filament already consumed been kept and tabulated before initiating the full production. Given that the slicing software provides all of this information, it would have been a simple matter to determine.

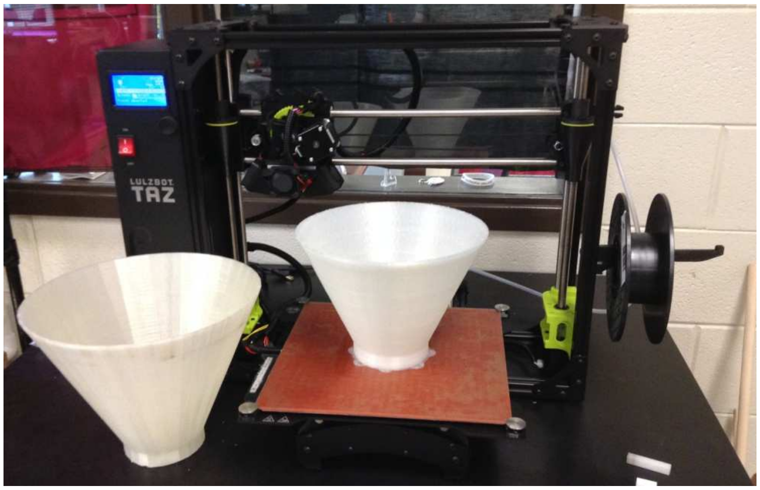
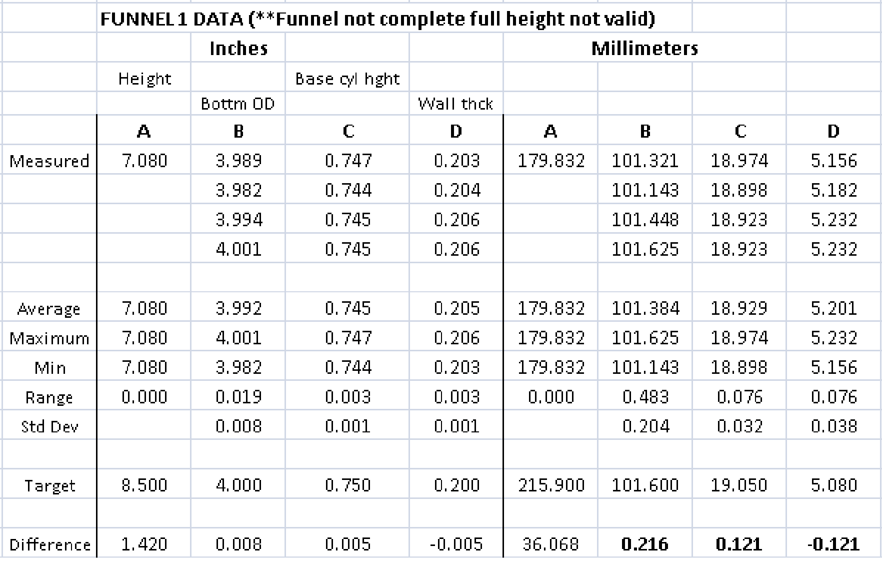


Figure 34: PLA test funnel version (left), Nylon 82% complete funnel version (right)

Fortunately HFS believed that it was a successful enough fabrication to begin some preliminary testing, and more filament has been ordered to fabricate more complete funnels.

With regards production accuracy, measurements on the first funnel, omitting height due to the fact that the part was not completed, resulted in a deviation from model design to physical part by only a maximum of 0.22mm (0.0087 inches) on its worst deviation from the average of measurements, that being the bottom outside diameter of the funnel.   For reference, given the funnels geometric shape, the measurements were taken at four points around the perimeter. Although, it is to be noted that these measurements were made with manual tools such as a tape measure and a digital caliper, these were extremely positive results in terms of production accuracy.



	FUNNEL 1 DATA (Funnel not complete full height not valid)**							
		Inches				**Millimeters**		
	Height		Base cyl hght					
		Bottm OD		Wall thck				
	A	**B**	**C**	**D**	**A**	**B**	**C**	**D**
Measured	7.080	3.989	0.747	0.203	179.832	101.321	18.974	5.156
		3.982	0.744	0.204		101.143	18.898	5.182
		3.994	0.745	0.206		101.448	18.923	5.232
		4.001	0.745	0.206		101.625	18.923	5.232
Average	7.080	3.992	0.745	0.205	179.832	101.384	18.929	5.201
Maximum	7.080	4.001	0.747	0.206	179.832	101.625	18.974	5.232
Min	7.080	3.982	0.744	0.203	179.832	101.143	18.898	5.156
Range	0.000	0.019	0.003	0.003	0.000	0.483	0.076	0.076
Std Dev		0.008	0.001	0.001		0.204	0.032	0.038
Target	8.500	4.000	0.750	0.200	215.900	101.600	19.050	5.080
Difference	1.420	0.008	0.005	-0.005	36.068	**0.216**	**0.121**	**-0.121**

Figure 35: Dimensional comparison between 3D model values and Nylon 82% funnel

One oddity that occurred related the material were the small “bubbles” that only occurred on inside wall of the funnel, not on the outside. They were easy to remove, and minor post processing and finishing work was already anticipated for each funnel, but it did create a question of material processing. One possible theory was the presence of moisture in the filament and that these bubbles were more of a result of evaporation during the FDM process, the fact that outside of the funnel does not have them was a curiosity. A potential solution to this problem which has yet to be explored for this particular case is known as “filament baking” where the filament will be placed in an oven and pre-heated to set temperature for a period of time to essentially remove the moisture. There is also a possibility to remove the bubbles with a change in slicing settings, specifically changing the way that the extruder is directed to move in the production of the outside curves. This is a controlled feature where the extruder would typically start from the same place to begin the next layer, but can be randomized to create a completely different layering start point. This would likely increase production time, and therefore, be of no significant benefit, but one of interest for future research.

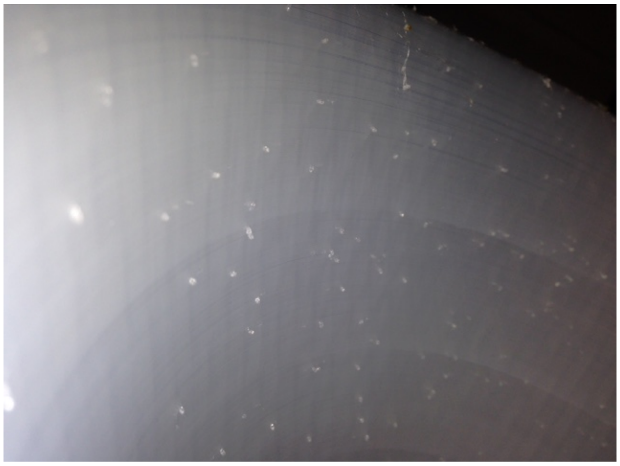


Figure 36: Nylon funnel interior face bubbles

Again as the bubbles are easily removed by the anticipated interior-finishing work, they were a non-issue as far as HFS was concerned.

Another problem that occurred on the first large print of the funnel that did not occur on any of the test prints was a pattern of delaminations or layer separations on the part. These disconnections were very well defined and although did not occur at uniform intervals, did appear to have some form of pattern. To solve this problem, slicing settings have been altered to correct for this problem, however due to time constraints, the full revised production will not be completed in time to include in this document, but current partial test runs have eliminated the delaminations thus far. The specific setting changes included a lower layer height to potentially increase layer adhesion, a slight increase in extruder temperature to facilitate additional layer adhesion, and a reduction of layer cooling fan speed. The fan speed reduction specifically will be to reduce the "cold layer" adhesion affect. Layer fans are very useful in producing higher quality FDM prints, however; in this case as the part geometry is very simple, does not involve any openings, overhangs, or bridging situations, the fans do not create a significant benefit that would be sacrificed due to their lack of use.

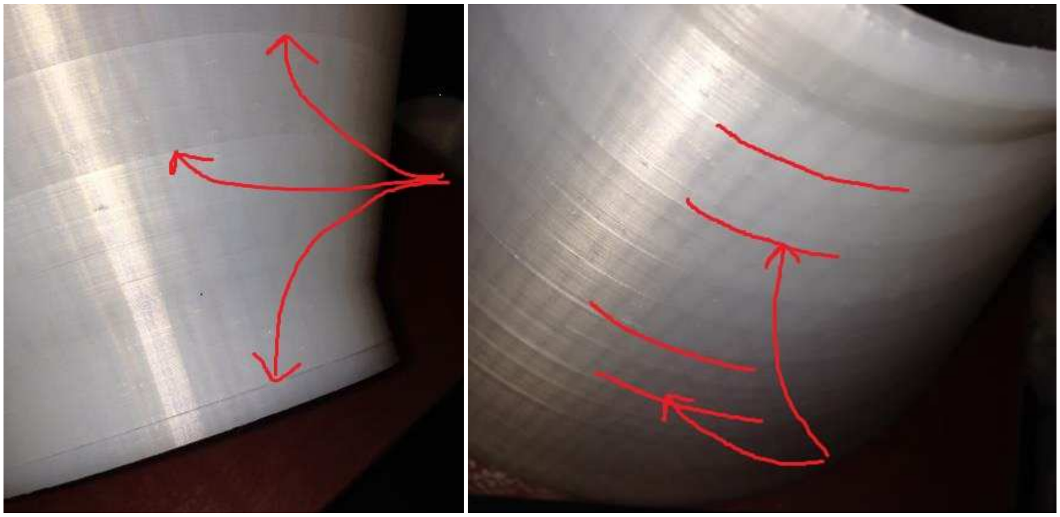


Figure 37: Nylon funnel delaminations

HFS Funnel Results

Although, testing and evaluation will be ongoing, HFS is currently and tentatively considering the project a success and will soon be relocating one of the TAZ 6 units to their facility to begin continual, on site funnel production. Considering cost of the filament and factors for energy consumption and minor maintenance, a very conservative value places the funnel production cost at $48 per funnel. With this in mind, the cost savings result in approximately $750 per funnel, a very significant value. Therefore, given the cost of the machine being approximately $2,500, HFS stands to recoup its equipment investment with only roughly 140-160 hours of operation. Given the machines can operate 24 hours a day, this means that the machine could pay for itself in its first week of operation. Comparatively speaking, given the significantly higher cost of automated, conventional, subtractive manufacturing equipment such as a CNC unit, it is very unlikely that such equipment could achieve this same accomplishment, and pay for itself in its first week of actual production.

Figure 38: Charlie Gist from HFS and the Nylon 82% funnel leaving the lab for service testing.

HFS goal with this experience is to begin to disseminate the results of this study with its 23 sister plants, located throughout the United States and 2 plants in Europe. With the intent of leading the way for additive manufacturing integration for its entire international system, and providing further research and leadership with the technology. It is anticipated that this will be an ongoing project for a significant period of time with more and more AM integration as new ideas and innovations present themselves, with many additional opportunities for research.

CONCLUSIONS

OBJECTIVE 1

The results of this objective were not nearly as conclusive as desired. The implication with the majority of the results is that slicing settings and the resulting internal structure had more unpredictable effects on performance and even annealing results than was expected. Although from these results, a case can be made that annealing low cost FDM produced parts can result in positive increase in strength, it is clear that more research and testing is necessary to generate predictive quantities. Likewise, as this objective focused only on using PLA filament, it is possible that of the many other materials available to FDM production, such as thermal polyurethane (TPU) or high impact polystyrene (HIPS) may respond more uniformly or possibly even more erratically given the internal structural controls associated with slicing settings.

It was obvious during the collection of data that less broad slicing setting adjustments should have been made and more single variable changes used. Likewise for the annealing, the part designs should have all been the same and no slicing settings made until a clear set of uniform results emerged. The original idea was that the broad changes in slicing settings would have distinct results and patterns from which to hone in at a later point, but clearly there is more tradeoffs between shell counts and infill percentages than was considered. Additionally, the infill pattern itself was never changed as a slicing setting, and with at least 5 different varieties of infill patterns available within S3D, that in of itself is whole other avenue of potential research and testing.

One slicing setting in particular may have more significance that was previously considered, that being layer height. Initially layer height was simply a concern of finish quality versus production time, however from both Objective 1 and even Objective 2, layer height may have a more significant structural performance value, specifically layer to layer adhesion or binding. It is now believed that the difference in layer height may even possibly affect the annealing process, as the layer to layer connection may impact the recrystallization process.

A key takeaway point from this slicing testing is the significant need to design and slice products for their operational performance, more so than just using a standard set of slicing settings as was used in the HFS small parts section of this study. Although AM creates a completely new opportunity to shape designs for specific applications, it is has become obvious that there are optimum slicing settings unique to specific product load direction, stress flow, and post processing treatments.

Therefore, if AM technology to be used to its fullest potential, designers and technicians need to fully understand what their products will be exposed to in terms of loads and stresses, and will need to have a strong understanding of material physics to slice and produce the best AM products. With such technical understanding, their AM products could reach new levels of optimized performance in terms of mass, shape, environmental impact, and functional lifespan.

OBJECTIVE 2

Granted the results are only preliminary and simplified, but they do make a strong case for the economic benefits of AM process integration, even if it is only a small scale. In the case of the small part maintenance production, there is ample evidence of potential savings, especially considering the low cost of entry. Assuming that existing staff, skilled in CAD 3D modeling were available or even remotely available for such training, a company could begin experimenting with AM integration at an extremely low risk threshold. Likewise, the funnel project demonstrates a significant potential savings in both purchasing comparisons and overall operational improvement. In the case of HFS, producing 24 funnels a year should allow them to reduce product loss due to process failures, but which is something that has never been tried before due to the potential cost of nearly $19,000 annually. If the new AM integration process fully succeeds the cost for 24 units annually would only be roughly $1,200, a price that could easily be managed with their current operating budget, and will likely result in other additional savings.

One issue that must be resolved prior to full production is obtaining Nylon 680 or some other FDA approved filament in more significant quantities, specifically in 1kg rolls or more. The current format of 0.5kg Nylon rolls leave little margin for error in funnel production and either results in a great deal of waste or exhausting the material supply prior to completion. There is a PLA FDA approved filament that may be an alternative option, but has not been explored at this time.

CONSIDERATIONS AND THE FUTURE

Over 150 FDM print hours were associated with this project over a course of roughly 3.5 months. Likewise, approximately 90 to 100 man hours were associated with the modeling, coordination, meetings, equipment set up, data collection, FDM experimentation, processing, and document drafting of this project. And as the project continues, we anticipate another 2 months of coordination, training, and testing, as well as at least another 150 hours of FDM print time before HFS is self sufficient in their own funnel production. From this information and experience, it is anticipated that low cost FDM integration on small part fabrication could be achieved with roughly 30 hours or less of print hours, and likely 40 man hours or less related to training and practice. The man hours especially would be reduced from this value if the technician or operator already had moderate 3D modeling CAD skills. For larger projects or continual production, such as with the HFS funnel, the FDM print hours for preparation should be anticipated to be between 100 to 200 print hours.

Also from this experience, it is recommended that FDM equipment integration include the installation of an equivalent power back up unit (UPS), given the lengthy uninterrupted operational potential of these FDM units, such measures would be well worth the cost. Likewise for that same reason, FDM units are recommended to be run on secure digital (SD) cards instead of USB connection to laptop or desktop computers. Although connection to a computer is desirable for equipment set up, communication issues over long periods of process time are likely to occur which will cause a production run to be essentially lost. Therefore, the g-code for a production run should be saved to an SD card and inserted into the FDM equipment for long prints to avoid failures. This experience has happened on more than one occasion, and it is highly recommended that if an FDM unit does not come with an SD card interface it should not be considered for integration.

This project also demonstrated the ease at which legal complications could arise for AM maintenance integrators. As it creates a new potential issue in terms of intellectual property, especially when part shape or design is considered. Previously, replacement parts for equipment were typically not cost effective to internally fabricate by conventional means, and therefore such copyright issues were not typically a concern or even noticed when produced by others for maintenance replacement applications. Most equipment manufacturers do not take the time to copyright their designs associated with commonly replaceable parts. But now, with the ease of recreating complex or even simple parts with little fabrication effort or expensive equipment, the issue of design copyright and infringement is likely to become a serious legal and political issue. Equipment manufacturers are likely to begin to decline in revenue on aftermarket or replacement parts as more and more equipment owner maintenance departments integrate AM. Thus, such manufacturers will be likely seeking ways to inhibit such actions by beginning to copyright individual design components or find new ways of regulation.

Going forward, given the preliminary results this work, another company has recently requested a similar AM integration project. A regional company known as Gorilla-Lift produces patented, trailer tailgate lift assisting devices, and is interested in evaluating FDM for internal operation purposes, as well as considerations toward full FDM production of specific parts they are having difficulty in producing using conventional manufacturing methods. The company has already set aside an allotment of funds toward the purchase of a separate FDM unit that is capable of reaching higher operating temperatures. Such capabilities will allow the FDM unit in question to produce parts in more engineering grade materials, reduce inventory needs, decrease development time, and provide an excellent case study.

Likewise, two grant applications have been submitted to the USDA and GE Additive for potential equipment expansion. The USDA application involves acquiring more appropriate testing equipment and other resources to facilitate more low cost FDM product testing. Therefore, if the USDA grant is approved, such research will likely be able to be provided and help to potentially address the issues found in Objective 1. The GE Additive grant is specifically focused on obtaining metal AM production equipment. And although the specifics of the equipment are not available at this time, one obvious directive will likely be the training and curriculum development necessary to prepare a workforce for AM metal production. As well as help to prepare the regional manufacturing industries for the AM product demands that are likely to begin growing, especially in the defense, aerospace, and medical markets.

REFERENCES:

Sevenson, Brittney. "Arizona State Students Conduct Study On How to Make 3D Prints Stronger." *3DPrint.com | The Voice of 3D Printing / Additive Manufacturing*, 08 May 2014. Web. 01 May 2017.

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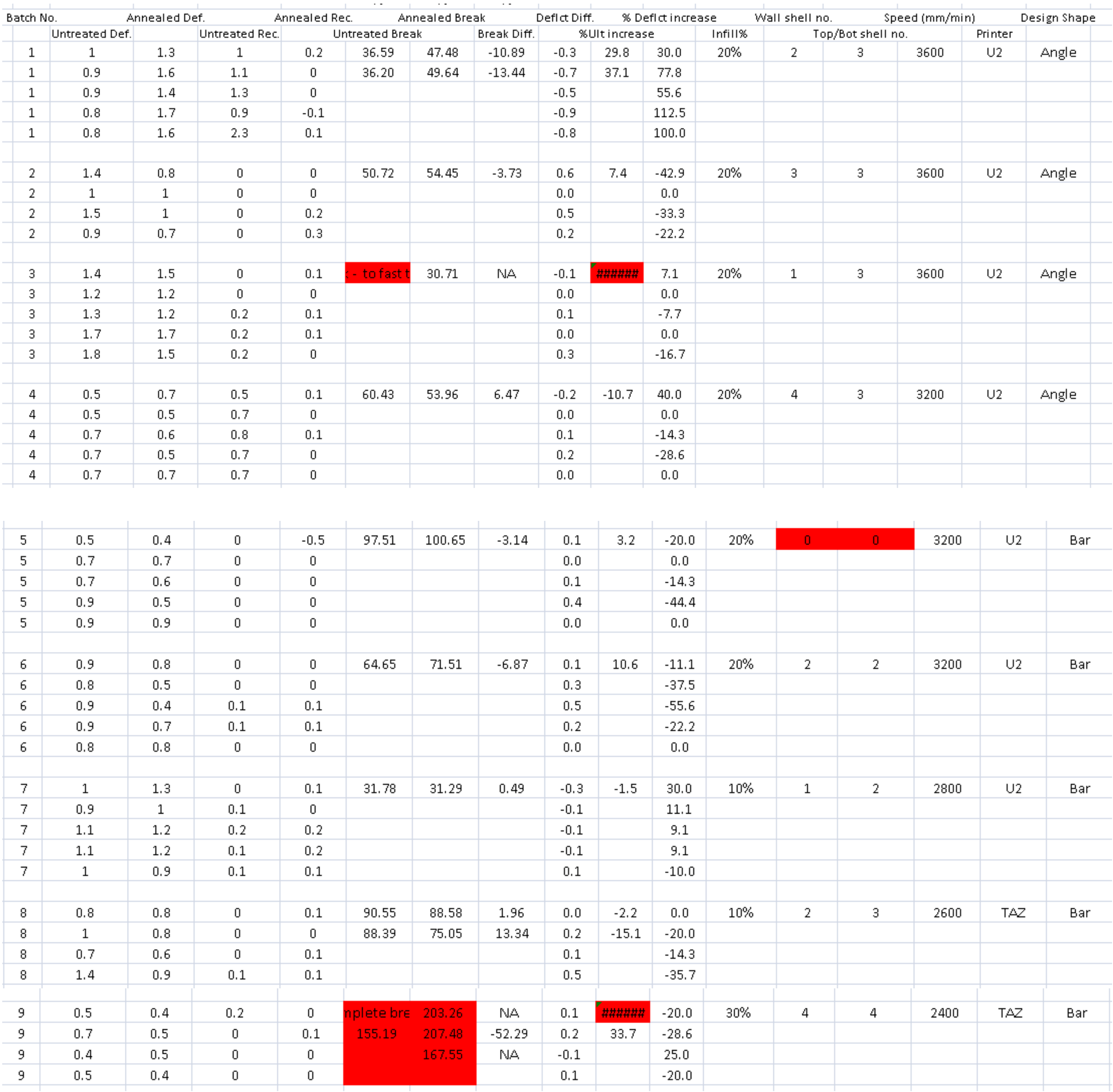
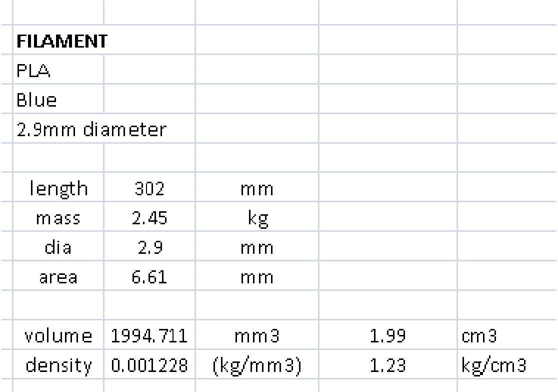
Likewise, an equally large thanks to both Kelly Goodson and Eric Harris of the Somerset Community College AM/3D Printing Lab, their technical assistance with data collection, modeling processing, and overall support were crucial in keeping everything rolling and printing over the months of this project.

APPENDIX



Batch No.	Untreated Def.	Annealed Def.	Untreated Rec.	Annealed Rec.	Untreated Break	Annealed Break	Break Diff.	Deflct Diff.	%Ult increase	% Deflct increase	Infill%	Wall shell no.	Top/Bot shell no.	Speed (mm/min)	Printer	Design Shape
1	1	1.3	1	0.2	36.59	47.48	-10.89	-0.3	29.8	30.0	20%	2	3	3600	U2	Angle
1	0.9	1.6	1.1	0	36.20	49.64	-13.44	-0.7	37.1	77.8						
1	0.9	1.4	1.3	0				-0.5		55.6						
1	0.8	1.7	0.9	-0.1				-0.9		112.5						
1	0.8	1.6	2.3	0.1				-0.8		100.0						
2	1.4	0.8	0	0	50.72	54.45	-3.73	0.6	7.4	-42.9	20%	3	3	3600	U2	Angle
2	1	1	0	0				0.0		0.0						
2	1.5	1	0	0.2				0.5		-33.3						
2	0.9	0.7	0	0.3				0.2		-22.2						
3	1.4	1.5	0	0.1	- to fast t	30.71	NA	-0.1	######	7.1	20%	1	3	3600	U2	Angle
3	1.2	1.2	0	0				0.0		0.0						
3	1.3	1.2	0.2	0.1				0.1		-7.7						
3	1.7	1.7	0.2	0.1				0.0		0.0						
3	1.8	1.5	0.2	0				0.3		-16.7						
4	0.5	0.7	0.5	0.1	60.43	53.96	6.47	-0.2	-10.7	40.0	20%	4	3	3200	U2	Angle
4	0.5	0.5	0.7	0				0.0		0.0						
4	0.7	0.6	0.8	0.1				0.1		-14.3						
4	0.7	0.5	0.7	0				0.2		-28.6						
4	0.7	0.7	0.7	0				0.0		0.0						
5	0.5	0.4	0	-0.5	97.51	100.65	-3.14	0.1	3.2	-20.0	20%	0	0	3200	U2	Bar
5	0.7	0.7	0	0				0.0		0.0						
5	0.7	0.6	0	0				0.1		-14.3						
5	0.9	0.5	0	0				0.4		-44.4						
5	0.9	0.9	0	0				0.0		0.0						
6	0.9	0.8	0	0	64.65	71.51	-6.87	0.1	10.6	-11.1	20%	2	2	3200	U2	Bar
6	0.8	0.5	0	0				0.3		-37.5						
6	0.9	0.4	0.1	0.1				0.5		-55.6						
6	0.9	0.7	0.1	0.1				0.2		-22.2						
6	0.8	0.8	0	0				0.0		0.0						
7	1	1.3	0	0.1	31.78	31.29	0.49	-0.3	-1.5	30.0	10%	1	2	2800	U2	Bar
7	0.9	1	0.1	0				-0.1		11.1						
7	1.1	1.2	0.2	0.2				-0.1		9.1						
7	1.1	1.2	0.1	0.2				-0.1		9.1						
7	1	0.9	0.1	0.1				0.1		-10.0						
8	0.8	0.8	0	0.1	90.55	88.58	1.96	0.0	-2.2	0.0	10%	2	3	2600	TAZ	Bar
8	1	0.8	0	0	88.39	75.05	13.34	0.2	-15.1	-20.0						
8	0.7	0.6	0	0.1				0.1		-14.3						
8	1.4	0.9	0.1	0.1				0.5		-35.7						
9	0.5	0.4	0.2	0	nplete bre	203.26	NA	0.1	######	-20.0	30%	4	4	2400	TAZ	Bar
9	0.7	0.5	0	0.1	155.19	207.48	-52.29	0.2	33.7	-28.6						
9	0.4	0.5	0	0		167.55	NA	-0.1		25.0						
9	0.5	0.4	0	0				0.1		-20.0						

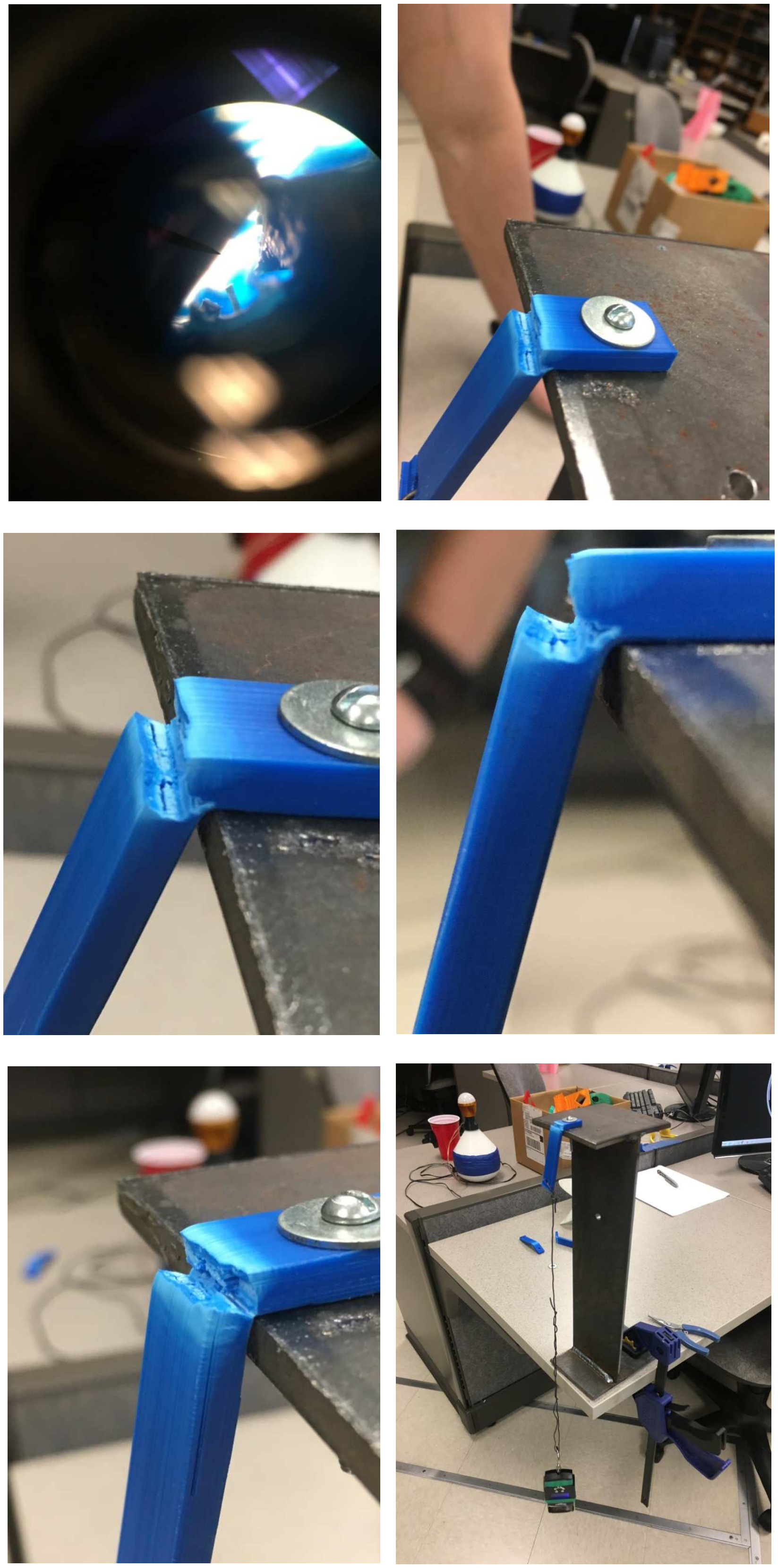
Appendix Figure 1: Part Test Data



FILAMENT				
PLA				
Blue				
2.9mm diameter				
length	302	mm		
mass	2.45	kg		
dia	2.9	mm		
area	6.61	mm		
volume	1994.711	mm3	1.99	cm3
density	0.001228	(kg/mm3)	1.23	kg/cm3

Appendix Figure 2: Filament data

Appendix Figure 3: Test related pictures



Appendix Figure 4: Test related pictures (continued)

Appendix Figure 5: HFS small parts installed for service testing