Spring 2024

Materials Testing for Large Format 3D Printing

William Jenkins
wj23@uakron.edu

Follow this and additional works at: https://ideaexchange.uakron.edu/honors_research_projects

Part of the Manufacturing Commons, Other Aerospace Engineering Commons, Polymer and Organic Materials Commons, and the Systems Engineering and Multidisciplinary Design Optimization Commons

Please take a moment to share how this work helps you through this survey. Your feedback will be important as we plan further development of our repository.

Recommended Citation
https://ideaexchange.uakron.edu/honors_research_projects/1846

This Dissertation/Thesis is brought to you for free and open access by The Dr. Gary B. and Pamela S. Williams Honors College at IdeaExchange@UAkron, the institutional repository of The University of Akron in Akron, Ohio, USA. It has been accepted for inclusion in Williams Honors College, Honors Research Projects by an authorized administrator of IdeaExchange@UAkron. For more information, please contact mjon@uakron.edu, uapress@uakron.edu.
Materials Testing for Large Format 3D printing

By:
William Jenkins

In Partnership with:
Additive Engineering Solutions

Final Report for AESE 497 Senior/Honors Design, Spring 2024

Honors Project Sponsor: David Peters
Honors Faculty Advisor: Scott Sawyer
Honors Reader 1: Austin Schmidt
Honors Reader 2: Jay Evanovich
Abstract

An ABS Carbon Fiber blend was printed into single walled hexagons at a variety of settings on a Cincinnati BAAM large format 3D printer. These hexagons were then cut down into sheets and had tensile and flexural test samples cut out of them, in order for materials testing to be performed. Tensile strength, tensile strain, young's modulus, flexural strength, deflection and elastic modulus were all determined. A desktop CNC machine and a planer were purchased for the manufacturing of these samples, and an efficient cutting procedure was designed and optimized. After all data collection concluded, this data was thoroughly analyzed, furthering Additive Engineering Solutions' understanding of the materials they print with, and how certain print settings affect those materials.
Table of Contents

1. Introduction ..................................................................................................................X
   1.1 Project Description .................................................................................................X
   1.2 Design Requirements ..............................................................................................X
2. Planning .......................................................................................................................X
   2.1 Research ..................................................................................................................X
   2.2 Process ....................................................................................................................X
3. Literature Review .......................................................................................................X
4. Codes & Standards .....................................................................................................X
5. Budget .........................................................................................................................X
   5.1 Cost ..........................................................................................................................X
6. Data Collection ..........................................................................................................X
7. Results/Data Analysis ...............................................................................................X
8. Conclusion ..................................................................................................................X
9. Future Steps ...............................................................................................................X
10. Acknowledgements .................................................................................................X
11. References ...............................................................................................................X
Definitions & Acronyms

AES: Additive Engineering Solutions

LFAM: Large Format Additive Manufacturing

Cincinnati BAAM: The 3D printers used at AES

ABS: Acrylonitrile butadiene styrene, a popular 3D printed polymer

ABS Carbon Mix: ABS mixed with carbon fiber for strength

Anisotropic: An anisotropic material has different values and properties depending on the direction in which it is measured

Bead Width: The width of a 3D printed bead

Bead Thickness: The thickness of a 3D printed bead

Convex-Concave Tool: A sample/display tool used to demonstrate the capabilities of large format 3D printing

Glass Transition Temperature: The temperature at which a material changes from a hard state to a softer one

Layer Time: The time it takes for a 3D printer to fully complete a layer of a print

Recoat Temperature: The temperature of a bead when the next layer is printed on top of it, measured using a FLIR thermal camera

Single Bead Wall: A 3D print with single bead walls is hollow, with only 1 wall of one bead width around the perimeter of the print
1. Introduction

Large Format 3D Printing is an emerging new industry that is at the forefront of the additive manufacturing world. With large 3D printers at a scale of up to 10'x20' this allows additive manufacturing to break into new industries and applications. With a field as new as this, there is lots of new knowledge to be gained and ways to fine tune the printing process. The data collected in this project will hopefully lead to a greater understanding of the properties of printed parts, and allow Additive Engineering Solutions to confidently adjust their print settings with hard data to back them up.

1.1 Project Description

The goal of this design project was to increase the base of knowledge that Additive Engineering Solutions has on the materials it prints, as well as their understanding of how certain print settings affect the strength of their materials. Testing was done using an ABS Carbon Fiber mix, and a material data sheet will be produced using the data collected. Additional data was also gathered for each material, at different bead width/height ratios. These include .75” bead width with .2” bead thickness, and .625” with .175” thickness. These combinations were studied at a recoat temperature of 105 degrees Celsius. Additionally, the effects of recoat temperature variation were studied on the .75”/.2” bead combination, with recoat temps of 70°C, 90°C, 105°C, and 120°C tested. It is hoped that by compiling these results AES will have a greater understanding of their materials and how print settings affect them, and be able to improve print quality through this knowledge.
1.2 Design Requirements

The base design requirements for this project are set by following ASTM guidelines, with additional processes made to follow AES standards. The printing of hexagons is standard for AES material testing as it is a shape that is easy to print, while also scalable and allows for many samples to be cut from them. All 3D prints were made following the AES standard production process. One big requirement for this project was that all machining was to be done outside of the workflow of the AES machining center. This is to ensure that machining is not bogged down by materials testing when more urgent projects are waiting, and will make it simple for future employees to continue on this research with minimal help or interruption to the standard workflow. To meet this design requirement, a Shapeoko desktop CNC router was purchased, and installed outside of the main machining center. When it came to materials testing, all samples were made in accordance with ASTM standards. Tensile testing dogbones followed ASTM D638, with slight modifications allowed within these standards, and flex testing followed ASTM D790 the same way. Great care was taken to follow these standards as closely as possible, with the goal to make all data repeatable and comparable across the board.

2. Planning

Lots of preparation was required in order for this project to run smoothly, and the goal was to put in as much time as possible on the front end, to make things run more efficiently later. The first steps of this project included brainstorming and researching the most efficient way to produce samples. It was decided that the best way to do this would
be through purchasing a dedicated desktop CNC machine to cut the 3D printed samples. This would allow for samples to be produced independently of AES’s machining center, greatly increasing throughput without having to wait on or bog down the machining department. On the desktop CNC machine, dedicated workholding fixtures and machine code were produced in order to allow the manufacturing of these material testing samples assembly line style, with only needing to line up the part for each step, and click run. The goal of this process was for it to be simple and streamlined enough that anyone could do it simply by reading through work instructions. Once the predicted number of samples needed was determined during phase I, the design and manufacturing of the 3D printed hexagons began in phase II. It was determined that the optimal size for the hexagons is one that is large enough to accommodate all samples that will be needed to be cut out from it, without any additional printing needed. This is to allow a single print to build up a large amount of stock to be machined, and once another print starts then the 3D printer and CNC machine can run concurrently.

2.1 Research

Much research was done during phase I of this project in order to prepare for the efficient manufacturing of all testing samples during phase II. One of the most helpful resources used was the ASTM D638 standard for materials testing. This standard covers the testing of tensile strength, tensile strain, and young’s modulus. Another extremely helpful read was ASTM D790, which covers flexural strength, displacement and flexural modulus. These documents covered all the types of testing that were
performed in phase II. Additional information was supplied by AES, in the forms of AES internal knowledge, and communications with others in the industry who have performed similar testing. This is how the method for 3D printing samples was determined. It was advised to 3D print a large hexagon out of single bead walls, cut it into its six separate sides, and then cut samples out from those. This seems to be a standard practice in the LFAM industry and using it here as well will help standardize processes and results.

2.2 Process

After planning out a road map, the core work of this project was divided into three separate sections: printing, machining, and testing. Step 1 was printing. To create many samples, it was decided that the easiest way would be to print many hexagons, with each able to be cut into 6 panels that could then have samples cut from them. A total of 5 hexagons were printed, at various print settings, using an ABS and Carbon Fiber blend. Hexagon 1 was printed with a .75” width bead, and a height of .2”, and a recoat temperature of 120 degrees celsius. An additional convex-concave tool was added to this print to slow down the layer time of the machine, but this tool is not used further within the scope of this project. Next, hexagon 2 and hexagon 3 were printed together. Hexagon 2 had a bead width of .75” and a bead height of .2”, while hexagon 3 was a slightly thinner bead at .625” and .175”. Both were printed with a target recoat of 105 degrees celsius. For hexagon 4, 90 degrees celsius was the recoat target, and 2 convex-concave tools were added to sufficiently slow this print down. Finally, hexagon 5 was printed using the same .75”/.2” bead as before, but at a very low recoat
temperature of 70 degrees celsius. While this print finished successfully, upon cooling, cracks appeared in some layers. This was considered as proof of a lower bound, and no additional recoat temperatures were tested. To accurately measure all of these recoat temperatures, a FLIR camera was used to watch each print layer by layer. As it took around 5 layers for the recoat temperature of each print to hit its target recoat, the bottom inch of each print was cut off and discarded during later stages of this project to ensure reliable data.

Figure 1: The First Layer of a Hexagon Being Printed

As printing wrapped up, I began step 2 of this project, machining. I started by cutting all hexagons into their 6 separate pieces, and then began the process of getting them flat. Since all test samples have an ASTM specified depth of ⅜", the printed
panels were too large to be used as is. Initially, the plan was to use the purchased Shapeoko desktop router, and a ½” facing bit to get all panels down to size. But after only one panel, it was apparent that this route would be far too time consuming. To solve this problem, a Grizzly planer was purchased, allowing each panel to be fed through and quickly planed down to size. This proved to be much more efficient, as well as more accurate than anticipated. Panels were very smooth and of uniform thickness, making this project exceedingly easier. From here, the panels were fixtured to the Shapeoko router, and cut into samples. Two different types of samples were created, dogbones for tensile testing, and long rectangular prisms for flex testing. A total of 20 samples were made of each type, from each hexagon. 10 in the X direction, and 10 in the Z direction, as 3D printing is anisotropic.
The final step of this project was testing, and 2 different types of tests were conducted. Tensile testing was all done according to ASTM D638, and all flex testing followed ASTM D790. A Shimadzu materials testing machine, and TrapeziumX software were used for data collection, making this whole process very simple. First, the dimensions of all samples were entered into TrapeziumX to assist with calculations. Then the appropriate testing apparatus was set up, either for tensile or flex testing, shown below in Figures 3 and 4.
Figure 3: An Example Tensile Testing Setup, Mid Test
After setup was complete, tests were run back to back until all samples had been tested. Data parameters collected include tensile strength, tensile strain, and young's modulus for tensile testing, and flexural strength, deflection, and elastic modulus for flexural testing. After all data was collected, data analysis began, which will be covered in depth in a later section.
3. Literature Review

Unfortunately, very little public literature is available on Large Format Additive Manufacturing as a whole, let alone materials testing specifically. To account for this, I reviewed the little guidance that I have, as well as did my best to extrapolate some literature from the world of standard size FDM printing. One resource that was at my disposal was some internal documentation from one of AES’ plastic suppliers. This slide was the basis of much of the setup for my project, but can not be shared here due to confidentiality. One change however, was that for my testing, the dogbones will be faced on both ends, removing all ribs that come from the 3D printing process.

One example of related literature on normal sized FDM printer materials testing is the paper “Materials Testing of 3D Printed ABS and PLA Samples to Guide Mechanical Design” by Daniel Farbman and Chris D. McCoy. This paper details the results of materials testing of FDM printed dog bones at a variety of settings. Some of these dog bones were printed in ABS, which is similar to the materials that I am using (ABS with added carbon fibers). Some of the variables that were tested in this paper were how infill percentage and infill geometry affect the strength of a print. Due to differences in the large format process, these settings are not applicable to my case, as all dogbones will have 100% infill and therefore no infill geometry either. The main parameter that I am testing is how varying recoat temperatures can affect strength. While I can find no directly applicable literature on this, I am hoping to produce comparable results by following the supplies procedures referenced above.
4. Codes & Standards

Two standards used extensively for this project were ASTM D638, and ASTM D790. ASTM D638 governs tensile strength, tensile strain, and young’s modulus. It requires a minimum of 10 test specimens be used per data sheet, 5 in the X-direction, and 5 in the Z-direction. With anisotropic specimens, it is extremely important to perform tests in both the X and Z direction. For this project, a total of 20 will be used, 10 in the X-direction, and 10 the Z-direction. ASTM D790 regulates flexural strength, deflection and flexural modulus. Like with ASTM D638, it requires a minimum of 5 specimens for each direction. For this project, 10 samples were fabricated in each direction to produce data with maximum reliability. ASTM also outlines the dimensions of samples to be tested in each of these documents. For all tensile testing, the AES standard dogbone was used, which is an ASTM Type III dogbone with some modifications to ease manufacturing as allowed by ASTM. Figure 5. outlines the allowed variances in dogbones from ASTM D638 testing.
ASTM D790 provides similar guidelines for specimen dimensioning, with some tolerancing allowed for ease of manufacturing. Specifically, I followed the specimen selection guidelines for anisotropic materials with a thickness greater than 1/16”. By following these standards all results should be accurate and repeatable.

When ASTM guidelines were not available, internal AES standard processes were followed wherever possible. This was very important to ensure homogeneity of results even if reproduced by another employee or in a different department. OSHA standards were also followed at all times, and appropriate PPE was always worn.

Personal safety is extremely important when completing any project, as injuries can mean a project may not be able to be completed due to safety reasons. OSHA standard
1910.133 was followed any time it was applicable, meaning proper eye and face protection was always worn on the shop floor for the duration of this project.

5. Budget

A nominal budget of $20,000 was given by AES in order to fund the completion of this project.

5.1 Cost

One of the largest single sums of this project was spent on the purchase of a desktop CNC machine that will be used to cut out 3D printed samples for materials testing. The budget given for the purchase of this machine was $5000 dollars and the machine was able to be purchased for slightly under this budget, along with an upgraded spindle and workholding kit. The remainder of this budget will go towards the cost of materials needed to 3D print samples, as well as general operating costs of all machinery used. Another large upfront expense was the purchase of a Grizzly planer, in order to speed up machining workflow by quickly planing the ABS plates instead of slowly facing them on the CNC machine. This purchase was approximately $2000. Another large cumulative expense of this project was materials cost. Throughout the printing of all ABS Carbon Fiber hexagons, a total of approximately 500 pounds of plastic was used. Assuming a bulk rate of $6 per pound of material, this leads to a final cost of roughly $3000 spent on material alone. On top of this, manpower hours must be considered in this cost calculation. I have spent approximately 300 hours on this project over the course of the last 2 semesters, at a pay rate of $17.50 per hour. This results in
$5250 being the minimum labor cost for this project, as the countless hours of assistance I received have not been calculated. Adding all of these costs together leads to a total of $15250, which is under budget. Notably, this does not include things like machine time, and machine wear, which if factored in could add significant costs.

6. Data Collection

The collection of accurate and analyzable data was extremely important for the success of this project. One of the most challenging pieces of data collection was making sure a print was recoating at an accurate and reliable temperature. To ensure this, a FLIR thermal camera was used to record all prints at all times, allowing the operator to adjust the machine on the fly in order to hit desired recoat temperatures. One common issue with maintaining a steady recoat temperature, is that a part usually starts out colder than expected. Due to losing heat through the bed, the first 5 or so layers of a print will often recoat cold even when the machine is running quite fast, which would normally result in a high recoat temperature. This can be seen below in Figure 6, where the second layer of a print is recoating at 30 degrees under target, despite a high machine speed.
In order to counteract this known issue, the bottom inch of all prints were not used, allowing approximately 5 layers for the temperature to stabilize and become consistent. As the prints continued, minute adjustments usually had to be made until around the halfway point of the print, where after that temperatures would stabilize and recoat on target with no interference necessary. An example of this stabilized recoat temperature can be seen in Figure 7.
Figure 7: An Acceptable Recoat Temperature is Achieved

The final image below, Figure 8, gives an idea of what a bead initially recoats at. In this case, with a starting point of around 220 degrees, it can take around 5 minutes to cool off 130 degrees to reach the target.
Figure 8: The Initial Temperature of a Bead can be Seen, 218 Degrees Celsius

With a hexagon alone, the machine would have to move incredibly slow to achieve this. To solve this, additional tools may be added to the print to slow day layer time, and these can be seen in all figures above. These tools are outside the scope of this project, and only serve to slow down layer times, while creating a functional sample tool at the same time.

The task of collecting the final data points from the material samples proved to be much simpler than recording an accurate recoat temperature. Using a Shimadzu materials testing machine, all data collection was recorded automatically and presented as a report in the accompanying software, TrapeziumX.
Figure 9: Example set up for Tensile Testing
Shown above in Figure 9 is an example of what my standard tensile testing setup looked like. Data is automatically collected by the machine during the test and sent to a report on an accompanying laptop nearby. Below, a sample flex testing setup can be found in Figure 10.
7. Results/Data Analysis

Upon the conclusion of testing, a total of nearly 500 data points were collected. All values presented below are an average of all 10 samples tested in each layer orientation. The first data point I am looking at is tensile strength, which is the maximum stress a material can withstand before breaking, while in tension. In Figure 11 below, the data for tensile strength in both the X and Z direction can be seen in ksi.

Figure 11: Tensile Strength Data

First looking at the X direction, it can be seen that 105°C is the clear winner, showing greater strength regardless of variations in bead size. 120°C seems to have a slight drop off in strength, and 90°C even more still. Looking at the Z direction now, things become less clear. It appears that 120°C is now the strongest in this direction, with larger bead 105°C close behind. Contrary to the X direction, a drop off can be seen
between the larger and smaller bead 105°C temperatures, with 90°C even being slightly higher than smaller bead 105°C, although not as strong as large bead 105°C or 120°C.

The next thing to look at is tensile strain, which is a measure of deformation under stress due to tension.

![Tensile Strain Data](image)

Figure 12: Tensile Strain Data

Seen in Figure 12 above, 90°C is the data point with the most strain before break in the X direction. When upping the recoat to 105°C a slight drop in strain can be noticed for both bead sizes. Stepping up once more to 120°C results in a significant decrease in maximum strain for the X direction. In Z however, the opposite seems to be true with the maximum strain value being seen at 120°C recoat. Strain drops for 105°C .75”, then again for 105°C .625”, before rebounding at 90°C. Just like with tensile stress, it appears that our highest values are at 120°C when testing in the weaker Z direction.
Below is a graph of the data collected for Young’s Modulus, which is a measure of stiffness, and the last data points collected under ASTM D638. The higher the Young’s Modulus, the stiffer the material while in tension.

![Young's Modulus Data](image)

*Figure 13: Young’s Modulus Data*

As seen in Figure 13, the data here appears to be more straightforward than that of tensile stress and strain. In both directions it can be seen that 105°C recoat temperature results in the highest Young’s Modulus, or stiffest material. 90°C printing results in a steep drop off of these values, while 120°C values are less than the 105°C’s, but not as low as 90°C.

Moving on to flexural testing data, obtained under ASTM D790, the first data points to analyze are of flexural strength, shown in Figure 14.
Flexural Strength is the maximum stress a material can withstand in bending, and is measured in ksi. Once again 105°C appears to be the sweet spot in the X direction, with a slight drop off towards lower recoats and steeper drop off towards the higher one. In the weaker Z direction a nicer linear trend can be seen, with 120°C being the highest strength and all other recoats dropping off from there.

Next up is the measurements of downward beam deflection during the 3-point bending test conducted. This deflection is simply measured in inches, and shown in Figure 15.
For the X direction, max deflection is seen at the lowest recoat temperature, 90°C. Minimum deflection is at 105°C .75", while the remaining 2 recoats are both in the middle. Looking now at Z, 120°C has the most deflection by far, even coming close to the deflection of the weakest X direction average. From here, deflection drops for first 105°C .75", and then 105°C .625" before rebounding slightly at 90°C.

Finally, elastic modulus will be analyzed. Elastic modulus measures the resistance of a material to elastic deformation caused by flexural stress. Below, Figure 16 shows the recorded data averages.
Figure 16: Elastic Modulus Data

First examining the X direction, 105°C is a clear sweet spot with drop offs in elastic modulus seen when both increasing and decreasing recoat temperature. In the Z direction however, not much change can be seen between recoats or bead sizes, but a very slight maximum is seen at 120°C.

8. Conclusion

The goal of this project was to provide empirical data as to how certain print settings affect the material properties of a printed part, and I will attempt to draw conclusions with the data that has been collected. As with all research, continuous testing is recommended to ensure the accuracy of these results, and the more samples that are tested the better that conclusions can be drawn. As it currently stands, it appears that the optimal recoat temperature for general purposes is 105°C, however it
may be beneficial to slightly raise or lower this depending on the specific requirements of the print. A notable observation is that each line graph of recoat temperatures did not necessarily behave the same in both the X and Z direction. Looking at tensile strength in Figure 11 for example, 105°C is the clear sweet spot in the X direction, with a loss in strength when moving to the 120°C recoat. However, when looking at the Z direction, no loss is associated with the 120°C recoat, and it is actually slightly stronger than 105°C. I believe this is due to the differences in the weak point of the dogbones in X vs. Z. When breaking along the stronger X direction, the samples do not fracture along layer lines, but instead the plastic itself must break. This is quite different to the Z direction, where every sample breaks cleanly along a layer line. When more heat is applied to the material while printing, like when increasing recoat temperature, it may actually make the ABS weaker once a certain point is reached. This could explain why after 105°C strength drops off. However, when samples break in the Z direction, the strength of the material is not the limiting factor, but the strength of the bond between layers is. So while recoating at 120°C may weaken the material, it increases the bond strength. This leads to the material appearing stronger, when in fact it is only the bond that is stronger, but the loss of material strength will not be noticed as the bond is the limiting factor.

It may be important to note that the glass transition temperature of ABS Carbon is 105°C. The effects of this on material properties is not entirely known, but it is usually considered best practice to recoat at a temperature above the glass transition point, in order to improve layer adhesion. While it may be possible to use the graphs provided above to independently tailor print settings based on the specific material property needs of a print, my general recommendation would be to recoat at 105°C, or slightly
above in order to ensure being above the glass transition temperature. For the Z axis specifically, slightly higher temperatures of around 120°C are recommended. Hopefully these broad guidelines can help to improve the strength and quality of prints at AES, and future research can continue to narrow down the specifics of optimal print settings.
10. Acknowledgements

I would like to thank Additive Engineering Solutions for all the support they have given me during the course of this project, and my engineering career. All employees were always willing to take time out of their busy schedules to answer my questions, and provided me with any knowledge they had. Without their support this project would not have been possible, and any and all help was greatly appreciated. I sincerely hope that the results of this project can benefit the company, just as this experience has greatly benefited me.
11. References

Available at: https://www.researchgate.net/publication/308709141_Materials_Testing_of_3D_Printed_ABS_and_PLA_Samples_to_Guide_Mechanical_Design