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CONTINUOUS FIBER 3D PRINTING USING UV-CURE EPOXY RESIN

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CONTINUOUS FIBER 3D PRINTING USING UV-CURE EPOXY RESIN

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BY THE COMMITTEE CONSISTING OF

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Abstract

In this thesis, a continuous fiber single epoxy inline impregnation 3D printer head using UV cure epoxy resin is developed and manufactured. Through the design process, the final design of the printer head was achieved, and it was able to print three 3-layer fiberglass laminate composites, as well as two carbon fiber composites. Both printed composite types were compared with a hand-layup composite, serving as a benchmark. Through visual observation with the naked eye, the printed composites showed more consistency than the benchmark composites. This was further proven through microscopic imaging. Comparing the composites under 20x+ magnification showed a significant difference between void sizes in the hand-layup carbon fiber composite sample and the printed carbon fiber composite sample. The printed composite sample had significantly less voids and smaller voids than the hand-layup composite sample. In addition, the printed fiberglass composites showed to have less excess epoxy on the bottom of the composite compared to the fiberglass hand-layup composite. This is visible when looking at it and some of the spot sizes were characterized using the microscope. All in all, this proof-of-concept prototype 3D printer head using UV cure epoxy was researched, completed, and functioned as designed, capable of manufacturing multilayer laminate composite samples.

Chapter 1: Introduction

1.1 What is Additive Manufacturing?

Additive Manufacturing (AM), also known as 3-Dimensional (3D) printing, is a relatively new field of engineering. AM is the process where a 3D product is made layer-by-layer. Using this technique, unique shapes and products can be manufactured that was previously not possible with traditional techniques, like milling, extrusion, and forging. 3D printing is a relatively new engineering field, so improvements, developments, and advancements in the field are happening every year [1].

One advancement in AM is the vast availability and affordability of 3D printers [2]. This means that the public has access to this technology and can use it. Polylactic acid (PLA) is a cheap and readily available material used in AM. Because it is cheap, it is a great material to use for prototyping, and more specifically rapid prototyping. Rapid prototyping refers to the process of making a prototype of a product without the use of traditional manufacturing methods [3]. This process is important to many fields of engineering, as it allows new products and parts to be manufactured, tested, and modified quickly and for a fraction of the cost and time as traditional methods.

Standard single filament 3D printers utilize extrusion to manufacture objects. This works by feeding filament into a hot nozzle that melts the material into a liquid that is laid down according to the product's shape. This process continues, as mentioned before, in a layer-by-layer way until the product is complete. However, PLA is not the only material used in AM.

Other methods and materials, such as metal, fiber, resin, and nanotubes, are used to manufacture a multitude of products, parts, and sensors across several different types of engineering fields [4], [5], [6], [7], [8], . Medical and dental fields also utilize AM technology to manufacture and fabricate artificial body parts, such as bones and teeth. [9], [10], [11], [12], [13]. These applications demonstrate the unique and versatile abilities of AM across multiple industries and areas of engineering.

1.2 Overview of Fiber Composites

A composite is made up of 2 or more parts. These parts are known as the matrix and the filler. The matrix is responsible for holding the composite together, while the filler is responsible for carrying the load. Typically, the matrix is some kind of epoxy resin, and the filler is a fiber, such as carbon fiber, glass fiber, or ceramic fiber. Fibers can vary in length within composites. Short-fiber and long-fiber, also known as continuous fiber, composites vary in material properties, function, and application [14],

[15], [16], [17]. Fiber length greatly contributes to the composites function. Short-fiber composites are not as strong as continuous fiber composites. Fibers in short-fiber composites can help prevent cracking throughout the composite because of their random orientation [18]. Orientation of short fibers within a composite is critical to its function. Within a matrix, these fibers are usually orientated in random directions, though sometimes they can be unidirectional. Continuous fiber composites are much easier to control fiber direction, though it should be noted that fibers may cross at some point. Continuous fiber composites typically come in unidirectional and multidirectional fiber orientations. But continuous fibers run throughout the composite, which provides better load distribution than short fibers throughout a composite [19]. Continuous fiber composites will be the primary focus for this research.

Normally, fiber composites are made of several layers, known as plies, of fibers. This is known as a laminate composite. If unidirectional fiber sheets are used to manufacture the composite, then alternating each sheet's orientation will allow for the composite to be strong in multiple axes. Depending on the application of a laminate composite, the orientation of the fibers provides significant advantages to the composites overall mechanical properties [20]. The figure below offers a visual of how ply orientations are used in composites.

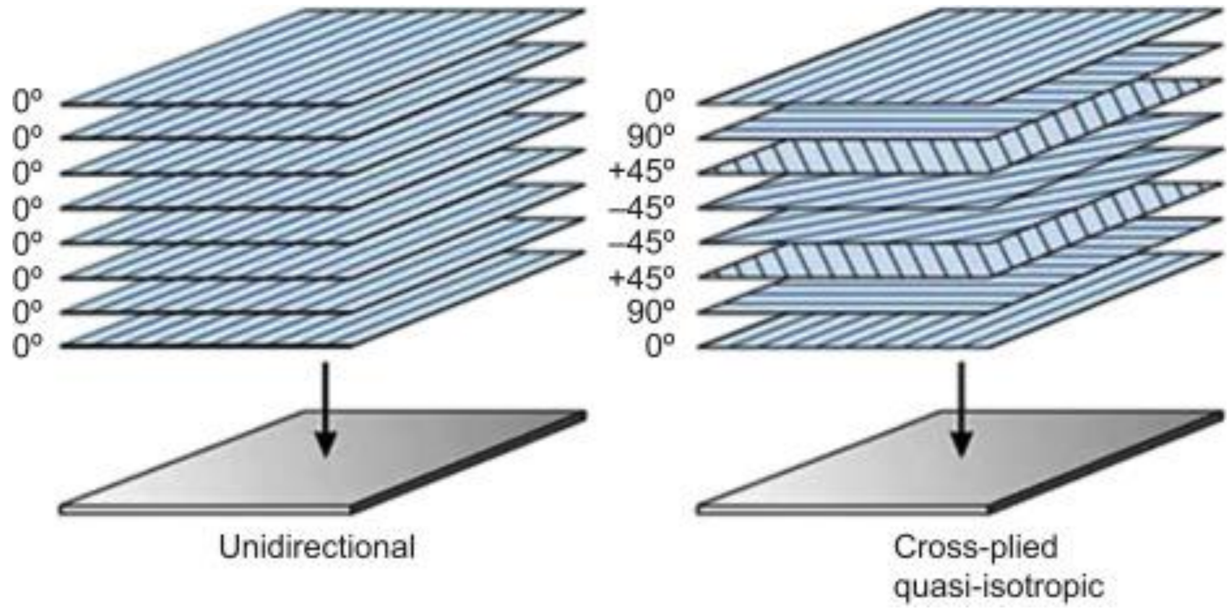


Figure 1: Multi-layer laminate composite showing unidirectional and multidirectional ply orientation [21].

The matrix of a composite is important because it helps distribute loads throughout the composite from fiber to fiber and ply to ply. Thermal cure epoxy resin is a common matrix used in laminate composites. It is made up of 2 parts, a resin and hardener, that cure through a chemical reaction, thus producing heat. To expedite the curing process, autoclaves and ovens may be used to ensure the resin is fully cured. Another type of epoxy is ultraviolet (UV) cured epoxy. Like the name suggests, UV cure epoxy only cures when exposed to UV light. This type of resin is especially useful in AM when manufacturing complex shapes [22]. In addition, UV resin can be used to repair damaged composites because it offers similar physical properties to traditional thermal cure resins [23]. All in all, epoxy is an important part of a composite laminate and makes up a majority of the composite, so it needs to be thoroughly cured to ensure the best physical properties of the composite.

Both fabrication and manufacturing require some post curing work. Whether it be polishing or trimming and cutting, some kind of work is necessary after the product is made. A composite may need to be trimmed and sanded before it is finished, much like a forged or cast metal part. These finishing details are important to the final product of the component, especially if a smooth surface finish is an important characteristic of the component. The more work that must be done on a component, the more likely it is to have a manufacturing or fabrication mistake. Therefore, the less post curing work that can be done on a part, the better.

1.3 Fiber Composite Additive Manufacturing

An advantage of AM in composites is post curing work. In many components, such as aircraft components, holes are drilled or cut through structure parts to reduce weight while remaining structurally intact. During this process, holes could be cut or drilled wrong, or the composite could become delaminated. Because of AM, this type of post curing work can be avoided. Using specially designed 3D printers, these components can be fabricated with the holes already in place, thus eliminating the need for cutting and drilling through the composite [24].

Through AM, both short and long fiber composites can be fabricated using a variety of methods [25], [26], [27], [28]. One method for short fiber composite fabrication is called liquid deposition molding (LDM), where short fibers are mixed into a liquid resin and then laid down through a nozzle [29]. A method for long fiber composite fabrication is fused filament fabrication (FFF). This is when prepreg composite filament is fed through a nozzle and laid down on the printing surface in the desired configuration. This is similar to standard 3D printing with plastic filaments, like PLA. Another method is inline impregnation, which runs dry fiber through an epoxy reservoir and then the wetted fiber proceeds through the nozzle to be laid onto the printing surface.

Post-processing in traditional composite fabrication is important and changes depending on the application of the composite. This also applies to 3D printed composites. There are several different factors to consider for post-processing. One factor is the temperature. The temperature of the oven a composite may enter after being printed or fabricated can change physical and mechanical properties of the composite [30]. Other methods include salt baths that utilize both heat and pressure to aid in the post-processing efforts of a composite [31]. A very common post-processing technique, especially in industrial applications, is an autoclave which utilizes high temperature and pressure to cure the composite.

1.4 Fiber Composite Additive Manufacturing in the Aerospace Industry

AM with fiber composites is a continuously growing and developing field, especially in the aerospace industry. Uniquely shaped parts and components, that may not be possible with traditional composite fabrication methods, can be fabricated in a uniform manner without extended post-fabrication procedures, like adhering 2 halves of a composite part together. The fabrication of parts using AM helps reduce the waste of both time and resources.

One comparison that can be made between traditional hand layup methods and AM methods, in the aerospace industry, is the use of composites in aircraft components. In an effort to reduce weight, thus reducing fuel consumption, commercial aircraft of composites [32]. Nacelles are the part of the aircraft that contain the engines companies like Boeing and Airbus are making more of their parts and planes out. They are important in directing airflow into and around the engine to ensure proper operation. Some composite nacelles, like on the Boeing 737 and 777, are manufactured using a hand layup method on half molds. Workers place pre-impregnated carbon fiber sheets on a mold according to engineering design drawings. Once each half is completed, the 2 pieces are adhered together to make the whole nacelle. Differently, the Boeing 787, with a composite fuselage, is manufactured using AM by wrapping a barrel mold in prepreg carbon fiber. Wrapping the fuselage takes several hours, and even days, but it is completely automated, apart from machine technicians and preparation work. The result is a single piece fuselage that requires no fusing of parts or pieces together.

Another advantage of the AM is the ability to control fiber orientation. As mentioned in section 1.2, fiber orientation plays a big role in the strength of a composite. AM can assist with the fabrication of composite structures in aircraft. By using specific fiber placement, the fibers in composite structures can be orientated to be most effective in the direction of the load and stresses the structure was designed for and will experience [33]. AM also allows for more complicated structures to be fabricated than traditional manufacturing techniques would allow. This again reiterates the point that AM would help cut the cost for fiber composite manufacturing in the aerospace industry.

1.5 State of the Art

As mentioned before, there have been many advancements in the field of AM since the 1980s. A recent advancement has been a 3D printer head capable of printing carbon fiber composite that utilizes an interlayer curing process [34]. This technique utilizes thermal cure epoxy as the primary matrix component but incorporates a UV curable resin outer layer that holds the shape of the composite until the thermal cure resin can fully cure. The image below offers a visual of how the printer head operated and impregnated the carbon fiber with epoxy.

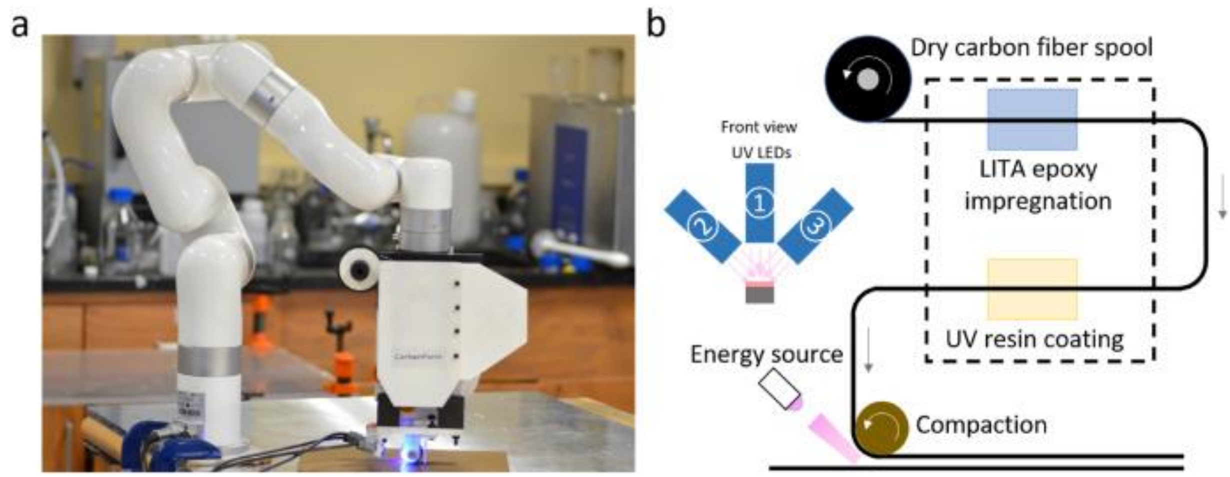


Figure 2: Dual epoxy continuous carbon fiber composite 3D printer head [34].

Another common application with continuous fiber 3D printing is using carbon fiber to reinforce composites made of other 3D printing material, like PLA [29], [35], [36]. This takes the standard form of 3D printing mentioned in section 1.1 and adds to it. While the filament is melted in the nozzle, carbon fiber can be run through the nozzle, thus creating a reinforced composite. The image below helps illustrate this process of creating a reinforced composite.

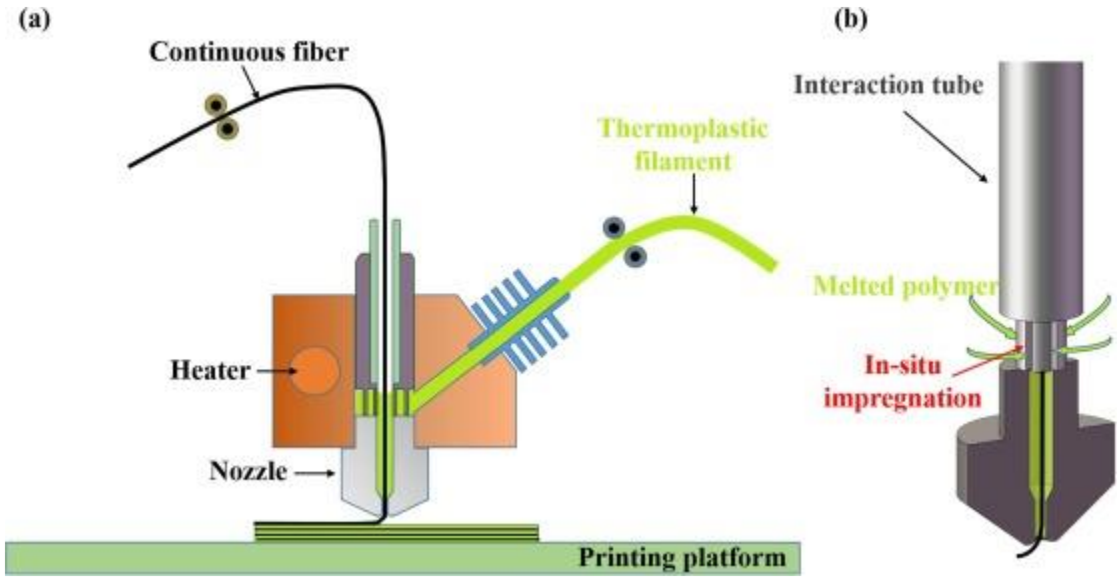


Figure 3: Diagram of how carbon fiber reinforced composites are made [36].

1.6 Thesis Outline

The goal of this research is to prove that a single epoxy inline impregnation technique using UV cure epoxy resin is a reasonable means to manufacture a fiber composite. In the following chapters of this thesis, the process of the research will be explored and explained. Chapter 2 will discuss the making of the printer head itself and the challenges that follow it. It will explain the inspiration for this research more in depth, as well as talk about ways we can improve upon past research. Chapter 3 will go into depth about the actual printing process to make a composite sample, and ways the process can improve. Chapter 4 will characterize the composite samples the printer head manufactured. It will also show a comparison between hand layup composites and the printed composites on a visual and microscopic scale. Finally, chapter 5 will conclude the thesis. It will discuss a summary of the research, problems and considerations run into during this research, and potential improvements that can be made to the printer head design in the future.

Chapter 2: Designing and Manufacturing a Continuous Fiber 3D Printer Head

2.1 Design Process of the 3D Printer Head

Making a continuous fiber 3D printer head is not a light task. Fortunately, previous research in this field has inspired design characteristics, as well as overall function. The printer head in Figure 2 is the inspiration for this project. However, instead of a thermal cure and UV cure epoxy resin, this version will only feature UV cure epoxy resin. This simplifies the overall design of the printer head.

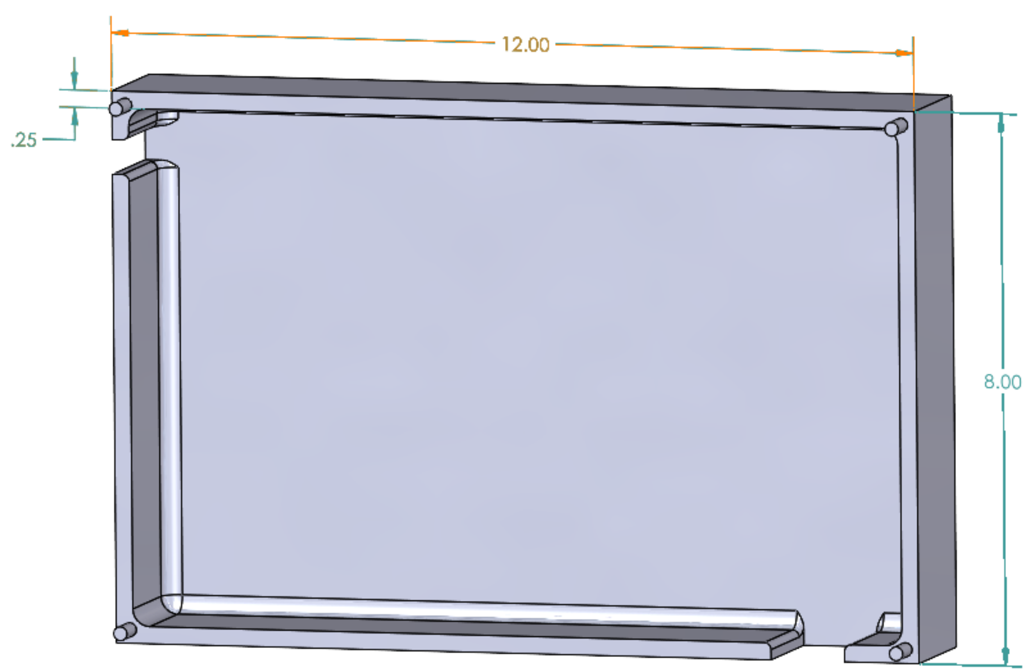


Figure 4: First iteration of the printer head shell. (Units in inches)

The first edition of this printer head shell can be seen in the figure above. The size that was initially thought of for the printer head was a 12-by-8-by-2-inch rectangular prism. It also includes fillets because the final product will be manufactured out of aluminum, so they assist with the machinability of the design. The 4 posts in each corner are bolts, and a lid, with matching hole locations, would be screwed on to the shell using a nut. Enclosing the printer head protects the inside of the head from outside debris which could cause damage or contaminate the fiber or epoxy. The head as reduced in size to focus on the design logic during the prototyping phase. This allowed for components to be manufactured faster and with less material.

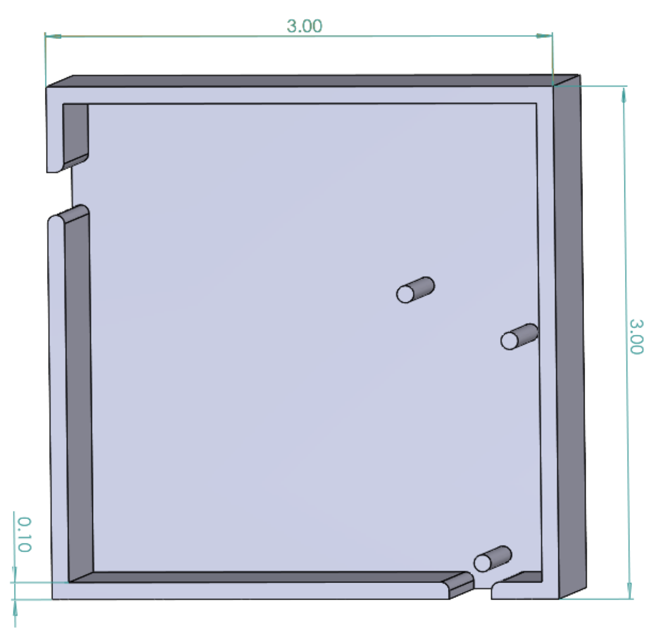


Figure 5: Second iteration of the printer head shell. (Units in inches)

The second iteration of the printer head, as seen in Figure 5, is reduced from the original size to a 3-by-3-by-1-inch rectangular prism. The 3 pins in the printer are to attach rollers that will help guide the fiber through the printer head. The empty space on the left is for an epoxy reservoir. A full model of the inside of the printer head can be seen in the image below.

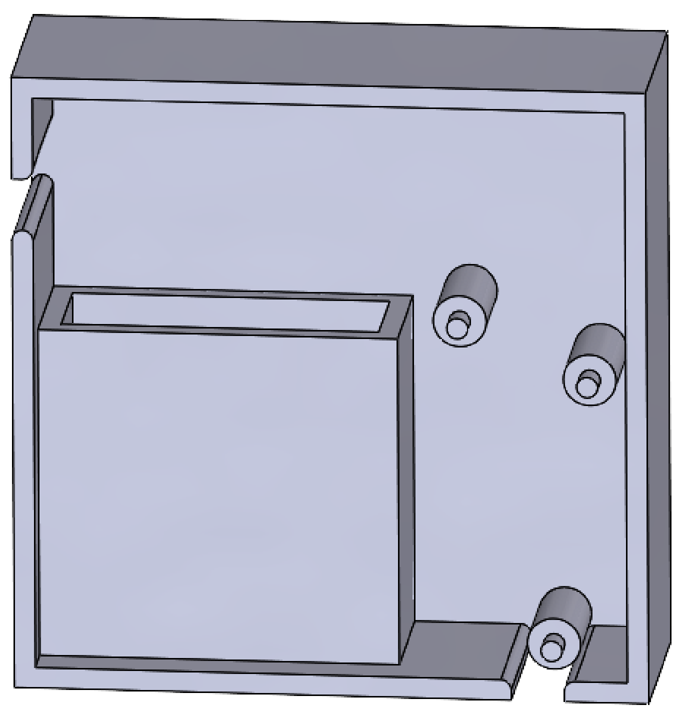


Figure 6: Fully assembled model of the first prototype design.

A few problems persisted with this design and the previous designs. Something that these designs must be mindful of is the weight of the overall design. One problem with these designs was tension within the system. This is because a motor or another driving force would pull the fiber through the system. Another issue was how fiber will be stored. The following image addresses the weight issue of the previous designs.

Figure 7: 3D printed truss shell with pins and epoxy reservoir.

This version improves upon the previous design in a few ways. The most totable is the use of a truss shape instead of a flat plate on the back side of the shell. The intent of this is to reduce overall weight while also maintaining the structural integrity of the shell itself. The other noticeable change is with the pins. Stainless steel pins were placed in drilled holes instead of the pins being a part of the shell. These pins were placed in 1/16-inch drilled holes. The reservoir (left side of Figure 6) has a pin running all the way through the bottom of reservoir. This ensures that the fiber runs to the bottom of the reservoir and is fully coated in epoxy. Notice how the outside of the reservoir has a wavy texture. This is because it was designed with holes already in place for the pins. Because of the way it was manufactured, the holes cause the side walls to sag and become wavy. Later designs include a complete wall with no holes. A 1/16-inch sized hole is later drilled straight through the reservoir for the pin.

The pin layout in Figure 7 was not sufficient in producing tension within the system. Tension within the system assists in many different ways. It helps keep fibers in order and from tangling, as well as allowing the printer head to lay down taut fiber on the printing surface. The initial fix for this problem was adding an additional pin to the shell, which can be seen in the figure below.

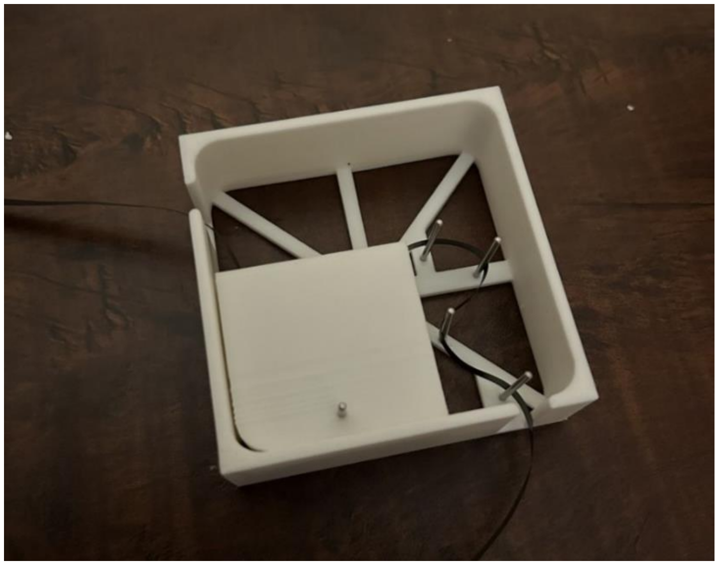


Figure 8: Printer head design with the additional pin to help introduce tension to the system.

While this did work to introduce tension into the system, there are better ways to solve this problem, and perhaps another problem. To solve the tension and fiber storage problem, a fly-fishing reel is used. On most fishing reels, there is a mechanism that prevents the fishing line from freely pulling out of the reel. This mechanism creates what is known as drag. A knob on the reel allows the amount of drag to be adjusted according to what the fisherman desires, or in this case, to the amount of tension desired in the system. Instead of the tension coming from pins within the printer head, it will result from the fiber storage spool, a fly reel.

Figure 9: Fly fishing reel that will hold the fiber and create tension within the system.

With this addition, the size of the printer head needed to be increased to effectively mount the reel to the shell. The design of the shell increased from a 3-by-3-by-1-inch rectangular prism to a 4-by-4-by-1-inch rectangular prism.

However, this was not the only addition to the next iteration of the design. The fiber needed to be pressed into the printing surface to ensure the fiber was flat before curing took place. Thus, a tab was added to the exit of the printer head that would allow pins to be installed that had rollers on them. Initially, 2 pins with rollers would be installed so that the printer head could operate forwards and backwards. The size increase as well as the tab for rollers can be seen in the model below.

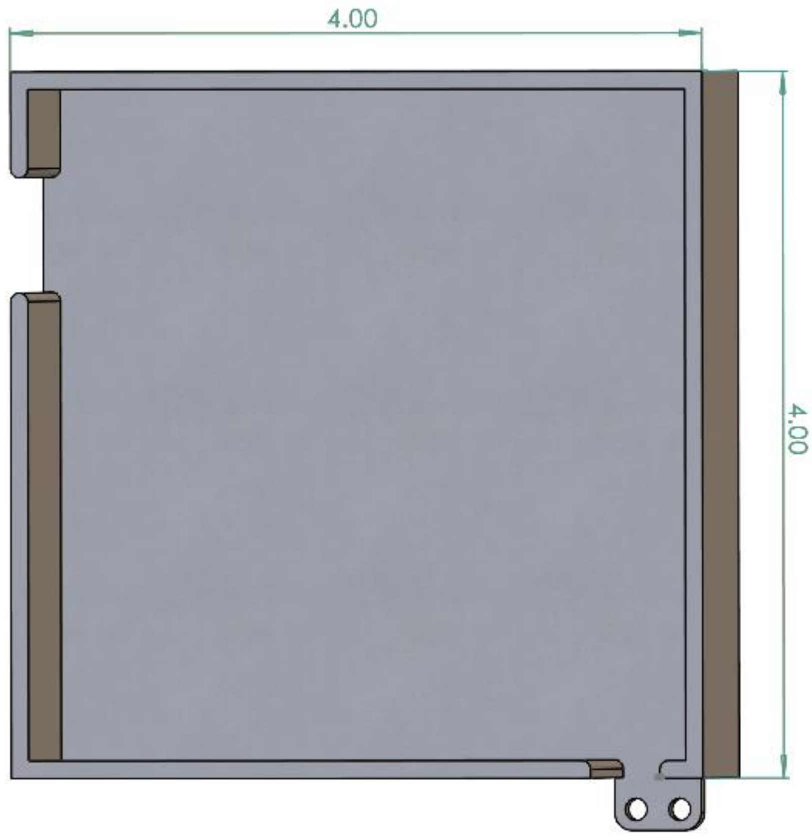


Figure 10: New edition of the printer head shell showing increased size and tab with holes for pins and rollers at the exit. (Units in inches)

One thing to note is that this version does not feature any pin holes inside the printer head. This is because a pin hole would later be drilled into the shell where a pin was needed. With this design, only 1 additional pin and roller is needed inside the printer to change the direction of the fiber after it comes out of the reservoir. After this adjustment, the next iteration featured a larger extrusion hole that allowed for the addition of a stepper motor at the exit to help drive the fiber and pull it through the system. The final prototype of this design can be seen in the figure below.

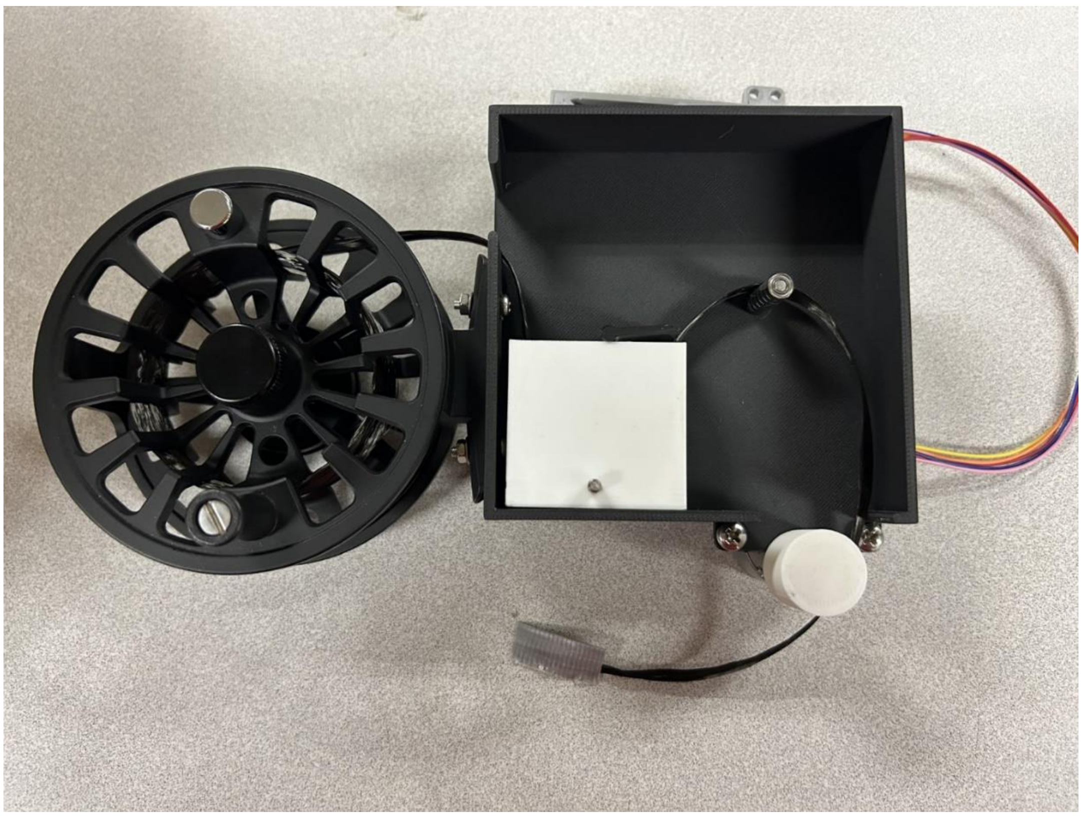


Figure 11: Final prototype design fully assembled with carbon fiber tow running through the printer head.

The black shell is the same as Figure 10, but with the modified exit as discussed in the previous paragraph. A roller was designed and manufactured to fit the stepper motor to press down the epoxy coated fiber to the printing surface. The pin seen near the middle-right of the shell is a 1/8-inch stainless steel pin with ball bearings on it. Seven ball bearings, with an outside diameter (OD) of 1/4 -inch, were pressed onto the pin. The ball bearings allowed the fiber to change direction while minimizing the friction that would be present if it were just a standard pin. The roller has a diameter of 0.91 inches, just large enough to ensure the roller will be in contact with the surface instead of the stepper motor hitting the printing surface first. The pin in the reservoir is different from previous designs, it is also a 1/8-inch diameter stainless steel pin. When the fiber exits the reservoir, it runs between the wall of the reservoir and a piece of rubber from a squeegee to remove excess epoxy from the fiber to ensure it is not over saturated. The reel and stepper motor are held on by screws and nuts, but the reservoir is hot glued to the shell to ensure it will not move while the fiber is being pulled through the system. At this point, the printer head is mechanically ready to make its first print.

2.2 Electronics for the Printer Head

The only 2 pieces of equipment that need electricity to operate are the UV lights and the stepper motor. The UV lights are a very simple circuit that will turn on at the push of a button. The stepper motor is more complicated than that. The stepper motor drives the entire printer and controls the speed of the fiber through the printer. It is a vital component of the printer head.

The stepper motor used is an Elegoo 28BYJ-48. The motherboard used is an Elegoo Uno R3. Using Arduino coding software, the proper code can be written to make the stepper motor run properly. The code written makes the stepper motor turn on when a button is pushed. This allows the user to have control over when the stepper motor is powered on. An image of the electronics can be seen in the image below.

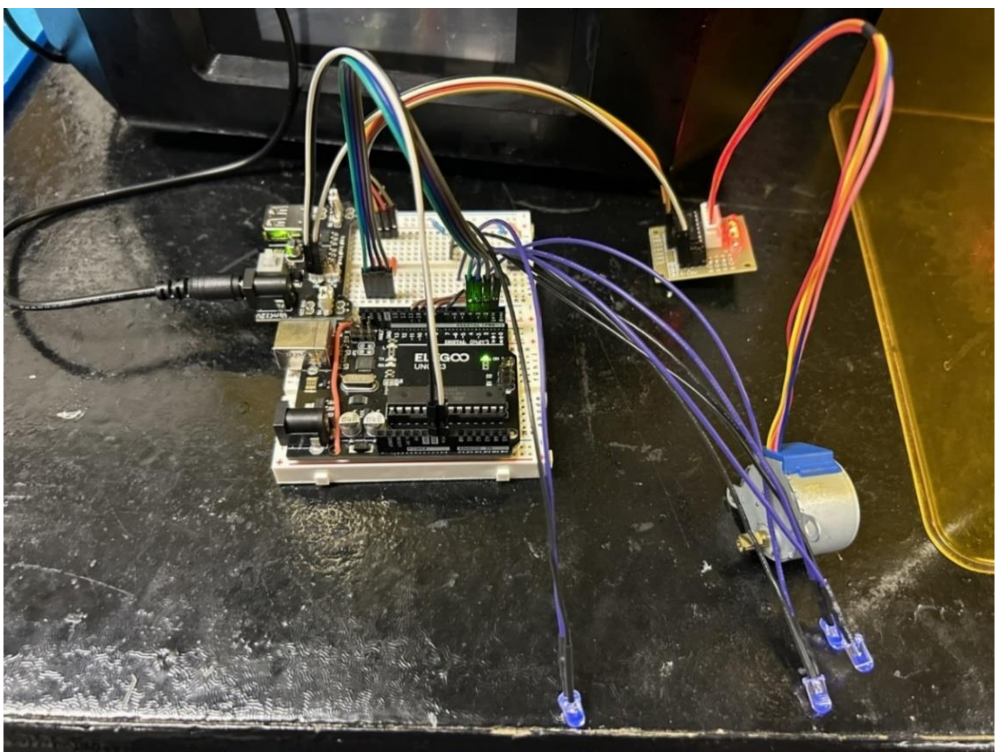


Figure 12: Electronic equipment and wiring for the printer head.

While not attached to the printer head yet, Figure 12 demonstrates what the hardware looks like for the printer head electronics. At the push of a button, the stepper motor rotates slowly, and the UV lights turn on. If a higher rotation rate is required, the speed variable can be changed within the code and uploaded to the Uno R3. Now, the system is fully functional and ready to print fiber composites.

2.3 First Prints and Composite Samples

Now that the prototype printer head is complete, it is time to print the first composites using fiber. But first, a hand-layup composite will serve as a benchmark to see how the printer head's products compare. This composite was made by taping down 2 ends of a unidirectional carbon fiber tow strip and using a syringe to apply the UV cure epoxy and spread it as evenly as possible with a gloved finger. After the fiber is covered the UV light-emitting diodes (LEDs) were used to cure the composite. The LEDs were used to see if they were compatible with the UV cure resin being used. After several minutes of using the UV LEDs, the sample was placed in a UV curing oven to finish. It cured for 2 minutes on both sides and was put in an isopropyl alcohol bath to remove any excess, uncured epoxy.

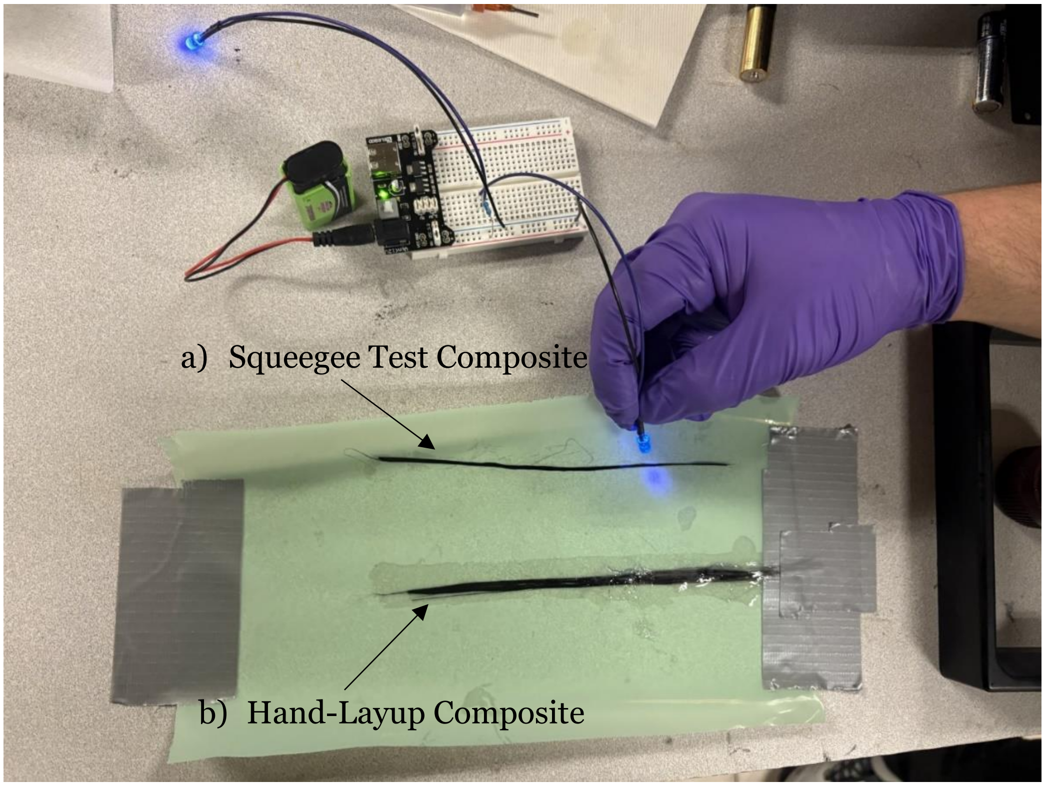


Figure 13: The benchmark composites curing under a UV LED.

There are 2 composites in the figure above, both presenting good data to consider and compare with the printed composites. Composite b is the hand-layup composite manufactured as described in the previous paragraph. There is far too much epoxy on this sample and once fully cured had sharp and jagged edges of cured epoxy. The amount of epoxy is hard to control when applying it by hand from a syringe. Composite a was manufactured by dipping the fiber strand in the epoxy and then running it through a slit of squeegee and then placed on the release film to cure using UV LEDs as depicted in Figure 13. The point of this composite was to prove that squeegee rubber was a good means to remove any excess epoxy before curing. However, passing the sample through a slit in the squeegee removed too much epoxy, thus needing another means to remove excess epoxy. This is why the fiber is passed between the squeegee and the wall of the reservoir as described in section 2.1. This technique also creates uniform and even spread of epoxy throughout the fiber.

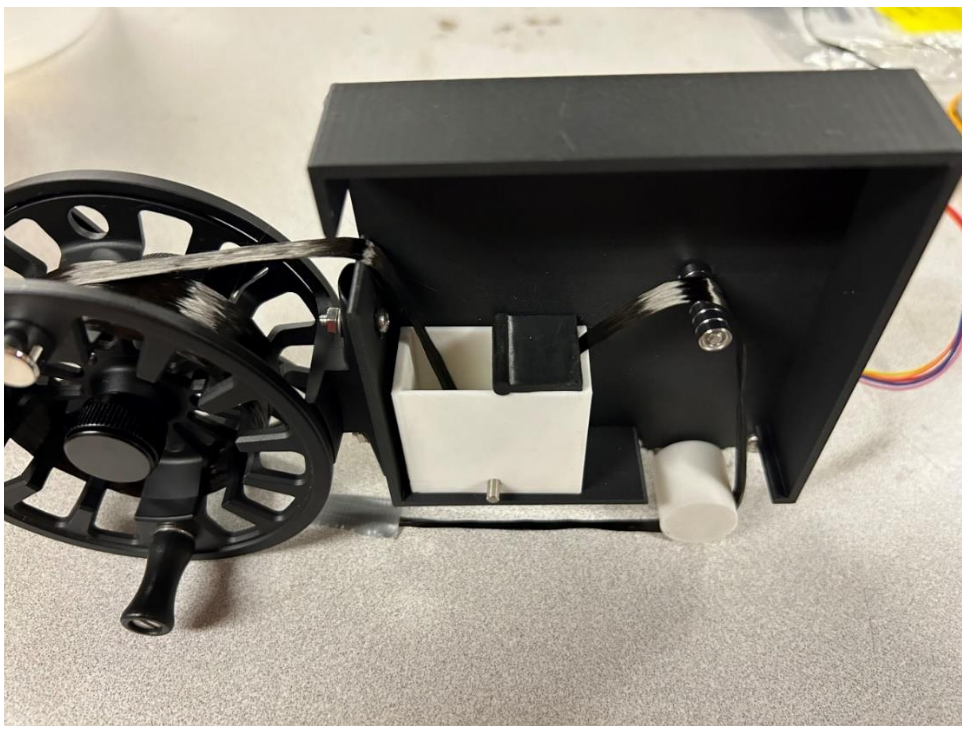


Figure 14: Prototype printer head setup to make the first printed composites.

The first printed composites turned out much better than the benchmark composites. It is important to note that the benchmark composites and the printed composites were only 1 layer of carbon fiber tow. The most notable improvement with the printed composites was consistency. The printer head's ability to produce consistent products is its first major success. The first printed composites manufactured were not perfect. The first strip that was laid down has some awol fibers that can be visualized in Figure 15. The second strip that was laid down is more uniform throughout the composite. The second strip was cut into 2 sections for comparison.

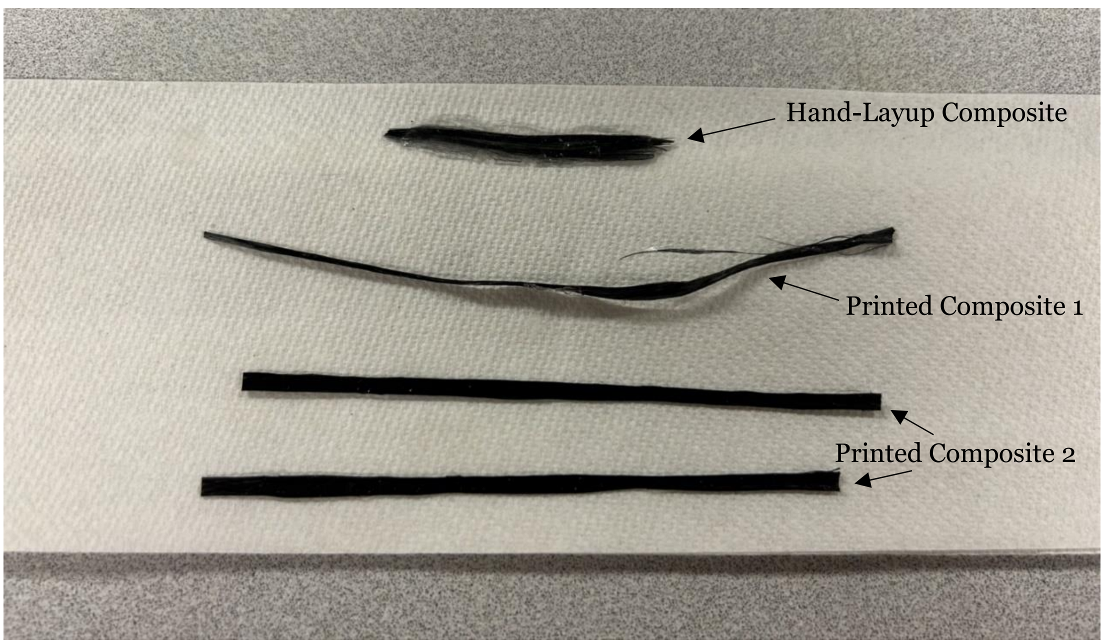


Figure 15: First printed carbon fiber composites compared to a section of the hand-layup composite.

The biggest observation of the printed composites and the hand-layup composite is the amount of epoxy. When applying epoxy via syringe, it is easy to apply too much causing jagged edges and inconsistencies throughout the sample once cured. Seeing the comparison between the samples, it is easy to see that the quality of the composite increased by using the printer head to make the sample. During printing, UV LEDs were held forward and aft of the roller to ensure the curing process would begin while printing. This would sometimes cause the epoxy to cure the fiber to the roller, so this was considered for future composite manufacturing. In addition, there is a major problem that arises with carbon fiber and UV light.

2.4 A Change in Printing Fiber

Carbon fiber is a commonly used material in composites and additive manufacturing. The only problem with using carbon fiber for this application is that UV light cannot penetrate through carbon fiber. Thus, UV cure epoxy will not cure on the bottom of the fiber or between layers of fibers because the UV waves cannot reach those areas. This is why UV LEDs were held forward and aft of the roller, as previously mentioned. So, a change in fiber is necessary. From this point, fiberglass plain weave tape is used to manufacture composites.

Chapter 3: Final Prototype Design and Composite Printing

3.1 Final Prototype Design

The final iteration of the printer head is similar to the last design in section 2.1. The only difference is that an UV LED light strip is placed underneath the printer shell. This light strip has its own power source, so it can be turned off and on using a switch. This way, the motor and the UV lights can operate independently. This addition to the printer can be seen in the image below.

Figure 16: Underside of the printer head showing the UV light strip.

3.2 Procedure for Composite Manufacturing

It is particularly important that users have the proper personal protective equipment (PPE). Because this printer head uses fiber and epoxy, gloves are to be worn while setting up, operating, and cleaning up the printer head. Because of the UV light, it is important that UV protective glasses are worn while the UV lights are turned on.

Once PPE is secured and worn properly, the fiber used for the printed composites can be wound around the reel. To wind the fiber, take the end of the fiber and wrap it around the reel once or twice making sure the end of the fiber is tucked under the overlapping layers. Once the fiber is taut and will not unravel if the reel is held and the fiber is pulled, the reel can be wound until the desired amount of fiber is reached. Put tape on fiber where it will be cut. This makes sure the fibers will not unweave once cut. Using fabric scissors or a roller blade, cut the fabric. Because the reel is a fishing reel, it features a drag knob. Turing the knob to the right will increase the amount of drag or resistance and turning the knob to the left will decrease the drag. It is recommended that the drag is at a minimal level for printing.

The next step to manufacturing a printed composite is to ensure the printing surface is clear of debris and clean. Isopropyl alcohol can be used to clean the surface as well as the release film. Release film is taped to the surface to ensure the epoxy does not adhere to the printing surface. It is important to note that the release film should cover a large enough surface so that the printed composite samples can comfortably fit during the printing process.

Once the release film is in place, the fiber can be run through the epoxy reservoir and between the squeegee and upper edge of the reservoir. Pull about half an inch of fiber out of the reservoir and then add 5 to 10 mL of UV cure epoxy to the reservoir. The epoxy used is ANYCUBIC High Clear Resin. A graduated syringe is useful to measure and transfer the epoxy to the reservoir. Note that a larger syringe nozzle will be needed because of the epoxy's viscosity.

When the epoxy is added, as seen in Figure 17, the fiber can be pulled over the pin and through the rest of the printer head so that the surface roller will be on top of the fiber. The fiber must be taped down to the surface, and the printing can begin. Pushing the button will turn the motor on and the UV lights are turned on when the switch is flipped. The printer should be held allowing the roller to press the wetted fiber into the surface, as seen in Figure 18. Do not inhibit the reel's ability to rotate.

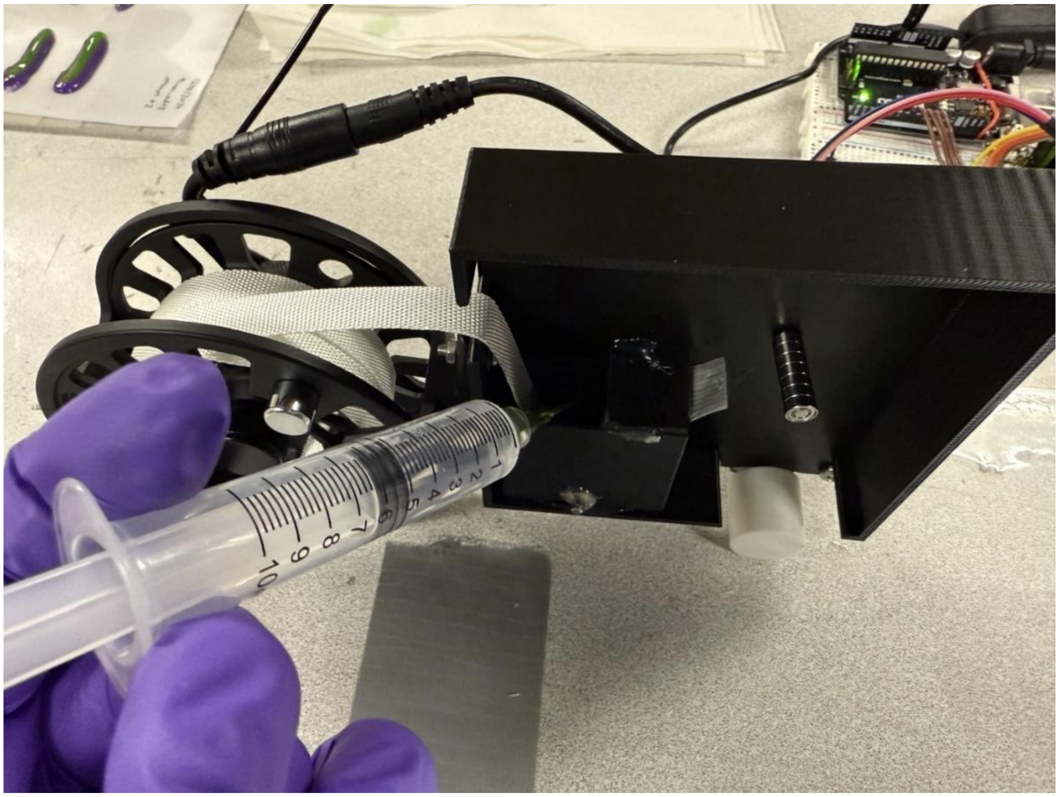


Figure 17: Adding epoxy into the reservoir with a syringe.

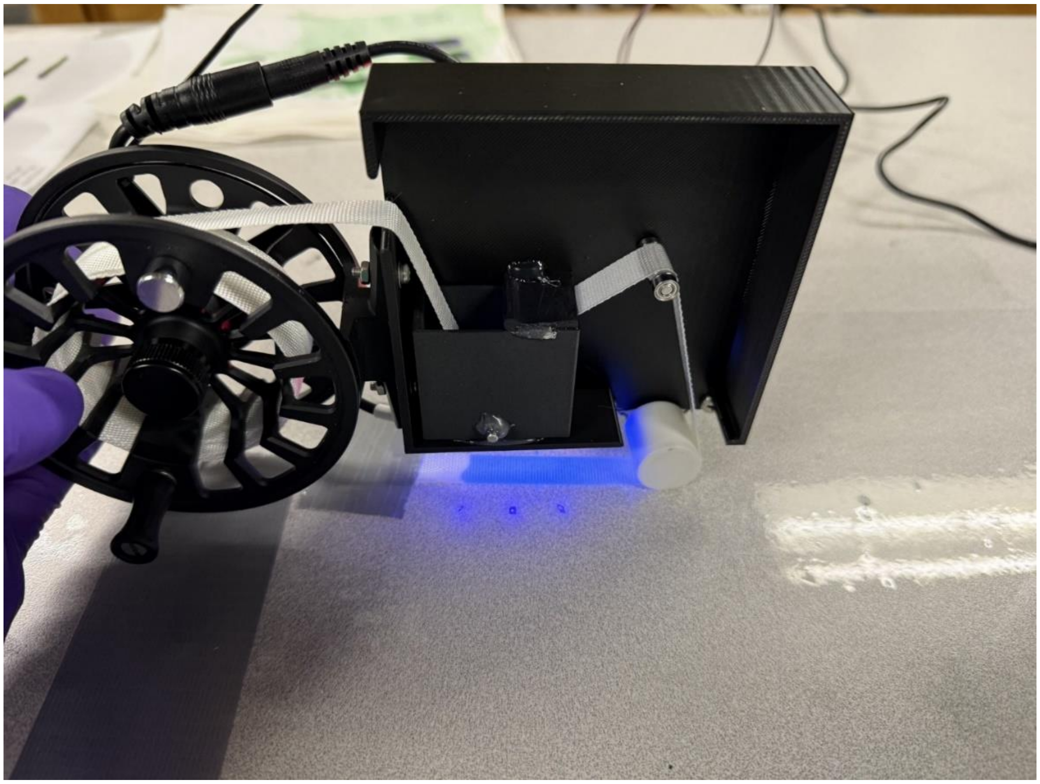


Figure 18: The manufacturing process of printing fiberglass samples.

3.3 Fiberglass Composite Samples

The process detailed in Section 3.2 outlines the preparation of the printer and printing surface for manufacturing printed composite samples. The fiberglass composites manufactured consist of three layers. Similar to the carbon fiber composite samples, a hand-layup fiberglass composite sample was manufactured for comparison with the printed fiberglass composite samples. The hand-layup composite and the first two printed composite samples were produced using the same release film. However, due to pooling issues with the epoxy, a change was made to a different release film. Sample 3 was manufactured on a green-tinted release film, as shown in Figure 19 and Figure 20, in an effort to reduce pooling.

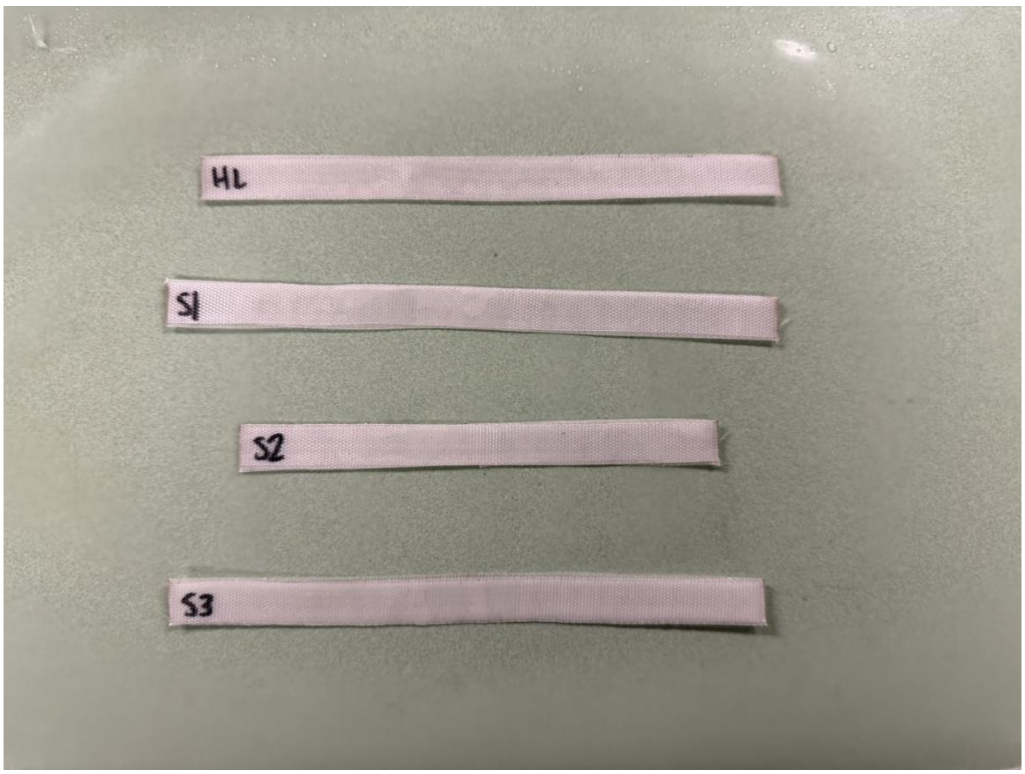


Figure 19: Top view of four fiberglass composite samples with IDs: HL - Hand-Layup composite sample, S1 -Composite Sample 1, S2 – Composite Sample 2, S3 – Composite Sample 3.

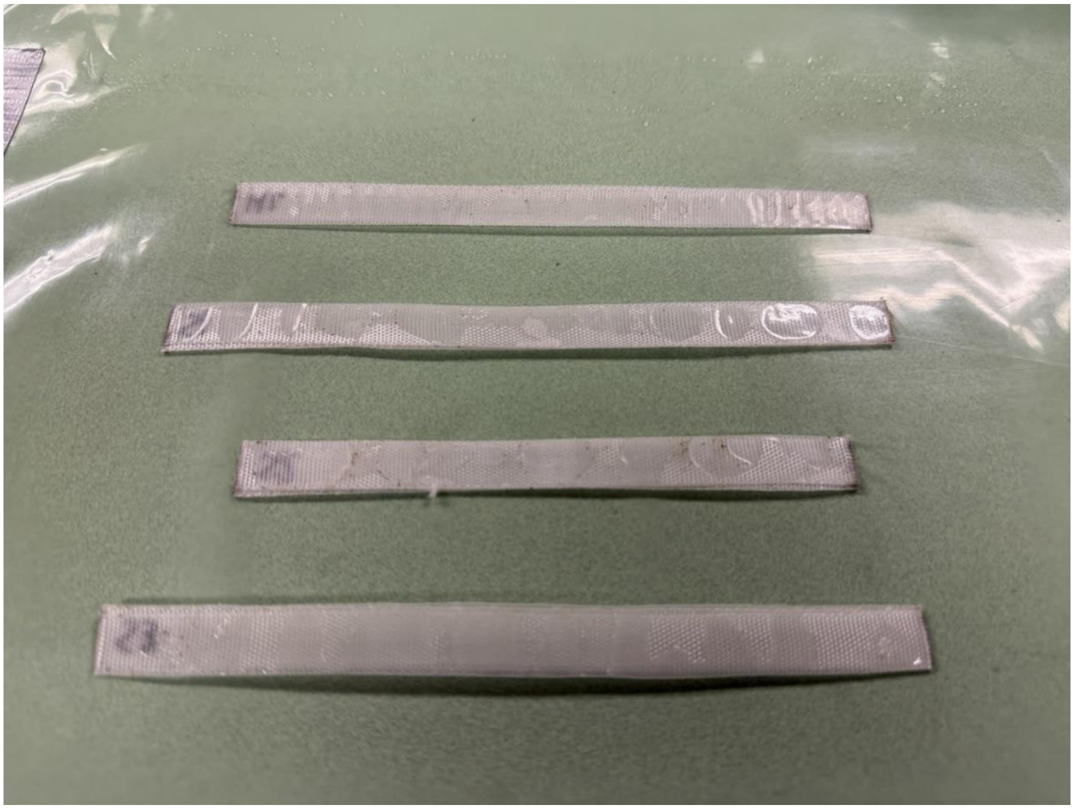


Figure 20: Back of the fiberglass composite samples to show pooling of epoxy. They are in the same order from top to bottom as Figure 19.

Chapter 4: Characterization of 3D Printed Continuous Fiber Composites

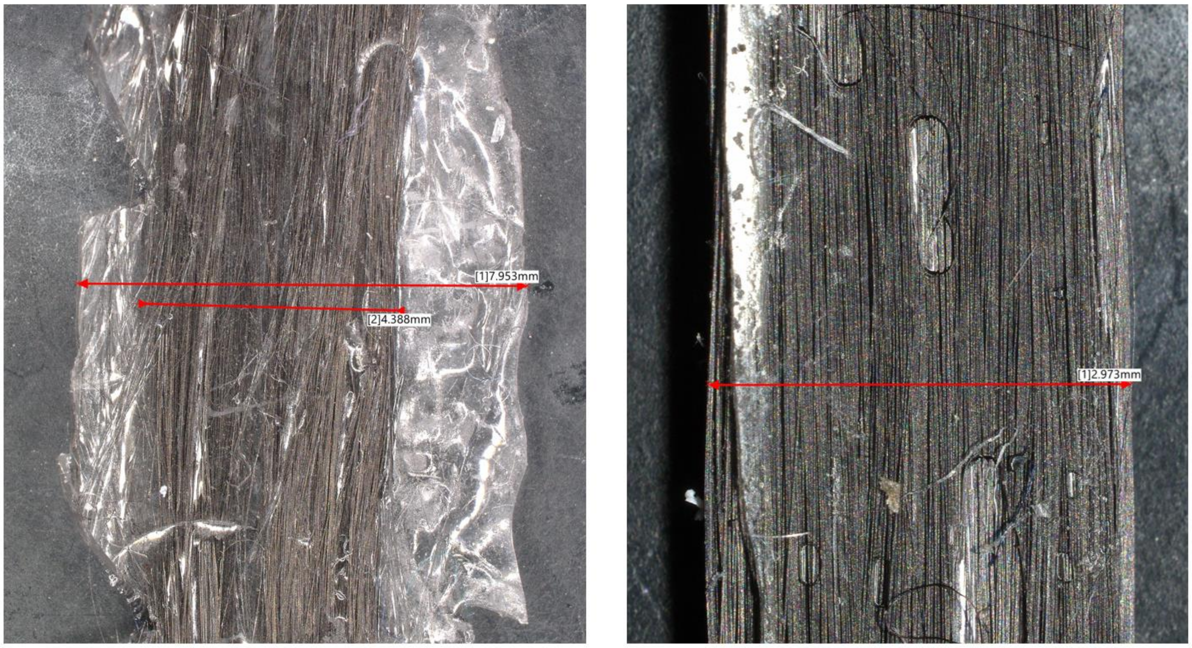
4.1 Visual Observations of Carbon Fiber Composites

Both the carbon fiber and the fiberglass composite samples are demonstrations of the functionality of the printer head. Composite quality drastically increased in both cases. It is easier to see in the carbon fiber composites, but overall, the printed composite samples seemed to be more uniform than the benchmark composite samples. The uniformity most likely occurred from the even coating of epoxy on the fiber that the printer head offers. This helps composites manufactured by the printer head to be more uniform throughout the whole composite. It also helps to avoid waste in materials. By scraping off excess epoxy from the fiber before it exits the reservoir, it can be reused in the reservoir and coat more fiber, thus reducing epoxy waste. Besides uniformity in epoxy coating, the fiber orientation also becomes more uniform. This is especially visible in the carbon fiber composite samples. Figure 15 can be referenced to see the difference in uniformity between the benchmark composite sample and the printed carbon fiber composite samples.

As mentioned in the paragraph above, there is a significant amount of epoxy visible on the hand-layup composite sample, whereas the printed composite samples do not have the same abundance of epoxy. Printed Composite Sample 1 has some awol fibers. This is because of the way the fiber was cut before being pulled through the printer. Once the fiber ran through the epoxy, it became much more uniform, as seen in printed sample 2 and the left end of sample 1.

4.2 Microscopic Observations of the Carbon Fiber Composites

A VHX 7000 digital microscope was used to take pictures and analyze the composite samples. The figure below offers 2 close-up pictures of the carbon fiber composite samples. The difference between the hand-layup composite and the printed composite is quite noticeable. The hand-layup composite is nearly 8 mm wide, while the printed composite is almost 3 mm wide. Just accounting for the fiber width, not including the excess epoxy, the width of the hand-layup composite is over 4mm wide. Given the comparison, the printed composite is much better quality and more uniform than the hand-layup composite. Note that the shape of composite sample 1 made microscopic images of the sample difficult, so there are no images of composite sample 1 under the microscope.



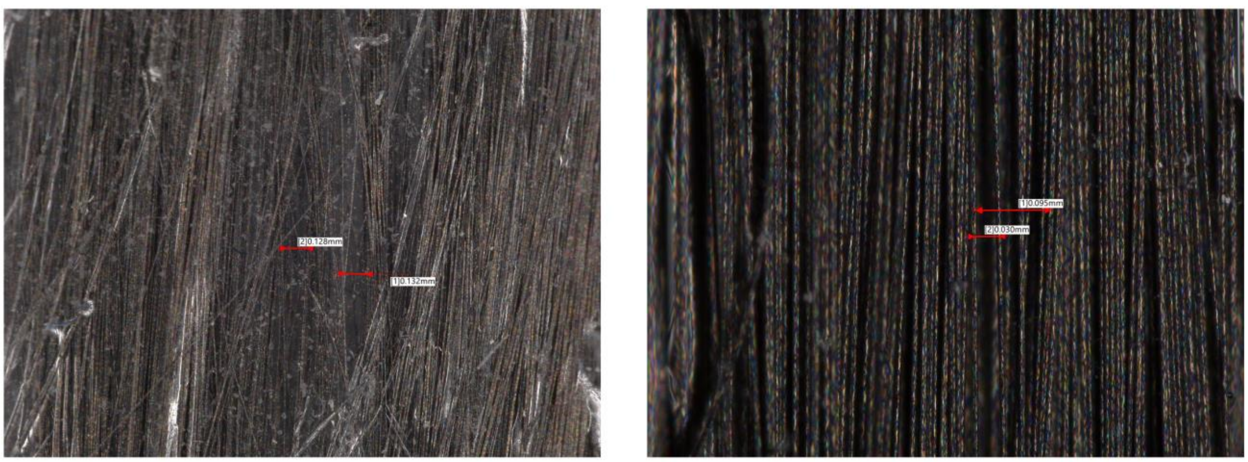
a) CF Hand-Layup Sample b) CF Sample 2

Figure 21: Microscopic images of the carbon fiber composite samples with width measurements.

Table 1: Width Measurements of the Carbon Fiber Composite Samples

Sample ID	**Width (mm)**
Hand-Layup Whole	7.953
Hand-Layup Fibers	4.388
2	2.973

The next set of images was recorded at a much higher magnification. This was done to get a better look at the voids within the sample. The hand-layup sample has voids about an eighth of a millimeter, whereas the printed composite has a void that is less than a tenth of a millimeter. Within that void, fiber strands are only a few hundredths of a millimeter apart. This aligns with the visual observations of the samples. On the microscopic level, the fibers are much more organized and closer together with the printed samples.



a) CF Hand-Layup Sample
b) CF Sample 2

Figure 22: Void measurements of the carbon fiber composite samples.

4.3 Visual Observations of the Fiberglass Composites

While there are clearer visual differences between the carbon fiber composites, the fiberglass composites look similar across all the sample types. This is because plain weave fiberglass is used to manufacture the composites instead of fiber tow. Plain weave fiberglass does not fray as much when cut, and it stays together much better when it runs through the printer head.

One characterization in all the fiberglass composites, though more noticeable in composite sample 3, is bowing. This is likely due to the epoxy curing. The heat caused by the chemical reaction of the curing epoxy may have caused the fibers to bow due to thermal expansion. Another characteristic of the composites is the layers are not all perfectly aligned. Each composite is made up of three layers. When the composites were manufactured, the next layer was not perfectly aligned with the previous. This is due to human error when manufacturing these samples. Another cause of this could be the uneven pressing down of the fiber by the roller, causing the fiber to shift on the roller during printing. These are just a few factors that may have caused the composite samples to be ununiform in some areas.

As mentioned in section 3.3, epoxy pooling on the bottom of composites was a problem. The hand-layup composite does not have as noticeable of uneven pooling as the printed composites, but rather a majority of the bottom of the composite is covered in excess epoxy. The printed composites, however, have pools of cured epoxy that stuck to the composite during the curing process. The uneven epoxy distribution on the bottom of the composites could have been a result of many things, such as printing pressure, release film bunching during curing due to differing thermal expansion coefficients between the release film and the fiberglass, and an uneven printing surface. A closer look of the fiberglass composite samples can offer a clearer look at these discrepancies across the different composite samples.

4.4 Microscopic Observations of the Fiberglass Composites

Just like the carbon fiber composites, pictures of the fiberglass composites were taken using a digital microscope and can be seen in the figure below. Seeing this up-close view of the fiberglass composites makes the offset layers even more noticeable. Composite samples 1 and 2 are the most inline, while the hand-layup composite sample and composite sample 3 have more offset between layers. The left side of the hand-layup composite has flared fibers that easily indicate the end of a layer. These fibers can be seen from all 3 layers, indicating all 3 layers are not perfectly aligned. The right side of composite sample 3 appears darker than the rest of the sample. The black background of the microscope through 1 layer of fiberglass is the cause of the darker color, again indicating all 3 layers are not perfectly aligned. While composite samples 1 and 2 are not perfectly aligned, they are a significant improvement from the hand-layup composite and composite 3. If composites are not perfectly aligned, then loads placed on the sample may not distribute evenly throughout the fibers, thus weakening the composite.

The flared fibers in the hand-layup composite are not as prevalent in the printed composites. This is an advantage for the printer head. The printer head was able to fully coat and press down the fibers creating a more uniform composite that does not have loose fibers. A more uniform composite leads to better load and stress distribution, which will in turn make the composite stronger.

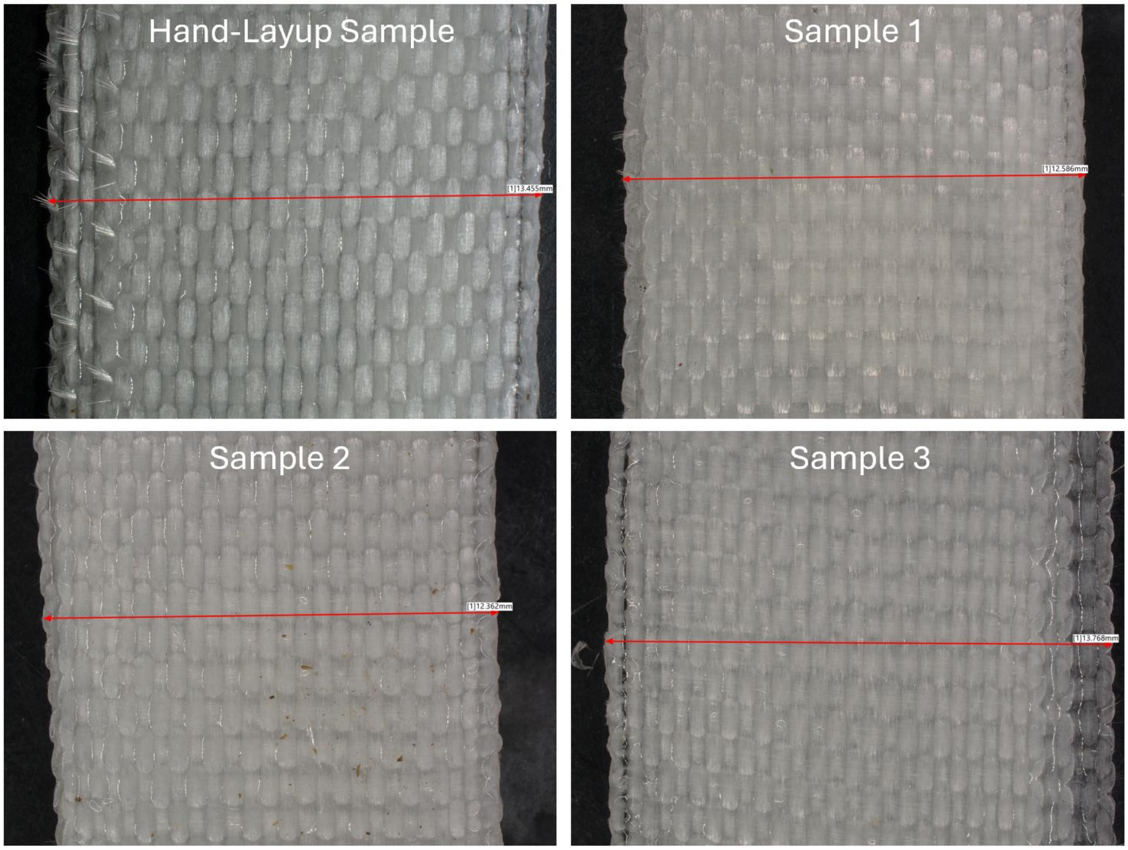


Figure 23: Microscopic images of fiberglass composite samples with width measurements in millimeters.

Table 2: Fiberglass Composite Sample Widths

Sample ID	Width (mm)
Hand-Layup	13.455
1	12.586
2	12.362
3	13.768

The above figure and table characterize the widths of each fiberglass composite sample as measured by the digital microscope software. The width of the fiberglass tape used is ½ an inch or about 12.7 mm. This means that the samples should be around this width. Composite samples 1 and 2 are very close to this width, being just a few hundredths of a millimeter from the raw fiber width. However, the epoxy could have bonded the gaps between the fibers making them smaller. The larger widths of the hand-layup composite and composite sample 3 are due to the layers not being aligned, as previously stated.

The last thing that was observed using the microscope was a quantitative observation of the epoxy pooling on the bottom of the composites. The excess epoxy is clearly visible in Figure 20, but the following figure offers a closer look at this epoxy.

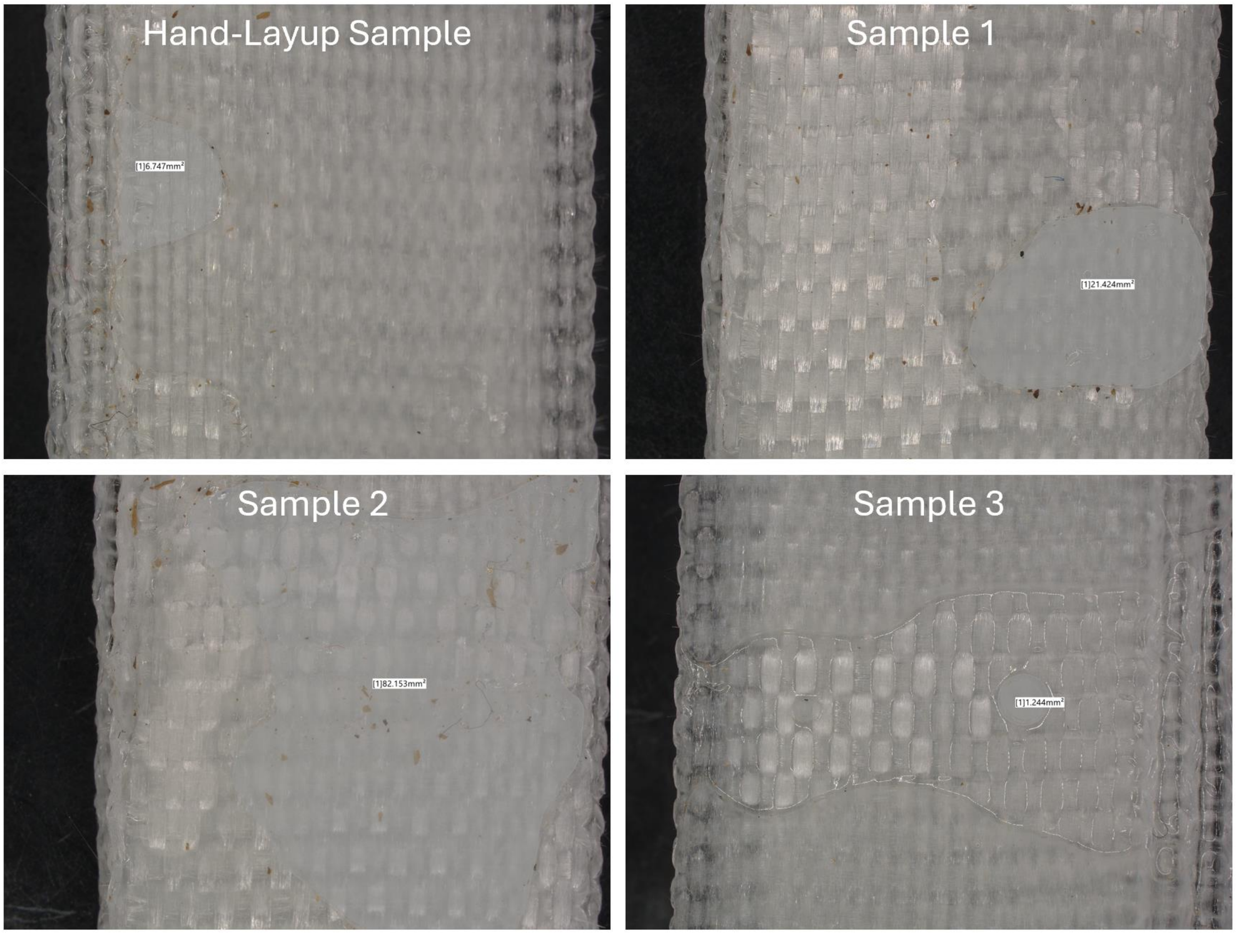


Figure 24: Bottom of fiberglass composites, showing excess epoxy pools.

While it is difficult to see, the shaded areas are areas of epoxy on composite samples 1, 2, and 3. The hand-layup composite measures the area where there is no excess epoxy because the rest of composite sample area contains excess. Only about 7 mm^2 of the hand-layup composite had the same texture as the top surface, indicating no excess epoxy. The printed composite samples have less epoxy than the benchmark composite. One reason this could have happened is the roller pressed down and rolled out the excess epoxy that was laid down. While each layer was being printed and laid down, the UV light source was on. This could have caused the epoxy to begin curing before any excess was rolled out. Another reason for the excess epoxy could be an uneven roller. Because the roller was 3D printed, mistakes in manufacturing could have made it not perfectly cylindrical, meaning there would be some deviation as it rotated. An adjustment to how the wetted fiber is compressed to the printing surface is a good direction for future research on this design.

Chapter 5: Conclusions and Future Work

5.1 Summary of Findings

The research that took place over the course of the last 2 years resulted in a prototype printer head capable of printing laminate composites using a single epoxy inline impregnation AM technique. Beginning from rough sketches and drawings to 3D models and renderings to a functioning prototype, this research came a long way, and a large body of knowledge obtained. Throughout this process, the engineering design process was utilized as ideas led to new and altered designs, and problems arose out of those designs that then led to redesigns, thus continuing the cycle. Ultimately, it led to a functioning printer head that can be improved in future research.

All in all, 5 composites, 2 carbon fiber and 3 fiberglass, were manufactured using the printer head designed in this research. Though only a single layer, the printed carbon fiber composites proved that the printer significantly increased the quality of composites from the hand-layup alternative. Visual observations and microscopic images proved that the printed carbon fiber composites are more uniform and orderly than the hand-layup composite. Because carbon fiber tow was used for these, individual fibers could easily be crossed over or tangled with other fibers, thus weakening the overall strength of the composite. Therefore, individual fiber uniformity is important. The widths of the composites are drastically different. The carbon fiber hand-layup composite is nearly 2 times the width of the printed composite, which is a significant difference.

The fiberglass composites were much closer in widths. This is partly because plain weave tape was used as opposed to fiber tow. The plain weave tape absorbs much more epoxy than the tow, and since it was weaved, kept its shape regardless of whether it was wet or not. This made it harder to distinguish quality between the hand-layup composite and the printed composite samples. Where the printed composites excelled over the hand-layup composite was in the consistency between each printed composite. Composite samples 1, 2, and 3 were all very similar with slight differences due to possible errors and printing conditions as discussed in section 3.3. The epoxy coverage was more consistent throughout these composites than the hand-layup composite, which contributed to the similarity between the printed composites.

All in all, the composites manufactured by the printer head were a better product than manufacturing the same sized composite using a hand-layup method. Because of the consistency between printed composites and their improvement from the hand-layup technique, the continuous fiber 3D printer head that utilizes UV cure epoxy is an appropriate means of manufacturing laminate composites.

5.2 Problems and Considerations

Throughout the course of this research, detours around roadblocks were necessary. The major problems run into were the carbon fiber and UV light issue, consistent printing pressure and printing alignment, and epoxy leaking. The carbon fiber and UV light issue was solved by switching to fiberglass. However, this was not the original intention of the research. It was supposed to utilize carbon fiber, but the issue caused a slight deviation to a different material. While similar, they are used for different applications. If carbon fiber is the desired material, then UV lights can be placed fore and aft of the roller as well as placing the composite in a curing oven after it is finished printing. It is important to ensure the epoxy between layers gets fully cured to prevent delamination.

The printing pressure and alignment consistency are a result of human inconsistency and error. The end goal of this research would be to attach this printer to a robotic arm or a standard 3D printer. This would allow for the roller to press the fiber down at a constant pressure as well as perfectly align each layer ensuring there is no overhang. Another issue that can be addressed regarding printing pressure is the roller itself. It is only attached to the stepper motor on one side, meaning that when the connection wears down, the roller can get a little loose and not be perfectly straight. Another motor may offer a longer rotating shaft that may offer a better way to attach the roller for consistency.

The final main issue was the epoxy leakage through the reservoir. This problem was initially masked with hot glue, but it seeped through over time. One solution would be to over drill the hole size for the pin in the reservoir. Then a gasket or O-ring could be used to fit in the hole that the pin would slide through. This could create a better seal between the pin and the reservoir wall and help account for any discrepancies when the hole was drilled.

5.3 Future Work

Taking the prototype and information gained from this research, there are several directions to go in the future. The biggest next step would be automatic integration onto a robotic arm. As previously stated, this was the original intent with this research, but due to time constraints, it was not achieved. One of the issues with putting it on a robotic arm is weight. The current design is around 5 pounds, which is under most robotic arm weight capacities. Any change in designs must be cautious of the weight limitations of robotic arms.

If automation is desired with this concept, a way to cut the fiber mid print is needed and a way to ensure fiber can be laid down again on top of the first layer. Scissors and a fabric rotary cutter were used to cut the fabric between layers while printing. This works, but only if small sized composites are manufactured. If a larger composite was manufactured or a more complex shape that took hours to complete, an automatic cutting device would allow the user to not have to focus on cutting the fiber, but rather ensure the whole process is running smoothly. An automatic cutting device would also allow for greater accuracy with the length of pieces. Composites with a specific length could be cut and manufactured within a few hundredths or thousandths of units of the desired length.

Another suggestion for future research and exploration for this concept is to make it bigger. The current design is intended to print ½-inch wide fiber samples. This is a very niche width for plain weave fiber tape. A more common fiber tape width is 1-inch. Increasing the printer size so that it can print fabric 1-inch wide opens the door for opportunity. Being a more standard size, 1-inch Kevlar and carbon fiber composites could be made and tested to be used for different applications. These applications could extend into the aerospace and defense industries using this technology to manufacture aircraft or spacecraft components, as well as custom Kevlar body armor for soldiers and law enforcement.

The final suggestion for future research and characterization is to test the physical properties of the printed composites. Having the properties of the printed composites allows for a comparison between aerospace grade composites and the composites manufactured by the printer head. The fiber volume fraction can also be calculated for the printed composites. Additionally, a way to control the fiber volume fraction of a printed composite would allow for a wider range of applications for the printed composites.

In conclusion, the results of this research are promising and offer a foundation for future work. Many of the roadblocks and detours experienced in this research can help guide and mentor future researchers in their quest to enhance the prototype and expand its functionality.

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