In-Situ Layup of 3D Printed Continuous Composite Materials

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***Abstract*—This project presents an innovative methodology for integrating continuous carbon fiber tow into 3D printing through post-nozzle layup fused filament fabrication (FFF). By introducing an additional rotational axis around the hot end of a conventional 3D printer, continuous carbon fiber tow can be precisely laid up under molten thermoplastic as it is extruded. A MATLAB script is employed to augment the G-code generated by slicing software, incorporating commands for controlling the rotational axis of the carbon fiber tow. This methodology offers significant advantages over traditional co-extrusion techniques, as it enables uninterrupted movement of the print head and minimizes manufacturing time compared to dual-nozzle approaches.**

***Index Terms*—3D printing, continuous composites, additive manufacturing.**

I. Introduction

ADDITIVE manufacturing has long been used to create parts with geometries that are not possible with conventional manufacturing methods, while composite materials have allowed engineers to optimize material properties for their parts. The combination of these two technologies provides engineers with unlimited possibilities to manufacture the optimal design to meet their parts specifications.

The most common way to combine FFF and composite materials has been to mix chopped fibers or powders to the desired matrix material and extrude that into filament for a 3D printer. While this layup method conveniently makes most FFF printers capable of producing composite material parts, with added stress on the printer, it misses the strongest form of composites; continuous fiber composites.

A. Layup Methods

How the matrix material and fiber are combined contributes significantly to the final characteristics of the composite. The most accessible form of composites with 3D printers is when the filament includes ground or chopped fibers. Although parts made from discontinuous fibers will have a higher tensile strength, fibers wear components like extrusion gears and nozzles faster than their matrix-only counterparts [1]. Additionally, being able to control the direction of the fiber will significantly improve the design of a part where the direction of stress is known.

The majority of FFF 3D printers designed to print continuous composites use in-situ impregnation or towpreg extrusion [2]. Both methods require the fiber to go through the hot end nozzle while the matrix material is being extruded. The largest benefit of these methods is that the fibers are evenly distributed into the matrix material. The print head is restricted with these methods in that it must extrude while the print head is moving because of the continuous fiber going through the hot end. This significantly limits the geometries the printer can make to only non-branching, monolithic parts.

The printer described in this paper overcomes the limitations of in-situ impregnation or towpreg extrusion by applying the fibers after the matrix is extruded. This brings the advantage of being able to move the print head without extruding the matrix material, only leaving behind a strand of fiber that can be more easily removed in post-processing. A complication with this method is that the fiber is not evenly mixed with the matrix material.

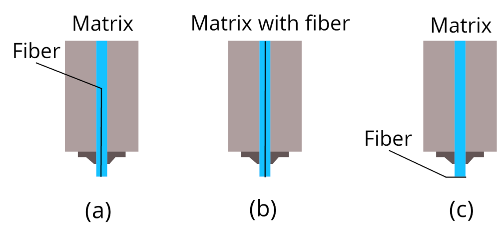

Fig. 1. Cross-section of common FFF continuous composite layup methods (a) in-situ, (b) towpreg, and (c) post nozzle layup.

B. Fibers

The most studied fibers in 3D printed composites are carbon, Kevlar, and glass fibers [3]. Among these, carbon fiber is most common for continuous composites because it is more available in tow form and has a higher Young's modulus than Kevlar and glass [4].

C. Matrix Materials

The matrix material forms the structure that holds the fibers in place and are typically either a thermoplastic or thermoset [5]. The thermoplastics used in FFF include PC, ABS, PLA, nylon, and PEEK, [5], [6] with the selection depending on desired properties of the final part and the capabilities of the printer.

II. Methods

The process for fiber and PLA layup starts with a solid model made in CAD software that is sliced in a 3D printing

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slicing software. G-code from an already sliced part is run through a series of MATLAB scripts to add additional extruder and U-axis commands. The main board controls the position of the U-axis with the same g-code file that is used to control the normal stepper motors, heaters, and other electronics for the printer. The U-axis directs fiber to the print head through a guide tube, which is then entrained for the rest of the print head's movement.

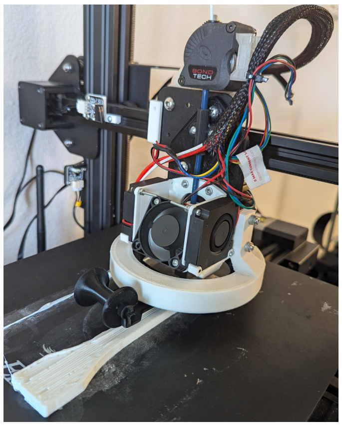

Fig. 2. Isometric view of the 3D printer while printing a sample with no carbon fiber.

A. Mechanical System

In order to realign fibers to be directed into the path of the print head, an additional axis of rotation was added. This new rotational axis was controlled by a 51mm NEMA 11 stepper motor with a spur gear that rotates a larger internal gear. This internal gear is concentric to the hot ends nozzle. Mounted on the internal gear was a spool holder and spool with the fiber material. A PTFE tube tangent to the spool guided the fiber to just under the nozzle. As the print head moved in the X and Y direction, the U-axis stepper motor moved the guide tube to be parallel and in front of the path of the print head. The fibers are pushed under the molten PLA, which quickly hardens, entraining the fiber into the part. Two part-cooling fans direct air to the nozzle to aid in cooling the PLA quickly.

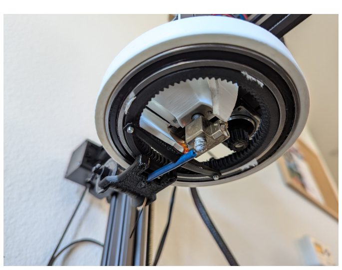

Fig. 3. Bottom-up view of the printer showing the rotational axis gearing, spool holder, and guide tube.

An 80mm inner diameter bearing is used to reduce the force required of the stepper motor to rotate the U-axis. The bearing is pressed into the stationary part of the U-axis, and the internal gear is then pressed onto the inside of the bearing. The internal and spur gear had a ratio of 1:5. Maintaining the outside diameter of the assembly was an important design concept because a larger diameter would reduce the available print head. The final usable print area was 118mm by 175mm.

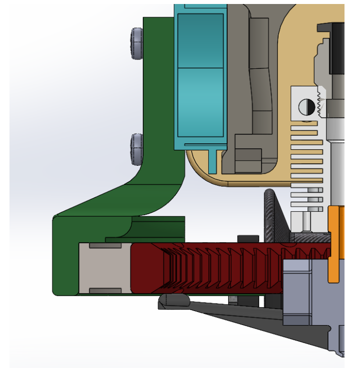

Fig. 4. Front facing section view of the CAD assembly showing the stationary part of the U-axis (green), the bearing (gray), and the internal ring (red).

An adhesive is applied to the build plate of the printer before printing to aid in the first layer staying in place. Fibers laid under the PLA left little surface area for the PLA to stick to the build plate. Additionally, the guide tube gently touches the build plate and can dislocate PLA with fiber when the U-axis has to move across the printed part. The PLA cools quickly enough that the guide tube coming in contact does not affect the shape of the PLA.

The standard 0.4mm and 0.6mm diameter nozzles did not provide enough clearance between the nozzle and the build plate for the fiber to go under the molten PLA, so a 1.4mm diameter nozzle was used. The larger nozzle provided ample clearance. The PTFE guide tube mounts were designed to come within 4mm of the nozzle and sharply curve the tube so that the fiber pointed down to the build plate.

B. Main board and Firmware

The stock main board for the Ender 3 V2 was only able to control five independent stepper motors and was replaced with a Duet 3 Mini 5+ that can control six independent stepper motors. Duet boards are highly customizable, and adding the new rotational axis mostly involved changing parameters specific to the stepper motor. Despite the MATLAB code limiting the rotation of the U-axis from 0° to 360°, the firmware placed effectively no limit on its rotation while testing the mechanical assembly.

TABLE I
U-AXIS FIRMWARE SETTINGS

Microstepping	16
Current limit	500ma
Steps per mm	444.44
Instantaneous speed changes	50mm/min
Max speed	2000mm/min
Max acceleration	400mm/s^2

C. 3D Slicer

The slicer used to convert the 3D model into g-code was Ultimaker Cura. The selection of slicing software was largely because the author is familiar with it and Cura has the few settings required for this layup method. The significant g-code changes happen in the MATLAB filter which will work with a g-code file from any slicing software. The most important setting that the slicer required was to be able to indicate the fiber orientation of each layer. The "Top/Bottom Line Directions" setting allowed for specifying alternating 0° and 90° fiber directions once all layers were defined as a bottom layer. A single outer wall was printed at the start of each layer to improve the dimensional accuracy of the part while minimizing the 0° oriented fibers in a 90° layer. To minimize the amount the print head would move without extruding, the inner PLA was extruded in a zigzag pattern.

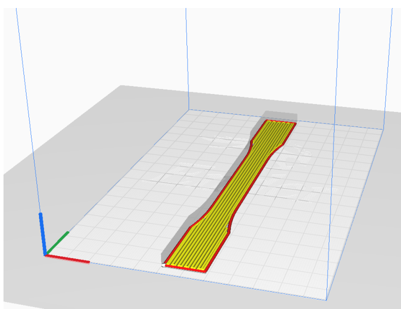

Fig. 5. Screenshot of Ultimaker Cura slicer showing first layer of sliced sample specimen.

The extrusion temperature was reduced to 190°C to prevent off gassing of the PTFE guide tube next to the nozzle. While the guide tube is never touching the nozzle, it is still in proximity and presented a potential hazard [7]. The 1.4mm nozzle extruded a cross-section 18.55 times larger than a standard 0.4mm nozzle, and so the print speed was reduced from 50mm/s to 9mm/s. The significantly lower speed had the added benefit of allowing the PLA to cool around the fiber, so the tension on the fiber distorted the part less.

Cylindrical shells were printed with the "spiralized outer contour" setting enabled. This allowed the shells to be printed in one continuous path instead of the print head stopping to move in the Z direction.

D. Matlab Filter

G-code from the slicer was run through four MATLAB scripts to prepare it for the printer. First, all comments were removed from the g-code so that commands added in later steps would be executed by the printer. At this step, a marker ";B" was added to lines that were movements and didn't include extrusion in them. Next, long print head movements were split into smaller, up to 5mm, movements. Since all new positions in a command line are completed at the time, a command to move in the X-direction 100mm and rotate the U-axis 90° will cause the U-axis to rotate slowly over the 100mm. Splitting that movement into twenty 5mm movements means that the U-axis rotates only for the first 5mm and reduces the distance the guide tube is misaligned.

The next two scripts added instructions for the U-axis and extruder. The script would use the previous coordinates and next coordinates to find the angle the print head was moving from the positive X-axis. The script would then append that angle to the line with a U in the format of "U0.0". The firmware was configured later to convert the 0-360° angle to movement of the U-axis. The last function added extruder commands to the new movements that were broken up in the second script. This script worked by finding how far the print head traveled and multiplying that distance by a mm/mm value found from the Cura slicer. Lines that contained the ";B" did not have extruder commands added to them, so no movement-only lines inadvertently gained extruder commands.

III. Material Choices

PLA was chosen as the matrix material because it is readily available for any hobbyist printer and is a material that many with FFF experience will be familiar with. Engineering thermoplastics like PEEK or even nylon would have provided a stronger matrix but require a 3D printer with capabilities too far beyond what is reasonable for an Ender 3 V2. PLA is able to withstand more strain than other easily printable materials [8] which is likely to allow the fiber to carry more of the stress before the matrix fails. This is important if the fibers are not being placed directly in the center of a part, like after a change in direction, so the fiber can become taught in the correct direction under load.

The primary fiber used for this project was unidirectional high-strength 1K carbon fiber tow. Carbon fiber is the leading fiber material for low-weight composite structures [2] for its high strength-to-weight ratio. Carbon fiber was also the only common fiber that was easily purchasable in 1K tow. The tow was untreated and was not spun in a fine strand in order to more easily spread under the extruded PLA.

TABLE II
Carbon Fiber Properties

Tensile Strength	4.19 GPa
Tensile Modulus	252.14 GPa
Elongation rate	1.66 %
Diameter	0.242mm

The layup method was also tested with copper wire. The copper wire was untreated bare wire with a thickness of 32GA (0.2mm). Copper wire was used to test the feasibility of 3D printed circuits with this layup method.

IV. Printed Samples

Quantitative results were obtained with samples printed per ASTM D638-14 following the under 7mm thickness type II for tension testing. With the printing parameters described above, this resulted in a part that would have six laminae, three of both 0° and 90°, starting with a 0° lamina. Samples were tested at a speed of 5mm/min.

Qualitative results were collected by printing an 80mm diameter cylindrical shell 10mm tall. This shape was chosen so that it would be visible where the layup method could or could not accurately place fibers.

V. Results

The layup method was able to produce parts that used carbon fiber as the fiber but were not effective with copper wire. The large volume that the fiber took up made calibrating how much to extrude very difficult. While control parts printed without any carbon fiber came out visibly under-extruded, with lines that were not touching, parts with carbon fiber were likely over-extruded.

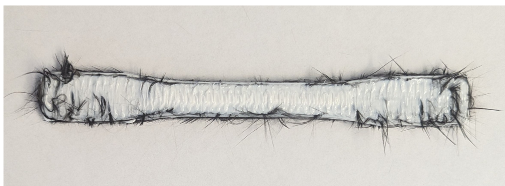

Fig. 6. Printed sample specimen with carbon fiber.

Long print durations with carbon fiber eventually led to knots forming around the spool. This is likely caused by the way that the fibers can be unevenly in tension as they are entrained in the part. If only a fraction of the fibers are being pulled into the guide tube, other fibers may start to collect before it or stay on the spool and further limit fiber leaving the spool. These knots could have also formed in the spooling process. The carbon fiber is packaged on a much larger spool than is practical to rotate with the printer, and it is respun onto a smaller spool. The tension from re-spooling the carbon fiber may have been the formation of these knots if some of the brittle fibers broke in the process. Additionally, the diameter of the spool could have simply been too small for the fiber to wrap around. Knots on the spool from fiber that never made it to the part also brings into question exactly how much of the fiber was actually going to the part.

Fig. 7. Halfway through printing a test specimen, a knot forms around the spool.

A. ASTM D638-14 Samples

None of the sample specimens, with or without carbon fiber, broke in the reduced section of the specimen. All samples broke at or just before the radius of the reduced section began. This is likely the product of multiple factors. Firstly, changes in the direction of the print head while extruding are where the lines in a single layer are most connected; refer to the zigzag design of Fig 5. As the printer makes the reduced section in the 90° lamina, much of the lamina is 11mm sections with a smaller zigzag connecting the individual lines. Secondly, after a change in print head direction, the carbon fiber is least aligned and becomes more aligned as a straight line is extruded. This means that the most aligned fibers are in the reduced section of the specimen. The larger amount of PLA and fibers in the principal direction results in the reduced section being stronger than the tabs to grip onto the sample.

The dimensional accuracy was affected by the use of the 1.4mm nozzle and the presence of the carbon fiber. The largest deviation was in the thickness of the carbon-filled specimens. The source of about 0.5mm of error on these parts was from peaks in the PLA from where the remelted PLA that was previously extruded and moved PLA further down the part. With the peaks removed, the error is much closer to the control prints, but certainly still more. Specimens were measured in three places along the reduced section and then averaged. Extrusion tuning and better dimensional accuracy would be possible with a smaller quantity of carbon fiber tow. Unfortunately, 1K tow is the smallest quantity available for carbon fiber, as with other potential fibers.

TABLE III
Deviation from nominal dimensions of printed specimens

Nominal dimension	Control	CF
13mm	13.32mm	14.03mm
6.36mm	6.42mm	7.28mm
Percent error	1.7%	11.2%

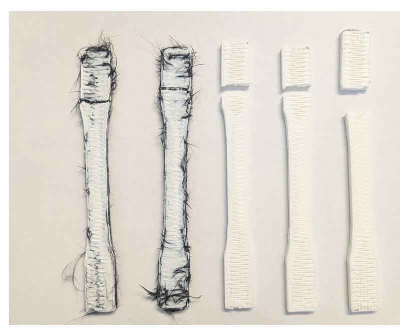

Fig. 8. Dog bone samples per ASTM D638-14 after failure from tension testing; two with carbon fiber and three without.

While the specimens did not break in the correct place, the force at which they broke was mostly consistent. The control samples broke at an average of 2,325.1N and the carbon fiber samples broke at an average of 3,649.8N. The lack of matrix in this section resulted in the two major pieces of the sample staying together with carbon fiber tow.

During the tension testing, both of the carbon fiber specimens had a saw-tooth-shaped strain/force graph prior to failure. This is potentially from strands of carbon fiber coming under tension and breaking at different times. The lack of matrix material to hold the fiber in place in the failure sections likely resulted in the fibers not being aligned in the principal direction until tension was applied. Void spaces also make up a sizable percentage of the final composite. The only compaction or impregnating of the carbon fiber and PLA was from the extruded PLA pushing the fiber onto the previous lamina. It is unlikely that this was sufficient compaction for these samples, significantly lowering the strength of the composite[9]. Slipping was not the cause of the saw-tooth behavior because the specimen grips showed only indentations from the knurling and no scratches from sliding.

Copper wire proved too difficult a material to print with this layup method. While carbon fiber tow would tend to spread out as it was bent, allowing some, then eventually all of it to be caught in the PLA, the wire would not behave like this. The wire had more of a tendency to bend upwards and not become entrained in the PLA to begin with. Under tension, the wire would frequently stay just above the nozzle opening, an issue that the carbon fiber had but was resolved with a larger nozzle. Once the wire went to the side of the nozzle, there was no way that it could become embedded in the PLA until there was another change in print head direction.

B. Cylindrical Shells

The cylindrical shells printed with carbon fiber and copper wire showed similar weaknesses of the layup method. The prints started from the top part of Fig. 9 and the print head moved counterclockwise for 10mm. Initially, the fibers do stay in the matrix but are separated after only approximately 60° of travel. At the bottom of the page, the U-axis must rotate from the 359° position all the way clockwise back to the 0° position. For the carbon fiber, this causes the fiber to loop around the nozzle and become realigned with the PLA for a large portion of the shell. The copper wire had more of a tendency to pull on the PLA and even start to cut it. This is because of the higher stiffness and density that the wire had over the tow.

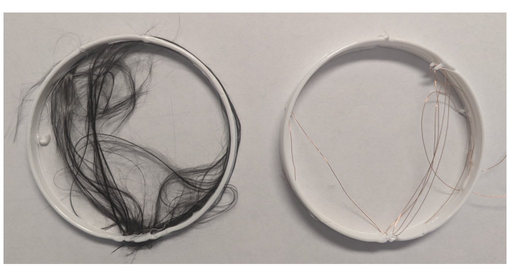

Fig. 9. Cylindrical shells' printed with carbon fiber (left), and copper wire (right).

VI. Conclusion

This layup method has shown to be a viable method of making a continuous fiber composite part. An additional axis that guides fiber tow into PLA sufficiently aligns the matrix and fiber over long parts. A passive feeding mechanism for the fiber into the matrix was also shown to work.

Many improvements would significantly improve the quality of a printed part with this layup method. A smaller nozzle with lower tow count carbon fiber would improve the dimensional accuracy of the parts while minimizing void spaces. Twisting the fiber to a smaller diameter may also improve dimensional accuracy. Better re-spooling techniques on a smoother spool may reduce the number of knots that form.

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