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3D Printing of Continuous Carbon Fiber-Reinforced Polymer Tee Pipe: Strategy Development and Demonstrator Fabrication

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Abstract. Conventional manufacturing techniques for continuous carbon fiber-reinforced polymers (CFRP) rely on costly, geometry-specific molds, which substantially limit design flexibility. To overcome these constraints, this paper proposes a robot-based, multi-axis Fused Filament Fabrication (FFF) approach for the production of CFRP components of complex geometries. The setup enables advanced material placement so that support structures and internal cores can be avoided, thereby reducing process preparation effort, post-processing requirements, and overall manufacturing cost. As a case study, a tee pipe geometry is investigated. A dedicated slicing strategy is developed in which the main pipe and the branching section are fabricated sequentially. This approach requires precise cutting and controlled re-adhesion of the CFRP material, a critical capability for extending conventional neat-polymer FFF processes to the additive manufacturing of CFRP. Experimental validation demonstrated the feasibility of the process, highlighting the critical role of an innovative technique called nozzle ironing for surface preparation, as well as the challenges associated with fiber cutting mechanisms. While the final component achieved structural coherence, leakage testing revealed porosity at specific interface regions, suggesting directions for future hardware refinement and process optimization.

Introduction

Carbon fiber-reinforced polymers (CFRP) have become indispensable in modern engineering due to their exceptional properties, specifically their high strength-to-weight ratio. These materials play a decisive role in sectors such as aerospace, where mass reduction directly correlates with increased efficiency and reduced fuel consumption [1]. However, a major disadvantage is the reliance on costly, restrictive molds that make automation of complex geometries highly demanding. In addition, conventional processes still used for complex-shaped parts, such as autoclave molding or hand lay-up, produce material waste, often require additional finishing to achieve high quality, and are generally not economically viable for small-series production [2].

To address these limitations, research has increasingly focused on Additive Manufacturing (AM), specifically Fused Filament Fabrication (FFF), also known as Fused Deposition Modeling (FDM), adapted to print with continuous CFRP filament [3]. While commercial 3-axis systems exist, they are often limited by planar layer deposition. Multi-axis systems, like robotic platforms, allow the print head and/or build platform to move, rotate and reorient with additional degrees of freedom, potentially eliminating support structures and allowing for load-path optimized fiber placement [4].

This paper addresses an alternative approach to manufacturing a tee pipe, such as those used in aircraft Environmental Control System (ECS) ducting, where components must be extremely lightweight and are produced in low quantities. Currently, these parts are primarily manufactured using bladder molding or bonded joint assembly, both of which are mold-dependent, limit design variability, require manual labor and are economically viable only at higher production volumes.

This paper focuses on the manufacturing of a tee pipe using continuous CFRP filament on a multi-axis robotic FFF system. First, the hardware setup is introduced, followed by material, process and hardware constraints, which define design and strategy requirements. Then a suitable printing strategy is developed that aims for good geometric fidelity and structural integrity without the use of support structures or sacrificial cores. Finally, the practical validation of the process through the production of a physical prototype is presented. The part is evaluated through a leak test and dimensional accuracy measurements. In the "Conclusion and Outlook" chapter, process limitations are discussed and possible work is outlined to improve process robustness, part quality and the applicability of multi-axis CFRP 3D printing as an alternative manufacturing route for complex, low-volume composite components.

State of the Art

CFRP Manufacturing.

Carbon fiber-reinforced polymers are composite materials consisting of carbon fibers embedded in a polymer matrix, which together yield exceptional mechanical properties at low weight. This unique combination has driven extensive research into their applications across industries, such as aerospace and automotive [2, 5].

For tee pipes specifically, methods such as filament winding and bladder molding are dominant. Filament winding creates rotationally symmetric parts but requires complex kinematics and/or lost cores to produce tee pipes. Moreover, it requires complex trajectory planning and usually results in non-uniform wall thicknesses [6]. Bladder molding allows for complex hollow structures like whole bicycle frames, but requires expensive, geometry-specific metal molds and rubber bladders [7, 8]. Alternatively, complex geometries are often assembled by joining simpler sub-components using adhesives or a co-curing process, which introduces potential weak points at the bond lines [9]. When using a thermoplastic matrix, welding is also a feasible method to join CFRP parts without the need for additional materials [10].

Additive Manufacturing with Continuous Fibers.

FFF is the most widespread layer-by-layer extrusion process, typically using thermoplastics in the form of filament. Conventionally used for rapid prototyping, there is an increasing trend to manufacturing functional parts. To improve the mechanical performance of printed parts, fibers are incorporated into the polymer matrix, with continuous fibers offering substantially greater reinforcement than short fibers [11]. Commercial printers from manufacturers like Markforged and Anisoprint successfully print with continuous CFRP [12, 13]. However, they are generally restricted to three-axis Cartesian systems with planar layer deposition which often requires support structures for overhangs. This reduces layer compaction as the compaction force partially acts towards the generally sparse infill support material, which is removed after printing and leaves behind a rather rough surface. Furthermore, they are limited to partly adding carbon fibers into a print part, instead of fully printing with towpregs (pre-impregnated CFRP filament). All these technologies for continuous fiber extrusion require a cutting unit to cut the fiber when needed to separate the deposited layer from the remaining fiber on the spool [14].

Robotic FFF and Slicing.

Standard 3-axis slicing generates planar layers, resulting in the staircase effect on curved upper surfaces and weak interlayer bonding always in the z-direction. Multi-axis robotic systems open the possibility for printing non-planar sliced layers, where layer orientation can change dynamically or follow the curvature of the part (tangential printing), thereby aligning fibers with load paths and reducing support requirements [4, 15]. This in contrast often requires complex and demanding programming, because conventional slicing software is mostly limited to 3-axis Cartesian systems.

Most publications focus on material properties, print parameter characterization and printing hollow pipes. However, there is a scarcity of literature describing the printing of technical, hollow components with additional geometries like branches, such as tee pipes, using continuous fibers on multi-axis systems. Particularly regarding the complex process of cutting and re-starting print paths with fiber-reinforced filament, which is crucial for the transition from neat polymer to continuous fiber printing of equivalent geometries and similar slicing effort when using towpregs.

Methodology

The Robot-Based Experimental Setup.

The experiments were conducted on a dual-robot setup. This system consists of two opposing 6-axis industrial robots (ABB IRB 2600-20/1.65) mounted on a common platform (Fig. 1a). Robot 1 carries a dual print head, while robot 2 manipulates the heated build platform (Ø400mm) and is hanging upside down on a cantilever beam. This robotic configuration enables greater flexibility in orienting the part, such as aligning the print direction with the gravity vector, achieved through motion of either the print head or the platform. Further info about the setup can be found in [16].

The printing system features two print heads mounted next to each other. The print head for printing conventional filament extrudes neat thermoplastics, while the other is equipped with a commercial Markforged fiber nozzle. This nozzle has an inner diameter of 1.3mm, characterized by a relatively rounded inner edge at the nozzle exit and extrudes a continuous carbon fiber towpreg [17]. The extruder used to extrude the towpreg is a Bondtech BMG extruder, modified such that it enables selective activation or deactivation of active filament feeding through a mechanical clutch mechanism. If active, this clutch mechanism engages gears, which then grab the filament to feed it to the nozzle. Another crucial component is the integrated cutting mechanism, which uses a servo-driven rotating blade to cut the continuous fiber strand. This unit is located between the nozzle and the extruder.

Program development employs RobotStudio, an ABB-specific offline programming environment enabling virtual system simulation and program verification prior to execution on the physical system. Robot code is written in RAPID, the ABB proprietary programming language. Each robot receives independent code that synchronizes with the other through dedicated commands. The geometry is not sliced using commercial software adapted for multi-axis systems; rather, toolpaths are generated through direct RAPID code programming, as current commercial slicing software is not optimized for robotic systems with this configuration. This approach provides geometric control but requires substantially greater programming effort compared to conventional 3D printer workflows.

Requirements and Constraints.

The robotic setup and the material properties of the carbon fiber filament impose strict constraints that need to be considered:

Material.

The towpreg with a nominal diameter of 0.375mm is also from Markforged. It has a Polyamide-based matrix and roughly 34.5% fiber content [18]. The filament is brittle and it is prone to breakage at room temperature. For initial test prints, a Polylactide (PLA) filament from BASF Ultrafuse with a nominal diameter of 1.75mm is applied.

Process.

The towpreg is mostly not actively extruded, as this could break the fibers because it is challenging to synchronize material placement with the nozzle-speed of the robot. Instead, passive extrusion is used, where the filament is pulled from the spool through the extruder and out the nozzle just by the movement of the print head. Active extrusion in contrast is when the mechanical clutch mechanism is engaged, and the gears grab the filament and feed it from the spool to the nozzle. The passive extrusion relies on the adhesion to the previous layer, for which the material needs to be firmly pressed onto it. Unlike neat polymers, the printing process cannot move the nozzle away from the print part by simply stopping the extrusion. The fiber must first be mechanically cut to prevent damage to the print part due to pulling on the fibers. After it is cut, the section between cutter and nozzle's orifice cannot be moved by the extruder, it needs to be removed by pulling it out. This requires a specific "run-out length” to be accounted for in the toolpath, which measures 44mm. From previous projects it is known that a layer thickness of 0.125mm must be kept to ensure sufficient bonding to the underlying layer.

Hardware.

The bulky print head and the large build platform create significant collision risks when printing complex geometries like the tee pipe. This requires collision detection prior to printing. Further constraints arise from axis range limitations and kinematic singularities encountered during build platform tilting, both of which are characteristic of robotic systems.

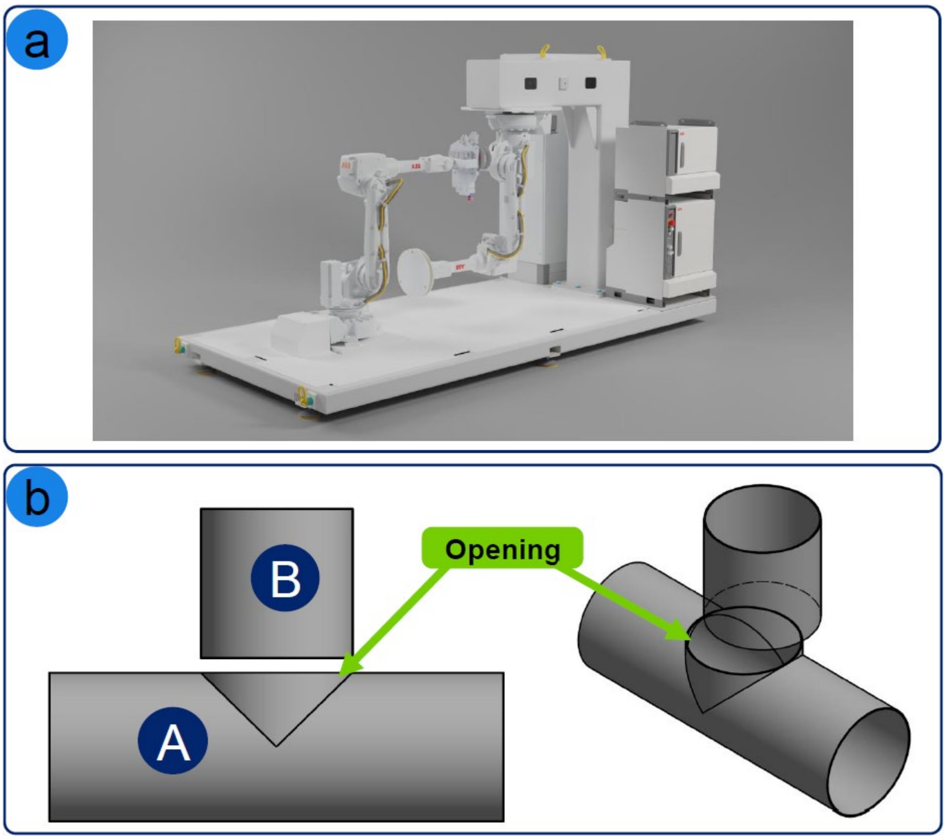

Fig. 1. a: Digital rendering of the robotic printing setup used. b: Tee pipe segmented into the main pipe A and the branch B, where the connecting surface is referred to as the opening.

Development of the Printing Strategy.

The selected component is a standard tee pipe with a perpendicular branch of the same diameter as the base pipe. The mean diameter is chosen to be 40mm. The tee pipe was segmented into two phases, as seen in Fig. 1b, to enable printing without the use of support structures. First, the main pipe with the opening was printed on a horizontally positioned heated build platform. Utilizing the multi-axis capability, the print bed with the finished main pipe was tilted by 90° to enable material deposition in the direction of the gravity vector to eliminate a potential negative influence on the fiber placement and to allow similar printing conditions as when printing the main pipe. The printing movement is done by the print head (robot 1). Following the hoop stress for internal pressure, circumferential placement of the fibers is chosen to meet the requirements for ECS ducting. The wall thickness is selected to be a single path width, to produce the lightest possible part.

Phase 1 (Main Pipe).

The main pipe is printed vertically on the build platform. A circular opening is left on the side wall to accommodate the branch. Above and below the opening there is a run-in and run-out zone which makes the opening rather elliptic, see Fig. 2c. Without this feature, material at the overhang (as seen in Fig. 2b) cannot be properly compacted, likely resulting in an unsuccessful print. This is due to insufficient layer overlapping because there is no support to take the re-adhering force for proper layer bonding. Before the opening starts, the main pipe needs to reach a height of 45mm to avoid collision when printing the branch pipe. The opening requires to cut the fiber and re-adhere it at every layer within the opening section. To do this successfully, filament is actively extruded until it sticks out the nozzle by approximately 2mm, which has been established through preliminary experimentation. Then the nozzle approaches the desired contact point of the next layer via a linear ramp movement and, upon reaching it, pinches the material between the nozzle and the previously printed layer. The ramp is parameterized with a start point that has a 5mm horizontal and 2mm vertical offset from the contact point. Pushing with the right force and extruding actively re-adheres the material after approximately 5mm of printing so the extruder can be switched to passive extrusion again. This is one of the two most crucial steps in manufacturing this tee pipe. The filament is cut by the run-out length before the end of the layer. At the cutting point, the print head stops its movement, closes the mechanical clutch mechanism of the extruder (active extrusion mode) to prevent the filament from slipping backward out of the extruder, and then resumes the movement to deposit the remaining material before the cut.

Phase 2 (Branch Pipe).

After Phase 1 is finished, the build platform is rotated by 90°. The branch pipe is then printed directly onto the elliptical side opening of the main pipe. As the cutting procedure separates the fibers, the fiber ends are not always even and their length can also vary depending on whether the re-adhesion took place slightly earlier or later than in the previous layer. To address this uneven surface created by cutting the fibers at the opening of the main pipe, a novel "nozzle ironing" strategy was developed. Before printing the branch, the hot nozzle slowly moves over the interface area without extruding material to smooth out irregularities and fuse loose fiber ends (Fig. 2a). This is done in several rounds, usually 3 to 4 rounds, depending on how uneven the surface is. Each time lowering the nozzle by roughly 0.1mm until an even surface line is created. After this is done, the branch pipe can be printed directly on that surface which is partly only as wide as a single path of the main pipe wall.

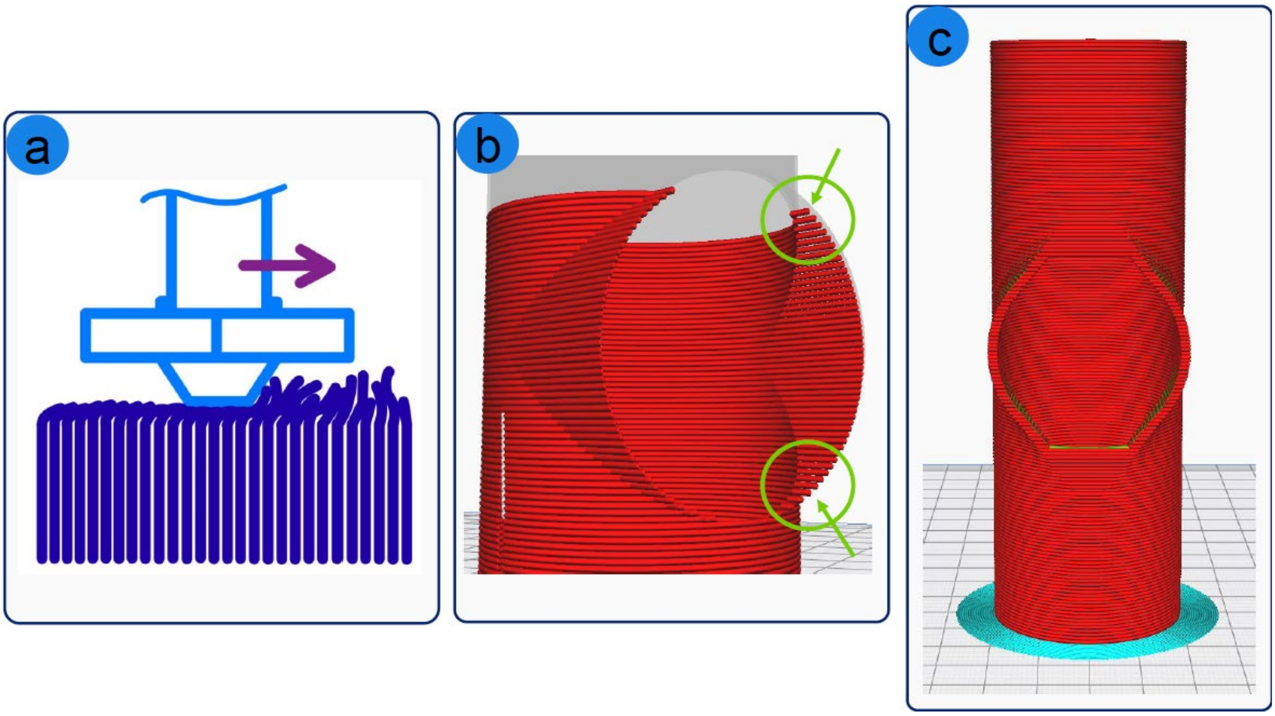

Fig. 2. a: Working principle of the nozzle ironing technique. b: Unrealizable overhang at main pipe without geometric compensation. c: Optimized main pipe with run-in and run-out zones and brim.

Manufacturing / Experiments.

The actual realization of the prototype was done in three steps: strategy tests with PLA, preliminary tests with CFRP filament and final printing of the tee pipe.

PLA Tests.

Initial tests were conducted using PLA, printed at 210°C, to verify robotic path planning and the absence of collisions and kinematic singularities during execution. No active part cooling is used throughout all prints. Print bed adhesion is known from previous projects to be best at 60°C bed temperature with a 5mm brim and a glue stick coating on the bed prior to the print start. By applying these parameters, print bed adhesion is ensured for all prints with both materials. During these PLA test prints, some minor issues in the robot code were corrected. Furthermore, these tests highlighted issues with absolute positioning accuracy when rotating the print bed after Phase 1, necessitating manual calibration of offsets. After the offset was compensated in the robot code, the experiment could be resumed and no further calibration was needed during the PLA tests.

Preliminary Tests with CFRP Filament.

Once the full tee pipe was printed with PLA, material-related parameters like layer height and nozzle temperature were adjusted to those of the CFRP filament. The nozzle temperature was set to 265°C for all CFRP prints. The tests with CFRP filament focused on the reliability of the cutting and re-adhering technique. Here, the specific ramping motion for pressing the severed fiber end onto the existing layer to ensure adhesion was tested repeatedly. For this purpose, only the opening section of the main pipe was printed, as it provided sufficient geometry for multiple iterations. This step was also used to further adjust parameters and proved that it is generally possible to successfully re-adhere the fibers automatically with minimal overhang. Fig. 3b shows a corresponding test print.

Printing the CFRP Tee Pipe.

The final step involved printing the full tee pipe with CFRP filament using the developed strategy. The printing speed was conservatively set to a maximum of 20mm/s and varied depending on the complexity of the print step. The most critical part, the re-adhering, was printed with only 2.5 to 5mm/s to permit adequate fiber cooling and substrate adhesion. The nozzle ironing was performed at a speed of approximately 1mm/s, while maintaining a printing temperature of 265°C, in order to promote effective heat transfer into the ironed material. This step is slow when relying solely on the nozzle's thermal energy.

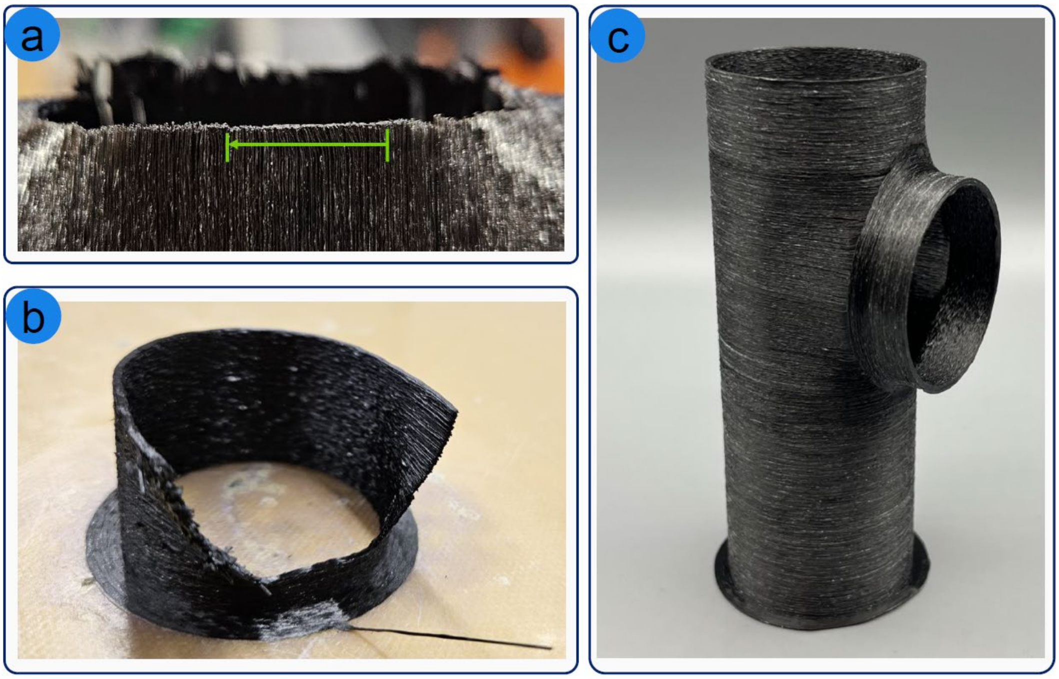

Fig. 3. a: Side view of the opening with nozzle ironing applied in the marked area and direction (showing an intermediate test part). b: Preliminary CFRP print to test the re-adhesion (left edge), featuring minimal overhang on the left edge and a uniform edge on the right, based on the cuts made in-process. c: Final result of the CFRP tee pipe printed with the described strategy.

Results

The tee pipe was successfully fabricated with CFRP without the use of support structures (Fig. 3c). The multi-axis strategy allowed for the reorientation of the part, ensuring that fibers were deposited as intended.

Main Pipe and Opening.

The main pipe was printed successfully. However, the filament feeding mechanism proved unreliable for the thin towpreg, requiring manual intervention to assist the feed after the cutting procedure. Filament was pushed out the nozzle and held with tweezers until the material bonded to the underlying layer. This resulted in long overhanging fiber material pieces at the re-adhering side of the opening. Holding the filament manually was also needed to avoid it sometimes slipping sideways rather than being pressed firmly against the already printed wall. The reason for this behavior is the large difference in diameter between the nozzle (1.3mm) and the filament (0.375mm), which allows for a relatively large movement of the filament within the nozzle. The resulting fiber ends protruding from the re-adhering points on the main pipe were manually trimmed using a fine saw to prevent high mechanical forces and to ensure a flush surface, even though preliminary CFRP filament tests demonstrated that this is ideally unnecessary.

Nozzle Ironing.

The nozzle ironing technique was then executed to smoothen the fitting surface, significantly improving the interface quality and ensuring successful branch attachment. An example with sideways bent layers can be seen in Fig. 3a. Moreover, it was found that fiber material ends as long as 1mm can be ironed down to achieve a good mating surface.

Branch Printing.

The branch was printed onto the ironed surface, starting with an elliptical shape defined by the main pipe opening and ending with the desired planar, circular shape. During the print of the first layer, it could be seen that it did not perfectly bond to some sections of the mating surface below, because of some slight deviations from the desired geometry.

Geometric Accuracy.

The mean diameter of the printed pipes was 39.5mm, deviating by 0.5mm from the nominal 40mm. This is likely due to calibration offsets of the robots, but it was not further investigated.

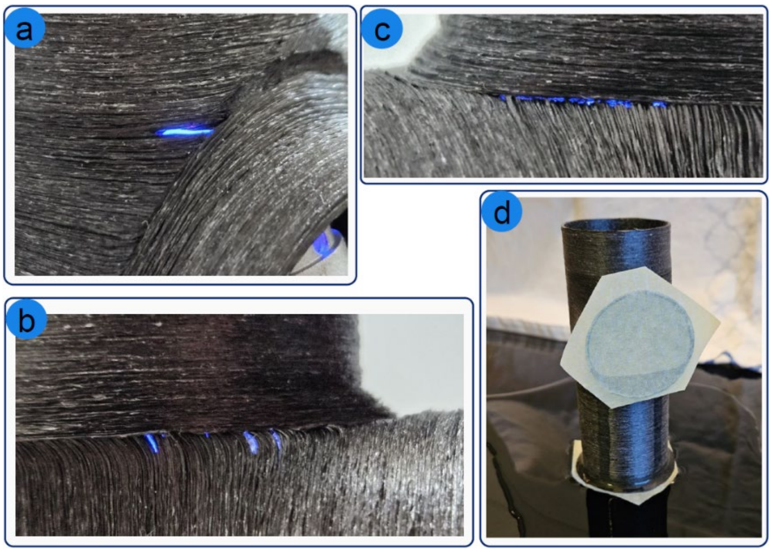

Fig. 4. a: Gap at bridging area, created by material that got pulled into the main pipe. b: Broken inter-layer connection due to manually cutting the fiber ends. c: Some during the process automatically cut fibers did not fully reach the nozzle ironing surface. d: Leakage test reveals some leaking areas, after filling the tee pipe with water (water level can be seen on the tape).

Defect Analysis.

Visual inspection by a backlight test to search for defects revealed three primary defect types. All defect types occur only at the joining area between the main pipe and the branch:

At the top of the branch connection, where bridging in the main pipe was necessary, the initial layers were slightly pulled to the center axis of the pipe. As a result, small gaps were created at the start and end area of the bridging, as can be seen in Fig. 4a.

On the side where the fibers were manually cut, small gaps remained (Fig. 4b). The cutting force led some inter-layer connections to break. Thus, this issue can be traced back to the unreliable feeding mechanism.

In some areas on the opposite side of the opening, the automatically cut fibers do not fully reach the surface of the nozzle ironing (Fig. 4c). This issue arises because the fibers are cut slightly too early. Adjusting the cutting locations in the robot code would resolve this issue.

Validation.

A leakage test was performed to assess the functional integrity of the printed part. The bottom and branch openings were sealed with adhesive tape, and the tee pipe was filled with water. It held the bulk of the water, demonstrating structural coherence. However, leaks were observed at the specific defect points identified above. Fig. 4d shows a stage of the leakage test where the water level had already dropped. With the exception of two narrow leakage traces extending downward on the left and right sides of the branch, the outer surface of the tee pipe remains dry, indicating the absence of additional leak paths.

Furthermore, a manual pulling test was performed at the branch to qualitatively test the bonding strength between the main pipe and the branch. It showed sufficient adhesion between the two subparts of the tee pipe.

Conclusion and Outlook

This paper presents a printing method for robotic printing of a continuous CFRP tee pipe. A slicing strategy involving part segmentation and build platform rotation was successfully implemented and executed. The main pipe was printed without issues and fiber cutting functioned as expected. The developed nozzle ironing technique was successfully utilized and proved to be valuable for creating a uniformly smooth surface to print the branch on. The branch pipe adhered to the base pipe and created a complete CFRP tee pipe. While the final part has slight deviations from the planned geometry, its fidelity remains acceptable. Functional validation revealed gaps at the cut and re-adhesion seams.

Multi-axis additive manufacturing has the potential to emerge as a viable alternative process for small-lot production and the fabrication of individualized components featuring complex CFRP geometries, such as the tee pipe considered in this study. The primary advantage demonstrated lies in the complete elimination of both support structures and dedicated molds, thereby enabling a high degree of geometric flexibility while significantly reducing lead time. However, the process stability is currently limited by hardware constraints. The reliability of the active feeding mechanism for the delicate fiber towpreg is the main bottleneck.

To establish multi-axis CFRP printing as a viable industrial alternative, not only these hardware challenges but also material development, particularly increasing the carbon fiber content, has to be addressed. Before its wide application, further optimization is needed; future work must therefore focus on:

- Improving the extruder grip on thin fibers to reliably extrude desired distances of filament and thereby eliminating manual intervention. An auxiliary heating system for nozzle ironing could be investigated to increase the speed at this process step. Addressing the deviation from the nominal size, a new nozzle for precise deposition shall be developed or path compensating strategies need to be applied. This can reduce geometric deviations and prevent the filament from slipping sideways at the re-adhering step. Developing automated path-planning software

that can handle various multi-axis systems and non-planar slicing natively to reduce the manual coding effort.
- Conduct further tests to quantify the strength and structural integrity of the printed tee pipe compared to traditional laminates. Destructive testing can address the strength of the connection between the main pipe and the branch, while structural integrity should especially be assessed at the fiber ends and the zones in which the nozzle ironing was performed.

By addressing these challenges, robotic CFRP printing has the potential to become a powerful tool for the flexible manufacturing of high-performance (non-critical), lightweight components.

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