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DESIGN AND IMPLEMENTATION OF A COAXIAL PHOTOPOLYMER COMPOSITE EXTRUSION TO ENHANCE TENSILE PROPERTIES OF 3D PRINTED PARTS

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ABSTRACT

The intersection of composite materials and additive manufacturing (AM) represents a promising area for advancements in the next era of manufacturing. In this paper, we describe the design and development of a novel coaxial photopolymer composite extruder, integrated into a robotic additive manufacturing system. This system is capable of manufacturing parts made from continuous fiber-reinforced polymer composites, significantly enhancing their mechanical properties. To demonstrate and compare the property enhancements achieved by this method, several sets of specimens were manufactured using three other AM techniques. The materials used for the specimens are thermoplastic or thermoset PLA and continuous Kevlar fiber bundles. The results of the tensile tests show a significant improvement in Young's modulus and ultimate tensile strength of the composite specimens, by factors of 6.5 and 8, respectively. These improvements enable the 3D printed parts to be used in structural applications.

1 INTRODUCTION

The integration of fiber-reinforcement into polymer materials through additive manufacturing presents an exciting avenue for enhancing tensile properties while having design flexibility and complexity [1]. By leveraging the precision and layer-by-layer construction capabilities of additive manufacturing, engineers can optimize the orientation and distribution of fibers within the composite, leading to improved mechanical performance [2]. Moreover, robotic additive manufacturing (RAM) has gained significant attention in recent years as a promising technique for fabricating complex structures with improved mechanical properties [3].

Fiber-reinforced composite materials play a crucial role in additive manufacturing processes. These materials are composed of a matrix, such as a polymer resin, reinforced with fibers, typically made from carbon, glass, or aramid. The incorporation of fibers into the matrix enhances the mechanical properties of the composite, making it an attractive choice for various applications. As studied by Zhuo et al. [4], epoxy resin utilized as a thermoset matrix material in continuous fiber 3D printing of composites aids in overcoming challenges associated with impregnating fibers with thermoplastic matrices and enhances consolidation of printed parts.

The combination of robotic technology with composite additive manufacturing allows for precise control and layer-by-layer deposition of materials, resulting in enhanced tensile properties. This paper aims to explore the use of robotic additive manufacturing for continuous fiber-reinforced UV-curable polymer composites to further improve tensile properties. Specifically, this research focuses on the use of UV-curable polymer as a matrix material for

continuous fiber-reinforced composites in robotic additive manufacturing. A robotic manipulator is of higher importance when dealing with continuous fiber reinforced composites as the orientation of fibers highly affects the mechanical properties of the final product. On the other hand, since this research is pursuing a system that can cure a UV-curable resin on-the-fly, the mechanism must be able to precisely keep pointing powerful UV rays to the extruded material. Therefore, a mechanism with higher degree of freedom can enable the system to successfully tailor mechanical properties of a part based on the orientation of fibers.
The rest of the paper is structured as follows. Section 2 introduces the materials and methods used in this research. Section 3 is dedicated to in-detail design and development process of composite extruder. Section 4 introduces four manufacturing methods used in the research to compare with each other. The results of the tensile tests are presented and discussed in Section 5. Finally, some concluding points are highlighted in Section 6.

2 MATERIALS AND METHODS

In this study, a state-of-the-art robotic additive manufacturing (RAM) framework [5] is utilized to fabricate continuous fiber-reinforced UV-curable polymer composites. The robotic system, programmed with specific parameters, was then employed to manufacture the composite. The manufacturing process involved a careful balance of speed, temperature, and pressure, with UV curing taking place concurrently. Several sets of tensile specimens are manufactured using the process, and their tensile properties were assessed through standard mechanical testing ASTM D3039—Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials [6].
In this research, a KUKA KR10 R1100-2 robotic manipulator is used. The robot is controlled by a KUKA KRC4 Compact controller provided with the robot. The developed composite extruder is attached at the end-effector of the robot via a manual tool changer (MC-16R; ATI Industrial Automation). The toolpaths for tensile specimens are developed by Python and converted to KUKA robot program using RoboDK software. The robot movements are carefully modified to achieve a continuous motion throughout the printing process to result in a uniform material extrusion. The synchronization between the extruder and the robot is done via a digital I/O connection. Specifically, an Arduino-based controller board (RAMBo V1.4) is connected to the KRC4 controller via a DC signal shifter to convert from 24 VDC (KRC4) to 5 VDC (Arduino). Therefore, KRC4 can control the extrusion of the extruder at each time instance.

3 COMPOSITE EXTRUDER DESIGN

The main innovation of the system would be an extruder able to co-extrude continuous fiber bundles and photopolymer liquid resin. Using liquid resin is a good way to create proper bond between fibers and resin inside the extruder [4]. The extruder should also be equipped with powerful enough UV lasers to cure the deposit in a fraction of a second. Therefore, the deposits are cured on-the-fly, creating proper fiber-matrix bond. In addition, since the deposited fiber-matrix is uncured just after the extrusion, there would be a proper intralayer and interlayer fusion.
The developed extruder must be maintenance-friendly. It is essential to engineer an extruder that can be assembled and disassembled relatively easily while using off the market parts. This entails meeting the demands of industrial-level manufacturing while maintaining precision and quality in fiber placement and resin distribution.

After several design iterations, a final design was developed and implemented using mostly off-the-shelf components. This design is illustrated in Figure 1 (a) and (b). According to this design, there are separate inlets for fiber and resin. The fiber is supplied by a spool provided on top of the fiber entrance. The resin is supplied to the extruder by a motorized syringe pump capable of supplying up to 100 mL of resin per run. The extruder, UV lasers, and fiber spool are attached to the end-effector of the robot using a custom-designed extruder mount (Figure 1 (c)). A gimbal mechanism is integrated into the design of the laser holders to easily adjust the direction of the UV lasers to achieve a satisfactory curing process. Figure 1 (d) shows the actual extruder, UV lasers, and fiber spool assembled on the robot via the extruder mount.

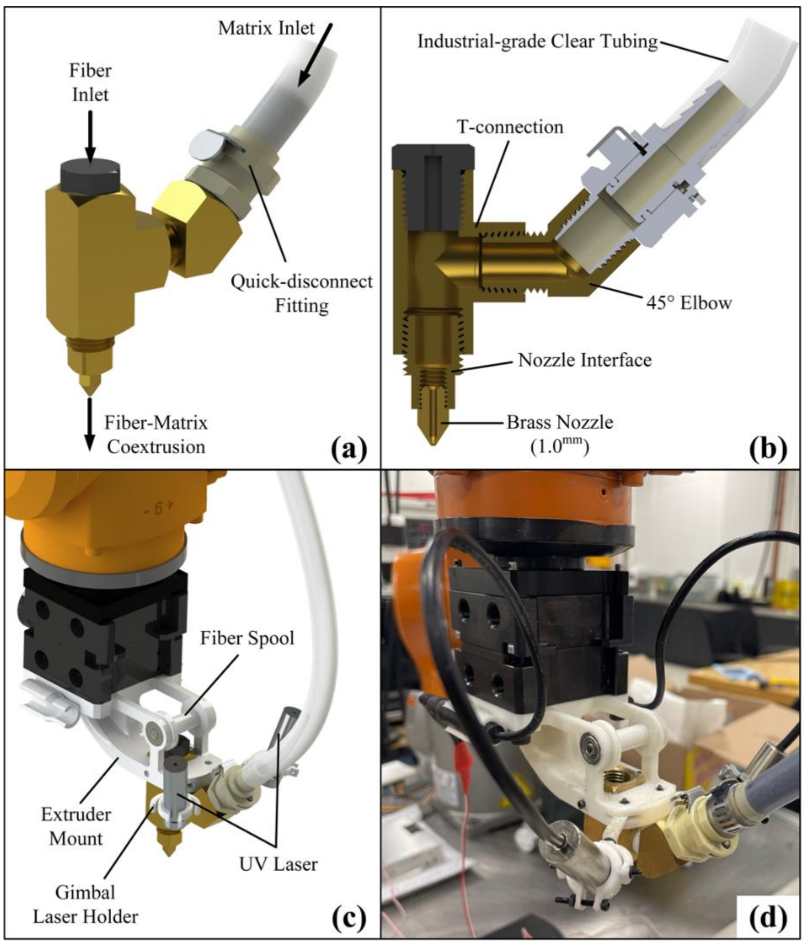

Figure 1 The design of the coaxial composite extruder. (a) The dimetric view of the designed extruder; (b) The side section-view of the designed extruder; (c) The components of the extruder mount on the robot; and (d) the actual extruder attached to the robot.

4 MANUFACTURING PROCESS

The selection of a manufacturing process is critical as it significantly influences the mechanical properties of the resulting parts, such as strength, ductility, and hardness. Furthermore, each manufacturing process possesses specific capabilities and limitations with respect to the types of materials it can effectively process and the geometry it can accurately produce. Given these variations, it is essential to carefully choose a process that aligns with the desired characteristics and functional requirements of the final product.

In this research, a comprehensive analysis of four manufacturing processes is conducted to reveal their respective strengths and weaknesses through standard tensile testing. By examining the inherent properties and operational mechanisms of each method, we aim to highlight their suitability for different applications based on material compatibility, achievable geometries, production efficiency, and cost-effectiveness.

The first method is Fused deposition modeling (FDM) also known as fused filament fabrication (FFF), a subset of material extrusion technique and common additive manufacturing method that uses thermoplastic polymers to create 3D parts layer by layer [7]. A Raise3D Pro2 Plus FDM printer is used to print tensile specimens. Since we are interested in a fair comparison between FDM parts and fiber-reinforced parts, the raster angle is selected constant and along the length of the specimen (0 degrees).

The second method is liquid crystal display (LCD) stereolithography (SLA) printing, a subset of SLA technique based on selective polymerization of liquid resin. This method is characterized by its precision and ability to produce complex geometry and high-quality surfaces due to the use of high resolution (4K or 8K) displays [8]. The reason to include this manufacturing method is that the material used in this technique is the same material chosen for matrix of the fiber-reinforced composite parts. In this research, a Flashforge Foto 13.3 printer is used to create a set of tensile specimens.

The third method is photopolymer extrusion (PE) which implemented by the novel extruder developed in this research for continuous fiber reinforced polymer composite material. This method is considered a subset of material extrusion. The difference between PE and FDM is the feedstock material. While FDM uses thermoplastic polymers that are reformed by raising the temperature, PE uses thermoset liquid polymers that are cured using a light source within or close to the ultraviolet wavelength range. In the fourth method, a coaxial photopolymer composite extrusion (CPCE) approach is introduced using the RAM system capable of coextruding continuous fibers and photopolymer resin. Through this research, we aim to provide a detailed comparison of these manufacturing processes, facilitating a better understanding of their application scopes and limitations.

The developed RAM framework equipped with the developed extruder is used to print two sets of tensile specimens. The first set is manufactured using a neat polylactic acid (PLA) resin. This set will provide a baseline for the tensile strength of the matrix. The second set is continuous Kevlar fiber reinforced PLA composites. By comparing the second set with the first set and FDM and SLA specimens, the effect of the embedded continuous fibers are demonstrated.

Table 1 Mean and standard deviation of the thickness and width of the manufactured tensile specimens using four different manufacturing techniques in this paper.

Specimen Type	Thickness Mean	Thickness STD	Width Mean	Width STD
FDM	17.78 mm	0.117 mm	3.52 mm	0.386 mm
LCD	17.38 mm	0.327 mm	3.55 mm	0.034 mm
PE	17.64 mm	0.252 mm	3.38 mm	0.442 mm
CPCE	17.66 mm	0.173 mm	1.98 mm	0.229 mm

5 RESULTS AND DISCUSSION

The tensile test has been done to characterize the manufactured specimens using FDM, LCD, PE, and CPCE approaches. Specifically, a monotonic tensile loading with a predefined displacement rate is applied to the specimens up to the specimen's failure. The main objective here is to compare the effect of addition of continuous Kevlar fibers in PLA matrix using the developed extruder.

As mentioned, the tensile tests are done according to ASTM-D3039 standard. The grip displacement measurements are considered for specimen strain calculations. In addition, tabs are added to the gripping area to improve the grip and avoid slippage during tensile testing.

The strain-stress response for five CPCE specimens are shown in Figure 2 (a). These specimens are chosen out of the total of six specimens based on the consistency of their results. From the stress-strain curves, the average Young's modulus and ultimate tensile strength (UTS) for CPCE specimens are 70.37 MPa and 169.03 MPa. Some fiber breakage patterns can be identified in the curves as the fiber strands fail before the final failure of specimen. Moreover, there is an inflection point at the beginning of the test (up to 0.4% strain) for all specimens. This behavior is not observed in other specimens sets (as shown in Figure 2 (b)) therefore; it indicates the fibers alignment to the loading direction. The Yonge's modulus is calculated based on the linear part of the curve after the fiber alignment region.

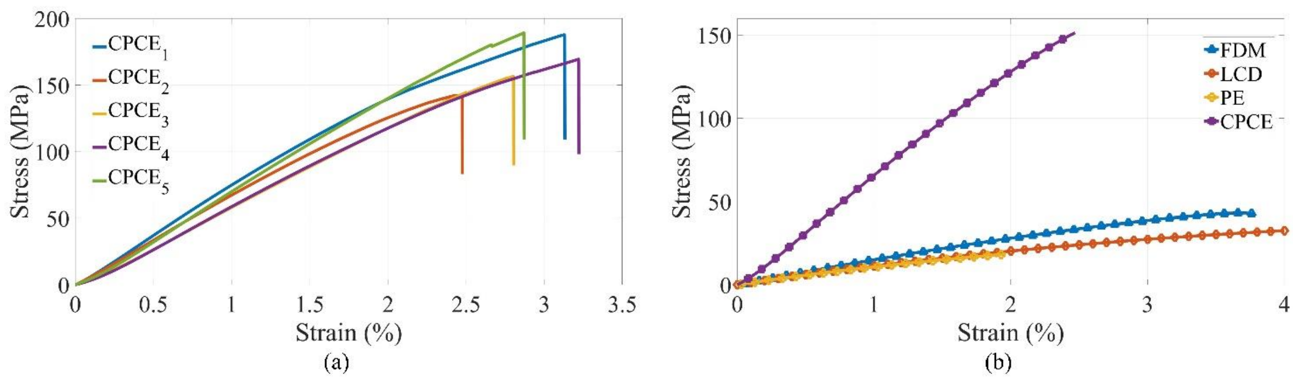

Figure 2 (a) Stress-strain diagram for (a) the five CPCE specimens and (b) average behavior of specimens in four different sets.

To compare the results from the tensile tests done on all the specimen sets, a stress-strain diagram is presented in Figure 2 (b). Each curve in this diagram represents the average response of five specimens in that set. The average response is obtained by interpolating all the data points from the experimental results and calculating average stress values at predefined strain values.

The average values for Young's modulus, UTS, and failure strain for the four specimen sets are presented in Table 2. The improvements on the tensile properties including Young's modulus and UTS are clearly identifiable by comparing the values of CPCE specimens with other ones. There is a 550% and 710% increase in tensile stiffness and strength compared to the PE specimens. This increase can enable 3D printers to manufacture load bearing parts instead of prototypes.

Table 2 Average values of Young's modulus, yield stress, ultimate tensile strength, and failure strain among the entire test specimens for FDM, SLA, PE, and CPCE manufacturing processes.

Specimen Type	Young's Modulus (GPa)	UTS (MPa)	Failure Strain (%)
FDM	1.510	43.30	3.95
SLA	1.137	38.06	9.32
PE	1.075	20.86	2.33
CPCE	7.037	169.03	2.90

6 CONCLUSION

In the past decades, followed by the emergence of additive manufacturing techniques, researchers have always strived to upgrade the 3D printed parts from prototypes to structural components. There are many advancements in the slicing methods, toolpath generation, polymer properties, and material reinforcements. In this paper, a coaxial extruder is designed and developed to coextrude continuous fibers along with photopolymer resin. The extruder is equipped with powerful UV-lasers that can cure the deposits on-the-fly. The extruder is then integrated into a robotic manipulator to be moved along predefined toolpaths to create 3D objects.

Using the developed system, two sets of specimens are manufactured to be compared to specimens created by FDM and SLA methods. The results demonstrate that the addition of continuous Kevlar fibers in PLA matrix could increase the Young's Modulus and UTS up to 6.5 and 8 times higher than their values in neat polymer specimens. However, the addition of fibers can lower the failure strain due to the nature of Kevlar fibers.

7 REFERENCES

[1] M. Kringer, C. Böhrer, M. Frey, J. Pimpi, and M. Pietras, "Direct Robotic Extrusion of Photopolymers (DREPP): Influence of microgravity on an in-space manufacturing method," *Frontiers in Space Technologies*, vol. 3, p. 899242, Aug. 2022, doi: 10.3389/FRSPT.2022.899242.

[2] M. Parker, N. Ezeokeke, R. Matsuzaki, and D. Arola, "Strength and its variability in 3D printing of polymer composites with continuous fibers," *Mater Des*, vol. 225, p. 111505, Jan. 2023, doi: 10.1016/J.MATDES.2022.111505.

[3] P. M. Bhatt *et al.*, "A robotic cell for multi-resolution additive manufacturing," *Proc IEEE Int Conf Robot Autom*, vol. 2019-May, pp. 2800–2807, 2019, doi: 10.1109/ICRA.2019.8793730.

[4] P. Zhuo, S. Li, I. A. Ashcroft, and A. I. Jones, "Material extrusion additive manufacturing of continuous fibre reinforced polymer matrix composites: A review and outlook," *Compos B Eng*, vol. 224, p. 109143, Nov. 2021, doi: 10.1016/J.COMPOSITESB.2021.109143.

[5] P. Nayyeri, H. Bougherara, and K. Zareinia, "Development of a Robotic Additive Manufacturing Framework for Fused Deposition Modeling: Technical Considerations," *Proceedings of the 10th International Conference on Control, Dynamic Systems, and Robotics (CDSR 2023)*, Jun. 2023, doi: 10.11159/CDSR23.216.

[6] "D3039/D3039M Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials." Accessed: May 01, 2024. [Online]. Available: https://www.astm.org/d3039_d3039m-08.html

[7] P. Nayyeri, K. Zareinia, and H. Bougherara, "Planar and nonplanar slicing algorithms for fused deposition modeling technology: a critical review," *International Journal of Advanced Manufacturing Technology*, vol. 119, no. 5–6, pp. 2785–2810, Mar. 2022, doi: 10.1007/S00170-021-08347-X/METRICS.

[8] W. Shan, Y. Chen, M. Hu, S. Qin, and P. Liu, "4D printing of shape memory polymer via liquid crystal display (LCD) stereolithographic 3D printing," *Mater Res Express*, vol. 7, no. 10, p. 105305, Oct. 2020, doi: 10.1088/2053-1591/ABBD05.