Influencing Factors and Optimization Study on Mechanical Properties of Continuous Fiber-Reinforced Composite Materials in 3D Printing

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Abstract. In recent years, Continuous fiber reinforced composites (CFRPCs) have been widely applied in 3D printing manufacturing due to their low density, high strength, and excellent performance, which can significantly enhance the performance of components compared to traditional single materials. With the development of related manufacturing technologies, the 3D printing technology of CFRPCs provided new ideas and directions for the quantity production of high-accuracy, low-cost, and customizable complex structural parts. This paper presents a comprehensive review of CFRPCs 3D printing technology. It illustrates the manufacturing processes and principles related to CFRPCs and analyses the factors affecting the mechanical properties of products from both material and production process perspectives, and summarizes corresponding performance optimization methods along with the latest research progress for each factor. Finally, the paper points out the shortcomings of existing studies and provides an outlook on future developments by synthesizing current development trends and research focuses in continuous fiber composite materials, which will serve as a valuable reference for guiding future research efforts and accelerating the industrial adoption of this promising manufacturing technology.

Keywords: 3D printing manufacturing, Continuous fiber reinforced composites, Fused deposition modeling, Mechanical Properties

1 Introduction

Continuous Fiber Reinforced Composites (CFRPCs) are widely used in fields such as aerospace, mechanical manufacturing, marine vessels, and biomedical applications due to their low density, high strength, fatigue resistance, and corrosion resistance[1]. Applied in 3D printing manufacturing, CFRPCs will overcome the weakness of insufficient strength in traditional FDM-printed parts and open new avenues for the manufacture of end-use components with high-precision, high-performance, and lightweight. However, the mechanical properties of the final products fabricated through this process are affected by a series of complex factors such as poor fiber-matrix bonding, insufficient interlayer strength, and stress concentrations induced

ICMEEA 2026, April 24-26, Singapore, Singapore

DOI 10.4108/eai.24-4-2026.2364891

by printing path. Systematically understanding and controlling these factors is crucial for advancing the maturity of this technology and facilitating its industrialization and commercialization. This paper provides a comprehensive discussion based on the bonding properties of materials and the influence of key process parameters to explore methods to improve the performance and offers an outlook on future development directions.

2 Process Overview

Based on different implementation methods, 3D printing technologies can be categorized into Selective Laser Sintering (SLS), Stereo Lithography Appearance (SLA), Laminated Object Manufacturing (LOM), and Fused Deposition Modeling (FDM) [2]. The continuous fiber reinforced polymer composites discussed in this paper are primarily applied to the FDM process.

Current processes commonly utilize continuous carbon fiber (CCF), glass fiber (GF), and Kevlar fiber as fiber reinforcements, with resins (PLA, ABS, PA, etc.) serving as the matrix. Some natural materials, like jute fiber and inorganic materials such as pyrolytic ceramics and alloys are also employed [3,4]. The core principle of continuous fiber reinforced composites lies in simultaneously depositing continuous fibers as reinforcements with the resin matrix. This leverages the high strength and impact resistance of continuous fibers to enhance the overall performance of the product.

FDM-based fiber-reinforced composite 3D printing processes can generally be categorized into single-nozzle extrusion, single-nozzle co-extrusion, and dual-nozzle extrusion. The single-nozzle extrusion method involves mixing fibers with the resin matrix to form composite filaments for printing, commonly used for chopped fiber particle composites. The latter two methods can both be applied to continuous fiber printing [5]. The printing process is illustrated in Figure 1.

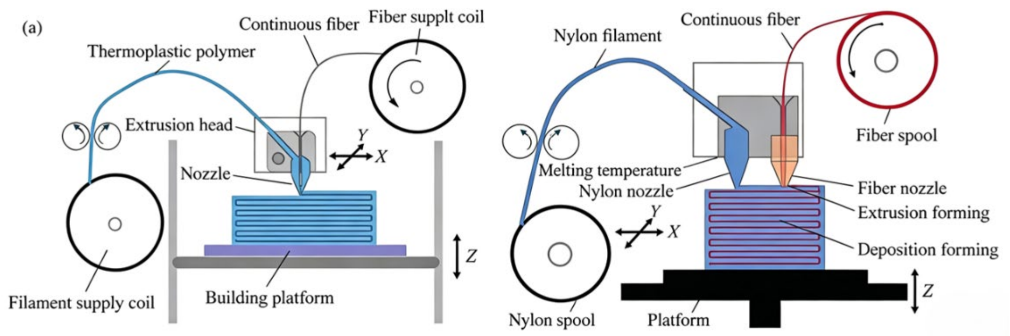

Fig. 1. Single nozzle printing; and Double nozzle printing [6,7]

3 Study on Factors Affecting the Performance of Craft Products

As a relatively precise manufacturing method, the performance of 3D-printed products is influenced by multiple complex factors, such as temperature, continuous fiber impregnation and pretreatment processes, and the compatibility between continuous fibers and the matrix. By controlling the temperature within a reasonable range, improving pretreatment processes, and selecting suitable continuous fibers and matrices, significant enhancements can be achieved in the products' flexural properties, structural density, interlayer strength, and bonding performance, ensuring product stability in industrial production.

3.1 The intrinsic influence of the material system

As shown in Table 1, continuous fibers endow composite materials with unique physical properties, playing a crucial role in determining the mechanical performance of the final product. Among widely used materials, carbon fiber can significantly enhance the bending and tensile properties of composites with its superior specific strength and specific modulus, which makes it the material of choice for producing high-performance, high-precision components. Glass fiber and Kevlar fiber are valued for their impact resistance and shear resistance, respectively. Some natural fibers, such as jute and ramie, garnered attention due to their lower cost and excellent biodegradability. However, their limited strength and stiffness, along with inherent variability and susceptibility to damage, continue to restrict their development and application [8,9].

Table 1. Common Material Parameters for Selected Continuous Fiber Composites [10]

Materials		Density(g/cm3)	Filament Diameter(mm)	Tensile Modulus (GPa)	Flexural Modulus (GPa)
Resin Matrix	PLA	1.24	1.75	0.9	0.8
	ABS	1.04	1.75	2.0	2.4
Continuous Fiber	Carbon Fiber	1.30	0.40	54.0	51.0
	Glass Fiber	2.40	0.30	21.0	22.0
	Kevlar Fiber	1.20	0.30	27.0	26.0
	Jute Fiber	1.46	0.80	5.0	/

The resin matrix serves to bond fibers and transmit loads, primarily categorized into thermoplastic resins and thermosetting resins. Thermoplastic resins can be processed and formed by heating to melt and cooling to solidify. During processing, there are no chemical changes that happen, which makes it possible to reprocess. Commonly used resin matrices include polylactic acid (PLA), polyamide (PA), and polyether ether ketone (PEEK) [6]. Among these, PLA is frequently used in the medical industry due to its excellent biocompatibility and biodegradability. Its relatively low printing temperature also makes it suitable for printing plant fiber composites that require moderate heat resistance [9]. Polyamide (PA) features extensive hydrogen bonding between molecules, resulting in superior corrosion resistance and mechanical properties. Its excellent flowability and permeability also make it a common matrix material for commercial printers. PEEK is a specialty polymer characterized by high strength, toughness, and heat resistance, making it widely adopted in aerospace and biomedical applications. Compared to thermoplastics, thermosetting resins offer superior corrosion resistance, heat resistance, and mechanical properties, but they cannot be reprocessed and have a shorter shelf life.

In traditional manufacturing methods where materials are deposited additively, interlayer performance largely depends on the properties of the substrate itself. However, the substrate often lacks sufficient strength and this makes the interlayer bonding a weak part in the whole component. In 3D-printed products, interlayer bonding only relies on the heat from the extruded filament to remelt the surface of the solidified filament beneath it, which results in a bond strength significantly lower than the material's inherent strength. Consequently, the interlayer interface becomes the weakest and most vulnerable point in the entire component. In practice, the configuration of printing parameters critically influences interlayer performance [11].

The fiber-matrix interface is a critical region within composite materials. In this area, fibers and matrix are bonded together through the synergistic effects of mechanical interlocking (resin infiltrating microscopic grooves on the fiber surface), chemical bonding (such as chemical reactions between sizing agents and fibers/resins), and van der Waals forces. Under ideal conditions, external forces applied to the component are transmitted through the matrix to the fiber matrix in the form of shear forces [9]. When composite materials are subjected to stress, if the interfacial bond strength is insufficient, debonding failure occurs first under shear stress. This disrupts the transfer of forces between the fiber and matrix, preventing effective stress redistribution. Microcracks at the interface then propagate further under intensified external forces, ultimately leading to macroscopic failure.

The bond strength at the interface is primarily influenced by the compatibility between the matrix and the fibers. Generally, the better the compatibility between the fiber bundle and the resin matrix, the higher the interface strength and the less likely delamination occurs. In their natural state, synthetic continuous fibers exhibit a relatively smooth surface and chemical inertness [9], making it difficult for them to bond with resins. Plant fibers, because of inherently rich in hydrophilic hydroxyl groups, exhibit poor compatibility with hydrophobic resins [12]. Therefore, specific processing techniques are required to enhance the bonding between continuous fibers and the resin matrix.

Improper impregnation processes may also yield similar outcomes. Generally, impregnation techniques can be categorized into in-situ impregnation and pre-impregnation. In the in-situ impregnation process, dry fibers and resin matrix are directly combined, impregnated, and extruded within the nozzle. Pre-impregnation, conversely, involves using pre-impregnated filaments directly during the printing process [5]. Due to the brief contact time between fibers and matrix, products from in-situ impregnation are prone to interfacial voids and poor bonding. Conversely, prepreg filaments exhibit superior interfacial quality and typically demonstrate significantly better mechanical properties than the former. However, prepreg filaments involve complex manufacturing, inconvenient storage, and low flexibility.

3.2 External Control of Printing Process Parameters

Temperature, layer thickness, and path planning all influence the product performance. Hui Mei et al. noted that higher temperatures can improve fiber-matrix interface bonding by affecting resin viscosity and fluidity, enabling more thorough fiber impregnation [7]. Layer thickness affects the interlayer bonding area. A smaller layer thickness means the distance between the nozzle and printing surface is closer, which can put greater nozzle pressure on the printing surface. This allows the molten resin matrix to be more tightly compressed into the fiber bundle and printing substrate, reducing composite porosity and enhancing mechanical properties [2]. Smaller layer thicknesses result in tighter fiber bundle bonding and more uniform fiber distribution. During fracture, relative displacement between fibers and matrix becomes less pronounced, yielding superior bonding that allows load transfer from the resin matrix to the fiber matrix [13].

Some researchers observed that the resin matrix exhibits viscoelastic behavior during high-temperature printing [14], which prevents the resin from timely curing. When the turning angle exceeds 90°, continuous fibers may be dragged forward by the rapidly moving nozzle, causing fiber displacement. Kui Wang et al. conducted experiments using carbon fibers and observed fiber deviation from the print path, along with potential fiber misalignment and fiber loss [15]. Research by Yu Long et al. explained that the tendency of the print path to turn induces significant stress concentration within the fibers. Upon reaching the turning point, a sudden surge in traction force occurs, ultimately manifesting as fiber slippage, retraction, or delamination [14]. Kui Wang et al. emphasized that fiber slippage at corners tends to create nodes with low strength and stiffness within the structure, particularly at sharp angles. Under applied loads, these nodes become stress concentration points, triggering localized failure and ultimately structural collapse. This effect is particularly pronounced in multi-cornered structures like honeycomb and rhombic patterns [15].

4 Performance Optimization Strategies

4.1 Materials

Some researchers attempted to treat both fibers and matrices to enhance fiber surface properties, enabling effective bonding and mutual locking with the resin matrix. Anjumol K S et al. employed plasma treatment on polypropylene (PPE) matrices, increasing the tensile strength and modulus of polypropylene-banana fiber composites by 6% and 25%, respectively [16]. Li Xiaoman et al. surface-treated flax fibers with 3-aminopropyltriethoxysilane (KH550), discovering that an appropriate amount of KH550 undergoes condensation reactions with both flax fibers and polylactic acid (PLA) matrix. This chemical bonding enhanced interfacial adhesion, increasing the tensile strength of treated specimens by 40% [17]. Some researchers employed nanomaterials such as graphene and carbon nanotubes for sizing continuous fibers. This process uniformly coated the fibers with nanomaterials, roughened the fiber surface, and generated active groups. Consequently, the resin wetted the fibers more effectively, thereby improving the bond between the fibers and the matrix [9].

4.2 Process Optimization

Rationally controlling temperature and printing speed based on material properties is another approach to process optimization. Junjie Li et al. attempted to establish a finite element model of the transient temperature field during deposition using polylactic acid carbon fiber filament as the research subject. By comprehensively considering planar and interlayer thermal effects, interlayer bonding quality, and corner offset risks, they ultimately determined the optimal printing temperature and speed parameters [18]. Their conclusions were validated by experimental testing. They found that both fiber displacement and component flexural strength showed a positive correlation with printing temperature, with changes leveling off after 240°C. At a printing speed of 1.25 mm/s, the structure exhibited optimal interlayer integrity, and its compressive modulus significantly outperformed components printed at other speeds.

4.3 Innovative Structural Design

By incorporating novel materials and internal structures, components may achieve multifunctionality and higher levels of lightweighting. P Qu et al. developed a bi-matrix co-extrusion process for hybrid continuous fiber composites using thermosetting epoxy resin and thermoplastic PET resin. They tested a hybrid continuous fiber layup configuration, finding through finite element and near-field dynamic model fitting that this novel combination significantly enhanced the component's flexural strength, with flexural energy absorption increasing by 126% [19]. This technique also enables customization of composite properties to meet specific performance requirements or to strike an optimal balance between high performance and cost-effectiveness. A. ElSherbiny et al. developed a novel fiber interlacing method termed “Z-direction stitching,” where filaments traverse in the interlaminar direction. This creates interlocking fiber structures between adjacent layers, transforming the structure from a simple two-dimensional stack into a three-dimensional entity [20]. When subjected to out-of-plane or shear loads, such structures effectively distribute the load rather than concentrating it at a single point between layers, as in traditional structures, which rely solely on the adhesive strength of the matrix polymer to resist external damage.

Optimal path design can effectively reduce fiber misalignment at path corners and enhance structural strength. Kui Wang et al. designed four distinct printing paths for the same structural shape. Experimental results revealed that printing path C, employing an interlaced trapezoidal construction method, exhibited the least fiber body slip, demonstrating the highest bending stiffness and specific load-bearing capacity. This demonstrates that well-designed paths can effectively leverage material properties to achieve maximum performance [15].

5 Limitations and Development Trends

Continuous fiber-reinforced composites, characterized by their low cost, high efficiency, and superior performance, are poised to capture an increasingly broader market share in the future. Currently, composite materials are trending toward lightweighting, high precision, and integrated solutions. By optimizing fiber orientation and component structures, weight reduction and performance enhancement are achieved. Intelligent, multifunctional printing equipment improves print accuracy, while modular printhead designs integrate diverse materials and fiber/matrix filament bundles of varying dimensions. This enables comprehensive material applications and composite design capabilities.

Existing research also holds considerable room for advancement. As previously mentioned, the mechanical properties of printed products primarily depend on the continuous fibers added, yet few components in current technical systems exceed a volume fraction of 50%. Flexibly adjusting the fiber volume fraction according to technical requirements and increasing the fiber proportion when necessary represent key future research directions. Simultaneously, due to the layer-by-layer deposition process, components produced by 3D printing exhibit certain porosity defects compared to those from traditional manufacturing. While the use of continuous composites and production process control can partially compensate for these defects, high porosity remains a critical issue requiring urgent attention in future research.

6 Conclusion

This paper analyzes factors influencing the mechanical properties of continuous fiber-reinforced composite materials from both material and manufacturing process perspectives. Depending on the latest research findings, this paper proposes targeted improvement and optimization methods and points out that the performance of final products can be improved by enhancing material bonding, refining processing techniques, adjusting processing environments, and designing novel fiber layup structures. This study summarizes the unique properties and influencing factors of continuous fiber composites, providing valuable guidance for their subsequent industrial applications. The application of continuous fiber composites in 3D printing manufacturing is changing the traditional component manufacturing approaches, which makes it possible to design and form the complex structures flexibly. As printing techniques diversify and equipment evolves toward intelligent, multifunctional capabilities, the precision, diversity, and composite design potential of manufactured products will reach new heights. Notably, mature testing standards for such components remain scarce, and systematic, standardized evaluation methods are still under development.

References

[1] Cheng, P., et al.: 3D Printed Continuous Fiber Reinforced Composite Lightweight Structures: A Review and Outlook. Sci. Rep. (2024)

[2] Su, W., Qian, B., Mao, J., et al.: Research progress on 3D printing of continuous fiber reinforced polymer composites. Aeronaut. Manuf. Technol. pp. 117–136 (2025)

[3] Matsuzaki, R., Ueda, M., Namiki, M., et al.: Three-dimensional printing of continuous-fiber composites by in-nozzle impregnation. Sci. Rep. 6. (2016)

[4] Mei, H., Yan, Y., Feng, L., Dassios, K. G., Zhang, H., Cheng, L.: First printing of continuous fibers into ceramics. J. Am. Ceram. Soc. 101. (2018)

[5] Nakagawa, Y., Mori, K. I., Maeno, T.: 3D printing of carbonfibre-reinforced plastic parts. Int. J. Adv. Manuf. Technol. 90, pp. 2811–2817 (2017)

[6] Long, Y., Li, Y., Fu, K.: Recent advances in 3D printed fiber reinforced composites: Processing technique and mechanical performance. Acta Mater. Compos. Sin. 39, pp. 4196–4212 (2022)

[7] Mei, H., Ali, Z., Yan, Y. K., et al.: Influence of mixed isotropic fiber angles and hot press on the mechanical properties of 3D printed composites. Addit. Manuf. 28, pp. 150–158 (2019)

[8] Tao, Y. B., Li, P., Zhang, J. F., et al.: A review of fused filament fabrication of continuous natural fiber reinforced thermoplastic composites: techniques and materials. Polym. Compos. 44, pp. 8200–8222 (2023)

[9] Sun, Z., Liu, L. Y., Liu, D. B., et al.: Development and mechanical properties of nano-modified continuous fiber reinforced thermoplastic composites. Acta Mater. Compos. Sin. 36, pp. 771–783 (2019)

[10] Kabir, S. M. F., Mathur, K., Seyam, A. F. M.: A critical review on 3D printed continuous fiber-reinforced composites: History, mechanism, materials and properties. Compos. Struct. 232. (2020)
[11] Krzykalla, D., Mesicek, J., Halama, R., et al.: On flexural properties of additive manufactured composites: Experimental and numerical study. Compos. Sci. Technol. 227. (2022)
[12] Anjumol, K. S., Sumesh, K. R., Vackova, T., et al.: Effect of plasma treatment on the morphology, mechanical, and wetting properties of polyethylene/banana fiber composites. Biomass Convers. Biorefin. (2024)
[13] Chen, K., Yu, L. G., Cui, Y. H., et al.: Optimization of printing parameters of 3D-printed continuous glass fiber reinforced polylactic acid composites. Thin-Walled Struct. 166. (2021)
[14] Yu, L., Zhang, J., Guo, Y., Zhang, Z., Fu, K., Li, Y.: Investigation of path deviation on 3D printing of continuous plant fiber-reinforced composites during turning. Compos. Part A: Appl. Sci. Manuf. 178. (2026)
[15] Wang, K., Wang, D., Liu, Y., Gao, H., Yang, C., Peng, Y.: Path Planning and Bending Behaviors of 3D Printed Continuous Carbon Fiber Reinforced Polymer Honeycomb Structures. Polymers. 15. (2023)
[16] Anjumol, K. S., Sumesh, K. R., Vackova, T., Hanna, J. M., Sabu, T., Spatenka, P.: Effect of plasma treatment on the morphology, mechanical, and wetting properties of polyethylene/banana fiber composites. Biomass Convers. Biorefin. (2024)
[17] Li, X., Li, P., Zhang, J., Kong, F., Tao, Y., Liu, K.: Effects of 3-Aminopropyltrialkoxysilane Dosages on the Properties of 3D Printed Continuous Flax Fiber/polylactic Acid Composite Materials. China Plast. Ind. 53. pp. 144–151 (2025)
[18] Li, J., Ruan, W., Ren, W., Li, Q., Quan, Z., Yu, J.: Simulation of temperature field and optimization of process parameters for in-situ impregnation 3D printing of continuous fiber reinforced composites. Compos. Part A: Appl. Sci. Manuf. 178. (2026)
[19] Qu, P., Kong, H., Li, X., Lei, Y., Guo, A., Wang, S., Wang, H., Hu, Y., Wan, Y., Takahashi, J.: Additive manufacturing of hybrid continuous carbon/basalt fiber reinforced composites based on bi-matrix co-extrusion. J. Mater. Res. Technol. 33, pp. 8683–8704 (2024)
[20] ElSherbiny, A., Qureshi, A. J., Mertiny, P.: Continuous carbon fiber 3D printing with interweaving deposition for enhanced mechanical performance in fused filament fabrication. Addit. Manuf. Lett. 8. (2025)