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# *A Review of Fiber Reinforced 3D Printing Technology*

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***Abstract.*** 3D fiber printing technology, using fiber addition in the printing matrix to improve the mechanical and thermal performance of printed structures, is an important branch in additive manufacturing, offering great capabilities in multiple aspects, such as material diversity and enhancing material strength, that other additive manufacturing methods do not have. This paper, through a method of literature review, explores the current state, applications, and challenges of 3D fiber printing, also giving a brief explanation of why fiber can enhance the performance of a structure, how fiber is distributed in the printed flow, and to what extent fiber improves the performance of the structure. By analyzing some previous studies, the paper finds that 3D fiber printing technology shows massive potential abilities in different areas such as healthcare, aerospace, and robotics. Although limitations of materials and the scale of printing post-processing still exist, 3D fiber printing has the ability to revolutionize manufacturing processes.

***Keywords:*** 3D printing, additive manufacturing, composite, fiber reinforced

## 1. Introduction

The rapid evolution of additive manufacturing, which is usually named 3D printing, has revolutionized traditional manufacturing paradigms. 3D printing technology can highly improve production efficiency and also reduce cost. And its high flexibility allows consumers to give more input to let the final product fit the expectations [1]. These advantages make 3D printing techniques used in many areas, such as rapid tooling, lightweight robotic components, aerospace, the medical industry, etc. [2-4].

However, there must be drawbacks to 3D printing products. For techniques such as fused deposition modeling, because there is a limited choice of materials, the final products have limited performance [5]. And for techniques such as selective laser sintering (SLS), a variety of materials can be used, such as metal powder and resin, but the equipment is often expensive. Therefore, fiber is added to composites to enhance the performance of the printed products. Fiber could improve the performance of products in multiple aspects. Flexural strength can have a dramatic rise of up to 400%, bending strength could increase to 180%, and have at most 10 times the workload of fracture values [6].

The performance of a printed product can vary in different conditions. One of which is the state of fiber. The composite strength of a composite depends on fiber length distribution, the fiber orientation distribution, the critical fiber length, etc. [7]. Thus, figuring out how fiber is distributed

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in printed flow is crucial to improving the performance of printed products. Lake P. Heller et al. have used simulation, simulating the fiber distribution in different positions of printing nozzles [8]. Moreover, different types of fiber can affect the performance. Different fibers, such as polyacrylonitrile fiber fillers (PAN), polyacrylonitrile short-cut fiber (PAN-sc), polyamide fiber fillers (PA), and alkali-resistant zirconium silicate glass short-cut fiber (glass fiber), not only affect the strength of the product directly, but also alter the orientation of the fiber [6].

This paper, through the method of literature review, systematically sorts out the research status, key technologies, and application scenarios of fiber-reinforced 3D printing technology. By analyzing relevant literature, this paper aims to summarize the latest progress of 3D fiber printing technology, explore its future development direction, and provide theoretical support and practical reference for related field research, pointing out the direction for future research.

## 2. Construction of fiber reinforcement

Salman Pervaiz et al. stated that composites are multiple materials mixed together at the macro level without chemical interaction, forming a fabric-matrix system. Different materials can show different properties. In composites, the discontinuous materials are called reinforcements, which have higher strength and are fibers in 3D printing, and the continuous materials are the matrix, which are usually weaker than the reinforcements. There are multiple choices of fiber that can be considered for use. Some common examples are glass, carbon, boron, and alumina. These materials have high strength but low plasticity, and the properties of each material could be different. Thus, to have different performances of final products, the choice of reinforcements can be different. Compared to reinforcements, matrix materials have weaker strength and higher plasticity. They bind each reinforcement and transfer the load to each reinforcement. The choice of matrix depends on the operating temperature of the composites. Many types of materials can be used as a matrix, such as polymers, metals, and ceramics and the most common matrix is plastics (see Figure 1) [9].

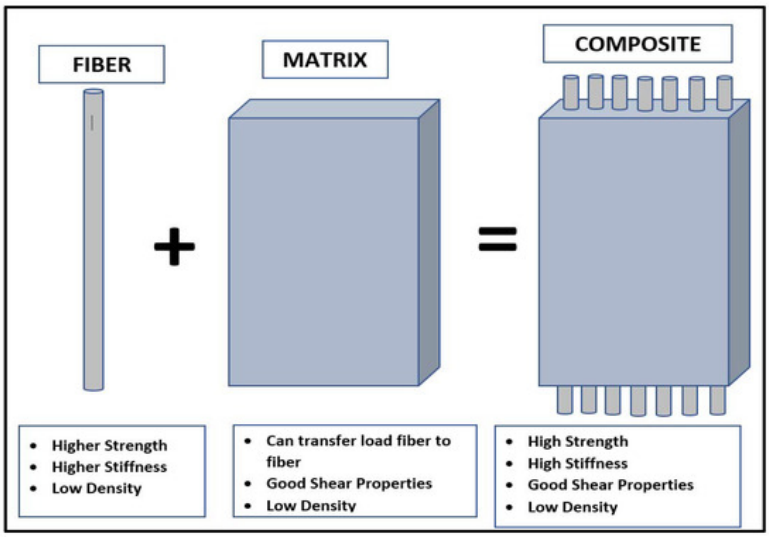



Figure 1: Structure of composite materials [9]

Matrix and fiber are bonded together with three mechanisms: Chemical bonding is the chemical interaction between the fiber surface and the matrix, such as covalent bonds, hydrogen bonds, is reflected by the interface energy. Mechanical interlocking and friction are the surface roughness between fiber and matrix or physical interlock structure produces friction resistance when stressed

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through interfacial friction shear stress; Thermal residual stress is the residual stress caused by the difference of thermal expansion coefficient in the manufacturing process, which affects the initial bonding state of the interface [10].

The fiber in the matrix could have different properties. The properties depend on the situation in which the composites are being used. For giant structures, the fiber could use high-strength materials such as metals. And the fiber could be longer and thicker to support a giant structure. These properties give the composites higher moment capacity and compressive, tensile, and flexural strengths [11]. For a specific situation, such as 3D printing, fibers are cut into small pieces to fit the printed product. The fibers in 3D printing are usually of lower strength, such as glass and carbon. Because fibers are cut into small pieces, they can have different orientations, which can determine the work of fracture and flexural strength [6]. The orientation in different positions of a matrix may be different [8]. But the orientation could be altered deliberately to reach the desired performance. Although the performance of fiber in 3D performance cannot be compared with that of a giant structure, it brings huge improvements.

## 3. Fiber reinforced 3D printing development status

### 3.1. Fiber 3D printing process optimization

Kui Wang et al. found that reducing the printing speed can reduce nozzle acceleration and deceleration at corners, decreasing the risk of fiber pullout from the matrix and improving geometric accuracy [12]. By adjusting layer thickness, contact pressure, and material deposition, it can be balanced. Lower layer thickness caused a tight space for depositing and a higher contact pressure between layers(see Figure2). But if the thickness is too low, the nozzle pressure can be high, reducing constraints of the matrix for the fiber. By modifying the G-code, sharp straight-angle corners were replaced with rounded ones, significantly reducing deviations between the actual deposited fiber path and the designed path. But the rounded corner should not be excessive, or it causes the printed path to deviate too far from the intended shape, reducing accuracy.

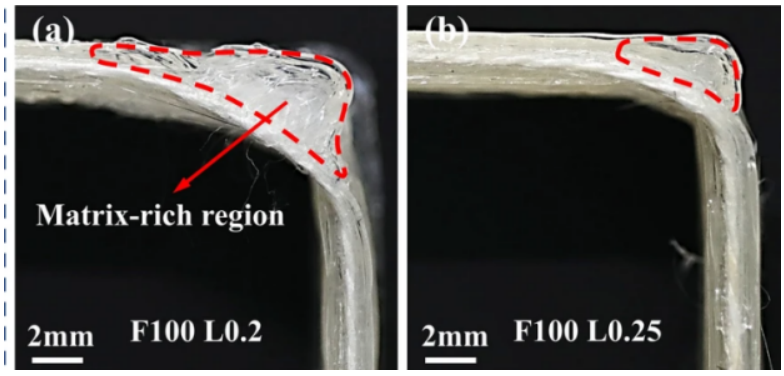



Figure 2: a) Printed structure of layer thickness of 0.2mm b) thickness of 0.25mm[12]

The parameter optimization could bring several improvements. Lower printing speeds and appropriate layer thickness reduce the risk of fiber pullout from the matrix and ensure the printed path closely matches the design, minimizing problems such as interlayer delamination and fiber breakage, increasing printing success. More importantly, the optimized parameter ensures the performance is consistent across different batches, making fiber-reinforced 3D printing suitable for industrial-scale production. Optimized rounded corners reduce material accumulation and fiber

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misalignment at sharp corners, resulting in more precise geometric shapes for thin-walled structures, decreasing stress concentration at sharp edges, enabling more uniform stress distribution under compressive loads, and delaying localized failure. The optimized printing path minimized fiber clustering and breakage, improving the overall strength and stiffness of the composite material. The optimized structures perform progressive folding deformation rather than sudden fracture during quasi-static compression tests, improving energy-absorbing efficiency.

### 3.2. Fiber reinforcement materials innovation

To have different performances and applications of printed products, the use of materials can vary. Yoel Fink and his team developed single-fiber textile networks [13]. They use fiber to integrate traditional computer components-sensor, computing device, etc.-in a single textile, using the electric flow and electric signal on the fiber to calculate. This kind of textile can perform functions related to the Internet of Things (IoT), such as data processing, reasoning, and smart response. Carbon nanotubes and graphene have extremely low electric conductivity, so data can be transferred between fiber textiles. Carbon nanotubes and graphene can also enhance the fiber's mechanical strength and flexibility, making the product made can be worn as real clothes. Other nanomaterials are also added into the composite to improve the strength further and significantly increase the extension strength, and durability. Nanomaterials have the ability to respond to their surroundings (temperature, humidity, pressure, light intensity, etc). The large surface area and high sensitivity make it suitable to be a sensor, and the ability to store and convert energy provides an energy resource, and the ability to make electric components, for example, a capacitor, combines with fiber and an actuator to form a dynamic system for real-time response to changes in the surroundings.

Environmental problems are a topic that has been paid more and more attention to. Haodao Li et al. discussed a new method, which is designing eco-friendly fiber-reinforced concrete (FRC) specifically used for 3D printing, as shown in Figure 3 [14]. The new concrete not only can ease the burden of environmental issues, reducing carbon emissions, but also improve the performance of the concrete. In eco-friendly FRC, glass, carbon, and especially natural fiber (bamboo and hemp fiber) are added to concrete to improve strength, durability, and crack resistance. The natural fiber has less influence on the environment and less demand on resources and energy. The traditional concrete is replaced by slag and coal ash, such as industrial by-products, reducing the usage amount of concrete and its carbon footprint, also increasing the durability and resistance to corrosion. The natural aggregate in concrete is replaced by building waste material (reclaimed sand and stone), reducing dependence on natural resources while decreasing the amount of waste effectively.

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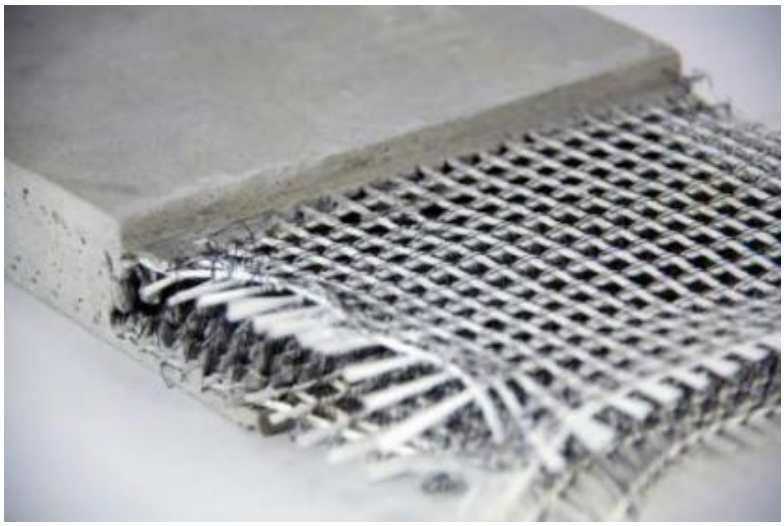


Figure 3: Fiber reinforced concrete [15]

The fiber plays a key role in the 3D printing of concrete. 3D-printed concrete may crack due to factors such as temperature changes, humidity changes, or too fast printing speed during the printing process. Adding fibers can prevent the formation of cracks effectively. The fiber can form an anti-crack net on the microstructure, dispersing the stress and preventing crack propagation. The fluidity of concrete can directly affect the 3D printing process. Concrete can be too thick or too thin. Fibers can help regulate the flow of concrete. Especially fibers such as polypropylene, steel fiber can enhance the dispersion and flow of concrete. 3D printing technology requires the concrete to solidify quickly after printing to support subsequent layers of printing. Fiber materials help speed up the solidification process by improving the bond of the concrete, allowing each layer to solidify quickly to ensure the next layer can be printed in time.

### 3.3. Equipment development

To have higher quality and better performance, or to get various characteristics of printed products, 3D printers are also developing. To have a more complex 3D printing operation, the industrial robot KUKA KR3 R540 is used as a multi-axial kinematic system with a movement controller, the KR C4 Compact RP DC4 XI1 X55 10, and a framework designed using the Siemens NX/NX Nastran computer-aided design and engineering system (see Figure 4) [16]. The robot has high accuracy positioning and repeatability, being capable of complex 3D printing operations. It can control the position of the printing head and carry out complex path planning. The printing head worked according to the Anisoprint CFC process. The printing head was compact and had various functions. The printing head can heat up to 400°C, making it able to print a variety of plastics. And it can cool the printing head to have a stable supply of plastic filaments. To ensure the consolidation of the composite, it has a special nozzle. The material supply is controlled by the industrial controller Bosch Rexroth CML25 with I/O modules. Material is heated via the RS-485 Protocol. The control system also uses a two-channel pulse width modulation (PWM) signal generation module to achieve accurate control of material supply. The HCS01.1E module and the MSM019B servo motor connection line are used as the drive system to ensure the precise transfer of materials and the smooth printing process.

The device is fully automated, from material supply and printing process, to the management of the control system, reducing the need for manual intervention and increasing production efficiency

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and accuracy. The device's control system is equipped with an industry-standard hardware platform with standardized communication interfaces for easy connection with high-end human-machine interface components, providing a user-friendly interface for operators to monitor and adjust the printing process.

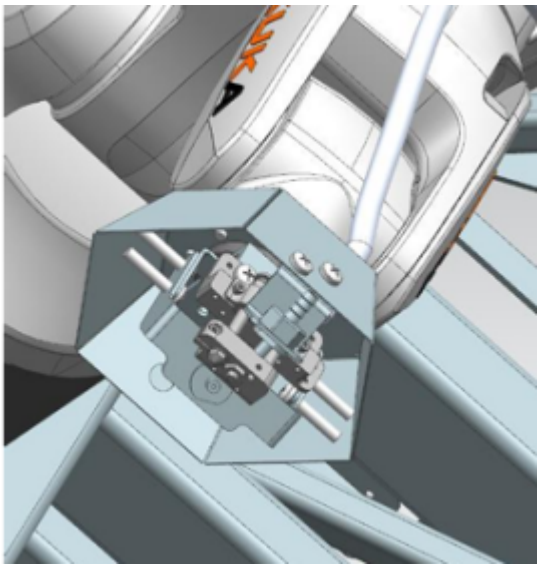


Figure 4: 3D model of printing head(left) manufacturing of parts(right) [16]



Figure 4: 3D model of printing head(left) manufacturing of parts(right) [16]

## 4. Specific case analysis

### 4.1. Methodology

Blake et al. used simulation to analyse the fiber orientation, mechanical properties, and thermal expansion in different printed flows of different heights of printing heads (level flow, falling flow, and bull nose flow with the nozzle at the same height, higher, and lower than the height of the printed flow, respectively) and an additional straight flow in which the flow does not touch the

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deposition plate [8]. The flow printed is considered a flow with a low Reynolds number, high viscosity, incompressible, isothermal Newtonian fluid. The flow has the following parameters: viscosity Newtonian 817 Pa·s, evaluated Carreau model for ABS at 230 °C, shear rate 100 $s^{-1}$, fluid density $\rho = 1154$ kg/$m^3$, inlet of nozzle is fully developed laminar flow with speed of 24 mm/s, and the speed of flow at the boundary is 0 as it is assumed to have no-slip boundary and no boundary stress. The outlet and the speed of the plate are set to be 101.6 mm/s. The height of the printed flow is 3mm from the printing plate, and the height of the nozzle is 3 mm, 4 mm, and 2.5mm for level flow, falling flow, and bullnose flow, respectively. The nozzle is set as shown in Figure 5.

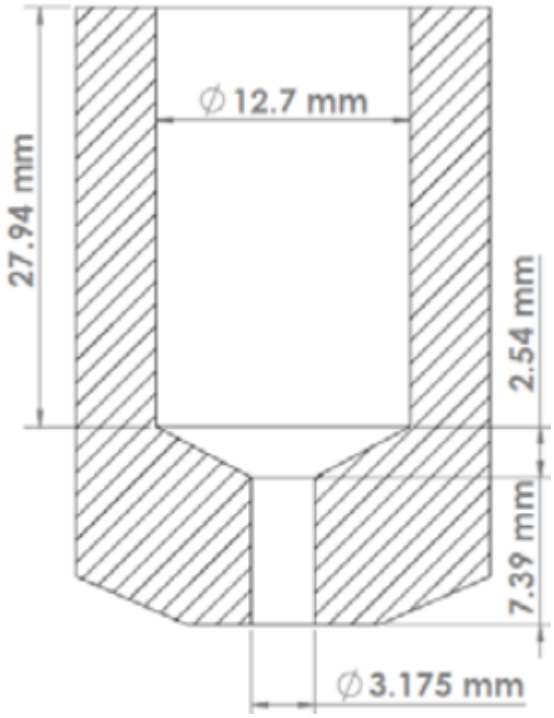



Figure 5: Shape and parameter of nozzle [8]

They use the information stated to determine the equations going to be used, calculating the fiber orientation through ten streamlines using the velocity and velocity gradients from the flow

Simulation. Elastic properties of the matrix can be determined using the orientation homogenization method [17]. The coefficient of thermal expansion is evaluated using a similar method stated before [18].

## 4.2. Result

Shape minimization is used to determine the extrudate shapes for deposition flows, and a volumetric flow loss is calculated to measure the amount of flow passing through the free surface boundary. The calculated free surface flow loss for level flow, falling flow and bull nose flow is 0.19%, 0.33% and 1.15%, respectively. As the flow is optimized, the objective function value decreases from 458.4 $mm^2/s^2$ to 1.6 $mm^2/s^2$ after 51 iterations of optimization. The objective function for the initial shape of straight flow is 54.4 $mm^2/s^2$. After minimization, straight flow has a loss of volumetric flow of 0.28%. The angle between streamlines has a large difference only when the flow is entering the nozzle or leaving the nozzle. The angle of fiber alignment varies across different types of the flow. The overall average alignment is about 2 degrees and at most 5 degrees. The falling and bullnose

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flows have large alignments at the mid-bottom position of flow. The ABS matrix material has a modulus of elasticity of 2.25GPa and a Poisson's ratio of 0.35 and carbon fiber has 230GPa and 0.2, respectively. The volume fraction is 13%. The longitudinal and transverse moduli vary from 6 to 8 and 3.1 to 3.4, respectively, and again, falling and bullnose flow have slight differences compared to level flow.

The simulation can predict the orientation of fiber in the printing flow and calculate the mechanical and thermal performance of the product. By comparing performance of product printed from different type of nozzle, understanding effect caused by different type of nozzle, and finally stating how to improve the quality of printed product, improving the strength, toughness and thermal stability of materials when manufacturing large scale, industrial composite parts, reduce deformation and delamination problems due to thermal expansion in large-scale additive manufacturing Improve its application potential in industrial production.

## 5. Conclusion

This paper presents a review of 3D fiber printing technology, focusing on the current state and key technologies and giving a brief introduction to composite materials and the principle of fiber reinforcement. It states the fiber distribution, nozzle position, and the influence of different printing conditions on fiber orientation, mechanical properties, and thermal performance, which would affect the material properties. The study finds that 3D fiber printing technology has significant potential in diverse fields, especially in industrial use. It can significantly improve the structural performance of printed products, with particular improvements in flexural strength, bending strength, and work of fracture values. Despite these advances, limitations still exist, such as material constraints, the need for post-processing, and scaling up for industrial applications. These limitations present opportunities for future research to further optimize fiber distribution techniques, improve material variety, and refine 3D printing processes for large-scale production.

This paper focuses on theoretical and simulation-based studies and the lack of practical experimental data. Although performance fiber in the matrix has been seen, there is a lack of research on fiber in the long term and in different conditions, and simulation hasn't compared the actual performance of fiber. In future studies, such areas of fiber reinforcement could be studied, and the simulation data could be compared with the experimental data to verify the accuracy of the simulation. In conclusion, while 3D fiber printing technology shows huge potential, there are still some areas that need to be improved and further research to make it more suitable for industrial-scale production.

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