Current Research Status in Continuous Fiber-Reinforced Composites Printing Path Planning

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Abstract. Continuous fiber-reinforced composite components manufactured using FFF (Fused Filament Fabrication) not only maintain inhaler material properties, but also make full use of the process provided by FFF, which has sensational advantages. This paper reviews aspects of the cell filling path mode, the amorphous cell filling path mode, and the generative filling path mode, traces the evolution from simple path planning to optimized methodologies, establishing a Unified Analytical Framework. This framework demystifies the strengths and weaknesses of existing strategies and systematically underpins the evaluation of new pathfinding algorithms.

Keywords: 3D printing, Path mode, continuous fiber-reinforced composites, FFF.

1 Introduction

Slice and path planning is the Key Steps of 3D printing, which relates closely to printing time, accuracy and performance. Traditional path planning technology usually meets path overlap, interruptions, redundancy, and an excessive number of bending angles; these issues will result in interruptions and accumulation of extruded material. Much research on how to improve the mechanical properties of printed products. In terms of printing, 3D printing using continuous fiber-reinforced materials can rapidly manufacture lightweight components with complex geometric features, and has become one of the most promising technologies in the field of advanced composite manufacturing. Continuous Fiber Reinforced Thermoplastic Composite (CFRTC) 3D printing technology as the most striking technologies, has made major Progress in fields of aerospace and automotive manufacturing, etc. Take Carbon Fiber Reinforced Thermoplastic Polymer (CFRTP) as an example, CFRTP has a high strength-to-weight ratio and rigidity, can be used in lightweight design in safety structural components. It also has high toughness, short molding cycle, recyclability, and suitability for mass production, has enormous potential in producing high-performance lightweight structures for mass-produced automobiles. C-FRTP products employing the FFF (Fused Filament Fabrication) process not only maintained the Inherent material properties of C-FRTP, but also fully leveraged the process provided by FFF. Without the need for molds and with short manufacturing cycles, it demonstrates outstanding advantages in producing high-performance composite components with complex geometric features. This paper provides a review of FFF based printing path planning strategies of continuous fiber-reinforced composites.

ICMEEA 2026, April 24-26, Singapore, Singapore

DOI 10.4108/eai.24-4-2026.2364913

2 Continuous Fiber-Reinforced Composite Materials

2.1 Carbon Fiber Reinforced Polymer CFRP

Carbon Fiber Reinforced Polymer (CFRP) typically formed using methods such as high-pressure sterilization and filament winding, has high strength, high chemical resistance, low density, with excellent mechanical properties, virtually free of voids or other defects. CFRP has widely applied to different industrial sectors, from aerospace, transportation, wind power generation to civil engineering concrete structures[1] [2].

2.2 Continuous Fiber Reinforced Thermoplastic Composite CFRTC

CFRTC is made by incorporating fibers into high-viscosity thermoplastic resin. Compared with thermosetting materials, CFRTC offers higher fracture toughness and impact strength, enhanced recyclability and faster processing speeds, and greater weldability. Continuous fiber-reinforced thermoplastic composites (CFRTC) have garnered attention in fields such as aerospace and automotive applications due to their recyclability, high specific strength and modulus, and high process efficiency. 3D printing technology shows tremendous potential in CFRTC processing, offering advantages such as no molds required, short production cycles, and the ability to manufacture complex structures.

3. The Cell Filling Path Mode

Recent advancements in additive manufacturing and increased accessibility have enabled the conception of new complex geometries. Multi-layer cell structure has multiple advantages: Lightweight, high rigidity, and large surface area-to-volume rati0. these structures are applied more and more in heat dissipation in the Aerospace Industry, especially in aircraft electric motor, to Reduce weight and save cost [3].

3.1.Rhombus Cell Structure

Traditional planar periodicity cell structure mainly has forms of triangle and square. K.Sugiyama et al. [1] Three-point bending tests conducted on sandwich structures with various core shapes demonstrate that their mechanical properties are largely dependent on the core shape. Due to the characteristics of fiber-reinforced composites, using fiber tension in the production process enables printing structures without support. K.Sugiyama et al. designed four core material shapes: honeycomb, rhombus, rectangle, circle. Research indicates that both ultimate load and flexural modulus increase with effective density. Among them, the rhombic core material exhibits the highest maximum load and flexural modulus per unit density, demonstrating the most optimal performance.

3.2 Kagome

Periodic cell structures can overcome uncertainty brought by uneven fiber distribution or complex layering process due to its geometric regularity as it provides predictable and uniform enhancement performance. Derived from Japanese, kagome was named as it is Similar to the

Japanese bamboo basket pattern, composed of a series of triangles sharing common vertices. Three-dimensional kagome structure composed of a pair of tetrahedral structures, vertically inverted and offset by 60 degrees from each other.[4] With its unique geometric structure, Kagome truss exhibits excellent shear resistance and energy absorption capabilities [5][6].

3.3 Novel Single-Stroke Path Planning Algorithm

Yamamoto et al.[7] proposed an innovative path planning method, aims to address fiber damage and print failures caused by path intersections in continuous carbon fiber 3D printing. This method generates a Euler graph based on the selected structure and applies Hierholzeral gorithm, translate a connected undirected graph G(V,E) representing the printed pattern, to ensure has a Eulerian circuit that traverses each edge exactly once. Identify the set of odd vertices, construct a complete graph, and solve the minimum-weight perfect matching. For each matched pair in the minimum-weight perfect matching, find its corresponding shortest path in the original graph. Duplicate each edge along this path once, and finally obtain the Eulerian graph by performing a union operation on the edge sets. The implementation path applies two rules without overlapping. Odd-Even Rule: when selecting the next vertex from the current one, skip one vertex, ensuring that the paths entering and exiting from that vertex alternate. Winding Number Rule: the path newly chosen can not cross any other paths previously planned at that vertex. They strictly judge by calculating angle to ensure path are separate, and non-interference. By generating single-pass non-crossing paths, achieved integrated printing of complex structures, eliminating fiber breakage and strength loss. Applicable to periodic patterns (honeycomb, triangular), variable-wall-thickness structures, and non-periodic patterns (Voronoi diagrams).

3.4 Multi-scale Topology Optimization

Huang et al. [8] established a design and manufacturing framework for C-CFRC topological lattice structures utilizing macro-topological morphology and micro-fiber trajectory optimization. Considering the difference between anisotropy and the regions between crystal cell intersections and edges of CCFRCs, evaluated the mechanical properties of the cross-shaped lattice unit cell using a numerical homogenization method. Based on the SOMP method, a continuous path generation approach was proposed that simultaneously optimizes both the macroscopic structural topology and the orientation of microscopic lattice units. This method generates continuous paths that follow the topological lattice structure, converting the optimization results into smooth, continuous 3D printing paths. For MBB beam, compared with traditional uniformly distributed periodic unit cells lattice structure, structural stiffness and peak load capacity increased by 182.94% and 57.96%, respectively, representing improvements of 143.72% and 20.71% compared to the fixed-cell topological lattice structure. The optimized drone arm can withstand 10.42 times the operational load.

4.The Amorphous Cell Filling Path Mode

4.1.The Traditional Amorphous Cell Filling Path Mode

According to Bi et al. [9], 3D printing filling path mode can be divided into 3 categories: Direction-parallel paths, contour-parallel paths, and space-filling curves. Traditional amorphous cell filling path mode mainly have line, zigzag, contour, spiral, Fermat spiral, Hilbert. Among them, line and zigzag are widely used because of its simplicity, but have problems of nozzle starts and stops frequently, producing sharp edges. Contour-parallel path though aligns well with the boundary, may result in underfilled or overfilled areas. The Hilbert path within the space-filling curve category may compromise print quality due to its frequent sharp corners. Therefore, seeking a path that is globally continuous and trajectory-smooth is crucial for maximizing print quality and efficiency.

4.2.Interconnected Microchannel Network

Li el al.[10] using FFF to produce Elliptical microchannel in CFRTP, propose and implement a 3D path planning strategy producing microchannel in CFRTP no need to cut the fiber. Generate G-code using Python scripts, design elliptical and slot-shaped holes via Bézier curves, and synchronize multi-layer paths to construct three-dimensional interconnect channels. Micro-pores are formed through path deformation design, with the printed paths surrounding the pores creating a microchannel network within the CFRTP. Continuous fibers are arranged around these micro-pores to form elliptical or channel-shaped pathways, thereby constructing a complex Y-shaped interconnected network. Maintaining continuity of fibers, thus significantly improved mechanical properties of composite materials, avoids the issues of fiber breakage and performance degradation associated with traditional microchannel fabrication methods.

4.3.Intersection Node Processing

Wang et al. [11] proposed a full-field filling path planning strategy driven by geometric and tensile properties to generate paths with Eulerian trajectory characteristics. The tensile strength of C-FRTP is enhanced by strategically dispersing all intra-layer and inter-layer intersections through optimization. Firstly generated based on Euler graph theory, ensuring the integrity of complex contours. Subsequently, by establishing a quantitative model linking intersection point distribution to tensile strength, path intersections are strategically dispersed both within and between layers to minimize their weakening effect on material strength, thereby achieving a significant enhancement in tensile performance. The novel path planning strategy proposed in this study simultaneously preserves the geometric features and tensile properties of target components during the manufacturing of parts with complex geometries. For example, the tensile strength and peak force of the test specimen with mounting holes reached 349.4 MPa and 2432 N, respectively, when printed using the new path planning strategy. Compared to the existing contour-parallel path, the new strategy achieved improvements of approximately 40.9% and 28.2%, respectively.

5. The Generative Filling Path Mode

5.1 Principal Stress Direction-Aware Streamlined Printing Path Planning

Traditional printing paths (such as contour and zigzag) are primarily designed based on geometric factors, not considered Anisotropy for FFF, leading to printed parts are prone to fracture under stress. Yan et al. [12] propose arranging the print path along the direction of the principal stress to significantly enhance the load-bearing capacity of the part at the same or even lower infill density. For the first time, the principal stress direction field (PSDF) is tightly integrated with the stream function theory. Through finite element analysis, the PSDF is extracted and treated as the tangential direction of the flow field. A stream function based on B-spline basis functions is used to analytically represent the PSDF, and its contour lines are extracted as potential printing paths. This approach analytically generates continuous printing paths that strictly adhere to mechanical principles. Through interpolation and trimming frameworks, the method was successfully extended to parts with complex features such as holes and grooves. This path-connecting strategy significantly enhances mechanical properties while maintaining printing efficiency comparable to or even superior to traditional methods.

5.2 Structural Optimization

Xia et al. [13] proposed a beam element skeleton optimization method considering manufacturing constraints. By directly integrating process constraints such as extrusion width and path continuity into the optimization model, it achieves lightweight design prioritizing manufacturability. This addresses the printing defects (e.g., underfilling, overfilling, path discontinuity) and insufficient mechanical properties inherent in traditional lightweight designs (e.g., periodic lattice structures, continuum topology optimization) when applied to material extrusion techniques. Structural optimization integrates the effects of bending moments, shear forces, and axial loads by refining beam elements, followed by generating paths using a global continuous path-filling method. This approach better approximates the actual stress characteristics observed in material extrusion processes. Specimens fabricated using this method exhibit superior mechanical properties compared to those produced with the widely adopted periodic lattice structures.

6. Challenges and Outlook

In summary, current research on FFF-based 3D printing path planning has established several distinct technical paradigms. Among them, the cell filling path mode, the amorphous cell filling path mode, and the generative filling path mode strategic foundations have evolved from geometric filling to complex performance-driven approaches, becoming the mainstream solution for addressing diverse application requirements. Although the aforementioned strategies all are designed to optimize print quality and efficiency, they have fundamental trade-offs and are less relevant. Current research is facing several key challenges. Firstly, the complex structural design and performance simulation prediction face challenges. How to optimizing the macro-level structure while ensure Continuous fiber arrangement and interfacial bonding quality at the micro/meso scale at the same time, is currently a lack of integrated solutions. Accurate prediction and optimization of lattice structures' compression, impact, and hysteresis properties remain complex. Failure modes are closely linked to manufacturing defects and node strength, with gaps existing between theoretical models and experimental results. Multifunctional integrated design necessitates incorporating structural load-bearing with thermal management, sensing, and other functions within composite lattice structures. This involves multiphysics coupling design, demanding synergistic optimization of material properties, geometry, and internal pathways (e.g., microchannels). Currently, this field remains exploratory, lacking systematic design methodologies and performance databases. Despite analytical and numerical simulation studies, simulation results heavily depend on accurate descriptions of manufacturing defects—such as voids, fiber bending, and interfacial debonding—and material anisotropy. These factors are difficult to fully replicate in simulations, leading to discrepancies between predicted and measured performance. The fundamental challenge lies in the fact that most methods still fall under the category of passive adaptation to the topology of geometric models, rather than active design of optimal manufacturing instructions. Second, manufacturing efficiency, precision, and scalability also face challenges. When producing continuous fiber composites using FFF-type processes, nozzle size and fiber diameter limit the minimum feature size and detail accuracy of structures, affecting the forming quality of slender members or complex nodes within the structure. Professional 3D printing equipment capable of handling continuous fibers—especially carbon fibers—is costly, and the printing process causes significant nozzle wear. At the same time, high-performance continuous fibers and thermoplastic matrix materials themselves are quite expensive, which limits the widespread adoption and application exploration of the technology. Finally, there are challenges in practical application verification and standardization. There is a lack of long-term performance and durability data, with most research focusing on testing static mechanical properties. Studies on the long-term performance of composite lattice structures under real-world conditions—such as dynamic loading, fatigue, and humid-heat aging—remain severely inadequate. This poses a major obstacle to its application in critical areas such as civil infrastructure. Moreover, there is a lack of unified design and evaluation standards: currently, design methodologies, process specifications, and performance testing standards for 3D-printed continuous fiber composite structures have yet to be established. Results from different studies are difficult to compare directly, hindering rapid technological iteration and engineering applications. Scaling up structurally validated designs and manufacturing processes from laboratory scale to actual engineering components reliably presents a comprehensive challenge involving manufacturing consistency, controllable performance, and cost-effectiveness. Artificial intelligence algorithms can be leveraged to develop integrated design software in the future, higher-precision and more intelligent multi-material printing equipment, and more systematic and in-depth databases of in-service performance. Through big data fitting, predictions and actual test results can be brought closer together, establishing a unified design evaluation standard.

7. Conclusion

This paper systematically reviews the research based on FFF 3D Printing Path Planning of Continuous fiber-reinforced composites. In cell filling path mode, the Rhombus cell structure and Kagome each exhibits outstanding properties, and through path planning to avoid intersections and topological optimization of lattice structures and manufacturing frameworks, improvements in mechanical properties and other characteristics can be achieved. The amorphous cell filling path mode for specific scenarios such as microchannels, it offers superior path planning advantages and also provides planning methods for handling intersection nodes. The generative filling path mode is an emerging field, viewed from a top-down perspective. Printing paths are planned along the principal stress direction to reinforce the structure from a printing principle perspective and optimize it from a force perspective. This paper innovatively reviews the topic from cell filling path mode, amorphous cell filling path mode, generative filling path mode. Building a unified analytical framework, modeled on the progression from simple structures to optimized approaches. This framework not only clearly reveals the intrinsic origins of the strengths and weaknesses of various strategies, but also provides a theoretical foundation for understanding and predicting the performance of new pathfinding algorithms. Future work may incorporate simulation analysis in relevant fields, expand the scope of the review, and further subdivide categories within each classification. In cell filling path mode, two-dimensional lattice stretching and complex three-dimensional trusses can be further subdivided. Advantages in other specific scenarios of amorphous cell filling path mode can be clearly categorized, such as handling irregularly shaped edges and corners. The generative filling path mode is a great perspective. Current research on this topic remains limited, further classification and research can be conducted in this field.

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