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Research Status of Curved Surface Slicing Technology in Multi-Axis 3D Printing

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Abstract. It is difficult to balance accuracy and efficiency for traditional plane slices in additive manufacturing, and the step effect and anisotropy will damage the mechanical properties of complex bending parts. Curved slices that conform to the geometry and load characteristics of the model have become a key driving factor for multi-axis printing. This article systematically reviews the surface slice method and divides them into four paradigms: geometric drive, mechanical drive, design and manufacturing collaboration, and artificial intelligence drive. The geometric driving method achieves non-support manufacturing and high surface quality, but lacks multi-load adaptability. The mechanically driven method significantly enhances the strength and stiffness of continuous fiber composite materials, but the uniformity of layer thickness and surface smoothness needs to be improved. Design-manufacturing collaboration can achieve concurrent structure and process optimization, although the computing cost is high. Artificial intelligence-driven technology provides an order of magnitude acceleration in predictive efficiency, but relies heavily on training data and shows limited interpretability. Key bottlenecks still exist, including strong layer thickness control, multi-material and multi-load adaptability, and path post-processing. This review clarifies the relative advantages and limitations of the current surface slicing technology, and provides a systematic reference framework for future physical information integration and end-to-end joint optimization. Compared with the existing review, this paper systematically sorts out the surface slice method driven by design and manufacturing collaboration and artificial intelligence for the first time, and puts forward a future development framework for the integration of physical information.

Keywords: multi-axis 3D printing, curved surface slice, geodesic distance field, main stress line, artificial intelligence

1. Introduction

Additive manufacturing converts digital models into physical parts through layer-by-layer stacking. As the core link between three-dimensional geometry and physical manufacturing, slices directly affect production efficiency, surface quality and mechanical properties. Early slicing mainly adopts the strategy of uniform layer thickness. Although it is simple to implement, thin layer printing takes too long, and thick layer brings a significant step effect, which makes it difficult to balance accuracy and efficiency. In order to solve this contradiction, researchers introduced the local geometric

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features of the model into slice decision-making and proposed an adaptive slice technology. Among them, the concept of local adaptive slices that divides the model into independent subblocks and determines the optimal layer thickness was first proposed; Hu et al. [1] further introduced candidate feature points and used multi-directional cutting and threshold screening to identify geometric complex areas, so as to dynamically adjust the layer thickness. These plane adaptive slicing methods provide an important theoretical premise for subsequent surface slicing technology.

However, the plane adaptive slice always takes the plane as the basic unit of the layer sheet, which cannot fundamentally eliminate the step effect and anisotropic defects when dealing with free surfaces or complex stress flows. At the same time, the increasing maturity of the multiaxial motion system makes the deposition of non-plane layers possible, prompting researchers to begin to explore curved slices. The curved layer fused deposition modeling (CLFDM) proposed by Chakraborty et al. [2] systematically demonstrated the feasibility and superiority of surface layer printing for the first time. Since then, a variety of surface slice methods based on geodesic distance field, scalar field, main stress line and data-driven neural network have emerged one after another, and the slicing process is deeply integrated with upstream and downstream processes such as process planning and topology optimization, showing a trend of transformation from "manufacturing-oriented design" to "manufacturing and design integration".

This paper aims to systematically review the research status of curved surface slicing technology in multi-axis 3D printing, and clarify the technical characteristics and applicable boundaries of various methods. Section 2 explains the limitations of plane slices and gives the overall classification framework of surface slices; Section 3 introduces the geometry-driven surface slice method; Section 4 discusses the surface slice strategy for mechanical performance optimization; Section 5 analyzes the coordination mechanism of surface slices and topology optimization; Section 6 comments on artificial intelligence-driven surface slice method; Section 7 summarizes the research conclusion. The existing review focuses more on geometrically driven surface slicing technology. This article comprehensively covers the latest progress of mechanical performance optimization, topological optimization coordination and artificial intelligence driving, providing a complete reference system for multi-axis 3D printing process planning.

2. Limitations of plane slices and the rise of curved slices

No matter how the layer thickness of the plane slice is adaptively adjusted, the slice layer is always limited to plane, so it is difficult to fundamentally improve the step effect and anisotropy problems when dealing with complex curved surfaces. As shown in Figure 1, the research of Fang et al. [3] on the GE-Bracket model shows that the plane slice path is often seriously misaligned from the main stress direction and cannot effectively connect multiple bearing areas, resulting in a significant limitation of the mechanical properties of the workpiece.

This contradiction between structure and manufacturing gave rise to the surface sectioning method. With the development of multi-axis printing technology, researchers began to expand the slice layer from plane to curved surface, so as to better meet the geometric characteristics and mechanical requirements of the model. The CLFDM proposed by Chakraborty et al. [2] is a pioneering work in this field, which systematically demonstrates the feasibility and superiority of curved surface layer printing for the first time. Since then, the direction of surface slicing has quickly become a research hotspot in the field of additive manufacturing, and a variety of surface slicing methods based on geodesic distance field, scalar field, main stress line, etc. have emerged, and the coordination with upstream links such as process planning and topology optimization has become closer and closer.

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According to the different technical driving factors, this paper divides the existing surface slicing methods into four categories: geometric drive, mechanical performance drive, design and manufacturing collaboration and artificial intelligence drive. As shown in Figure 2, the following sections will be discussed in turn.

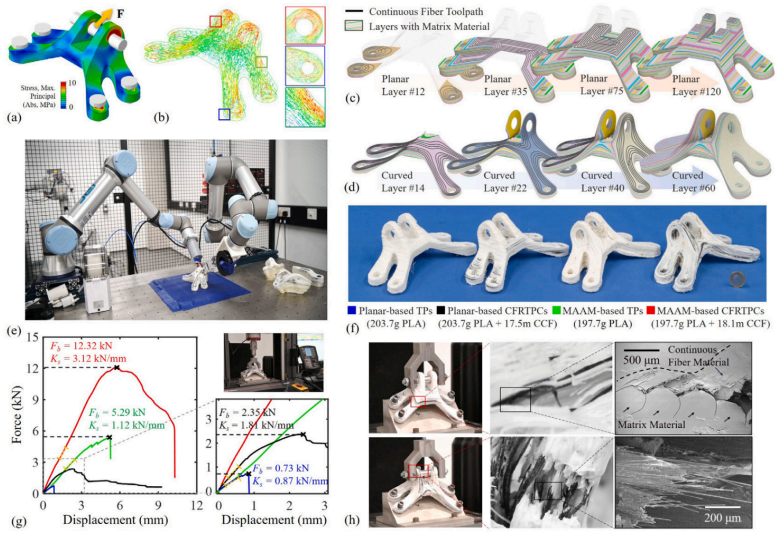

Figure 1. Comparison of plane slice and surface slice (a) Load conditions and stress distribution of GE-Bracket model; (b) Main stress flow; (c) Plane slice path misaligned with stress direction; (d) Curved slice path aligned with stress direction; (e) Dual robot printing system; (f) Models manufactured by different strategies; (g) Tensile test results; (h) Fracture morphology comparison (reprinted from Fang et al. [3], 2024, CC BY 4.0)

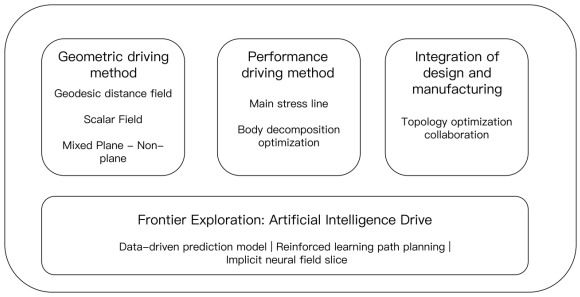

Figure 2. Classification framework of curved surface slicing methods (photo credit: original)

3. Geometrically driven surface slicing method

The geometrically driven surface slice method generates the surface layer completely based on the geometric characteristics of the model, such as curvature and distance field. No external load information is required, which is the basis of surface slicing technology. Its main goal is to eliminate the step effect, reduce the supporting structure and improve the surface quality through the surface layer envelope.

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3.1. Surface slices based on the geodesic distance field

The geodesic distance field method constructs the curved surface layer of the natural envelope by calculating the equivalent surface of the geodesic distance in the model surface or space. Xu et al. [4] proposed a surface layer decomposition algorithm based on the surface geodesic line: first establish a geodesic distance field on the surface of the model (Figure 3), and then generate a non-plane slice layer wrapped along the equivalent surface of the distance field, so as to significantly reduce or even completely eliminate the supporting structure, while greatly improving the surface quality of complex curved surfaces. The method uses the mathematical properties of the geodesic distance to ensure the smooth transition and interference-free between the surface layers.The essence of the geodetic distance field method is to transform the three-dimensional model into a distance calculation on a two-dimensional manifold, so it is naturally suitable for simply connected surfaces, but there will be a problem of distance field discontinuity for multiply connected surfaces (such as perforated parts).

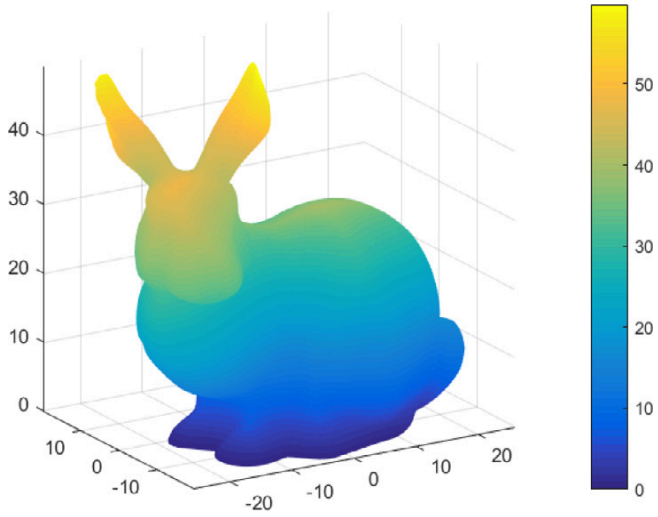

Figure 3. Geodesic distance field on the Stanford rabbit model (reprinted from Xu et al. [4], 2019, CC BY 4.0)

3.2. Coordinate generation of curved surface slices and internal structures based on scalar field

This kind of method expands the distance field from the model surface to the three-dimensional volume, constructs a global scalar field in the body space, and realizes the integrated self-support generation of the surface slice layer and the internal filling structure. Li et al. [5] further established a global geodesic distance field in the three-dimensional space of the molding model, and realized the collaborative generation of the curved slice layer and the internal grid filling structure based on this distance field. Its core advantage is that both the curved surface and the internal grid structure of the model have self-supporting characteristics, which realizes the integrated design of self-supporting performance inside and outside the molding structure. However, the method is relatively sensitive to the change of layer thickness in the direction of the scalar field gradient, and the control of layer thickness uniformity in the high-curvature mutation area still needs to be further optimized.

Furthermore, Lau et al. [6] proposed a partition-based print sequence planning algorithm for scalar field-based multi-axis additive manufacturing, which solves the collision problem between

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the nozzle and the in-process workpiece and realizes adaptive slicing with self-support constraints, further improving the practicability of scalar field slicing technology.

3.3. Mixed plane-non-plane slicing strategy

The hybrid plane-non-plane slice strategy refers to the use of traditional plane layer filling inside the model, and the use of non-plane curved surface layer covering in the outer surface area to take into account the internal filling efficiency and surface quality. Fortunato et al. [7] proposed a fully automatic non-plane slicing algorithm to keep the plane layer filling inside the model, and cover the upper and lower outer surfaces with non-plane layers. This strategy of "difference inside and outside" effectively eliminates the step effect of the outer surface and enhances the adhesion on the complex substrate, providing a low-cost and easy-to-achieve hybrid implementation method for curved surface slices.

The above geometric driving methods solve the problem of "how to generate a curved surface layer" well, but most of them slice the model as a whole under the assumption of no load, and have not included physical factors such as the mechanical state during service into the decision-making of layer morphology.

4. Curved surface slice method for mechanical performance optimization

Unlike the geometric driving method, the surface slice method for performance optimization directly maps the mechanical performance requirements to the slice geometry, and improves the strength, stiffness and other mechanical indicators of the piece by optimizing the morphology and direction of the surface layer.

4.1. Surface slices based on the main stress line

The surface slice based on the main stress line converts the main stress line field obtained from finite element analysis into a scalar field, and then generates a surface layer distributed along the stress direction, so that the main direction of the printing path is consistent with the carrying path. Fang et al. [3] combined the main stress line (PSL) analysis with scalar field optimization to generate curved surface layers and internal printing paths arranged along the stress direction for continuous fiber-reinforced composites. Figure 4 shows the complete process of the method: starting from the load and boundary conditions, the main stress distribution is obtained through finite element analysis, the main stress line is extracted, the optimization scalar field is calculated, and finally the curved surface layer sequence and continuous fiber path are generated. The innovation of this method is to directly map the mechanical property requirements into the slice geometry, so that the slice direction is consistent with the main stress direction, thus significantly improving the structural mechanical properties.The main stress line slicing method is only applicable to a single load condition. When the part is subjected to multi-directional alternating load, the stress direction will change. At this time, the fiber enhancement effect of a single direction will be significantly reduced.

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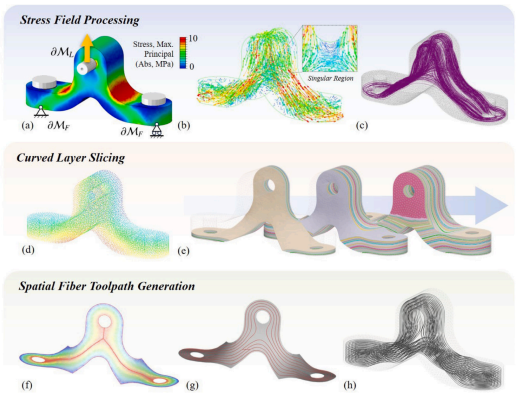

Figure 4. Surface slice and continuous fiber path generation process based on the main stress line (a) Model input and boundary conditions; (b) Main stress distribution; (c) Extracted main stress line; (d) Optimized scalar field; (e) Generated surface layer sequence; (f-g) Continuous fiber path on each surface layer (reprinted from Fang et al. [3], 2024, CC BY 4.0)

4.2. Optimization of printing direction based on body decomposition

The printing direction optimization based on body decomposition decomposes the model into multiple sub-blocks and specifies the optimal printing direction for each sub-block, so as to coordinate the printing direction with the main stress direction while avoiding support interference, so as to achieve mechanical performance enhancement. Bi et al. [8] proposed a body decomposition optimization method that takes into account the enhancement of mechanical properties and the effectiveness of support. Figure 5 shows the optimization decomposition results of the method on three models of L-shaped beams, Stanford rabbits and mechanical brackets. Different colors represent different sub-blocks and their printing directions. This method avoids placing the sub-interface in the high-stress area by optimizing the decomposition plane, while encouraging the maximum main stress direction to be perpendicular to the construction direction, which improves the mechanical properties of the workpiece while ensuring unsupported printing.

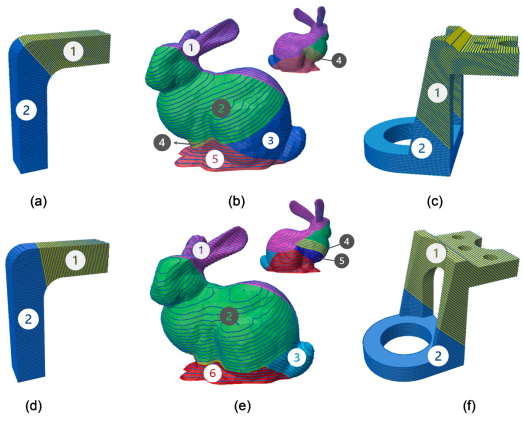

Figure 5. Optimization results of body decomposition(a) Optimized decomposition of L-shaped beam (2 sub-blocks); (b) Optimized decomposition of Stanford rabbit (5 sub-blocks); (c) Optimized decomposition of mechanical bracket (2 sub-blocks) (reprinted from Bi et al. [8], 2023, CC BY 4.0)

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5. The coordination of surface slice and topology optimization

In the traditional serial design-manufacturing process, the results of topology optimization often fail to meet the manufacturing constraints of surface slices, which leads to post-processing modification and even design rework. In order to solve the problem of disconnection between structure and process, Xu et al. [9] proposed a surface slicing method that cooperates with topological optimization. The method no longer regards model geometry as a fixed input, but while optimizing the structural topology, it generates a "process scalar field" by solving thermal diffusion and Poisson's equation. The field equivalent surface directly defines the shape of the surface slice. The framework incorporates self-support constraints into the optimization goal, and realizes the parallel optimization of structural topology and slice process, marking the paradigm shift from "manufacturing-oriented design" to "manufacturing and design integration". As shown in Figure 6, Xu et al. [9] concurrently optimize the structural topology and process scalar field to make the generated surface slices meet the self-support constraints, and the layer thickness is uniform and continuous. Different colors in the figure represent different printing layers, which intuitively reflects the parallel optimization effect of structure and process.

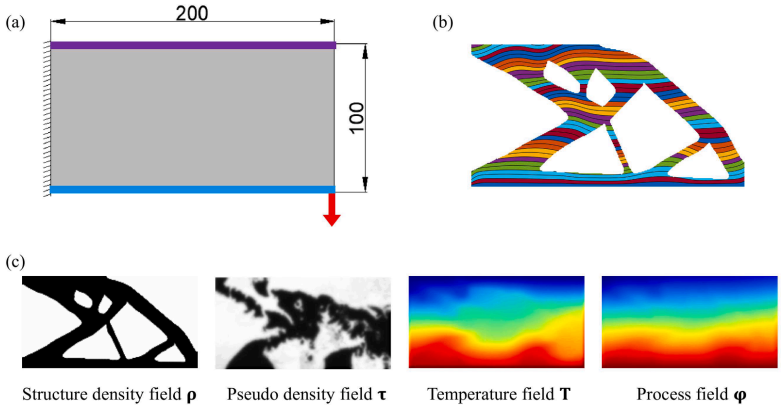

Figure 6. Short cantilever beam topology optimization and surface slice coordination results(a) Boundary conditions; (b) Optimized multi-axis additive manufacturing design; (c) Related scalar field (reprinted from Xu et al. [9], 2025, CC BY 4.0)

6. Artificial intelligence-driven surface slicing method

In recent years, artificial intelligence technology has promoted the transformation of surface slices from "geometric drive" and "physical drive" to "data drive" and "learning drive", showing significant advantages in prediction efficiency and automation level.

Falco et al. [10] combined the deep neural network (DNN) with the adaptive slice algorithm for the geometric control of cold spraying additive manufacturing. The method uses physical models to generate training data, so that the neural network can quickly predict the sedimentation morphology under different process parameters, and dynamically adjust the layer thickness accordingly. The calculation time is two orders of magnitude shorter than the traditional method. As shown in Figure 7, they constructed two deep neural network architectures to predict the two-dimensional cross-sectional contour and complete three-dimensional morphology of single-channel deposition respectively, and the prediction accuracy reached 0.59% (2D) and 2.62% (3D) of the relative L^2 error.

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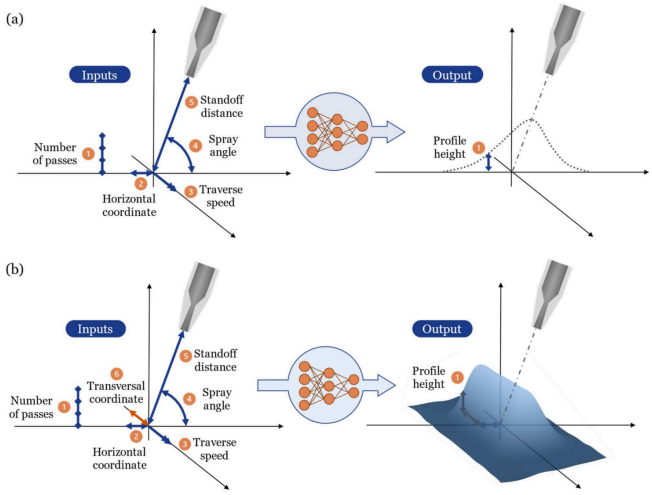

Figure 7. Deep neural network prediction model in cold spraying additive manufacturing (a) 2D DNN architecture (predicting cross-sectional contour); (b) 3D DNN architecture (predicting three-dimensional sedimentation morphology) (reprinted from Falco et al. [10], 2025, CC BY 4.0)

Huang et al. [11] modeled tool path planning into sequence decision-making problems, and used the deep Q network to optimize the printing order and path selection. This method significantly reduces sharp cornering (up to 93.3%) and reduces thermal deformation (24.9%) in scenarios such as continuous fiber printing, providing new ideas for the joint optimization of curved surface slices and path planning.

The INF-3DP framework proposed by Qu et al. [12] uses the implicit neural field to unify the curved surface slices, tool path generation and collision-free motion planning of multi-axis printing. The framework directly encodes the manufacturing target into the neural field optimization, realizes end-to-end slice path generation, and achieves two orders of magnitude acceleration compared with the traditional method.

7. Conclusion

This paper adopts the method of classification and review, taking geometric drive, performance optimization, topology optimization coordination and artificial intelligence drive as the analysis framework, and systematically sorts out the research progress of multi-axis 3D printing surface slice technology.

Judging from the horizontal comparison of the four types of methods, the geometric driving method takes the geodesic distance field and the scalar field as the core, which can realize the automatic generation of the curved surface layer and the self-support design of internal and external integration under no load information. The hybrid plane-non-plane strategy eliminates the outer surface step effect at a low cost, but this type of method generally lacks the active regulation ability of the service mechanics state, and is difficult to take into account strength and stiffness under multi-load conditions. The mechanical property driving method highly matches the slice direction with the bearing path through main stress line analysis and body decomposition optimization, which significantly improves the rigidity and strength of continuous fiber-reinforced composite materials. However, its layer thickness uniformity depends on the gradient distribution of the scalar field, and the smoothness control of the curved surface in the high-curvature area is still weak, and the automation ability of body decomposition on complex topologies is limited. The design and

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manufacturing collaborative method embeds self-support constraints into the topology optimization process, which realizes the parallel solution of structural topology and surface slices, and fundamentally avoids the disconnection of the traditional serial process. However, it is necessary to solve the topological optimization and Poisson equation at the same time, the calculation cost is high, and at present it is mainly limited to simple topological configurations. The artificial intelligence-driven method uses technologies such as deep neural network, deep reinforcement learning and implicit neural field to achieve two to three orders of magnitude calculation acceleration in sedimentary morphology prediction, path optimization and end-to-end slice generation, but its performance is highly dependent on the coverage of large-scale high-quality training data, and the generalization ability under unseen working conditions is insufficient, and the "black box" characteristics lead to the lack of transparency and interpretability of slice decision-making.

Overall, curved surface slicing technology has made important breakthroughs in supportless molding and single load performance enhancement, but there is still an urgent breakthrough in key issues such as multi-material/multi-load coupling adaptability, layer thickness uniformity robust control, complex structure path post-processing and AI interpretability.

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