Research Progress on Support Structures for 3D Printing

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Abstract. 3D printing achieves the formation of complex structures based on the principle of layer-by-layer stacking. The supporting structure is the key to ensuring the stability of suspended parts and preventing deformation and collapse, directly affecting the success rate of printing, model accuracy and cost. Traditional support technologies have bottlenecks such as large contact areas that are prone to leaving marks, difficult removal, and excessive material waste. In high-precision scenarios, they may also affect the performance of parts and are hard to meet the demands of multi-material printing and the manufacturing of large and complex components. To break through the limitations of large-scale application of 3D printing and solve the pain points related to support, the research on support structures has significant theoretical value and practical significance, and has become a focus of industry attention. Starting from the social and theoretical background of the support structures in 3D printing, this article provides a comprehensive review of the problems encountered in the support structures of 3D printing in recent years. Research on 3D printed support structures covers three directions: materials, algorithms, and structural design. New support materials such as hydrogels and water-soluble PVA can reduce the difficulty of post-processing and environmental impact. Topological optimization, the minimum spanning tree algorithm and other optimization algorithms can reduce the amount of support materials used. Innovative support structures such as tree-shaped and octagonal prism-shaped, have shown advantages. At present, the support structure still faces problems such as high cost, easy shrinkage of parts or environmental pollution caused by post-processing. The main development directions are the non-support algorithm and intelligent post-processing technology.

Keywords: 3D Printing, support materials algorithm optimization structural innovation

1 Introduction

As a transformative advanced manufacturing technology, 3D printing, with its unique principle of layer-by-layer stacking, has achieved precise shaping of complex structures in fields such as industrial manufacturing, medical implants, and aerospace, breaking the shape limitations of traditional manufacturing. As the core guarantee of the printing process, the support structure plays a crucial role in supporting the suspended parts, conducting thermal stress, and preventing the deformation and collapse of the model. The rationality of its design directly determines the printing success rate, model accuracy, and manufacturing cost. In fused Deposition Modeling (FDM), support can prevent the molten material from sagging. In stereolithography (SLA)

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molding, the support can counteract the displacement caused by resin shrinkage and buoyancy. In metal printing, supports need to alleviate thermal stress concentration even more to reduce crack defects.

The 3D printed support structure is a key auxiliary part to ensure the successful printing of complex models. Its function is similar to that of scaffolding in construction, providing support for suspended, bridging and other structures during the printing process. After printing, it needs to be removed. The core significance of 3D printed support structures lies in ensuring the formation of complex models. They are the "essential auxiliary" for printing non-planar structures such as overhangs and hollowed-out structures, directly determining the success of the printing and the precision of the parts.

However, traditional support techniques have significant bottlenecks, such as the large contact area between grid-shaped supports and the model, the tendency to leave surface marks and difficulty in removal, and the need for a large amount of material stacking for columnar supports. In high-precision application scenarios, surface damage caused by support removal may directly affect the biocompatibility of medical implants or the mechanical properties of aviation components. With the increasing demand for multi-material printing and the manufacturing of large and complex components, the optimization of support structures has become a core issue for breaking through the large-scale application of 3D printing technology. Therefore, conducting a review of its research progress has significant theoretical value and practical guiding significance.

This article will report the research progress of 3D printed support structures from the aspects of support materials, algorithms, and support structure design. These issues jointly restrict the precision improvement and cost control of 3D printing technology.

2 Innovation in supporting materials

2.1 Hydrogel serves as the supporting material

At present, most of the ceramic 3D printing technologies based on slurry extrusion are single extrusion head 3D printing technologies, which have certain limitations when preparing complex-structured parts. The double extrusion head 3D printing technology provides feasibility for preparing ceramic parts with complex shapes. The key to dual-extrusion head 3D printing lies in the selection of support materials and structures as well as the removal of supports. Hydrogel, as a highly hydrophilic three-dimensional network structure gel, possesses excellent mechanical properties and shape retention while having an extremely high water content. Wu Xuexue et al. [1] prepared graphene /SiC composites by using hydrogel as the supporting material for 3D printing with dual extrusion heads. As a supporting material, hydrogel can not only be conveniently removed through high-temperature pyrolysis, but also has the advantages of low cost and environmental friendliness. It avoids the post-treatment problems such as significant dimensional shrinkage of sintered parts, cumbersome support removal process and environmental pollution caused by the traditional use of calcium carbonate [2], graphite slurry and starch-based slurry as support materials [3][4].

2.2 Water-soluble supporting materials

Water-soluble support materials have become a research hotspot due to the convenience of post-treatment. With the rapid development of fused deposition modeling technology, the demand for materials in this industry is becoming increasingly urgent. Wang Feilong successfully developed polylactic acid 3D printing consumables and polyviny alcohol water-soluble support materials through toughening modification of polylactic acid and plasticizing modification of polyvinyl alcohol [5]. Toughened PLA printing consumables were successfully prepared by using PBAT to modify PLA, which solved the problems of high brittleness, easy breakage and poor impact resistance of printed products of pure PLA, and broadened the application range of PLA. The PVA was plasticized and modified with glycerol and PEG200, and the PVA water-soluble support consumables were prepared by melt extrusion, avoiding the possibility of damage to the model caused by manual stripping of the support. However, the high water retention of PVA makes printing jobs more difficult and PVA is also very expensive. The support structure printed with Hydro-Support has a very high tensile strength, and its material performance is close to that of PLA. Such a feature enables 3D printed parts to easily remove the Hydro-Support structure within a few hours after being placed in water.

2.3 Gelatin Composite Material - Polyvinyl alcohol (PVA) bio-ink

Gelatin composite material - polyvinyl alcohol (PVA) bio-ink is designed to achieve self-support for the preparation of thick-layer three-dimensional porous scaffolds with good permeability. The bioink proposed by Phillips R K et al. [6] contains gelatin solution, gelatin microgel and polyvinyl alcohol (PVA), among which PVA acts as a sacrificial porogenic agent to promote the formation of pores after printing. This bio-ink is a compound of polyvinyl alcohol and gelatin, with a volume/weight ratio of 1:5. The rheological properties of this bio-ink exhibit shear thinning behavior and yield stress fluid characteristics suitable for extrusion 3D printing. Among them, the yield stress fluid characteristics can achieve a physical cross-linking mechanism based on blocking during the printing process. This mechanism works in synergy with the thermal cross-linking of the gelatin solution, enabling the printed structure to maintain its shape. The printed scaffolds exhibit excellent printing accuracy and structural integrity in both two-dimensional (2D) lattice and three-dimensional tubular geometric structures.

3 Innovation and optimization of algorithms

3.1 Topology Optimization

The combination of topological optimization and finite element analysis has become an important direction in support design. Through iterative calculation, the material minimization distribution is achieved under the premise of meeting strength constraints. Taking topological optimization as the method for lightweight structure design and adopting fused deposition modeling 3D printing technology, the influence of parameters (volume fraction and penalty factor) during the topological optimization process on the total deformation of the workpiece under bending load is explored. The workpiece quality before and after topology optimization under different filling rates was compared, and the bending performance of the workpiece at different fused deposition modeling 3D printing speeds after topology optimization was explored. The results show that when the volume fraction is 40% and the penalty factor is 3, the maximum deformation of the model after topological optimization meets the optimization objective. Topologically optimized workpieces printed by 3D printing can achieve a 50% weight reduction while maintaining a relatively high bending force [7].

3.2 Automatic Generation Algorithm for the Optimal Forming direction of SLM parts

Ge Yunyan proposed an automatic generation algorithm for the forming direction of SLM parts based on fuzzy multi-attribute decision-making for the planning problem of the forming direction of parts in the selective laser melting process [8]. This method is divided into two steps: Firstly, the STL model of the part is read. The HDBSCAN clustering algorithm is used to cluster the triangular patches in the STL model of the part, and the candidate forming directions of the SLM part are generated based on the divided clusters. Then, the volume of the support structure, volume error, surface roughness, forming time and forming cost are predicted and estimated to obtain the attribute values. A fuzzy multi-attribute decision-making scheme is introduced to process the attribute information and obtain the comprehensive preference score of each candidate forming direction, thereby locating the optimal forming direction of the SLM part. The case model shows that this method is operable and effective. The comparative experiment presents a set of freeform surface part models, verifying that compared with the traditional method, the proposed method takes into account the intrinsic connection among the attributes of SLM parts and improves the accuracy.

3.3 Minimum Spanning Tree Algorithm (MST)

The core value of the Minimum Spanning Tree (MST) in 3D printed support structures lies in achieving stable support with the least materials and the lowest cost. Essentially, it transforms the area of the model to be supported into a graph structure and optimizes the material usage and stability of the support through the minimum weight connection feature of MST. The discrete points to be supported are taken as "vertices", and the connections between vertices are regarded as "edges". The weight of the edges is defined as the length of the support path plus the cost of printing difficulty. Then, the MST is obtained through the Prim/Kruskal algorithm. At this time, the edges of the MST are the optimal support paths. By converting the edges of MST into solid supports (such as columnar or tree-shaped supports), the "ring-free feature" of MST can avoid cross-redundancy of supports and reduce the difficulty of post-processing.

4 Innovation and optimization of supporting structures

4.1 Tree-shaped support

Tree-shaped support achieves a balance between mechanical properties and material efficiency by simulating the branch morphology of tree growth. This is a novel external support method. Combined with the instance segmentation technology in artificial intelligence, it can better solve problems such as collapse, deformation, and precision loss during the 3D printing process, and improve production efficiency [9]. Its core advantage lies in the step-by-step transmission of the load to the substrate, with concentrated contact points with the model, and minimal surface damage during removal [10].

4.2 Octagonal prismatic support structure

The octagonal prismatic support structure is an optimized structure based on the prismatic support structure. When generating it, the octagonal prismatic support structure is produced using Matlab. Compared with the traditional support structure, it has different degrees of optimization in the printing results. The octagonal prism support structure is closer to a cylinder compared with the traditional prism, thus greatly saving material consumption and printing time. Taking the inclined plane model as an example, compared with the support structure generated by Cura software, the octagonal prismatic support structure consumes 27.23% of the material and takes 14.85% of the printing time. Take the suspended ball model as an example. Compared with the support structure of the Inspire S250 printer, the octagonal prismatic support structure reduces the printing time by 26.98% and saves 22% of the materials. Compared with Cura software, 8.6% of the printing materials were saved. Taking the artificial auricle model as an example, the octagonal prismatic support structure reduces the printing time by 63% compared with the Inspire-S250 type, saves 22% of the main material, and no printing support material is required [11].

4.3 Add support rings to the pipe mesh structure

In response to the problem of insufficient mechanical properties of the tubular network structure, Lu Hao proposed an on-demand structural design method of adding support rings to enhance mechanical properties [11]. A mechanical simulation model for the tubular mesh structure was established. Finite element analysis was conducted on the radial support performance and axial compressive resistance performance of the tubular mesh structure, and the influence laws of structural parameters on the radial support performance and axial compressive resistance performance of the tubular mesh structure were obtained. The simulation results show that adding support rings can effectively improve the radial support performance and axial compression resistance performance of the pipe network structure.

5 Existing problems and challenges

The support structure is a non-functional part and needs to be removed after printing, which directly leads to a waste of 10% to 30% of consumables, especially having a significant impact on the cost of high-priced materials such as metals and resins. The support needs to be removed manually or with special equipment, which can easily scratch the surface of the model (especially for resin parts). The support in complex inner cavities may not be completely cleaned, increasing working hours and the risk of scraping.

Sintering is prone to cause problems such as dimensional shrinkage of parts during the post-treatment of support materials. Li et al. [2] prepared alumina parts with a suspended structure using 50% filled calcium carbonate as the supporting material. During the sintering process of the parts, calcium carbonate decomposed to form calcium oxide, which was removed in an acid solution or water. The sintered parts experienced significant dimensional shrinkage (15% to 19%). Martinez-vazquez et al. [3] prepared alumina parts using graphite slurry as the supporting material. The solid content (mass fraction) of the graphite-based slurry was less than 50%. The shrinkage rate of the parts after sintering was relatively large, and the flexural strength of the printed parts after drying was relatively low, which was (1.04±0.04) MPa.

Handling supporting materials is prone to polluting the environment. Li et al. [4] prepared hollow alumina-based ceramic balls using starch-based slurry as the supporting material. During the sintering process, the starch-based support could be completely removed. However, due to the addition of polyvinylpyrrolidone solution to the supporting material, the removal process had a certain impact on the environment. It can be seen that even if the supporting material itself is an environmentally friendly material, However, it is also possible that the solvents used to remove the supporting materials are not environmentally friendly and cause environmental damage.

6 Future development direction

Develop support materials with special properties, such as soluble materials that can dissolve in water in a shorter time, and intelligent responsive materials that can automatically change their physical properties according to environmental changes such as temperature and humidity, making them easy to remove. In addition, biodegradable materials will also become an important development direction to reduce environmental impact.

The adoption of no support can completely avoid a series of problems brought about by the use of support materials. For instance, Barile Gianluca et al. [12] proposed a new no support algorithm in the 3D printing process of fused deposition modeling materials. This method can print suspended structures without support. This method is relatively easy to operate and only utilizes the built-in sensing devices and structures in standard 3D printing equipment, without the need for additional hardware. The proposed method can be applied to various objects, including long-span bridge structures and convex surface structures. Barile Gianluca et al. conducted precise tests on this algorithm for cantilever structures and bridge structures of different shapes. The analysis results show that regardless of the structural shape, the supported structure demonstrates the best accuracy in almost all measurement items. At present, the unsupported algorithms for SLA and metal printing still need to be studied.

Realize the automated and efficient removal of support structures. Through robot technology and intelligent devices, accurately identify and remove the supports, reducing manual operations and damage to the model surface. Meanwhile, augmented reality (AR) technology is utilized to assist in post-processing, providing more intuitive guidance for the support removal process. Research on multi-material composite support structures, combining the advantages of different materials, such as using high-strength materials in critical parts and degradable or easily removable materials in non-critical parts. In addition, the support structure and the functional structure are integrated in design, enabling the support to play a role during the printing process. After completion, part or all of it is transformed into a part of the functional structure.

7. Conclusion

The 3D printing support structure is a core auxiliary component that ensures the precise formation of complex models. It plays a crucial role in supporting suspended parts, conducting thermal stress, and preventing model deformation and collapse. The rationality of its design directly determines the printing success rate, model accuracy, and manufacturing cost. It has significant theoretical value and practical significance for breaking through the limitations of large-scale application of 3D printing and meeting the demands of multi-material printing and the manufacturing of large and complex components.

In recent years, significant breakthroughs have been made in the research of 3D printed support structures in three major directions: materials, algorithms, and structural design. At the material level, hydrogels and Hydro-Support materials can be conveniently removed through high-temperature pyrolysis and are environmentally friendly. They can avoid problems such as part shrinkage and cumbersome post-processing caused by traditional support materials. Gelatin-pva bio-ink has achieved self-supporting formation of thick-layer porous scaffolds by virtue of its unique rheological properties. At the algorithmic level, topological optimization combined with finite element analysis can minimize the support material while meeting the strength constraints. The automatic generation algorithm for the optimal forming direction of SLM parts can determine the optimal forming scheme by comprehensively considering multi-dimensional attributes. The minimum spanning tree algorithm can achieve the optimal configuration of the support path and material usage through graph structure transformation. At the structural design level, tree-shaped supports can achieve stepwise load transmission with minimal damage to the model surface. Compared with traditional supports, octagonal prismatic supports can significantly save materials and printing time. Adding support rings to the tubular mesh structure can significantly improve its radial and axial mechanical properties.

Although many advancements have been made in research, 3D printed support structures still face two core challenges: cost and post-processing. Support consumables cause material waste, and high-value materials such as metals and resins are particularly affected by this. At the same time, post-treatment is prone to cause dimensional shrinkage and surface damage of parts, and the removal of solvents from some supports can cause environmental pollution.

In the future, on the one hand, the research and development of new support materials that can dissolve rapidly, respond intelligently and are biodegradable can be accelerated to reduce the difficulty of post-treatment and environmental impact. On the other hand, it is necessary to focus on breaking through the unsupported algorithms in the SLA and metal printing fields to achieve unsupported printing of complex structures. In addition, the precise and automated removal of supports can be achieved by relying on robots and AR technology, promoting the development of support structures towards intelligence, greenness and functional integration.

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