Research on Printing Large-Scale Models Using Multi-Color 3d Printing Technology

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Abstract. Multi-color 3D printing, as a branch of 3D printing, is continuously driving the advancement of 3D printing. Multi-color 3D printing technology has now entered a new phase of rapid development, overcoming the limitations of traditional printing methods in producing large-scale multi-color models. This paper reviews research progress in printing large-scale models using multi-color 3D printing technology, against the backdrop of advancements in multi-color 3D printing. This paper first introduces the principles and significance of multi-color printing, then describes research progress from three aspects: material selection, partitioning strategies, and printing equipment. Finally, it analyzes and discusses the challenges that remain to be addressed and potential directions for future development in this field. This paper analyzes the interlayer bonding strength and thermal warpage mechanical properties of materials from two research perspectives. It then clarifies the significant role of surface subdivision algorithms in multi-color printing and large-scale model segmentation. Finally, by comparing single-nozzle and multi-nozzle systems, it concludes on the capabilities and limitations of multi-nozzle extruders. It is suggested that explore the mechanical properties in future research—such as interlayer adhesion—of different colors and materials, or incorporate reinforcing materials to modify the base materials. This paper proposes improvements and developments for multi-nozzle extruders to find equipment more suitable for large-scale multi-color printing.

Keywords: 3D printing; Multi-color; Partitioning; Nozzle.

1. Introduction

The development of multi-color 3D printing technology is inextricably linked to the evolution of 3D printing technology. In 1983, Chuck Hull invented SLA 3D printing technology, which he termed stereolithography, marking the official birth of 3D printing technology. Early 3D printing systems focused on processing and manufacturing a single material, so their multi-color printing capabilities were extremely limited. In recent years, 3D printing technology has made rapid strides, achieving significant progress in the field of large-scale model manufacturing. Qi Ge's team proposed a centrifugal multi-material 3D printing method for multifunctional heterogeneous objects. The CM 3D printer can fabricate large-area heterogeneous 3D structures, with applications in digital materials, robotics, and ceramic devices [1].

Multi-color printing technology associated with large-scale models is breaking through the limitations of traditional manufacturing, demonstrating tremendous potential in fields such as aerospace, automotive, biomedical, and electronic devices. Multi-color 3D printing technology has become a key driver in the field of advanced manufacturing. Using multi-color 3D printing saves time when printing large multi-color models and simplifies the printing process.

This paper analyzes and compares the interlayer adhesion of multi-color printing using several common materials for large-scale models. It ultimately summarizes their limitations and directions for improvement. This paper then analyzes the principles of surface partitioning algorithms and summarizes their strengths and weaknesses when partitioning large-scale models. Finally, this paper analyzes the principles of extruders, compares the advantages and disadvantages of single-nozzle versus multi-nozzle designs, and summarizes the benefits and limitations of extruders in multi-color printing.

The purpose of this study is to find suitable materials and printing equipment for producing large-scale multi-color models, analyze the principles and characteristics of large-model segmentation strategies, and enhance the print quality and efficiency of multi-color large-scale models.

2. Multi-Color Printing Overview

Multiple technical approaches enable multi-color 3D printing, each featuring unique material processing methods and color blending mechanisms. Common techniques for multi-color 3D printing include multi-color FDM printing and full-color MJF printing.

FDM is one of the most common 3D printing processes. Multi-color FDM utilizes two or more independent nozzles or a single nozzle for multi-color printing. During printing, multiple nozzles load different colored materials such as PLA and ABS, printing according to the program from the slicing software [2].

MJF (Multi-Jet Fusion) is a high-end 3D printing technology introduced by HP. It employs a CMYK (cyan, magenta, yellow, black) four-color inkjet system for full-color printing. During the printing process, the nozzle first sprays a melting agent and a refining agent onto the surface of the powder bed, followed by the spraying of CMYK four-color inks. By precisely controlling ink volume and distribution, the required colors are mixed. Finally, the heating unit melts and cures the powder, permanently fixing the colors within the model [2].

Zhang Zongyun believes that multi-color 3D printing is one of the key technological approaches in the field of smart manufacturing. Multi-color 3D printing technology provides an effective method for achieving precise color reproduction in the field of smart manufacturing [3].

Multi-color 3D printing technology serves not only as a visual presentation tool but also finds applications in product development, medical education, and numerous other fields. Its application scenarios are constantly expanding. Its value manifests on an aesthetic level, transforming traditional design workflows, boosting printing efficiency, and enhancing the user experience.

3. Selection of Materials

3.1. Multi-Color 3D Printing Materials Suitable for Multi-Color Printing Using FDM Technology

Materials available for multi-color printing using fused deposition modeling (FDM) include polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), acrylonitrile styrene acrylate copolymer (ASA), and others.

ABS of different colors exhibit weaker interlayer adhesion, particularly when printed at low temperatures or in open environments, where it is prone to warping and delamination. Under high-temperature sealed conditions, it can significantly improve the interlayer adhesion of different colored ABS materials [4].

Compared to ABS, ASA offers superior heat resistance and weather resistance [5]. ASA exhibits mechanical properties similar to ABS and possesses relatively good overall mechanical performance [4].

PLA is a new type of biodegradable material. PLA materials of different colors exhibit good interlayer adhesion during fused deposition modeling. The PLA's melting characteristics enable it to achieve good interlayer adhesion at relatively low temperatures. Experiments conducted by Zou Neng et al. demonstrated that the interlayer bond strength of PLA is higher than that of ABS and ASA [6].

3.2. Research on Material Selection for Large-Scale Models

During the printing of large multi-color models, adjacent layers exhibit thermal gradients, making the material prone to heat accumulation. Heat accumulation during printing generates residual stresses, leading to warping, thermal deformation, and other issues [7]. Insufficient material melting efficiency leads to inadequate interlayer adhesion [8]. Printing materials must meet requirements such as high-temperature resistance and warp prevention.

ABS, PLA, and ASA are commonly used thermoplastics in fused deposition modeling (FDM) 3D printing.

PLA (polylactic acid) is made from renewable resources such as corn starch or sugarcane. It is more environmentally friendly than ABS and ASA, and emits no irritating odors during printing. Printing PLA is easier than ABS and ASA. No heated bed is required when printing with PLA. PLA is less prone to warping than ASA and ABS. Its low warping tendency facilitates printing large, multi-color models. However, PLA is less heat-resistant than ABS and ASA [9]. When used for large, multi-color models, PLA material may have problems with high temperatures. ASA has better impact resistance and weatherability than PLA and ABS [10].

ABS is better than PLA in terms of impact resistance and wear resistance. Moreover, ABS is relatively heat-resistant, with a heat deflection temperature of approximately 100°C. ABS also has some drawbacks. It is relatively difficult to print, prone to warping and cracking, and releases gases such as styrene during printing [11]. If ABS material is used for printing, a heated bed and strict temperature control are required. These operations increase the difficulty of printing large models, and the material must be ventilated after printing is complete. In terms of printing results for large multi-color models, ABS produces outcomes similar to ASA.

4. Rapid Prototyping Technology Based on Partitioning Strategy

4.1. Principles of Rapid Prototyping Based on Partitioning

When printing large multi-color models, oversized models must be sectioned for printing.

Using a surface partitioning algorithm for the block allocation strategy, each module can be assigned colors or materials independently. Originally, multi-nozzle extruders could only extrude materials in a few colors. To use more colors, the filament had to be changed. After partitioning, a single extruder can fulfill the requirement of printing individual modules without changing filament, thereby improving printing efficiency.

Before applying the surface partitioning algorithm, the model first segments different color blocks. First, use the color block segmentation method to separate areas of different colors. Then, apply surface segmentation algorithms to further subdivide these distinct color blocks. This approach reduces printing time and improves printing efficiency.

The surface partitioning algorithm is a least-squares fitting algorithm. Its principle is easy to understand. First, determine the highest starting point and establish the search direction P0. Search for the point where the search direction changes along the search direction P0, using the formulation to compute the location. After determining the point where the search direction changes, the partition surface normal direction Pd' is obtained. As shown in Figure 1. New search direction—Pd' is the direction opposite to the partition surface normal. Repeating the above steps determines the optimal partition surface [12].

$$\mathrm{n}i \cdot (-\mathrm{Pd}) + \sin \alpha > 0 \tag{1}$$

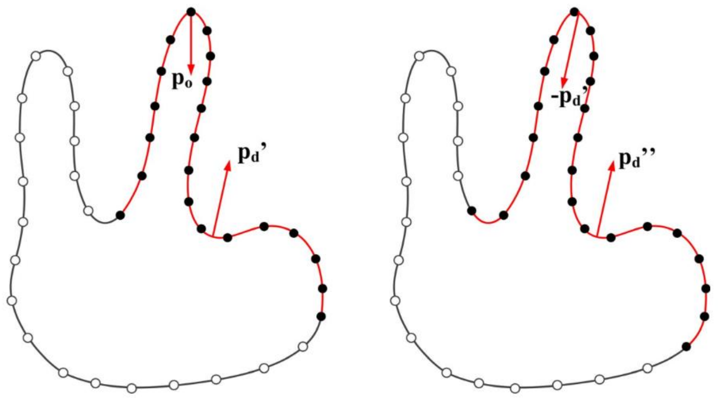

Fig. 1 The left and right pictures show the first round of downward search and the second round of downward search, respectively [12].

In Figure 2, after obtaining the partition surface, cut along the partition surface to remove the upper component, completing one partitioning operation. The partition surface is marked by a blue line, separating the top blue component from the bottom white component.

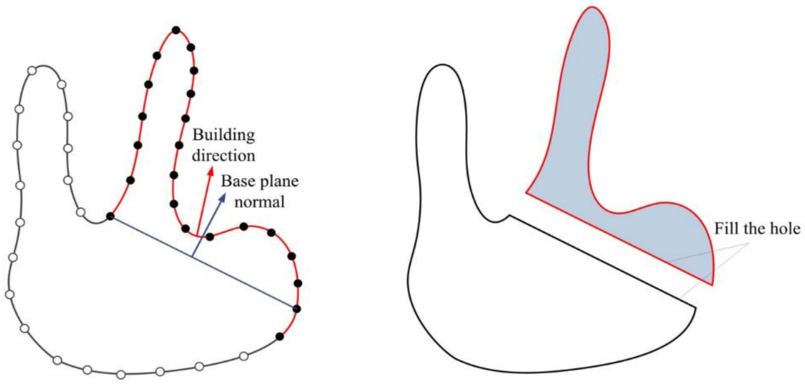

Fig. 2 Left and right images show the partition surface (blue line) and the separation of upper and lower components [12].

The following is a flowchart of the surface division algorithm Figure 3. Input a model to be solved to the program and analyze if no cut is required. If it is, the process is over. If not, find the starting point and start searching for the best partition surface. After the software slices the model, the sliced parts are taken and continued to be analyzed to see if they need to be sliced. If the program comes up with a result that needs to be sliced repeat the steps and vice versa end the process.

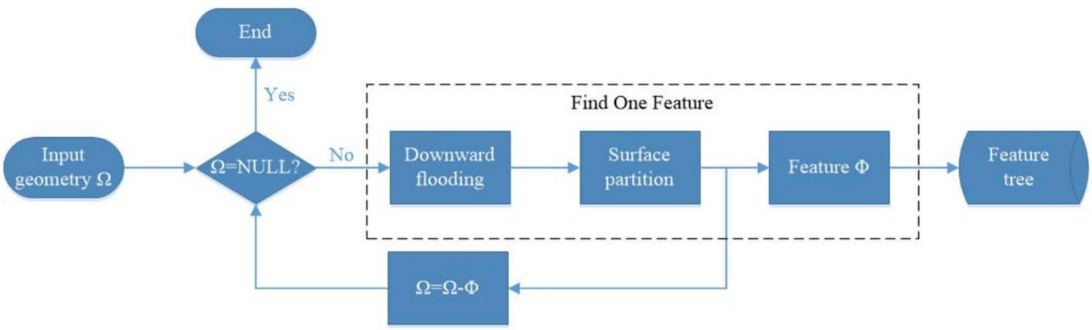

Fig. 3 The above figure shows the flowchart of the surface division algorithm [12].

Extending the surface division algorithm, the color blocking method is designed in this paper. The color block division method is similar to the surface division algorithm.

First, the program sets the starting point, then the search point advances in all directions, stopping when it reaches the edge of a color-changing block or when it reaches a point where the color change is obvious to a certain degree. Since this method is only used to separate color blocks with welldefined colors, it does not need to achieve the accuracy of the surface division algorithm, so it does not need to repeat the calculation.

Use the surface division algorithm with the color blocking method to slice a multi-color large model. If one of the cutting conditions of either the surface division algorithm or the color blocking method is satisfied, the cut can be made.

When using a hierarchical structure without support features, the program ranks modules of different colors and sizes. The program starts by slicing the smallest branch, slices the middle branch after slicing the small branch, and finally slices the large branch. The print slice model order is then the exact opposite of the slice order.

Figure 4 shows an example of a tree decomposition diagram. Starting with module 1 at the top and slicing down to module 2 below, then to module 3 on the left, slicing down until it is no subdividable. In Figure 4, the left picture shows the resultant diagram after cut-and-sort, and the right one is the simplified hierarchy diagram.

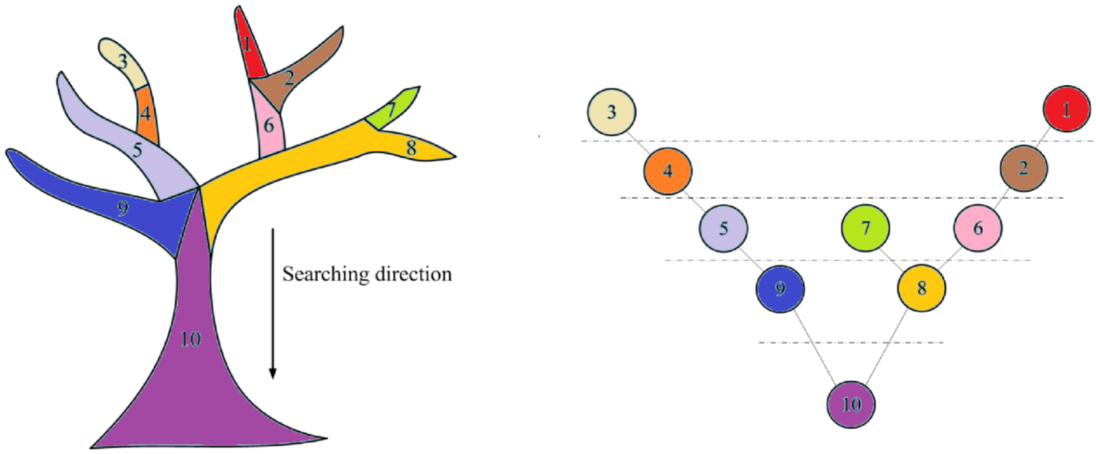

Fig. 4 Left and right shows the tree decomposition and hierarchy diagrams respectively [12].

The program will correct the print sequence if the nozzle is too large and collides with a printed branch. The cross-printing method was used to solve the problem of printhead interference in printing branching models [12]. Figure 5 shows, on the left, a picture of a conflict between the nozzle printing and the position of the already printed branch, and on the right, a simplified hierarchy picture.

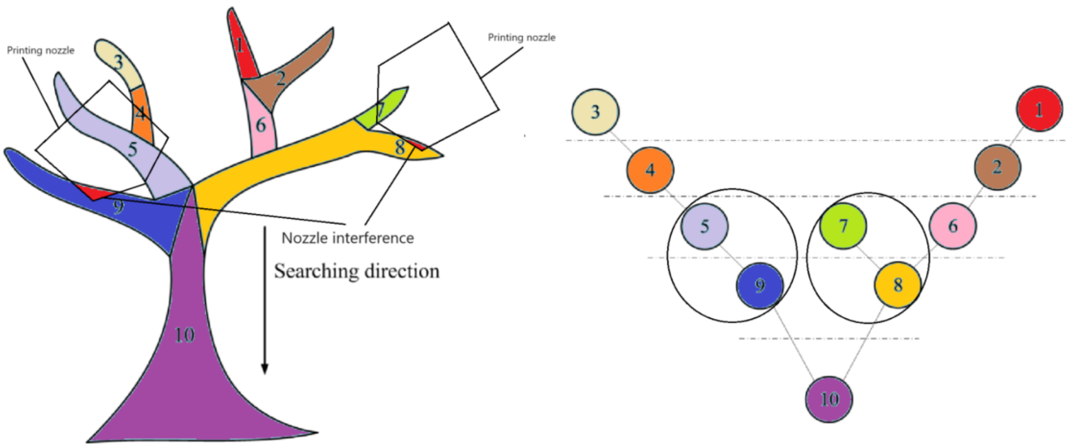

Fig. 5 Nozzle interference and hierarchy diagrams on the left and right respectively [12].

4.2. Partitioning-Based Rapid Prototyping Applications

The color blocking method is used to slice and divide multi-color models. It can be divided into different color blocks, or color distinction is more obvious in the color blocks, reducing the difficulty of printing.

The surface division algorithm (least squares fitting algorithm) is mainly used for slicing complex surface models. It can be used on non-flat surfaces on the color block after separating out the different colors. For example, artwork or hydrodynamic models. It utilizes iterative computation of pressure direction to divide the chunking surface, avoiding the step effect and support waste associated with traditional parallel slicing. It improves the efficiency of multi-color printing.

The unsupported hierarchical structure is mainly used for printing tree-like or fractal structures such as vascular networks, plant roots, etc. It adopts the way of cutting from small to large and cross printing. It effectively avoids printhead collision problems in multi-color printing and realizes zero-support printing. By dynamically adjusting the print sequence, it effectively avoids the problem of collision between the printhead and the model.

5. Multi-Color 3D Printing Equipment

5.1. Single-Nozzle Extruder

Single-nozzle extruders feature a simpler structure and smaller size compared to multi-nozzle extruders, so printing with them is more convenient for monochrome applications. However, in multi-color printing, after the single-nozzle extruder extrudes any color material, it must switch to another color filament to continue multi-color printing. Since residual material from the previous color remains inside the nozzle, continuing to use it without expelling the leftover material may result in color mixing. The extruder must be completely emptied of the previous color material before it can be used again.

The remaining color materials have approximated numerical estimates, and the required amount of mixed color material to be extruded is calculated using the formula. After extruding an amount of material equal to or greater than the mixed color material into the excess material placement area, the next color material can be used.

For single-nozzle multi-color 3D printing equipment, the Bambu X1 Carbon from the company Bambu Lab can be used in conjunction with AMS [13]. The Bambu X1 Carbon supports multi-color printing with materials such as PLA, PETG, ABS, and more. It does not support printing with soft materials. The schematic diagram of the 3D printing extruder is shown in Figure 6. The material is squeezed by gears and shafts as it travels from the cold end to the hot end, where it is melted by high temperatures before finally being extruded from the equipment.

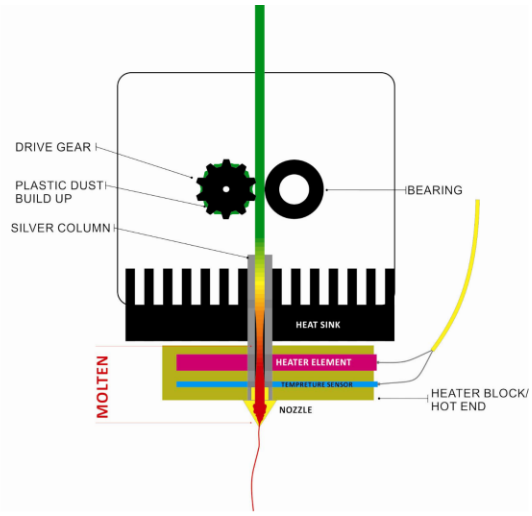

Fig. 6 Schematic Diagram of a 3D Printing Extruder [14].

5.2. Multi-Nozzle Extruder

Single-nozzle extrusion equipment wastes a significant amount of material and consumes considerable time, whereas multi-nozzle extrusion equipment resolves this issue.

Abilgaziyev A. et al. designed a multi-nozzle extruder. This extruder employs Fused Filament Fabrication (FFF) technology. It can achieve multi-color 3D printing by operating through multiple independent nozzles simultaneously [14].

The extruder structure is primarily divided into two modules. The first module is the cold-end section. It can transport solid plastic filament (filament material) to the hot end via gears and shafts. It is typically controlled by a gear mechanism driven by a stepper motor, using friction to feed the filament into the hot end. Figure 7 shows the cold end design and the filament feeding mechanism.

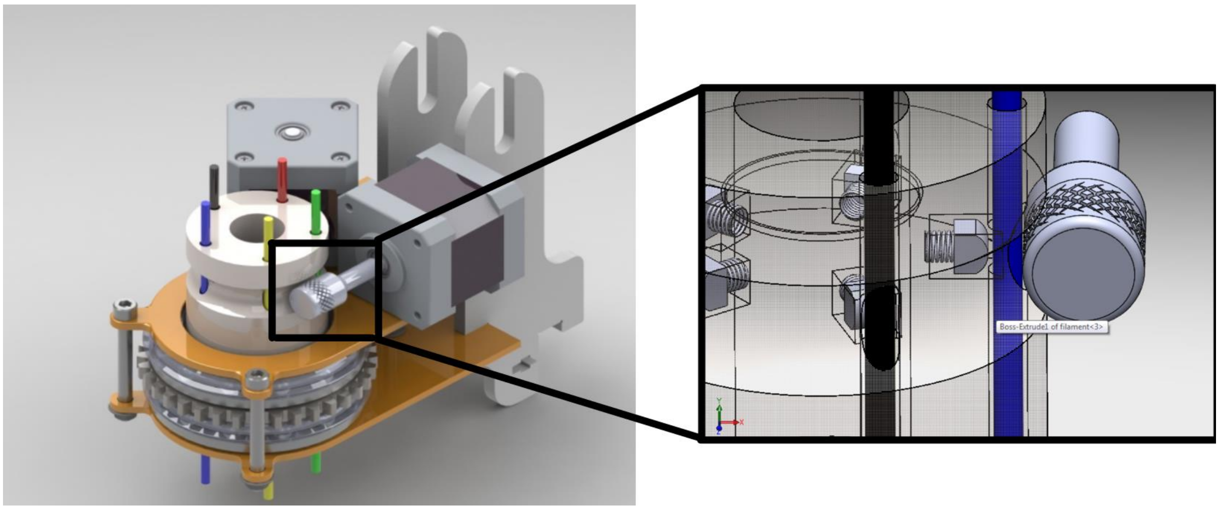

Fig. 7 Cold-end design diagram and wire-feeding mechanism [14].

In multi-nozzle systems, the cold end is designed as a rotating cylinder. The cylinder is equipped with multiple filament feed channels, each corresponding to a specific material. By adjusting the rotating cylinder, different wire materials can be selected at the cold end to control the extrusion of various materials. Figure 8 shows a 3D view of the cold-end explosion.

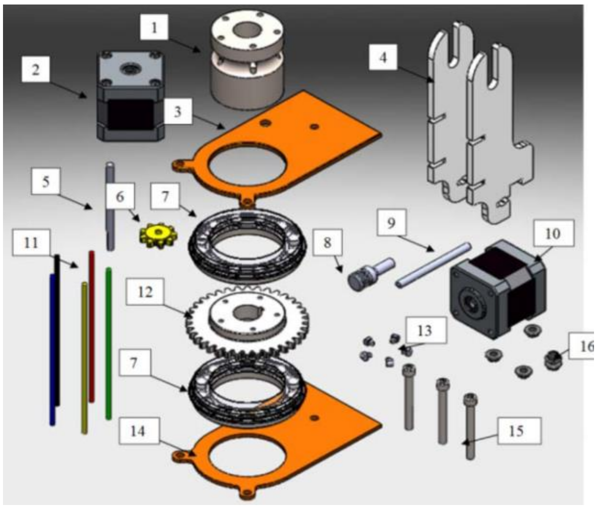

Fig. 8 3D View of Cold-End Explosion [14].

The second module is the hot end. It consists of multiple independent nozzles, and each nozzle is equipped with a heating chamber. The material is heated to a molten state in the heating chamber (typically at temperatures between 150°C and 250°C). Then the molten material is extruded through the nozzle and deposited onto the printing platform. To reduce overall weight, the hot end of this extruder is constructed from brass or aluminum alloy and designed for lightweight performance. The cold end transfers material to the hot end via a Bowden cable, reducing the weight of moving parts and thereby increasing printing speed.

Multi-nozzle extruders offer numerous advantages. Multi-nozzle extruders support multi-color printing, capable of simultaneously using up to five different filament materials or colors without pausing for mid-print material changes. Multi-nozzle extruders enhance multi-color printing efficiency compared to single-nozzle extruders. Single-nozzle extruders can only extrude one color at a time, requiring additional time for material changes and nozzle cleaning during color switching.

Multi-nozzle extruders have increased printing speed. It employs a Bowden design that fixes the cold end, reducing the weight of moving parts and accelerating printing speed [14].

Multi-nozzle extruders feature a simpler structure and lower cost. This multi-nozzle extruder requires only two stepper motors to drive five nozzles, making it more cost-effective than traditional multi-nozzle systems [14].

The multi-nozzle extruder exhibits high reliability. This multi-nozzle extruder employs a support plate structure made of ABS material. Its safety factor (FOS) reaches 8.1, ensuring long-term stable operation of the multi-nozzle extrusion equipment [14].

6. Limitations and Development Trends

Different colors and materials require further investigation of mechanical properties, such as interlayer bonding strength, during fused deposition. Large models consume more material due to their size. Therefore, less expensive materials can be selected.

The color block division method lacks precision in segmenting color blocks, and individual slices may still require multiple color materials for printing after division. Surface division algorithms involve substantial computational overhead for calculating partitioned regions, making them relatively inefficient for dividing large models.

Multi-nozzle systems increase mechanical complexity. This modification results in a device with a larger size than typical printing equipment. Moreover, when printing models with narrow branches, the printing operation of a multi-nozzle extruder is significantly more complex than that of a single-nozzle extruder. The precision requirements for the rotating cylinder and the pushing mechanism are high. When switching filament materials, the extruder may experience blockages or uneven extrusion. During multi-color 3D printing, this situation severely impacts both multi-color printing efficiency and multi-color printing quality. Multi-nozzle calibration is more challenging than single-nozzle calibration, requiring precise equipment adjustments to prevent misalignment. Therefore, multi-color printing requires more precise digital models than monochrome printing. Cleaning multi-nozzle equipment is more cumbersome, especially when different materials are mixed, the extrusion port is prone to residue buildup [14]. The thermal management of multi-nozzle extruders is complex. Each nozzle requires independent temperature control. When multiple hot ends are operating simultaneously, the extruder may experience thermal interference. Large multi-color models are relatively sensitive to temperature. Thermal interference may affect the mechanical properties of large multi-color models. Multi-nozzle extruders are still commonly used in laboratory applications due to their high cost. For multi-color printing to achieve large-scale commercialization, multi-nozzle extruders still need to reduce their cost.

7. Conclusion

This paper analyzes the interlayer adhesion and thermal warpage properties of materials from two research perspectives: multi-color printing and large-scale modeling. The slicing strategy enables printing without changing material on the extruder, and large models with a size that is too large require slicing into sections. This paper analyzes the principles of printing equipment and compares the advantages and disadvantages of multi-nozzle versus single-nozzle systems. It concludes that multi-nozzle configurations are more suitable for multi-color printing, and that multi-nozzle extruders significantly enhance multi-color printing efficiency.

PLA, ASA, and ABS— the common printing materials—each have their own advantages and disadvantages when printing large, multi-color models. In actual use, operators should also select options according to requirements. This paper clarifies the role of multi-nozzle extruders in multi-color printing through a comparative analysis between single-nozzle and multi-nozzle extruders.

Since this paper only analyzed the interlayer adhesion of different colors of the same material, the interlayer adhesion and other mechanical properties of different colors and materials require further investigation. There is still room for optimization in the color block division method. Multi-color printing equipment requires in-depth research, and more suitable printing devices may exist for large-model multi-color printing.

References

[1] Cheng J, Wang R, Sun Z, et al. Centrifugal multimaterial 3D printing of multifunctional heterogeneous objects. Nature Communications, 2022, 13: 7931.

[2] How is multi-Color 3D Printing Achieved? The Technical Path from Dual-Color FDM to Full-Color MJF. 2024.

[3] Zhang Z Y. Color Reproduction and Control in Color 3D Printing for Cultural and Creative Products in the Intelligent Manufacturing Field. Jinan: Qilu University of Technology, 2024.

[4] Ji X H. Modification of ABS and ASA Materials and Investigation of Their FDM Forming Characteristics. Fuzhou: Fujian Normal University, 2017.

[5] Lan M, Chen M, Chen G, et al. Overview and Development Trends of ASA Resin Technology. Chemical Engineering Science and Technology, 2024, 32(06): 90–94.

[6] Zou N, Qian L, Huang S. Experimental Study on the Mechanism of Fused Deposition Modeling and Its Flexural Mechanical Properties. Experimental Technology and Management, 2022, 39(2): 34–39.

[7] Castelló-Pedrero P, García-Gascón C, Bas-Bolufer J, et al. Impact of deposition time per layer in large format additive manufacturing with glass fiber reinforced ABS. Manufacturing Letters, 2024, 40: 164–167.

[8] Bourell D, Kruth J P, Leu M, et al. Materials for additive manufacturing. CIRP Annals, 2017, 66(2): 659–681.

[9] Zhang Y. Modification and Injection Molding Foaming Process of Polylactic Acid (PLA). Beijing: Beijing University of Chemical Technology, 2024.

[10] Stratasys. ASA and PLA Material Hardness: In-Depth Analysis and Application Comparison. 2024.

[11] Long N Y. Research Progress on ABS Materials Suitable for Additive Manufacturing. Plastic Additives, 2025, (03): 55–57+63.

[12] Xu K, et al. Support-Free Layered Process Planning Toward 3 + 2-Axis Additive Manufacturing. IEEE Transactions on Automation Science and Engineering, 2019, 16: 838–850.

[13] Bambu Lab X1 Series | Desktop 3D Printer | X1C | Bambu Lab. 2024.

[14] Abilgaziyev A, Kulzhan T, Raissov N, et al. Design and development of multi-nozzle extrusion system for 3D printer. In: 2015 International Conference on Informatics, Electronics & Vision(ICIEV),2015:1-5.