

Experimental Determination Study on the Minimum Acceptable Purge Volume Multiplier in Desktop Single-Nozzle Multi-Color Extrusion 3D Printing

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Abstract. At present, existing multi-material 3D printing can realize color switching and functional integration in the same component, but desktop single-nozzle systems still face problems such as color contamination, material waste, and efficiency decline during the material change process. Therefore, this paper adopts a two-layer four-color test piece, and under the visual acceptability criterion, compares the influence of different parameters on the area of the color mixing segment and printing time under controlled parameter-variable conditions. This paper finds that, for several typical color combinations, in the pre-experiments, conventional printing speed, nozzle temperature, and the area and shape of the printed part have limited influence on the area of the color mixing segment; the final results show that the amount of waste is approximately linearly related to the purge volume multiplier; the printing time of multi-color multi-material printing is only strongly related to part volume; and it is explained that the visually acceptable minimum purge volume in desktop systems is a threshold problem of purge volume multiplier that is limitedly affected by other conventional parameters and can be experimentally determined by small-scale test pieces. This study can provide reference for parameter setting to reduce material waste under the premise of ensuring acceptable appearance quality in desktop single-nozzle multi-color printing. At the same time, this paper also shows that it is feasible to determine the minimum purge volume multiplier of different color combinations by using small-scale test pieces, providing an experimental basis for subsequent related parameter optimization and evaluation method research.

Keywords: desktop extrusion 3D printing, material switching, printing efficiency, color mixing contamination, minimum acceptable purge volume

1. Introduction

Multi-material extrusion 3D printing can realize color switching, functional partitioning, and local property regulation in the same component. Nazir et al. reviewed the design, properties, applications, and challenges of multi-material additive manufacturing, and pointed out that multi-material manufacturing has obvious advantages in functional integration [1]. However, for desktop single-nozzle systems, the material switching process still easily produces problems such as color

mixing contamination, additional purged material, and increased non-forming time. Therefore, the material change process is an important link affecting printing quality and material utilization rate.

Existing studies mainly focus on material bonding, process parameter influence, and transition behavior in multi-material printing. Freund et al. studied the influence of process conditions on interfacial bonding in multi-material extrusion molding [2], Richter et al. analyzed the interfacial bonding behavior of different thermoplastic materials in multi-material extrusion manufacturing [3], and Delia et al. further discussed and further summarized the main factors affecting multi-material interfacial bonding [4]. These studies indicate that multi-material printing results depend not only on the materials themselves, but are also closely related to parameter control in the forming process. For the color transition problem in multi-color printing, Hergel et al. studied color transition and print quality control methods in multi-filament printing [5], Takahashi et al. proposed a single-nozzle multi-material printing method based on programmable filament [6], and Zhang Fan et al. studied the color mixing delay problem in FDM full-color 3D printing [7]. In addition, Lei et al. analyzed the influence of process parameters on FDM printing morphology and properties, indicating that parameters such as speed and temperature will change the extrusion state [8]. The above studies provide a basis for understanding interfacial behavior, the role of process parameters, and color transition problems in multi-material and multi-color printing, but there is a lack of direct experimental determination basis for the specific practical problem of "how to adjust parameters to reduce printing cost under a certain acceptable quality criterion" in actual desktop single-nozzle multi-color printing. At the same time, although the official equipment documents give parameter descriptions such as purge volume, prime tower, and retraction, such materials mainly provide a basis for empirical settings and still cannot answer the question of how to determine parameters for achieving the minimum acceptable printing cost under different color combinations.

Therefore, this paper aims to study the minimum acceptable printing cost parameter settings and their determination method for different color combinations in desktop single-nozzle multi-color extrusion 3D printing. For this purpose, this paper will introduce the experimental platform, criteria, and independent variable settings; then through pre-experiments screen out conventional parameters with limited influence on the color mixing segment, and then carry out purge volume multiplier tests around several typical combinations, and discuss the rationality of using small-scale test pieces for threshold determination in combination with control experiments, attempting to provide more direct experimental reference basis for parameter setting in desktop single-nozzle multi-color printing.

2. Materials and methods

2.1. Experimental platform and materials

The experimental platform is a Bambu Lab A1 combined with an AMS 2 Pro automatic material change system, as well as common basic consumables in four colors: red, yellow, gray, and black. The research object is limited to multi-color printing under desktop single-nozzle conditions. Considering that the model surface is greatly affected by path, geometry, and local occlusion, and the research focus of this paper is the material change contamination behavior in desktop single-nozzle systems. And as shown in Figure 1, because the existing solution is to set a prime tower and additionally purge waste material during material change, although it can reduce the influence caused by color mixing, the cost is transferring the defect segment into additional waste material and time consumption:

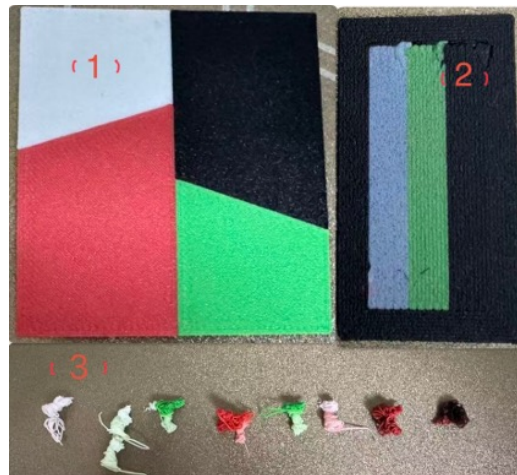


Figure 1. Schematic diagram of material change defects and existing control methods in desktop single-nozzle multi-color printing: (1) test piece body (2) the first segment of defective material after material change is received by the prime tower (3) transition waste purged during the material change process

Therefore, this study uses a two-layer four-color test piece for printing under the condition of turning off the prime tower, and gives priority to observing the visible color mixing segment area on the test piece and the change in printing time, as the main basis for the research and analysis of the expected results.

2.2. Evaluation and observation criteria

This paper divides the evaluation indicators into the following two categories: the first is quality-related indicators, including whether the color mixing segment is visible and the clarity of the color mixing boundary; the second is cost-related indicators, including waste amount and additional time. Considering that the research goal is oriented to the actual parameter tuning scenario of desktop equipment, this paper does not pursue absolute zero contamination at the microscopic level, but takes "the color mixing segment disappears under naked-eye observation or is basically indistinguishable" as the visual acceptability standard. Correspondingly, the lowest purge volume multiplier that makes the sample reach this state is defined as the minimum acceptable purge volume multiplier.

2.3. Experimental design idea

The design of this experiment follows the idea of "screen first, then focus, then verify". Considering that the color mixing contamination in desktop single-nozzle multi-color printing may be jointly affected by multiple parameters at the same time, this paper first consults the official equipment parameter descriptions and the current research status to determine several process parameters, and observes in the pre-experiments the influence on the color mixing segment area and printing time within the set range, screens out parameters with relatively limited influence, and determines the main experimental parameter, namely the purge volume multiplier.

On this basis, in order to avoid accidental results in a single experiment, under the condition that each parameter is printed twice and it is confirmed that there is no large error, gradient parameter testing is carried out, and then smaller step sizes are added near the critical interval for repeated

testing, so as to determine the approximate lowest purge volume multiplier reaching the visual acceptability state.

In addition, in order to judge whether this threshold mainly reflects a local control problem of residual material in the material change, rather than being significantly affected by the overall size or the shape of the mixing region, this paper only further sets supplementary control experiments of proportional enlargement and shape change, and under the condition of keeping the process parameters unchanged, compares the state of the color mixing region and the change in printing time of test pieces of different sizes, so as to verify the rationality of using small-scale test pieces to determine the minimum acceptable purge volume multiplier.

2.4. Independent variables of pre-experiments and discussion

The purpose of the pre-experiments is to screen process parameters with relatively limited influence on color mixing contamination, and accordingly determine the subsequent formal experimental variables. According to the adjustable parameters in the software and the influence between several process parameters and basic states by Lei et al. [8], as well as the official public equipment documents [9-12], the parameters related to material change are roughly the following categories: purge parameters, prime tower parameters, retraction amount parameters, basic speed parameters, and temperature parameters. This study mainly aims to reduce consumable amount and improve efficiency and quality, therefore as shown in Table 1, printing speed, nozzle temperature, and purge volume multiplier are mainly selected as independent variables, and discussed according to the parameter intervals used by users in actual use.

Table 1. Key independent variables and necessity analysis [8-12]

Variable name	Corresponding meaning in software	Influence	Variation
Printing speed	Material extrusion speed during printing	The first segment after material change is unstable, and printing speed affects print quality [8]	50-200mm/s
Nozzle temperature	Nozzle temperature in the normal printing stage of the model body	Nozzle temperature affects printing precision [8]	190-245 °C
Purge volume multiplier	Overall multiplier adjustment to the original purge volume automatically calculated by the system	Directly affects the discharge degree of old material, the length of the color mixing segment, and the amount of waste	0.3-0.9

2.5. Formal experimental procedure and supplementary experiments

The formal experiment selects three groups of color transitions, red→yellow, yellow→gray, and gray→black, as cases. First, four purge volume values of 0.3, 0.5, 0.7, and 0.9 times are set, and each value is printed twice for coarse screening, observing the approximate interval in which the color mixing segment disappears, and then finer multiplier points are added near the critical interval for repeated testing to determine the approximate lowest purge volume multiplier reaching the visually acceptable state, while at the same time recording the amount of waste.

In addition, in order to investigate whether the color mixing contamination is affected by model size and the shape of the mixing region, the experiment further carries out control printing by proportionally enlarging the test piece or changing the shape of the color mixing region under the condition that the color combination process parameters remain unchanged, and compares the

control mixing region area and state to analyze whether this phenomenon is a local residual material problem in material change.

3. Results and discussion

3.1. Analysis of pre-experimental results

The pre-experimental results show that within the range of conventional parameters set in this paper, as shown in Figure 2 and Figure 3, the color mixing contamination area of the printed test pieces is similar under different printing speed or nozzle temperature conditions, and its influence is more reflected in subtle changes in the sharpness of the interface boundary and the smoothness of the color transition. From this it is concluded that the above parameters have no significant influence on printing efficiency and the area of the color mixing segment, and the printing time during the above printing processes, including preparation time, differs little, all being 18–20 minutes, indicating that the value of adjusting relevant parameters in actual use is relatively limited. In contrast, as shown in Figure 4, the purge volume multiplier has a more direct influence on the control effect of the color mixing segment, so the subsequent formal experiments focus on the purge volume multiplier.



Figure 2. Printing results at printing speeds of 50 mm/s, 100 mm/s, 150 mm/s, and 200 mm/s



Figure 3. Printing results at nozzle temperatures of 190°C, 210°C, and 230°C



Figure 4. Printing results at purge volume multipliers of 0.3, 0.5, 0.7, and 0.9

3.2. Analysis of formal experimental results

In the formal experiment of purge volume multiplier, the three groups of color transitions red→yellow, yellow→gray, and gray→black show different threshold characteristics. Combined with the coarse screening results and repeated testing results in the critical interval, red to yellow reaches the visually acceptable state at about 0.6, yellow to gray reaches the visually acceptable state at about 0.65, while gray to black increases to about 0.9 to reach the visually acceptable state.

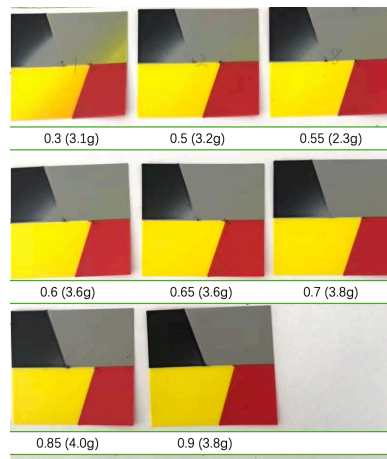


Figure 5. Printed parts under different purge volume multipliers and waste amount annotations

Further statistics find that, as shown in Figure 6, the amount of waste shows an approximately linear relationship with the purge volume multiplier, and reducing the purge volume multiplier can significantly reduce the amount of waste.

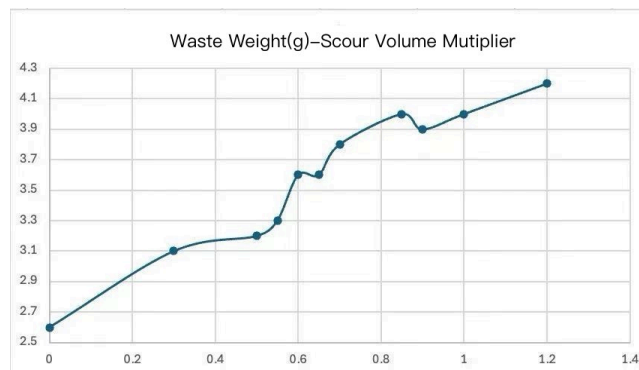


Figure 6. Corresponding waste amount when the purge volume multiplier takes 0.3, 0.5, 0.55, 0.6, 0.65, 0.7, 0.85, 0.9, 1, and 1.2 respectively (the horizontal axis is purge volume multiplier, the vertical axis is waste amount, unit: g)

This result indicates that under the same equipment and uniform criterion, the minimum multiplier required for different color combinations to reach the acceptable state is not consistent. Although the official equipment has already given corresponding purge volume coefficients according to different color combinations [9-12], the results of this experiment show that under specific equipment and a uniform criterion, this coefficient still has further compression space, and the minimum visually acceptable purge volume multiplier can be determined by the printing test of small-scale test pieces, and there exists a minimum threshold.

3.3. Proportional enlargement experiment and its meaning

In the formal experiment, under the same parameter conditions, after proportionally enlarging the test piece, another group was printed again with the same parameters. The results show that the contamination area and the color mixing region did not show a trend of local enlargement or inversely proportional reduction with the overall printing area or shape of the model; while the printing time increased significantly, and the comparison of the same parameters with different volumes increased by about 14 minutes on average. This phenomenon indicates that within the process range set in this paper, the color mixing contamination is closer to a threshold problem controlled by residual material in material change, rather than a phenomenon affected by other factors. In other words, the minimum-scale test piece in the experiment has rationality for the test of the minimum acceptable purge multiplier, and the minimum visually acceptable purge volume multiplier is a threshold that can be determined by certain experimental testing.

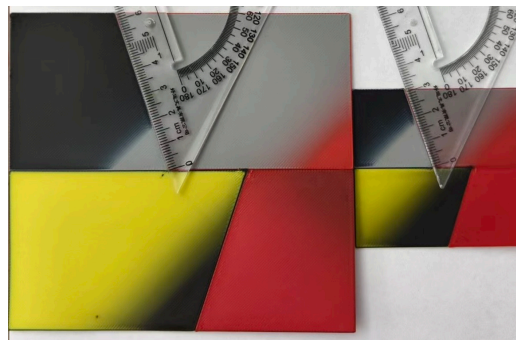


Figure 7. Comparison of color mixing area of test pieces of different sizes under the same process parameters

3.4. Advantages, limitations, and outlook discussions

This study has the advantage that the problem is clearly targeted and can directly correspond to the actual parameter tuning needs in desktop single-nozzle multi-color printing. And this paper takes "visual acceptability," a judgment method closer to actual application, as the criterion, and discusses the minimum purge volume multiplier required for several color combinations under the premise of ensuring appearance quality, proving that color mixing contamination can be approximately determined by the single variable of purge volume multiplier. Compared with simply pursuing complete absence of contamination, this has more reference significance for the balance demand between quality and material consumption in actual printing.

At the same time, compared with large and complex models, the small-scale test piece adopted in this paper has lower material and time cost, is more intuitive, and is convenient for repetition. The results of the proportional enlargement experiment also show that under the same parameters, the

color mixing contamination area did not enlarge synchronously with the overall size, and the use of small-size test pieces in this experiment has certain rationality.

However, this paper still has certain limitations. The standard under naked-eye observation has certain subjectivity, and may be affected by factors such as observer, lighting, and color contrast, and although the experimental procedure of this paper is convenient to reproduce on different experimental platforms, consumables, and color combinations, the specific values cannot be directly generalized to all printing platforms and material systems. In addition, this paper pays more attention to appearance contamination, while more properties of printed parts have not yet been discussed in depth.

Therefore, subsequent research can further introduce image processing and color difference analysis methods, for example, using ImageJ/Fiji or Python to select ROI regions from printed part images, convert them into CIELAB color space, and calculate the ΔE_{00} distribution of different color transition regions based on the CIEDE2000 color difference formula. Then the color difference results can be visualized in the form of heat maps, used to compare the degree of color transition among different printed parts, and carry out more objective quantitative evaluation of the color mixing region;

At the same time, more color combinations, material types, and printing platforms can be expanded to improve the generality of the conclusions. In addition, color mixing control can also be analyzed together with the mechanical properties, interfacial bonding, and overall forming quality of printed parts, so as to establish a more comprehensive parameter optimization method for multi-color/multi-material printing.

4. Conclusion

This paper studies the determination of the minimum acceptable purge volume multiplier under different color combinations and its relationship with printing cost around the problem of color mixing contamination control in desktop single-nozzle multi-color extrusion printing.

The research results show that within the experimental range set in this paper, the influence of conventional printing speed and nozzle temperature on the area of the color mixing segment is relatively limited, and they do not show a dominant role as significant as that of the purge volume multiplier. In contrast, the purge volume multiplier has a more direct influence on color mixing contamination control and printing cost, among which the amount of waste increases approximately linearly with the increase of the purge volume multiplier. The minimum acceptable purge multiplier required by different color combinations under the same criterion is not the same. The supplementary experiments of proportional enlargement and shape control further indicate that under the same process parameters, the color mixing contamination is closer to a local threshold phenomenon controlled by residual material in material change, rather than being mainly affected by the overall model size and the shape of the mixing region. Therefore, it is reasonable to use small-scale test pieces for this experiment to a certain extent.

Subsequent research can further combine image processing or color difference analysis methods to carry out more objective quantitative characterization of the color mixing region, and expand to more material systems, color combinations, and equipment conditions, to improve the scope of applicability of the conclusions and the universality of the method. At the same time, interfacial bonding quality and mechanical properties can also be combined to further improve the parameter optimization method in desktop multi-color printing and improve the experimental reference value.

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