Optimization design of color mixing nozzle based on multi physical field coupling

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Abstract. Fused deposition modeling, as one of the most widely used types of 3D printing, is undoubtedly a good method when it comes to personalizing custom production and producing some complicated parts which cannot be machined by cutting tools. However, existing FDM printers are restricted to printing only monochrome objects due to the poor mixing quality and nozzle blockage caused by the irrational structure of nozzle. In this paper, the 3D model of the color mixing nozzle is designed by SolidWorks software at first. Second, the temperature field and the stress field are simulated by using ANSYS software. Comparing the simulation results, the main reason for the blockage at the notch of the throat pipe is revealed. Some other design flaws, including the position of the thermistor, the shape of the flow channel and the material selection of each component, are found out and optimally modified. Finally, the nozzle is optimized, and the rationality of the optimization design is verified by thermal-mechanical coupling field analysis. The problem of nozzle blockage in the printing process is settled, and the printing quality and stability are significantly improved.

1. Introduction
In recent years, 3D printing technology is developing rapidly in the fields of complex structural parts manufacturing, cultural relics restoration, biomedicine, automobile and aerospace. 3D printing, also known as additive manufacturing (AM) technology, is a kind of technology that creates components directly through pre-designed digital model parameters obtained from three-dimensional solid data or reverse engineering [1]. Compared with traditional material processing technology, 3D printing is a bottom-up manufacturing technology, which is a useful complement to traditional manufacturing technology [2]. With the continuous development of 3D printing technology and the growing demand for personalized consumer goods, an increasing number of people consider that the future of 3D printing will usher in the next industrial revolution [3-4].

Fused deposition modelling (FDM) technology, as one of the most commonly used types of 3D printing, is based on extruding filamentary materials such as thermoplastic PLA or ABS from heated nozzles, and then depositing melt according to the scanning path of each layer of parts. With the completion of one layer, the printing platform drops or the nozzle raises a layer thickness to superimpose and deposit a new layer, repeating the superposition process until the model is formed [5-6]. It is crucial for FDM forming process to keep the temperature of the semi-fluid forming material just above the melting point, excessive temperature can easily lead to uneven filament drawing or even
broken wire, while insufficient temperature can easily lead to blockage of nozzle and deficient adhesion. The main advantages of this technology for industrial machines include: high material utilization rate, low material cost, abundant optional materials, simple process, environmental protection and pollution-free [7]. Currently, there are mainly the following ways to realize color mixing printing: printing with single extruder and nozzle, changing different color materials to continue printing, while printing with multi-extruder and single nozzle is to control the ratio of several different colors of materials to blend out the desired color [8]. Dyeing printing with full color ink, printing the entity before coloring, and printing with double or multiple nozzles is to control the extrusion time of different color materials to achieve color mixing printing. However, most printing nozzle devices can print using only monochrome wire, which limits the application of 3D printers. Therefore, it is necessary to further study the color mixing printing [9].

In order to solve the problems of poor mixing quality, low printing accuracy and blockage caused by irrational nozzle structure in printing process, this work is focused on studying the main three-in-one-out color mixing nozzle, and making a comparative analysis of temperature field and stress field of the color mixing nozzle. The 3D model of the color mixing nozzle is established by SolidWorks software, and the temperature and stress fields of the color mixing nozzle are solved in ANSYS software. Comparing the solution results, the main reason and exact location of nozzle blockage are revealed, and other shortcomings are optimized.

2. Principle of analysis

2.1 Effect of temperature stress

Steady-state temperature stress exists under normal working conditions, while transient temperature stress will be produced during heating or cooling [10]. The influence of temperature inhomogeneity on the stress and deformation of structure is not only caused by thermal strain and stress, but also by the change of mechanical properties such as elastic modulus, Poisson's ratio, yield stress and thermal expansion coefficient with temperature. According to the principle of thermal expansion, if the metal parts are not uniformly heated, there will be inconsistent temperature rise on both sides. For example, when the upper side temperature is higher than the lower side, the expansion of the metal parts on the upper side will be greater than that on the lower side, which causes the metal parts to bend downward and produce thermal deformation. The deformation caused by thermal expansion is based on the following equation:

\[ \Delta L = \delta \left( L + \Delta / 2 \right) \Delta t \]  \hspace{1cm} (1)

Where \( \Delta L \) is the sizing of expansion (mm), \( \delta \) represents the linear expansion coefficient of materials (\( ^\circ \text{C}^{-1} \)), \( L \) represents the dimensions in the direction of X and Y (mm), \( \Delta t \) represents the temperature difference (\( ^\circ \text{C} \)), and \( \Delta \) represents the tolerance of parts (mm). The error sensitive direction of 3D printing nozzle is in X and Y axis direction, which means that the deformation in these two directions will directly affect the printing accuracy of the nozzle.

2.2 Principle of thermal analysis

Thermodynamics is a common phenomenon in physical field. The purpose of thermodynamic analysis is to calculate the temperature distribution, thermal gradient, heat flux and other physical quantities in the model. Heat transfer is caused by the difference of temperature inside or between objects [11]. According to the mechanism of heat transfer, the basic ways of heat transfer can be divided into conduction, convection and radiation. By analysing the heat transfer characteristics of the nozzle, it can be seen that the dominant heat transfer mode is the contact surface conduction, followed by convection, and finally the radiation heat transfer can be neglected. When there is a temperature difference inside an object, heat is transferred from the high temperature part of the object to the low temperature part of the object called heat conduction, which obeys Fourier law:

\[ q = -K \frac{\partial T}{\partial n} \]  \hspace{1cm} (2)
Where $q$ and $K$ represent respectively the heat flux and the heat conductivity, while $\frac{\partial T}{\partial n}$ represents the temperature difference along the $n$ direction, and the symbol $-$ indicates the direction in which heat flows to a lower temperature. When the surface contact heat conduction mode has a great influence on the deformation of the nozzle head, while the effect of convection and radiation is relatively small, in order to optimize the layout of nozzle parts, increasing heat convection and radiation can be adopted to reduce the surface contact heat conduction with large temperature difference.

2.3 Thermal-mechanical coupling field analysis

There are many physical fields in practical engineering, such as temperature field, stress field, electromagnetic field and other fields. Most of the problems we have to solve are the superposition of these physical fields because these physical fields usually interact with each other. Thermal structure coupling analysis refers to the type of analysis that solves the influence of temperature field on stress, strain and displacement in the structure [12]. For the thermal structure coupling analysis, the indirect sequential coupling analysis method is usually used in ANSYS, which loads the temperature field obtained by thermal analysis into the structure as the body load to solve the stress distribution of the structure.

The indirect sequential coupling analysis method of thermal structure is divided into three steps: the first step is thermal analysis to obtain the temperature field of the structure. In the second step, the elements in the model are transformed into the corresponding structural analysis units, and the thermal analysis results obtained in the first step are loaded on the nodes as the body loads. The last step defines the options needed for structural analysis and carries out structural analysis [13].

3. Simulation Analysis

3.1 Establishment of nozzle model

In this paper, 3D modeling of color mixing nozzle is carried out with the widely used SolidWorks 3D design software. The main components of the model include: radiator, throat, heating block, heating pipe, thermistor, nozzle and PLA wire, which is shown in Figure 1, saved as IGES entity file format and imported into ANSYS software to simulate the temperature and stress fields, so as to find out the main reasons and exact location of easy blockage, as well as some other design defects. After optimization design, the temperature field and stress field are simulated and analyzed to verify the rationality of the optimization design.

![Model diagram and model profile of color mixing nozzle.](image)

1. PLA wire 2. Radiator 3. Throat 4. Heating block 5. Thermistor 6. L-type flow channel 7. Heating pipe 8. Nozzle head

Figure 1. Model diagram and model profile of color mixing nozzle.

3.2 Materials and boundary conditions of color mixing nozzle

After importing the solid model into ANSYS software, the material attributes are given to the parts firstly. The main materials used are Aluminum Alloy, Structural Steel, Copper Alloy, Iron and Stainless Steel, which can be selected appropriately according to the requirements of parts in Ansys.
Engineering Materials Database. In addition, material properties can also be customized, generally selecting typical values. In the coupled analysis of thermal structure, the density, thermal expansion coefficient, thermal conductivity, specific heat, Young's modulus, Poisson's ratio and other parameters are mainly involved. The main material parameters are shown in Table 1.

| Parameters          | Density (kg·m⁻³) | Expansion coefficient (C⁻¹) | Thermal conductivity (W·m⁻¹·C⁻¹) | Specific heat (J·kg⁻¹·C⁻¹) | Young modulus (Pa) | Poisson ratio |
|---------------------|------------------|-----------------------------|----------------------------------|----------------------------|-------------------|---------------|
| Aluminum Alloy      | 2770             | 2.30E-05                    | 170                              | 875                        | 7.10E+10          | 0.33          |
| Structural Steel    | 7850             | 1.00E-05                    | 60.5                             | 434                        | 2.00E+11          | 0.30          |
| Copper Alloy        | 8300             | 1.80E-05                    | 401                              | 385                        | 1.10E+11          | 0.34          |
| Iron                | 7200             | 1.10E-05                    | 52.0                             | 447                        | 1.20E+11          | 0.28          |
| Stainless Steel     | 7750             | 1.70E-05                    | 15.1                             | 480                        | 1.93E+11          | 0.31          |
| Polylactic acid     | 1300             | 6.00E-04                    | 6.80                             | 1950                       | 3.5E+09           | 0.45          |

The structure of the model is not complicated, and the area of the temperature field and stress field is relatively large. Therefore, the nozzle, heating block, throat and radiator, which are smaller than the whole temperature field area, should be meshed as far as possible, using hexahedron dominating grid method to ensure the accuracy of calculation [14]. For the setting of boundary conditions, it mainly includes heating temperature, heating time and convection heat transfer. In view of the working environment of the nozzle for printing PLA wire and the printing temperature is generally about 210°C, setting the temperature boundary at the heating pipe is 210°C, the heating time is 300S and the ambient temperature is 22°C. There are three main ways of heat transfer: heat conduction, heat convection and heat radiation. The heat conduction between the contact surfaces is the main heat transfer mode. The heat convection occurs due to temperature difference between the components and the air, and the convective heat transfer coefficient is set to 100 W/(m²·K) based on the empirical value. With relatively low nozzle temperature and heat transfer efficiency, the heat radiation can be ignored.

3.3 Simulation analysis of temperature field and stress field in heating process

In this paper, the transient temperature analysis method is used to study the temperature field distribution of the color mixing nozzle when it is heated to a specified temperature, and the results of the temperature field are loaded into the statics analysis model of the structure as initial conditions. Finally, the temperature, stress and strain of the nozzle and PLA wire are analyzed.

(a) Temperature field cloud chart. (b) Deformation cloud diagram of PLA wire in X-axis.

Figure 2. Cloud chart of thermal structural coupling analysis.

As is shown in Figure 2 (a), it can be seen that the temperature of the color mixing nozzle drops continuously from bottom to top, indicating that the temperature is transferred from the heating tube to
different parts, the temperature decreases continuously and convection heat transfer occurs with air during this process. The minimum temperature of the nozzle is about 32.78°C while the maximum temperature is about 210°C, which is located at the far end of the radiator and at the end of the heating pipe respectively. The average temperature of the nozzle is above 197°C, which is higher than the melting point of the PLA wire, so the heat is fully utilized to ensure the smooth and uniform filamentation. However, the flow channel in the heating block is L-shaped, which is not conducive to the entry of wire, causing blockage easily when the temperature drops. In addition, the thermistor is located on the side cylinder of the heating block and in the middle of the two heating tubes, and the temperature is about 185°C, which is lower than that of the heating block, so it cannot reflect the temperature distribution of the whole heating block and the flow channel. The temperature of the throat pipe decreases obviously from the heating block end to the radiator end, but it is still higher at the position of the notch in contact with the radiator, and the average temperature is about 75°C. Due to the high temperature of the throat pipe, PLA wire is obviously heated and expanded at the notch, resulting in a large deformation. From the deformation cloud diagram of PLA wire in X-axis shown in Figure 2 (b), we can find out that the sum of the absolute values of the deformation of the PLA wire at the notch is 0.38 mm, and the deformation rate reaches 21.71% when the diameter of the PLA wire is 1.75 mm, which is caused by the expansion of the wire at the notch of the throat pipe.

4. Optimization design and verification

Based on the analysis of the thermal-mechanical coupling field of the color mixing nozzle, some defects were found as described above, and the color mixing nozzle was optimized in SolidWorks, as shown in Figure 3 (b). The following improvements are made to the nozzle:

- Firstly, the thermistor is moved from the cylinder side of the heating block to the center of the upper surface of the heating block. Since the three heating pipes are symmetrical, this position can reflect the whole temperature distribution of the heater in theory;
- Secondly, the L-shaped flow channel in the heating block is improved to streamlined flow channel, so that the PLA wire can reach the nozzle smoothly after melting, and the nozzle will not accumulate in the channel when the temperature drops, resulting in blockage of the nozzle. However, considering that the streamlined flow channel is difficult to be processed, the flow channel is designed as an obtuse angle type to avoid blockage in some degree, as shown in figure 3 (a);
- Finally, the notch of the throat is removed to avoid blockage caused by the expansion of the wire.

Through the analysis of the thermal-mechanical coupling field of the color mixing nozzle again, the rationality of the improvement of the color mixing nozzle is verified.
The thermal-mechanical coupling field analysis of the color mixing nozzle after optimized design is carried out. From Figure 4 (a), the temperature of the thermistor is about 205°C, which can reflect the whole temperature distribution of the heating block more accurately, especially the temperature distribution of streamlined flow channel. As can be seen from Figure 4 (c), the maximum equivalent stress of the throat in contact with the heating block is about 22099MPa, and the equivalent stress is about 2.2N on the 1 cm², which decreases from bottom to top because of the decrease of PLA deformation and expansion, and the stress at the notch is about 10.78MPa, which indicates that the PLA deformation and expansion at the notch is negligible and will not cause blockage. The deformation of PLA wire decreases obviously after removing the notch of the throat pipe, which is shown in Figure 4 (b), and the maximum occurs in the position where the throat pipe is in contact with the heating block because the temperature at this point is the highest for both the throat pipe and the PLA wire. However, the deformation of PLA at the top of the throat is only 0.13mm, the deformation rate is only 7.43%, which is 14.28% lower than that of the nozzle before optimization.

During the heating process, the nozzle will deform due to the effect of thermal expansion and cold contraction, affecting the accuracy and quality of printing. As can be seen from Figure 5 (a), a fixed constraint is imposed on the left side of the fixed platform, and a certain deformation occurs after the nozzle is heated. The maximum deformation is located at the lower right of the heating block with a maximum value of 0.12mm. The deformation of X-axis is the main factor affecting the printing process, and the deformation of Y-axis or Z-axis only affects the relative position of printing. As
shown in Figure 5 (b), the nozzle is in the negative direction of the X-axis, and the deformation sign is negative, indicating that the nozzle deforms in the negative direction of the X-axis, and the deformation value decreases continuously from top to bottom, and the absolute maximum value is about 0.089mm. The diameter of nozzle is 0.4mm and the thickness of printing layer is 0.2-0.3mm. Therefore, the deformation of the optimized nozzle has little effect on printing accuracy, which can be neglected. By the way, the material with less heating deformation can be used as the raw material of the nozzle and the printing platform can be adjusted with a certain amount of heating deformation to improve the printing accuracy.

Temperature transfer between components in 3D printing process is significant for forming quality and precision [15]. Each component of the color mixing nozzle has different requirements for heat conduction, heat resistance and heat dissipation. The radiator has higher requirements for heat conduction and heat dissipation, and the throat pipe has a high requirement for heat resistance, which prevents heat transfer to the throat pipe as far as possible, resulting in PLA wire deformation blocking nozzle due to excessive temperature [16]. The heating block requires higher heat conduction to improve energy utilization, and the nozzle also requires higher heat conduction, so as to avoid the problem of uneven filament drawing and broken wire caused by low temperature. According to the requirements of heat conduction, heat resistance and heat dissipation of the above components, the temperature field of radiator, throat pipe, heating block and nozzle components were analyzed by finite element method. The maximum and minimum temperatures of the components under different materials are shown in Table 2.

| Materials       | Structural Steel | Aluminum Alloy | Copper Alloy | Iron | Stainless Steel |
|-----------------|------------------|----------------|--------------|------|-----------------|
| Radiator        | Min/°C           | 29.40          | 37.10        | 43.81 | 45.53           | 27.64 |
|                 | Max/°C           | 106.81         | 86.89        | 71.10 | 196.91          | 203.26|
| Throat pipe     | Min/°C           | 47.91          | 66.09        | 82.65 | 45.53           | 27.64 |
|                 | Max/°C           | 195.82         | 185.94       | 174.81 | 196.91          | 203.26|
| Heating block   | Min/°C           | 125.35         | 165.21       | 186.41 | 118.94          | 66.31 |
|                 | Max/°C           | 210.35         | 210.11       | 210.06 | 210.24          | 211.08|
| Nozzle          | Min/°C           | 190.53         | 199.55       | 197.37 | 188.91          | 163.75|
|                 | Max/°C           | 202.21         | 202.87       | 202.81 | 201.04          | 202.86|

It can be seen from Table 2 that the maximum temperature corresponding to Copper Alloy material is the lowest, which is 71.10°C, indicating that the heat dissipation performance of the Copper Alloy material is the best among the five materials. Therefore, it is concluded that the most suitable material for radiator parts is Copper Alloy. On the contrary, the throat pipe requires good heat resistance of materials, and the minimum temperature of Stainless Steel is 27.64°C, indicating that Stainless Steel is the most suitable material. According to the maximum and minimum temperatures of the heating block components in Table 2, it can be seen that the temperatures of various materials corresponding to the maximum temperatures are about 210°C. The reason is that the heating temperature is set at the highest temperature of 210°C, which appears at the heating block. The minimum temperature of Copper Alloy is the highest, which is 186.41°C, indicating that the heat conduction of Copper Alloy is better than that of other materials. Therefore, the most suitable material for heating block parts is Copper Alloy. Similarly, nozzle components are mainly concerned with heat conduction, so the most suitable material for nozzle parts is Copper Alloy, followed by Aluminum Alloy.

5. Conclusions

In this paper, the three-dimensional modeling and thermal-mechanical coupling field analysis of the three-in-one-out mixing nozzle of FDM 3D printer are carried out, and the design of the color mixing nozzle is optimized. According to the analysis of temperature field and stress field of the color mixing nozzle, the deformation value of PLA wire at the notch is 0.38mm, and the deformation rate reaches
21.71% when the diameter of PLA wire is 1.75mm. The exact location of nozzle blockage is pointed out, that is, at the notch of throat. After optimizing the throat notch, the deformation of PLA at the top of the throat is 0.13mm and the deformation rate is only 7.43%. Compared with the nozzle before optimizing, the deformation rate is reduced by 14.28%, which means the problem of blockage caused by wire expansion in the throat notch is basically solved. In addition, the thermistor is moved from the cylinder side of the heating block to the center of the upper surface of the heating block, which can more accurately reflect the overall temperature distribution of the heating block, especially the temperature distribution in the flow channel. Meanwhile, the flow channel is optimized from L-shape to streamlined structure, which makes the wire flow more smoothly and avoids blocking the flow channel when the temperature drops. Finally, the temperature field of the main part of the color mixing nozzle is analyzed to determine the most suitable material for each component. The most suitable material for throat components is Stainless Steel, followed by Iron, and the most suitable materials for radiator, heating block and nozzle are Copper Alloy, followed by Aluminum Alloy. The conclusion mentioned above basically solves the problem of nozzle clogging, which lays a solid foundation for further study of color mixing 3D printing.

Acknowledgments
This work was supported by Major Science and Technology Special Program of Zhejiang Provincial Science and Technology Department. No. 2015C01035.
This work was also supported by Key R & D Projects of Zhejiang Provincial Science and Technology Department. No. 2017C01019.

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