DOI: 10.21062/mft.2024.045 http://www.journalmt.com

Development and Simulation of a Hybrid Extrusion Mechanism for Enhanced Surface Quality and Precision in FDM 3D Printing

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FDM forming 3D printers may encounter problems such as rough printing surface and poor accuracy during operation. This study mainly utilizes the complementary advantages of piston extrusion mechanism, sliding vane pump extrusion mechanism, and plunger pump extrusion mechanism to design a parallel combination of three nozzle extrusion mechanism, and conducts simulation experiments to verify its effectiveness based on temperature distribution data comparison. It basically avoids the irregular voids and faults caused by the thermal phase change of materials passing through the nozzle during the printing process.

Keywords: FDM molding, 3D printer, extrusion mechanism

1 Introduction

FDM (Fused Deposit Modeling) [1] molding 3D printing reflects the huge advantages compared to traditional manufacturing, with low prices and fast shipping, greatly improving economic benefits [2], and its convenience goes without saying. When a broken machine lacks parts, the drawings can be used to quickly print out parts with precise dimensions, providing a new solution for manufacturing. However, in terms of printing methods, existing printers still face many bottlenecks and exploration problems.

For example, FDM has a slower speed when printing large or high-resolution objects, and is limited by the size of the printer nozzle, making it difficult to achieve details. The mechanical properties of the parts usually have anisotropy, resulting in differences in strength and durability in different directions. At the same time, the surface often has obvious hierarchical textures, which affect aesthetics and functionality. To break these bottlenecks, it is necessary to continuously develop and optimize existing equipment, design new printing technologies to improve the quality of the parts [3-7].

2 Materials and Methods

2.1 Problems analysis

The FDM forming 3D printer mainly consists of a wire feeding mechanism, a heating chamber, a nozzle, and a lifting workbench (Fig. 1).

Among them, as a key component of FDM, the nozzle is related to the quality of the 3D printed object. The main function of the nozzle is to heat the solid material inside to a molten state, and then the material is extruded from the nozzle by an extrusion mechanism. According to the slicing data, the material is bonded and solidified layer by layer, ultimately obtaining a solid body. Especially when manufacturing cantilever parts it is prone to deformation due to lack of support. In order to avoid deformation of the cantilever part, it is necessary to add support parts. When the support and model materials are the same, a single nozzle can be used. But nowadays, two nozzles are often used and heated independently from each other, using different materials to manufacture parts and supports, which can easily lead to rough printing surfaces, poor accuracy, and even errors. Due to the use of hot melt applicators, the material passes through the nozzle with a phase change caused by the heat in the middle part. The pressure of the wire feeding during the phase change is also affected, resulting in irregular voids between the materials and even faults, which in turn produce a "step effect" on certain inclined surfaces [3]. This paper analyzes the problem of the extrusion mechanism in the printer applicator, and we have optimally designed a new extrusion mechanism in series connection for this problem.

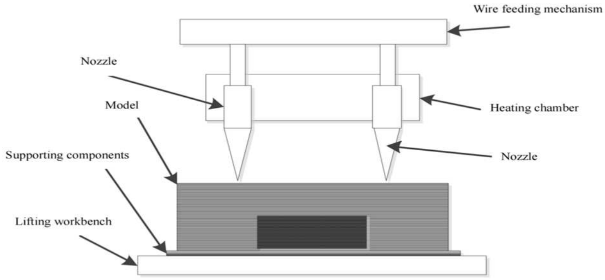

Fig. 1 *The basic structure of a dual nozzle FDM forming 3D printer*

3 Discussion of results

3.1 Optimized design of extrusion mechanism

3.1.1 Optimized design of piston extrusion mechanism

The basic principle of the piston extrusion mechanism is to use a solid material as a piston to convey the material by a stepper motor, and the molten material as the fluid to be pushed to extrude the molten material through the nozzle [4]. However, the general material has a certain viscosity after melting, and the residual material often accumulates in the flow channel and heating chamber, which eventually leads to the blockage of the whole extrusion mechanism, which not only affects the print quality but also is harmful to the machine itself. And because the material diameter is smaller than the inner diameter of the venture pipe, resulting in poor sealing, which is easily a cause salivation problem [5].

This paper optimizes the extrusion mechanism by inserting a Teflon [6] hose inside its venture pipe, the position of which is shown in Fig. 2. Teflon material is a high quality material that is resistant to high and low temperatures and has high self-lubricating [7] properties as well as excellent surface non-stick properties. Therefore, adding Teflon hose in the venture pipe can ensure the fluidity of the material process and make the problems of material accumulation and blockage in the extrusion mechanism be solved effectively.

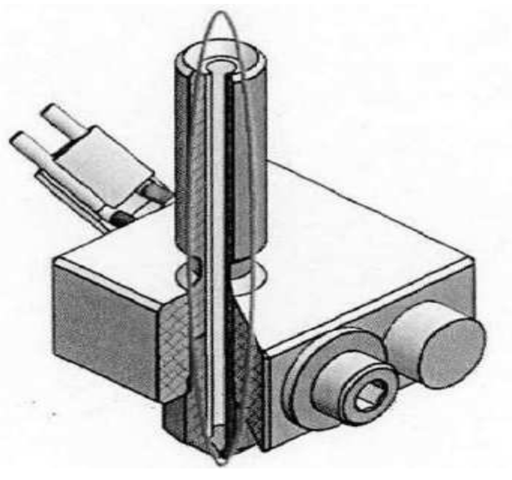

Fig. 2 *Position of Teflon Hose in the Channel*

Given the miniaturization size of the flow channel and heating chamber of each part of the extrusion mechanism, the thread size of the initially selected venture pipe and nozzle is 6 mm, and the material selected for the venture pipe is carbon steel with a tensile strength of 5 M Pa, and the material selected for the nozzle is copper with a tensile strength of σ 1. According to the strength calculation, since the torque of the selected two-phase stepper motor at full load is 7.8 kg·m and the diameter of the tooth top circle of the wire feeding friction pulley is 10 mm, the minimum pull force required to pump the material can be calculated as F=65 N. Since both the pushing and the pumping processes are carried out by means of the wire feeding friction pulley, in this case the material is moved towards the nozzle by a pushing force of 65 N. Considering that the Teflon hose is self-lubricating [8], the frictional behavior of the molding material inside the extrusion mechanism with the walls of the runner and heating chamber is negligible. And the tensile force on the threaded part under the action of the material can be expressed as F1 = 65 N; and we can conclude from the inherent tensile strength of the material and the fluid model formula that the strength of the added Teflon hose in the venturi pipe as well as the nozzle section can meet the standard requirements for threaded connection strength.

3.2 Optimized design of sliding vane pump extrusion mechanism

The sliding vane self-priming pump [9] structure is more compact compared to the piston extrusion mechanism, the overall size is smaller with smoother operation, less pulsation and noise, more uniform flow during operation, and its efficiency is higher compared to the general gear pump [10]. This paper aims to design a sliding vane extrusion mechanism based on it, by driving the rotor through the drive shaft, and drive the vane to achieve impeller rotation. The rotor is placed eccentrically in the pump body chamber, due to the existence of positive and negative pressure difference thus achieving self-priming. The vane can be reset by means of a spring connected to the rotor, and using the rotor so that the tip of the vane is always in contact with the stator coil, driving the fluid to achieve transmission and flow with stable flow rate. The flow rate of the channel can be estimated in the range of 0.001~0.09 mL/s according to the length of the wire extruding when the machine is idle, and the size of the pump body is designed by obtaining the relevant raw data through several experiments. Because the material flow required by the nozzle is very small and its flow stability of the pump also has high requirements, therefore, the constant acceleration and deceleration surface is selected as its internal surface. After that, the size of the sliding vane pump is scientifically designed according to the corresponding sliding vane pump calculation formula. The formula for calculating the flow rate is:

$$Q = \frac{1}{60}\pi\, bn\eta_{pv}\,(R^2 - r^2) \tag{1}$$

Where:
n…The stepper motor speed;
b…The width;

η…The volumetric efficiency;

R…The maximum circular radius of the curve inside the pump body;

r…The minimum circular radius of the curve inside the pump body.

A typical extrusion mechanism requires less flow, so the prime mover must be equipped with a reducer to limit and reduce the rotor speed. Given the processing capability and accuracy as well as the miniaturization of the volume, we chose stator diameter of D=20 mm, rotor speed of n=60 r/min and flow rate of q=0.09 mL/s. Taking into account the flow pulsation, we selected the number of vanes Z=15 and the vane width b=8 mm. Combining all the above parameters into formula (1) for calculation, the final dimensional parameters of each part can be derived, as shown in Table 1.

Tab. 1 *Table of Design Parameters of Sliding Vane Pump Extrusion Mechanism*

Parameter Name	**Stator Diameter/mm**	**Rotor Diameter/mm**	**Vane Width/mm**	**Vane Number/mm**	**Stator and Rotor Eccentricity /mm**	**Pump Volumetric Efficiency/% Degree/(r/min)**	**Rotor Speed**
Symbols	D	d	b	Z	e		b
Parameter Value	20	16	8	15	2	0.1	60

3.3 Optimized design of plunger pump extrusion mechanism

The main part of the plunger pump extrusion mechanism is designed based on the swash plate plunger pump as the prototype [11-12]. The main cylinder part of the piston pump acts as the rotor, driven by the transmission gear to do one-way rotation, and the plunger is located inside the oil chamber and rotates simultaneously with the cylinder. The ball joint at the non-oil pressure end of the plunger is connected to the piston shoe[13] in the form of a hinge joint, which allows it to move around the shaft on the piston shoe. When the axial distance between the contact point and the cylinder end face changes, the plunger can be made to reciprocate, thus achieving the purpose of changing the volume of the oil chamber to realize the process of oil absorption and discharge. According to the principle of motion, the design of the extrusion pump in the plunger pump extrusion mechanism can be optimized. For the arrangement q_b of the plunger pump, i.e., all the volume of oil discharged from plunger chamber exists as follows:

$$q_b = F_Z\, S_{max}\, Z = \frac{\pi}{4}\, d_z^2 S_{max}\, Z \qquad (2)$$

Where:

d_Z…The outer diameter of the plunger;

F_Z…The cross-sectional area of the plunger;

S_{max}…The maximum achievable stroke of the plunger;

Z…The number of plungers.

Using the pump cylinder speed of 60 r/min and the maximum plunger stroke Smax of 2 mm as the parameter substituted into formula (2), we can obtain the plunger outer diameter dZ = 5.35 mm. A plunger pump extrusion mechanism can be designed based on these parameters.

3.4 Combined design of three types of extrusion mechanism

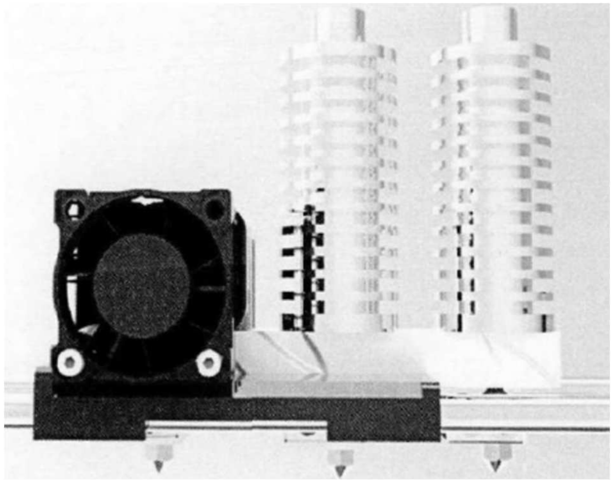

Fig. 3 *A three nozzle extrusion mechanism*

The efficiency of the cooperation among the three extrusion mechanisms is further improved by effectively arranging the three extrusion mechanisms [9]. The piston extrusion mechanism, sliding vane pump extrusion mechanism and plunger pump extrusion mechanism are combined in parallel to form a three-nozzle extrusion mechanism design. The reason for doing so is: the control accuracy of the piston extrusion mechanism is low and the overall mass is small, and the processing accuracy and difficulty are low, but its disadvantage is that the material is not uniformly heated and the discharge volume is unstable, and it is easy to have the problem of salivation and overflow; t, the common advantage of the sliding vane and the plunger pump extrusion mechanism is that the material is heated uniformly and the discharge volume is stable, which can effectively alleviate salivation and overflow, and the plunger pump extrusion mechanism is able to stabilize

ISSN 1213–2489
e-ISSN 2787–9402

the material flow rate in the whole channel, however, they share the same disadvantage of high processing accuracy and difficulty, and its control accuracy requirement is high as well. Their advantages and disadvantages complement each other exactly, so we proposed the design of a three-nozzle extrusion mechanism by combining three extrusion mechanisms together (Fig. 3).

3.5 Experimental simulation

The internal fluid velocity and temperature fields in the model of the optimized extrusion mechanism were simulated using FLUENT [14-18], and the temperature distribution data were obtained and compared with the corresponding actual parameters in the existing 3D printer to verify the feasibility of the design.

3.6 Temperature distribution state of the extrusion mechanism

As shown in Fig. 4, it can be obtained through the simulator that after stabilizing the heating temperature, the temperature of the heating block and nozzle are both stable at 483K (209.85 ℃). For existing 3D printers, when the molding material is PLA, the default working temperature of the heating part of the extrusion mechanism is 210 ℃. The designed extrusion mechanism has a temperature that is basically consistent with the working temperature of the heating part of the existing extrusion mechanism, which meets the requirements for PLA material melting. At the same time, under the action of the heat dissipation system, the average temperature of the exposed part of the throat is 340 K (about 67 ℃), and the heat dissipation effect is good. It can be seen that the temperature distribution in the heating part of the optimized extrusion mechanism is relatively uniform, which can ensure that the material is uniformly heated inside the heating chamber, and the quality of the molten material is good.

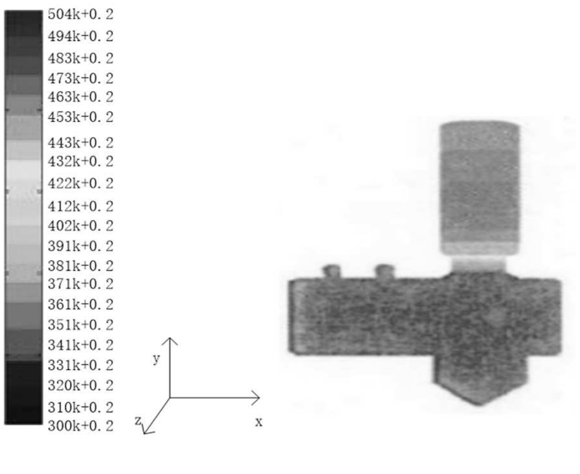

Fig. 4 *Temperature distribution diagram of the working state of the extrusion mechanism*

3.7 Flow rate distribution state of the basin part inside the extrusion mechanism

To facilitate the analysis, we simplify the problem of molten material flow in the flow channel to the problem of viscous fluid flow in the pipe.

Fig. 5 can be obtained through the simulator. Through the simulator, it can be obtained that the molten material near the wall is flowing fast because it is less affected by its own viscosity, while the fluid interior is flowing slowly because of the coarseness effect. However, the flow velocity is stable in all parts of the axial direction, and there is no problem of hysteresis. The maximum internal basin flow rate is about 0.067 ml/s during stable operation and about 0.062 ml/s after stabilization within 0.09 ml/s which is the flow rate of the existing extrusion mechanism

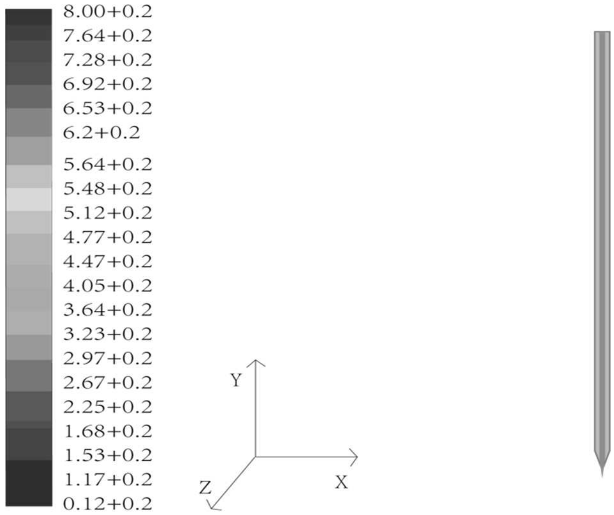

Fig. 5 *Flow velocity distribution in the watershed during the operation of the extrusion mechanism*

3.8 The temperature distribution state of the material in the flow channel

Fig. 6 can be obtained through the simulator, the temperature distribution state of the material is consistent with the temperature distribution state inside the extrusion mechanism. The heating chamber and the nozzle have more high temperature, while the temperature of the other parts is below 500 K. Therefore, the material shall not melt in the venturi pipe, thus avoiding the problem of clogging of the venturi pipe. During normal operation, the heating temperature of ABS needs to be within 240 °C to avoid deformation of the material, while the temperature of ABS material can be stabilized below 226.8 °C during the normal operation of the optimized heating device, which is in line with the temperature requirement of the material. Therefore, the overall heating part of the optimized extrusion mechanism is able to meet the temperature distribution requirements of the actual 3D printing process without affecting either the melting of the material or the deformation of the finished material due to high exit temperatures.

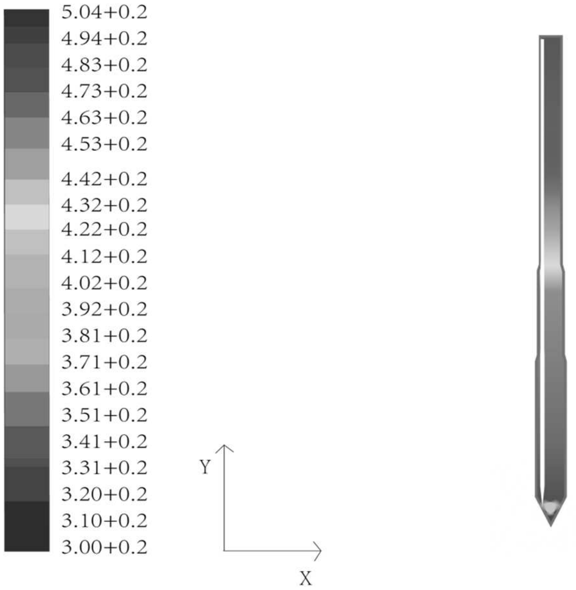

Fig. 6 *Temperature distribution during material operation*

4 Conclusions

In this paper, we analyze the impact of FDM technology in existing 3D printers on the extrusion mechanism, and improve the existing piston extrusion mechanism and add new materials to reduce the flow rate inside the channel and the viscosity of the material to the pipe wall, and also design the corresponding size of the plunger pump extrusion mechanism and sliding vane pump extrusion mechanism to form a three-nozzle extrusion mechanism to improve the quality of 3D printing products. Through experimental simulations, it can be concluded that the designed extrusion mechanism can meet the standards of existing 3D printers while meeting their performance requirements.

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