Theoretical analysis of FDM printing technology and experimental analysis based on low melting point soft materials

Fengyang Liang1*, Yehua Shi2, Yongwei Yu3, Gonglong Liu1 and Di Wang2
1Shanghai Institute of mechanical and electrical engineering, Shanghai, China
2School of Mechatronic Engineering and Automation, Shanghai University, Shanghai, China
3School of Petrochemical Engineering, Changzhou University, Changzhou, Jiangsu, China
*Corresponding author e-mail: liangfengyang163@163.com

Abstract. This paper summarizes the 3D printing process, analyses the working principle of FDM technology, and analyses the motion control and the temperature control. Using the platform built by myself, the feasibility of the application of the low-melting soft material fused deposition process in three-dimensional molding and mild printing was further verified.

1. Introduction
Fused deposition modeling (FDM), with its simple operation, fast forming speed, high utilization rate of raw materials, and many other advantages, has achieved great social and economic benefits and is widely used in machinery, automobiles, aerospace, medical, Arts and architecture [1].

2. Printer working principle and system composition

2.1. FDM printing principle
Under the control of the computer, the extrusion head of the printer heats and melts various thermoplastic materials, and the melted material is piled up in a path, and the material is rapidly solidified. After the deposition of one layer is completed, the distance between the table and the extrusion head is increased by the thickness of one layer in a predetermined increment, and then the deposition is continued, and the layers are stacked until the entire solid shape is completed.

In the actual printing process, in order to ensure that the pre-designed physical prototype can be printed quickly and stably, the basic workflow of the FDM printer system is shown in Fig. 1.

Figure 1. Flow chart of FDM printing
2.2. The composition of the FDM printing system

The FDM printing system consists of two parts: the mechanical structure and the control system. The structure of the specific FDM printing system is shown in Fig. 2.

![Figure 2. The structure of the FDM printing system](image)

(1) Mechanical structure

The fuselage structure and working platform are the main body of the printer. The fuselage structure requires high strength and good stability. The fuselage frame is made of large-size aluminum alloy profiles, and the level is fine-tuned at four corners. The working platform consists of a platform bracket and a hot plate. A horizontal fine-tuning screw equipped with a spring is installed between the hot plate and the platform bracket to ensure the working platform level and provide structural support for the printer to print high-precision printed parts.

(2) Control System

The 3D printing control system is the core of the entire printer, equivalent to the "brains" and "nerves" of the printer. After receiving the Gcode command sent by the slicing software, the instruction is first parsed and the heating and motor motion are controlled.

3. Analysis of control principle

3.1. Analysis of motion control principle

The motion process of a 3D printer based on FDM printing technology consists of two parts, one part is the three-axis relative movement of the extrusion head and the working platform in the XYZ direction; the other part is that the printing material is extruded under the action of the extrusion mechanism and uniformly coated on the working platform. All movements in the printing process are based on a DC stepper motor as a power source, supplemented by a driver, limit switch sensor and controller to form a motion control hardware system. All movements in the printing process are based on a DC stepper motor as a power source, supplemented by a driver, limit switch sensor and controller to form a motion control hardware system. In the motion control software system, due to the conversion of the 3D CAD model into the STL format, any form of spatial complex surface is considered to be composed of a series of small straight line segments, and the motion trajectory of each surface is composed of several small straight line segments, the programming algorithm is mainly focused on the interpolation of straight segments.

(1) Stepper motor control principle

The stepping motor is a motor that converts the input pulse signal into angular displacement or linear displacement output, which is an ideal motion control actuator for 3D printers and has the characteristics of simple structure, high control precision and no cumulative error in continuous operation [2]. It can be seen from the working principle diagram of the two-phase hybrid stepping motor shown in Fig. 3 that
the two phases can be A+ and A-, and B+ and B-. The higher the pulse frequency, the faster the motor rotates [3].

Figure 3. Two-phase stepper motor works

(2) Linear interpolation algorithm

The classic Bresenham algorithm, which is widely used in line generation, is used in the 3D printing controller firmware. The classic Bresenham algorithm is a rasterization line generation algorithm. A rasterized line is a series of pixel points generated to simulate the generation of a line. Its principle is to construct a set of virtual unit vertical grid lines, that is, a unit coordinate system, through the center of each row of pixels. According to the order of the line generation from the start point to the end point, calculate the distance between the line and the intersection of each unit vertical grid line, and then determine the pixel point of the column pixel closest to the intersection point [4].

Assuming that the line is generated in the first quadrant, the starting point coordinate is (x1, y1) and the ending point coordinate is (x2, y2). If the slope of the line is |k| < 1, for each pixel added in the x direction, whether or not a pixel is added in the y direction is determined according to the error term $\varepsilon$, as shown in Fig. 4. If $\varepsilon > 0.5$, y direction moves forward one step, that is y++; if $\varepsilon \leq 0.5$, then y direction does not move, that is, y takes the original value.

Figure 4. Errors of the Bresenham algorithm

If |k| > 1, the x, y in the algorithm can be exchanged, where $k = \Delta y/\Delta x - 0.5$.

The classical Bresenham line generation algorithm steps are as follows [5]:

Step1: Let the error term $\varepsilon = -0.5$, calculate the slope $k$, and let $\varepsilon = \varepsilon + k$;

Step2: If $\varepsilon \leq 0$, then the x direction moves one step, that is, x++, the y direction does not move; otherwise, the x direction moves one step, the y direction also moves one step, and $\varepsilon = \varepsilon - 1$, that is, x++, y++, $\varepsilon$--; when x=1, it turns to Step4;
Step3: $\varepsilon = \varepsilon + k$, turn to Step2;
Step4: over

3.2. Analysis of temperature control principle
FDM printing mostly uses thermoplastic polymer materials. When these materials reach a certain temperature, they melt and become liquid. At different temperatures, the fluidity of the materials is different, and when the temperature rises to a certain temperature, the material will decompose and denature. The fluidity of the material must be matched to the extrusion mechanism in order to allow the silk to be quantitatively extruded and the filaments to be uniform, which is one of the key factors for high quality printing. Whether the temperature can be accurately controlled, this will have a great impact on the print quality, and even directly related to the success or failure of printing.

In the precise temperature control, the PID method is often used to control the heating. It has a simple structure, is easy to implement and has a wide application range [6]. The PID controller is a linear regulator whose control quantity is a linear combination of the ratio (P), integral (I), and derivative (D) of the deviation $e(t)$, where the deviation $e(t)$ is the difference between the set value $r(t)$ of the controlled quantity and the actual measured value $y(t)$.

$$e(t) = r(t) - c(t)$$

(1)

The proportional, integral and differential of the deviation are linearly combined to form a control quantity, and the controlled object is controlled.

$$u(t) = K_p\left[e(t) + \frac{1}{T_i}\int e(t)dt + T_d\frac{de(t)}{dt}\right]$$

(2)

Where $u(t)$ is the output of the controller; $e(t)$ is controller input, which is the difference between the given value and the output value of the controlled object, called the deviation signal; $K_p$ is the scale factor of the controller; $T_i$ is the integration time of the controller; $T_d$ is the differential time of the controller.

In the PID control, the setting of the control parameters is troublesome, and the differential term and the integral term cannot be accurately calculated, and can only be approximated by numerical calculation methods. Fuzzy control is a computer numerical control based on fuzzy aggregation, fuzzy linguistic variables and fuzzy logic reasoning. the basic idea of fuzzy control is to use computer to realize human control experience [7]. Therefore, in heating control, PID control is often used in conjunction with fuzzy control.

4. Experimental process and analysis
Since there are few related studies on the melt extrusion of low-melting soft materials, I verified the feasibility through experiments and laid the foundation for the design and manufacture of general-purpose FDM printers.

4.1. Experimental process
(1) experimental purposes
It mainly verifies the feasibility of melt extrusion of low melting point soft materials.
(2) Experimental materials and devices
The experiment uses a medium-temperature wax used for precision casting as a material, and its melting point is 80-100 °C, and the shrinkage rate is 0.9-1.3. The experiment uses the three-axis motion platform of Korea DASAROBOT company, model: DTR3-3310-S-EZ-EM, its motion stroke is: x (0~300 mm), y (0~300 mm), z (0~100 mm), and the repeat positioning accuracy is 0.01mm. A melt extrusion device is installed on the dispenser platform to form an experimental system, as shown in Fig. 5.
The choice of nozzles is extremely critical throughout the experimental system. Since the molten cast wax is highly viscous, it requires extremely high fluidity in the nozzle. Referring to the dispenser needle dispensing needle can meet the requirements of uniform glue output [8], this experiment uses Japan MUSASHI Musashi integrated dispensing needle, as shown in Fig. 6.

(3) Experimental methods and steps:
Based on the traditional FDM molding process, this experiment studied the main factors affecting the quality of melt extrusion: pressure $p$, nozzle diameter $d$, platform moving speed $v$, etc. Because the cast wax is a low-melting soft material and is affected by the uncertain factors in the nozzle, the phase change problem is involved in the melting process of the cast wax. The extrusion of the molten cat wax is a complicated process, and the extrusion amount cannot be accurately determined. This will affect the uniform extrusion of the cast wax. In order to accurately deposit the molten wax, it is necessary to require the same quality of the extruded slurry per unit time. The experiment uses the control variable method to ensure that the cast wax is uniformly extruded from the nozzle and accurately formed on the working platform.

Experiment 1: Taking the driving air pressure $p$ as a variable, the air pressure is too low, the processing rate is lowered, and the nozzle is easily blocked; Too much air pressure will make the deposition line width ($w$) too large, affecting the accuracy of the parts. The pressure should not be too low or too high, and a reasonable pressure range should be chosen.

Adjust the pressure controller to change the pressure $(p)$ in the barrel, the effect of the pressure $(p)$ size on the line width $(w)$ of the cast wax was investigated. As the air pressure continues to increase, the line width is also constantly increasing. The air pressure determines the extrusion speed; the extrusion
speed is basically proportional to the amount of extrusion per unit time. However, there are cases where the line width is unstable.

Experiment 2: Taking the nozzle diameter $d$ as a variable, the diameter of the nozzle directly affects the molding quality. The smaller the nozzle diameter, the better the molding quality and the higher the printing accuracy. However, when the diameter of the nozzle is too small, the continuity of the melt extrusion of the cast wax is affected, resulting in a change in the thickness of the deposition line and a blockage of the nozzle due to the material particles.

In the experiment, five nozzle diameters $(d)$ were selected, which were 0.4 mm, 0.5 mm, 0.6 mm, 0.7 mm, and 0.8 mm, the heating temperature was 80 °C, the air pressure $(P)$ was 0.4 MPa, and the platform moving speed was 6.6 mm/s. Six groups of experiments were carried out separately, and the results of the parameters after the test are shown in Table 1.

| $d$/mm | 0.4 | 0.5 | 0.6 | 0.7 |
|--------|-----|-----|-----|-----|
| $h_0$/mm | 0.331 | 0.478 | 0.595 | 0.731 |
| $w$/mm | 0.51 | 0.67 | 1.344 | 1.497 |

As can be seen from the above table data, as the diameter of the nozzle increases, the layer thickness and line width of the deposition section are constantly increasing. The line width $w$ of the cast wax obtained by deposition is slightly larger than the nozzle diameter $d$. This is because when the molten wax leaves the nozzle, since the temperature of the cast wax itself is much higher than the ambient temperature, the cast wax at the outlet will rapidly expand, and then quickly Condensation. The relationship diagram is shown in Fig. 7. Because of the large particles in the cast wax, nozzles with a diameter of 0.3 or less are prone to plugging. When the diameter is above 0.7, the line width will increase sharply, which will affect the molding accuracy. Therefore, the nozzle diameter is preferably between 0.3 mm and 0.7 mm.

![Figure 7. Effect of change in nozzle diameter (d) on line width (w)](image-url)

**4.2. Experimental analysis of result**

The above experimental results show that by optimizing some process parameters, a single-layer cast wax line with good quality can be obtained, as shown in Fig. 8.
Figure 8. Molding effect under better process parameters

The experiment verified the feasibility of the cast wax fusion deposition process in three-dimensional molding and mold printing, and provided the necessary foundation for the subsequent experiments.

5. Summary

In this paper, through the analysis of motion control and temperature control in the printing process, and the medium temperature wax used in precision casting as the material, the feasibility of melt extrusion molding of low melting point soft materials was verified, which laid the foundation for the subsequent design and manufacture of a general-purpose FDM printer.

References

[1] P. Jain, A. M. Kuthe, Feasibility Study of Manufacturing Using Rapid Prototyping: FDM Approach, Procedia Engineering. 63 (2013) 4-11.
[2] Sakamoto text. Stepper motor application technology. Science Press. 2010.
[3] B.X. Yu, Z.L. Chen, H.L. Li, Design of two-phase stepping motor drive circuit, Hua Dian Technology. 31(2009) 28-30.
[4] G.P. Li, J.Q. Tan, Improved Straight Bresenham Algorithm, Journal of Hefei University of Technology Natural Science. 26 (2003) 1000-1004
[5] Z.L. Li, S.D. Deng, An improved bisection iterative Bresenham line generation algorithm, Electronic Design Engineering. 7 (2015) 61-63.
[6] Y.F. Peng, Research on Active Vibration Control Based on Fuzzy PID Control Theory, Dalian University of Technology. 2013.
[7] Q. Sun, R. Li, P. Zhang, Stable and optimal adaptive fuzzy control of complex systems using fuzzy dynamic model, Fuzzy Sets & Systems. 133 (2003) 1-17.
[8] L. Miao, Design of precision curve dispenser. Hefei University of Technology. 2010.