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Structural Design of FDM 3D Printer for Low-melting Alloy

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Abstract. Since the metal additive manufacturing technology has some problems, such as high printing cost, low efficiency and high porosity, a method of fused deposition modeling (FDM) and metal additive manufacturing combined was proposed. In this study, a FDM 3D printer suitable for low melting alloy was designed based on the physical characteristics of low-melting alloy. Firstly, a set of overall structure design scheme was proposed. Secondly, the extrusion structure of key parts of FDM printer was designed. Then, the virtual assembly of the designed parts was carried out and the prototype was made. Finally, the frame was analyzed by finite element simulation method. The results show that the frame meets the needs of strength and stiffness.

1. Introduction

Additive manufacturing (AM), also known as 3D printing, has been widely used in aerospace, automotive and other applications for prototyping and manufacturing of parts. Metal additive manufacturing especially is becoming successful in the industrial field due to the performance requirements of component stiffness, strength, smoothness and other aspects [1]. At present, relatively mature metal additive manufacturing technologies include selective laser sintering (SLS), selective laser melting (SLM), electron beam selective melting (EBSM) and so on [2-4]. However, these technologies are relatively expensive in machine, high in printing cost, and all materials used are high-melting metals. In the forming process of metal additive manufacturing, the hot deformation of metal parts is large, and holes are easy to appear [5, 6].

Fused deposition modeling (FDM) is one of the most widely used 3D printing technologies currently [7]. Desktop FDM printer is characterized by low price, simple operation and strong material adaptability. The melting point of low-melting alloy is lower than 232℃, and is in the temperature ranges of material used for FDM [8]. Low-melting alloy can directly use the FDM printer to print out the compact structure of the product [9, 10].

In this paper, the structure design of FDM 3D printer for low-melting alloy is carried out, which provides certain basis for expanding the application scope of FDM and the application fields of low-melting alloy.

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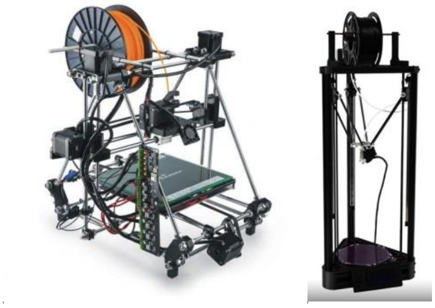
2. Overall structural design

The properties of low-melting alloy are different from polymer. On the basis of the desktop FDM 3D printer for polymers, the corresponding overall structure design is carried out according to the characteristics of low-melting alloy.

2.1. Motion system selection

The motion system only completes the scanning and lifting action of the extrusion mechanism, and its precision determines the motion precision of the 3D printer. At present, the mainstream FDM 3D printer mainly adopts two structures: Cartesian type and parallel-arm type, as shown in Figure 1. The Cartesian 3D printer's motion along the X and Y axes is accomplished by belts and pulleys and along the Z axis is driven by the lead screw. The parallel-arm 3D printer is driven by rods and sliders that are connected to each other. Compared with Cartesian 3D printer, parallel-arm 3D printer is simple to assemble in structure, relatively complex in debugging process, and slightly less stable and accurate in printing [11]. In this paper, the structure of FDM 3D printer for low-melting alloy adopts Cartesian type.



(a) (b)

Figure 1. Motion system structures of 3D printer; (a) Cartesian type and (b) parallel-arm type.

2.2. Frame structure design

As the bearing mechanism of the whole 3D printer, the base and support seat of the body of the 3D printer bear all dynamic load and static load of the printer in the working process. Therefore, the stiffness, strength, stability, reliability and overall weight of the body should be considered in the design.

Aluminum alloy has the advantages of low density, high strength and good mechanical properties, aluminum alloy for the processing of body parts can ensure that the 3D printer has small size, small weight and compact structure. Commonly used aluminum alloy materials include sections, bars and so on, as shown in Figure 2. In this paper, aluminum alloy bar is selected as frame material and the fuselage structure is shown in Figure 3.

(a) (b)

Figure 2. Different structures of aluminum alloy; (a) aluminum alloy sections and (b) aluminum alloy bars.

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Due to the good processing performance and non-toxic, acrylic materials can be used as frame rib material. While ensuring the strength and stiffness, it can also reduce the weight of the 3D printer and facilitate the adjustment during the design and installation process. The floor structure is shown in Figure 4.

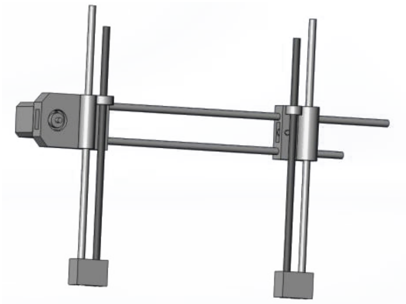

Figure 3. Frame structure

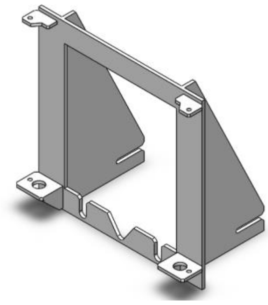

Figure 4. Acrylic rib structure

2.3. Transmission mechanism design

The FDM printer for low-melting alloy is different from ordinary FDM printer in the feeding device, so it is necessary to combine the existing transmission structure and its characteristics with the characteristics of low- melting metal material to select and design. FDM printer commonly used transmission mechanism has ball-screw transmission and toothed belt transmission.

The principle of the ball-screw transmission structure is to change the mode of motor rotation into the mode of linear motion. The screw rod is connected to the motor and rotated. The nut connected to the screw rod will change into a linear motion mode according to the lead of the ball screw pair according to the rotation Angle of the screw rod, so as to realize the process of motion transformation, as shown in Figure 5(a). Ball-screw transmission has the advantages of high efficiency, high rigidity, micro and high speed feed.

The principle of toothed belt transmission structure is to drive the active toothed wheel through the motor and transfer it to the fixed working platform on the belt, so as to finally make the object move. Usually, a group of plane movements can be realized by two groups of toothed belt transmission structure, as shown in Figure 5(b). Toothed belt transmission has the advantages of simple structure, smooth transmission, and can prevent overload slipping.

(a) (b)

Figure 5. Ball-screw transmission and toothed belt transmission; (a) ball-screw transmission and (b) toothed belt transmission.

The extrusion mechanism of low-melting alloy 3D printer needs to move rapidly in the X direction, and the printing platform needs to move rapidly in the Y direction. Therefore, the toothed belt drive is selected in the X and Y directions. The motion precision in the Z direction is directly related to the surface precision of the printing parts, and it must ensure the stability and the amount of movement during the movement, so the ball screw drive is selected.

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2.4. Stepping motor selection

The stepping motor provides driving force for the transmission system and is the power source. When selecting stepping motor, the volume, weight, running parameters and cost price of the motor are very important. According to the performance requirements of low melting point alloy FDM printer, motor suitable for parameters is selected. After the comparison of various parameters and performance of different motors, the JK42HS40-1704-13A stepping motor is selected, as shown in Figure 6. The main specification parameters of the stepper motor are shown in Table 1.

Figure 6. JK42HS40-1704-13A stepping motor

Table 1. Parameters of JK42HS40-1704-13A stepping motor

Weight (kg)	Stepping Angle (°)	Rated Current (A)	Rated Torque (N M)
2.82	1.8	1.7	0.42

3. Extrusion mechanism design

Extrusion mechanism of 3D printer for low-melting alloy mainly has two important functions in melting the low-melting alloy material and extruding the material to the platform. The degree of melting of low-melting alloy is depended on the temperature interval of material. The nozzle keeps constant temperature after reached a certain temperature, and the nozzle is heated by the heating rod when the temperature is low. The quality of extrusion mechanism decides the quality of printing model to a certain extent, and it also plays an important role on the service life of the machine.

3.1. Extrusion Mode Selection

The extrusion modes of nozzle usually have three ways of plunger type, spiral type and piston type, as shown in Figure 7. The principle of the plunger extrusion mechanism is to extrude the melted material by pushing and pressing of the un-melted wire. The plunger extrusion mechanism has the advantages of simple structure, low cost, and the feeding speed can be controlled by the motor. But it has a limited friction driving force, weaker feeding speed and stability. The spiral extrusion mechanism extrudes the melted material by the screw. Compare with plunger extrusion mechanism, it has a large extrusion pressure, stable feeding and other advantages, but the screw has the complex structure, which makes the machining becomes difficult, and increases the cost. The piston extrusion mechanism extrudes the melted material by the pressure from the piston, it has a large extrusion pressure, but it is not applied to the wires. These three extrusion modes all can achieve the material feeding, melting and extrusion. The plunger extrusion mode was adopted considering the price, structure and other aspects.

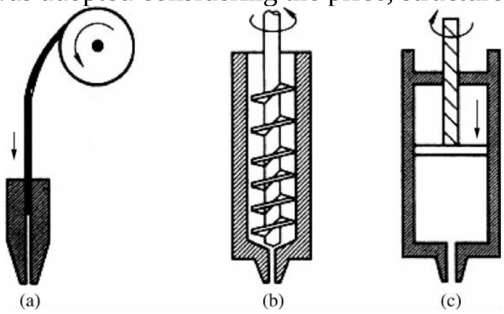

Figure 7. Extrusion ways of nozzles

3.2. Heating Device Design
The nozzle is generally heated by the heating block and the heating rod. The important basis for the heating rod selection is the melting temperature of material. The single-head cylindrical heating rod is used, and it can be divided into two types by the power, one type is high power density heating rod with the power at among 12~25W/cm^2, another type is medium and low power density at among 5~11W/cm^2. The melting point of low-melting alloy is lower than 232℃, so the heating rod with the medium and low power was selected.

Thermistor is a type of sensitive element, which can be divided into positive temperature coefficient (PTC) thermistor and negative temperature coefficient (NTC) thermistor according to different temperature coefficients. Thermistor is sensitive to temperature and show different resistance values at different temperatures. When the temperature is higher, PTC thermistor has a larger resistance value and NTC thermistor has a lower resistance value. According to the characteristics of low-melting alloy, NTC thermistor was selected in this paper. The selected heating rod and thermistor are shown in Figure 8.

The selection of thermal conductivity material of the heating block is mainly based on its heat dissipation performance, thermal conductivity coefficient, hardness and other parameters to decide. Commonly, the materials of heating block include aluminium, copper and so on. The material can transfer more heat under the same temperature gradient when the heat conductive coefficient is larger. Therefore, red copper was selected as the material of heating block. The heating block was designed as hexagonal structure, as shown in Figure 9.

Figure 8. The heating rod and thermistor

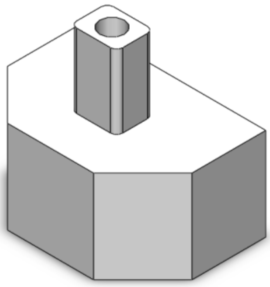

Figure 9. The model of heating block

Integrated extrusion mechanism is shown in Figure 10.

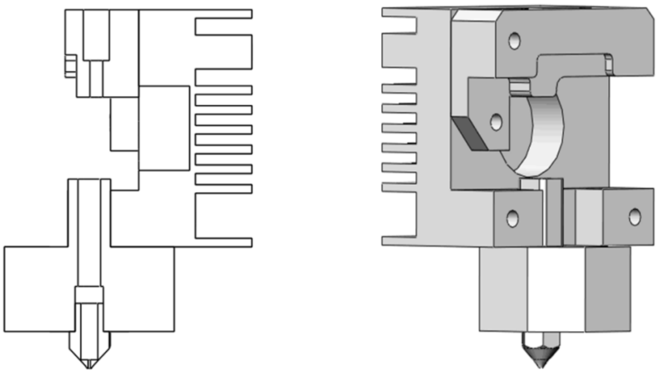

Figure 10. The model of extrusion mechanism

4. Printer platform design
Ordinary FDM printer is prone to warp when printing because the temperature difference between extrusion and room temperature is very large. According to the characteristics of low-melting alloy, the temperature of print platform was set at about 60℃. The heating rod was used for heating and placed at the bottom of the platform. The 3D model and the entity are shown in Figure 11.

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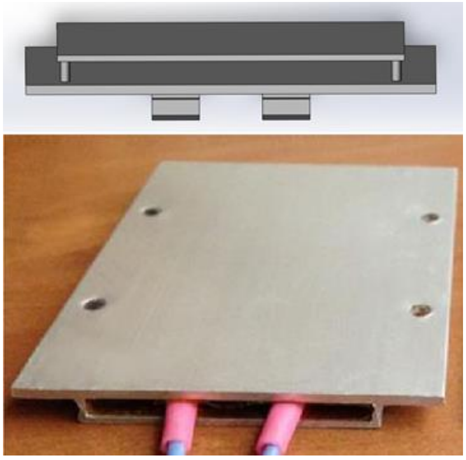

Figure 11. The 3D model and the entity

5. Virtual assembly and prototype manufacture

The Solidworks software was used to build 3D model for each part, then assemble them according to their restraint relationships, and finally complete virtual assembly of the 3D printer for low-melting alloy. The diagram of 3D virtual assembly is shown in Figure 12, and the prototype is shown in Figure 13.

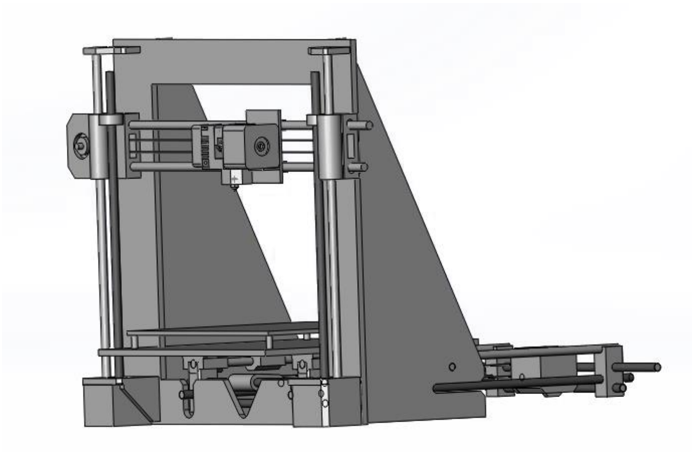

Figure 12. The diagram of 3D virtual assembly

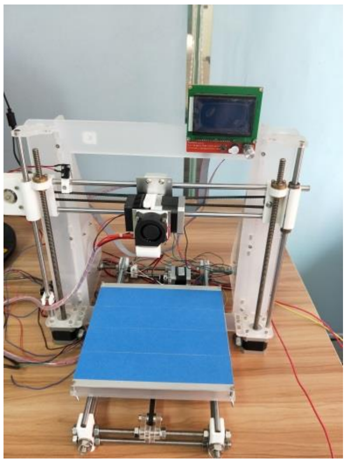

Figure 13. The prototype

6. Finite element analysis

The frame supports the printer as it moves. Static analysis of the frame can be used to analyze its rationality. The structure of the rack was simplified to reduce the difficulty of grid generation and the analysis process and then directly imported into ANSYS Workbench.

The material of the frame is 2024-T351 aluminum alloy, and its performance parameters are shown in Table 2.

Table 2. Parameters of 2024-T351 aluminum alloy

Density ($g\ cm^{-3}$)	Young's modulus (GPa)	Poisson's ratio	Tensile strength (MPa)
2.82	68	0.30	470

The mesh was divided after the parameters of the material were set. The size was constrained and the length was set to 8mm. Then, the 3D model of mesh division was generated, as shown in Figure 14. The number of node was 10143 and the number of element was 1870.

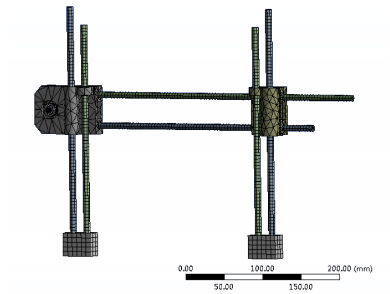

Figure 14. The diagram of mesh division

The diagrams of the equivalent stress, the equivalent strain, and the total deformation are shown in Figure 15, Figure 16, and Figure 17, respectively.

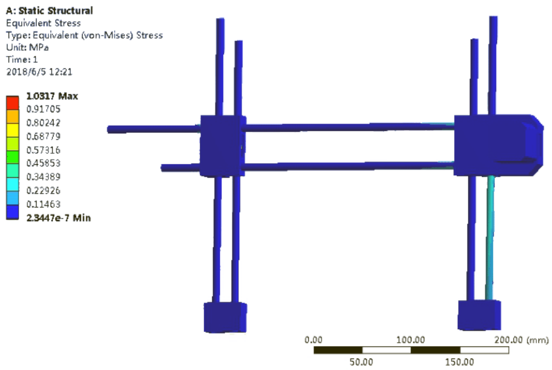

Figure 15. The diagram of frame equivalent stress

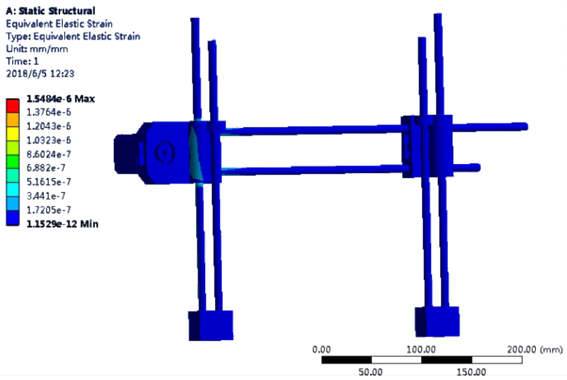

Figure 16. The diagram of frame equivalent strain

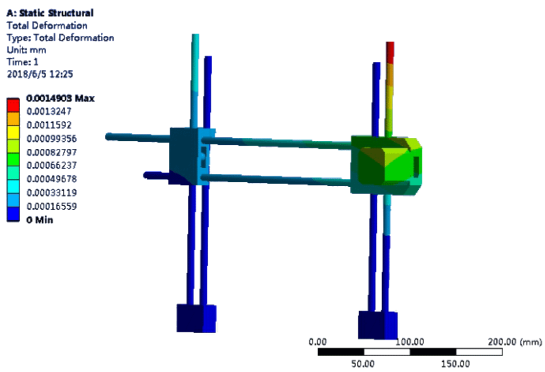

Figure 17. The diagram of frame total deformation

As can be seen from Figure 17 to Figure 19, the maximum stress that the frame can withstand is 1.1MPa, which can meet the performance requirement of strength. The maximum deformation of the frame is 0.001mm, which meets the printing design requirements. The maximum stress of the frame is located at the connection, which meets the design requirements.

7. Conclusion

In this paper, the FDM 3D printer designed, processed and assembled can realize the metal additive manufacturing of low-melting alloy with low cost and simple operation, making up for the shortcomings of the existing metal additive manufacturing equipment with high cost and low density. The rationality of the structure of the FDM 3D printer for low-melting alloy is verified by finite element analysis.

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