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Numerical Simulation of a New Nozzle Based on the Principle of FDM Forming Performance

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Abstract

In order to obtain the ideal parameters about influence degree of melting supplies and the ideal cooling structure of throat, and provide empirical datum for further research, this paper has used finite element method (FEM) to analyze a new type of FDM nozzle structure to study the effect of temperature on the nozzle head of different degree of melting of PLA supplies, the impact of different cooling air flow at the degree of melting of the PLA supplies, and the effects of differently cooling structure of the degree of melting of PLA supplies. The simulation results show that the heat dissipating structure with 195 ℃, nozzle temperature, 180 W/(m^2·℃) forced convection coefficient and Φ 25mm heat pipe diameter of circumstances has good forming effect. In other words, the structure not only has an excellent performance in the throat but also could provide stable and reliable technical support for FDM prototyping equipment.

Keywords: *Rapid Prototyping Technology, Numerical Simulation Analysis, Nozzle Head, Finite Element Method*

1. Introduction

With the fierce market competition and the development of science and technology, the time of new products for research and development has been shortened, in other words researchers must be able to rapidly create newer and better products respectively. As an advanced production technology Rapid prototyping technology appears in the 1990 s, due to its remarkable ability in shortening the development cycle of new products and reducing the development cost, it enables companies to react immediately and improve the market competitiveness [1-3].

Fused deposition molding technology is such a technology that heats the silk material (such as heats shrink material) to melt into liquid, determines the geometry (3D graphics) according to the CAD model by computer, melts heat shrinkable materials into filaments by nozzle and then accomplishes extrusion molding [4-6].Therefore, the nozzle of the fused deposition forming technology is one of the key components in rapid prototyping.

2. The Improvement of Traditional Nozzle

At present, the melt extrusion spray head structure as shown in figure 1 is mostly fission structure which is composed of brass nozzle, aluminum heating block, heating pipe and so on. Due to the complex split type nozzle structure, molten material is easy to adhere to inner surface of brass nozzle, even blocked, and fission structure inevitably exists gaps that make molten material easy to overflow between the components. As shown in Figure 2, in order to improve the disadvantages of traditional nozzle, the whole nozzle structure has been adopted by 304 stainless steel integrated design. Figure 3 shows the inner structure of nozzle; D1 and D2 respectively are the cross section of circular pipe. New nozzles can improve the printing equipment and the efficiency of printing, save the component costs and simplify the whole structure.

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The numerical simulation of new type nozzle used by finite element methods provides theoretical basis for the next step research.

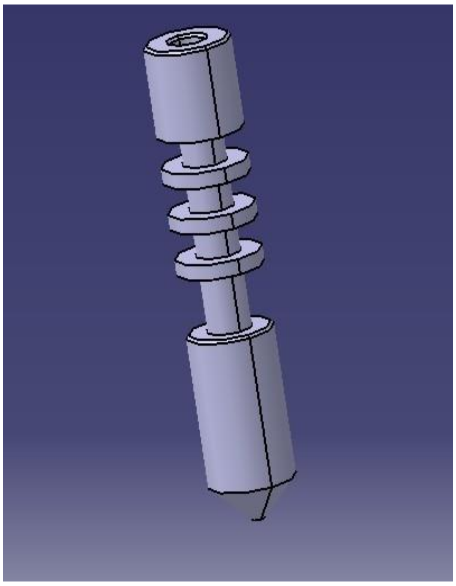

Figure 1. Traditional Nozzle

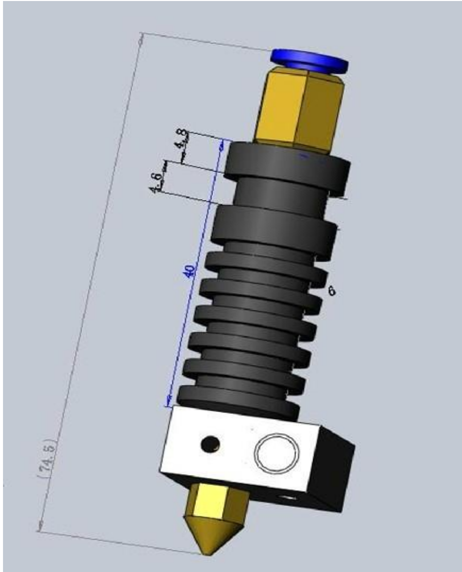

Figure 2. New Type Nozzle

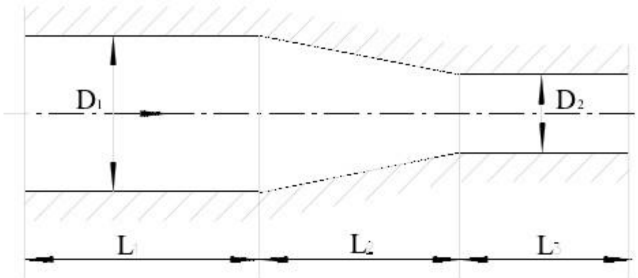

Figure 3. Inner Structure of Nozzle

3. To Analyze New Type Nozzle

Thermal simulation of fused deposition molding process belongs to nonlinear thermal analysis problem, so it must be described by the heat conduction differential equations as [7]:

$$\rho c\frac{\partial T}{\partial t}-\frac{\partial}{\partial x}\left(k_x\frac{\partial T}{\partial x}\right)-\frac{\partial}{\partial y}\left(k_y\frac{\partial T}{\partial y}\right)-\frac{\partial}{\partial z}\left(k_z\frac{\partial T}{\partial z}\right)-\rho Q=0 \quad (1)$$

Among the formula：

ρ show the density of materials $(\mathrm{kg/m^3})$;
c show that the specific heat of materials $(\mathrm{J/(kg \cdot K)})$;
k_x, k_y, k_z respectively show the heat transfer coefficient of material along the X, Y, Z direction $(\mathrm{W/(m\hat{}2 \cdot {}^\circ C)})$;
T show the temperature;
t show the time;
$Q = Q(x, y, z, t)$ show the internal heat source density $(\mathrm{W/kg})$。

The heat balance equation shows that the incoming heat and the heat generated by the internal heat source are always in balance with the required heat for warming objects.

New type nozzle adopts 304 stainless steel, whose density is 7.93 x 10-3 g/mm3, coefficient of thermal conductivity is 17.45W/(m^2·℃), specific heat of 500J/·℃. Figure 4 shows finite element model for a quarter of the nozzle, which is free meshed by ANSYS Solid7.0 thermal unit. The nozzle initial and boundary conditions has been set, initial conditions can be expressed by type (1):

$$T(x, y, z, t)\big|_{t=0} = T_0 \tag{2}$$

nozzle cooling is mainly by natural and forced convection manner, whose boundary conditions are as follows:

$$-K \frac{\partial T}{\partial y}\bigg|_{y=0} = \varepsilon_\theta \sigma \left(T_{y=0}^4 - T_{sur}^4\right) + h\left(T_{y=0} - T_{env}\right) \tag{3}$$

Among the formula：
ε_θ show the effective emissivity of the object；
σ show the Stefan - Boltzmann constan，about $5.67 \times 10^{-8} W / \mathrm{m}^2 \cdot K^4$;
T_{sur} show the environment temperature；
T_{env} show the heat transfer fluid temperature of environment；
h show convective heat transfer coefficient。

PLA (polylactic acid) has lower melt strength, print model more easily to be shaped, excellent gloss surface and varied color [8-10]. As shown in figure 5,PLA not only has good thermal stability, processing temperature is 170 ~ 230 ℃, but also good resistance to solvent, so by way of simulating and analyzing the thermal changes of the nozzle area could indirect analyze PLA's melting condition. The thermal changes of 1, 2 are the main observation of study.

2.4. The Simulation Results and Analysis

Table 1 ~ 3 is under the condition of different temperatures and heat transfer, different inner hole diameter in 1, 2, as shown in figure 5 mark of temperature range, the optimal selection of the reasonable structure of heating environment provide theoretical basis for further improvement.

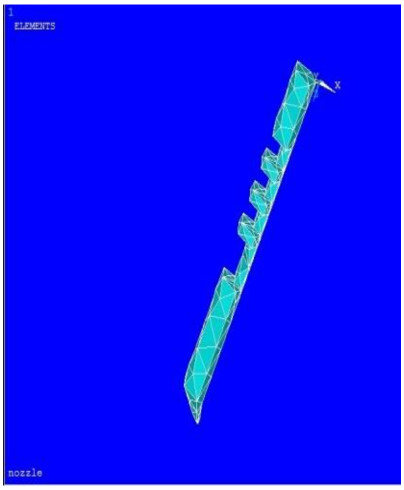

Figure 4. A Quarter of the Nozzle

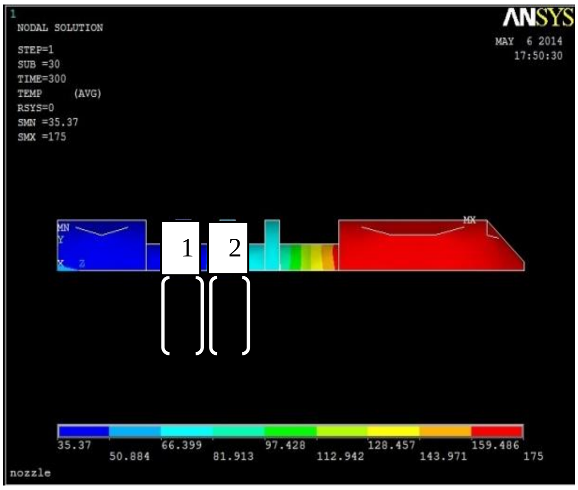

Figure 5. The Temperature Distribution Cloud

Table 1. Inner Hole Diameter of Φ 2.5 Mm under Different Heating Temperature Distribution of the 1, 2

Heating temperature /℃ — 1, 2, section of temperature distribution /℃ — Convective heat transfer coefficient /W/(m^2·℃)	175	185	195	205	215
20	100~110、110~120	106~116、116~126	112~122、122~132	117~128、128~139	122~134、134~145
100	51~66、66~80	53~70、70~85	54~72、72~89	56~75、75~93	59~79、79~97
180	42~59、59~75	44~61、61~79	45~64、64~82	46~66、66~86	48~70、70~90

Table 2. Inner Hole Diameter of Φ 2.2 Mm under Different Heating Temperature Distribution of the 1, 2

Heating temperature /℃ — 1, 2, section of temperature distribution /℃ — Convective heat transfer coefficient /W/(m^2·℃)	175	185	195	205	215
20	101~112、112~123	107~118、118~129	113~124、124~135	118~130、130~141	123~136、136~148
100	52~68、68~83	54~72、72~88	55~74、74~91	57~76、76~96	61~80、80~100
180	43~60、60~77	45~63、63~81	46~66、66~85	47~68、68~89	49~73、73~94

Table 3. Inner Hole Diameter of Φ 1.8 Mm under Different Heating Temperature Distribution of the 1, 2

Heating temperature /℃ — 1, 2, section of temperature distribution /℃ — Convective heat transfer coefficient /W/(m^2·℃)	175	185	195	205	215
20	101~113、113~125	108~120、120~131	114~126、126~138	119~132、132~144	124~138、138~151
100	53~70、70~86	55~74、74~91	56~76、76~94	58~78、78~99	62~82、82~103
180	44~62、62~80	46~65、65~84	47~68、68~88	48~70、70~92	50~75、75~97

3. Test Model and Orthogonal Experimental Design

3.1. FDM Equipment and Test Model

The surface accuracy and shape accuracy, dimensional accuracy to measure often determine the precision of FDM. In order to test the different parameter combination to affect the accuracy of forming parts of the printer, a 200 x 200 mm square test has been designed. Engineering prototype with 150X220mm print range, forming material PLA and nozzle with 0.4 mm diameter are used to test. The data measuring test piece five times is taken mean value D as experimental data. Dimension error $\varepsilon = |D - D_a|$

3.2. Orthogonal Experiment Scheme

Through the error analysis of the experimental parameters, heating temperature (A), throat diameter (B), layer thickness (C), and convective heat transfer coefficient (D),the four process parameters are selected as the research object, and then three levels are assigned to them respectively. In order to determine the best combination orthogonal experiment is used to study the impact of the four parameters on forming parts of the error. As shown in Table 4, theoretical guidance is based on the numerical simulation data, then follow Table 5 $L_9(3^4)$ to do orthogonal experiments.

Table 4. Process Parameters

Level	Factors			
	A	B	C	D
	heating temperature/℃	throat diameter/mm	layer thickness/mm	convective heat transfer coefficient/W/(m^2·℃)
1	175	18	0.1	20
2	195	22	0.2	100
3	215	25	0.3	180

Table 5. Orthogonal Experiment Scheme and Results

The numbers	Experiment methods				Experiment results
	A	B	C	D	Dimensional error /mm
1	1	1	1	1	1.33
2	1	2	2	2	0.55
3	1	3	3	3	0.72
4	2	1	2	3	0.47
5	2	2	3	1	1.11
6	2	3	1	2	0.23
7	3	1	3	2	0.69
8	3	2	1	3	0.30
9	3	3	2	1	0.96

3.3. Results Analysis

Through the experiment following phenomenon is showed in 17, when the lower the temperature is, the larger the layer thickness is, and under the natural wind blowing, tests form larger defects. Because of the poor state of the molten material silk, thick and large sliced, and not enough air flow convection cooling, making the material bond is reduced, thereby bonding between the layers is not close to cracking, scuffing, directly affect the quality of molded parts . However， when the temperature is too high and the wind is too large, Molding effect is also not good , as shown in Figure 6. This is because the temperature is too high, the melt completely, causing the wire quantity increase, coupled with peripherals fan forced air convection, making just been extruded material rapidly solidified, forming a stacking phenomenon, even dislocation or skewed.

Figure 6. A Test Sample Which Heating Temperature Is 215 ℃, the Throat Diameter is Φ18mm and the Thickness is 0.3 Mm in Natural Convection Coefficient of 180 W/(M^2·℃)

Table 6 shows the analysis results, the effect of process parameters on size error from big to small in turn is: The heating temperature>The convective heat transfer coefficient>The layer thickness>The throat diameter. In optimization experiments, it is impossible to study each interaction of both factors, and according to the experience, because of the interaction effect between them, the heating temperature and the convection coefficient in the process of forming need to be matched. As can be seen from Table 7, at a heating temperature of 195 ℃, the convection coefficient is 180W/(m^2·℃), the size of the error is the smallest.

Table 6. Mean Value and Range Value of Dimension Error (Mm)

level	heating temperature	throat diameter	layer thickness	convective heat transfer coefficient
(1 The sum of the index of level test)The mean 1	1.040	0.830	0.637	1.023
(2 The sum of the index of level test)The mean 2	0.527	0.687	0.720	0.583
(3 The sum of the index of level test)The mean 3	0.633	0.683	0.843	0.593
The extremum R	0.513	0.147	0.206	0.440

Table 7. Dimension Error of Heating Temperature and the Convective Heat Transfer Coefficient Interaction (Mm)

heating temperature/℃	convective heat transfer coefficient/W/(m^2·℃)		
	20	100	180

175	1.78	0.67	0.76
195	0.98	0.30	0.41
215	1.21	0.44	0.38

4. Conclusion

This paper has optimized the design of traditional 3D printing nozzle as well as used the finite element numerical simulation to analyze the structure of a new type of nozzle, in which the effect of temperature on the nozzle head of different degree of melting of PLA supplies, the impact of different cooling air flow at the degree of melting of the PLA supplies, and the effects of differently cooling structure of the degree of melting of PLA supplies have been considered, so as to achieve ideal parameters and the structure. With the help of experiment in examination and correction, $A_2B_3C_1D_2$ has good forming effect. The structure not only has an excellent performance in the throat but also could provide stable and reliable technical support for FDM prototyping equipment.

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