Mechanical Influence Analysis and Experimental Study of 3D Printing Fault

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Abstract. The occurrence of faults in 3D printing is random. Faults in the printing have a great influence on printing quality, which may affect the surface quality, dimensional accuracy and mechanical properties of the printed part. Serious malfunctions can cause printing to fail, resulting in waste. In order to better understand the influence mechanism and extent of faults on printed parts, the paper conducts the analysis of generation mechanism and mechanical influence of two types of printing faults such as congealed tumor and overhang printing based on experiments. The paper also summarizes the mathematical expressions of the influence of printing fault, which aims to provide a reference for further fault monitoring, removing and compensating.

1. Introduction
3D printing technology has been widely used in aerospace, machinery manufacturing and other industries. However, the strength and accuracy of printed parts are still important factors restricting the development of 3D printing[1]. Moreover, current 3D printers rarely have fault online monitoring function[2]. If a failure occurs during the printing, the mechanical properties of the part will be reduced to a certain extent and even the printing fails. In order to explore the influence of faults on printing quality, the paper conducts an analysis of fault generation mechanism and mechanical influence based on experiments. The purpose is to grasp the influencing factors and extent of printing quality which is caused by printing faults, so as to provide a basis for research on fault diagnosis and compensation.

2. Experimental Conditions
The experiment uses a delta3D printer (as shown in Figure 1). The printing material is PLA, the diameter of filament is 1.75mm and the filament has 3 colors. The printer belongs to FDM type and can realize two printing modes which are colorful switching and gradual mixing. During printing the filament is pulled out by the friction wheel and then transported through the duct to the nozzle to be heated. The filament is extruded through the orifice of the nozzle after being fused. The accumulation is started on the leveled hot bed according to the process parameters and scanning path which are set before printing. The accumulation gradually increases from bottom to top. The filament enters the nozzle according to a single type when the printing mode is colorful switching. The filament enters the nozzle in linkage when the printing mode is gradual mixing.
3. Analysis of Fault Generation Mechanism

From the perspective of the entire printing, faults such as filament breakage and transportation obstruction, nozzle clogging and accumulation skewing can occur at any time. Minor malfunctions may have a small influence on printing quality. Some faults (as shown in Figure 2) have a significant influence on printing quality and need to be removed or compensated in time.

The congealed tumor is formed because the printer has only one nozzle. The former printing material will inevitably remain in the cavity of the nozzle when switching the printing material. Residual material will be brought out when the new material is extruded. Due to the inconsistent temperature of the two materials it will entangle into a lump when cooling, forming a hard congealed tumor.

Overhang printing is generated because a certain material suddenly breaks, jams or runs out during printing. There is no material supply for the nozzle. The printer fails to detect the lack of filament and continues printing. At this time, the movement of the nozzle is an empty stroke. There is no filament accumulation on the printed part. The nozzle re-ejects the filament when the next material is used. Due to the empty stroke in the front, the filament at this time will slowly overlap with the printed part after overhanging due to gravity and fan blowing. Therefore, overhang printing is generated.
4. Analysis of Mechanical Influence
Congealed tumors are very hard. If they are not removed in time, the nozzle will collide with the congealed tumors during the movement and generate strong vibration. It may cause the printed layer to detach from the hot bed or the nozzle may directly crush the congealed tumor which will seriously affect the quality of the part. In order to investigate the collision mechanism of the nozzles, a collision model as shown in Figure 3 is constructed.

Through experiments and analysis, we can know:
1) The congealed tumor is bonded to the hot bed. The force analysis can be regarded as the force model of cantilever beam when the nozzle collides with the tumor, as shown by a, b and c in Figure 3.
2) The direction of the collision force F is constantly changing, which is related to the movement path, contour shape, filling method of the nozzle.
3) Congealed tumors will leave the hot bed during continuous collisions. The detached congealed tumor is blown out by the fan or dropped into the internal grid of the printed part.
4) Congealed tumors may sometimes be higher than the current printing layer, as shown by c in Figure 3. The nozzle will press the congealed tumor when starting the next layer printing, which will easily damage the printed layer or internal support, and reduce the precision of the product.

The occurrence of overhang printing is random. Considering that the printed layer and the hot bed need to be firmly bonded, the printed layer can be regarded as a vertical cantilever beam during the force analysis. After overhang printing the filament sprayed by nozzle is randomly placed on the printed layer, which will generate a certain inclination with the printed layer. It is assumed that the diameter does not change and remains the same diameter as the nozzle after the filament is extruded from the nozzle. Let the diameter of nozzle is d, the height of the printed layer AC is h1, the height of the printed layer AB which is overhung is h2, and the inclination angle between the printed layer which is overhung and the printed layer is θ. Figure 4 shows the force model of overhang printing.
\[ G_1 = G \cdot \cos \theta \]  
\[ G_2 = G \cdot \sin \theta \]  

G1 can be decomposed into G3 and G4 at the top (point A) of the printed layer according to the transmissibility of the force.

\[ G_3 = G_1 \cdot \cos \theta = G \cdot (\cos \theta)^2 \]  
\[ G_4 = G_1 \cdot \sin \theta = \frac{G \cdot \sin 2\theta}{2} \]

G3 will compress the printed layer and G4 will bend the printed layer. G2 will have a bending effect on the printed layer which is overhung. It can be calculated that the stress and deformation caused by each force component are as follows.

4.1 Influence of G1

The compressive normal stress generated by G3 is:

\[ \delta_{3\text{max}} = \frac{G_3}{\pi^2 t^4} = \frac{4G(\cos \theta)^2}{\pi d^2} \]  

The amount of compression deformation generated by G3 is:

\[ \Delta h = \frac{G_3 h_1}{E t^2} = \frac{4Gh_1(\cos \theta)^2}{E \pi d^4} \]

The maximum bending normal stress generated by G4 is:

\[ \delta_{4\text{max}} = \frac{M_{\text{max}}}{w_z} = \frac{G_1 h_1^3}{3E t_z} = \frac{16Gh_2 \sin 2\theta}{\pi d^4} \]  

The maximum bending deflection generated by G4 is:

\[ W_{4\text{max}} = \frac{G_4 h_1^3}{3E t_z} = \frac{32Gh_1 \sin 2\theta}{3E \pi d^4} \]

The maximum bending rotation angle generated by G4 is:

\[ \alpha_{4\text{max}} = \frac{G_4 h_1^2}{2E t_z} = \frac{16Gh_2 \sin 2\theta}{E \pi d^4} \]

4.2 Influence of G2

The printed layer which is overhung and the printed layer need to be firmly bonded at point A to ensure that the subsequent filaments sprayed by nozzle can stick. Therefore, it can be regarded as a cantilever beam at point A.

The maximum bending normal stress is:

\[ \delta_{2\text{max}} = \frac{M_{\text{max}}}{w_z} = \frac{G_2 h_2^2 \sin \theta}{3E t_z} = \frac{16Gh_2 \sin \theta}{\pi d^3} \]

The maximum bending deflection is:

\[ W_{2\text{max}} = -\frac{G_2 h_2^2 (h_2^2)}{6E t_z} \left( 3h_2 - h_2^2 \right) = -\frac{20Gh_2^2 \sin \theta}{3E \pi d^4} \]

The maximum bending rotation angle is:

\[ \alpha_{2\text{max}} = -\frac{G_2 h_2^2}{2E t_z} = -\frac{8Gh_2 \sin \theta}{E \pi d^4} \]

It can be seen from the above calculation expressions that the overhang printing will produce additional bending stress, compressive stress and deformation. These quantities are related to the diameter of nozzle, the height of printed layer, the height of printed layer which is overhung, inclination angle, material properties (E elastic modulus) and other parameters, as shown in Table 1.
Table 1. Parameter relationship of additional stress and deformation during overhang printing

| Influence parameter | Characterization | d | h₁ | h₂ | E | θ |
|---------------------|------------------|---|----|----|---|---|
| G₄                  | δ₄ₘₐₓ            | 3rd power | 1st power | unrelated | unrelated | sin2θ |
|                     | W₄ₘₐₓ            | 4th power | 3rd power | inversely proportional | unrelated | sin2θ |
|                     | α₄ₘₐₓ            | 4th power | 2nd power | inversely proportional | unrelated | sin2θ |
| G₃                  | δ₃ₘₐₓ            | 2nd power | unrelated | unrelated | unrelated | (cosθ)² |
|                     | Δh               | 2nd power | 1st power | inversely proportional | unrelated | (cosθ)² |
|                     | δ₂ₘₐₓ            | 3rd power | unrelated | unrelated | 1st power | sinθ |
| G₂                  | W₂ₘₐₓ            | 4th power | unrelated | inversely proportional | 3rd power | sinθ |
|                     | α₂ₘₐₓ            | 4th power | unrelated | inversely proportional | 2nd power | sinθ |

From the above analysis, we can know:

1) Overhang printing will have additional bending and compression effects on the printed layer. It is closely related to the diameter of nozzle, the height of the printed layer (that is the position where the overhang printing occurs), the inclination angle and the elastic modulus of the printed material. The biggest impact is the 4th power series. The diameter d of nozzle and inclination angle θ have the widest range of influence, and have different influence extent on each characterization quantity. When the bending stress is too large, the warp separation of the first printing layer and the hot bed will be caused, resulting in printing failure. Bending deformation and compression deformation can cause shape errors and height errors of the printed layer.

2) When overhang printing occurs, the angle θ of the printing filament is uncertain and is a variable. It is found that the change of θ is related to the size and shape of printing profile, scanning path, and printing speed through experimental and theoretical analysis.

3) The printed layer which is overhung will have a bending effect due to its own gravity. It is closely related to the diameter of nozzle, the height of printed layer which is overhung, the inclination angle, and the elastic modulus of the printing material. The biggest impact is the 4th power series.

5. Conclusion

The paper theoretically analyzes the generation mechanism of two types of printing fault (congealed tumors and overhang printing) through 3D printing experiments. It also develops the mechanical influence analysis of these two types of fault and builds a mechanical analysis model. The mathematical expressions of additional stress and deformation are summarized. The specific influence parameters and extent of the fault are found.

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