Experimental Study on the Dimension Error of Bridged Structures Printed by Fused Deposition Modeling

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Abstract. Fused deposition modeling, a popular additive manufacturing technology by extruding thermoplastic materials, can be used to print structural parts with complex geometries. However, when a part appears an overhanging structure, it is usually necessary to add an auxiliary support structure. The added structure not only causes material waste but also secondary damage to the printed part owing to removing the support structure in post-processing. To understand the dimension error of bridged structures without support structures, this paper experimentally investigated the effects of the bridging span, layer thickness, nozzle speed and temperature on the sagging deformation of the bridged structures. The limitation of bridging span and the sensitivities of the printing parameters were found.

1. Introduction

Additive manufacturing is a layer-by-layer process, which can build parts with extremely complex geometry and a high degree of freedom that other traditional methods cannot achieve. Fused deposition modeling (FDM) or fused filament manufacturing (FFF) is one of the most popular additive manufacturing technologies [1], which prints parts by extruding thermoplastic materials. FDM prints a part layer-by-layer on a processing platform along the pre-planned path on the sliced surfaces of the computer-designed three-dimensional model. There is a limit to the FDM process that the angles between the downward surfaces of a part and the horizontal platform should be greater than a critical angle of 45° usually [2]. If all the downward surfaces meet this requirement, the corresponding part is of self-support, otherwise, the molten filament would collapse during printing [3]. Adding an auxiliary support structure (ASS) is a common way to deal with this problem [4]. When parts have complex profiles or structures such as overhanging, hollow, spherical surfaces, ASS can prevent the printed objects from deforming or even collapsing under gravity, thereby keeping the designed shape. However, the introduction of support structures has some disadvantages [5], such as more materials, longer printing time, limiting the printing flexibility, and the most important problem is that the surface quality could be damaged due to the required additional post-processing procedures.

The part with bridged features is of a typical supportless structure widely appears in FDM’s applications. This work will carry out an experimental study on the quality of the bridged structures printed by the FDM, specifically, find the limitation of the FDM process printing a bridged structure and examine the effects of the process parameters, such as the horizontal span, layer thickness, nozzle speed, and temperature, on the dimension error of the finished part.
2. Experimental setup

2.1. Experiment and material

The utilized 3D printer for this study is the A7 JGMaker (JGMaker Co. Ltd., Shenzhen, China), in which the nozzle temperature \( T_n \), platform temperature \( T_p \), layer thickness \( S \), nozzle speed \( V_n \), and filling density and style can be adjusted. The printed material is PLA. In the experimental study, only the process parameters \( T_n, S, \) and \( V_n \) are changed, and the other related parameters are fixed and given in Table 1.

| Parameter                  | Value       |
|----------------------------|-------------|
| Filament diameter (mm)     | 1.75±0.05   |
| Nozzle diameter (mm)       | 0.4         |
| Fan speed (rpm)            | 250         |
| Platform temperature (℃)   | 60          |
| Filling density (%)        | 100         |
| Filling style              | Grid        |

2.2. Model of bridged structures

A bridged structure was designed as shown in figure 1. The biggest challenge to successfully print this structure results from the bridge deck due to the angle between the downward surface and the piers in which is 0°. This implies the bridge deck is fully supportless, and printing this feature is at a high risk of collapse.

![Figure 1. The computer-designed model of a bridged structure for FDM printing.](image)

3. Results and discussion

To examine the effects of the process parameters on the dimension error of the bridged structure, we find the limitation of the bridging span for the FDM process first and then do a series of experiments with different process parameters at a fixed bridging span that allows the structure can be successfully printed.

3.1. Limitation of the bridged structure

To find the limitation of the bridged structure, we changed the bridging span from 25 to 43 mm and print the structures using the parameters listed in Table 1 and the nozzle temperature \( T_n=200 \) °C, layer thickness \( S=0.2 \) mm, nozzle speed \( V_n=60 \) mm/s. The finished parts with different bridging spans are shown in figure 2. The results show that the deformations at the decks of the cases with a bridging span of less than 33 mm and filament sagging under the deck are almost invisible, while the defor-
mation is significant and filament sagging can be seen for the cases with a bridging span of greater than 37 mm. With the increase of the bridging span, the deformation is larger and the number of the sagging filament becomes more and these filaments are even unbonded with the layer on their top. The results indicate that the limitation of the bridged structure for the FDM process should be in the range of 33 to 37 mm.

![Figure 2. The finished parts with different bridging spans.](image)

### 3.2. Effect of process parameters

The bridging span in this section is fixed as 35 mm and the total thickness of the deck is designed as 5 mm. The nozzle temperature, layer thickness, and nozzle speed are changed in three levels, specifically, 200, 210, and 220 °C for the nozzle temperature, 0.1, 0.2, and 0.3 mm for the layer thickness, and 20, 40, and 60 mm/s for the speed. See Table 2 for the full design of experiments.

| NO. | $S$ (mm) | $T_n$ (°C) | $V_n$ (mm/s) | $h$ (mm) |
|-----|----------|------------|--------------|----------|
| 1   | 0.1      | 200        | 20           | 6.03     |
| 2   | 0.1      | 200        | 40           | 6.01     |
| 3   | 0.1      | 200        | 60           | 6.06     |
| 4   | 0.1      | 210        | 20           | 6.02     |
| 5   | 0.1      | 210        | 40           | 6.03     |
| 6   | 0.1      | 210        | 60           | 6.06     |
| 7   | 0.1      | 220        | 20           | 5.99     |
| 8   | 0.1      | 220        | 40           | 6.01     |
| 9   | 0.1      | 220        | 60           | 6.13     |
| 10  | 0.2      | 200        | 20           | 5.98     |
| 11  | 0.2      | 200        | 40           | 5.99     |
| 12  | 0.2      | 200        | 60           | 6.01     |
| 13  | 0.2      | 210        | 20           | 6.01     |
| 14  | 0.2      | 210        | 40           | 6.03     |
| 15  | 0.2      | 210        | 60           | 6.50     |
| 16  | 0.2      | 220        | 20           | 6.18     |
| 17  | 0.2      | 220        | 40           | 6.25     |
| 18  | 0.2      | 220        | 60           | 6.32     |
| 19  | 0.3      | 200        | 20           | 6.14     |
| 20  | 0.3      | 200        | 40           | 6.13     |
| 21  | 0.3      | 200        | 60           | 6.18     |
| 22  | 0.3      | 210        | 20           | 6.22     |
| 23  | 0.3      | 210        | 40           | 6.23     |
| 24  | 0.3      | 210        | 60           | 6.23     |
| 25  | 0.3      | 220        | 20           | 6.22     |
| 26  | 0.3      | 220        | 40           | 6.33     |
| 27  | 0.3      | 220        | 60           | 6.37     |

The largest thickness of the deck of the finished parts is measured by a vernier caliper and listed in the right column of Table 2. The difference between the thickness and the corresponding designed
value evaluates its deformation. Doing a linear regression between the deformation and the process parameters $T_n$, $S$, and $V_n$, we can obtain an equation as:

$$
\Delta h = 0.190 \times \left[ \frac{S - 0.1}{0.3 - 0.1} \right] + 0.141 \times \left[ \frac{T_n - 200}{220 - 200} \right] + 0.119 \times \left[ \frac{V_n - 20}{60 - 20} \right] + 0.911 \tag{1}
$$

The coefficients of the normalized process parameters at the right-hand side indicate the importance of the corresponding parameter to the deformation. The results indicate that the contribution from the change of the layer thickness to the deformation is the most important, the nozzle temperature taking the second place and the nozzle speed last, and the deformation increases as any one of these three parameters increases. The reasons for the effects of the layer thickness and the nozzle temperature could be that: 1) the diameter of the molten filament increases as the increase of the layer thickness, and the cooling rate is smaller for a molten filament with a larger diameter while the gravity force is larger, as a consequence, its sagging deformation increases. 2) the molten filament needs more time to be cooled down at a higher nozzle temperature, resulting in a larger displacement of the molten filament due to the movement of the molten fluid due to the gravity force and thus a larger sagging deformation. The reason for the nozzle speed could be very complex and related to the polymer entanglement stress due to the nozzle extrusion at different feed rates of the PLA. In addition, the constant term at the right-hand side tells us that the inherent deformation of the bridged structure at the bridging span of 35 mm under the tested process window is approximately 1 mm.

4. Conclusion

This work carried out an experimental study on the supportless structure, bridged structure as an example, by the FDM process. The limitation of the bridging span that allows the bridged structure can be successfully printed was found in the range of 33-37 mm. The sagging filaments on the downward surface of the deck are even unbonded with the layer on their top once the bridging span is greater than 37 mm. The effects of the layer thickness, nozzle temperature and speed on the deformation of the bridge deck were examined and their relationships and sensitivities were given by a linear regression equation. The results indicated that the deformation increases as the increases of any one of the layer thickness, nozzle temperature and speed. It was also found that the contribution from the change of the layer thickness to the deformation is the most important, the nozzle temperature taking the second place and the nozzle speed last. This work could be helpful to optimize the process parameters for printing a part with bridged structures.

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