DETAILING THE CONFIGURATION TO PERFORM BETTER CLAY PRINTING

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Abstract. In this paper, we introduce an in-depth study on the performance of clay Additive Manufacturing (AM) process under various printing configurations. Our objective is to examine the filament behavior through clay extrusion with the focus on its printability, geometrical accuracy, and mechanical performance. Such research contributes to AM clay and ceramic artefacts in terms of the shaping and durability. The tests initiate with single layer extrusion which intends to investigate the relations between filament profile and input parameters, such as: Extrusion configurations (Layer height H, nozzle diameter D, velocity ratio R between extrusion and nozzle movement) and Printing-path parameters (Curvature). Subsequently, we apply the configurations from single layer extrusion on multiple layers printing test. The benchmark is based on the consistency of filament in each layer, the bonding strength between layers and the maximum flexural stress along build-up direction.

Keywords. Additive Manufacture; Robotic Fabrication; Clay Printing.

1. Introduction

As a natural composite of rock, soil mixed with water and other minerals with organics, clay is known as one of the earliest building construction material. In the practices of AM clay extrusion, various applications could be found as tableware (Herpt, 2018), arts & crafts (Pacelli, 2016), and architectural installations (Friedman et al., 2010; Ceramic Constellation Pavilion, 2017). The researches approach assorted aspects such as fine detailing with 0.4 millimeter layer height (Herpt, 2018; Pacelli, 2016), large-scale printing works up to 2 meters in height (WASP, 2016) and small robots’ application in large artifact (IAAC, 2013).

In the AM process of clay extrusion, the dimension of the nozzle determines the shape and size of filaments. The diameter of a nozzle represents the minimal feature size as known as the resolution of printing work (Gibson, Rosen, & Stucker,
Various filaments profile also results in different bonding surface area between layers which affects the mechanical performance of overall artifact. It is necessary to study the effects of orifice shape with other fabrication parameters such as extrusion velocity and nozzle speed (Kwon et al., 2002). Calvert & Crockett investigated the correlation between extrusion and nozzle speed with epoxy slurry. They indicated that with a given nozzle set and extrusion velocity, the cross-section of extruded filament changes with nozzle movement speed. By setting nozzle speed to 50% and 200% of the ideal speed, barrel distortion and pincushion distortion of filament profiles could be observed respectively (Calvert & Crockett, 1997).

In this paper, our aim is to explore the effects of clay printing configurations, the nozzle size, extrusion flow rate, and nozzle velocity on the appearance and mechanical performance of the printing work. The structure of this paper is as follow. In section 2, we introduce the experimental set-up including the design of work cell, testing material, and printing configurations. Section 3 demonstrates the single layer printing test with a focus on the filament appearance and adhesion under straight and curvilinear printing path. Section 4 discusses the mechanical performance of multi-layer printing work under various printing configuration. In the end, we address our conclusion and further research plans.

2. Experimental set-up

2.1. PRINTING HARDWARE AND MATERIAL

We utilized a ram pump mechanism to execute the constant clay extrusion through a rounded nozzle as shown in Figure 1. A combination of NEMA 34 stepper motor with a 1:40 reduction gearbox was opted as the actuator which provided enough torque to extrude rather viscous clay. This worked with a lead screw, a cylinder, a piston and frames as the extrusion end effector. The clay extruder was mounted on an ABB IRB 6620 robotic arm which serves as positioning apparatus enabling the accurate movement with our heavy end effector up to 30 kg when fully loaded with clay. The printing material remained the same from the authors’ previously research: terracotta clay with a water ratio between 35-40%.
DETAILING THE CONFIGURATION TO PERFORM BETTER
CLAY PRINTING

Figure 1. Schematic of work cell. Left: Diagram of printing system, (a) Personal computer, (b) Robotic arm controller, (c) Robotic arm, (d) End effector. Right: The assembly of the end effector.

As for the aforementioned ram extrusion end effector, each round per minute (rpm) of the motor extruded out 1/90 ml clay. We first investigated the rpm setup for optimal extrusion. The optimal extrusion represents that with a given nozzle movement velocity and printing layer height, the filament width equals the nozzle diameter. In this scenario, for a 4 mm nozzle with 50 mm/s speed, the rpm was set as 18. In a similar fashion, rpm 36 for 8 mm nozzle.

2.2. SINGLE LAYER PRINTING CONFIGURATION

Our single layer printing experiments initiated with determining the correlation of filament width and nozzle movement velocity for constant linear extrusion. A set of nozzles in 4 mm and 8 mm diameter were employed for the tests on a flat Medium Density Fiberboard. Each nozzle set underwent three printing tests targeting on linear and curved performance. The extrusion followed a sinuous printing path with a 250 mm long-side, that exams seven configurations with 1 mm printing layer height and nozzle velocity at 50, 45, 40, 35, 30, 25, and 20 mm/s with the ratio at 100, 90, 80, 70, 60, 50, and 40% of optimal extrusion speed. The performance of each filament was examined in terms of the smoothness, fluctuation on filament edges, and the adhesion.

Figure 2. Single layer printing path, linear printing on the left and curvilinear on the right.

Subsequently, the extrusion was performed with a flat spiral path to analysis its performance under different local curvatures. Observation of curvature printing
will be focused on the smoothness of filament and the adhesion that whether filament detaches with printing base or the former layer.

2.3. MULTI-LAYER PRINTING CONFIGURATION

As introduced above, the filament width could change due to the nozzle movement velocity variation, indicating that there could be various combinations of nozzle diameter and velocity to achieve a given width. Therefore, our objective of the multi-layer printing test was to verify the mechanical performance of the samples printed with various nozzle diameters through bending tests. We printed out specimens with a dimension of 100 mm (height) X 100 mm (width) X 8 mm (thickness). There were 20 pieces of samples printed with a 4 mm nozzle and another 20 with an 8 mm nozzle. All the samples were printed with a fixed extrusion flow rate with the motor set at 36 rpm and a constant nozzle velocity at 50 mm/s to ensure the same amount of clay distribution. We sealed 10 samples of each nozzle setup with double-layer plastic bags immediately after the printing work to maintain the humidity to study the mechanical performance in the printing process. The rest were exposed in the lab condition for the natural air drying process over 120 hours. Before the bending test, half of the specimens were cut into half along the printing layer direction the rest were along the cross-layer direction. Subsequently, we measured the bonding width between layers to calculate the bonding area. Furthermore, the specimens underwent the 3-point bending test with Instron 5943 series electromechanical universal testing system. The aim was to analyze the adhesion between the bonded layers as well as the along layer direction. This experiment determines the suitable configuration to perform different printing thickness of clay artifacts.

<table>
<thead>
<tr>
<th>Nozzle Diameter (mm)</th>
<th>Condition</th>
<th>Bending Test Direction</th>
<th>Number of Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Dry</td>
<td>Along Layers</td>
<td>10</td>
</tr>
<tr>
<td>8</td>
<td>Humid</td>
<td>Along Layers</td>
<td>10</td>
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<td>4</td>
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<td>10</td>
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<tr>
<td>8</td>
<td>Dry</td>
<td>Along Layers</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>Dry</td>
<td>Cross Layers</td>
<td>10</td>
</tr>
<tr>
<td>8</td>
<td>Humid</td>
<td>Cross Layers</td>
<td>10</td>
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<tr>
<td>4</td>
<td>Humid</td>
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<td>Cross Layers</td>
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</tbody>
</table>
3. Result and Discussion

3.1. SINGLE LAYER PRINTING RESULT

We executed the single-layer linear extrusion test over ten times to monitor the filament behavior. As expected, by reducing the nozzle movement speed while maintaining the extrusion flow rate, the deposited filament could become wider. The average width of the filaments increased gradually from 4 mm to 8 mm when changing the nozzle speed from 100% to 50% of the optimal (Figure 3). When reducing the nozzle speed to 40%, the extrusion became unstable which means the variation of width and texture was unpredictable. Besides printing in the manner of decreasing the nozzle speed in sequence, we also tested the extrusion with increasing speed from 40% to 100% as shown in the middle image of Figure 3. This was followed by the flat spiral printing test. Our observation on the printing samples included:

- The reduction of nozzle speed increases the variability of the filament. The more the nozzle speed be decreased, the more variation on the width of the filament can be spotted through the extrusion.
- There is no obvious challenge when printing under various local curvatures and radius.
- The adhesion between filament and printing base increases with a decreasing nozzle speed.
- When constant print with a low nozzle speed, the redundancy of extrusion material can be monitored and it accumulates.
- Printing starts with low nozzle speed instantly result in a messy edge condition and will transmit it until nozzle speed reaching 90% of the optimal as shown in the middle image of Figure 3. On the contrary, printing starts with high nozzle speed does not have the same effect.
3.2. MULTI-LAYER PRINTING RESULT

3.2.1. Overall observation

We first observed the flexure from the appearances of the specimens through and after the bending processes (Figure 4). Afterward, we had a glance at the general bending results data as well as the flexure curves to further understand such phenomena (Figure 5). In the end, we compared and contrasted the distinctions between specimens printed with 4 mm and 8 mm nozzle as well as different results in along-layer and cross-layer directions. We picked up the mean value of every test group in ten and listed them in Table 2. The summary of our glancing is as:

- For the tests of humid samples, flexural cracks happen as winding curves around loading area when force been applied in the cross-layer direction. In the along-layer direction, the clay specimens fail at their bonding between layers.
- Clay printing work gains stiffness and yield strength through the air-drying process in both along and cross-layer directions. This effect comes along with a deformation type change from elastic (humid) to plastic (dry) as shown in Figure 5.
- The flexure stress at maximum load has a huge standard deviation as 1.20816 Mpa (28.7%) for 8 mm printing dry samples when force been applied across layers. Such a huge deviation also happens at other cross-layer loading tests, see Table 2.
3.2.2. Comparisons on along-layer and cross-layer directions

The flexure test comparisons in this section indicate the differences in the mechanical performances of 3D printed clay artifacts on along-layer and cross-layer direction. The along-layer represents that forces been applied along the layer printed direction which aims at testing the bonding strength between layers. The cross-layer tests are intended to study the flexure across the filament layers when load been applied across layers. Here, we choose the mean value of every testing group to make the comparison diagrams in curve charts as in Figure 6.

![Figure 6. Flexure tests comparisons between along-layer and cross-layer directions.](image)
At first glance, all the results directly show that the specimens survive larger flexural stress when loads been applied across layers in both humid and dry conditions. These indicate the bonding adhesion between layers is always the weaker portion in the clay printing work. In this scenario, the layer bonding strength has to be key criteria to concern about, especially when bending moments happen crossing layers. When printing with an 8 mm nozzle, the maximum flexural stresses of the printing work do not have significant differences in each direction in humid condition (Figure 6, top right). However, when beyond the maximum, the layer bonding tends to fail immediately other than the progressively deform in the other direction.

3.2.3. Comparisons of printing work with 4 mm and 8 mm nozzles

The bending test results of printing works via 4 mm and 8 mm nozzles show opposite performances on along-layer and cross-layer directions. 8 mm samples have larger maximum flexural stresses when testing the adhesion between layers with along-layer loads. However, referring to the other direction, printing with 4 mm and 8 mm nozzles have similar performances in humid conditions. 4 mm samples even perform better in terms of their higher peak of flexural stress when dried (Figure 7, bottom right). Our conclusion of such behavior is when printing with 4 mm, although extrusion could produce 8 mm filament layers, the bonding strength between layers highly depends on the original size of the nozzle. On the other hand, a smaller nozzle size does not reduce the performance on the along layer direction.

Figure 7. Flexure tests comparisons between specimens printed via 4 mm and 8 mm nozzles.

4. Conclusion

In this paper, we took upon a systematic approach for studying the impacts of AM clay configurations on the filament appearance, extrusion compacity and mechanical characteristics of printing work. We would like to exam the maximum
DETAILING THE CONFIGURATION TO PERFORM BETTER
CLAY PRINTING

width of filament a nozzle could produce without losing the extrusion constancy as well as how was the mechanical performance compared with printing with a larger nozzle. In this scenario, we employed a pair of nozzles with 4 mm and 8 mm diameters as a case study. The results revealed that when printing with a 4 mm nozzle, by reducing the nozzle movement speed to 50% of the optimal speed which produced 4 mm wide filament while maintaining the extrusion flow rate, it enabled a constant extrusion of 8 mm filament. This offered us an opportunity that by manipulating nozzle movement speed, clay printing work could be built with various thicknesses without the necessity of changing nozzle sets.

Subsequently, we asked a derived question from the nozzle effect listed above that how was the mechanical performance of a clay printing work done with a small nozzle compared with a larger one. To respond to this question, we examined 80 pieces of specimens through bending tests in humid and dry conditions to study the flexural stress in along-layer and cross-layer directions. The results indicated that the ones printed with a smaller nozzle had weaker performance in their layer adhesions in the humid condition. However, after the air-drying process, clay gained stiffness and maximum flexural stress resulted in an enhanced bonding strength that closed the gap of layer adhesion differences between two nozzle sets. This offered us the confidence to keep practicing researches about these printing configurations to produce end products.

Furthermore, we propose follow-up researches by investigating the mechanical performance of clay printing after kilning. Extra sets of nozzle diameter combinations are also expected to further understand the impacts of the printing configurations.

References


