Solid Freeform Fabrication 2017: Proceedings of the 28th Annual International
Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference
Reviewed Paper

Approaching Rectangular Extrudate in 3D Printing for Building and Construction by Experimental Iteration of Nozzle Design

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Abstract

In Extrusion based 3D Printing technology, the voids could be reduced and the surface finish of printed parts could be improved with extrudate shape optimization. For large-scale 3D Printing technology like 3D Printing for Building and Construction, reducing printed layer height would increase the fabrication time drastically, while having few effect on voids reduction and surface finish improvement. In this paper, an iterative experimental approach to achieve the optimized nozzle design for rectangular shaped extrudate was proposed. Two nozzle prototypes were manufactured by Fused Deposition Method and implemented for experimental tests, then a new nozzle design was created based on the experimental extrudate shapes. This process iterated until a good rectangular extrudate shape was obtained. Printing tests were conducted with the optimized nozzle, which showed the designed nozzle could help to eliminate the voids among the printed parts and guarantee good surface finish without losing the speed of printing.

1 Introduction

The 3D Printing Technology, also known as rapid prototyping [1], which is capable of fabricating solid parts from virtual data like Computer-aided Design (CAD) model, is developing very fast recently. The ease of tool accessibility and tool path planning highly increases the freedom of design and eliminates many restrictions in traditional manufacturing processes. Hence, the 3D Printing technology may bring benefit to research institutes and industries like aerospace and tissue engineering which require highly customized manufacturing process. Among various kinds of 3D Printing technologies, the extrusion-based technologies are of great interest to researchers because these technologies are suitable for a wide range of materials with lower cost and higher acceptability for popularization. Although the extrusion

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based 3D Printing has exciting potentials, the imperfect surface finish caused by layer-by-layer printing is still an issue.

In the past effort of improving the surface finish, it was found that the lesser the layer height of the printing, the better the surface finish [2]. This guideline is widely accepted in most industries like Fused Deposition Modeling (FDM) [3–5], However, such modification will increase the fabrication time proportionally to the improvement of surface finish. For large-scale 3D Printing requirement like the 3D Printing in Building & Construction (3DPBC) [6], the surface finish needs to be improved in several orders of magnitude and, thus, the printing time would become unacceptable.

The optimization of the nozzle shape can be one method to change extrudate formation and improve the surface finish without reducing the layer height. In the extrusion based deposition, the extrudate shape can affect the stacking of different printing path. For instance, the round nozzle would produce extrudate with a cross section of elliptical shape and hence result in high void density in the printed part [7]. The extrudate shape also affect the surface finish of the part because of the staircase effect especially in the large-scale 3D Printing. Khoshnevis tried to improve the surface finish issue caused by elliptical extrudate by using the mold on the nozzle, but the mold is too bulky so it is mostly used in printing the outer layers [8]. Asgarpour utilized the control of printing parameters which include the pump frequency and printing speed to approach an optimized extrudate formation, but the obtained parameter was found harmful to the printer [9]. The relationship between the extrudate shape and the nozzle shape was also studied. Simulation method, which treats the material as non-Newtonian fluid and utilizes the inverse prediction simulation to calculate corresponding nozzle shape, was widely proposed in polymer extrusion area [10–12]. However, few researchers have tried to introduce the inverse prediction technique into the 3D printing area due to the cost and time consumption of making a small sized customized nozzle. As a result, previous studies in calculating the optimized nozzle shape in Bellini's research [11] and Wang et al.'s research [12] has stopped at the step of flow simulation.

The 3DPBC is an ideal area to test the nozzle optimization technique for 3D Printing. The nature of the large-scale printing also guarantees a large design freedom for the nozzle. The outlet of the nozzle can be designed and manufactured by desktop 3D Printing technology but not through complex traditional manufacturing processes. In this paper, iterative experimental approach is utilized to approach rectangular extrudate. Two nozzle prototypes were manufactured by FDM and implemented on a large scale gantry printer for experimental tests conducted with cementitious material. The design of second generation nozzle is then calculated based on the printing results of these prototypes. Experiment using the second generation nozzle showed that a good rectangular extrudate shape was obtained.

2 Iterative Experimental Approach

In the iterative experimental approach applied in this study, the dimension of digital nozzle design was considered as the input, and the dimension of extrudate cross section was considered as the output. The entire processes between the input and output, i.e., thermal shrinkage of FDM printing process, die swelling when extrudate comes out from nozzle, impact when extrudate hits previously deposited layer, compression from subsequently deposited layer, gravity, and shrinkage during hardening process, were all combined to an implicit function f.

However, even the dimension of nozzle design and extrudate cross section cannot be expressed explicitly. In this case, finite points were sampled as the indicators of the dimensions. In this study, the nozzle design and extrudate were sliced into five sections horizontally, thus, giving twelve sample points in the iterative approach, as shown in Fig. 1. The sample points of nozzle design were recorded as $D_1, D_2, \ldots,$ and D_{12}. The samples of extrudate cross section area were recorded as E_1, E_2, …, E_{12}. And the sample points of targeted extrudate cross section area were denoted as $T_1, T_2, \ldots, T_{12}$. Therefore, the implicit function f can be denoted as $f(D_n) = E_n$, and the target of this iterative approach becomes equavalent to finding the root of a series of equations

$$F_n = 0 \quad n = 1, 2, \ldots, 12 \tag{1}$$

where

$$F_n(D_n) = f_n(D_n) - T_n = E_n - T_n \quad n = 1, 2, \ldots, 12 \tag{2}$$

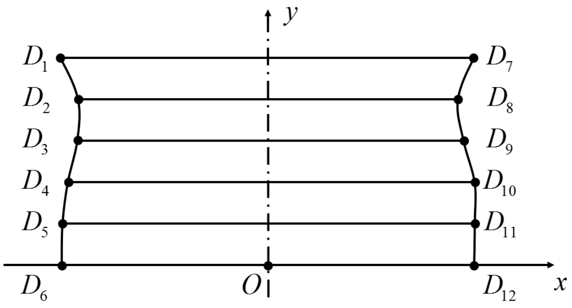

Figure 1: The schematic of the sample points in nozzle design and extrudate cross section area.

Newton's method was used in this study to find the roots of the series of equations. The classical Newton's method requires the analytic expression of the function is known to get the first order derivative. However, in this case, the function mapping from the designed dimension of nozzle to the dimension of final part is unclear. To address this issue, two initial experiments were conducted to obtain the first order derivative numerically, and thus, the classical Newton's method can be modified to

$$\begin{aligned} D_{i+1,n} &= D_{i,n} - \frac{F_n\left(D_{i,n}\right)}{F_n'\left(D_{i,n}\right)} \\ &= D_{i,n} - \frac{F\left(D_{i,n}\right)}{\frac{F\left(D_{i,n}\right)-F\left(D_{i-1,n}\right)}{D_{i,n}-D_{i-1,n}}} \\ &= D_{i,n} - \frac{E_{i,n} - T_{i,n}}{\frac{E_{i,n}-E_{i-1,n}}{D_{i,n}-D_{i-1,n}}} \end{aligned} \tag{3}$$

where $n = 1, 2, \ldots, 12$ and $i = 2, 3, 4, \ldots$

3 Experiment and Results

3.1 Experiment setup

The experiment was conducted on a gantry concrete printer commanded by a traditional CNC controller assembled by Mitsubishi, which is shown in Figure 2. This gantry printer can provide three translational degree of freedom and one rotational degree of freedom. The gantry served as a placement system for the nozzle and to control the direction of the nozzle to follow printing trajectory. The nozzle outlet part was the primary research target in this paper. The coordinates of points on nozzle cross section were firstly calculated through data processing method introduced in Section 2 and then connected by spline lines to generate a CAD model in SolidWorks. Then the CAD models were printed by FDM desktop printer Ultimaker 2+. The sealing property of the nozzle was checked every time before the printing.

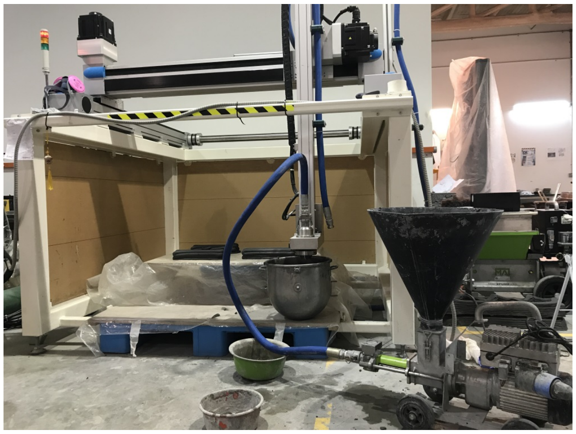

Figure 2: The gantry and pump system used for printing process.

To analyze the surface finish problem with cross-sectional view, the print path was designed to include of two long straight lines which could provide enough observations on cross-sectional view. The two straight lines were connected by two turnings to form a close loop. Three layers were printed following the designed printing path, as shown in 3. Since the bottom layer will be affected by the substrate and the top layer will be affected by the nozzle, only the middle layer was picked to analyze extrudate formation.

Figure 3: Part printed using the second generation nozzle.

The printing material used in the experiment was mortar, which is cementitious material similar to cement and concrete. During printing process, the nozzle speed was kept at 100 mm/s, the mortar was delivered to nozzle through a hose by a MAI Pictor Pump which used auger screw as actuation mechanism of material flow, as shown in Figure 2. Since the pump speed is controlled by an analogue knob, the flow rate needs to be calibrated each time before printing experiments. As the calibration, a simple straight line was printed using a 30 mm × 15 mm rectangular outlet nozzle, and the width of the printed line was measured and flow rate was adjusted until the layer width was within the range of 29-31 mm.

During the hardening process of printing material, volume shrinkage problem was observed in the first 48 hours kept in room temperature. Therefore, 48 hours was chosen as the time gap between the printing and testing of the printed parts. After 48 hours, the printed parts were cut into pieces by a Struers Secotom-15 diamond cutter as shown in Figure 4 and 3 samples were chosen randomly. The selected samples were set on a table adjusted with a level vial. The photos were taken by an iPhone 7 with the help of a level app to ensure the photo taking is perpendicular to the cross section. A ruler of 20 cm long was placed near the sample and the camera changed the focus until the photo width was exactly 20 cm. A piece of white paper was placed under the sample and there were several lines drawn on the paper to help locating the area for sample placement. While taking the photos, the photo's height width ratio was set to 1:1 and the flash light was on to counter the shades in the picture. Then these photos were processed to find the exact dimension of the extrudate.

Figure 4: The cut pieces of sample printed by the second generation nozzle.

3.2 Results

The two nozzle prototypes used for the first iteration were rectangular and trapezoid shaped nozzle as shown in Figures 5 and 6, the dimensions of nozzles and corresponding extrudates are shown in Tables 1-4.

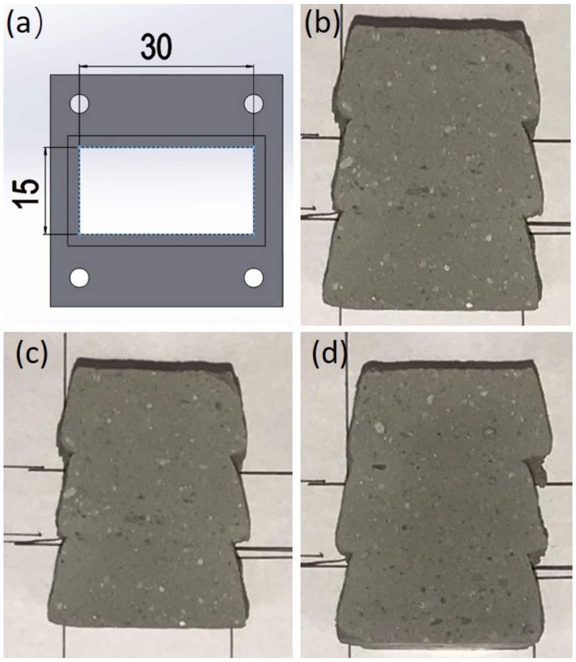

Figure 5: The rectangular nozzle (a) design and (b, c, d) corresponding extrudate cross sections.

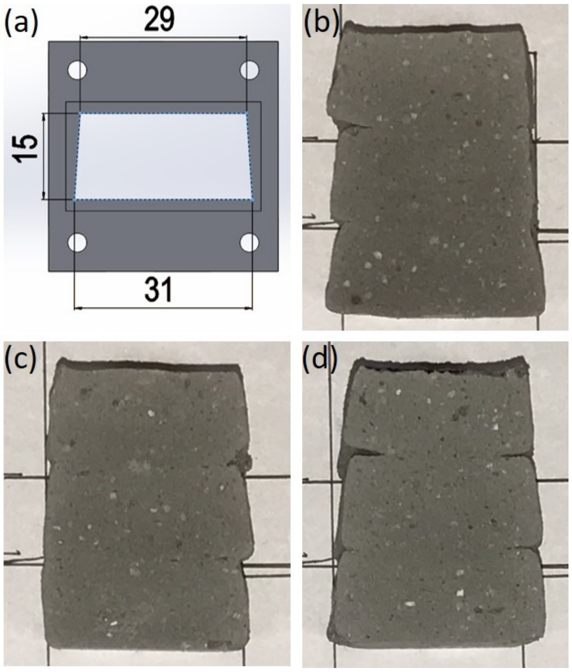

Figure 6: The trapezoid nozzle (a) design and (b, c, d) corresponding extrudate cross section.

Table 1: The dimensions of rectangular nozzle.

Point number	Distance from the middle line (mm)	Point number	Distance from the middle line (mm)
D1	-15	D7	15
D2	-15	D8	15
D3	-15	D9	15
D4	-15	D10	15
D5	-15	D11	15
D6	-15	D12	15

Table 2: The average dimensions of extrudates with rectangular nozzle.

Point number	Distance from the middle line (mm)	Point number	Distance from the middle line (mm)
D1	-15.67	D7	15.15
D2	-16.67	D8	16.47
D3	-17.00	D9	17.26
D4	-17.86	D10	17.80
D5	-18.25	D11	18.19
D6	-17.66	D12	17.80

Table 3: The dimensions of trapezoid nozzle.

Point number	Distance from the middle line (mm)	Point number	Distance from the middle line (mm)
D1	-15.48	D7	15.48
D2	-15.28	D8	15.28
D3	-15.08	D9	15.08
D4	-14.88	D10	14.88
D5	-14.68	D11	14.68
D6	-14.48	D12	14.48

Table 4: The average dimensions of extrudates with trapezoid nozzle.

Point number	Distance from the middle line (mm)	Point number	Distance from the middle line (mm)
D1	-15.34	D7	15.54
D2	-16.34	D8	16.07
D3	-16.27	D9	16.34
D4	-16.53	D10	16.67
D5	-16.80	D11	16.80
D6	-17.00	D12	17.00

Then the dimension of second generation nozzle was computed based on Eq. (3). As shown in Figure 7, the dimensions of nozzles and extrudates are shown in Tables 5 and 6. It can be seen that the extrudate formation has been significantly improved, and the maximum angle between wall and vertical direction is only approximately 5 degree. In this case, the extrudate can be considered as good rectangular.

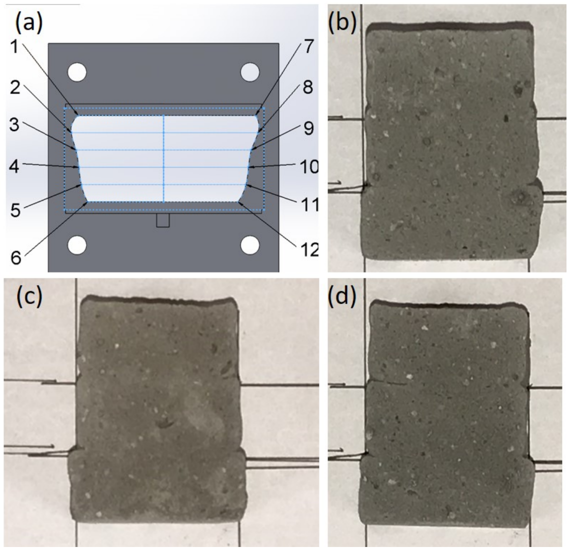

Figure 7: The second generation nozzle (a) design and (b, c, d) corresponding extrudate cross section.

Table 5: The dimensions of the second generation nozzle.

Point number	Distance from the middle line (mm)	Point number	Distance from the middle line (mm)
D1	-15.97	D7	14.83
D2	-16.40	D8	16.03
D3	-15.22	D9	15.19
D4	-14.74	D10	14.70
D5	-14.29	D11	14.27
D6	-12.92	D12	13.19

Table 6: The average dimensions of extrudates with the second generation nozzle.

Point number	Distance from the middle line (mm)	Point number	Distance from the middle line (mm)
D1	-16.07	D7	15.94
D2	-16.20	D8	16.07
D3	-16.05	D9	16.18
D4	-16.07	D10	16.20
D5	-16.01	D11	16.33
D6	-16.27	D12	16.14

4 Summary

An iterative experimental approach to achieve the optimized nozzle design for rectangular shaped extrudate was proposed. Two nozzle prototypes was were manufactured by a desktop FDM printer and implemented for experimental tests, then a new nozzle design was created based on the experimental extrudate shapes. This process iterated until a perfect good rectangular extrudate shape was obtained. Printing tests conducted with the optimized nozzle showed the designed nozzle could lead to a good rectangular extrudate shape.

Although this study only tried to get rectangular shaped extrudate, this method can be applied to get any shaped extrudate to fit in different curved surfaces without compromising extrudate size. Once the relationship between nozzle shape and extrudate formation is established, corresponding algorithm can be applied in slicing process to assign different extrudate formations to the paths, and then the printer should be able to change nozzle shape to actually extrude the correct extrudate.

However, this experimental approach requires at least one experiment to initialize the iteration, which can be time consuming in some cases. And applying numerical approximation of the first order derivative into Newton's method may result in singular coefficient matrix in practice, which would require manually adjustment to continue the iteration. An explicit or numerical function to summarize all the steps listed in Section 2 would be the most ideal solution for this method.

Acknowledgement

The authors would like to express their gratitude to Yiwei Wong for offering the printing material used in this study, and to the National Research Foundation and Singapore Center for 3D Printing for funding and supporting this research.

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