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Effect of Nozzle Orientation on Accuracy of Formed Objects in FFF Process of Additive Manufacturing with Dual-Arm Robot

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Fused Filament Fabrication (FFF), one of the Additive Manufacturing (AM) technologies, forms three-dimensional objects by extruding thermoplastic resin to deposit material. Conventional FFF machines have several weak points due to the flat layer. FFF using a vertically articulated robot, especially dual-arm robot, is expected to solve these problems. The redundant degrees of freedom allow material extrusion in free directions. However, the effect of the nozzle orientation on the shape of formed object is not known enough. Therefore, in this paper, some experiments were conducted with actual fabrication in different orientations of extrusion nozzle: in which the nozzle was oriented perpendicularly to five planes with angles varying by 45°. Additionally, the effect of the layer height was also investigated. The fabrication was tested at several layer heights from 0.5 mm to 3.0 mm. As a result, the fabrication could be completed well when the layer height was smaller than the diameter of the extrusion nozzle. However, when the layer height was larger than the nozzle diameter, the formed object had some shape errors at every angle of nozzle orientation.

1. Introduction

Additive Manufacturing (AM) is a manufacturing technology that deposits materials along a forming path generated from a 3D model. Fused Filament Fabrication (FFF) is a technology that melts thermoplastic resin and extrudes it through a nozzle. Since FFF is easy to handle and low cost due to its simple mechanism, it is widely used in various fields and industries. FFF machines generally use a 3-DOF fabrication mechanism. The extrusion nozzle is placed at the top in downward orientation. The material is extruded toward the bed placed at the bottom. Although this method can be applied to any deposition process, there are several limitations and problems with the formed objects: *1*. support material is required for formed objects with overhanging parts; *2*. parts to be formed with an inclined face have staircase-effect; and *3*. formed objects show anisotropy. The curved surface deposition with robot-arm has been studied as one solution to these drawbacks[(1)(2)]. Especially, a method using a vertically articulated robot has several advantages: *I*. the robot arm can change the contact angle of extrusion nozzle with the formed object to suit the situation; *II*. the redundant degrees of freedom of the robot arm enable fabrication at any position and orientation in 3D space. However, vertically articulated robots have the singularity problem, which makes it difficult for the robot to be in some specific postures[(3)(4)]. This is a negative specification on fabrication. Therefore, our laboratory decided to avoid this problem by using two 6-axis vertically articulated robots, which obtain more redundant degrees of freedom. One arm has an extrusion nozzle, and another arm has a build plate. The robot performs FFF process with dual-arm motion. When curved surface deposition with dual-arm motion is performed, the nozzle has various orientation because extrusion is performed with various posture. In conventional FFF, the material extruded in parallel with the direction of gravity. In dual-arm deposition, however, it is necessary to consider the effects of gravity and other factors during fabrication. Therefore, in this study, the effect of nozzle orientation on the accuracy of the modeling process is investigated.

2. Experimental Devices

The appearance of a fabrication system used in this study is shown in Figure 1. The vertically articulated robots are xArm6 manufactured by UFACTORY. The arm is operated using

UFACTORY Studio, that is a control software for xArm6, and a software development kit for Python. An extrusion nozzle used in a commercial FFF device is attached to the end of one arm. The bed shown in Figure 2 is attached to the end of the other arm and it serves as the base for modeling. The bed has five planes as shown in Figure 2. The bed is hold for the nozzle to have access from downward (0°) to upward (180°) in 45° increments. The G-code of the forming path was created manually. An image of forming path used in this experiment is shown in Figure 3. The forming path was designed to draw a 30 mm square with lines spaced 3 mm apart inside it. Two or three layers of this process were performed, in which the forming path direction of layer is orthogonal to each other.

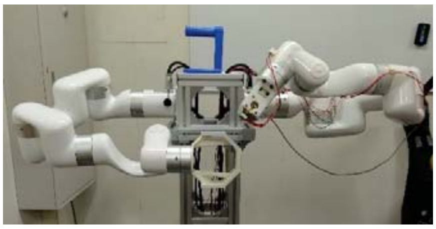


Fig. 1 Fabrication system

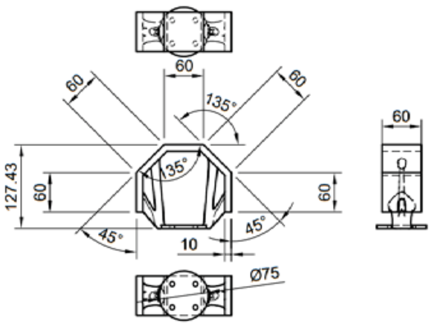


Fig. 2 Bed with 5 planes

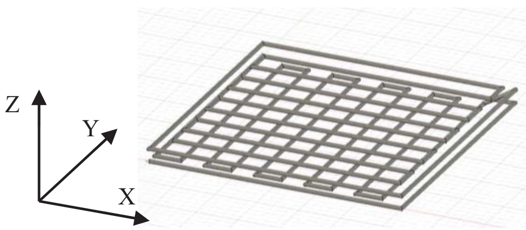
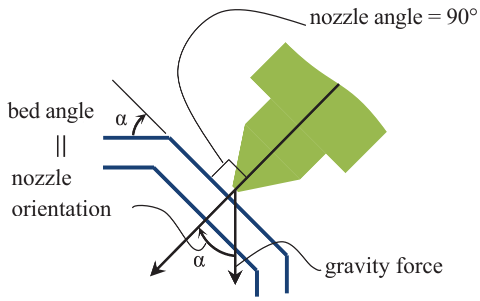


Fig. 3 Image of forming path

The fabrication is performed at each inclining bed angle in turn. As shown in Figure 4, the extrusion nozzle is always perpendicular to one of the planes to be fabricated. The nozzle orientation is equivalent to the bed angle. Therefore, the effect of the nozzle orientation on fabrication can be evaluated. Table 1 shows the various parameters and conditions of the fabrication process. The diameter of the extrusion nozzle was 1.5mm that is appropriate for large size fabrication and for advanced use of composite materials(5). The distance from the extrusion nozzle to the bed was the same length as the layer height, which was adjusted with a feeler gauge.



Fig, 4 Extrusion direction during fabrication

Table 1 Fabrication conditions and parameters

Temperature	24℃
Humidity	61%
Diameter of extrusion nozzle	1.5mm
Width of resin injection	1.5mm

3. Experiment of the effect of bed angles

If the angle of the extrusion nozzle is not downward, FFF deposition process may not be possible. Therefore, a confirmation experiment is conducted. The layer height is 1.5 mm and the nozzle feed rate is 3.777 mm/s. The forming path is two layers.

3.1 Experimental Results

Fabrication was completed in all bed angles. A photograph of the formed object during the fabrication process is shown in Figure 5, and photographs of the formed objects after the fabrication were shown in Figure 6.

Fig. 5 Fabrication with an inclining bed angle of 45°

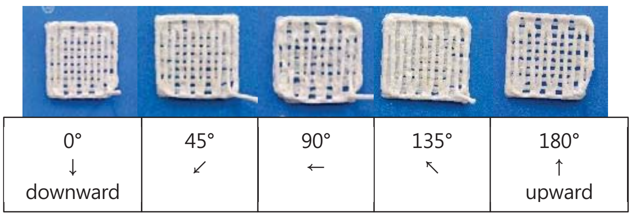


Fig. 6 Formed object at each extrusion direction

3.2 Discussion

It was shown that fabrication was possible even when the angle of the extrusion nozzle was different from the usual. There was not a fatal problem in the formed objects for each extrusion nozzle orientation. However, as shown in Figure 7, in case of forming from diagonally above or below, there is a slight collapse of the first layer. The reason may be that the plane of the bed and the motion plane of the nozzle were not parallel. When moving the arm in parallel with horizontal or vertical plane, several joints will occupies the motion. On the other hand, in the inclining plane motions, the number of joints involved in the movement is more than that of horizontally or vertically motion. Therefore, the calibration is more important, and the calibration error resulted in crushing of resin in some areas. This indicates that the position and orientation of each arms must be calibrated with high precision for using as a dual-arm robot.

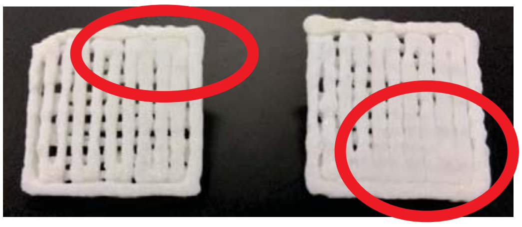


Fig. 7 Backside of formed object (left: formed from diagonally above, right: formed from diagonally below). The resin is crushed and the gap is disappeared. It can be seen that the distance between the extrusion nozzle and the bed was different depending on the location.

4. Experiment of the effect of layer height on accuracy

In Chapter 3, it was shown that fabrication is possible at any bed angles, but the distance between the nozzle and the bed affects the shape of formed object. Therefore, we will investigate the effects of changing the layer height and the distance between the nozzle and the bed at each nozzle orientation.

4.1 Experimental Methods

The fabrication system and various parameters are basically the same as in Chapter 2. The nozzles are set to face downward (α = 0°), sideways (α = 90°), and upward (α = 180°). For each nozzle orientation, the test objects were fabricated with changing the layer height from 0.5 to 3.0 mm in increments of 0.5 mm. The number of layers is three. The third layer is the same forming path as the first layer and added on the second layer. The distance between the extrusion nozzle and the bed at the start point, which means the first layer height, was adjusted using a feeler gauge. The second and the t hird layer height are same as the first layer, but they are controlled by robot program. The movement speed of the nozzle for each layer height is shown in Table 2.

Table 2 Extrusion nozzle feed rate per layer height

Layer height	Extrusion nozzle feed rate
0.5mm	9.585mm/s
1.0mm	5.192mm/s
1.5mm	3.777mm/s
2.0mm	3.116mm/s
2.5mm	2.771mm/s
3.0mm	2.598mm/s

4.2 Experimental Results

Fabrication was completed at each bed angle and at each layer height. The results are shown in Figure 8. Formed objects layer height of 0.5, 1.5, and 3.0 mm was scanned by a 3D scanner. For the average height of formed object was calculated from the maximum and minimum height of the scan data, and the results are shown in Table 3 and Figure 9.

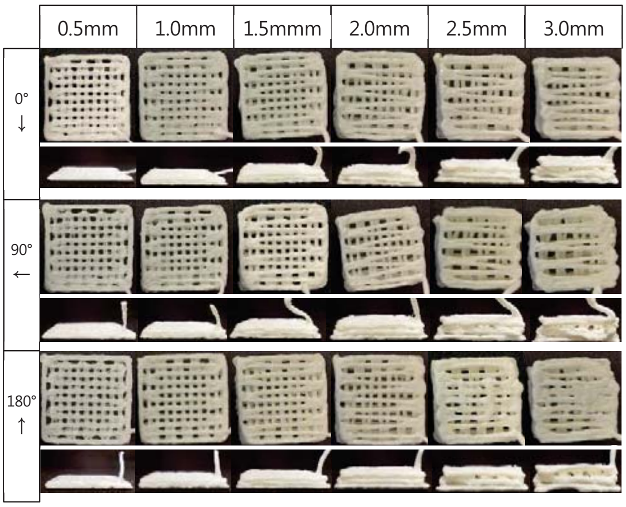


Fig. 8 Differences in formed objects depending on layer height at each extrusion nozzle orientation. Upper section: Photo of top surface, Lower section: Photo of side surface

Table 3 Measured height of formed objects

Condition			Result		
Nozzle orientation [deg]	Layer height [mm]	Nominal height [mm]	Maximum height [mm]	Minimum height [mm]	Average height [mm]
0	0.5	1.5	2.303	1.661	1.982
0	1.5	4.5	4.988	4.213	4.600
0	3.0	9.0	9.133	6.674	7.903
90	0.5	1.5	2.834	1.589	2.211
90	1.5	4.5	4.991	3.862	4.426
90	3.0	9.0	9.919	7.635	8.777
180	0.5	1.5	2.294	1.059	1.677
180	1.5	4.5	4.881	2.990	3.935
180	3.0	9.0	10.072	7.447	8.759

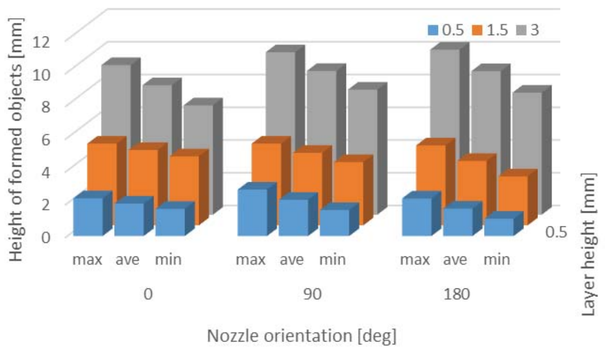


Fig. 9 Height of formed objects

4.3 Discussion

From the photographs in Figure 8, Table 3 and Figure 9, it can be seen that objects can be fabricated without falling down in any nozzle orientation. It is thought that the extruded material is pressed and sticked to the bed when the nozzle diameter is larger than the layer height. However, the larger layer pitch, the less accuracy of the formed objects in all conditions of nozzle orientation.

In case of the nozzle facing downward (α=0°), the outline portion of the third layer is thicker than that in central portion when the nozzle diameter is 2.5 and 3.0 mm. The reason is the resin of outline is placed off course and the infill resin overlap on the outline resin. Therefore, the outline becomes thicker than the nominal size.

In case of the nozzle facing sideways (α=90°), forming paths of the second layer are distorted when the layer height is more than 1.5 mm. When the nozzle moves horizontally with respect to the ground, the resin is pulled by gravity and drooped. However, the outline portion of the third layer does not rise even though the layer height is 2.5 mm and 3.0 mm. It is thought that the infill resin droop avoids to overlap with outline resin.

In case of the nozzle facing upward (α=180°), there are large areas without adhesion between higher and lower layers when the layer height is more than 1.5mm. This occurs in both outline and infill paths. This phenomenon is seen in other nozzle orientations, but the size of the gap between layers is extremely large in the nozzle facing upward.

To summarize, it is said that if the layer height exceeds the diameter of the extrusion nozzle, which is 1.5mm, the formed object will receive adversely affects. Conversely, if the layer height is within the diameter of the extrusion nozzle, the nozzle orientation does not bring a large effect on fabrication.

5. Conclusions

Dual-arm robot AM is considered for FFF with curved surface deposition. For planning the motion program of robot arms, the effect of nozzle orientation on accuracy is investigated.

Using a dual-armed robot, fabrication was performed by changing the extrusion nozzle orientation from downward to upward in 45° increments. Fabrication was completed in all orientations. If the layer height is smaller than the diameter of the extrusion nozzle, the extrusion nozzle orientation has little effect on fabrication.

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