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OPTIMIZATION OF PRINTING PARAMETERS FOR 3-D PRINTED PLA

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1. Abstract

In this work, 3D printed part of PLA was checked for dimensional accuracy and printing parameters were optimized for getting optimal design. For doing so we selected nozzle temperature and step size as printing parameters for optimization. Design of Experiment (DOE) was done using Minitab to check optimal parameters. We concluded that increasing the nozzle temperature increases the dimensional accuracy of the printed part and decreasing the step size will increase the dimensional accuracy.

2. Introduction

With the advent of technology in the manufacturing sector, 3-D printing has come across to be one of the novel and efficient ways to mass produce parts with intricate details. It gives us the flexibility to deal with a wide range of geometries. Almost any geometry can be 3-D printed by using a digital model data from an Additive manufacturing file (AFM). Unlike the conventional manufacturing processes wherein material is removed from a large chunk, 3-D printing incorporates the addition of material in a layer by layer fashion. This makes it an attractive tool in rapid prototyping and additive manufacturing fields. There are various 3-D printing technologies that can be classified under the following types: Extrusion, Light polymerized, Power bed, Laminated, Power Fed, Wire etc. In this work, we will be focusing on Fused Deposition Modelling (FDM) technology which comes under the type Extrusion.

Just like the conventional 2-D printers, 3-D printers also come with a printer resolution. Printer resolution determines the quality of the print like any other 2-D printer. The printer resolution is calibrated based on two factors, namely, Layer thickness and X-Y resolution. The layer thickness determines the minimal distance between two subsequent layers. Typical layer thickness is around 100 µm, however some machines can print as fine as 16 µm [1]. The X-Y resolution is the same as that of the laser printers. Typical X-Y resolution for 3-D printers is 510-250 dpi. The quality of a print can be determined by evaluating the printed part based on the following aspects: Dimensional accuracy, Bridging performance, Overhang performance, Negative space tolerance, Fine positive space features performance, Mechanical resonance in XY*.

Although 3-D printing technology can produce any geometry, but it is very difficult to maintain the quality. A simple solid cube would have a better print quality as compared to that of a cube with internal lattice structure of the same dimension. Therefore, it can be said that the quality of the print is dependent on the shape and complexity of the geometry. However, we can still achieve a better quality print for intricate geometries by optimizing the printing parameters. We used Response Surface Method for optimization. Further to validate the optimized results, Design of Experiment (DOE) approach using Minitab was employed. We used PLA for printing due to the ease of processability and availability of the material.

3. Methodology

The geometry used to run the experiments for optimization was selected based on the print quality of seven different geometries printed at default parameters (Fig 1). These geometries were printed based on the various calibration aspects cited in Introduction section (*). Affinibot was used to 3-D print these parts. Pyramid shaped part (B) was then selected to be optimized for dimensional accuracy due to its initial failure.

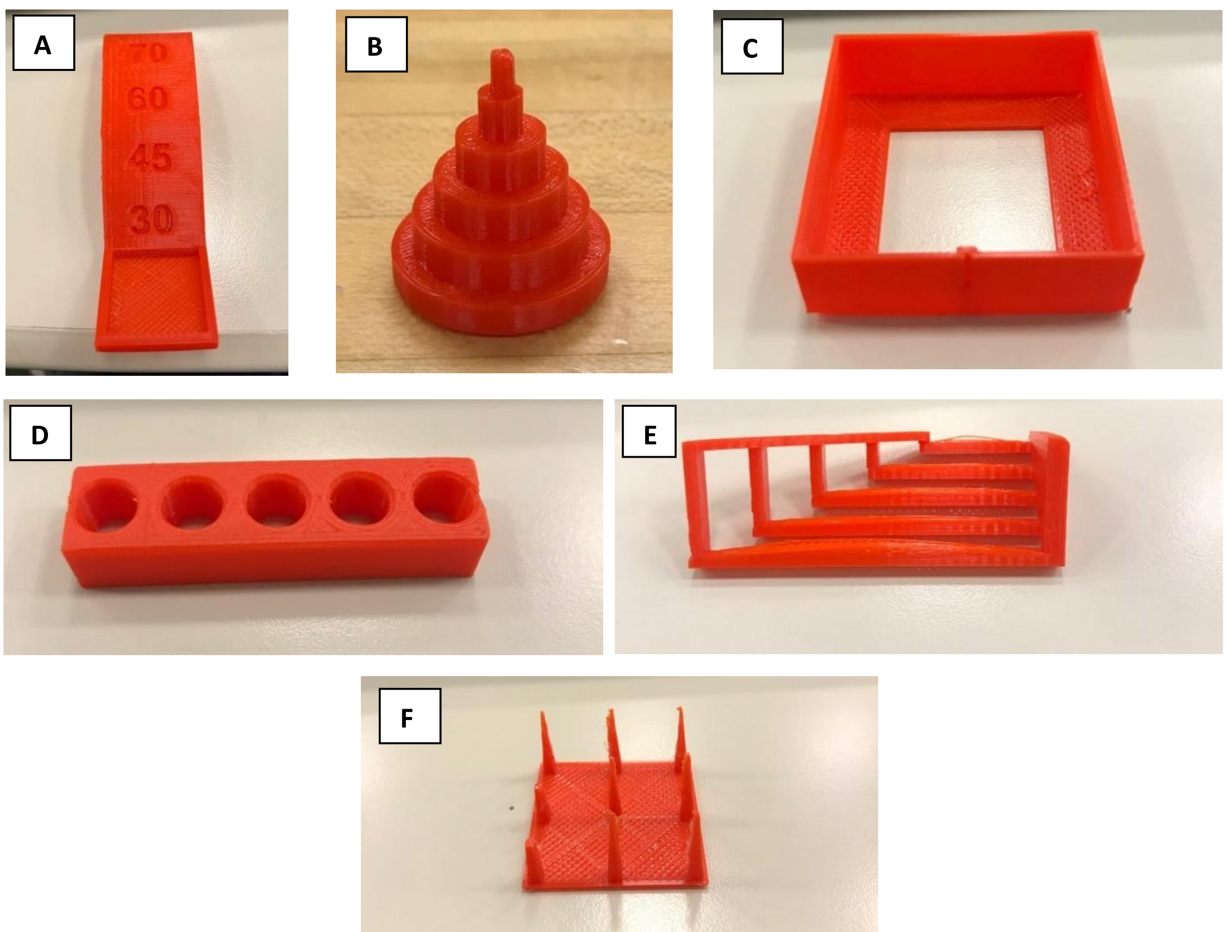

Figure 1 Printed parts as per different calibration aspects. (A) Overhang performance; (B) Dimensional accuracy; (C) Mechanical resonance in XY; (D) Negative space tolerance; (E) Bridging performance; (F) Fine positive space feature performance.

The pyramid shape has six circular steps with decreasing diameter from bottom to top. The calibration aspect for the pyramid is dimensional accuracy. [2] The following are the guidelines to check the dimensional accuracy of the printed pyramid:

1. Assign the print a "1" if average deviations in X and Y are greater than 0.4 mm.
2. Assign the print a "2" if average deviations in X and Y are between 0.4 and 0.3 mm.
3. Assign the print a "3" if average deviations in X and Y are between 0.2 and 0.3 mm.
4. Assign the print a "4" if average deviations in X and Y are between 0.1 and 0.2 mm.
5. Assign the print a "5" if average deviations in X and Y are between 0 and 0.1 mm.

We considered changing the nozzle temperature and the step height for the print structure as they are closely co-related to the printer resolution. Table I shows the modifications of the parameters for four different runs. The initial print was at 0.1 mm step height and 210 ºC nozzle temperature.

Table I. Modification of the parameters for different runs.

S.No	Parameters	Run 1	Run 2	Run 3	Run 4
1.	Bed Temperature (ºC)	0	0	0	0
2.	Filament Temperature (ºC)	210	210	230	230
3.	Nozzle Diameter (mm)	0.5	0.5	0.5	0.5
4.	Step Size (mm)	0.2	0.4	0.2	0.4
5.	Flow Rate (%)	100	100	100	100
6.	Travel Speed (mm/s)	50	50	50	50

Based on the Response Surface method, we scored and evaluated the performance of the parts as shown in table II. The average effect of a factor is defined as the change in the level on that factor averaged over the levels of the other factors. This can be represented mathematically as:

$$\boldsymbol{A = \frac{ab + a}{2n} - \frac{b + (1)}{2n} = \frac{1}{2n}[ab + a - b - (1)]} \qquad (\mathbf{1})$$

Similarly,

$$\boldsymbol{B = \frac{ab + b}{2n} - \frac{a + (1)}{2n} = \frac{1}{2n}[ab + b - a - (1)]} \qquad (\mathbf{2})$$

And,

$$\boldsymbol{AB = \frac{ab + (1)}{2n} - \frac{a + b}{2n} = \frac{1}{2n}[ab + (1) - a - b]} \qquad (\mathbf{3})$$

Where n= number of runs.

Table II. Performance table for different runs.

Dimensional accuracy of pyramid								
S.No	Four Factorial Design	A	B	Score				
		Nozzle temperature	Step size	I	II	III	IV	Total
1.	(1) A low; B low	210	0.2	4	4	4	3	15
2.	(a) A high; B low	230	0.2	4	4	5	5	18
3.	(b) A low; B high	210	0.4	3	4	2	3	12
4.	(ab) A high; B high	230	0.4	3	4	3	4	14

We will further discuss this table and the performance outcomes in the next section.

Figure 2 Printed pyramids for four different runs.

To further validate the outcome from the Response surface method and to optimize the result, we used Design of Experiment (DOE) approach. Table III depicts the DOE data.

4. Results and Discussion

4.1 Response Surface Method:

Based on the three equations (1, 2 & 3) listed in the previous section, we can observe the effects of the parameters. Substituting the values from table II in these equations, we get:

$$A = \frac{1}{2(4)}(14 + 18 - 12 - 15) = 0.625$$

$$B = \frac{1}{2(4)}(14 + 12 - 18 - 15) = -0.875$$

$$AB = \frac{1}{2(4)}(14 + 15 - 18 - 12) = -0.125$$

Table III. Design of Experiment (DOE) data.

S.No.	Process Parameters		Objective function x (mm)
	Nozzle temperature (ºC)	Step size (mm)	
1.	230	0.4	24.75
2.	230	0.2	24.82
3.	210	0.2	24.8
4.	210	0.4	24.72
5.	230	0.4	24.87
6.	230	0.2	24.83
7.	210	0.2	24.84
8.	210	0.2	24.85
9.	210	0.4	24.86
10.	230	0.2	24.9
11.	230	0.2	24.95
12.	210	0.4	24.68
13.	210	0.4	24.72
14.	210	0.2	24.76
15.	230	0.4	24.71
16.	230	0.4	24.82

The main effect of A (nozzle temperature) is positive; this suggests an increase in the nozzle temperature would increase the dimensional accuracy. On the contrary, the main effect of B (step size) is negative; this suggests that an increase in the step size would decrease the dimensional accuracy. The interaction AB also has a negative value which suggests that an increase in both the factors simultaneously would adversely affect the dimensional accuracy.

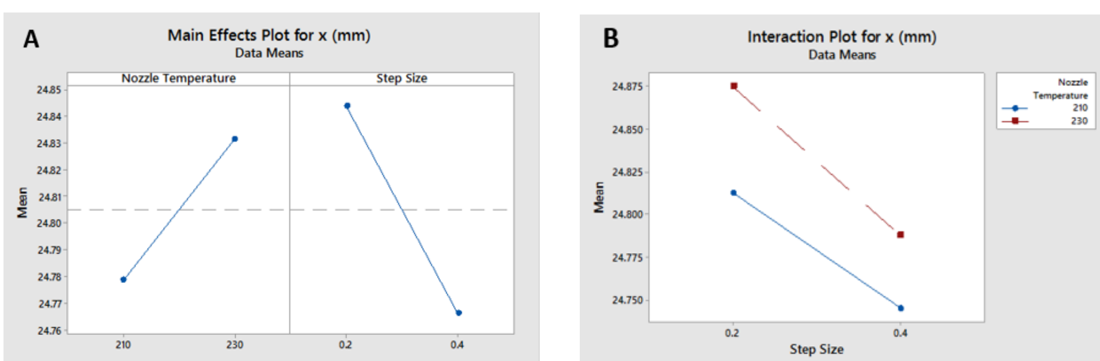

Figure 3 A- Main effects plot for nozzle temperature and step size; B- Interaction plot for nozzle temperature and step size.

It can be validated from the left block of the main effects plot that as the nozzle temperature increases the dimensional accuracy also increases. The right block in the same main effects plot shows that a decrease in the step size increases the dimensional accuracy. This gives us a general idea about the effects of change in the printing parameters on the dimensional accuracy. Further, the interaction plot shows us the combined behavior of the interaction between the two factors. A combined increase in both the factors would result in a poor dimensional accuracy. Therefore, as per the observations, we can say that, to achieve better dimensional accuracy, one needs to increase the nozzle temperature and decrease the step size.

4.2 Optimization Using DOE:

A full factorial DOE was used to obtain the probability value (P-value) for each factor with respect to the dimensional accuracy (dimensions in X-direction). The obtained P-values would help us in determining the significance of each factor on the dimensional accuracy. The full factorial DOE analysis was done for a confidence interval of 95%. Therefore, a P-value less than 0.05 is considered to reject the null hypothesis. The results from the full factorial DOE (figure 4) shows that the P-value for step size is 0.028 which is less than 0.05. Therefore, it is evident that step size is a significant factor that affects the dimensional accuracy of the printed part.

As per the pareto chart (figure 5A), the step size is responsible for a standardized effect of almost 2.5. This also indicates that step size is a major factor that influences the dimensional accuracy. It can also be observed that the step size and the nozzle temperature contribute a cumulative standardized effect of 2.160. Hence, it is apparent that step size and the nozzle temperature closely affect the dimensional accuracy of the print.

Full Factorial Design

Design Summary

Factors:	2	Base Design:	2, 4
Runs:	16	Replicates:	4
Blocks:	1	Center pts (total):	0

Factorial Regression: x (mm) versus Nozzel Temperature, Step Size

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	2	0.035050	0.017525	4.49	0.033
Linear	2	0.035050	0.017525	4.49	0.033
Nozzel Temperature	1	0.011025	0.011025	2.82	0.117
Step Size	1	0.024025	0.024025	6.15	0.028
Error	13	0.050750	0.003904		
Lack-of-Fit	1	0.000400	0.000400	0.10	0.763
Pure Error	12	0.050350	0.004196		
Total	15	0.085800			

Figure 4 Full factorial DOE result.

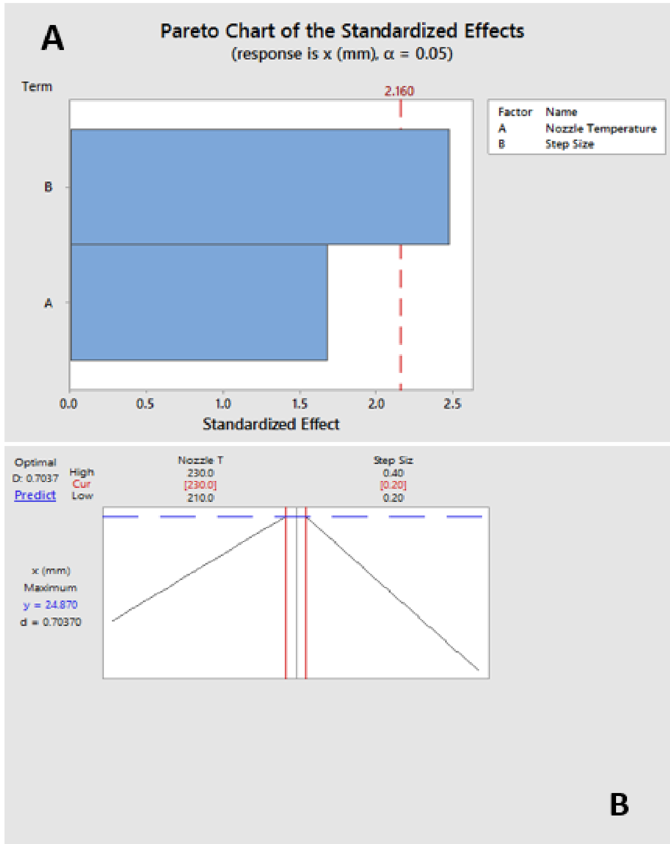

Figure 5 A-Standardized effect using Pareto chart; B- Optimized result.

As per the results from the Full factorial optimizer in Minitab, the optimized results are as follows:

1. Nozzle Temperature: 230 ºC.
2. Step size: 0.2 mm.

It can also be observed from the d-optimality value that the optimization conditions are achieved to a degree of 70.3%.

5. Conclusion

Printed part was checked for dimensional accuracy and the printing parameters were optimized to achieve the optimal design. The printing parameters selected for optimization were nozzle temperature and step size. Nozzle temperature directly influences the flow rate and therefore a higher nozzle temperature would result in continuous flow and would restrict clogging of the nozzle. The step size determines the distance between two consecutive layers. Maintaining a minimum step size ensures that the layers adhere to each other properly with no sagging or bulging in between. We concluded that increasing the nozzle temperature and decreasing the step size, increases the dimensional accuracy of the printed part using PLA. However, other factors such as the geometry, print pattern and infill density also affect the dimensional accuracy and the print quality.

6. References

[1] "Objet Connex 3D Printers". *Objet Printer Solutions*.

[2] http://www.thingiverse.com/MAKE/collections/2015-test-prints-make-annual-guide-to-3d-printing