Analysis of dimensional variation in fused deposition modeling based 3D printing process parameters for better dimensional control

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KEYWORDS

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Surface Roughness,
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ABSTRACT

Additive Manufacturing (AM) is most promising technology in today's manufacturing scenario. This technology is also known as 3D printing. Additive manufacturing construct the components by adding the material layer by layer. With advancement in technology additive manufacturing finds its application in almost every manufacturing sector and can build components of metal, polymers and composites. It offers huge design freedom and manufacture intricate shapes and parts of complex designs. This paper presents analysis of process parameters of Fused Deposition Modeling (FDM) for better dimensional accuracy. Different process parameters of FDM such as layer thickness, infill percentage and printing speed are considered for analysis. It is observed during this analysis that percentage variation of printed part inside diameter compared to that of 3D model inner diameter varied from 1.52% to 3.9%. Whereas percentage variation of square side of the printed part when compared with 3D model square side varied from 1.01% to 2.83%.

1. Introduction

Layers of material are added to create objects in additive manufacturing (AM). Due of its better capabilities, additive manufacturing is appealing to numerous manufacturing companies worldwide. These days, it's also employed to produce parts for final usage in addition to prototype production. A number of industry fields, including aerospace, transportation, medicine, and consumer goods, use additive processing (Jin et al., 2014). Metal, plastic, and composite parts can be created via additive manufacturing. Numerous additive manufacturing techniques are utilized to create complex shapes for a wide range of purposes.

One of the crucial AM processes used to create plastic and plastic composite parts is Fused Deposition Modelling (FDM). In FDM, material is deposited layer by layer through a nozzle after a plastic filament has been extruded through a heated extruder. A 3D representation of the thing to be printed generates the codes that control how the nozzle travels. The stages of 3D printing are depicted in Figure 1. Making a 3D model of the thing to be produced is the first step in the FDM method of 3D printing. Following this, the model is turned into an STL file, which is then divided into a number of layers using the appropriate tools. Finally, the components are created and cleaned in accordance with the specifications (Patil et al., 2022; Deomore & Raykar, 2021; Manglam et al., 2022; D'Addona et al., 2021; Rayksr & D'Addona, 2020; Raykar et al., 2020).

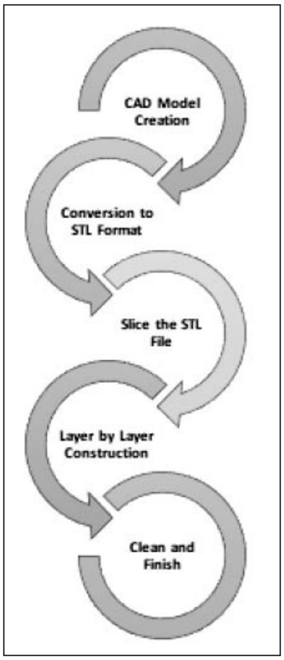

Fig. 1. Steps in 3D printing with FDM. (Patil et al., 2022; Deomore & Raykar, 2021; Manglam et al., 2022; D'Addona et al., 2021; Raykar & D'Addona, 2021; Raykar et al., 2020)

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FDM is an additive manufacturing technology that uses numerous process parameters with varied outcomes. As a result, it is a very complicated process to analyze. A lot of research is being done to determine how different FDM process factors affect the numerous responses that are engaged in it.

Numerous process variables, including layer thickness, infill percentage, bed temperature, nozzle speed, and infill pattern, affect FDM's performance. FDM may deliver excellent results in terms of time, cost, and print quality if the aforementioned parameters are properly chosen. Researchers from all over the world are working very hard to determine how the aforementioned process parameters affect the FDM result. Wang et al. (2007) investigated of effect layer thickness, deposition method, support method, Z- and X-direction deposition orientation, and construct site. The most crucial factor for dimensional accuracy, in their opinion, is the deposition orientation in the Z-direction.

Chinmay et al. (2022) investigated effect of process parameter on surface roughness of FDM parts using ANOVA, Mean Effect Plots and Contour Plots. According to their investigation, build orientation and layer thickness are the most influencing parameters as far as surface roughness is concerned. They also predicted that the best working range for achieving surface roughness below 6 µm is orientations 0˚ to 15˚ and 85˚ to 90˚, with layer thickness ranging from 0.12 to 0.16 mm and infill densities between 80% and 90%.

Layer thickness, build orientation, raster distance, and air gap were examined by Sood et al. (2009) from the perspective of dimensional aberrations in length, width, and thickness. The most important determinant for deviations in breadth and thickness, as well as for changes in length, was discovered to be layer thickness.

From the study of current research on FDM, it can be pointed out that, a clear picture of effect of process parameters on dimensions of FDM printed parts must be investigated in detail. In this analysis product features like a hole diameter and a internal square cavity and their dimensions are thoroughly studied and investigated on the basis of FDM process parameters namely layer thickness, infill percentage and printing speed. General linear model-based analysis of variance (ANOVA) is used for analysis.

2. Experimental Details

In this investigation a rectangular body of PLA material is printed which have a through hole of 8 mm diameter and through square cavity with 8 mm side in the body 2D drawing of which is shown in Fig 1.a and actual printed components are shown in Fig. 1.b.

For design of experiment, Response Surface Methodology (RSM) approach is used. Central Composite Design (CCD) with three factors is used to create set of experiments. For analysis, forward selection method is used with alpha 0.25. Regression equation are also generated to see effect of process parameters on inside and outside dimensions.

The details of experimental setup are given in Table 1 along with the specifications.

To assess effects of parameters on dimensions of FDM printed parts three process parameters each of them having three levels are selected. These

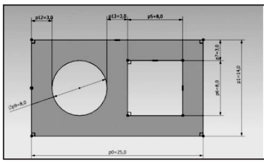


Fig. 1a

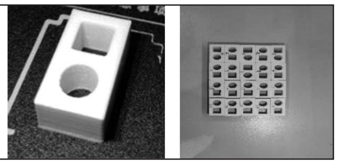


Fig. 1b

Table 1
Details of experimental work.

Item	Details
3D Printing technology	Fused Deposition Modelling
3D Printer	Flashforge Finder 3D printer (140 mm^3).
Filament Diameter	1.75 mm
Nozzle Diameter	0.4 mm
Slicing Software	Flashprint
File Type	STL
Nozzle Temperature	220^o C
Infill Pattern	Line
Shell Thickness	0.80 mm
Material	Polylactic Acid (PLA)
Specimen Specifications	As per Fig.1 (hole diameter and square cavity 8 mm through)
Instrument used to check the dimensions	A calibrated digital vernier caliper with L.C. 0.01 mm

process parameters and their levels are given in Table 2.

RSM based Central Composite Design approach is used for Design of Experiment with parameters shown Table 2. The details of CCD are shown in Table 3.

For slicing 3D models Flashprint software is used, a sliced model is shown in Fig. 2. All 20 models as per above array are sliced with the mentioned process parameters and then printed on Flashforge Finder.

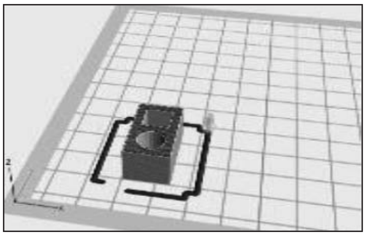
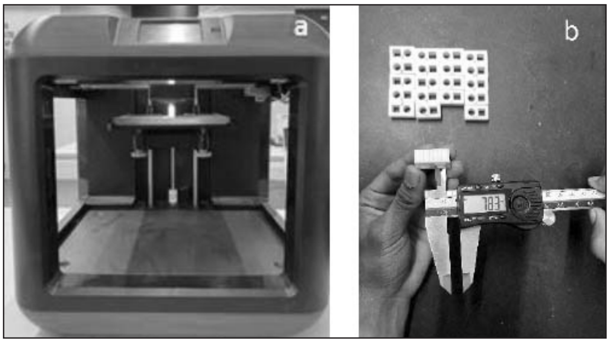


Fig. 2. Slicing of component.



a. 3D printing set up

b. Testing of fabricated parts

Fig. 3 (a, b): Set up of printer and testing of specimen.

Table 2
Process parameters and their levels.

Process Parameters	- (Low)	+ (High)
Layer height (mm)	0.12	0.14
Infill Density (%)	70	80
Print Speed (mm/sec)	80	100

Table 3
Central composite design through RSM.

Std Order	Run Order	PtType	Blocks	LT	Infill %	Printing Speed	Inner Dia. (ID)	Square Side (SS)
18	1	-1	2	0.16000	75.000	106.33	7.78	7.91
16	2	-1	2	0.16000	83.165	90.00	7.70	7.80
13	3	-1	2	0.12734	75.000	90.00	7.81	7.88
20	4	0	2	0.16000	75.000	90.00	7.79	7.87
15	5	-1	2	0.16000	66.835	90.00	7.82	7.78
17	6	-1	2	0.16000	75.000	73.67	7.74	7.83
14	7	-1	2	0.19266	75.000	90.00	7.83	7.82
19	8	0	2	0.16000	75.000	90.00	7.80	7.84
5	9	1	1	0.14000	70.000	100.00	7.88	7.88
1	10	1	1	0.14000	70.000	80.00	7.84	7.85
11	11	0	1	0.16000	75.000	90.00	7.82	7.92
10	12	0	1	0.16000	75.000	90.00	7.84	7.90
4	13	1	1	0.18000	80.000	80.00	7.72	7.78
7	14	1	1	0.14000	80.000	100.00	7.70	7.79
12	15	0	1	0.16000	75.000	90.00	7.82	7.83
8	16	1	1	0.18000	80.000	100.00	7.83	7.79
6	17	1	1	0.18000	70.000	100.00	7.85	7.79
2	18	1	1	0.18000	70.000	80.00	7.76	7.80
9	19	0	1	0.16000	75.000	90.00	7.74	7.79
3	20	1	1	0.14000	80.000	80.00	7.71	7.81

Table 4
ANOVA for hole diameter (ID).

Source	DF	Adj SS	Adj MS	F-Value	p-Value
Regression	3	0.030859	0.010286	6.40	0.005
LT	1	0.000294	0.000294	0.18	0.674
Infill %	1	0.024023	0.024023	14.94	0.001
Printing Speed	1	0.006541	0.006541	4.07	0.061
Error	16	0.025721	0.001608		
Lack-of-Fit	11	0.019638	0.001785	1.47	0.353
Pure Error	5	0.006083	0.001217		
Total	19	0.056580			

Table 5
ANOVA for square side (SS).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	0.007902	0.002634	1.31	0.305
LT	1	0.005386	0.005386	2.68	0.121
Infill %	1	0.001033	0.001033	0.51	0.484
Printing Speed	1	0.001483	0.001483	0.74	0.403
Error	16	0.032118	0.002007		
Lack-of-Fit	11	0.020635	0.001876	0.82	0.639
Pure Error	5	0.011483	0.002297		
Total	19	0.040020			

After printing all 20 components, the hole diameter (ID) and square side (SS) are measured by a calibrated digital vernier caliper with least count of 0.01mm. Measurement setup is shown in Fig. 3 b. The results are shown in Table 3.

3. Results and Discussions

For analysis, forward selection method of CCD-RSM is used with alpha 0.25. Regression equation are also generated to see effect of process parameters on inside and outside dimensions. Regression equations for hole diameter (ID) and square side (SS) along with corresponding ANOVA are shown below in Table 4 and 5.

From ANOVA Table 4, it is clear that infill percentage is most influencing parameter for inner diameter at p-value 0.001. For inner diameter after infill percentage p-value for printing speed is 0.061 so printing speed is second influencing parameter and layer thickness has least influence on inner diameter with p-values 0.674 for this investigation. The same trend is visible from regression equation, the coefficient for layer thickness is 0.235 which is largest amongst all three process parameters therefore it has highest influence on hole diameter.

Further in this investigation from ANOVA Table 5, it is visible that most influencing parameter for square side is of layer thickness with p- value 0.121. Second influencing parameter for square side is followed by printing speed with p-value 0.403, and least influencing parameter for square side is of infill percentage with p-value 0.484. In regression equation the coefficient for printing speed is 0.00105 which is largest amongst all three parameters therefore it has highest influence on square side.

To sum up, it can be seen that layer thickness, infill percentage and printing speed are very important parameters for dimensional control of FDM based 3D printing. Layer thickness has great impact on dimensions because smaller layer thickness

Table 6
Deviations of actual dimensions from CAD and regression models.

Experiment Number	Actual Dimension and CAD		Regression Analysis and Actual Dimension			
	% variation in Inner Diameter (ID)	% variation in Square Side (SS)	Predicted Inner Diameter (ID)	Predicted Square Side (SS)	% error Inner dia. (ID)	% error Square Side (SS)
1	2.827763	1.1378	7.825	7.850	0.573	-0.766
2	3.896104	2.564103	7.719	7.818	0.252	0.234
3	2.432778	1.522843	7.781	7.866	-0.372	-0.184
4	2.695764	1.651842	7.789	7.833	-0.016	-0.476
5	2.30179	2.827763	7.858	7.847	0.484	0.855
6	3.359173	2.171137	7.753	7.816	0.163	-0.185
7	2.171137	2.30179	7.796	7.800	-0.431	-0.258
8	2.564103	2.040816	7.789	7.833	-0.144	-0.093
9	1.522843	1.522843	7.849	7.872	-0.400	-0.100
10	2.040816	1.910828	7.804	7.851	-0.456	0.014
11	2.30179	1.010101	7.789	7.833	-0.401	-1.115
12	2.040816	1.265823	7.789	7.833	-0.658	-0.859
13	3.626943	2.827763	7.729	7.793	0.115	0.171
14	3.896104	2.695764	7.764	7.855	0.820	0.821
15	2.30179	2.171137	7.789	7.833	-0.401	0.034
16	2.171137	2.695764	7.773	7.814	-0.732	0.311
17	1.910828	2.695764	7.858	7.832	0.102	0.535
18	3.092784	2.564103	7.814	7.811	0.689	0.140
19	3.359173	2.695764	7.789	7.833	0.626	0.545
20	3.761349	2.432778	7.720	7.834	0.123	0.300

indicates very less gaps between the height patterns of walls getting printed, this creates a finer surface with less deviations from the CAD dimensions. Similarly with higher infill percentage components become more solid which in turn makes them more accurate for their dimensions. Therefore, these parameter settings and their levels must be taken into construction while printing FDM parts.

While printing components with FDM polymer filament is deposited on printed bed through a heated nozzle. The temperature depends on material to be printed as plastics filament is heated and the further get school during printing process there is tendency that dimensions on CAD model and actual printed components may vary. This variation depends on different features of components like fillet, inside dimensions, long projections. Lot of research is going to assess variations in dimensions of 3D printed parts. The analysis of shrinkage of 3D printed part requires special attentions.

During the analysis, dimensional deviations of actual printed part are compared with the dimensions in CAD model. % Dimensional variations are calculated from CAD dimension and actual measured dimensions; these are shown in Table 6. In this analysis the prediction algorithms are generated using regression method, the values of which are compared with actual dimensions. These deviations are shown in Table 6. Following are the regressions equations for inner diameter and square side.

Inner Dia. = 8.189 + 0.235 LT - 0.00849 Infill % + 0.00221 Printing Speed

Square Side = 8.031 - 1.005 LT - 0.00176 Infill % + 0.00105 Printing Speed

It can be seen that percentage variation of printed part inside diameter compared to that of 3D model inside diameter varies from 1.52% to 3.9%. Whereas percentage variation of square side of the printed part when compared with 3D model square side it varies from 1.01% to 2.83%.

The minimum variation in inner diameter is found 0.14 mm layer thickness, 70 infill percentage and 100 mm/sec printing speed. Whereas maximum variations are found at two experimental runs that are 0.16 mm layer thickness, 83.167 infill percentage and 90 mm/sec printing speed and at 0.14 mm layer thickness, 80 infill percentage and 100 mm/sec printing speed.

Further it is found that the minimum variation in square side is at 0.16 mm layer thickness, 75 infill percentage and 90 mm/sec printing speed. Whereas as maximum variations are found at two experimental runs 0.16 mm layer thickness, 66.835 infill percentage and 90 mm/sec printing speed and at 0.18 mm layer thickness, 80 infill percentage and 80 mm/sec printing speed. This conforms effectiveness of smaller layer thickness and infill percentage from 75 to 80 % for better dimensional control.

From the regression equation, the predicted inner diameter and square side are calculated which are shown in the Table 6. And it can be seen that the percentage variations of predicted dimensions obtained from regression equation when compared with dimensions obtained from actual printed parts for inner diameter ranges from 0.016% to 0.82%, for square side it varies from 0.014% to 1.115%. The minimum variation for dimensions obtained from regression equation in inner diameter are found at 0.16 mm layer thickness, 75 infill percentage and 90 mm/sec printing speed. Whereas maximum variation is found at 0.14 mm layer thickness, 80 infill percentage and 100 mm/sec printing speed. Also for square side minimum deviation is found at 0.14 mm layer thickness, 70 infill percentage, and 80 mm/sec printing speed. Maximum deviation is found at 0.16 mm layer thickness, 75 infill percentage and 90 mm/sec printing speed. This indicates accuracy of regression method for prediction of outputs in 3D printing.

4. Conclusions

Following are some of the significant conclusions observed during investigation.

- Layer thickness, infill percentage and printing speed are very important printing parameters for Fused Deposition Modelling.
- Due to effect of temperature at nozzle and actual printing interface there is variation in dimensions of actual printed parts as when compared to CAD model dimensions.
- It is seen that percentage variation of printed part inside diameter compared to that of 3D model inside diameter varied from 1.52% to 3.9%.
- Whereas percentage variation of square side of the printed part when compared with 3D model square side varied from 1.01% to 2.83%.
- Regression analysis is useful tool to predict performance of FDM for better dimensional control. Regression trend indicates very close fit of regression predicted values with actual values.

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