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Investigation of Shrinkage Variation in 3D Printed Models

Optimization and Variation of Shrinkage with respect to printing parameters for PLA material in 3D printed objects

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Abstract: Fused deposition modeling (FDM) is most efficient method to print products with high complexity. The most vital parameters for FDM are infill density, infill pattern, layer thickness, printing speed, printing orientation, nozzle temperature and diameter. This study will investigate the effect of varying parameters on shrinkage of 3D printed objects. The parameters selected for this study are- infill percentage, layer thickness and printing speed. A Taguchi array of 64 combinations of these parameters is obtained using Minitab software. Polylactic acid (PLA) material is used to print the 3D objects using all the combinations of printing parameters form the array. The object is designed using computer aided design (CAD) software. The object selected for printing is cuboid with circular hole at center, to demonstrate the shrinkage in both, linear dimensions as well as circular dimension. The printer used for this entire study is Creality 10S Pro. At the end, this study will provide a generalized equation for the dimensions based on actual obtained data, which can be used to determine the dimension of object theoretically before fabricating it, thus we can provide the necessary shrinkage allowance to the design of model.

***Index Terms* – fused deposition modeling, additive manufacturing, polylactic acid, Taguchi L64 Array, 3D printing.**

I. INTRODUCTION

Additive manufacturing is one of the most effective processes to print an object with complex features within minimal time. Additive manufacturing belongs to the modern technologies for producing and manufacturing 3D objects. In this process, the required object is printed by building up layer by layer over one another by a specific material like PLA until the entire object is completely printed. Additive manufacturing has become popular among the manufacturing processes because it has certain abilities and advantages over other manufacturing processes. One of the satisfactory advantages is to produce complicated geometrical objects without need of machining and tooling [1].

Fused deposition modeling (FDM), we also call it as 3D printing comes under additive manufacturing. It is an important key in manufacturing revolution. This technology is integration of various components that help us to produce parts without wastage of material and tooling processes [2].

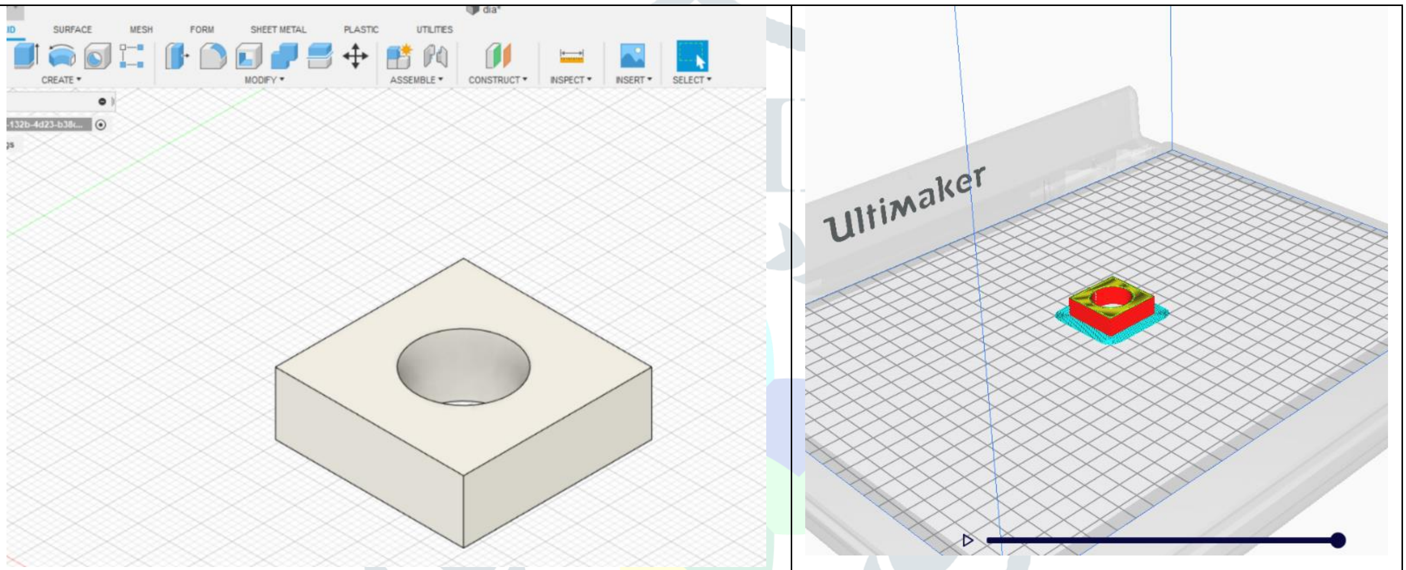
Maintaining quality and productivity in the 3D printing process is very important. However, it is a bit difficult to control productivity and quality for several parameters that affect additive manufacturing process. Most of setups and setting are carried out by trial-and-error methods which is time consuming process [3]. Shrinkage is one of the major issue faced while producing the object via 3D printing. Shrinkage is a natural property of a material, but it can be controlled to some extent in order to achieve the product with better dimensional accuracy. Thus, this study will provide the best optimized combination of parameters to minimize shrinkage and will present a linear regression equation to predict the shrinkage in dimensions of the 3D model. It is believed that a better dimensional accuracy is obtained by setting up the best combination of parameters [3]. The parameters that influence the dimensional accuracy are infill density or infill percentage (IP), layer thickness (LT), nozzle temperature (NT), bed temperature (BT) and printing speed (PS). Among all this parameters infill percentage, layer thickness and printing speed are the parameters that can be manually controlled and plays a major role in shrinkage behavior of the 3D printed objects [4]. Several object samples will be printed according to Taguchi L64 array, regression analysis will be performed on those combinations and an optimized result will be obtained.

Jelena and Gojko found that the variation in printing speed has effect on dimensional accuracy of shapes like circle and square [5]. They emphasized on the result that circular shape shows poorest dimensional accuracy and the highest printing speed gives better dimensional accuracy. Ilies and Niklas made research on design of dimensional reduction compensation modeling, in which they concluded that infill patterns have negligible effect on shrinkage. However, the density of infill affects the shrinkage of object [6].

Thus, from above context we found that there are not much studies done regarding shrinkage of 3D objects and methods to optimize the dimensional accuracy of printing objects.

II. METHODOLOGY

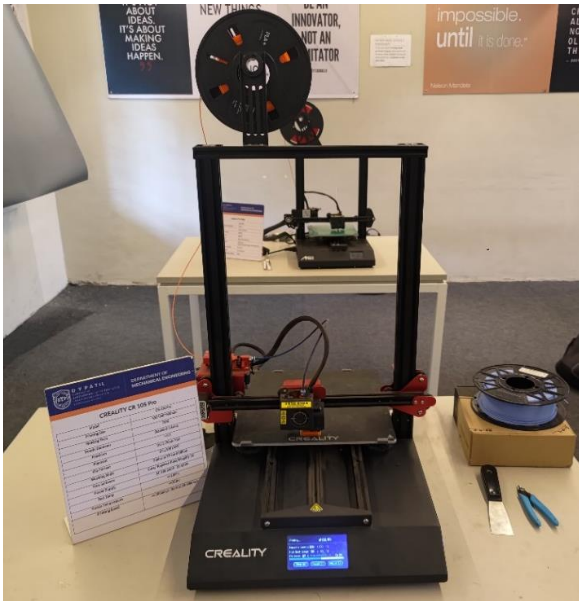
The design of the object is done using Computer Aided Design (CAD) as shown in Fig.1.a) and the dimension selected are: sides 30mm, inner circle diameter 20mm and height of object 10mm. For the experiment Taguchi L64 array is created using Minitab software (refer Table 1). Then the CAD design is converted and saved as stereolithographic file format (STL). After finalizing the design this STL file is done slicing according to the 64 combinations of parameters provided in the array (Table 1) using Ultimate Cura software.



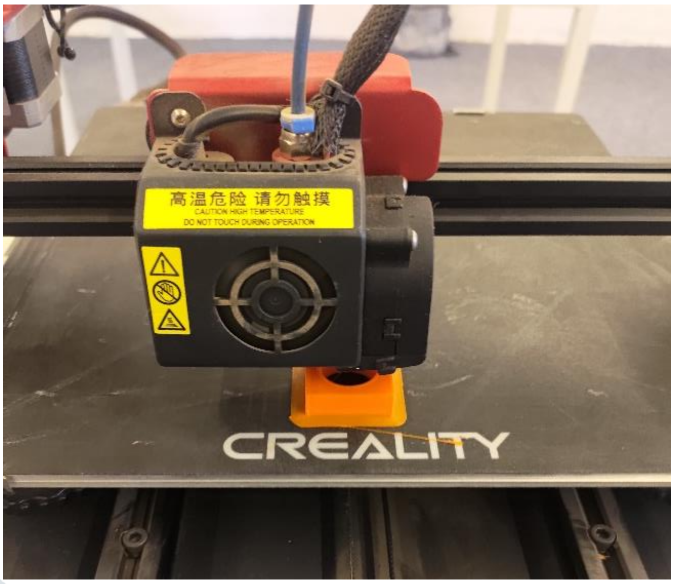
a) CAD design b) Slicing of Object

Fig. 1: Designing of Object

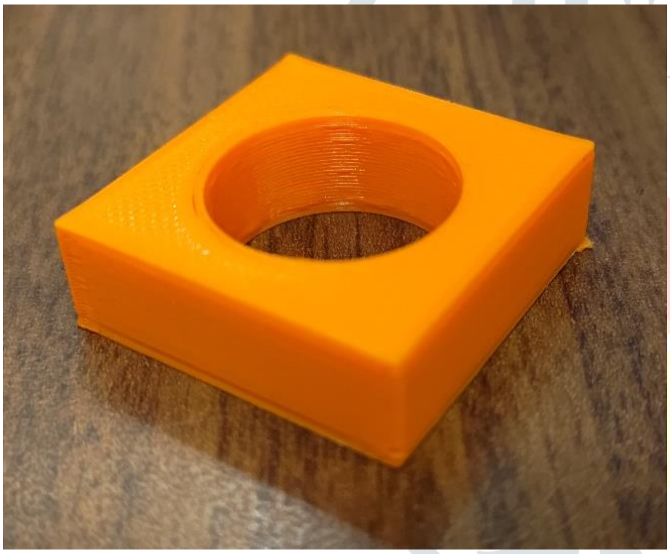
The material selected for printing the sample objects is PLA because it is most widely used printing material in 3D printer. After finalizing the material 64 objects were printed on the printer- Creality 10S Pro (Fig.2.a). All the 64 printed objects are then tested for their dimensional measurement via using digital Vernier (Fig.2.d). To get most accurate measurements and to avoid the manual errors we decided to measure every dimension thrice and then finalize the average of the three measurements as final obtained dimension. Thus, these readings are further compared and analysed in the results.



a) 3D Printer (Creality 10S Pro)



b) Printing Process



c) Printed model

d) Object Measurement

Fig. 2: Printing and Measurement

III. Experimental Setup

Table 1: Table of Experimental Work

Printer	
3D Printer	Creality 10S Pro
3D Printing Technology	Fused Deposition Modelling
Nozzle Diameter	0.4mm
Nozzle Temperature	210º C
Bed Temperature	60º C
Printing Material	
Material	Polylactic Acid (PLA)
Filament Diameter	1.75mm
Specimen Details	
Shape Specification	Cuboid (sides-30, height-10) with a circular hole (diameter-20)
Slicing Software	Ultimate Cura
File Type	Stereolithographic file format (STL)
Infill Pattern	Line
Dimension Measuring Instrument	Digital Vernier

To demonstrate the effect of printing parameters on the shrinkage of PLA printed models, the three selected parameters to be used and each of them with four different levels are mentioned in the Table 2.

Table 2: Parameters and their different levels

Parameters	1	2	3	4
Layer Thickness (mm)	0.14	0.16	0.18	0.20
Infill Percentage (%)	55	65	75	85
Printing Speed (mm/sec)	70	80	90	100

The Taguchi L64 array has been created using these three printing parameters with all possible combinations of the four different levels. The table given below shows the combinations of changing parameters for all the printed objects. The dimensional measurement of all the printed object is noted using the digital Vernier and these reading can be observed in the column of Obtained Dimensions in Table 2. The measured dimensions are- sides of cuboid, inner diameter of hole and height of the object.

The analysis of the obtained dimensions is done in Result. Using the combination of parameters and the shrink dimensions, a linear regression equation is obtained using Minitab software, which is further used to calculated the shrink dimensions theoretically (column of theoretically obtained dimensions in Table 3). The comparison of Theoretical and experiment dimensions, shrinkage error and effect of the selected parameters on shrinkage is also discussed in the result section.

Table 3: Taguchi L64 Array

Sr. No.	Parameters			Obtained Dimensions			Theoretically Obtained Dimensions			% Error
	LT	IP	PS	Side (Actual=30)	Inner Diameter (Actual=20)	Height (Actual=10)	Side (Actual=30)	Inner Diameter (Actual=20)	Height (Actual=10)	
1	0.18	75	100	29.915	19.62	9.95	29.9979	19.59371	9.93779	0.89%
2	0.2	65	70	29.855	19.72	10.065	29.9324	19.61955	9.92913	0.41%
3	0.16	75	80	29.475	19.705	9.975	29.9779	19.66547	9.94377	1.16%
4	0.18	55	70	29.86	19.78	9.96	29.9508	19.67621	9.93789	0.66%
5	0.18	65	90	29.815	19.625	9.96	29.9832	19.62691	9.93823	0.96%
6	0.18	75	90	29.83	19.77	9.99	29.9802	19.60981	9.93701	0.61%
7	0.2	55	80	29.83	19.755	10.045	29.9531	19.62055	9.93113	0.45%
8	0.2	65	100	29.815	19.59	9.93	29.9855	19.57125	9.93147	1.12%
9	0.14	65	80	29.955	19.73	9.93	29.9963	19.72213	9.95253	0.73%
10	0.16	75	70	29.855	19.61	9.935	29.9602	19.68157	9.94299	1.03%
11	0.18	75	70	29.835	19.685	9.83	29.9448	19.64201	9.93545	1.28%
12	0.14	75	90	30.015	19.705	9.94	30.011	19.68893	9.95209	0.67%
13	0.18	65	100	30.06	19.45	9.97	30.0009	19.61081	9.93901	0.95%
14	0.14	85	90	30.37	20.02	9.915	30.008	19.67183	9.95087	0.16%
15	0.18	55	80	30.095	19.57	9.94	29.9685	19.66011	9.93867	0.81%
16	0.14	55	80	30.08	19.7	9.935	29.9993	19.73923	9.95375	0.63%
17	0.16	75	100	30.035	19.365	10.055	30.0133	19.63327	9.94533	0.84%
18	0.16	65	90	30.03	19.615	9.995	29.9986	19.66647	9.94577	0.62%
19	0.2	55	70	30.155	19.65	9.85	29.9354	19.63665	9.93035	0.91%
20	0.18	55	90	30.07	19.685	9.87	29.9862	19.64401	9.93945	0.88%
21	0.2	55	90	30.085	19.6	9.735	29.9708	19.60445	9.93191	1.46%
22	0.14	55	90	30.585	19.81	9.88	30.017	19.72313	9.95453	0.07%
23	0.14	65	70	30.11	19.76	9.835	29.9786	19.73823	9.95175	0.83%
24	0.14	65	100	30.03	19.77	9.91	30.0317	19.68993	9.95409	0.65%
25	0.14	85	80	30.16	19.73	9.88	29.9903	19.68793	9.95009	0.67%
26	0.16	85	70	29.865	19.725	9.9	29.9572	19.66447	9.94177	0.94%
27	0.16	55	100	29.83	19.74	9.885	30.0193	19.66747	9.94777	1.01%
28	0.2	65	80	29.81	19.73	9.92	29.9501	19.60345	9.92991	0.93%
29	0.14	75	100	29.855	19.835	9.945	30.0287	19.67283	9.95287	0.62%
30	0.18	65	80	29.77	19.74	9.825	29.9655	19.64301	9.93745	1.27%
31	0.14	85	70	29.795	19.88	9.93	29.9726	19.70403	9.94931	0.66%
32	0.18	85	80	30.03	19.63	9.875	29.9595	19.60881	9.93501	1.00%
33	0.16	65	80	29.83	19.8	9.925	29.9809	19.68257	9.94499	0.77%
34	0.16	55	90	30.105	19.745	9.955	30.0016	19.68357	9.94699	0.46%
35	0.2	85	90	29.84	19.745	9.945	29.9618	19.55315	9.92825	0.79%
36	0.14	55	70	29.96	19.7	9.95	29.9816	19.75533	9.95297	0.71%
37	0.16	85	100	30.115	19.685	9.915	30.0103	19.61617	9.94411	0.68%
38	0.18	85	90	29.8	19.82	9.88	29.9772	19.59271	9.93579	0.92%
39	0.2	75	80	29.965	19.755	10.035	29.9471	19.58635	9.92869	0.33%

40	0.2	75	90	29.99	19.685	10.035	29.9648	19.57025	9.92947	0.42%
41	0.14	55	100	29.97	19.715	9.97	30.0347	19.70703	9.95531	0.61%
42	0.18	65	70	29.835	19.715	9.975	29.9478	19.65911	9.93667	0.74%
43	0.18	85	100	29.845	19.83	9.945	29.9949	19.57661	9.93657	0.64%
44	0.14	65	90	29.805	19.65	10.05	30.014	19.70603	9.95331	0.63%
45	0.18	55	100	29.815	19.47	9.915	30.0039	19.62791	9.94023	1.37%
46	0.14	75	70	29.805	19.64	9.965	29.9756	19.72113	9.95053	0.93%
47	0.16	85	90	29.955	19.635	9.97	29.9926	19.63227	9.94333	0.76%
48	0.2	65	90	30.055	19.725	10.03	29.9678	19.58735	9.93069	0.30%
49	0.2	75	70	30.01	19.625	9.955	29.9294	19.60245	9.92791	0.76%
50	0.16	85	80	29.825	19.67	9.945	29.9749	19.64837	9.94255	0.93%
51	0.14	75	80	30.055	19.54	9.925	29.9933	19.70503	9.95131	0.96%
52	0.2	85	70	30.13	19.34	9.95	29.9264	19.58535	9.92669	1.12%
53	0.14	85	100	30.195	19.51	10.015	30.0257	19.65573	9.95165	0.55%
54	0.16	65	100	30.005	19.44	10.07	30.0163	19.65037	9.94655	0.69%
55	0.18	75	80	30.155	19.39	9.91	29.9625	19.62591	9.93623	1.14%
56	0.2	85	100	30.365	19.395	9.885	29.9795	19.53705	9.92903	0.99%
57	0.16	75	90	29.975	19.33	10.075	29.9956	19.64937	9.94455	0.89%
58	0.16	55	80	30.145	19.715	10.085	29.9839	19.69967	9.94621	0.03%
59	0.2	75	100	29.975	19.28	9.725	29.9825	19.55415	9.93025	2.14%
60	0.16	65	70	30.095	19.48	9.96	29.9632	19.69867	9.94421	0.89%
61	0.18	85	70	30.09	19.395	9.98	29.9418	19.62491	9.93423	0.97%
62	0.2	85	80	30.12	19.315	9.86	29.9441	19.56925	9.92747	1.48%
63	0.16	55	70	30	19.675	9.96	29.9662	19.71577	9.94543	0.68%
64	0.2	55	100	30.03	19.595	9.885	29.9885	19.58835	9.93269	1.03%

IV. RESULT AND ANALYSIS

Form the tabular data obtained (refer to Table 3), it can be observed that the shrinkage in circular dimensions is highest as compared to the linear dimensions. However, among the linear dimensions the object height i.e., vertical linear dimension is more affected by shrinkage as compared to sides of object i.e., horizontal liner dimensions. The horizontal linear dimension had negligible reduction, it is very much closer to the actual dimension. So as can make an assumption that the order in which the dimensional accuracy is affected by shrinkage:

circular dimension > vertical linear dimension > horizontal linear dimension

From the data we found, the maximum shrinkage is 1.46% for the parameterized combination of layer thickness-0.20mm, infill percent-55% and printing speed-90mm/sec. Whereas the minimum shrinkage is obtained at combination of layer thickness-0.14mm, infill percent-85% and printing speed-90mm/sec, which is 0.16%. From this we can infer that layer thickness has direct effect on shrinkage, as highest layer thickness (0.20mm) showed highest shrinkage and lowest layer thickness (0.14) showed minimal shrinkage. So, the combination of layer thickness-0.14mm, infill percent-85% and printing speed-90mm/sec gives us most accurate object dimensionally.

Using the obtained dimensions and respective parameters, we obtained a liner regression equation with three variables from the Minitab software which is applicable to all the printed objects. The format of equation is answer = constant + (coefficient*parameter) + (coefficient*parameter) + (coefficient*parameter). The three equations for three kinds of dimensions are:

1. Linear Horizontal Dimension: S = 29.982 - 0.770*LT - 0.00030*IP + 0.00177*PS
2. Linear Vertical Dimension: S = 10.007 - 0.377 LT - 0.000122 IP + 0.000078 PS
3. Circular Dimension (Diameter): S = 20.239 - 1.978 LT - 0.00171 IP - 0.00161 PS

Where S = Shrink Dimension
LT = Layer Thickness
IP = Infill Percentage
PS = Printing Speed

These equations can be used to determine dimensions of any object to be printed with PLA material. This will help us to predict the shrinkage reduction in the object and thus necessary allowance can be applied to the actual design. According to the equations obtained, we can understand the relationship between parameters and dimensional shrinkage. The coefficient of layer thickness is the factor that majorly affects the actual dimension among those three parameters, so we can conclude that layer thickness is the most vital parameter that leads to shrinkage in printed model. Greater the layer thickness, greater will be the shrinkage reduction in object. And the least affecting parameter among these three is printing speed. So, the order of parameters affecting shrinkage is: layer thickness > infill percent > printing speed.

V. CONCLUSION

This study investigated the effect of varying parameters on shrinkage of 3D printed objects. The parameters selected for this study are- infill percentage, layer thickness and printing speed. Polylactic acid (PLA) material is used to print the 3D objects using all the combinations of printing parameters form the Taguchi L64 array. The object selected for printing is cuboid with circular hole at center, to demonstrate the shrinkage in both, linear dimensions as well as circular dimension.

Following are the important conclusion made from the study:

1) The shrinkage in circular dimension is found to be more significant compared to other linear dimensions. The order of shrinkage significance is: circular dimension > vertical linear dimension > horizontal linear dimension.
2) The combination of layer thickness-0.20mm, infill percent-55% and printing speed-90mm/sec has maximum shrinkage among all 64 combinations, i.e., 1.46%.
3) Whereas the combination of layer thickness-0.14mm, infill percent-85% and printing speed-90mm/sec has the most accurate object and has minimal shrinkage of 0.16%.
4) Form the equation obtained we infer that the layer thickness is directly proportional to shrinkage percent and has a major effect on the shrinkage of printed object. Reducing layer thickness minimizes the shrinkage in the object.

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