2018

An Investigation on Selected Factors that Cause Variability in Additive Manufacturing

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Abstract
Additive manufacturing (AM) brings significant freedom in design, yet it can get hard to produce the same part at identical dimensional tolerances; this is also known as the reproducibility problem. Reproducibility, the ability to produce the same part under similar conditions, is one of the major challenges in AM as reproducibility plays an important role in the replacement of worn-out or damaged parts in an assembly. The objective of this paper is to identify the impacts of two most common factors (i.e., layer thickness and printing speed) on the dimensional accuracy of additively manufactured parts through a designed experiment. A full-factorial experimental design involving these factors at three levels is implemented to investigate them. We printed a dog bone testing specimen by using Poly Lactic Acid (PLA) polymer and Fused Filament Fabrication (FFF) technology. The dimensional properties of the parts are then measured to statistically compare the variability in each level to derive significant factors and their levels. The results show that printing speed has a significant effect on deviation in length but has no effect on deviation in height. Also, layer thickness and interaction between layer thickness and printing speed can cause significant variation in height.

Keywords
Reproducibility, FFF, PLA polymer, Design of Experiments (DOE)

Disciplines
Industrial Engineering | Industrial Technology | Operational Research

Comments
This proceeding was published as Velineni, Anusha, Elif Elçin Günay, Kijung Park, Gül E. Okudan Kremer, Thomas M. Schnieders, and Richard T. Stone. (eds. K. Barker, D. Berry, and C. Rainwater) "An Investigation on Selected Factors that Cause Variability in Additive Manufacturing." In *Proceedings of the 2018 IISE Annual Conference* (2018): 983-988. Posted with permission.

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An Investigation on Selected Factors that Cause Variability in Additive Manufacturing

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Abstract

Additive manufacturing (AM) brings significant freedom in design, yet it can get hard to produce the same part at identical dimensional tolerances; this is also known as the reproducibility problem. Reproducibility, the ability to produce the same part under similar conditions, is one of the major challenges in AM as reproducibility plays an important role in the replacement of worn-out or damaged parts in an assembly. The objective of this paper is to identify the impacts of two most common factors (i.e., layer thickness and printing speed) on the dimensional accuracy of additively manufactured parts through a designed experiment. A full-factorial experimental design involving these factors at three levels is implemented to investigate them. We printed a dog bone testing specimen by using Poly Lactic Acid (PLA) polymer and Fused Filament Fabrication (FFF) technology. The dimensional properties of the parts are then measured to statistically compare the variability in each level to derive significant factors and their levels. The results show that printing speed has a significant effect on deviation in length but has no effect on deviation in height. Also, layer thickness and interaction between layer thickness and printing speed can cause significant variation in height.

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1. Introduction

Fused Filament Fabrication (FFF), is a popular rapid prototyping technology widely used in industry to build complex geometrical functional parts in a short time. It is a layer additive manufacturing process that uses thermoplastic materials or metal wires to produce parts. Due to its advantages of cost, and material use efficiency, FFF shows great potential in mold fabrication, bio-medical device design [1, 2], tissue engineering [3] and other industrial fields. A great deal of research has been done on the surface finish of FFF parts in recent years to investigate the factors that cause variability [4, 5]. However, further research is needed to explain the reasons of dimensional inaccuracy in AM for specific technology, material, process parameters and geometric complexity.

Dimensional inaccuracy is measured in terms of deviation from the specified dimensions of the part such as height, length and width. The possible factors that cause dimensional inaccuracy are the type of material, temperature variation, support structures, machine error and process parameters such as layer thickness, build orientation, and deposition speed [3, 6, 7]. All these factors may vary according to material, technology and the complexity of the part printed. In this study, we will focus on variability in dimensional properties of the AM parts that are caused by the process parameters- layer thickness and printing speed. We investigate their effects on the dimensional accuracy by a full-factorial design of experiment (DOE) of the parts produced from PLA by FFF technology. The outcomes of this research provide optimal levels of factors that can be used to produce dimensionally more accurate products using FFF. It is important to consider the variability in AM parts as they replace worn-out or damaged parts that need to be built again with the same tolerances; progress on this specific area will enhance adoption of this technology in industry.

In section 2, we present a summary on the recent studies on dimensional accuracy for FFF technology. Section 3 discusses our methodology, DOE, to evaluate the effect of factors on the response parameters. In Section 4, we perform an ANOVA test to determine statistically significant factors that cause variability. Additionally, main effect and interaction effect plots provide us the optimal settings of factors for dimensional accuracy. Section 5 concludes the paper and provides insights.

2. Literature review

FFF manufactured parts exhibit geometrical inaccuracy which has been evaluated in different studies. Ippolito et al. [8] designed and manufactured benchmark parts that showed geometrical deviations up to +0.7 mm. Poor tessellation accuracy is one of the reasons that leads to inaccuracy in parts due to errors in the data source. Hällgren et al. [9] compared the results of tessellation from six different Computer Aided Design (CAD) systems, which showed that tessellation effects may be visible even when dimensional requirements are fulfilled. They proposed a method for three-dimensional (3D) data exchange that can facilitate different materials and different densities in the same part to accomplish the geometric requirements.

Process parameters are other factors that cause dimensional inaccuracy. The most common parameters that require setup are the raster angle, tool path, layer thickness, build orientation, and printing speed [10]. Dul et al. [11] built specimens along three orientations: horizontal, vertical and perpendicular. They compared compression molded parts and 3D printed parts and showed that build orientation affects the dimensional accuracy since the direction of filament deposition changes with the orientation. Chang and Huang [12] considered raster width, raster angle, contour width, and contour depth on dimensional accuracy. Their study concluded that the contour width is the significant factor which affects dimensional variation. Dawoud et al. [13] investigated raster angle and gap on both dimensional accuracy and mechanical properties like, tension and flexural strength. They showed that even these two factors influence mechanical properties, there is no significant effect of raster gap or angle on dimensional accuracy. Bakar et al. [10] studied the effect of raster width and layer thickness on dimensional accuracy and surface finish. Their study stated that printing the parts with lower layer thickness and raster angle decreases the deviation in dimensions. However, their study did not provide statistical evidence. Melenka et al. [14] investigated effect of layer thickness, build orientation and the infill percentage on dimensional accuracy when MakerBot 3D printers are used. In contrast to the findings in [10] and [11], their findings showed that layer thickness and build orientation fail to achieve significance as factors on dimensional accuracy. Percent infill is the significant factor that causes dimensional accuracy.

The above mentioned works from the literature reveal that there is a need to further investigate the effect of layer thickness due to the conflicting results of in [11] and in [14]. Moreover, even though studies exist tackling the effect of printing speed on surface finish [10, 15, 16], there is a need to investigate its effect on dimensional accuracy. In order address these gaps in the literature, we investigate the main and interaction effect of printing speed and layer thickness for FFF technology and PLA material. We determine optimal setting of printing speed and layer thickness that minimizes the dimensional inaccuracy.

3. Methodology

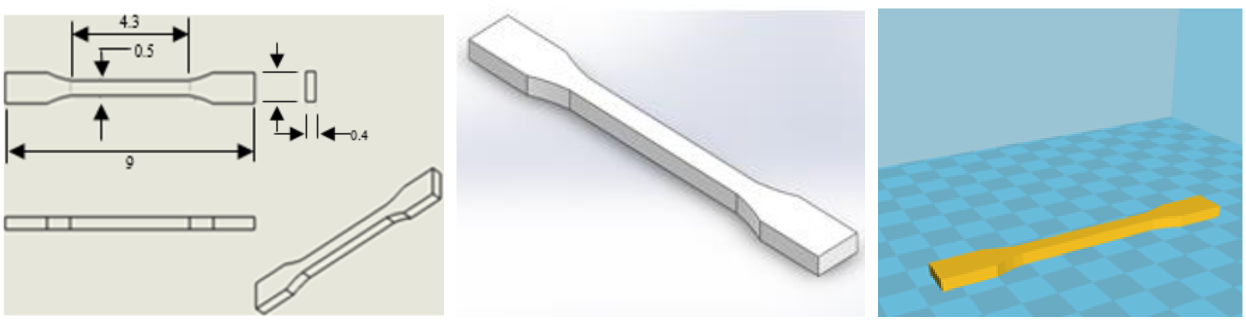
Design of experiment (DOE) is a method used to find the cause and effect relationship between factors and their levels that affect process outputs [17]. The goal of this study is to investigate the effect of layer thickness and printing speed on dimensional accuracy. Our hypothesis is that a part's dimensional accuracy in height and length might be affected by layer thickness and printing speed. We consider two factors: layer thickness and printing speed with three levels constituting nine different experiments. The factor levels are tabulated in Table 1. All the experiments were replicated thrice for a total of 27 runs. A full factorial design was used to investigate the main effects of factors, and also interaction effects between the factors. We run all 27 experiments randomly without following any order so that the machine can be set to different process parameters rather than replicating the same parts thrice in a row. All the experiments are run under the same conditions; all other factors except layer thickness and printing speed were kept constant and same for all experiments. We use PLA polymer to build the parts on the FFF machine. The 3D printer is Monoprice Maker Select V2 with build volume of 8"×8"×7", 100-micron resolution, 1.75mm filament diameter, 100mm/sec print speed and maximum temperature of 260 °C.

The building part in Figure 2 is a dog bone shaped tensile testing specimen (9.00×1.00×0.4cm) taken from the literature [11]. Figure 2(a) shows the 2D and isometric sketch of the specimen. The CAD model of the part shown in Figure 2

(b) was created using SOLIDWORKS, and then converted to a STL file in Figure 2(c) using CURA 15.04 software. With CURA, we were able to vary the levels of factors such as layer and shell thickness, traction, density, bed temperature, support structure and many more advanced features.

Table 1: Two factors with three different levels each

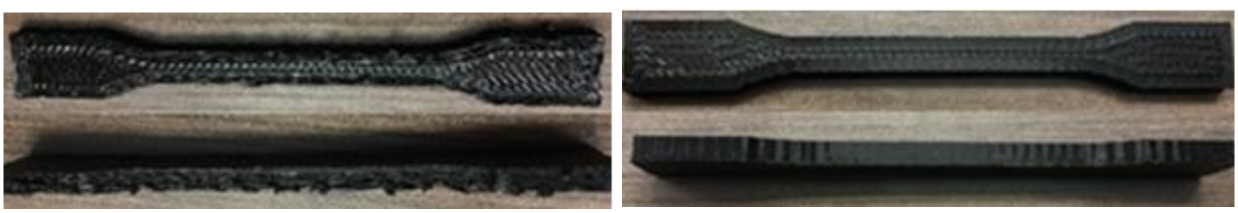
Factor	Factor Labels	Level 1	Level 2	Level 3
Layer thickness(mm)	A	0.1	0.2	0.3
Printing Speed(mm/s)	B	60	80	100



(a) (b) (c)

Figure 2: A dog bone shaped specimen printed in the experiments

Figure 3 illustrates the specimens printed in different layer thickness and printing speed. The printing duration for building each part varies with the levels of factors. Figure 3(a) shows the specimen printed in 0.3 mm layer thickness and 100mm/s printing speed which took 6 min per part. Figure 3(b) presents the part set up with 0.1 mm layer thickness and 60mm/s printing speed which took the longest printing time of 18 min per part.



(a) (b)

Figure 3: 3D-printed parts in different factor level settings

4. Results

The deviation in the length and height from the original CAD model of the specimen are the outcomes of the experiments used for the dimensional accuracy investigation. The deviation in length and the height are calculated by subtracting the dimensions of the printed specimen from the reference length (9.00 cm) and the height (1.00 cm) in the CAD model. Overall length and height are measured at same location for each part using digital Vernier calipers. Table 2 represents the deviation in overall length and height for each experiment.

In order to examine the statistical significance of factor effects on each response, we performed analysis of variance (ANOVA) using Minitab 15 statistical software. Our hypothesis in this study is that the layer thickness, printing speed and the interaction between two factors might have significant effects on deviation from overall length and height. The ANOVA results for deviation from overall length are presented in Table 3. With regards to adjusted R^2, 25.87% of the variation on the response, i.e. deviation in overall length, can be explained by our model. We observe from the results that the printing speed is the statistically significant factor that affects the deviation in overall length (p-value=0.035). Layer thickness and interaction between layer thickness and the printing speed do not have significant effects on the deviation from the nominal length.

Table 2: Experimental results for deviation in overall length and height

Experiments		Deviation in overall length (cm)			Deviation in Height (cm)		
Factor A	Factor B	R1	R2	R3	R1	R2	R3
0.1	60	0.040	0.017	0.030	0.006	0.005	0.004
	80	0.020	0.029	0.020	0.000	0.000	0.006
	100	0.030	0.032	0.033	0.007	0.004	0.006
0.2	60	0.100	0.034	0.030	0.005	0.005	0.000
	80	0.018	0.020	0.017	0.016	0.010	0.016
	100	0.042	0.041	0.038	0.018	0.027	0.013
0.3	60	0.040	0.040	0.062	0.020	0.020	0.023
	80	0.034	0.033	0.030	0.012	0.016	0.012
	100	0.023	0.020	0.022	0.020	0.010	0.002

Table 3: ANOVA results for deviations from overall length

Source	DF	SS	MS	*F*-value	*P*-value
A-Layer Thickness	2	0.0004454	0.0002227	1.06	0.366
B-Printing Speed	2	0.0016936	0.0008468	4.05	0.035
A×B	4	0.0014317	0.0003579	1.71	0.191
Error	18	0.0037647	0.0002091		
Total	26	0.0073354			
R^2 = 48.68% Adjusted R^2 = 25.87%					

[*]DF: degrees of freedom; SS: sum of squares; MS: mean square error

Having identified the printing speed as a significant factor on deviation from length, in the next step, the optimal setting of this factor is determined. A main effect plot will assist us in finding the effect of printing speed on the mean response, i.e., deviation in the overall length. Figure 4 illustrates the main effect plots of layer thickness and printing speed on the mean response. Since layer thickness does not have a significant impact to explain the variation in the length, we only focus on the main effect plot for printing speed (Factor B). With regards to Figure 4, the minimum deviation in overall length from the reference value occurs when printing speed is in Level 2. Therefore, the optimum condition of the printing speed based on the mean response is Level 2, which is 80 mm/s. Because neither layer thickness (Factor A) nor the interaction between printing speed and layer thickness (A×B) has a significant impact on the mean response, any level of Factor A may be chosen in the design. The mean response (i.e., deviation in overall length) at the optimum factor level is estimated from the main effect, printing speed. The predicted mean response is calculated using the equation, $\hat{\mu} = \bar{T} + (\bar{B}_2 - \bar{T})$ [18]. In the equation, $\hat{\mu}$ shows the predicted mean response at the optimal condition and $\bar{T}$ is the overall mean of deviation in length, and $\bar{B}_2$ is the mean of the observations when printing speed is 80 mm/s. Therefore, the predicted deviation in length is $\hat{\mu} = 0.0331 + (0.0245 - 0.0331) = 0.0245\text{cm}$.

The other response we considered in this study is deviation in height. We perform an ANOVA test in order to determine the significant factors effecting this deviation. The results are presented in Table 4. According to the adjusted R^2 value, a measure of model fit, 66.36% of the variation on the mean response (i.e, deviation in height) can be explained by process parameters. Table 4 illustrates that layer thickness (Factor A) and the interaction between layer thickness and printing speed (A×B) have significant impacts on the deviation in height (*p*-value =0.000 and *p*-value =0.001, respectively).

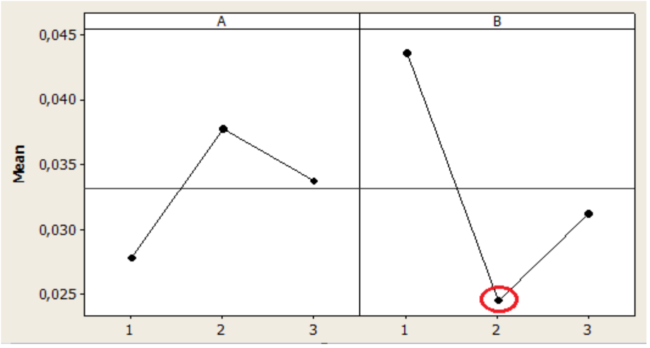


Figure 4: Main effects of overall length difference

Table 4: ANOVA results for deviation in height

Source	DF	SS	MS	*F*-value	*P*-value
A-Layer Thickness	2	0.0005636	0.0002818	14.44	0.000
B-Printing Speed	2	0.0000267	0.0000134	0.69	0.517
A×B	4	0.000567	0.0001418	7.26	0.001
Error	18	0.0003513	0.0000195		
Total	26	0.0015087			
R^2 = 76.71% Adjusted R^2 = 66.36%					

*DF: degrees of freedom; SS: sum of squares; MS: mean square error

After determining the statistically significant factors affecting the deviation in height, we proceeded to determine the optimal setting of Factor A and Factor B. Figure 5 and Figure 6 show the main effects and the interaction effect on the mean response for deviation in height. In Figure 5, the main effect plots show that the mean values are smaller for Factor A in Level 1 (shown with red circle). Since there is an interaction effect between Factor A and Factor B, we cannot determine optimal factor settings by only considering the main effect plot. In the interaction effect plot in Figure 6, the deviation in the height changes based on the level of Factor B. Therefore, the interaction effect should not be ignored in the determination of the optimal factor settings. When Factor A is in Level 1, the minimum deviation in height occurs if the Factor B is in Level 2 (red circled in Figure 6). The optimal setting that satisfies the minimum deviation in height is printing parts with 0.1mm layer thickness and 80mm/s printing speed. The predicted mean response (i.e., deviation in overall height) at the optimum factor level is estimated by $\hat{\mu} = \bar{T} + (\overline{A_1B_2} - \bar{T}) = 0.0104 - (0.0020 - 0.0104) = 0.0020\text{cm}$.

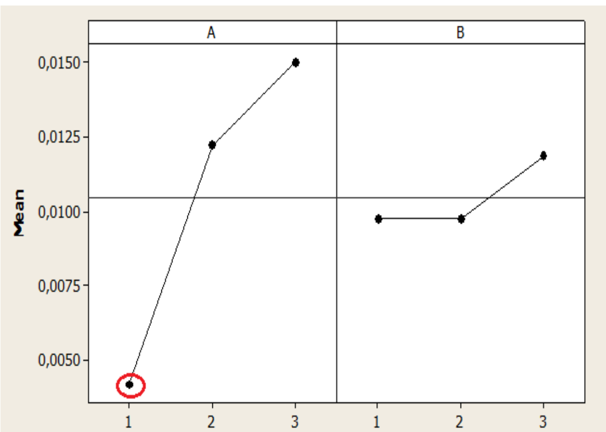


Figure 5: Main effects of height difference

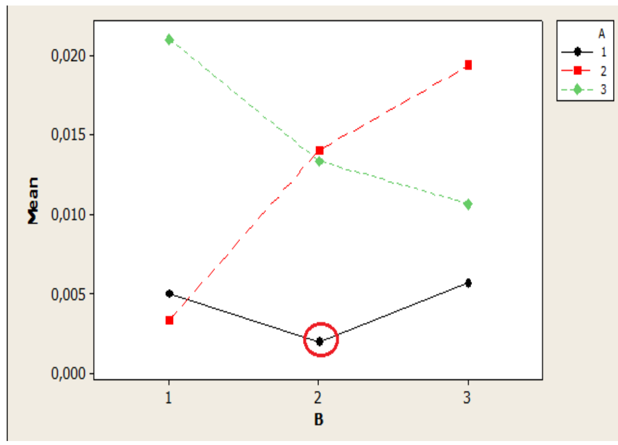


Figure 6: Interaction effects of Factor A & B

5. Conclusions

In this study, we investigate effects of process parameters namely, layer thickness and printing speed on dimensional accuracy using PLA material and FFF technology. We conduct a full-factorial experimental design with three levels of each parameter. Each set of experiment is replicated thrice, yielding 27 runs/prints. As we focus on dimensional accuracy, we measure the differences from target length and height as per the CAD model in each observation. The minimum difference in mean for both length and height is desired to comment on the effectiveness of the process parameters. Given the results, we conclude that printing speed has a statistically significant effect on the deviation in the overall length. To get as minimal deviation in length as possible, printing speed is set to 80 mm/s. However, there is no statistical evidence that the layer thickness or the interaction between two factors impacts deviation of the overall length. On the other hand, both layer thickness and the interaction between layer thickness and printing speed have statistically significant effects on deviation in height. Therefore, considering both the main effect plots and the interaction effect plot, the most desirable factor levels to minimize the deviation in height are A_1B_2: 0.1mm of layer thickness and 80mm/s of printing speed. As a future study, we will investigate the effect of these factors to dimensional inaccuracy when different material and technology are used. The comparison between two set of experiments will provide new knowledge on the factors' dependence on different technology and the material choices.

Acknowledgement

This study was partially funded by U.S. National Science Foundation (#1723736) for Gül E. Okudan Kremer. Also, this work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MIST) (No. 2018R1C1B5040256) for Kijung Park.

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