Evaluation of Linear Dimensional Accuracy and IT Grades of Carbon-Reinforced PETG Parts Fabricated via Fused Deposition Modeling

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Abstract. Dimensional accuracy is a critical quality attribute in fused deposition modeling (FDM). This study investigates the effect of five process parameters i.e. layer thickness, build orientation, printing speed, air gap, and nozzle temperature on the percentage error in linear dimensions of FDM-fabricated parts. Three orthogonal dimensions, namely length (printing direction), width (perpendicular to the printing direction), and thickness (build direction), were considered for dimensional measurements. Experiments were designed using the Taguchi method with five parameters at five levels, employing an L25 orthogonal array, and statistical analysis was performed using Minitab software based on the “smaller-is-better” signal-to-noise ratio criterion. The results revealed that the percentage error in length was minimal and remained below 1%, whereas significantly higher errors were observed in width and thickness due to anisotropic shrinkage and layer-wise deposition effects. Main effects and Pareto analyses indicated that build orientation is the most influential parameter, followed by nozzle temperature and layer thickness, while printing speed showed the least influence. Residual analysis confirmed the adequacy of the developed model. An optimal combination of process parameters was identified to minimize dimensional error, and improvement in dimensional precision was quantified through IT grade evaluation.

Keywords: Percentage error, FDM Process, ANOVA Analysis, IT Grades

1 Introduction

The advantages of additive manufacturing (AM) in the ability to create complex geometries with minimal material waste and shorter manufacturing time have made it a transformative manufacturing process. Fused Deposition Modelling (FDM) is one of the most popular AM techniques because of its simplicity and low cost as well as the ability to use a variety of thermoplastic materials. On the other hand, traditional FDM

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polymers tend to be poor in mechanical properties and dimensional stability which prevent them from being used for functional parts or load-bearing parts. To overcome these limitations, in recent years carbon-reinforced polymer (CRP) composites have received great attention in the aircraft industry. FDM fabricated parts can be stiffened, strengthened and have good thermal resistance with the addition of thermoplastic matrix and carbon fibres or carbon based fillers [1,2,3]. In particular, carbon-reinforced polyethylene terephthalate glycol (PETG) has been identified as a suitable material since it has the right balance of printability, toughness and improved mechanical properties. In several studies, the mechanical, dynamic and deformation properties of carbon-reinforced PETG parts produced with FDM were reported to be improved [4,5,6]. The effects of important process parameters on mechanical properties, including layer thickness, printing speed, orientation and nozzle temperature, have also been widely studied [7,8]. Although much work has been done on mechanical and thermal properties, dimensional accuracy is still a major concern for FDM, particularly for composite filaments reinforced with mechanical properties. The carbon reinforcement affects the melt flow, cooling rates, and bonding between layers, all of which can have a significant impact on dimension accuracy [9, 10]. The dimensional deviation, surface roughness, and geometric accuracy of reinforced FDM parts have been analyzed in the past by statistical and optimization based methods [11, 12]. Most investigations, however, report dimensional errors in absolute terms or as percentage error which may not fully reflect the functional significance of dimensional variation[13-18].

In manufacturing practice, the International Tolerance (IT) grades, which are set by ISO 286, give a standardized, size independent dimension accuracy measurement. Although IT grade analysis is widely used in traditional manufacturing processes, it is limited in use when manufacturing reinforced polymer components using FDM. Relatively few studies have tried to correlate dimensional errors with a standardised tolerance classification, especially for carbon-reinforced PETG systems. Moreover, existing literature is lacking on the use of Taguchi-based experimental design and IT grade assessments for evaluating the linear dimensional accuracy. The novelty of the present study is the systematic evaluation of the linear dimensional accuracy of FDM-fabricated carbon-reinforced PETG components based on ISO grade analysis, not only with percentage error. The use of Taguchi method based design of experiments (DOE) is used to explore the impacts of important process parameters on dimensional performance. The selective discussion of IT grades of critical linear dimensions enables a standardized, industrially relevant evaluation of the dimensional quality of carbon-reinforced PETG materials produced using FDM, thereby providing a deeper understanding of the ability of these materials to be manufactured and their tolerance capabilities.

2. Material and Method

2.1 Material

The carbon-reinforced PETG glycol was used as a feedstock material in this study, and the incorporation of the carbon reinforcement gives enhanced stiffness, dimensional stability and thermal resistance properties to the neat PETG which render it suitable for functional and load-bearing parts produced using fused filament fabrication techniques.

2.2 3D Modeling of Test Specimen

For the assessment of percentage error in linear dimension and IT grade a rectangular test specimen of nominal dimension of length 150 mm, Width 12.5 mm, thickness 10 mm was taken in this study. To guarantee the correct geometric definition and dimensional accuracy, the three-dimensional CAD model of the specimen was developed with CATIA V6 software. The finished CAD model was then exported as an STL (stereolithography) file format compatible with fused deposition modeling (FDM) printers, and appropriate for additive manufacturing. The dimension of test specimen is given in Figure 1.

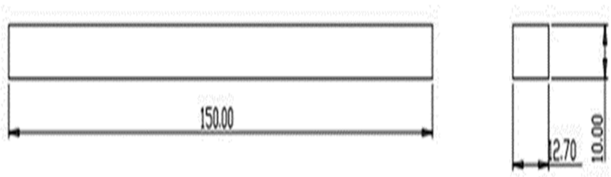

Figure 1Dimension of Test Specimen

2.3 Design of Experiment

The experimental design adopted in this work was developed by the Taguchi method, a powerful statistical tool that is commonly applied to the process optimization with minimum number of experimental trials. The taguchi method is based on orthogonal arrays which is used to systematically investigate the effect of several process parameters on performance characteristics with minimum experimental cost and time. This method allows for a means of assessing each parameter effect and relative importance in controlled experimental conditions. For the present investigation, five process parameters were chosen which are known to affect the dimensional accuracy of fused deposition modeling (FDM) process. The following process parameters were selected, and used here to investigate process variability over a wide parameter range: layer thickness (0.1–0.3 mm), build orientation (0°–90°), printing speed (20–100 mm/s), air gap (1–3 mm), and nozzle temperature (230–250 °C). These parameters were selected to simulate the multi-faceted effect of the deposition geometry, the thermal state and the flow behavior of the material during printing. An appropriate experimental design matrix was constructed according to a taguchi orthogonal array, in order to have a balanced design with all the factors and levels represented. The resulting design matrix used for this analysis is shown in Table 1. A Taguchi-based experimental design is used for analyzing the effect of the process

Parameter percentage error in linear dimension and it grade of the fabricated specimens, which is a statistically efficient method.

Table 1: Design of Experiment

Layer Thickness	Orientation	Printing speed	Air gap	Nozzle Temperature
1	1	1	1	1
1	2	2	2	2
1	3	3	3	3
1	4	4	4	4
1	5	5	5	5
2	1	2	3	4
2	2	3	4	5
2	3	4	5	1
2	4	5	1	2
2	5	1	2	3
3	1	3	5	2
3	2	4	1	3
3	3	5	2	4
3	4	1	3	5
3	5	2	4	1
4	1	4	2	5
4	2	5	3	1
4	3	1	4	2
4	4	2	5	3
4	5	3	1	4
5	1	5	4	3
5	2	1	5	4
5	3	2	1	5
5	4	3	2	1
5	5	4	3	2

2.4 Fabrication of Test Specimen

Test specimens were made with a fused deposition modeling (FDM) 3D printer (Ultimaker S5) with a standard brass nozzle. The feedstock material used was carbon reinforced PETG filament of 1.75 mm diameter. The filament was dried before printing to prevent moisture from being trapped in the filament during extrusion, which could lead to inconsistencies in fabrication. The printing parameters used were the layer thickness (0.1 – 0.3 mm), build orientation (0 – 90°), printing speed (20 – 100 mm/s), air gap (1 – 3 mm) and nozzle temperature (230 – 250 °C) which were selected according to the taguchi design matrix generated for the study. To ensure proper bed adhesion and reduce warping during the printing process, the build platform temperature was kept at the appropriate temperature for PETG. All specimens were printed in a build chamber with controlled environment to minimize the effect of ambient airflow and temperature changes. The air temperature in the printing area is kept at about 25 ± 2 °C, and the relative humidity is controlled below 40%, because the ambient moisture content is easy to be absorbed by the petg-based materials, and moisture absorption will cause the dimensional accuracy and surface quality to be affected. The printed specimens were left to cool down in the build chamber to reduce residual thermal or chemical stresses and dimensional deviation, and any minor support structures and surface irregularity were removed by hand. The samples were then kept in a dry place until being measured in terms of size and analysed.

2.5 Measurement of Percentage Error in Linear Dimension

A digital vernier caliper was used to measure the linear dimensions of the fabricated specimens for dimensional accuracy evaluation. The least count of the instrument used for measurement was of the order of 0.01 mm, which was suitable for measuring the small dimensional deviations in the printed specimens. The measurements were made at room temperature to prevent errors due to temperature changes. The percentage errors obtained for the various selected linear dimensions are presented in Table 2. The percentage error of the linear dimension was observed to be less than 1% for all of the experimental runs, which shows acceptable dimensional accuracy of the fabricated specimens. The magnitude of percentage error was relatively low, so it was not taken into account as one of the main response parameters in the next investigation. The percentage error in the linear dimensions was determined by the relation (1) as follows: Fabricated test specimens are shown in figure 2.

Percentage error = (Actual dimension − CAD dimension)/CAD dimension×100……………………(1)

2.6 Calculation of IT Grade

The international tolerance (IT) grades were used to quantify the dimensional accuracy of the fabricated specimens according to ISO286, which provides a framework for the consideration of manufacturing tolerances. The IT grades classify dimensional deviations into discrete sets of tolerances which allows the comparison of dimensional quality for various manufacturing processes. Since no bi-lateral tolerance limits were set ahead of time and just one measured dimension was present for each specimen, the effective tolerance (t) was estimated as twice the absolute deviation from the nominal dimension.

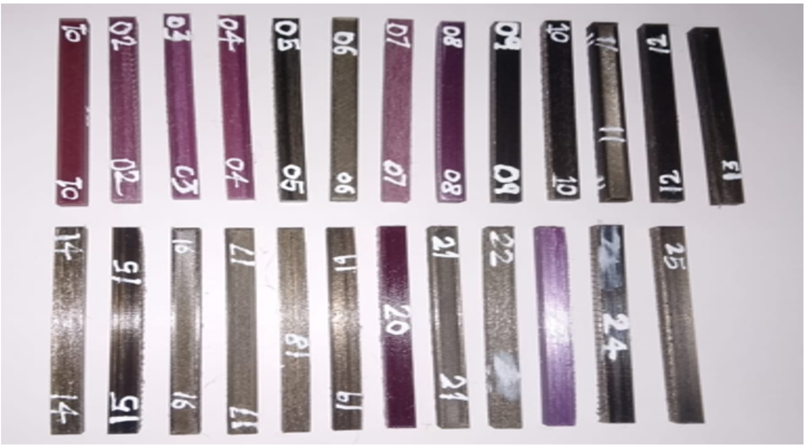

Fig. 2Fabricated Test Specimen

Table 2 Measurement of Percentage error in linear dimension

Run Order	Percentage Error in width	Percentage Error in thickness	Average Percentage error	S/N Ratio
1	1.18	4.8	2.850	-9.096
2	4.31	1.4	2.700	-8.627
3	3.83	1.6	2.230	-6.966
4	5.05	0.1	2.670	-8.530
5	4.37	0.5	2.500	-7.958
6	0.84	3.5	2.900	-9.247
7	1.56	2.5	2.275	-7.139
8	1.82	4.2	2.780	-8.880
9	4.32	2.1	3.200	-10.10
10	4.53	2.5	3.870	-11.75
11	0.64	4.3	2.560	-8.164
12	3.53	1.8	2.060	-6.27

13	3.75	1.3	2.300	-7.23
14	4.66	1	2.600	-8.29
15	5.82	1.8	3.900	-11.2
16	1.17	2.8	2.100	-6.44
17	0.63	5.3	3.700	-11.3
18	4.24	2.3	3.400	-10.6
19	6.16	0.1	2.800	-8.94
20	2.45	4.2	3.800	-11.5
21	3.66	0.9	2.100	-6.44
22	0.67	4.5	2.400	-7.60
23	2.17	3.4	2.600	-8.29
24	5.53	2	3.795	-11.5
25	5.85	1.4	3.495	-10.8

3.0 Result Discussion

3.1 **Effect of Process Parameters in Linear Dimension**

The main effects plot (Figure 3) for the process parameters (smaller is better) for dimensional accuracy of the printed specimens clearly illustrates that the selected process parameters have a significant effect on the dimensional accuracy of the printed specimens. The effect of layer thickness is also evident: thin layers (low value) give high S/N which means small dimensional error, good geometric resolution with less staircasing effect, while the thick layers (high value) give low S/N, which means that the dimensional error is increased, the geometric resolution is reduced and the staircasing effect is increased. Build orientation affects dimensional accuracy significantly and can be clearly seen in the S/N ratio. S/N ratios are high with some orientations, but very low with poor orientations, which is believed to be due to anisotropic shrinkage, layer-by-layer error accumulation and non-uniform cooling. Printing speed has a moderate impact, with the low to intermediate speed resulting in better dimensional accuracy because of stable material deposition and adequate interlayer bonding time, and high speed causes higher dimensional error caused by flow instability and temperature gradients. The air gap parameter is not linear and a smaller air gap or near zero air gap will lead to better bead overlap and reduce voids which will decrease dimensional error; larger air gaps will increase dimensional error. Not surprisingly, nozzle temperature is one of the most significant parameters, with an optimum found that maximises the S/N ratio – temperatures lower than this will result in insufficient melting and poor flow, whereas temperatures higher will result in over-extrusion and thermal shrinkage, both of which will increase the percentage error. Figure 3 is a table of the response of Signal to Noise Ratio. The ANOVA analysis for the dimensional analysis is given in Table 4.

Table 3Response or Signal to Noise Ratios

Level	Layer Thickness	Orientation	Printing speed	Air gap	Nozzle Temperature
1	-3.711	-4.391	-5.714	-5.687	-7.835
2	-6.188	-4.395	-3.771	-4.214	-4.504
3	-4.590	-3.083	-6.218	-6.246	-1.951
4	-5.339	-4.795	-4.713	-4.148	-6.807
5	-5.100	-8.262	-4.511	-4.633	-3.831
Delta	2.477	5.179	2.447	2.097	5.884
Rank	3	2	4	5	1

Table 4 Analysis of Variance of percentage error in linear dimension

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	5	6.2877	1.2575	9.28	0.000
Layer Thickness	1	0.2672	0.2672	1.97	0.176
Orientation	1	2.8992	2.8992	21.39	0.000
Printing speed	1	0.3934	0.3934	2.90	0.105
Air gap	1	0.2258	0.2258	1.67	0.212
Nozzle Temperature	1	2.5021	2.5021	18.46	0.000
Error	19	2.5753	0.1355		
Total	24	8.8630			

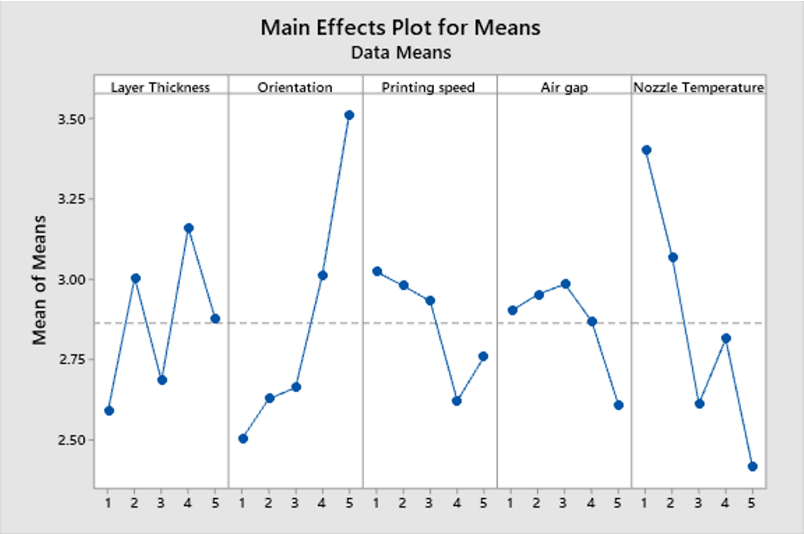

Fig. 3Main effect plot of Percentage error in linear dimension

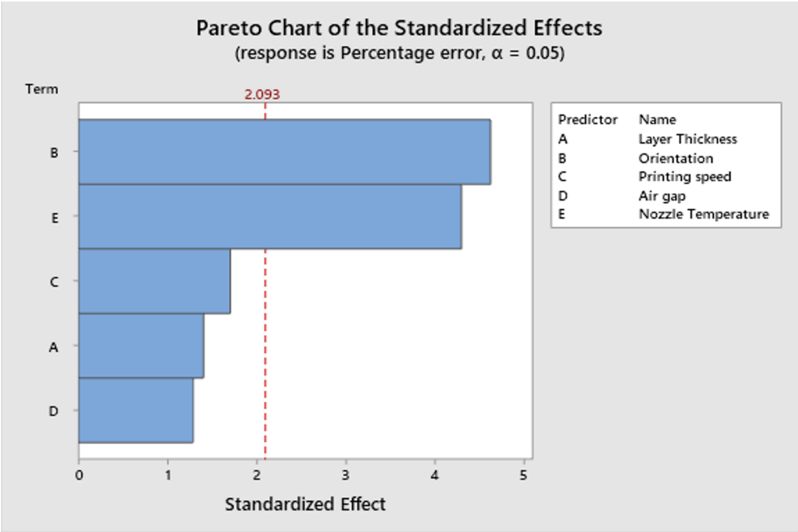

Fig. 4 Pareto Chart of the effect of process parameters

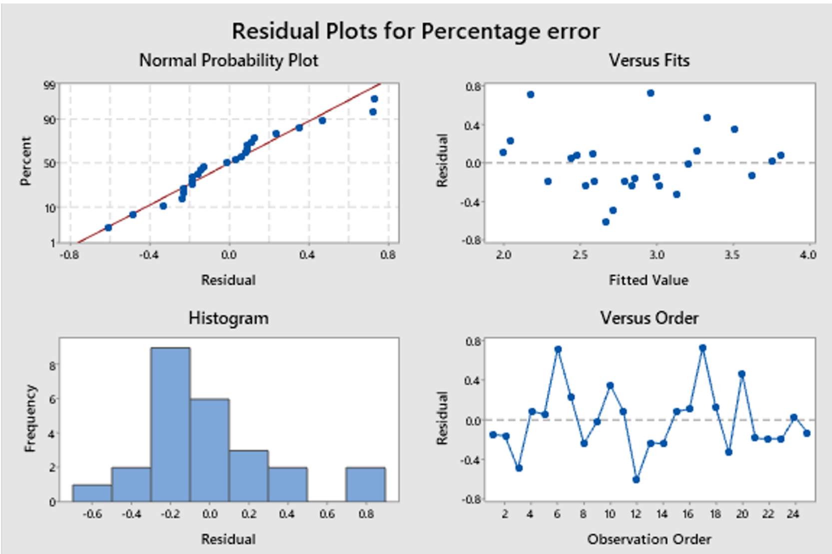

Fig. 5 Residual plot for percentage error in linear dimension

The Pareto chart of standardized effects in average percentage error at significance level $\alpha = 0.05$ (Fig. 4) clearly shows the influence of the process parameters on the dimensional accuracy. Build orientation (B) has the largest standardized effect and only exceeds the reference line (2.093), suggesting it is statistically significant and has the most influence on percentage error. This shows that part orientation is one of the most important factors that affects dimensional deviations, which are mostly associated with anisotropic material properties, cumulative layer-wise deviations, and the non-uniform thermal shrinkage in the printing process. The second most significant effect, but less dominant than the other two effects, is nozzle temperature (E), related with the melt flow behavior, the quality of the interlayer fusion and thermal contraction. The thickness of the layers (A) as well as the air gap (D) have moderate influences on dimensional accuracy, which is related to the control over the bead geometry, layer resolution and internal void formation. For printing speed (C), the lowest standardized effect was observed, suggesting that this parameter has a relatively small effect on the percentage error in the range of parameters studied. The residual plots for average percentage error show that the statistical model developed is adequate and reliable. Normal probability plot of residuals has a straight line fit suggesting that the error terms are normally distributed and there are no obvious outliers. The histogram of the residuals also supports this point as it has a near-symmetric distribution about zero, indicating that there is no skewness and supporting the normality assumption. The plot of residuals against fitted values (Figure 5) exhibits no pattern or funnel-shaped distribution around the line of zero or no error, thus confirming the homoscedasticity of the data and demonstrating that the model fits the data well. Furthermore, there is no systematic trend or cyclic pattern in the plot of the residuals against the order of the observations, suggesting that there were no time- or sequence-related disturbances in the experimental runs and that the residuals are independent.

3.2 Analysis of IT grade

The width dimension is mainly in IT7–IT9 as suggested in the IT grade analysis (Table 5), which suggests the dimension has relatively higher dimensional variability. This is predominantly due to effects of lateral flow, raster overlap and thermal expansion that occur during the deposition that significantly affect the width accuracy. The thickness dimension, on the other hand, has better dimensional control and most of the specimens have IT7–IT8 grades. Layer height and stacking sequence are more stable and repeatable and more important for thickness than lateral deposition. Overall, the results validate that width is more sensitive to variations due to process, while thickness exhibits better dimensional consistency, as would normally be expected in additive manufacturing.

Run	CAD breadth	Actual breadth	CAD thickness	Actual Thickness	IT Grades (Breadth)	IT Grades (Thickness)
1	12.7	12.88	10	10.48	IT8	IT8
2	12.7	12.85	10	10.14	IT8	IT7

3	12.7	12.97	10	10.16	IT8	IT8
4	12.7	13.45	10	10.01	IT9	IT6
5	12.7	13.34	10	10.05	IT9	IT7
6	12.7	12.86	10	10.58	IT8	IT8
7	12.7	12.96	10	10.25	IT8	IT8
8	12.7	12.81	10	10.42	IT7	IT8
9	12.7	13.22	10	10.21	IT9	IT8
10	12.7	13.36	10	10.25	IT9	IT8
11	12.7	12.77	10	10.55	IT7	IT8
12	12.7	12.93	10	10.18	IT8	IT8
13	12.7	12.98	10	10.13	IT8	IT7
14	12.7	13.12	10	10.1	IT8	IT7
15	12.7	13.62	10	10.18	IT9	IT7
16	12.7	12.76	10	10.4	IT7	IT8
17	12.7	13.24	10	10.53	IT9	IT8
18	12.7	12.95	10	10.23	IT8	IT8
19	12.7	13.05	10	10.01	IT8	IT6
20	12.7	13.43	10	10.42	IT9	IT8
21	12.7	12.87	10	10.09	IT8	IT7
22	12.7	13.02	10	10.45	IT8	IT8
23	12.7	12.81	10	10.34	IT7	IT8
24	12.7	13.41	10	10.2	IT9	IT7
25	12.7	13.41	10	10.14	IT9	IT7

Table 5 IT grade for the printed samples corresponding to experimental run

4.0 Conclusion

The present study demonstrates that dimensional accuracy in FDM is highly anisotropic and strongly dependent on process parameters. The length dimension along the printing direction exhibited minimal percentage error (<1%), while width and thickness showed comparatively higher deviations. Taguchi-based analysis confirmed that build orientation is the most significant parameter affecting dimensional accuracy, followed by nozzle temperature and layer thickness, whereas printing speed has a relatively minor effect. The statistical model was validated through residual diagnostics, and an optimal parameter combination was successfully determined to minimize percentage error. The improvement in dimensional tolerance, as reflected by the IT grade, highlights the effectiveness of the proposed optimization approach. These findings provide practical guidance for improving dimensional accuracy in FDM-fabricated components.

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