Dimensional Accuracy of 3D Printed Dog-bone Tensile Samples: A Case Study

Dragos Gabriel Zisopol
Mechanical Engineering Department, Petroleum-Gas University Ploiesti, Romania
zisopol@zisopol.ro

Alexandra Ileana Portoaca
Mechanical Engineering Department, Petroleum-Gas University Ploiesti, Romania
alexandra.portoaca@upg-ploiesti.ro (corresponding author)

Maria Tanase
Mechanical Engineering Department, Petroleum-Gas University Ploiesti, Romania
maria.tanase@upg-ploiesti.ro

Received: 23 May 2023 | Revised: 11 June 2023 | Accepted: 26 June 2023

ABSTRACT

Three-dimensional (3D) printing technology has revolutionized manufacturing by enabling the rapid production of complex objects. However, ensuring dimensional accuracy in 3D printed parts remains a significant challenge due to various factors, including the selection of appropriate parameters during the Fused Deposition Modeling (FDM) process. Achieving dimensional accuracy is crucial in determining the reliability of a printing machine to produce objects that meet the expected results. This study aims to investigate the influence of FDM parameters (filling percentage and layer thickness) on the final dimensions of 3D printed parts made from polylactic acid (PLA) through a systematic experimental and statistical approach. The goal is to identify the optimal process parameter settings that minimize the error percentage in the dimensions of the printed parts using the Taguchi method. Overall higher dimensional accuracy was obtained, influenced mainly by the layer thickness parameter (in the case of Y direction dimensions) and by the filling percentage (in the case of Z direction dimensions – corresponding to sample thickness). The findings of this study provide valuable insight into identifying the optimal configuration for producing PLA 3D-printed components.

Keywords-3D printing; FDM; PLA; dimensional accuracy; printing process parameters

I. INTRODUCTION

3D printing is a modern technology that offers numerous possibilities for creating complex-shaped objects by utilizing a Computer-Aided Design (CAD) model [1, 2]. This technology has already had a significant impact across various industries [3-13]. One of the commonly used additive manufacturing techniques is Fused Deposition Modeling (FDM), which involves depositing thermoplastic filaments layer by layer through extrusion. FDM has gained immense popularity as a manufacturing technology primarily because of its affordability, versatility in material selection, and the ability to customize printed parts. However, the FDM has certain limitations such as printing time and surface quality that can be adjusted based on the specific requirements of the intended application through process parameters such as layer height, infill percentage, printing speed, etc. ABS, PLA, PETG, and PC are among the most popular thermoplastic materials used in FDM [14]. The mechanical properties of FDM-printed components are greatly influenced by the design and processing conditions of the printing process [3, 14-19]. While extensive research has been conducted on the impact of the process parameters on the mechanical properties of printed parts [3, 14-16, 18, 21-30], only limited studies [1, 13, 15, 17, 31-38] have focused on the dimensional accuracy of 3D printing and its relationship with the process settings.

Authors in [1, 27, 32] showed that the layer thickness has the most significant influence on the dimensional characteristics of 3D printed parts. The main objective of [36] was to identify the 3D printing technology that results in the highest level of accuracy among three different methods. The geometric analysis showed that for simple shapes, the FDM and SLS technology had much lower accuracy than the MJ technology (PolyJet method).

Authors in [13, 16, 26, 28] investigated the influence of parameters such as filling percentage, layer thickness, printing direction, on the dimensional accuracy of 3D printed spur gears made of different materials (PLA, nylon, ABS, PETG). Authors in [17] compared the dimensional accuracy of spur gears produced using Fused Filament Fabrication (FFF) technology with two different polymeric materials, PLA and nylon-PA6. The findings indicate that the PLA exhibits better overall dimensional accuracy. Furthermore, the gears printed with nylon, which had a lower infill ratio compared to PLA, showed less form errors. Very important findings are highlighted in [14], in which a statistical calculation is used to establish the influence of FDM parameters (height of the deposited layer at one pass and filling percentage) on the dimensions of the shaft diameter and the bore diameter of cylindrical spur gears made of PLA, revealing that the filling percentage has a greater influence on the dimensional accuracy of cylindrical spur gears made of PLA.

In the this article a novel approach was used by examining the impact of FDM parameters (layer thickness and filling percentage) on the dimensional accuracy of dog-bone tensile test pieces manufactured from PLA. Consequently, the obtained dimensional measurements for the test pieces (thickness and width) were compared against their respective nominal values to determine the accuracy percentage. The results of the current work have a significant contribution in the identification and quantification of the predominant influence between the two parameters under investigation, through rigorous measurements and statistical analysis.

II. MATERIALS AND METHODS

The present study was performed using the working methodology shown in Figure 1.

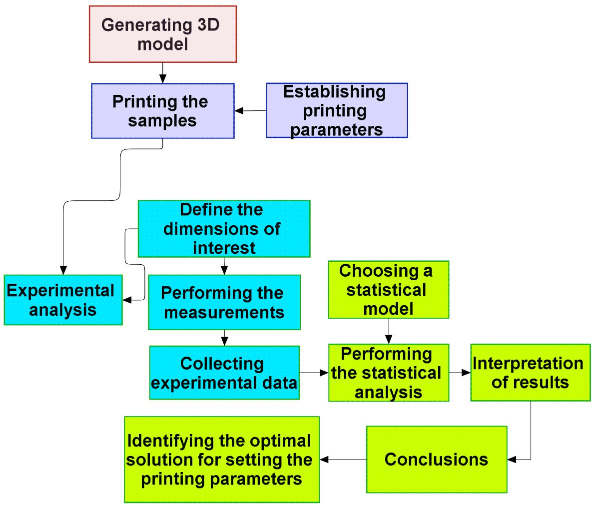

Fig. 1. Working methodology.

A. *Sample Preparation*

For the experimental study, a total of 40 samples (fabricated with PLA) were printed, consisting of 5 samples for each combination of 2 different layer thicknesses (0.10 mm and 0.20 mm) and 4 filling percentages (25%, 50%, 75% and 100%). The shape and dimensions of the samples are shown in Figure 2.

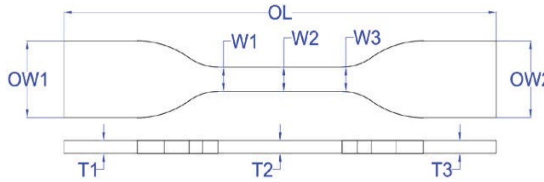

Fig. 2. Tensile test specimen - dimesional details.

A Raise E2 3D printer was used, which has a volume capacity of 330×240×240 mm. The printing parameters are presented in Table I.

TABLE I. 3D PRINTING PARAMETERS

Constant parameters	**Variable parameters**
Build orientation: X-Y	Layer thickness: L_t = 0.10 and 0.20 mm
Print speed: 80 mm/s	Filling percentage: F_p = 25%, 50%, 75%, 100%
Deposition temperature: 200 °C	
Infill model: lines, 45°orientated	

The indicated dimensions from Figure 2 were measured for all samples. The width and thickness were measured at both ends of the section (OW1, OW2, respectively T1 and T3) as well as the middle (W1, W2, W3, respectively T2). Since the most important part for the dog-bone tensile test specimen is the gauge section, three measurements were made in this area, for each specimen.

B. *Statistical Analysis of the Measured Data*

In order to establish the influence of printing parameters on the dimensional accuracy of the printed samples, statistical calculations were performed, determining (for each dimension presented in Figure 1) the arithmetic mean $\bar{x}$, standard deviation σ, and dispersion σ^2 [39, 40]:

$$\bar{x} = \frac{x_1 + x_2 + \ldots + x_n}{n} \quad (1)$$

$$\sigma = \sqrt{\frac{\sum(x_i - \bar{x})^2}{n}} \quad (2)$$

$$\sigma^2 = \frac{1}{n}\sum(x_i - \bar{x})^2 \quad (3)$$

The results were analyzed with the Minitab software, in order to identify the importance of the printing parameters and their influence on the dimensional accuracy of the 3D PLA printed samples. The considered factors were the filling percentage and the layer thickness and the standard deviation of the results was considered. Interpreting the standard deviation for dimensional accuracy involves understanding that a higher standard deviation indicates greater variability or inconsistency in the measurements. This means that the printed objects may have more significant deviations from the desired dimensions, with some measurements being larger and others smaller than the target value. On the other hand, lower standard deviation suggests that the measurements are closer to the desired dimensions, indicating a higher level of accuracy and consistency in the printing process. Therefore, when assessing dimensional accuracy, a smaller standard deviation is desirable as it reflects a more precise and reliable printing process with minimal variations in the printed objects dimensions. So, the quality characteristic "smaller is better" was taken into account for the analysis of the signal-to-noise (S/N) ratio and the optimum level of the two investigated factors was selected based on the S/N ratio plots.

III. RESULTS AND DISCUSSION

The dispersion values for the measured dimensions indicated in Figure 2, for the printing parameters investigated, are presented in Figures 3-6.

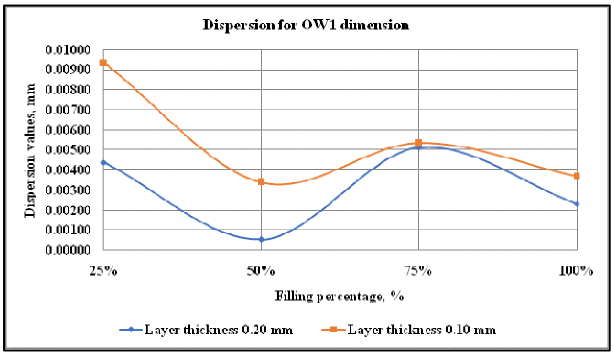

Fig. 3. The dispersion values for OW1 dimension.

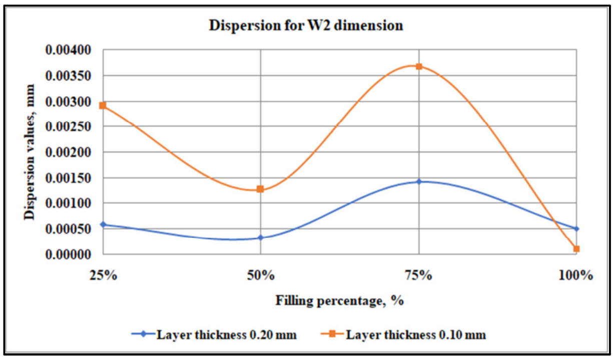

Fig. 4. The dispersion values for W2 dimension.

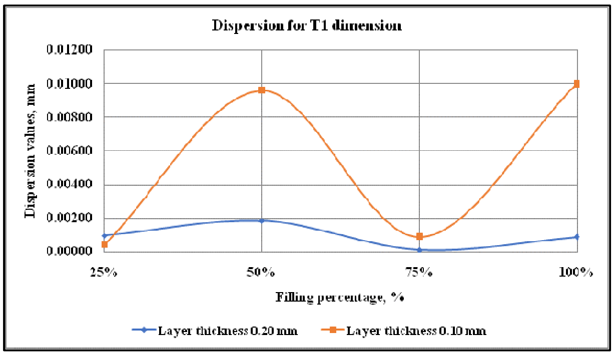

Fig. 5. The dispersion values for T1 dimension.

For exemplification, in the case of dimensions W2 and T2, Figures 7 and 8 were used to select the best values of process parameters. The plot displays the average values of a response variable for different factor levels. Interpreting the main effect plot for "smaller is better" means supposes focusing on minimizing the response variable. The plot helps identifying which factor levels or combinations of levels result in smaller values of the response variable. The optimum combination of printing parameters is filling percentage 100% and layer thickness 0.2 mm (for the W2 dimension) and filling percentage 75% and layer thickness 0.1 mm (for the T2 dimension).

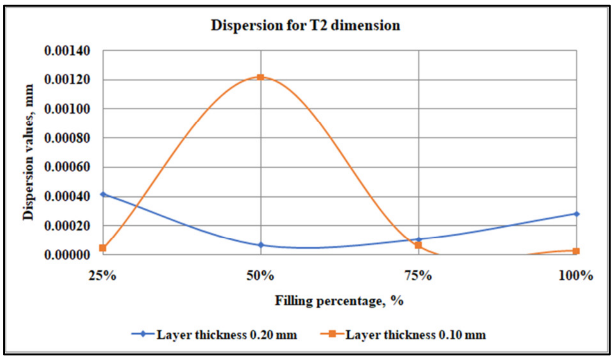

Fig. 6. The dispersion values for T2 dimension.

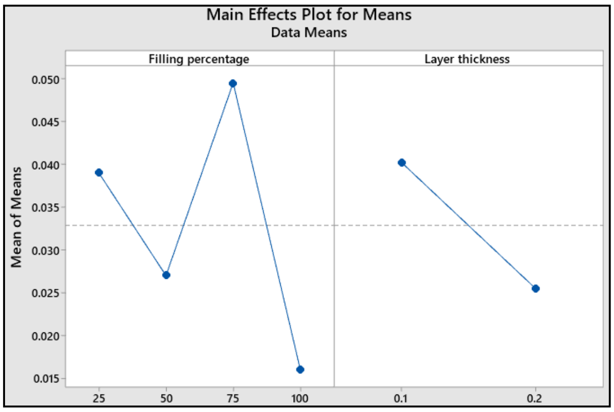

Fig. 7. Main effect plot for W2 dimension.

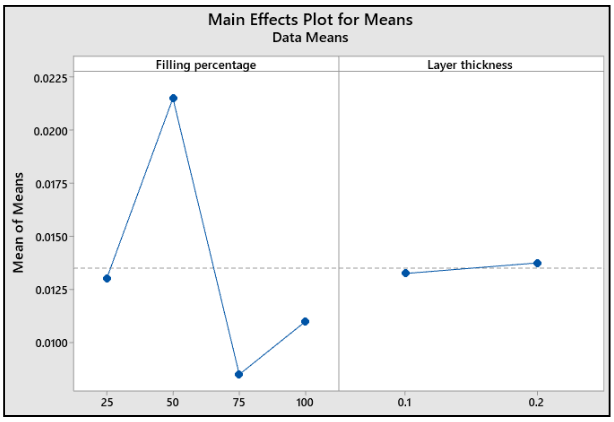

Fig. 8. Main effect plot for T2 dimension.

In order to identify the most significant factors that lead to smaller standard deviation, the Pareto chart (Figures 9 and 10) can be used. Therefore, in the case of the W2 dimension (Y direction) the term influencing significant the dimensional accuracy is layer thickness, while in the case of the T2 dimension (Z direction) the most significant factor is filling percentage. The same problem was investigated in [14], but on PLA spur gears. It was observed that filling percentage has a greater influence on the dimensional accuracy of 3D printed parts.

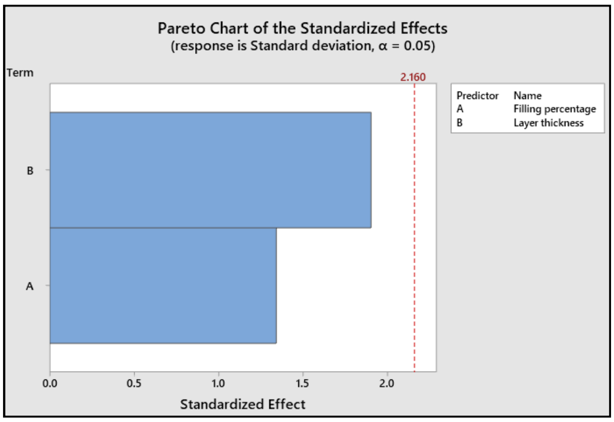

Fig. 9. Pareto chart for the W2 dimension.

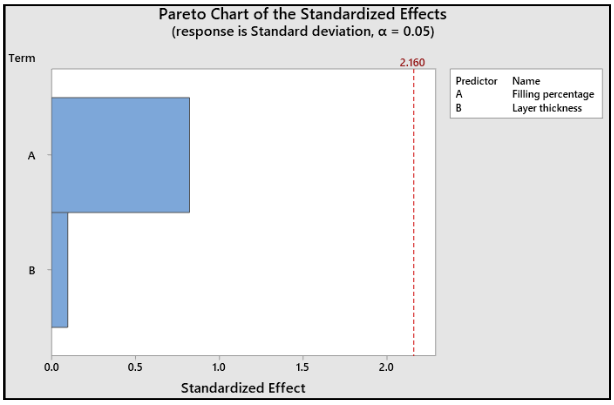

Fig. 10. Pareto chart for the T2 dimension.

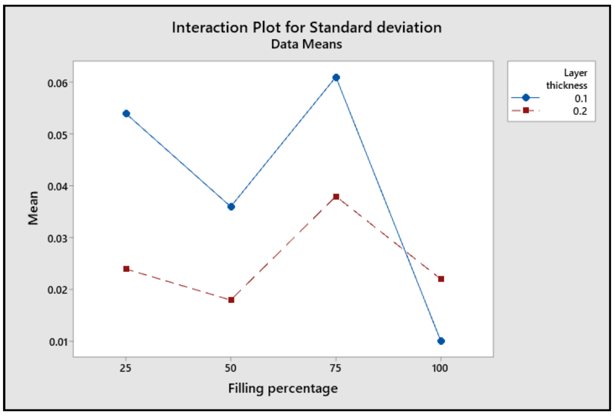

Fig. 11. Interaction plot between data means (W2 dimension).

The interaction plots in Figures 11 and 12 reveal that the target dimensions values are obtained with 0.2 mm layer thickness, excepting at 100% filling percentage (in the case of the W2 dimension) and 0.1 mm layer thickness in most cases (in the case of the T2 dimension). In both cases, if 50% infill percentage is applied, then larger layer thickness is recommended in order to obtain smaller dimensional errors. In order to quantify the level of accuracy achieved for each measured dimension, the average percentage deviation was calculated and is graphically represented in Figure 13.

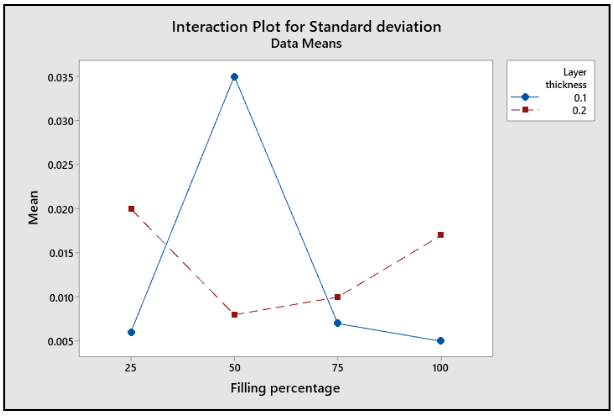

Fig. 12. Interaction plot between data means (W2 dimension).

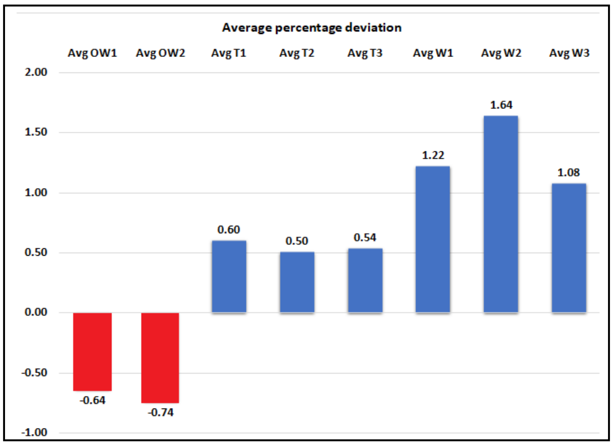

Fig. 13. Average percentage deviation.

In Figure 13, a reasonably accurate printing process can be highlighted, as the deviation is relatively small (on average, the measured dimensions of the 3D printed parts deviate by approximately 1.64% from the expected dimensions). The biggest values of the average percentage deviation were obtained for the W1, W2 and W3 dimensions (Y direction) and the smallest for the T1, T2 and T3 (Z direction), suggesting a directional influence on the accuracy of the printed parts (the printing process is more prone to dimensional variations in the Y direction compared to the Z direction). Also, it can be seen that the average deviation percentage values are positive (the real measured values are bigger than the nominal values) for all the analyzed dimensions, except OW1 and OW2 dimensions (representing the width of the external area of the samples) which recorded negative values. The results are in accordance with the findings in [1], where the accuracy of dog-bone test specimens ranged between 97% and 99% and in [37] where the dimensional error values ranged from 0.82% to 2.60%. Another important aspect is that, overall, the dispersion values were smaller for 0.20 mm than for 0.10 mm layer thickness, indicating 0.20 mm for less variability and higher accuracy. These results confirm the statement from [1] that as the number of layers increases (the thickness of the layer decreases), the dimensional accuracy of the 3D printed part tends to decrease. The same conclusion was mentioned in [37], where cubic parts were 3D-printed using PLA and FDM, observing that layer height of 0.25 mm resulted in lower dimensional errors compared to 0.05 mm layer height.

IV. CONCLUSIONS

In this paper, theoretical-experimental analysis was conducted in order to evaluate the influence of the printing parameters layer thickness and filling percentage on the dimensional accuracy of 3D-printed PLA dog-bone tensile samples, while the results were compared with those of other similar studies. The positive average percentage deviations for most dimensions indicate that, on average, the measured dimensions of the 3D printed parts are larger than the expected or intended dimensions. The highest accuracy was obtained for thickness dimensions T1, T2, T3. A remarkable influence was noticed for the layer thickness parameter on the accuracy of dimensional characteristics, observing that is better to increase the layer thickness. Adjusting the layer thickness can improve the dimensional accuracy in the Y direction, while varying the filling percentage can have a notable effect on the dimensional accuracy in the Z direction. By focusing on optimizing these factors, it is possible to reduce the variability and achieve smaller standard deviations, thereby enhancing the overall dimensional accuracy of the PLA 3D-printed parts.

The findings from this study have broad implications for the additive manufacturing industry, in which dimensional accuracy plays a vital role in determining the functional performance and reliability of printed components. By understanding the influence of FDM parameters on part dimensions, manufacturers can optimize their printing processes, minimize post-processing requirements, and enhance the overall product quality.

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