

DIMENSIONAL ANALYSIS OF PLA AND PETG PARTS BUILT BY OPEN SOURCE EXTRUSION-BASED 3D PRINTING

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Abstract. *Widespread open source initiatives within the context of extrusion-based 3D printing have made this technology accessible to all levels of users. However, aspects such as low dimensional quality of the parts produced, or difficulty in interaction with the process parameters and the printing materials affect the satisfaction of the consumers of these systems. In this sense, the goal of this article was to contribute to the acknowledgement of the 3D printing system, and thus to the relation user-machine, through the analysis of the influence of material types — Polylactic Acid (PLA) and Poly(ethylene terephthalate glycol) (PETG) — and process variables (deposition strategies and number of perimeters), confronted in Taguchi's experimental design, varying the internal and external dimensions of the printed parts. Additionally, the masses of the built samples were measured, and the materials were characterized by a melt flow index (MFI) test. The results demonstrated that the dimensions of the manufactured components were strongly influenced by the type of material used due to the greater variations in the filament diameter (before being processed) when compared to the nominal value and the high fluidity of the polymer, and by the deposition strategies. PETG stands out as a material with good printing capability, with better dimensional quality along all the parts' directions, making it suitable for applications that require greater conformity in measurements.*

Keywords: 3D Printing, Extrusion, Open Source, PLA, PETG.

1. INTRODUCTION

Extrusion-based 3D printing technologies are currently the most widely used in the market. The simplicity of these techniques, coupled with factors such as the expiration of some of the FDM (Fusion Deposition Modeling) process patents and the development of the "maker movements", allowed the recent growth in the use of open source machines, especially in non-professional applications (Gibson *et al.*, 2015; Volpato *et al.*, 2017; Minetola and Galati, 2018; Ramli *et al.*, 2018). However, the dimensional accuracy and the final quality of the products built by these systems often disappoint, particularly users without engineering knowledge (Ramli *et al.*, 2018).

The dimensional accuracy and the resolution of the final products built by extrusion-based 3D printing depend on the process parameters and on the properties of the building material (Turner and Gold, 2015). Variables as extrusion temperature, layer thickness and width, printing speed, material flow, raster angle, among others, influence the dimensions of printed parts (Lanzotti *et al.*, 2015; Equbal *et al.*, 2017; Polak *et al.*, 2017). Geometric properties of the components are also affected by the rheological characteristics and the shrinkage of the materials (Bähr and Westkämper, 2018). According to Valerga *et al.* (2018), a higher fluidity of the material at high temperatures causes the printed elements to increase their size along the XY axes and decrease in Z. The authors further emphasize that effects such as bubble formation during extrusion influence the measurements of the manufactured components.

Ramli *et al.* (2018) draw attention to the fact that many users are not familiar with process parameters and printing materials, which may limit their control of the equipment. In this sense, this article aims to contribute to the acknowledgement of the 3D printing system, and thus to the relation user-machine. It is presented a complementary and deepened study of a previous paper (Santana *et al.*, 2017) that aimed at developing a parametric calibration methodology based on the analysis of factors such as: slicing software, layer thickness, printing speeds, infill density, temperature, and extrusion multiplier. In addition to evaluating new parameters, the current step investigated the impact of different materials on the dimensions of geometries with different directional characteristics.

2. MATERIALS AND METHODS

The behavior of the internal and external dimensions of extrusion-based 3D printed parts was evaluated varying three factors: deposition strategy (D_s), number of perimeters (P_n) — Fig.1 (a) — and type of material (M_t). Regarding the building parameters D_s and P_n , the first one corresponds to the infill pattern applied to the material deposition within the layers delimited by the perimeters. The patterns most used are the raster, and the concentric types, or the combination of these two (Volpato *et al.*, 2017). The second parameter mentioned, number of perimeters, is equivalent to the number of continuous lines placed side by side in a layer (Ćwikła *et al.*, 2017).

For each factor three levels were established, and the experimental conditions were determined through a Taguchi L9 orthogonal array (Tab.1). Other process parameters were kept constant, based on the best settings found previously (Santana *et al.*, 2017). Three parts were individually made by combining different factors and levels in a *Prusa Hephestos I3* 3D printer, generating a total of 27 samples. The planning of the printing process was performed with *Slic3r* software (version 1.2.9). A parallelepiped geometry was used as standard for the analysis, Fig.1 (b). Regarding the choice of materials — type of material (M_t) —, two filaments of Polylactic Acid (PLA) — a natural (transparent) one from the *BQ* supplier, "PLA n", and a pigmented (blue) one, "PLA b" from the *3D INK* manufacturer —, and one of Poly (ethylene terephthalate glycol) (transparent) (PETG) supplied by *RepRap.pt*, all with a theoretical diameter of 1.75 mm, were used.

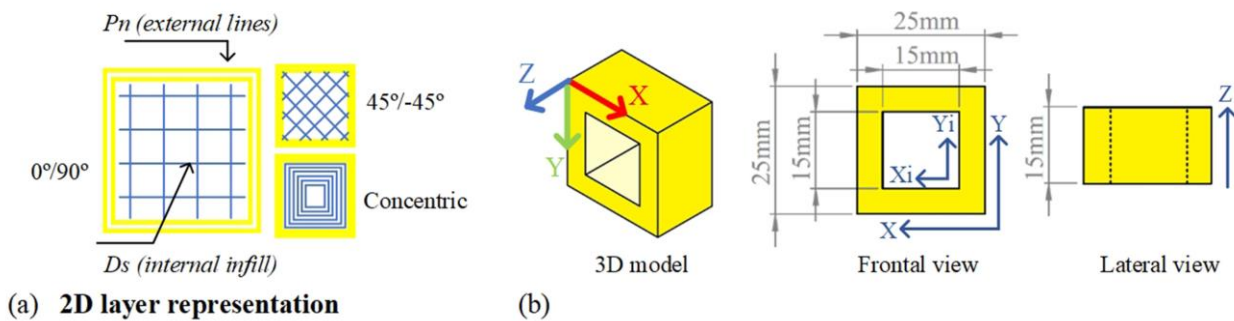


Figure 1. Process parameters representation (a) and (b) geometry proposed for the dimensional analysis study.

In each of the main directions of the geometry, X and Y (internal and external), and Z, three measurements were taken by using internal and external micrometers (with resolutions of 0.025 mm and 0.0025 mm, respectively). The mass of the samples was also measured (weighing scale, $d = 0.005g$). The materials used in the work were characterized by a melt flow index (MFI) test (*MFI Daventest* equipment), applying a load of 2.16kg, cut time of 10s, and temperatures of 210°C for PLAs, and 235°C for PETG; these temperatures are the same as those used in the 3D printing manufacturing of the samples. Finally, the variation of the filament diameter was also verified before being processed. Five measurements were made along 200 mm of material, using the same external micrometer previously mentioned.

3. RESULTS AND DISCUSSIONS

Table 1 shows the average values of the dimensions by direction and experimental condition.

Table 1. Experimental design (Taguchi L9) and dimensional analysis results.

| Conditions | Parameters | | | Dimensions (mm) | | | | |
|------------|-------------------|----------|--------------|--------------------|--------------------|--------------------|--------------------|--------------------|
| | D_s | P_n | M_t | X | Y | Z | X_i | Y_i |
| 1 | 0°/90° | 1 | PLA b | 24.75 ±0.01 | 24.76 ±0.01 | 15.01 ±0.01 | 15.07 ±0.00 | 15.04 ±0.02 |
| 2 | 0°/90° | 2 | PLA n | 25.24 ±0.02 | 25.28 ±0.02 | 15.22 ±0.03 | 14.64 ±0.02 | 14.58 ±0.08 |
| 3 | 0°/90° | 3 | PETG | 24.81 ±0.01 | 24.90 ±0.01 | 14.89 ±0.03 | 14.97 ±0.00 | 14.93 ±0.00 |
| 4 | 45°/-45° | 1 | PLA n | 25.49 ±0.02 | 25.65 ±0.04 | 15.53 ±0.03 | 14.28 ±0.00 | 14.19 ±0.06 |
| 5 | 45°/-45° | 2 | PETG | 24.79 ±0.02 | 24.86 ±0.00 | 14.84 ±0.02 | 14.95 ±0.02 | 14.94 ±0.02 |
| 6 | 45°/-45° | 3 | PLA b | 24.89 ±0.02 | 24.99 ±0.01 | 15.33 ±0.02 | 14.82 ±0.01 | 14.73 ±0.00 |
| 7 | Concentric | 1 | PETG | 24.69 ±0.02 | 24.66 ±0.03 | 14.67 ±0.02 | 15.08 ±0.01 | 15.04 ±0.01 |
| 8 | Concentric | 2 | PLA b | 24.83 ±0.02 | 24.86 ±0.00 | 15.11 ±0.01 | 14.99 ±0.03 | 14.95 ±0.03 |
| 9 | Concentric | 3 | PLA n | 25.05 ±0.05 | 25.09 ±0.03 | 14.92 ±0.03 | 14.70 ±0.05 | 14.66 ±0.06 |

Note: deposition strategies for conditions 1 to 6 are the raster type, varying the raster angle in 0°/90° and 45°/-45°.

The results were evaluated by the analysis of variance method (ANOVA, $\alpha = 95\%$), which aimed at identifying the significant factors for the variation of the internal and external dimensions of the parts. The ANOVA method allowed us to verify that the type of material was the factor with the highest contribution percentage for changes in X dimensions (77.6%, $P = 0.00$), X_i (71.4%, $P = 0.00$), Y (67.8%, $P = 0.00$), Y_i (68.4%, $P = 0.00$), and Z (51.6%, $P = 0.00$), followed by the deposition strategy parameter with percentages of 10.3% ($P = 0.00$), 18.4% ($P = 0.00$), 17.3% ($P = 0.00$), 18.7% ($P = 0.00$), and 27.4% ($P = 0.00$). The number of perimeters, in all cases, did not present statistical significance. The average of the dimensions, by factors and levels, with the respective standard errors (SE), are depicted in the graphs of Fig. 2 (a) and (b).

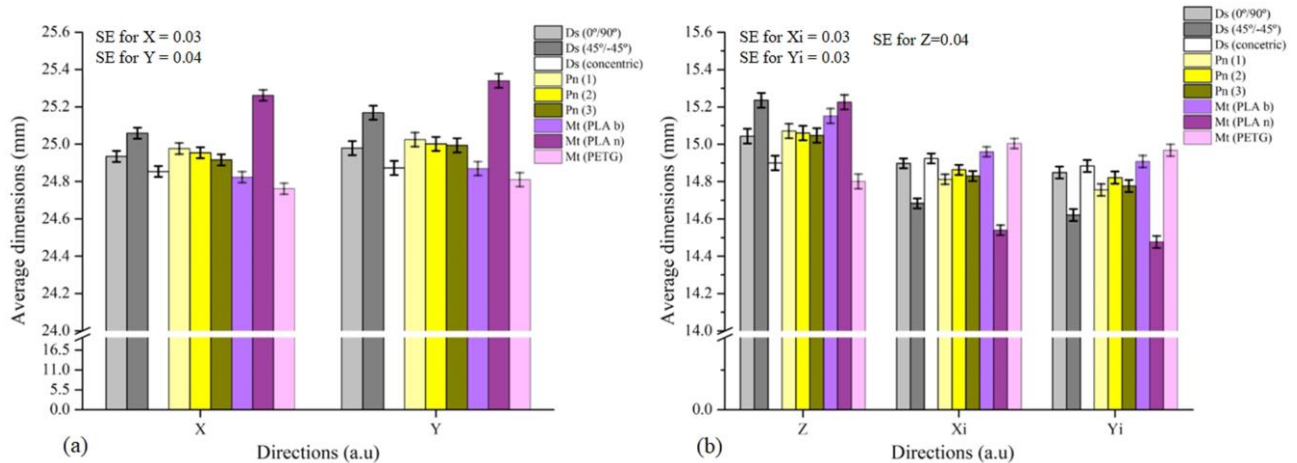


Figure 2. Average dimensional values per factors and levels, (a) 25 mm and (b) 15 mm dimensions.

The natural PLA, in most cases, was responsible for the larger dispersions in the dimensions around the nominal value. This effect may be related to the fluidity characteristics of the material, which has a higher MFI — (22.24 ± 2.22) g / 10min — approximately 49% and 51% higher than the PLA (blue) — (14.95 ± 0.55) g / 10min — and PETG — (14.70 ± 1.29) g / 10min —, respectively. The higher fluidity of the "PLA n" is interesting for the polymer extrusion process. However, dimensional results indicate that flow can remain high while the deposited filaments are accommodated within and between the layers. A longer stabilization time, to increase the material viscosity and to guarantee self-support of the deposited structures, causes the inner layers filaments to keep deforming over time, due to the pressures generated by the nozzle and the neighboring filaments themselves, thus generating dimensional distortions in all directions of the parts.

In addition to the higher fluidity, the natural PLA filaments showed a significant variation in its diameter, around +0.03 mm, in relation to the theoretical (nominal) value of 1.75 mm. Since the theoretical value was maintained in the *Slic3r* configurations, the software did not compensate the amount of material to be deposited, with the parts having larger masses than the calculated, Fig. 3 (a). The fluidity of the polymer may have also contributed to the larger masses of the parts in "PLA n". The ease of being extruded, in addition to the effects described by Gibson *et al.* (2015), as the presence of internal pressures in the deposition system caused by the mass of softened material and gases, may have contributed to the excessive insertion of material into the layers. The excess of material, therefore, was responsible for the increase of external dimensions and internal reduction in most of the experimental conditions in which "PLA n" was present. Especially in parametric combination 4 (Tab.1), these effects are clearly observed on the surface of the parts, with wrinkled appearance, formation of drops of residual material and deformations on the edges of the samples, Fig. 3 (b). This situation was similar to the concepts described by Santana *et al.* (2017).

According to the Tukey test, the PETG and "PLA b" parts presented statistical equality in the X, X_i , Y and Y_i directions, differing only in Z-axis dimensions, in which PETG demonstrated the best results. This behavior of similarity between the materials is possibly related to their close MFI values, with a difference of only + 2% of the index of the blue PLA relatively to PETG. Given the exceptions, the parts manufactured with these materials were the ones that most approached the projected values for the samples, Tab.1. Following the previous reasoning, these better responses may be associated to the low fluidity of the materials, which contributes to a faster stabilization of the deposited elements, and to the smaller diameter of the filaments, 1.73 ± 0.00 mm for the "PLA b" and 1.69 ± 0.01 mm for PETG. These features, when associated with the best settings for the extrusion multiplier (Em) identified in a previous study (Santana *et al.*, 2017) ($Em = 0.9$), ensured that the manufactured parts did not present exaggerated masses when compared to the amount of material to be deposited, calculated by *Slic3r* — Fig.3 (a). The adjustment in the amount of material guarantees better results in the dimensional aspect, since the volume of matter deposited does not exceed the physical limits of the actual volume of the model to be manufactured.

Finally, in terms of deposition strategies, the worst results were obtained by using a $45^\circ / -45^\circ$ raster strategy. One of the causes for the larger variations in the dimensions of the printed parts with such strategy can be related with the complexity of the zig-zag and inclined trajectories, associated to the space and the freedom to accommodate the deposited filaments (reduced, since the samples edges had 5 mm dimensions and were built with 100% infill density), and the higher volume of material applied in the transition zones between two consecutive trajectories — as presented in previous studies (Santana *et al.*, 2017). The effects of the strategy are further aggravated when combined with critical levels of other parameters (Tab.1), as in the case of condition 4, related to "PLA n", generating considerable reductions in internal dimensions and increase in the Z axis, and in condition 6, in which there was accumulation of material in the central region of the structures, increasing the value of the Z dimension due to the reduction of accommodation spaces in the edges caused by the greater number of perimeters.

Infill patterns that alter layers with deposition of long vectors (raster $0^\circ / 90^\circ$), or that build parts by the successive reproduction of the main profile of the object (concentric) tend to improve the dimensional performance because they assist in the process of accommodating filaments using smooth movements. The results are improved when such strategies are combined with materials with better characteristics for the printing process, in this case PETG and blue PLA, as shown in conditions 3 and 8 of Tab.1.

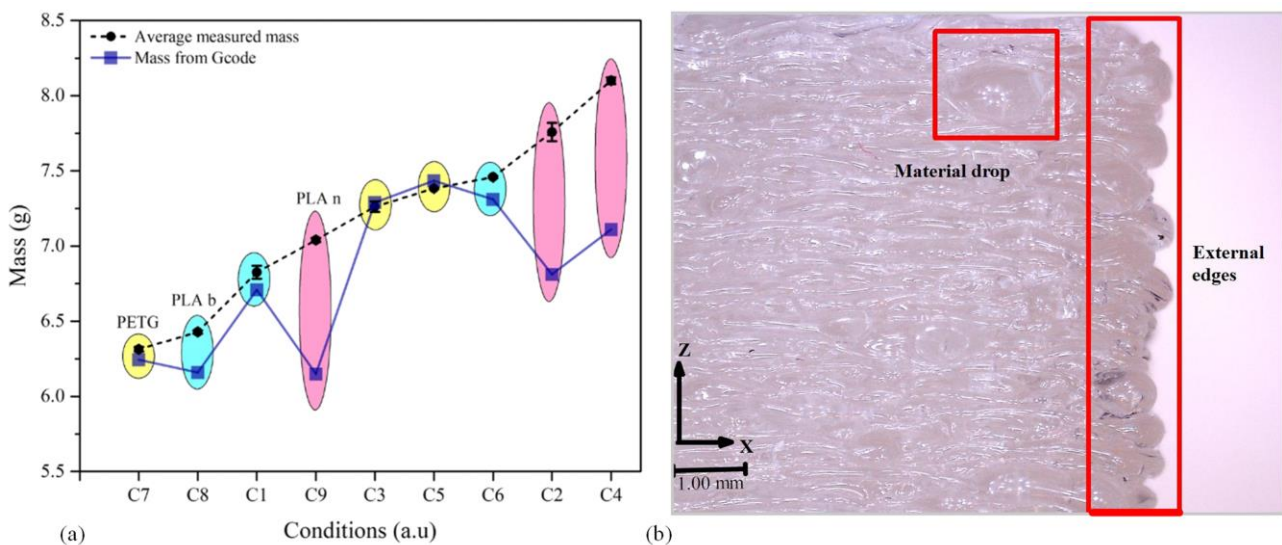


Figure 3. Average mass of samples versus calculated mass from the Gcode (a), and excess material “PLA n” (b).

4. CONCLUSION

The results of this study highlight the major statistical contribution of materials to dimensional variation in 3D printed parts. Authors understand this should alert users to the importance of recognizing the overall characteristics of materials before setting the printing parameters. Even theoretically identical materials, but only different in color and suppliers, as in the case of PLAs, can have significantly different dimensional responses. This is due to numerous factors that act directly on the behavior of the 3D printing process, such as variations in filament diameter and flow characteristics, which may be related to the chemical formulation of the polymeric filaments and thus to the different filaments' suppliers available.

Although not experimentally varying the extrusion temperature, this study corroborates the work of Valerga *et al.* (2018) when we consider the fluidity index analysis of different materials. As in the case investigated by Valerga *et al.* (2018), higher fluidity conditions generated greater dimensional deviations, which were also observed in the current research, both in external and internal directions. However, unlike the results obtained by Valerga *et al.* (2018), in this investigation, considering only the PLAs, the transparent version obtained worse dimensional results than the pigmented one. Nevertheless, the color effect may have been suppressed by the rheological characteristics of the materials. The choice of color did not make a difference when it came to different materials with close indexes of fluidity, such as blue PLA and PETG (transparent), which presented statistical equality in most dimensions.

This work agrees with the findings of the first study carried out by the authors (Santana *et al.*, 2017), since the excess of material, once again, was responsible for the greater dimensional variations of the printed parts. In addition to corroborating the previous findings, this study complements it, since it shows that the origin of the largest volumes of deposited material may not only be related to the calculations performed by the slicing software, but also by the inadequate adjustment by the user of the diameter of the filament, and by the viscous properties of the materials. Although in the previous study it was observed that the extrusion temperature did not influence the dimensional quality

of parts, the scenario then was centered on a single material. Now, by varying the polymers (even if considering the same synthetic materials, but with different colors and suppliers), users should be careful when adjusting the processing temperature to control the viscous behavior of the material. The "PLA n" parts can probably be improved by reducing the extrusion temperature, along with properly setting variables such as extrusion multiplier and filament diameter.

Finally, strategies that combine the use of right and shallow deposition angles improve the dimensional aspect, as they assist in the process of accommodating deposited filaments. A base configuration of parameters can be established, since the adjustments of the first study and the configurations found in this step showed similar results for "PLA b" and PETG. However, peculiarities of the materials must be considered in the calibration process. Considering the best results for PETG in the Z axis, this material proved to have good printing characteristics, which makes it a suitable option for applications that involve fine dimensional control, as elements for assembly.

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