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INFLUENCE OF NOZZLE TEMPERATURE ON DIMENSIONAL TOLERENCES OF SPECIMENS PRODUCED WITH MATERIAL EXTRUSION MANUFACTURING

José Guilherme de Freitas Peres
Lucas Resende Gomes
Alexandre Zuquete Guarato
Federal University of Uberlândia (UFU), BR 050 KM 78, Campus Glória, Uberlândia, MG
jose_dfreitas@ufu.br; lucas.resende@ufu.br; azguarato@ufu.br

Abstract. *Additive Manufacturing (AM) technology has some advantages when compared with the established manufacturing processes, such as the ability of manufacturing specimens with complex geometries, little waste of material, efficient use of energy and the capability of quickly obtaining low quantity of complex specimens. However, due to the high number of manufacturing parameters that affect dimensional and geometrical tolerances AM is still generally limited to prototype specimens. One of the most widespread AM process is the Material Extrusion (ME), which uses thermoplastic filaments. During Material Extrusion process, several printing parameters may affect the final quality of the specimen. This work aims to experimentally analyze the influence of the nozzle temperature on the dimensional tolerances of specimens produced through ME process. A simple specimen is designed with a commercial CAD software. The specimen has different topological geometries such as planes, cylinders, and holes. The manufacturing process is carried out using a GTMax3D CORE A3V2 printer and white ABS filament. The following nozzle temperatures are investigated: 210 °C, 230 °C and 250 °C. Dimensional measurements are carried out using micrometers under controlled environment. Results indicate that the nozzle temperature of 250 °C leads to better overall dimensions but 210 ºC nozzle temperature is required for better dimensional tolerances of the inner diameter of the specimen.*

Keywords: *Additive Manufacturing, Material Extrusion Process, Nozzle Temperature, Dimensional Tolerance, ABS.*

1. INTRODUCTION

Unlike conventional and widely used manufacturing processes such as turning, milling, grinding and electrical discharge machining (EDM) that removes material in order to manufacture a specimen, Additive Manufacturing (AM) technology is defined as the manufacturing process made by the successive addition of material in form of layers (Lieneke et at., 2016). AM has some advantages when compared with the established manufacturing processes, such as the ability of manufacturing specimens with complex geometries, little waste of material, efficient use of energy and the capability of quickly obtaining low quantity of complex specimens (Volpato et al., 2017).

To remain competitive in the market, industries are always looking for faster and cheaper alternatives (Sahu et al., 2014). Thus, AM has grown significantly on several industrial sectors such as mechanical, medical, architectural, fashion and art (Carneiro et al., 2019). Nevertheless, AM generally produces specimens with overall inferior properties in relation to identical specimens produced by traditional manufacturing methods. This is due to poor layers bonding, residual stress and shrinkage of the thermoplastic material (Sood et al., 2009; Volpato et al., 2017). Fundamental problems such as surface quality, material strength, precision and accuracy restrain the technology from having a wide implementation in the industry for end use specimens and therefore AM is still generally limited to prototype specimens (Ribeiro et al. 2019; Jerez-Mesa et al., 2017).

One of the most widespread AM process is Material Extrusion (ME). ME process consists in the deposition of a fused thermoplastic filament from an extruder nozzle with controlled movements in the three dimensions over a printing bed. The nozzle or the printing bed moves a height equivalent to the thickness of one layer in the direction of Z axis. After the deposition of several layers, the final specimen is built. During this process, several printing parameters may affect the final quality of the specimen such as nozzle temperature, printing bed temperature, speed of the printing head, etc. (Volpato et al., 2017).

To optimize the quality of specimens manufactured with ME process, the adjustment of manufacturing parameters can bring significant improvements in quality of the specimen without the need of additional expenses with software and hardware improvements (Sood et al., 2009). The literature presents several works on the improvement of mechanical properties through adjustments in manufacturing parameters. Ribeiro et al. (2019) investigated the influence of the nozzle temperature on mechanical properties using tensile test on specimens made of PETG XT and they observed that higher temperatures result in higher Young's Modulus.

Carneiro et al. (2019) studied the influence of printing bed temperature on the hardness and overall dimensions of ABS samples. The study shows that printing bed temperature has little influence on hardness but had significant influence on macro overall dimensions.

Jerez-Mesa et al. (2017) used Taguchi's Design of Experiments to analyze the effect of printing parameters such as diameter of the extruder nozzle, layer thickness, infill density and printing speed on fatigue strength. Specimens were manufactured in PLA and it was found that printing speed has no significant influence fatigue. Authors suggest the following settings to optimize fatigue lifespan: 75% infill percentage, 0.5 mm extrusion nozzle diameter and 0.3 mm layer thickness.

There are still scarce works in the literature that focus on evaluating the dimension and geometric tolerances of specimens made with ME process. Vishwas et al. (2018) examined the specimen building orientation, layer thickness and wall thickness on tensile strength and dimensional accuracy of ABS and Nylon specimens. The results highlight that the best parameters combination for ABS is 0.2 mm layer thickness, 30° building orientation and 0.8 mm wall thickness and the optimum results for Nylon is 0.3 mm layer thickness, 15° building orientation and 0.4 mm wall thickness.

Alsoufi et al. (2019) analyzed the influence of nozzle temperature in ME 3D printed Pure PLA and Advanced PLA+. It was observed that measured dimensions were enlarged along the height and reduced along the width and length in relation to the original CAD project dimension.

Mora et al. (2019) used a 3D structured light scanner (Steinbichler COMET L3D) to assess the influence of layer thickness, printing speed and building orientation on dimensional characteristics of ABS specimens. Dimensions, tolerances and deviations can be obtained quickly and with low cost through reverse engineering techniques. They measured dimensional deviations up to 0.6% in volume.

Sajan et al. (2018) studied the effect of bed temperature, nozzle temperature, print speed, infill percentage, layer thickness and number of loops in circularity error and surface quality of ABS parts. It was concluded that to maximize the surface quality and to reduce circularity error, the optimal combination of parameters was bed temperature of 110°C, nozzle temperature of 220 °C, print speed of 0.035 m/s, infill of 30%, layer thickness of 0.4 mm and 3 loops.

Gomes et al. (2021) investigated the influence of printing speed and specimens built per cycle on dimensional and geometrical tolerances of specimens manufactured by ME. The study shows that the printing speed of 72 mm/s with 1 specimen per cycle led to a better geometrical result and the printing speed of 96 mm/s with 2 specimens per cycle led to a better dimensional tolerance.

The present research aims to investigate the influence of the nozzle temperature on the dimensional tolerances of specimens produced through Material Extrusion with ABS filament.

2. METHODOLOGY

Figure 1 presents the CAD project of the specimen. The specimen has a simple geometry in order to be easy to manufacture and it has different topological geometries such as planes, cylinders and holes. The specimen is designed with SolidWorks 2019 software and exported as an STL file. This file is sliced and the 3D printing G-code is generated with Simplify3D software.

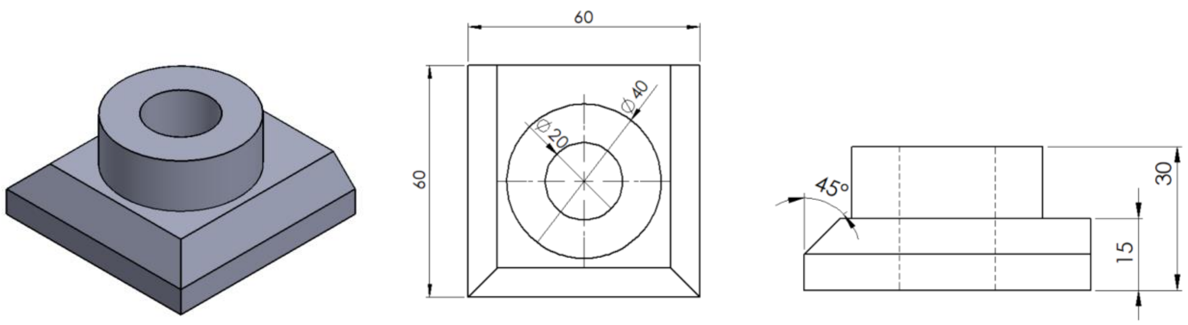

Figure 1. Isometric, upper and side view of the specimen.

Three specimens are produced using a *GTMAX3D CORE A3V2* printer using white Acrylonitrile Butadiene Styrene (ABS) from 3D Fila. Each specimen is produced at a nozzle temperature: 210 °C, 230 °C and 250 °C. Specimens 1, 2 and 3 were made for each nozzle temperature studied. The printing bed is pre-heated at 110 °C. The specimen is removed from the printer after 30 minutes the specimen is built. 3D printing parameters are presented in Table 1 and specimens nominal dimensions are indicated in Table 2.

Table 1. Printing parameters kept constant for all specimens.

Setting	Parameters	Values
Quality	Layer thickness (mm)	0.12
Speed	Set speed (mm/min)	7200
	Print speed (% of set speed)	100
	Infill print speed (% of set speed)	50
	Outline layers print speed (% of set speed)	30
	Supports print speed (% of set speed)	90
Shell	Number of Top layers	10
	Number of Bottom layers	5
	Number of Perimeter layers	5
Temperature	Bed temperature (°C)	110
	First layer nozzle temperature (°C)	250
Skirt	Number of Skirt layers	1
	Skirt offset from specimen (mm)	0.50
	Number of Skirt outlines	2
Environment	Room temperature (°C)	25 ± 2

Table 2. Specimens nominal values.

Dimension	Value
Width (mm)	60
Length (mm)	60
Height 1 (mm)	30
Height 2 (mm)	15
Outer diameter (mm)	40
Inner diameter (mm)	20

Measurements were carried out using three different micrometers:

- Mitutoyo micrometer with measuring range of 25-50 mm and graduation of 0.001 mm,
- Pantec micrometer with measuring range of 50-75 mm and graduation of 0.001 and,
- Tesa inside micrometer with measuring range of 17-20 mm and graduation of 0.005 mm.

They are cleaned using 99.8% Purity Isopropyl alcohol and set to zero using standard cylinders.

A micrometer support is used to prevent heat exchange between operator and micrometers as shown in Figure 2. Measurements are taken in a climatized room (20 ± 1 °C) and all specimens and micrometers were acclimatized for 24 hours.

Figure 2. Micrometer support

The dimensions to be measured are width, length, height 1, height 2 and cylinder outer and inner diameter as shown in Figure 3. For each dimension, five measurements are taken alternatively for each specimen and always at the same position to reduce error due to flatness deviation. Width and length are measured using Pantec micrometer, height 1, height 2 and outer diameter are measured using Mitutoyo micrometer and inner diameter was measured using Tesa inside micrometer. To measure the height 2, it was necessary to use a calibrated cylinder of 20.000 mm so the specimen could fit in the measuring range of the micrometer.

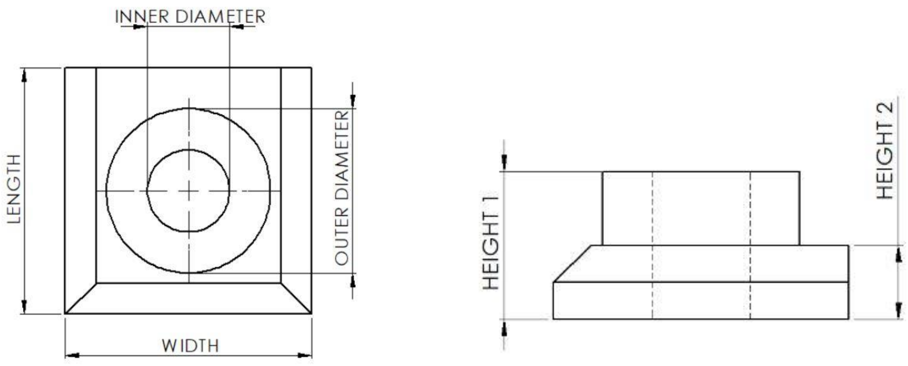

Figure 3. Dimensions to be measured.

3. RESULTS AND DISCUSSION

Figure 4 shows an example of the manufactured specimen. The original forms from the CAD project are preserved and the surface is smooth.

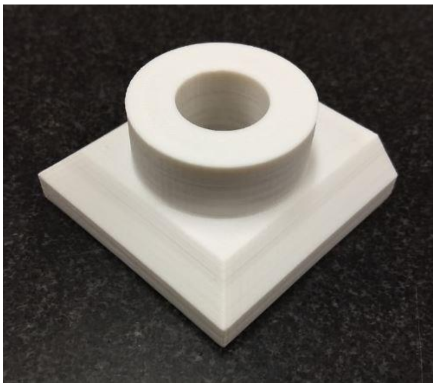

Figure 4. Manufactured specimen.

Table 3 presents the measurement results.

Table 3. Experimental results.

Specimen No.	Nozzle Temperature (°C)	Measurement No.	Width (mm)	Length (mm)	Height 1 (mm)	Height 2 (mm)	Outer Diameter (mm)	Inner Diameter (mm)
1	**210**	1	59.522	59.488	29.873	15.105	39.666	19.865
		2	59.508	59.496	29.874	15.107	39.662	19.860
		3	59.558	59.488	29.875	15.095	39.681	19.875
		4	59.533	59.485	29.875	15.107	39.668	19.845
		5	59.512	59.473	29.872	15.103	39.648	19.845
2	**230**	1	59.652	59.658	29.870	15.073	39.714	19.820
		2	59.668	59.645	29.855	15.055	39.738	19.815
		3	59.684	59.675	29.869	15.062	39.773	19.760
		4	59.665	59.640	29.863	15.055	39.721	19.790
		5	59.674	59.627	29.849	15.050	39.754	19.790
3	**250**	1	59.722	59.702	29.833	15.088	39.778	19.715
		2	59.764	59.721	29.837	15.085	39.781	19.730
		3	59.779	59.728	29.826	15.089	39.785	19.705
		4	59.773	59.715	29.822	15.078	39.789	19.705

5	59.765	59.703	29.824	15.074	39.756	19.715

As measurements were taken at 20±1 °C and manufacturing process are carried out at room temperature (25±2 °C). An adjustment is made using the linear thermal expansion equation as shown in Eq. (1)

$$\Delta L = L_0 \alpha \Delta T \tag{1}$$

where ΔL is the linear expansion, L_0 is the initial linear value, α is the linear expansion coefficient and ΔT is the change in temperature. The linear expansion coefficient adopted for ABS was $\alpha = 78.10^{-6}\ [1/°C]$ (RGPBALLS, 2021) and temperature variation considered was 5 °C.

Table 4 shows the adjusted average values for each specimen with expanded uncertainty with a 95 % probability confidence coverage (INMETRO, 2012).

Table 4. Measurements average and uncertainty.

Specimen No.	Width (mm)	Length (mm)	Height 1 (mm)	Height 2 (mm)	Outer Diameter (mm)	Inner Diameter (mm)
1	59.550 ± 0.025	59.509 ± 0.010	29.885 ± 0.002	15.109 ± 0.006	39.680 ± 0.015	19.866 ± 0.016
2	59.692 ± 0.015	59.672 ± 0.023	29.873 ± 0.011	15.064 ± 0.011	39.755 ± 0.030	19.803 ± 0.028
3	59.784 ± 0.028	59.737 ± 0.014	29.840 ± 0.008	15.088 ± 0.008	39.793 ± 0.016	19.722 ± 0.012

3.1 Width data analysis

Figure 5 highlights the width average value in comparison to the project value. It is possible to observe that specimen 3 is the most accurate with a dimensional deviation of 0.44 % and specimen 1 is the least accurate with a deviation of 0.82 %. Moreover, there is an improvement of approximately 46 % when temperature is increased from 210 to 250 ºC.

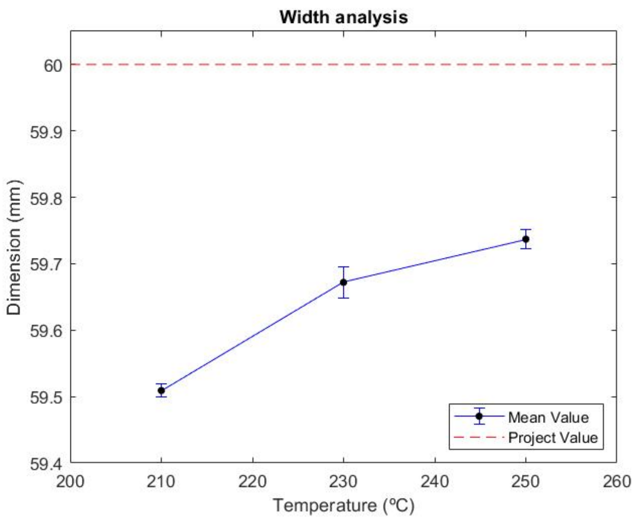

Figure 5. Width average and project value comparison.

3.2 Length data analysis

Figure 6 demonstrates the length average value in comparison to the project value. The most accurate specimen for the length dimension is specimen 3 with a dimensional deviation of 0.36 % and the least accurate is specimen 1 with 0.75 % in the dimensional deviation. Specimen 3 showed an improvement of approximately 52 % on the dimensional accuracy in comparison to specimen 1.

The nozzle temperature influence in width and length are very similar but the length dimension was approximately 13 % more accurate. This difference is probably due to the layer orientation that differs from width to length.

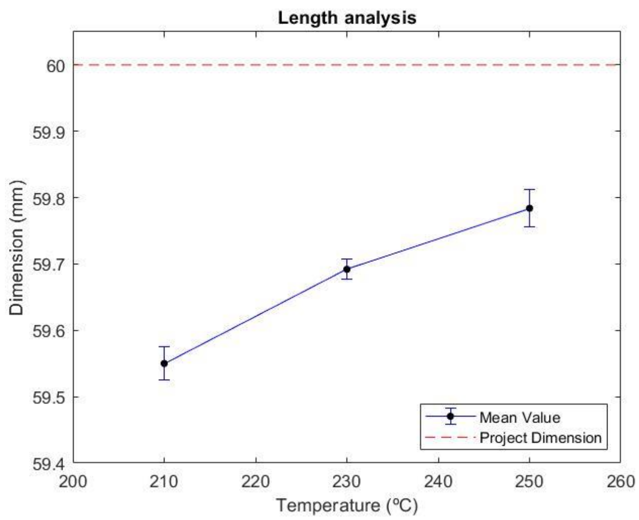

Figure 6. Length averages and project value comparison.

3.3 Height 1 data analysis

Figure 7 illustrates the height 1 average value for each printing temperature. For the height dimension, specimen 1 is the most accurate specimen with 0.38 % deviation and specimen 3 is the least accurate specimen with 0.53 % deviation. Specimen 1 has 28 % better results in comparison to the specimen 3.

As reported by Alsoufi et al. (2019), the height is expected to have a greater dimension than the one from the CAD project. However, the recently printed filament that has not yet solidified is likely to spread out and flatten the specimen. This outcome is more perceptible the greater the specimen height is and the fact that the height dimension of the specimen proposed in this work is more than 9 times greater than the one proposed by Alsoufi et al. (2019) might be the reason for the different results.

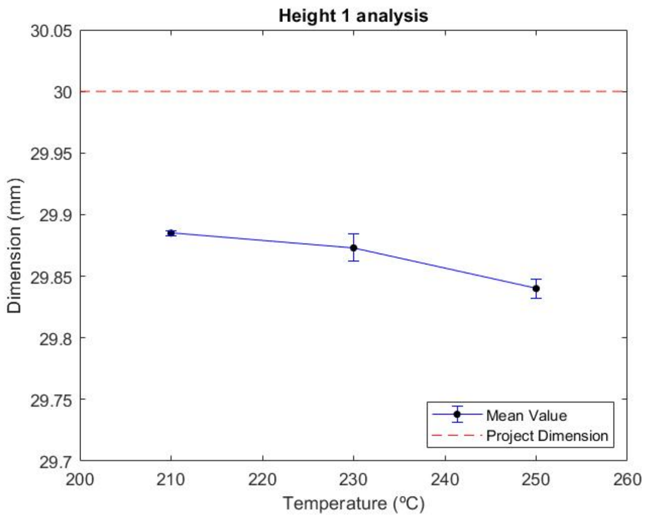

Figure 7. Height 1 averages and project value comparison.

3.4 Height 2 data analysis

Figure 8 presents the height 2 average value for each printing temperature.

For this dimension, specimen 2 is the most accurate with 0.43 % deviation, specimen 3 is the least accurate with 0.73 % deviation and specimen 3 has 0.59 % deviation. Comparing to specimen 3, specimen 2 has an improvement of approximately 41 % in accuracy.

For height 2, which has a smaller dimension, the result reported by Alsoufi et al. (2019) can be perceived. All specimens have greater nominal dimensions than the CAD dimensions.

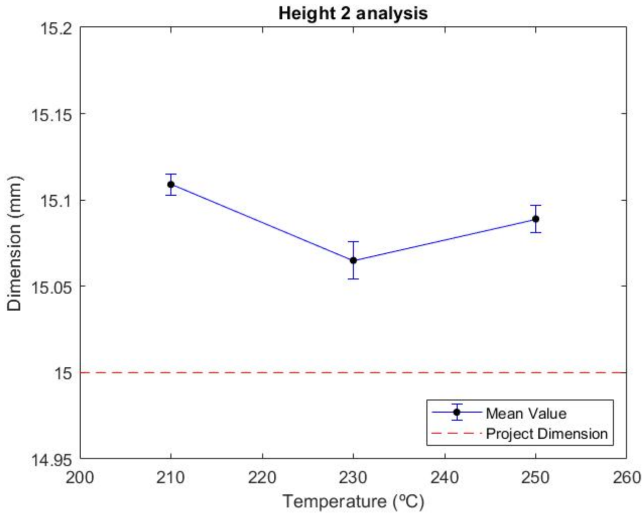

Figure 8. Height 2 averages and project value comparison.

3.5 Outer diameter data analysis

Figure 9 illustrates the average outer diameter for each printing temperature.

For the outer diameter, the best result occurs with specimen 3 (0.52 % deviation from CAD project) least accurate occurs with specimen 1 (0.80 % deviation). Specimen 3 shows a result approximately 35 % better than specimen 1.

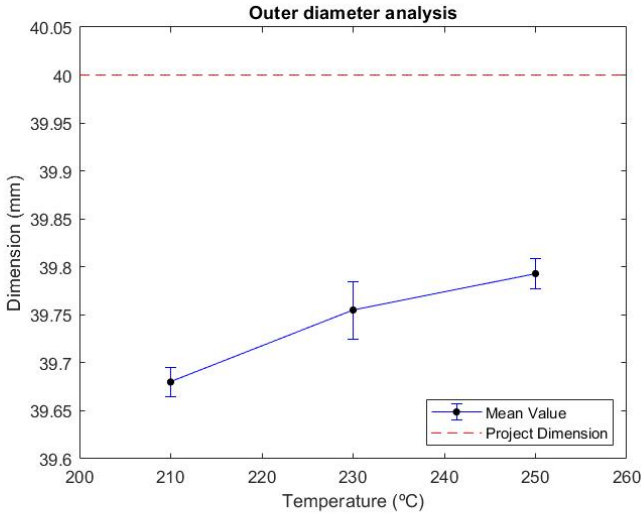

Figure 9. Outer diameter averages and project value comparison.

3.6 Inner diameter data analysis

Figure 10 shows the average inner diameter for each printing temperature.

For the inner diameter, specimen 1 is the most accurate (0.67 % dimensional deviation) and the least accurate is specimen 3 with 1.39 % deviation. Specimen 1 was approximately 52 % better than specimen 3.

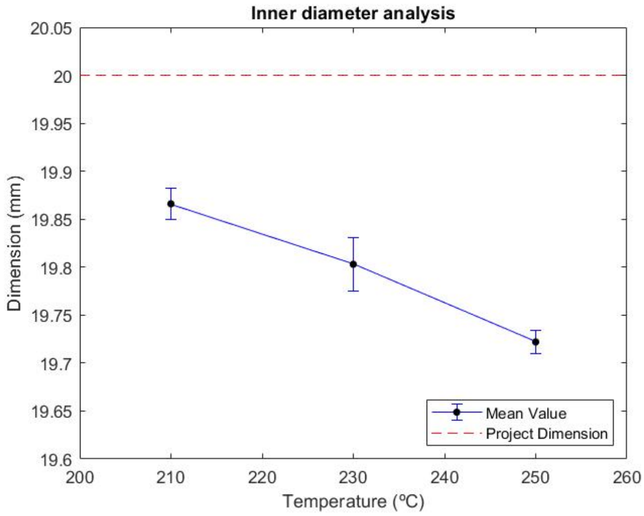

Figure 10. Inner diameter averages and project value comparison.

4. CONCLUSION

In this paper, the influence of the nozzle temperature on dimensional tolerances of specimens produced with ME manufacturing is experimentally investigated. Three specimens were built with different nozzles temperatures (210, 230 and 250 °C) and 6 dimensions are measured in each specimen using micrometers. It is important to mention that, due to the low number of specimens, it is not possible to statistically state that the result obtained is exclusively due to the nozzle temperature parameter and is likely that there is a portion of influence from the others parameters in the final result. Thus, further studies with a larger number of specimens are needed.

As result, there was no temperature value for the nozzle extruder that presented an optimal tolerance for all dimensions of the specimen. When the nozzle temperature is 250 °C width, length and outer diameter dimensions have the best accuracies. At this temperature and for those dimensions, a mean improvement of 22 % is observed compared to other temperatures analyzed. The dimensional deviations are approximately 0.44 % for width, 0.36 % for length and 0.52 % for the outer diameter. Nozzle temperature of 210 °C shows the best accuracies for the height 1 and inner diameter dimensions, 0.38 % dimension deviation for the height 1 and 0.67 % dimensional deviation for the inner diameter, respectively. Concerning the height 2, it was the only dimension that had dimensional values greater than the CAD project and the nozzle temperature of 230 °C showed the best results with a dimensional deviation of 0.43 %.

As conclusion, the nozzle temperature of 250 °C should be used for the ABS filament when an optimal dimensional tolerance for width, length and outer diameter is desired. However, if it is wanted to have an optimal dimensional tolerance for the inner diameter, the temperature of 210 °C should be used. Furthermore, the nozzle temperature of 230 °C can be used to have a reasonable dimensional tolerance in all dimensions as it obtained the best results for height 2 and intermediate dimensional tolerances for the others dimensions.

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6. REFERENCES

Alsoufi, M. S., Alhazmi, M. W., Suker, D. K., Alghamdi, T. A., Sabbagh, R. A., Felemban, M. A., and Bazuhair, F. K., 2019. Experimental Characterization of the Influence of Nozzle Temperature in FDM 3D Printed Pure PLA and Advanced PLA+. *American Journal of Mechanical Engineering*, Vol. *7, No.* 2, 45–60.

Carneiro, L. R., Barbar, G., Pereira dos Santos, L. C., & Zuquete Guarato, A., 2019. *Influência da Temperatura da Mesa de Impressão 3D na Dureza e Dimensões Geométricas de Amostras em ABS*. *Proceedings of the 26th Congresso Nacional de Estudantes de Engenharia Mecânica.*

Gomes, L. R., Guarato, A. Z. and Peres, J. G. F., 2021. Geometrical and Dimensional Tolerances of Specimens Produced by Additive Manufacturing as Function of Printing Speeds and Number of Parts per Cycle. *Submitted in the Proceedings of 26th ABCM International Congress of Mechanical Engineering.*

INMETRO, 2012. Evaluation of measurement data: Guide to the expression of uncertainty in measurement – GUM 2008. Rio de Janeiro, Brazil. 141 p.

Jerez-Mesa, R., Travieso-Rodriguez, J. A., Llumà-Fuentes, J., Gomez-Gras, G., and Puig, D. 2017. Fatigue lifespan study of PLA specimens obtained by additive manufacturing. *Procedia Manufacturing*, *13*, 872–879.

Lieneke, T., Denzer, V., Adam, G. A. O., and Zimmer, D, 2016. Dimensional Tolerances for Additive Manufacturing: Experimental Investigation for Fused Deposition Modeling. Procedia CIRP, 43, 286-291.

Mora, S. M., Gil, J. C., and López, A. M. C., 2019. Influence of manufacturing parameters in the dimensional characteristics of ABS specimens obtained by FDM using reverse engineering techniques. *Procedia Manufacturing*, *41*, 968–975.

RGPBALLS, 2021. ABS BALLS. https://www.rgpballs.com/en/abs-balls/. Accessed 16 June 2021.

Ribeiro, F., Oliveira de Miranda, M. F., dos Santos Saad, N., and Zuquete Guarato, A., 2019. Experimental Analysis on the Mechanical Properties of Petg Specimens Made With Fused Deposition Modeling Manufacturing. *Proceedings of the 25nd International Congress of Mechanical Engineering*.

Sahu, R. K., Mahapatra, S. S., and Sood, A. K., 2014. A Study on Dimensional Accuracy of Fused Deposition Modeling (FDM) Processed Specimens using Fuzzy Logic. *Journal for Manufacturing Science & Production*, Vol. *13*, No. 3, 183–197.

Sajan, N., John, T. D., Sivadasan, M., & Singh, N. K. (2018). An investigation on circularity error of components processed on Fused Deposition Modeling (FDM). *Materials Today: Proceedings*, Vol. *5*, No. 1, 1327–1334.

Sood, A. K., Ohdar, R. K., and Mahapatra, S. S., 2009. Improving dimensional accuracy of Fused Deposition Modelling processed specimen using grey Taguchi method. *Materials and Design*, Vol. *30*, *No.* 10, 4243–4252.

Vishwas, M., Basavaraj, C. K., and Vinyas, M., 2018. Experimental Investigation using Taguchi Method to Optimize Process Parameters of Fused Deposition Modeling for ABS and Nylon Materials. *Materials Today: Proceedings*, Vol. *5*, No. 2, 7106–7114.

Volpato, N. (Org), Ahrens, C. H., Carvalho, J., Costa, C. A. Foggiatto, J. A., Lima, M. S. F., Munhoz, A. L. J., Santos, J. R. L. and Silva, J. V. L., 2017. *Manufatura Aditiva: tecnologias e aplicações da impressão 3D (In Portuguese)*. Edgard Blucher, São Paulo, Brazil. 400 p.

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