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ANALYSIS OF THE MECHANICAL RESISTANCE OF SAMPLES PRODUCED BY 3D PRINTING WITH DIFFERENT PARAMETERS USING THERMOPLASTIC PLA

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ABSTRACT

3D printers are equipment that can manufacture products with different techniques, such as stereolithography (SLA), selective laser sintering (SLS) and fused deposition modeling (FDM). These machines were developed to produce three-dimensional prototypes, combining complex geometries and lower weight. In this context, in the present work mechanical tests were carried out on test specimens manufactured from PLA thermoplastic. The mechanical resistance of printed parts was analyzed with variation of different parameters such as printing temperature, line thickness, speed, percentage and type of filling. A 3D printer with the FDM method, a tensile testing machine and specimens with dimensions in accordance with the ASTM D638 standard were used. The results obtained showed that most parameters behaved as expected in comparison with other results from bibliographic references, emphasizing that an adequate choice of printing parameter has a positive influence on the tensile strength of parts printed in 3D printers.

Keywords: 3D printers. PLA. Print parameters. Mechanical resistance.

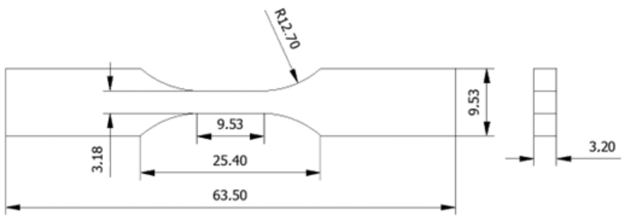
INTRODUCTION

3D printers are machines that emerged in the 1980s with physical engineer Charles Hull, with the aim of producing three-dimensional prototypes. This technology is increasingly used in industrial processes, such as the production of complex automotive and aerospace parts, medical and dental prosthetics, and personalized molds [1].
3D printers work by stacking layers, creating the final object. Some processes used are stereolithography (SLA), selective laser sintering (SLS) and fused deposition modeling (FDM). FDM is the most common process, as it is more accessible, simpler and it is based on extrusion of filament, where the thermoplastic material is directed through a nozzle selectively to form the layers [2-4]. Thermoplastics have made this technique expand, and currently, the most consumed material in 3D printing is Polyatic Acid (PLA). PLA is a bio-based polymer with an amorphous characteristic, biodegradability, easily processed, high tensile strength and stiffness [5]. In the extrusion process, this material is recommended to produce objects that do not require high mechanical efforts and high temperatures [6].
Due to their great constructive power, 3D printers are increasingly present in various layers of society, allowing professionals greater freedom to design parts with complex and lighter

geometries [7]. Variation in printing parameters directly impacts the appearance and mechanical properties of printed parts [4]. Some of these parameters are filling pattern, number of layers, layer height and thickness, melting temperature, filling percentage, among others [8]. Therefore, studies that provide greater assertiveness regarding the parameters used in the most varied techniques used in 3D printers are essential. Thus, the objective of this work is analyzing the print parameters that influence the mechanical resistance of specimens produced by 3D printing using PLA thermoplastic.

MATERIALS AND METHODS

The filament used was thermoplastic PLA with a diameter of 1.75 mm from the manufacturer 3D Fila. To create the test specimens, an FDM 3D printer, Makerbot, model Replicador Mini, was used, as shown in Fig. 1-a.



a) b)

Fig. 1 – a) 3D printer used to print the test specimens; b) Dimensions of printed specimens in accordance with ASTM D638 [9] (millimeters).

Four printing parameters with 3 possibilities each were examined. In total, 40 samples were printed with all the conditions presented in Table 1. The dimensions of the specimens are shown in Fig. 1-b conforms to ASTM D638 [9]. The build orientation of the specimens and the raster direction angle were flat and 0/90°, respectively.

Table 1: Variation of parameters used for printing specimens on the 3D printer.

Combination of parameters			
Parameters	Condition 1	Condition 2	Condition 3
Temperature (°C)	185	198	210
Layer Thickness (mm)	0.08	0.1	0.4
Fill Geometry	Diamond	Hexagonal	Linear
Velocity (mm/s)	10	25	50

Mechanical tests were carried out in accordance with ASTM D638 using an Instron M10-16927 universal mechanical testing machine, present in the materials laboratory of the Mechanical Engineering Course at the Federal University of Maranhão (UFMA). For each combination of printing parameters, 4 repetitions were performed to ensure sufficient data dispersion. A flat-type gripper with pneumatic drive was used. After modeling the specimen in AutoCad, the file was saved in STL format and transferred to the printer. After loading the file into the printer, adjustments to the printing parameters are made. Then the software will generate the layers and the printing strategy. Thus, the printing process is ready to start.

After printing the specimens, the dimensions (thickness, reduction width, and length) of the specimens were measured using a micrometer with a resolution of 0.01 mm. Then the geometry data obtained is loaded into the universal traction machine, the sample fixed between the claws, starting the loading process until fracture at a rate of 5 mm/min. After breaking the test piece, the machine software generates stress-strain graphs.

RESULTS AND DISCUSSION

The analysis of the results occurred when evaluating the dimensions of the specimens after 3D printing and obtaining the traction x deformation curves. The analysis of the parts is responsible for demonstrating whether the parts reach the appropriate measurements, according to the designed model.

DIMENSIONAL ASSESSMENT

Condition 1 - Temperature

The evaluations of the geometry of the specimens printed at three different extrusion temperatures are presented in Table 2, which shows the dimensions of the specimens after printing is completed. It is noted that the samples printed at 210 °C had the most discrepant dimensional values in relation to the reference values, presenting lower precision. Accuracy may vary according to the printing parameter, and the greater inaccuracy of parts at a temperature of 210 °C may have been caused by molecular diffusion, a natural process in printing at high temperatures [10].

Table 2: Average sample dimensions under different temperature conditions.

Temperature (°C)	Thickness (mm)	Width (mm)	Length (mm)
185 °C	3.20 ± 0.08	3.30 ± 0.08	63.50 ± 0.47
198 °C	3.38 ± 0.10	3.40 ± 0.00	63.20 ± 0.06
210 °C	3.60 ± 0.06	3.40 ± 0.00	63.10 ± 0.00
REF	3.20	3.18	63.5

Condition 2 - Layer Thickness

Table 3 shows the dimensions for each line thickness used after printing. It is noted that for thicknesses of 0.08 and 0.1 the measurements are very close to the reference. However, for 0.4 mm there was a big difference, due to the large amount of material that is deposited in each layer, which makes the line heavy and impairs dimensional accuracy.

Table 3: Average sample dimensions under different line thickness conditions.

Layer Thickness (mm)	Thickness (mm)	Width (mm)	Length (mm)
0,08	3.18 ± 0.05	3.33 ± 0.05	63.23 ± 0.05
0,1	3.20 ± 0.08	3.30 ± 0.08	63.50 ± 0.47
0,4	3.10 ± 0.00	3.50 ± 0.08	63.48 ± 0.49
REF	3.20	3.18	63.5

Condition 3 - Fill Geometry

Table 4 presents the dimensions of the printed samples using diamond, hexagonal and linear filling types. The average values of the sample dimensions showed little variation in relation to the projected measurements for thickness and length. The width did not show adequate values, which shows that the print cannot reach the expected value.

Table 4: Average sample sizes in the different filling conditions.

Fill Geometry	Thickness (mm)	Width (mm)	Length (mm)
Diamond	3.20 ± 0.00	3.43 ± 0.05	63.33 ± 0.1
Hexagonal	3.20 ± 0.08	3.30 ± 0.08	63.50 ± 0.47
Linear	3.20 ± 0.05	3.40 ± 0.06	63.30 ± 0.05
REF	3.20	3.18	63.50

Condition 4 - Printer Velocity

Table 5 shows the dimensions of the samples from condition 5 – printing speed, with no large variation in dimensions between conditions. Print speed determines the speed at which the head moves while printing the part. This is a parameter that directly influences printing time, making it shorter, reducing printing time [11]. However, increasing the speed can cause insufficient cooling and vibration problems in the part due to the sudden movement of the head at high speed, which can generate imperfections in the quality of the part [12]. The measurements were similar for both speeds, except for 50 mm/s, which showed greater thickness. This variation is caused by poor layer deposition due to the higher speed.

Table 5: Average dimensions of the parts under different speed conditions.

Printer Velocity (mm/s)	Thickness (mm)	Width (mm)	Length (mm)
10	3.20 ± 0.00	3.40 ± 0.13	63.30 ± 0.00
25	3.20 ± 0.08	3.30 ± 0.08	63.50 ± 0.47
50	3.30 ± 0.06	3.30 ± 0.05	63.40 ± 0.10
REF	3.20	3.18	63.50

Overall, the printer was efficient in printing the thickness and length of the samples. However, the reduced session width was not achieved by any condition, which shows that the 3D printer needs improvements in layer generation for very narrow widths.

ASSESSMENT OF TENSILE STRENGTH

By analyzing the maximum stress and strain for each condition studied, those conditions with the best results can be observed in more detail by evaluating the dispersion presented.
Fig. 2 shows the maximum tensile stress and strain values for different printing temperatures. It can be observed that the temperature of 185 °C presented the highest tensile strength value, exhibiting little variability in maximum tension between the tested samples. Therefore, working at lower temperatures is beneficial for higher tensile strength values. Temperatures of 198 and 210 °C showed more pronounced dispersions between repetitions, being a negative factor together with lower tensile strength. The deformation between the samples was similar, with the temperature of 210 °C showing the highest average deformation between the temperature conditions and 198 °C the lowest deformation. At 198 °C there appears to be a weakness in PLA, which drops its tensile strength, which is restored at 210 °C.
In condition 1 in which the parts are printed at different extrusion temperatures, the samples present a phenomenon called molecular diffusion, in which "when one layer is deposited on another, the lower layer will, locally, melt again due to the heat emitted by the upper layer"

[10]. This process directly affects the quality of the bonds, as the higher the extrusion temperature, the lower the viscosity of the polymer, making the polymer chains weaker.

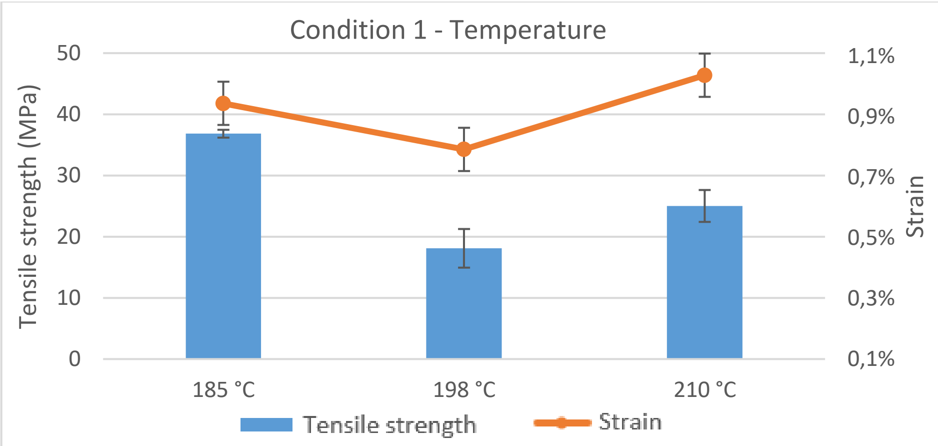


Fig. 2 - Maximum tensile stress and deformation values for different printing speeds.

Fig. 3 shows the tensile strength and deformation values for the different thicknesses studied. It is observed that the 0.1 mm line thickness presented a higher tensile strength value compared to the other thicknesses and less dispersion in the data. The thickness of 0.4 mm showed the highest dispersion value of the sample data and the lowest tensile strength. According to Galina et al. [13], the mechanical resistance of the printed part is directly related to the number of layers. The smaller the extruded filament, the greater the number of layers in the part, since with the smaller line thickness, there is an increase in contact and adhesion between the layers, resulting in increased resistance [14]. The thickness of 0.08 mm showed worse results compared to 0.1 mm. This result may have been affected due to the function of the extruder nozzle not allowing thicknesses smaller than 0.1 mm, which impairs the stability of the deposited line. The deformation was lower in the condition with greater mechanical resistance.

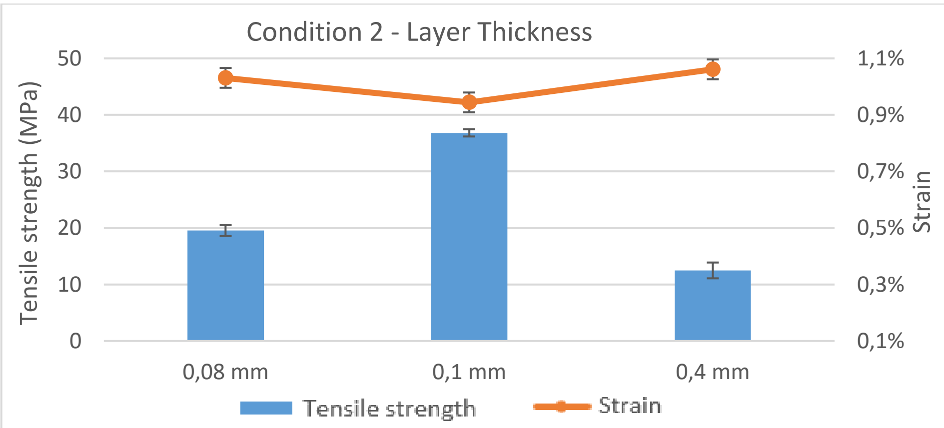


Fig. 3 - Maximum tensile stress and deformation values for different line thicknesses.

Fig. 4 shows the maximum tensile strength and deformation for condition 4 on type of filling. The maximum tensile strength results presented statistically equal data within the standard deviation. On average, diamond filling could be a more advantageous option, combining mechanical resistance and good deformation, but its high dispersion is a negative factor. A positive point for hexagonal filling was its low dispersion of results. For maximum deformation, the linear condition presented worse results than the hexagonal and diamond conditions, due to their structure. Geometries with simple lines are considered more fragile, as presented by the linear filling type, however this type of geometry is printed in less time [15].

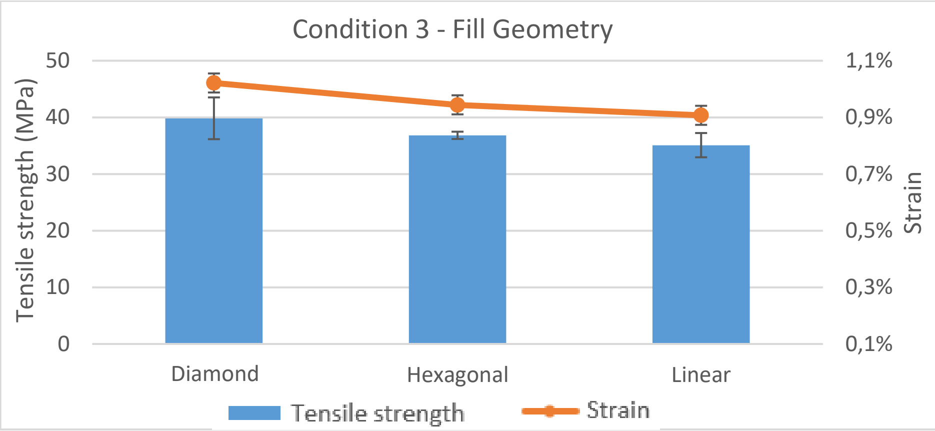


Fig. 4 - Maximum tensile stress and strain values for filling geometries

Fig. 5 shows the result of tensile strength for different printing speeds. The 25 mm/s speed condition showed a higher average value of maximum tensile strength, as well as a more uniform print due to the smaller standard deviation. The speed of 10 mm/s showed greater dispersion between the data obtained and a lower maximum resistance value. This demonstrates that very slow material deposition has a direct impact on print quality. Increasing the speed to 50 mm/s can be beneficial for productivity gains, as it presented a mechanical resistance value close to the ideal condition of 25 mm/s. The maximum deformations are statistically equal on average, with a tendency to increase as printing speed increases.

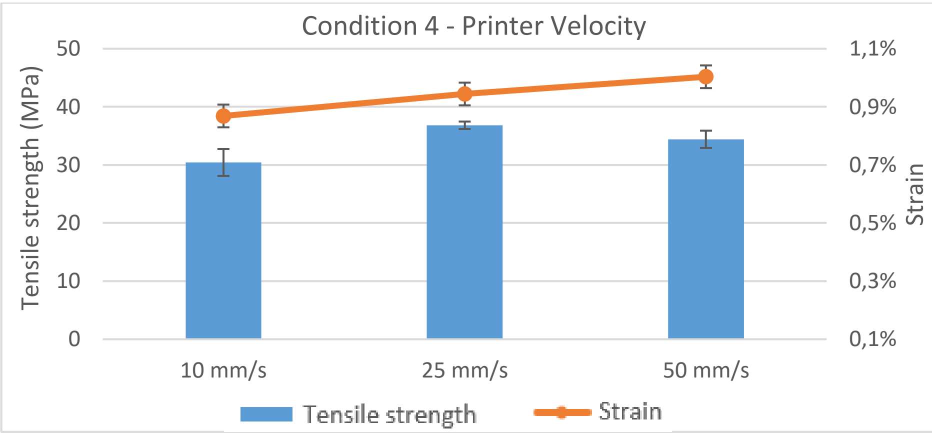


Fig. 5 - Maximum tensile stress and deformation values for printing speeds.

CONCLUSIONS

From the results obtained through the tensile test of specimens manufactured by 3D printing using PLA material, varying parameters such as printing temperature, layer thickness, printer velocity and fill geometry, the following conclusions can be drawn:

- Regarding printing temperature, the lowest temperature of 185 °C showed higher tensile strength values. Therefore, the higher the printing temperature, the less resistant parts tend to be.
- For the line thickness condition, the behavior of the 0.1 mm samples proved to be more efficient than the other thicknesses of 0.8 and 0.4 mm, as the smaller the thickness of the

layers, the greater the adhesion of the material, resulting in increased resistance, with the thickness 0.08 being impaired due to the extruder nozzle.

- The type of filling with diamond geometry presents higher mechanical resistance values, but with high dispersion. The hexagonal type presented lower dispersion and a statistically equal mean value.
- A printing speed of 25 mm/s has the best mechanical resistance results. Choosing 50 mm/s may be interesting as it reduces printing time by 50%, with little loss in terms of mechanical resistance.

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