COB-2021-1105
3D PRINTING PARAMETERS EFFECT ON THE FLEXURAL STRENGTH OF POLYLACTIC ACID (PLA) PARTS

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Abstract. The objective is to evaluate the effect of 3D printing parameters on the flexural strength of samples printed of polylactic acid (PLA). From the results of this study is possible to predict the mechanical strength of the parts printed on a commercial printer and select the best combination of printing parameters. For this, the experimental research method was used. PLA was used to produce rectangular samples of 3.20mm thick, 12.70mm wide and 125.00mm long according to the ASTM D 790 standard. A commercial printer was used for the sample production. The printing parameters such as layer thickness, wall thickness and infill density were adjusted to print 81 samples with 27 different parameters combinations and 3 repetitions. The printed samples were tested using a 3-point bend testing. Design of Experiments (DOE), Analysis of Variance (ANOVA) and Response Surface Methodology (RSM) were used for the results analysis. The results of means, standard deviations (SD) and variation coefficients (CV) of flexural strength are also presented. The response surface graphs were generated by combining the printing parameters and the flexural strength. It can be concluded that the printing parameters has an effect on the flexural strength of the PLA printed samples, prototypes and parts.
Keywords: Mechanical Properties. 3D Printing. Additive Manufacturing. Polylactic Acid. Polymers.

1. INTRODUCTION

The additive manufacturing (AM) or 3D printing is often used as a rapid prototyping (RP) technique and for the production of functional parts. This manufacturing process consists of producing parts through the addition of material, usually polymers parts are produced, and however, metals and ceramics parts can also be produced. AM enables to produce parts with complex geometries, reduced production time and minimize raw material waste when compared to subtractive manufacturing processes. The AM process takes place in three stages in computerized systems: Computer-Aided Design (CAD), Computer-Aided Engineering (CAE) and Computer-Aided Manufacturing (CAM) (Cheah *et al*., 2005; Volpato, 2017). Currently, there are several AM processes such as Fused Deposition Modeling (FDM) which is one of the most common AM processes. In addition, there are several models and brands of commercial printers on the market, where each one of them has its own configurations. These commercial printers have predefined printing parameters for their users. However, the combination of predefined selected printing parameters generates parts and prototypes with different mechanical properties. The predefined printing parameters are the best fit for every the printing process. There is a lack of information about the printing parameters effect on the mechanical strength of printed parts.

Currently, AM has been presented and discussed by several researchers with the aim of defining the mechanical properties of printed materials. Mohamed, Masood and Bhowmik (2015) reviewed the some research carried out in determining and optimizing the process parameters of the FDM process. The results show that optimization of process parameters of FDM additive manufacturing technology is one of the most critical design tasks in quality evaluation indicators for obtaining high quality parts, enhanced material response and enhanced properties. The authors showed that the printing parameters influenced in surface roughness, mechanical properties, dimensional accuracy, material behavior and build time according with reviewed literature. They suggest that the printing parameters must be studied and analyzed in future research. Chacón *et al*. (2017) studied the effect of build orientation, layer thickness and feed rate on the mechanical performance of PLA samples manufactured with a 3D printer. Tensile and three-point bending tests were carried out to determine the mechanical response of the printed specimens. The results showed that the mechanical properties increase as layer thickness increases. The authors found that the effect of layer thickness on

mechanical properties changes due to construction orientation. Nugroho *et al*. (2018) studied the flexural properties of samples produced by 3D printing using FDM. The samples were produced in PLA with different layer thicknesses between 0.1 to 0.5 mm. The results showed flexural strength increases with increasing printing layer thickness from 0.4 to 0.5 mm. These results confirmed that the layer thickness influences the flexural strength of printed samples. Kuznetsov *et al*. (2018) studied the influence of geometrical parameters of the 3D printing process on printed part strength. The samples were printed in PLA with different nozzles and layer thickness using FDM. They were tested with a universal electromechanical testing machine and a test rig for three-point bending. The results showed that part strength decreased along with layer thickness increase. Aloyaydi, Sivasankaran and Ammar (2019) investigated the influence of infill density on microstructure and flexural behavior of 3D printed parts. For this, the authors conducted three points bending test in PLA samples printed in FDM. The results showed that the percentage of infill density influenced the bending characteristics, where an increase in flexural modulus can be noticed due to the increase in fill density. Corapi *et al*. (2019) performed uniaxial tensile testing for the determination of mechanical strength, modulus of elasticity and elongation of PLA printed samples. They used the FDM process to produce the samples for uniaxial tensile testing. Quasi-static tests were carried out to characterize the material and the process considering three spatial growth directions. The results showed that the horizontal samples have higher ultimate tensile strength (UTS) and elastic modulus than vertical and on side samples. Furthermore, the toughness varied as function of impression orientation of the samples. Therefore, printing orientation is an important printing parameter. Kolodziej *et al*. (2019) carried out experiments in PLA to verify the influence of parameters such as infill density, infill type and orientation. They found that the elastic modulus and bending strength increased with increasing infill density. Abeykoon, Sri-Amphorn and Fernando (2020) studied the effect of processing conditions such as infill pattern, infill density, infill speed, and printing materials on the mechanical, thermal and morphological properties of 3D printed samples. They used five different 3D printing materials: polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), carbon fiber reinforced PLA (CFR-PLA), carbon fiber reinforced ABS (CFR-ABS) and carbon nanotube reinforced ABS (CNT-ABS). Their results showed that elastic modulus of the printed parts increased as the infill density is increased. In the flexural tests, all samples broke in the middle, and the CFR-PLA and pure PLA showed the highest and the lowest bending modulus, respectively. Flexural tests were not performed in samples of the same material and different printing parameters. Gonabadi, Yadav and Bull (2020) studied the influence of following process parameters, orientation and infill density, on the mechanical behavior of PLA samples produced by FDM. The results showed that the tensile strength and Young's modulus increased with increasing infill density, similar to the results reported by Kolodziej *et al*. (2019). Minh and Tuyet (2020) studied the process parameters' effect (solid layer top, vertical shell, infill pattern, and infill density) on the flexural properties of PLA components produced by the FDM technique. They observed that flexural strength increased with increasing infill density.

The previous literature review shows the importance of selection of printing parameters in the cost and quality of printed parts, such as surface roughness, mechanical properties, dimensional accuracy, material behavior, build time and others. The process parameters are the critical factors and these must be studied and analyzed in future research. There are some physical constraints imposed on FDM machine, such as: (1) specific values range of layer thickness, infill density and wall thickness, and the operator cannot select any other value because they are restricted by the nozzle diameter; (2) each nozzle diameter has its own raster width range; (3) number of contours is limited to the specific values; (4) different printing volume according to 3D printer model; (5) filament material and its dimensional and geometric characteristics because they are restricted by the printing head and machine constraints, and (6) other constraints. Some advances have been made in optimizing printing parameters such as the use of desirability function for multi objective optimization of FDM process parameters (D'Addona *et al*., 2021), optimization of process parameters of FDM using VIKOR technique (Raykar and D'Addona, 2020) and the use of other techniques for optimization of printing process parameters. All the reported works demonstrated the importance of understanding the effect of printing parameters on the printing process of parts. However, there is still a lack of information on the effect of printing parameters on mechanical properties for all printers on the market. Each commercial printer has its own standard configuration, as well as its own components such as a print head, print filament and modeling bases.

The objective of this work is to study the effect of 3D printing parameters on the flexural strength of PLA printed samples. From results analyses to predict the mechanical strength of the parts printed on the commercial printer and select the best combination of printing parameters.

2. MATERIALS AND METHODS

Figure 1a shows the test samples (SP) of 3.20 mm X 12.70 mm X 125.00 mm (thickness X width X length) according to ASTM D 790 standard. The ASTM D 790 is the standard test method used for the flexural properties of plastics, reinforced or unreinforced, including composites and insulation materials. The SP were produced using polylactic acid (PLA) filament of 1.75mm diameter and gray color, Cliever brand. Figure 1b shows the Cliever brand 3D printer – model CL2 Pro Plus used for the production of the SP and Figure 1c shows the AM process by FDM.
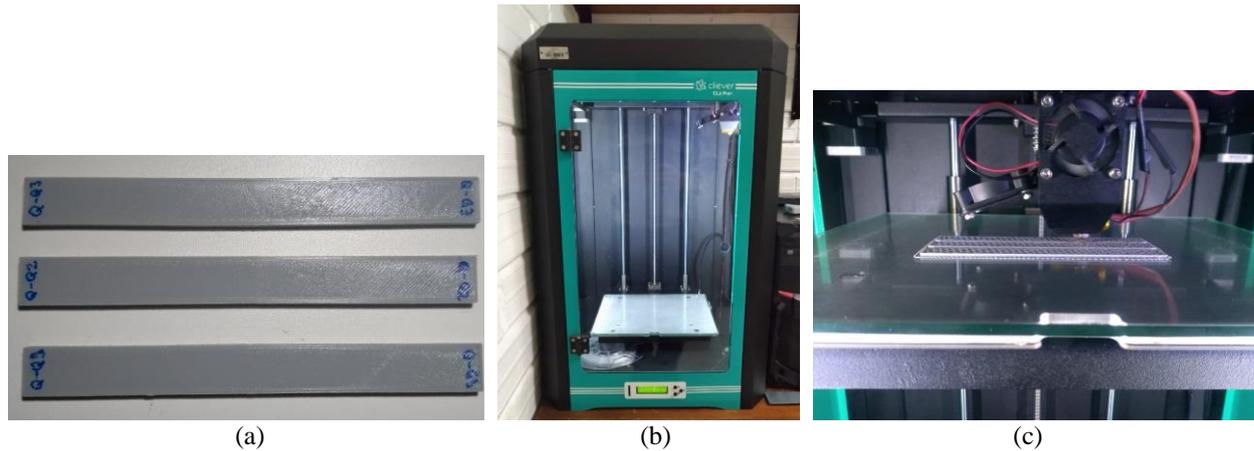
(a) (b) (c)

Figure 1 – Image of (a) test SP, (b) 3D printer and (c) FDM.

Table 1 shows the printing parameters (infill density, wall thickness and layer thickness) selected to study their effects on flexural strength.

Table 1. Selected printing parameters.

Material	Printing Parameters		
	Infill Density (%)	Wall Thickness (Perimeter)	Layer Thickness (mm)
PLA	10	2	0.15
	25	3	0.19
	50	4	0.25

Fixed printing parameters are activation angle between layers, printing speed and SP position. Design of Experiments (DOE) and Response Surface Methodology (RSM) were used for the work. Table 2 shows the variable printing parameters that generated 27 different combinations named from A to AA. In addition, three SP of each combination were printed to verify the results repeatability. In total 81 SP were produced.

Table 2 – Definition of SP and combination of printing parameters.

SP	Printing parameters		
	Layer Thickness (mm)	Wall Thickness (Perimeter)	Infill Density (%)
A	0.15	2	10
B	0.19		
C	0.25		
D	0.15	3	
E	0.19		
F	0.25		
G	0.15	4	
H	0.19		
I	0.25		

Table 2 – Definition of SP and combination of printing parameters.

SP	Printing parameters		
	Layer Thickness (mm)	Wall Thickness (Perimeter)	Infill Density (%)
J	0.15	2	25
K	0.19		
L	0.25		
M	0.15	3	
N	0.19		
O	0.25		
P	0.15	4	
Q	0.19		
R	0.25		
S	0.15	2	50
T	0.19		
U	0.25		
V	0.15	3	
W	0.19		
X	0.25		
Y	0.15	4	
Z	0.19		
AA	0.25		

Figure 2a shows the measurement of SP using the digital caliper. The tests were carried out in an EMIC – model DL2000 universal testing machine, Figure 2b, with 2 tons capacity and 3-point flexural test fixture. The machine was configured with a support span of 55 mm and a test speed of 0.1 mm/min., 21.4 °C test temperature and 54% relative humidity according to the ASTM D790 standard. Figure 2c shows the SP positioned on the flexural test fixture during testing.
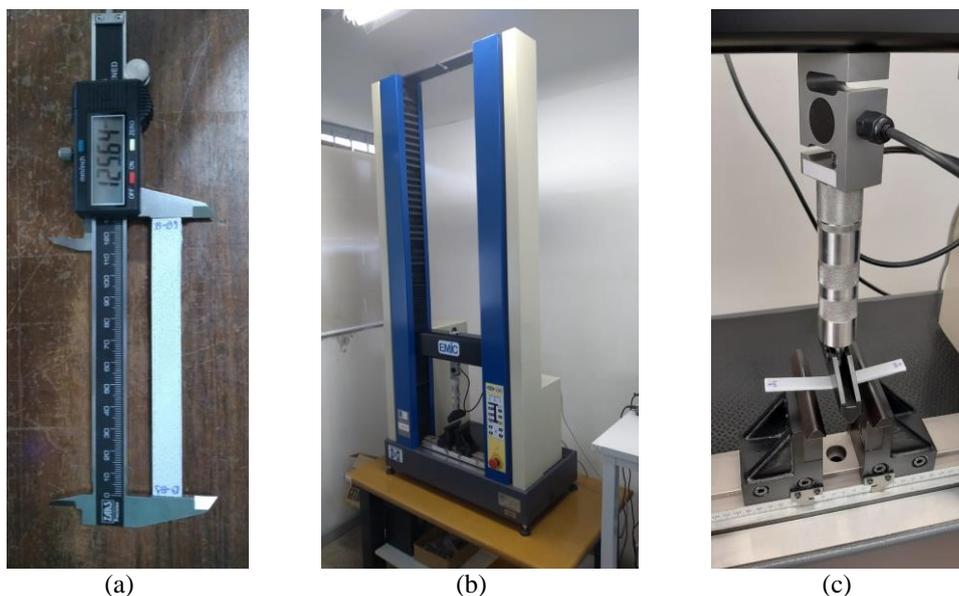

(a)   (b)   (c)

Figure 2 – Image of (a) SP measurement, (b) universal testing machine and (c) flexural testing.

3. **RESULTS AND DISCUSSION**

All SP were measured in the dimensions of thickness, width and length as shown in Table 3.

Table 3. Sample dimension of SP related to printing parameters.

SP	Printing parameters			Sample Dimensions								
				Length			Width			Thickness		
	Layer Thickness (mm)	Wall Thickness (per.)	Infill Density (%)	SP1 (mm)	SP2 (mm)	SP3 (mm)	SP1 (mm)	SP2 (mm)	SP3 (mm)	SP1 (mm)	SP2 (mm)	SP3 (mm)
A	0.15	2	10	125.67	125.80	125.73	13.21	13.21	13.17	3.38	3.41	3.45
B	0.19			125.63	125.57	125.74	13.22	13.04	13.03	3.42	3.51	3.44
C	0.25			125.53	125.79	125.54	12.95	13.16	13.09	3.36	3.40	3.35
D	0.15	3		125.68	125.73	125.81	13.15	13.21	13.22	3.43	3.40	3.39
E	0.19			125.52	125.98	125.65	13.04	13.08	13.13	3.42	3.48	3.40
F	0.25			125.53	125.73	125.62	12.97	13.20	13.06	3.34	3.39	3.43
G	0.15	4		125.71	125.77	125.77	13.21	13.21	13.11	3.45	3.42	3.42
H	0.19			125.68	125.89	125.58	13.13	13.06	13.16	3.46	3.40	3.40
I	0.25			125.73	125.72	125.67	13.08	13.08	13.09	3.39	3.40	3.38
J	0.15	2	25	125.30	125.35	125.41	12.97	12.96	13.02	3.47	3.47	3.45
K	0.19			125.52	125.63	125.70	13.11	13.06	13.09	3.44	3.47	3.40
L	0.25			125.65	125.47	125.44	13.02	13.02	13.01	3.38	3.40	3.39
M	0.15	3		125.58	125.56	125.65	13.03	13.05	13.06	3.42	3.40	3.48
N	0.19			125.74	125.68	125.81	13.12	13.08	13.10	3.41	3.47	3.42
O	0.25			125.08	125.77	125.68	13.12	13.26	13.05	3.39	3.39	3.38
P	0.15	4		125.74	125.61	125.57	13.13	13.19	13.03	3.39	3.43	3.47
Q	0.19			125,55	125.64	125.60	13.20	13.16	13.14	3.46	3.46	3.39
R	0.25			125.68	125.69	125.69	13.15	13.15	13.25	3.41	3.42	3.40
S	0.15	2	50	125.72	125.61	125.63	12.92	13.02	13.03	3.50	3.44	3.42
T	0.19			125.61	125.52	125.54	12.97	13.00	13.03	3.45	3.44	3.40
U	0.25			125.71	125.93	125.67	13.06	13.18	12.98	3.41	3.44	3.48
V	0.15	3		125.66	125.69	125.71	13.05	13.21	13.11	3.49	3.45	3.40
W	0.19			125.61	125.74	125.61	13.11	13.13	13.05	3.50	3.43	3.50
X	0.25			125.67	125.70	125.75	13.09	13.03	13.13	3.46	3.45	3.40
Y	0.15	4		125.84	125.70	125.71	13.16	13.15	13.14	3.42	3.47	3.45
Z	0.19			125.67	125.66	125.72	13.13	13.17	13.19	3.49	3.56	3.48
AA	0.25			125.63	125.79	125.79	13.15	13.22	13.27	3.41	3.47	3.43

The mean and standard deviation (SD) of the dimensions were calculated and the result shows values of 125.66 mm (SD = 0.13 mm), 13.10 (SD = 0.08 mm), and 3.43 mm (SD = 0.04 mm), respectively. These SD are associated with the accuracy of the printing process since the printer's dimensional tolerance is 0.2 mm as reported by the manufacturer, *Cliever Indústria e Comércio de Produtos Tecnológicos S/A*.

Table 4 shows the mean flexural strength, standard deviation (SD) and coefficient of variation (CV) obtained for all printing parameters combination.

Table 4. Mean flexural strength, SD and CV of all SP related to printing parameters.

SP	Printing parameters			Results					
	Layer Thickness (mm)	Wall Thickness (per.)	Infill Density (%)	Flexural Strength (MPa)					CV (%)
				SP1	SP2	SP3	Mean	SD	
A	0.15	2	10	38.03	40.21	36.80	**38.35**	1.73	4.50
B	0.19			44.85	44.60	45.53	44.99	0.48	1.07
C	0.25			61.39	58.07	61.00	60.15	1.81	3.02
D	0.15	3		42.19	40.35	44.08	42.21	1.87	4.42
E	0.19			55.44	51.42	55.43	54.10	2.32	4.29
F	0.25			67.09	62.60	62.81	64.17	2.53	3.95
G	0.15	4		44.29	47.07	48.99	46.78	2.36	5.05
H	0.19			55.67	59.26	61.59	58.84	2.98	5.07
I	0.25			68.70	68.48	69.24	68.81	0.39	0.57
J	0.15	2	25	43.87	45.71	43.85	44.48	1.07	2.40
K	0.19			51.78	59.49	51.32	54.20	4.59	8.47
L	0.25			67.34	66.92	69.16	67.81	1.19	1.76
M	0.15	3		50.77	52.32	52.12	51.74	0.84	1.63
N	0.19			56.16	58.33	55.09	56.53	1.65	2.92
O	0.25			74.64	68.69	69.36	70.90	3.26	4.60
P	0.15	4		60.79	57.30	52.01	56.70	4.42	7.80
Q	0.19			66.24	56.70	53.85	58.93	**6.49**	**11.01**
R	0.25			69.09	68.23	68.43	68.58	0.45	0.66
S	0.15	2	50	59.38	59.81	63.79	60.99	2.43	3.99
T	0.19			69.81	70.32	70.05	70.06	**0.26**	**0.36**
U	0.25			74.11	73.06	72.31	73.16	0.90	1.24
V	0.15	3		62.93	60.84	64.33	62.70	1.76	2.80
W	0.19			67.98	70.40	69.26	69.21	1.21	1.75
X	0.25			75.05	77.47	77.02	76.51	1.29	1.68
Y	0.15	4		64.07	60.15	66.65	63.62	3.27	5.14
Z	0.19			69.76	65.66	67.64	67.69	2.05	3.03
AA	0.25			82.07	75.83	78.67	**78.86**	3.12	3.96

Table 4 show that the largest standard deviations of 6.49 MPa (CV = 11.01%) was found in "Q" condition. While the smallest standard deviations of 0.26 MPa (CV = 0.36%) was found in "T" condition. The highest flexural strength, 78.86 MPa, was observed in the "AA" condition printed with the largest values of layer thickness, wall thickness and infill density, 0.25 mm, 4 and 50%, respectively. On the other hand, the lowest flexural strength, 38.35 MPa, was observed in the "A" condition printed with the smallest values of layer thickness, wall thickness and infill density, 0.15 mm, 2 and 10%, respectively. These results are as expected, once largest values of layer thickness, wall thickness and infill density result in a greater amount of PLA filament deposited, increasing the mechanical properties of the SP. Furthermore, these results are similar to that found by Nugroho *et al.* (2018), Kolodziej *et al.* (2019), and Minh and Tuyet (2020). Figures 3, 4 and 5 show the influence of infill density, wall thickness and layer thickness on the flexural strength of the SP.
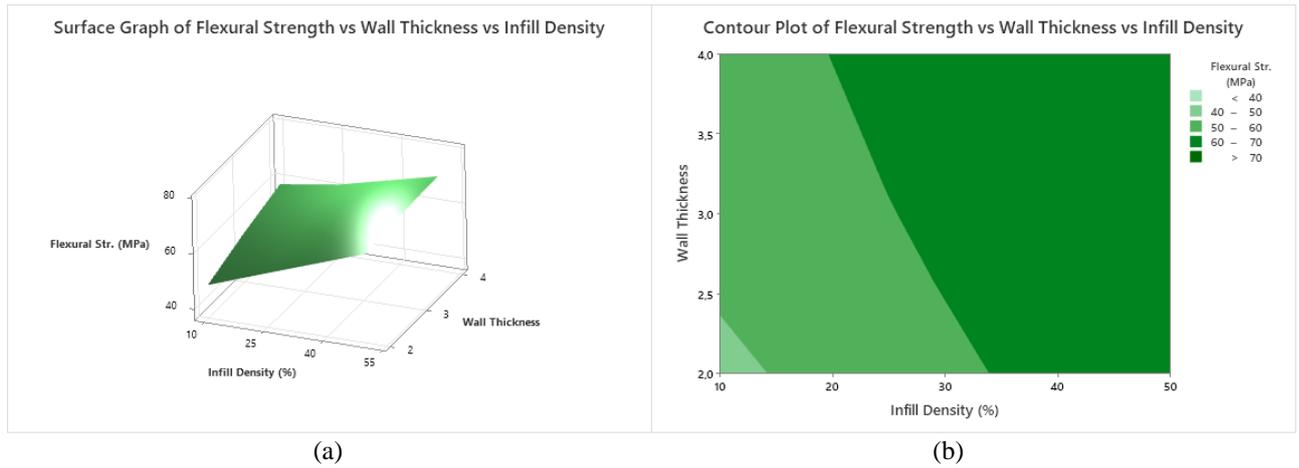
Figure 3. Flexural strength vs. Infill Density vs. Wall Thickness (a) Surface and (b) Contour Plot.
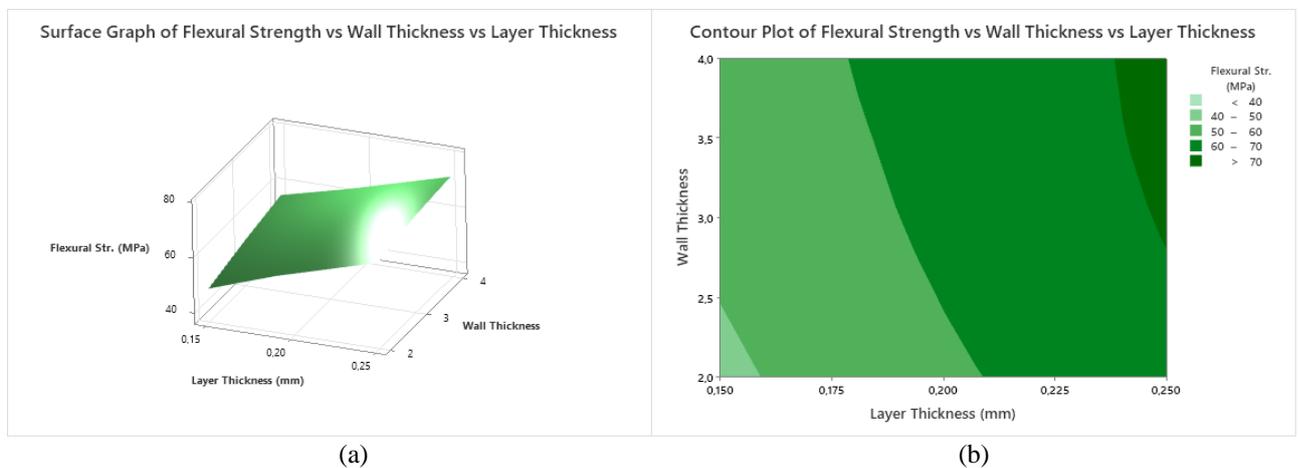

Figure 4. Flexural strength vs. Layer Thickness vs. Wall Thickness (a) Surface and (b) Contour Plot.
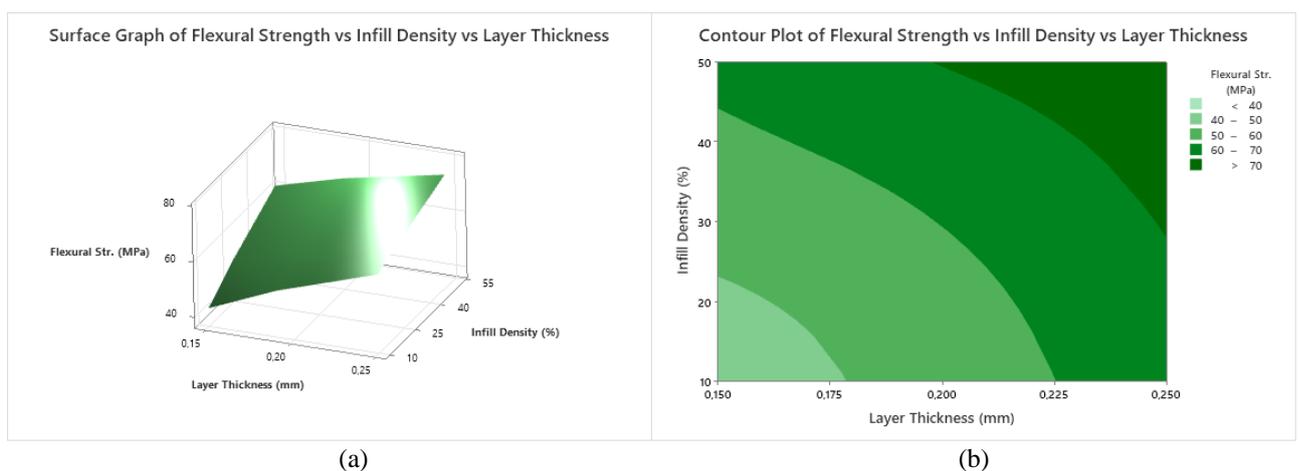

Figure 5. Flexural strength vs. Layer Thickness vs. Infill Density (a) Surface and (b) Contour Plot.

The Figures 3, 4 and 5 show that flexural strength increases with increasing layer thickness, wall thickness and infill density. For example, in the condition with layer thickness of 0.19 mm and 10% infill density an increase in wall thickness from 2 to 3 and from 3 to 4 caused an increase in flexural strength of 10 MPa (20.24%) and 4 MPa (8.76%), respectively. In spite of expected, a linear and proportional behavior of flexural strength related to wall thickness was

not observed. The reason may be the variation in the results of the flexural tests, which showed a standard deviation of around 4.59 MPa. Another reason could be the variation in the printing process. Anyway, these results allow to predict the effect of printing parameters on the flexural strength of samples produced by 3D printing of PLA filament. In addition, the results can help to selected optimal printing parameters. Analysis of variance (ANOVA) for flexural strength is shown in Table 5.

Table 5. ANOVA for flexural strength.

Source	Sum of square	Degree of freedom	F-value	P-value		Contribution (%)
Infill Density	1190.5	2	66.07	0.000	Significant	39.68
Wall Thickness	168.9	2	9.38	0.001	Significant	5.63
Layer Thickness	1460.7	2	81.06	0.000	Significant	48.69
Error	180.2	20				6.00
Total	3000.3	26				100.00

From Table 5, it can be inferred that layer thickness has the highest impact on flexural strength (48.69%) followed by infill density (39.68%) and wall thickness (5.63%). The significance of each process parameter is observed using P and F value at 95% confidence interval. Lower P value, i.e., less than 0.05 justify the significant effect of considered parameters on the research. All printing parameters are significant, but the layer thickness and infill density have been identified as the most significant input parameters for flexural strength. Increase in the infill density increase material quantity required to print the part. This generates greater mass and strength for the printed part. However, increase in the layer thickness reduces layers quantity required to print the part. This creates fewer regions between layers that can generate slip due to poor adhesion between layers and, consequently, increases flexural strength.

5. CONCLUSIONS

This research has shown that the flexural strength of 3-D printing PLA samples produced by FDM has a clear dependence of printing parameters. Flexural strength of PLA printed samples increase as infill density, wall thickness and layer thickness were increased. These effects of printing parameters on flexural strength are in agreement with previous studies reported in the literature.

By analyzing printing parameters vs. flexural strength, we note an increase of flexural strength due to an increase in layer thickness, wall thickness and infill density. This is expected because more PLA filament is consumed in the production of the sample and, consequently, they will have greater mechanical strength. According to the ANOVA, All printing parameters are significant, but the layer thickness and infill density have been identified as the most significant input parameters for flexural strength.

As a concluding remark, the results obtained in this study can be used to predict the flexural strength of PLA printed samples and then to support selecting process of the optimal printing parameters. This will assist in the printing process of various prototypes and functional parts that require greater mechanical strength, allowing for greater reliability and precision in the process of selecting printing parameters.

6. ACKNOWLEDGEMENTS

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8. **RESPONSIBILITY NOTICE**

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