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STUDY OF TEST BODIES MANUFACTURED THROUGH FDM 3D PRINTING OF THE MATERIAL PLA

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Abstract. Additive Manufacturing (AM) – in particular, 3D Printing – achieved a high growth in terms of market share in the past two decades and research regarding the engineering problems envolved in the process has become absolutely relevant. One of the greatest challenges present in the 3D printed parts is the high anisotropy showed by them and this study aims at adressing the issue via tension tests with test bodies (TBs) printed through Fused Deposition Modeling (FDM) using the material Polylactic Acid (PLA). Three printing patterns (Lines, ZigZag and Concentric) and three printing positions (Flat, On-Edge and Upright) were applied, so that two TBs were manufactured with the combination of each of these characteristics and – with the mean value for the TBs of same configuration – the Force vs. Displacement and Stress vs. Elongation curves were obtained. An a posteriori analysis of the Stress vs. Elongation curves made it possible to estimate the values of the Elasticity Modulus (E), Initial Yield Limit (σ_{Y_0}), Ultimate Tensile Strenght (σ_u) and Percentual Elongation at Fracture ($E\%_f$) for each of the configurations. It was stablished as the best configuration the concentric pattern and flat printing position, because it was the one which achieved the highest toughness and mechanical strenght ($E = 3087 \pm 78$ MPa, $\sigma_{Y_0} = 49.6 \pm 1.3$ MPa, $\sigma_u = 57.9 \pm 0.4$ MPa, $E\%_f = 8.8 \pm 1.2$). A deep fragilization was demonstrated for parts manufactured with the load direction perpendicular to the printing plane ($E = 2682 \pm 53$ MPa, $\sigma_{Y_0} = 28.8 \pm 1.1$ MPa, $\sigma_u = 34.4 \pm 2.4$ MPa, $E\%_f = 1.5 \pm 0.2$), so that this condition must be avoided in terms of mechanical design.

Keywords: Additive Manufacturing, 3D Printing, Fused Deposition Modelling (FDM), Polylactic Acid (PLA), Tension Test

1. INTRODUCTION

Additive Manufacturing (AM) is a process in which parts are made through the deposition of material with the aid of a tridimensional model and is defined in opposition to Subtractive Manufacturig methodologies (ASTM, 2012). 3D Printing – a term often used as a synonym of AM – can be defined as the technique which makes it possible to obtain 3D objects via slicing of a tridimensional model in layers and subsequent deposition of material layer-by-layer (ASTM, 2012) as shown in Figure 1.

The concept of 3D Printing has been made popular in recent years and its cost has been substantially reduced so that many sectors within the Industry have since come to make use of the process as a means of obtaining final products. This widespread use of the emergent technology revealed some of its limitations and engineering challenges when it comes to the mechanical design of 3D printed parts.

One of the greatest challenges of designing such parts is predicting how the anisotropy – highly present in them (Ngo *et al.*, 2018) – will affect the mechanical behavior depending on the direction in which the load is applied. A study that explores that topic, therefore, is highly needed and relevant to the literature.

The most popular kind of 3D printing is Fused Deposition Modelling (FDM), a process that begins by a heated nozzle initially depositing melted plastic on a bed in the shape of the first layer of the sliced part. On top of the first layer, the subsequent layers are stacked up until the final object is formed.

In terms of materials used in FDM, Polylactic Acid (PLA) has shown to be the more promising one for a multitude of applications. The reason is that, since it is made out of fermented organic waste Garlotta (2001), the material is completely renewable and does not contain any toxic substance in its composition. PLA is specially useful in medical applications such as prosthetics because of its fine mechanical properties and non-toxicity. In that sense, Heo *et al.* (2017) developed in the year of 2017 a part which combined FDM 3D Printing using PLA with hydrogel and gold nanoparticles to produce a prosthesis that helps regenerating bone tissue (Figure 2).

Nowadays, PLA is used in many areas of the Industry (Figure 3) and the global increase of its use is estimated as

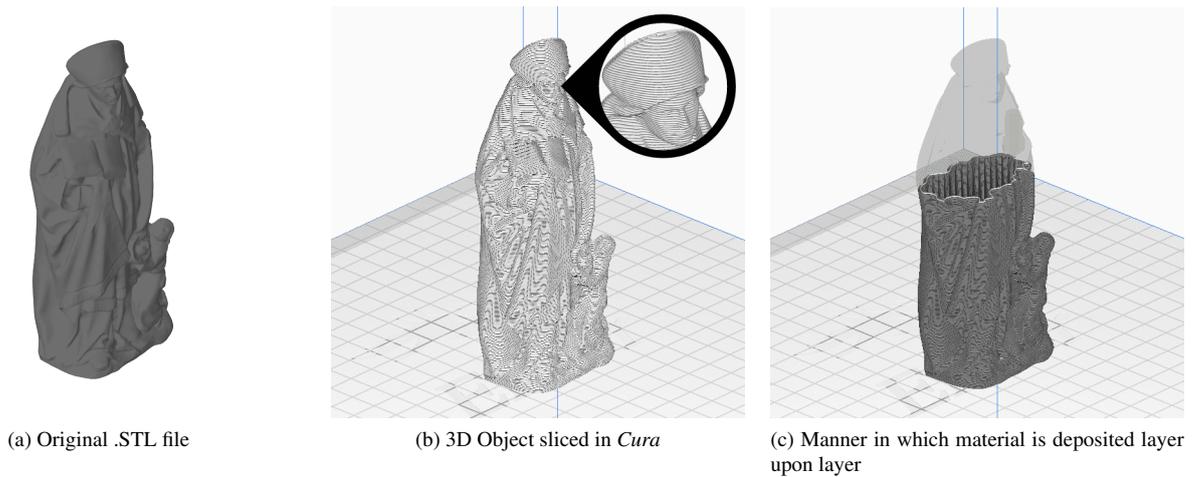| (a) Original .STL file | (b) 3D Object sliced in *Cura* | (c) Manner in which material is deposited layer upon layer |

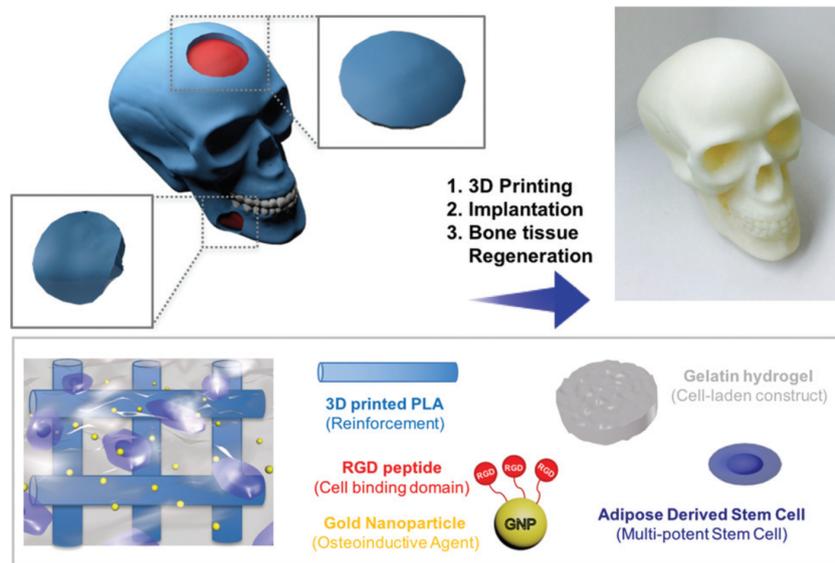Figure 1: Steps in the preparation of a 3D model for 3D Printing

Figure 2: Development of bone prosthesis with the aid of AM via FDM in PLA (Heo *et al.*, 2017)

18.1% by year through the years of 2021 to 2028 (Balla *et al.*, 2021). It is therefore extremely relevant to determine its mechanical properties and it was chosen as the material to be applied in this study.

2. OBJECTIVES

The objectives of this paper are:

1. To determine the Elasticity Modulus (E), the Initial Yield Limit (σ_{Y_0}), the Ultimate Tensile Strenght (σ_u) and the Percentual Elongation at Fracture ($E\%_f$) of the material PLA via tension testing considering

$i.$ the different printing positions (Flat, On-Edge and Upright)

$ii.$ the different printing patterns (Lines, ZigZag and Concentric)

2. Establish the combination of printing position and pattern which provided the largest values for the studied parameters.

3. FUSED DEPOSITION MODELLING (FDM)

The FDM process is defined by the standard ASTM (2012) as "a material extrusion process used to make thermoplastic parts through heated extrusion and deposition of materials layer by layer; term denotes machines built by Stratasys, Inc." It
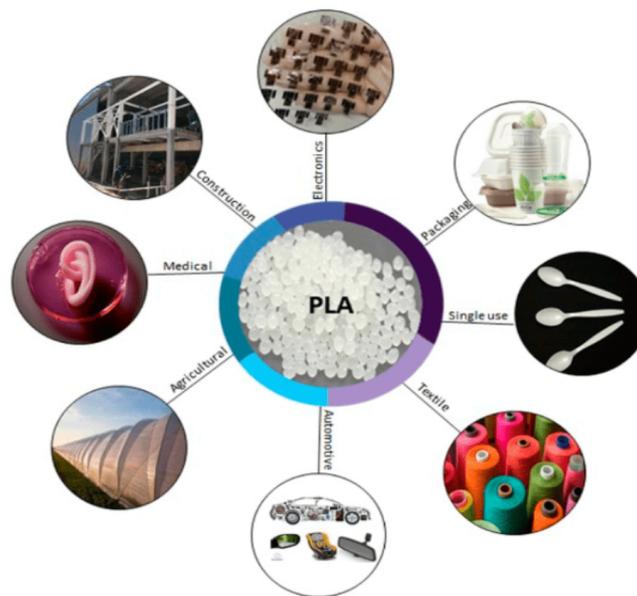
Figure 3: Applications involving PLA in the many areas of the Industry (Balla *et al.*, 2021)

makes use, therefore, of thermoplastics manufactured as rolls of filament which feed material to a heat controlled nozzle. The material reaches its semi-liquid state and is deposited, layer upon layer, to form the final part Kristiawan *et al.* (2021). Figure 4 ilustrates the process where the filament (a) passes through the extruder (b) and is melted forming the piece (c) over the bed (e). If the part contains excentric angles, support (d) is necessary.

The printing patterns of each layers are communicated to the machine via a GCODE file generated by the slicing of a CAD model. The file provides position coordinates for the nozzle, which travels the desired patterns.
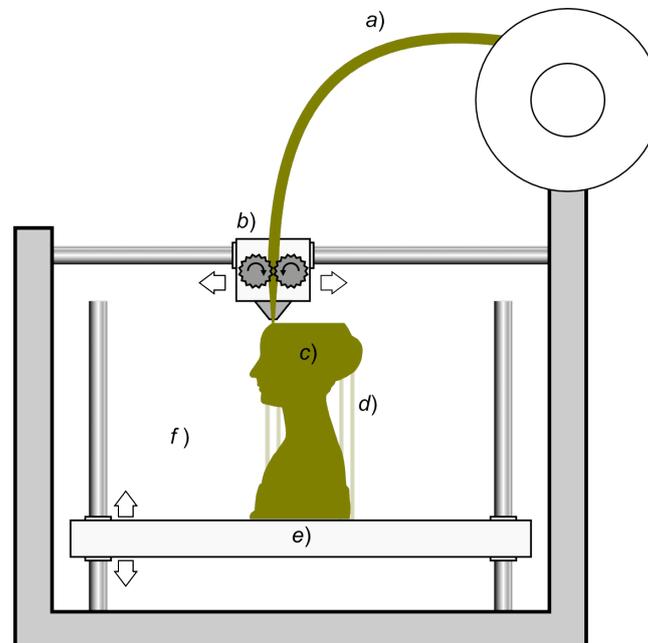

Figure 4: Working of the FDM process Scopigno *et al.* (2017).

Parameters such as layer height, printing pattern, infill density, nozzle temperature, bed temperature and printing speed can be modified for the fabrication of objects. The ones which have the largest impact on the mechanical properties of the parts are layer height, printing pattern and thickness (Ngo *et al.*, 2018). However, it is not an easy task to determine the optimal value for a given parameter, since each of them is related to the others in some way (Kristiawan *et al.*, 2021). That makes it hard to stablish the combination which will provide the highest mechanical properties of the piece.

Apart from the slicing configurations of the parts, it is possible to choose between many polymeric thermoplastics to produce them. The ones with a most widespread use are Acrylonitrile butadiene styrene (ABS) and Polylactic Acid

(PLA), although Polypropilene's usage has been gaining steam – specially in Japan – in recent years (Kristiawan *et al.*, 2021).

Because of its low cost and simplicity in application (Ngo *et al.*, 2018), FDM is the most widespread 3D Printing process. Its advantages and limitations are shown in Table 1.

Table 1: Advantages and limitations of the FDM process, as described by Ngo *et al.* (2018), Gibson *et al.* (2021), Kristiawan *et al.* (2021) e Wong and Hernandez (2012)

Advantages	Limitations
✓ Low cost of both materials and equipments ✓ Simplicity ✓ High possibility of customization ✓ No kinf of post-processing is needed ✓ Low material waste ✓ Equipment with day-to-day dimensions	✘ Weak mechanical properties ✘ Anisotropy ✘ Suports are necessary for some parts ✘ Bad finishing due to the low resolution along the z axis ✘ Only a limited number of materials can be applied ✘ Low production rate

4. POLYLACTIC ACID (PLA)

PLA is a thermoplastic biopolymer of high strenght and high elasticity modulus (Garlotta, 2001) which usage has greatly increased in the last decades. Its molecular base lies on the Lactic Acid ($HOCH_3CHCOOH$), a molecule naturally produced in the muscles of mammals and artificially produced via fermentation of organic matter, such as sugar cane, maize starch and cornn glucoze. (Gupta *et al.*, 2007). It is also possible to obtain Lactic Acid (LA) via celulose, fish and cooking waste Balla *et al.* (2021).

LA is most commonly produced, however, through the fermentation of maize starch using bacteria of the *Lactobacillus* kind. For its polymerization and transformation into PLA, there are three possible routes: (1) direct condensation in a vaccum with the application of solvents; (2) azeotropic condensation/dehidration; (3) formation of the intermediary molecule *lactide* via depolymerization and repolymerization, so that the use of solvents is not necessary (Gupta *et al.*, 2007).
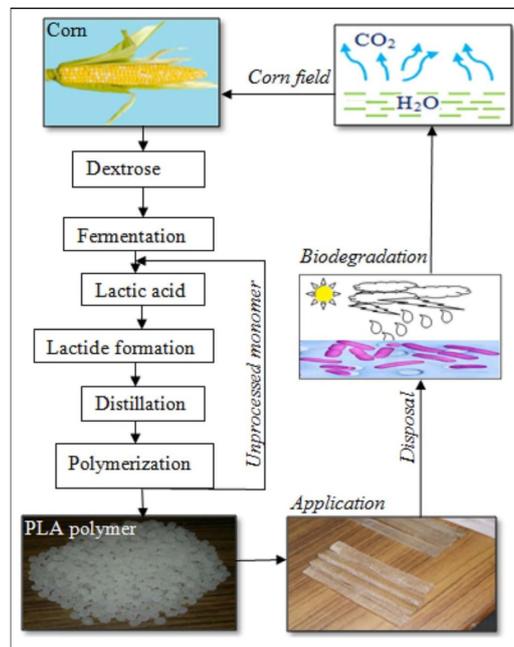

Figure 5: PLA's life cycle (Bajpai *et al.*, 2014)

Besides having mechanical properties similar to Polyethylene Terephthalate (PET) and Polypropilene (PP) (Bajpai *et al.*, 2014), PLA has the advantage of being 100% renewable because of its life-cycle. The plastic is naturally degraded generating CO_2 and H_2O, which can be consumed in the production of agricultural byproducts that feed organic material back into the cycle of its obtaining(Bajpai *et al.*, 2014) (Figure 5).

PLA's non-toxicity allied to its degradation that does not producid damaging substances make it specially convenient for the biomedical applications (Balla *et al.*, 2021). It is also a great material for the FDM application because of its

relatively low melting point. That characteristic can also be a drawback since that makes PLA not very temperature-resistent. Its glass transition temperature and melting point are about 60-70°C and 170°C-180°C, respectively (Gupta *et al.*, 2007). Some intervals for the mechanical properties of PLA found in literature are shown in Table 2.

Table 2: Typical properties of PLA found in literature (Chacón *et al.*, 2017)

Property	Value
σ_u [MPa]	15.5-72.2
E [MPa]	2020-3550
$E\%_f$ [%]	0.5-9.2

5. MATERIALS AND METHODS

In the standard ASTM (2015) it can be found a general method for tension testing of test bodies made of polymers, where a way of obtaining its mechanical properties is described. The same document provides some geometries for the design of test bodies and the Type I was chosen among those available. The resulting test body is shown in Figure 6.
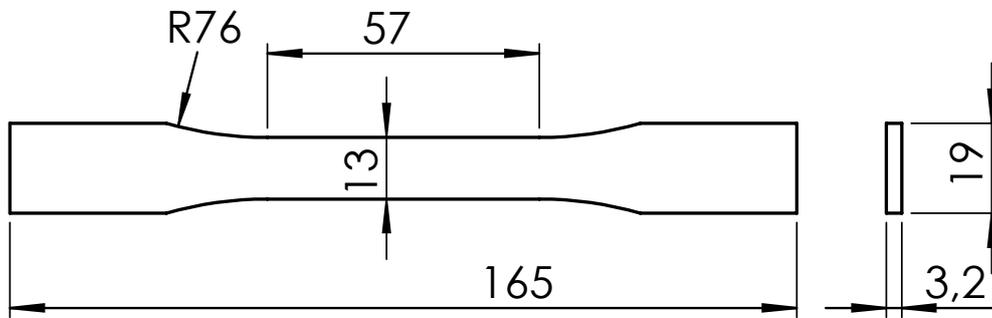

Figure 6: Technical Drawing of the tension test body printed in many configurations. Measures in mm

The machine in which the test bodies were printed was Creality's Ender 3 V1, which is an affordable and widespread model. PLA was chosen as the material of the parts and the slicing parameters used are the ones shown in Table 3.

Table 3: Printing parameters which were kept constant in the manufacturing of all test bodies

Parameter	Value
Nozzle diameter [mm]	0.4
Layer height [mm]	0.2
Wall line count [-]	0
Infill density [%]	100
Nozzle temperature [°C]	215
Bed temperature [°C]	60
Filament flux [%]	104
Printing speed [mm/s]	60.0
Retraction distance [mm]	6.0
Retraction speed [mm/s]	25.0

The parameters which changed were the printing position and printing pattern. There are 3 possible printing positions, as shown by Figure 7, and Chacón *et al.* (2017) gives them the names *Upright*, *On-edge* and *Flat*. In terms of printing patterns there are many from which it can be chosen, but 3 were applied. Those are the Lines, ZigZag and Concentric patterns (Figure 8).

The symbology used to represent each of the printing positions/patterns is the one demonstrated by Figure 9.

The combination of printing position/pattern among the available ones results in 9 possible cases. Since 2 test bodies were printed for each combination, 18 of them were manufactured in total and the tests were performed in a MTS *Landmark* equipment. Since only the parameters E, σ_{Y_0}, σ_u and E_f will be obtained and failure was not always occurring at the center region of the test bodies, a clip gage was not used and the data was acquired directly from the force/displacement
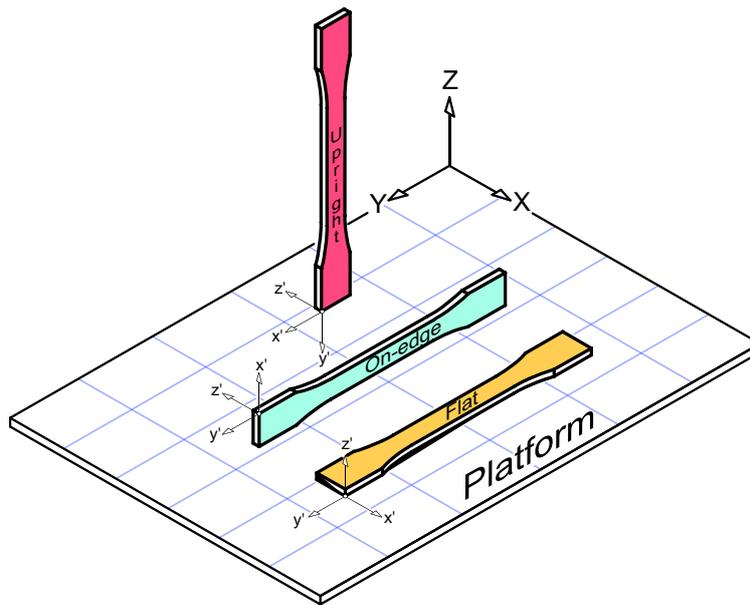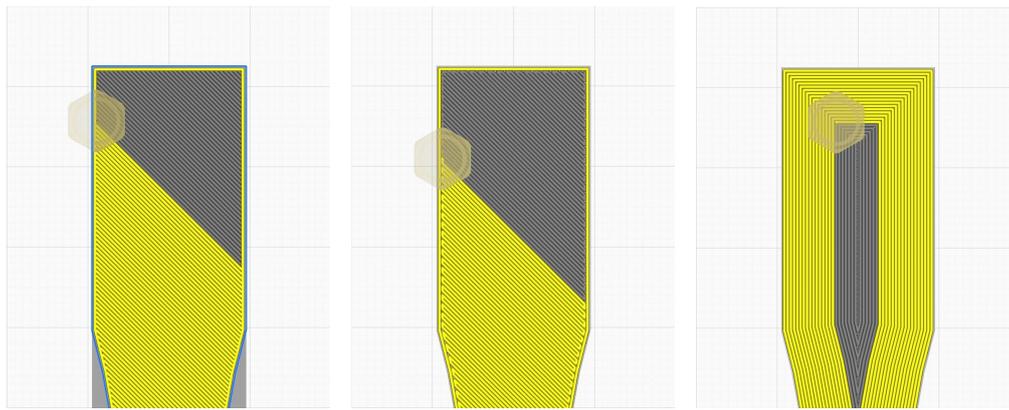
Figure 7: Possible printing positions (Chacón *et al.*, 2017)

| (a) Lines | (b) ZigZag | (c) Concentric |

Figure 8: Illustration of the chosen deposition patterns via slicing in the software *Cura*

| (a) Flat | (b) On-Edge | (c) Upright |

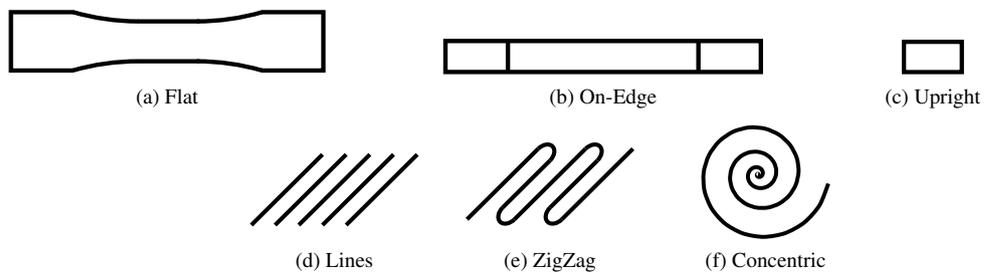| (d) Lines | (e) ZigZag | (f) Concentric |

Figure 9: Symbology used to express the printing positions/patterns

given by the machine. The parameters inserted in the computer program that runs the MTS equipment are the ones in Table 4 and the test bodies positioned in the machine can be found in Figure 10.

Table 4: Parameters applied to the MTS machine for the tension tests

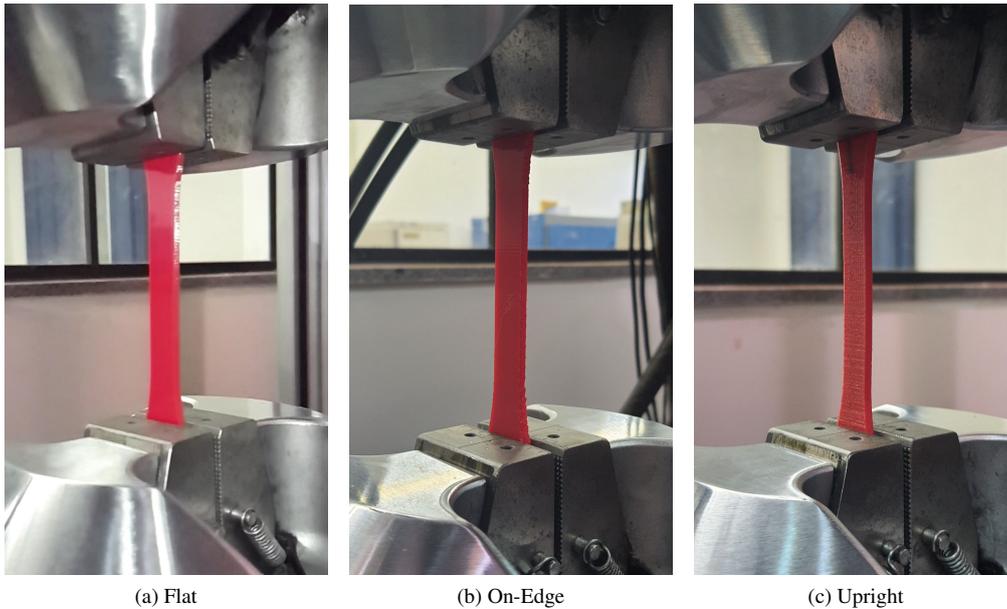| Parameter	Value
Control [-]	Force
Superior/Inferior force limits [N]	4500/-2000
Claw separation speed [mm/min]	2.5
Superior/Inferior displacement limits [mm]	10/-2

(a) Flat   (b) On-Edge   (c) Upright
Figure 10: Test bodies in each of the printing positions submitted to tension tests in the MTS machine

To evaluate the increase and decrease of the values obtained for each test body, a parameter I is defined such that

$$I = \frac{P - P_{ref}}{P_{ref}} \times 100\% \tag{1}$$

which indicates the percentual increse/decrease of a certain parameter (P) in relation to a reference parameter (P_{ref}). As reference parameters the values correspondent to the first combination tested were chosen.

6. RESULTS AND DISCUSSION

Having made all the relevant considerations and having the routine read the Force vs. Displacement for each of the test bodies, it was possible to obtain the Force vs. Displacement and Stress vs. Elongation curves for them – taking the average value of the ones of same printing position/pattern – as illustrated by Figure 11.

The first relevant piece of information taken from the data analysis is the trend of part embrittlement as one walks towards the Upright printing position, regardless of the deposition pattern. The highest supported force was for the test bodies printed in a Flat position and with a Concentric filling pattern (Figure 11a). Although it demonstrates brittle behavior due to the fracture shape, it is the toughest specimen and its plastic region is prolonged and withstands greater displacement before rupture occurs. With regard to the deposition pattern, it is clear that the Concentric provides better resistance, supporting greater forces and displacements. The Flat position test bodies consistently showed a larger plastic region and were able to withstand greater forces. In the case of Stress vs. Elongation, the analysis is maintained because the final shape obtained is the same (Figure 11b).

The curves for the test bodies printed in Upright position are almost superimposed, with a slightly worse performance of the parts printed by ZigZag pattern. Regarding the position, the Flat was the one that consistently presented the best results, but in the case of the combination of the Concentric pattern with the On-Edge position, there was an equivalence and even a reduction in the brittle behavior of the part. In the case of the On-Edge position with other deposition patterns than the Concentric one, the test bodies showed fragile behavior and less resistance, although not as fragile and less resistant as the Upright position test bodies.

(a) Force vs. Displacement
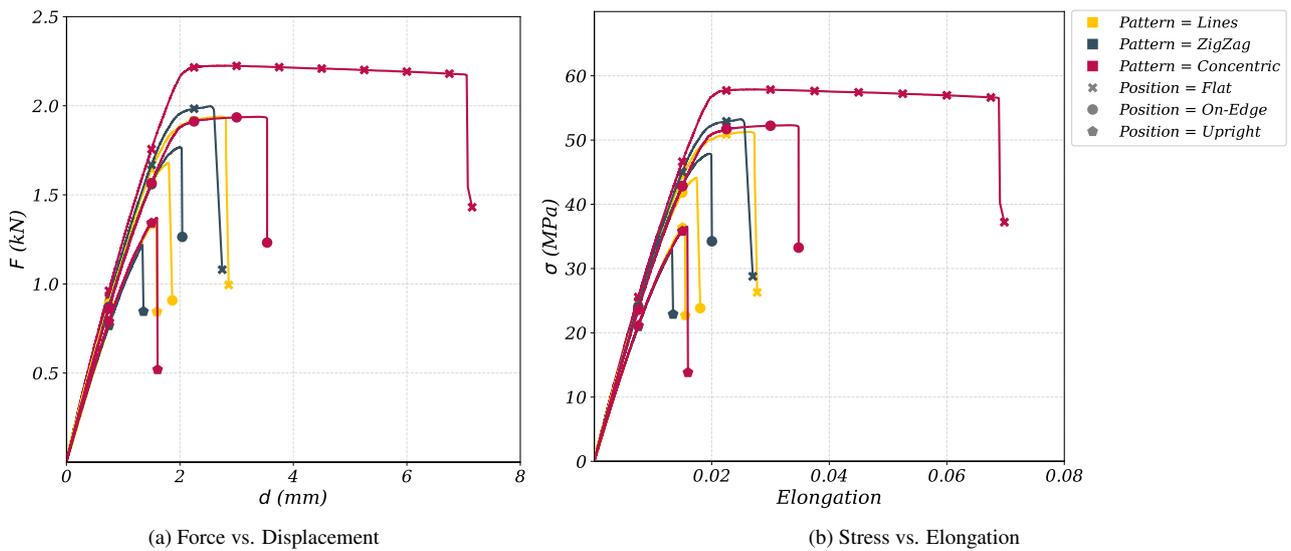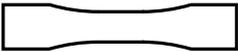(b) Stress vs. Elongation

Figure 11: Mean curves obtained for all the test bodies

In terms of mechanical properties, their averages for each of the configurations are shown in Table 5. The highest value for the Elasticity Modulus – which means greater stiffness – is given by the test body printed in the Flat position and with Lines pattern, but the others in that same position showed values statistically equivalent to it. The E shows a tendency to decrease as one moves towards the Upright printing position, in all deposition patterns. The greatest deviation ($I = -15.82\%$) from the first value occurred in the Upright position of the Concentric pattern. The trend for σ_{Y_0} is also towards a decrease as one goes towards the test bodies printed in Upright position, although the flow has started earlier for the PCs with flat position and line pattern. A higher initial yield strength means the need for greater stress to enter the plastic regime and therefore (as this must not be achieved for design within the elastic limit), greater strength. Equivalence and overlapping of ranges for this parameter were demonstrated between test bodies printed in Flat position with Lines and ZigZag patterns with respect to those printed in On-Edge position with Lines, ZigZag and Concentric patterns. The test body with the highest resistance and positive deviation from the reference value was printed in a F;at position ($I = 22.17\%$) with a Concentric pattern, and the one with the lowest resistance and greatest negative deviation was printed in an Upright position and with a ZigZag pattern ($I = -25.62\%$). The same analysis carried out for σ_{Y_0} can be extended to σ_u, which increase means greater capacity to withstand a given stress level without failure occurring. Again, the test body with the highest value of the variable for this case was the Flat position and Concentric pattern ($I = 12.86\%$) and the lowest values were the Upright position and ZigZag and Concentric patterns ($I = -32.94\%$, -29.04%). In the case of $E\%_f$, a greater discrepancy was present regarding the analysis of the test bodies (tab:prop-af), and its increase means a greater capacity of the test body to undergo displacement without the failure occurring. The highest value of the parameter occurred for the PCs in a Flat position with a Concentric pattern ($I = 203.45\%$) and On-Edge with a Concentric pattern ($I = 89.66\%$), through an extension of the plastic regime, as demonstrated by their Stress vs. Elongation curve. The cases in which the elongation was lower were, as in the other analyses, those in the vertical position in which an overlap was observed in their ranges.

The highest value of the variables follows, therefore, the test bodies that undergo elongation in the direction of deposition of the fibers that compose them. It is natural to think that, for an anisotropic material composed of fiber association, the direction of greatest resistance is the longitudinal direction of the fibers, while the direction in which they are stacked will be the one of least resistance.

Table 5: Mean values of the parameters: Elasticity Modulus (E), Initial Yield Limit (σ_{Y_0}), Ultimate Tensile Strenght (σ_u) Percentual Elongation at Fracture ($E\%_f$) for the test bodies in each of the configurations.

	/////	/////	◎
	$E = 3090 \pm 47$ MPa ($I_E = 0.00\%$) $\sigma_{Y_0} = 40.6 \pm 1.5$ MPa ($I_{\sigma_{Y_0}} = 0.00\%$) $\sigma_u = 51.3 \pm 0.1$ MPa ($I_{\sigma_u} = 0.00\%$) $E\%_f = 2.9 \pm 0.2$ ($I_{E\%_f} = 0.00\%$)	$E = 3071 \pm 51$ MPa ($I_E = -0.61\%$) $\sigma_{Y_0} = 44.1 \pm 0.9$ MPa ($I_{\sigma_{Y_0}} = 8.62\%$) $\sigma_u = 54.1 \pm 1.7$ MPa ($I_{\sigma_u} = 5.46\%$) $E\%_f = 3.2 \pm 0.3$ ($I_{E\%_f} = 10.34\%$)	$E = 3087 \pm 78$ MPa ($I_E = -0.01\%$) $\sigma_{Y_0} = 49.6 \pm 1.3$ MPa ($I_{\sigma_{Y_0}} = 22.17\%$) $\sigma_u = 57.9 \pm 0.4$ MPa ($I_{\sigma_u} = 12.86\%$) $E\%_f = 8.8 \pm 1.2$ ($I_{E\%_f} = 203.45\%$)
	$E = 2923 \pm 15$ MPa ($I_E = -5.40\%$) $\sigma_{Y_0} = 40.2 \pm 3.2$ MPa ($I_{\sigma_{Y_0}} = -0.98\%$) $\sigma_u = 46.5 \pm 3.5$ MPa ($I_{\sigma_u} = -9.36\%$) $E\%_f = 2.2 \pm 0.3$ ($I_{E\%_f} = -24.14\%$)	$E = 3028 \pm 11$ MPa ($I_E = -2.01\%$) $\sigma_{Y_0} = 38.2 \pm 2.6$ MPa ($I_{\sigma_{Y_0}} = -5.91\%$) $\sigma_u = 49.5 \pm 2.7$ MPa ($I_{\sigma_u} = -3.51\%$) $E\%_f = 2.3 \pm 0.2$ ($I_{E\%_f} = -20.69\%$)	$E = 2894 \pm 38$ MPa ($I_E = -6.34\%$) $\sigma_{Y_0} = 42.7 \pm 1.4$ MPa ($I_{\sigma_{Y_0}} = 5.17\%$) $\sigma_u = 52.4 \pm 1.7$ MPa ($I_{\sigma_u} = 2.14\%$) $E\%_f = 5.5 \pm 0.3$ ($I_{E\%_f} = 89.66\%$)
	$E = 2683 \pm 85$ MPa ($I_E = -13.17\%$) $\sigma_{Y_0} = 30.8 \pm 1.2$ MPa ($I_{\sigma_{Y_0}} = -24.14\%$) $\sigma_u = 37.6 \pm 0.5$ MPa ($I_{\sigma_u} = -26.70\%$) $E\%_f = 1.6 \pm 0.1$ ($I_{E\%_f} = -44.83\%$)	$E = 2682 \pm 53$ MPa ($I_E = -13.24\%$) $\sigma_{Y_0} = 28.8 \pm 1.1$ MPa ($I_{\sigma_{Y_0}} = -29.06\%$) $\sigma_u = 34.4 \pm 2.4$ MPa ($I_{\sigma_u} = -32.94\%$) $E\%_f = 1.5 \pm 0.2$ ($I_{E\%_f} = -48.28\%$)	$E = 2601$ MPa ($I_E = -15.82\%$) $\sigma_{Y_0} = 30.2$ MPa ($I_{\sigma_{Y_0}} = -25.62\%$) $\sigma_u = 36.4$ MPa ($I_{\sigma_u} = -29.04\%$) $E\%_f = 1.6$ ($I_{E\%_f} = -44.83\%$)

7. CONCLUSION

The conclusions of this work were:

- ❖ The 3D Printed parts via FDM process presented anisotropy and their properties varied greatly depending on the chosen printing position/pattern;

- ❖ The test bodies printed in the Flat position witha Concentric pattern presented the highest mechanical strenght and tenacity ($E = 3087 \pm 78$ MPa, $\sigma_{Y_0} = 49.6 \pm 1.3$ MPa, $\sigma_u = 57.9 \pm 0.4$ MPa, $E\%_f = 8.8 \pm 1.2$);

- ❖ The test bodies manufactured in an Upright position presented the most brittle behavior and lower resistence ($E = 2682 \pm 53$ MPa, $\sigma_{Y_0} = 28.8 \pm 1.1$ MPa, $\sigma_u = 34.4 \pm 2.4$ MPa, $E\%_f = 1.5 \pm 0.2$);

8. ACKNOWLEDGEMENTS

9. REFERENCES

ASTM, 2012. "Standard terminology for additive manufacturing technologies". *ASTM International F2792-12a*.

ASTM, 2015. "Standard test method for tensile properties of plastics". *ASTM International D638-14*.

Bajpai, P.K., Singh, I. and Madaan, J., 2014. "Development and characterization of pla-based green composites: A review". *Journal of Thermoplastic Composite Materials*, Vol. 27, No. 1, pp. 52–81.

Balla, E.D., Daniilidis, V., Karlioti, G., Kalamas, T., Stefanidou, M., Bikiaris, N.D., Vlachopoulos, A., Koumentakou, I. and Bikiaris, D.N., 2021. "Poly(lactic acid): A versatile biobased polymer for the future with multifunctional properties—from monomer synthesis, polymerization techniques and molecular weight increase to pla applications". *Polymers*, Vol. 13.

Chacón, J., Caminero, M.A., García-Plaza, E. and Núñez, P.J., 2017. "Additive manufacturing of pla structures using fused deposition modelling: Effect of process parameters on mechanical properties and their optimal selection". *Materials & Design*, Vol. 124, pp. 143–157.

Garlotta, D., 2001. "A literature review of poly (lactic acid)". *Journal of Polymers and the Environment*, Vol. 9, No. 2, pp. 63–84.

Gibson, I., Rosen, D.W., Stucker, B., Khorasani, M., Rosen, D., Stucker, B. and Khorasani, M., 2021. *Additive manufacturing technologies*, Vol. 17. Springer.

Gupta, B., Revagade, N. and Hilborn, J., 2007. "Poly (lactic acid) fiber: An overview". *Progress in polymer science*, Vol. 32, No. 4, pp. 455–482.

Heo, D.N., Castro, N.J., Lee, S.J., Noh, H., Zhu, W. and Zhang, L.G., 2017. "Enhanced bone tissue regeneration using a 3d printed microstructure incorporated with a hybrid nano hydrogel". *Nanoscale*, Vol. 9, No. 16, pp. 5055–5062.

Kristiawan, R.B., Imaduddin, F., Ariawan, D., Ubaidillah and Arifin, Z., 2021. "A review on the fused deposition modeling (fdm) 3d printing: Filament processing, materials, and printing parameters". *Open Engineering*, Vol. 11, pp. 639 – 649.

Ngo, T.D., Kashani, A., Imbalzano, G., Nguyen, K.T. and Hui, D., 2018. "Additive manufacturing (3d printing): A review of materials, methods, applications and challenges". *Composites Part B: Engineering*, Vol. 143, pp. 172–196.

Scopigno, R., Cignoni, P., Pietroni, N., Callieri, M. and Dellepiane, M., 2017. "Digital fabrication techniques for cultural heritage: A survey". *Computer Graphics Forum*, Vol. 36.

Wong, K.V. and Hernandez, A.F., 2012. "A review of additive manufacturing". *International Scholarly Research Notices*, Vol. 2012, pp. 1–10.

10. RESPONSIBILITY NOTICE