# A Comparative Analysis of the Mechanical Properties of Annealed PLA

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**Abstract-In order to obtain better performance, 3D printed parts can be the subject of post-processing operations like sanding, gap filling, polishing, annealing, epoxy coating, and metal plating. This paper takes into consideration the most commonly used material filament for FFF technology PLA and studies the mechanical characteristics through tensile and 3-point bending tests. The obtained results reveal significantly higher values of the mechanical properties after applying a 3-hour heat treatment at 75°C, for the following combinations of parameters: layer thickness of 0.10, 0.15, and 0.20mm and infill percentage of 50%, 75%, and 100%.**

***Keywords-3D printing; annealing; tensile test; 3 point bending test; flexural strength***

## I. INTRODUCTION

The need to achieve time and cost reduction of part fabrication allowed 3D printing technology to attract scientific interest. Although FFF is a commonly used method for obtaining parts, it has several disadvantages, like low cohesion between the fused layers, low tensile properties, and low resistance to humidity. In order to improve the mechanical characteristics and increase the percentage of crystallinity in the parts obtained by FFF annealing, a post-process heat treatment can be applied [1-3]. After a 3D printed filament is heated to be extruded through a nozzle, it is often relatively rapidly cooled. Uneven cooling may cause the shrinkage of the layers, which results as the effect of inadequate heat propagation in the structure of the printed part, especially in in the extremities. Therefore this process causes the tensile and compressive stresses to accumulate in the structure of the polymer.

Annealing consists in gradually heating in the oven of the samples or parts, at a temperature between the glass transition and the melting temperatures. This treatment consists of heating and cooling slowly in order to increase the bounding crystalline structures in the polymer and redistribute the stresses inside the printed part which will give higher crystallinity, mechanical resistance, and rigidity. Recrystallized PLA products also present a huge advantage compared to amorphous products: much higher Heat Deflection Temperature (HDT). While amorphous PLA products have an HDT of 50°C, semi-crystalline PLA products have an HDT of 130°C. Although PLA can be recrystallized after processing into a product, the products shrink and significant warpage occurs during recrystallization due to the increasing crystallinity. Distortion-free semi-crystallized PLA products can only be made during the process using nucleating agents [3-5].

The aim of this paper is to compare the influence of signaling factors, such as layer thickness and percentage of filling of PLA printed parts on the tensile and bending properties with annealed PLA printed parts in terms of various printing parameters.

## II. MATERIALS, METHODS AND PROCEDURES

### A. Set-up Process Parameters

Although 3D printing offers a wide range of applications, it still has certain limitations that may be improved through annealing. Because 3D printed materials have an amorphous molecular structure and no precise melting point, they gradually soften until they completely melt. This feature can be used as an advantage because in the event of annealing, the molecules in the material rearrange themselves, which can result in improved mechanical characteristics, i.e. making an object stronger. The specifications collected from filament producers of the PLA material used in this study are shown in Table I. In this experimental study, three infill percentages were used: 50%, 75%, and 100%, and in order to asset the

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mechanical characteristics, tensile and flexural tests were conducted on the annealed and unannealed samples and the results were compared. For the annealing heat treatment, the samples were kept for a period of 3h at a temperature of 60$^{0}$C, with a very slow cooling. All samples were cooled together in an oven.

TABLE I. 3D PRINTED SAMPLE PARAMETERS

| Parameters | Material specifications |
|---|---|
| | **PLA** |
| Nozzle diameter | 0.40mm |
| Build orientation | Flat |
| Top solid layers | 4 layers |
| Bottom solid layers | 4 layers |
| Outline/perimeters shell | 3 outlines |
| Internal fill pattern | Lines |
| External fill pattern | Rectilinear |
| Internal infill angle offsets | 180° |
| Extruder temperature | 210°C |
| Heated bed temperature | 60°C |
| Default printing speed | 70mm/s |
| Filament diameter | 1.75mm |
| Filament density | 1.24g/cm$^3$ |

## B. Sample Preparation

The samples were printed with a Raise E2 3D printer with a volume capacity of 330×240×240mm. The design of the samples, later converted in STL format, was made in Autodesk Inventor and Idea Maker software was used to adjust process parameters such as internal structure pattern, infill percentage, and layer thickness. The printing speed was set to 80mm/s in X-Y deposition direction at a deposition temperature of 200°C.

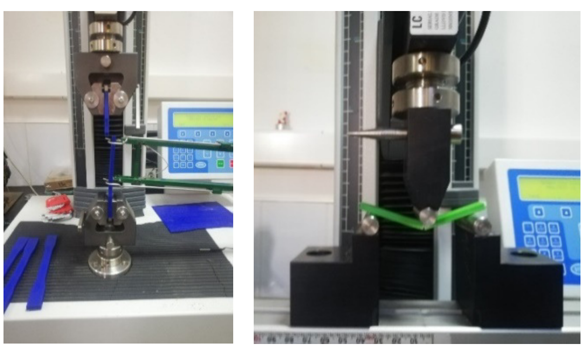

Fig. 1. Tensile and flexural sample testing on the Lloyd LRX Plus Testing Machine.

The process parameters considered as variables were the thickness of the deposited layer (0.1, 0.15, and 0.20mm) and the infill percentage (50%, 75%, and 100%). A Lloyd LRX Plus Testing Machine (Figure 1) was used for both tensile and flexural tests.

## C. Tensile Tests

In order to evaluate the mechanical behavior, in the first phase, tensile tests were performed [6]. Sets of 5 specimens were printed for each of the characteristics considered in the study, with standard dimensions of 165mm length, 5mm thickness, and 13mm width.

## D. Flexural Tests

This method is used to study the bending behavior and to determine the flexural strength. The test speed was set at 1mm/min and the distance between the supports was determined to be 64mm (L=16h, where h is the height of the sample [7]). All tests were performed at 20°C and the samples were acclimatized for 24h. The geometrical features of the samples were made with standard dimensions of 10mm width, 4mm thickness, and 80mm length.

# III. RESULTS AND DISCUSSION

## A. Tensile Tests

Due to the vast volume of content resulting from the testing of a large number of samples, instead of presenting the tables with the values of all 5 determinations, it was opted to do it only for layer thickness of 0.1 and only for the ultimate tensile strength. For 0.15 and 0.20 layer thicknesses, only the values of the averages of the determinations of linear specific deformation and Young's modulus are given. The average of the 5 determinations made for each sample, is also presented in graphical form for the better understanding of the differences between the samples with heat and without heat treatment.

TABLE II. ULTIMATE TENSILE STRENGTH TEST VALUES OF UNANNEALED PLA FOR 0.1 LAYER THICKNESS

| Infill % | Ultimate tensile strength, MPa | | | | | |
|---|---|---|---|---|---|---|
| | Sample | | | | | |
| | 1 | 2 | 3 | 4 | 5 | Average |
| 50% | 24.64 | 24.90 | 24.77 | 24.69 | 24.18 | 24.64 |
| 75% | 25.90 | 25.92 | 26.54 | 27.04 | 26.36 | 26.35 |
| 100% | 31.92 | 33.82 | 32.25 | 33.74 | 35.82 | 33.51 |

TABLE III. ULTIMATE TENSILE STRENGTH TEST VALUES OF ANNEALED PLA FOR 0.1 LAYER THICKNESS

| Infill % | Ultimate tensile strength, MPa | | | | | |
|---|---|---|---|---|---|---|
| | Sample | | | | | |
| | 1 | 2 | 3 | 4 | 5 | Average |
| 50% | 32.06 | 30.42 | 30.61 | 30.23 | 31.76 | 31.02 |
| 75% | 35.44 | 34.99 | 34.90 | 37.10 | 37.10 | 35.90 |
| 100% | 42.60 | 43.49 | 41.09 | 43.80 | 48.72 | 43.94 |

As can be seen in Tables II and III, the ultimate tensile strength values of all tested samples are higher, which reveals that annealing modifies the mechanical characteristics of the parts obtained by 3D printing in a positive way. They have been increased by enriching the material's crystallinity, which carried out higher values of ultimate tensile strength, as can be graphically seen in Figures 2-4. For each value of layer thickness studied, an ascending trend can be observed with increasing infill percentage.

TABLE IV. ULTIMATE TENSILE STRENGTH TEST VALUES OF UNANNEALED PLA FOR 0.1 LAYER THICKNESS

| Mechanical characteristics | Infill percentage | | | | | |
|---|---|---|---|---|---|---|
| | 50% | | 75% | | 100% | |
| | WA | A | WA | A | WA | A |
| Ultimate tensile strength, MPa | 24.64 | 31.00 | 26.35 | 35.90 | 33.51 | 43.91 |
| Linear specific deformation, % | 6.47 | 5.52 | 5.73 | 5.01 | 5.64 | 4.85 |
| Young's modulus, MPa | 2312 | 2120 | 2423 | 2146 | 2523 | 2224 |

As can be seen in Tables IV and V, a comparison was made between the average values of samples without annealing (WA) and of the annealed (A). An increasing trend of about 30% for the values of ultimate tensile strength can be observed, regardless of the infill percentage of the samples. The linear specific deformation and Young's modulus both have a decreasing tendency.

TABLE V. ULTIMATE TENSILE STRENGTH TEST VALUES OF ANNEALED PLA FOR 0.15 LAYER THICKNESS

| Mechanical properties | Infill percentage | | | | | |
|---|---|---|---|---|---|---|
| | 50% | | 75% | | 100% | |
| | WA | A | WA | A | WA | A |
| Ultimate tensile strength, MPa | 25.94 | 30.04 | 28.04 | 34.77 | 40.07 | 48.05 |
| Linear specific deformation, % | 3.54 | 3.01 | 4.19 | 3.90 | 4.72 | 4.08 |
| Young's modulus, MPa | 2124 | 1931 | 2266 | 2130 | 2607 | 2528 |

TABLE VI. ULTIMATE TENSILE STRENGTH TEST VALUES OF ANNEALED PLA FOR 0.2 LAYER THICKNESS

| Mechanical properties | Infill percentage | | | | | |
|---|---|---|---|---|---|---|
| | 50% | | 75% | | 100% | |
| | WA | A | WA | A | WA | A |
| Ultimate tensile strength, MPa | 23.80 | 27.49 | 26.96 | 31.95 | 35.58 | 41.63 |
| Linear specific deformation, % | 3.76 | 3.45 | 3.71 | 3.52 | 3.59 | 3.31 |
| Young's modulus, MPa | 1813 | 1586 | 2132 | 2076 | 2248 | 2187 |

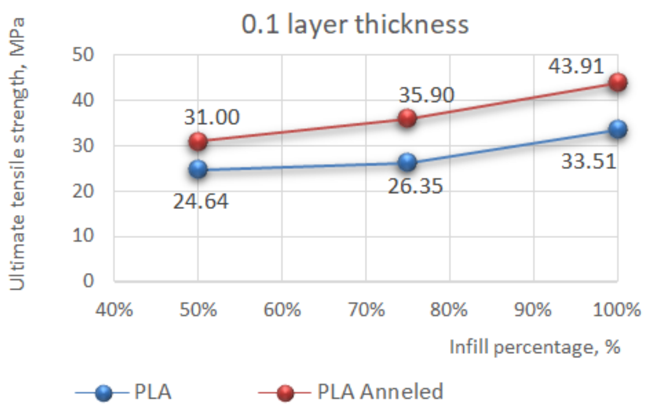


Fig. 2. Ultimate tensile strength variation of 0.1 layer thickness for varying infill procentage.

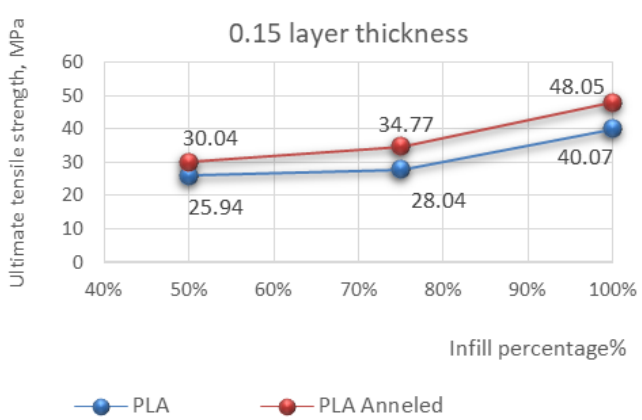


Fig. 3. Ultimate tensile strength variation of 0.15 layer thickness for varying infill procentage.

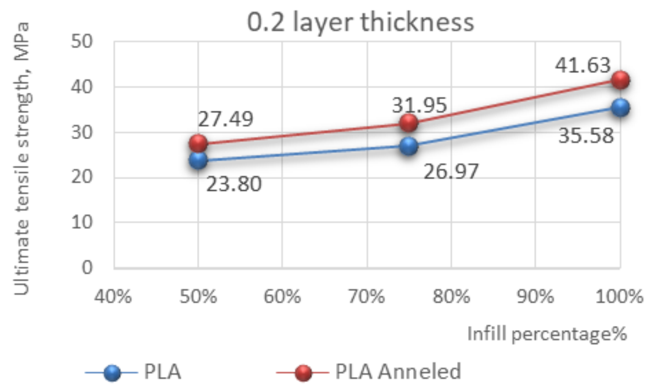


Fig. 4. Ultimate tensile strength variation of 0.2 layer thickness for varying infill procentage.

The average of the determinations made for the values from Tables IV-VI, is being presented in graphical form in order to highlight the differences between the A and the WA samples.

## *B. Flexural Tests*

As with the tensile tests, 5 test samples were performed for each of the 3 infill percentages of 50%, 75%, and 100%. As can be seen in the comparative graphical representations of Figures 5-7, the values of maximum flexural strength are clearly higher in the case of annealed samples. As in the tensile tests, there is a tendency for values to increase by about 15% for 0.1 and 0.15mm layer thickness [8]. The values obtained for 0.2mm layer thickness are lower, although here too there is an upward trend.

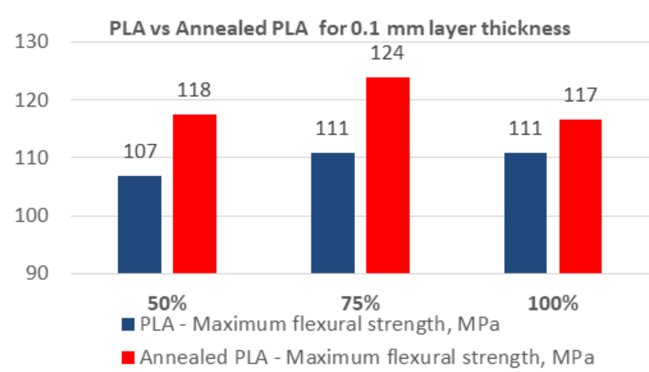


Fig. 5. Maximum flexural strength comparison between PLA and annealed PLA for 0.1mm layer thickness.

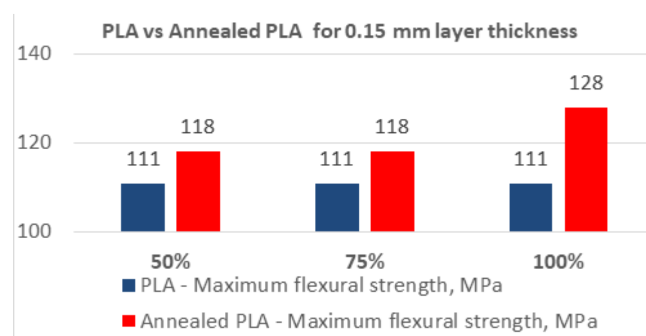


Fig. 6. Maximum flexural strength comparison between PLA and annealed PLA for 0.15mm layer thickness.

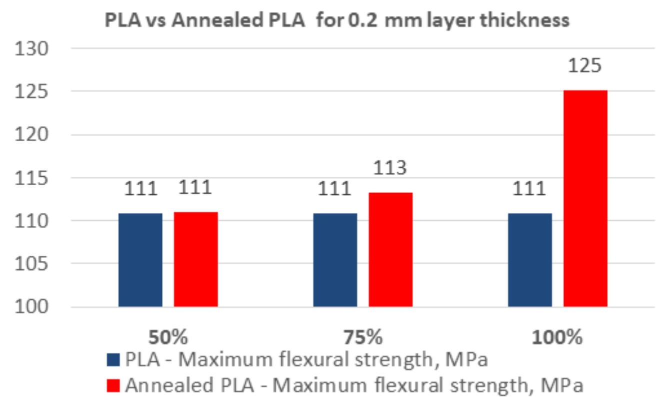


Fig. 7. Maximum flexural strength comparison between PLA and annealed PLA for 0.2mm layer thickness.

## IV. CONCLUSIONS

The objective of this paper was to highlight the variation of mechanical characteristics of annealed PLA 3D printed materials, with different parameters of the technological process.

When comparing the average values of samples with and without annealing, an increased trend of about 30% for the values of ultimate tensile strength can be observed, regardless of the infill percentage of the samples. Both linear specific deformation and Young's modulus have a decreasing tendency. Similar results have been obtained in other studies, for example a 30.25% increase in the ultimate strength compared to the as-printed samples was found in [9-11]. An annealing of 1h duration resulted in 24% increase in ultimate strength in [12].

Maximum flexural strength values are clearly higher in the case of annealed samples. There is a tendency for values to increase by about 15%, very similar to the 11%–17% obtained in [13].

Several signal factors such as deposition style and orientation and also raster gap and width can influence the values of the mechanical characteristics of the 3D printed samples without annealing. Also, soaking time and cooling rate can lead to different values for the heat treated parts. So, having taken into account all these aspects, the differences between the values in this article and the values from other studies [8, 10, 11, 14] can be explained. Future work will focus on the way the main factors of the annealing process influence the main mechanical properties of 3D printed parts.

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