A CASE STUDY ON THE EFFECT OF PRINTING TEMPERATURE ON THE TENSILE STRENGTH OF 3D PRINTED PARTS WITH PLA MATERIAL

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Abstract. The fusion between the layers of a 3D printed part greatly influences the overall mechanical properties and can reduce its applications in certain domains. In order to obtain a better bonding between layers a study on the influence of printing temperature on the tensile strength of 3D printed parts is needed. The mechanical experiments were made on printed parts with polylactic acid material (PLA) on an open-source 3D printer with filament fabrication technology (FFF). The study is made on parts with the same layer height, infill ratio, dimensions, printed at the same speed. The obtained results show the influence of material printing temperature and the fast cooling on the mechanical properties of the 3D printed parts.

Keywords: 3D printer, polylactic acid material, tensile strength, filament fabrication technology,

1. INTRODUCTION

The 3D printing technology started as a rapid prototyping technology and later started to be used as a manufacturing method due to the offered advantages such as production cost reduction, minimization of material loss, ability to create complex geometries and the low intensive level of labor required. There are many areas in which the 3D printing technology has found new applications such as: construction and civil engineering, aerospace, biomedical engineering, and robotics [1-11].

In 3D printing one of the most used production techniques is the fused filament fabrication (FFF). This method of producing 3D parts involves the deposition of extruded polymeric material through a heated nozzle in a layer-by-layer manner until the desired object shape is obtained. In the printing process defects like gaps between layers, adhesion variation from layer to layer and part shrinkage during the cooling period after printing can affect the mechanical property of the 3D part [12,13].

Several parameters such as layer thickness, build orientation, infill pattern, infill density, printing speed have strong influence on mechanical properties of the 3D printed parts [13-15]. As such, in order to obtain good quality components several process variables and their effects need to be understood and optimized.

With the growing interest in 3D printing technologies the number of polymer materials used for additive manufacturing is also increasing. Polylactic acid (PLA) is one of the most used in FFF printing technology. The PLA material is a aliphatic polyester which is derived from lactic acid [16].

The PLA material is biodegradable, has low toxicity, has high hardness and strength. The limitation in the usage of PLA is due to the low temperature deflection, brittleness and poor crystallization [17].

In recent years the increase of oil prices started a trend to replace the petroleum-based polymers with biodegradables materials in 3D printing production in order to improve the eco-friendliness of the parts. In literature are some works that evaluates the mechanical properties of polymers such as PLA [18,19].

The orientation in which a 3D printed part is build and the produced effect have been studied in order to improve the mechanical capabilities of the objects obtained with FFF technology. The results show that the best mechanical properties are obtained if the tensile load direction is the same as the direction of the filament deposition [13,20,21]. Only recently studies on flexural, tensile and compressive properties in relation with printing orientation and infill density of 3D parts were made. Most of previous research focuses on build orientation, infill pattern, infill density and raster angle with less attention at the influence of temperature and usage of fan cooler to reduce part warping on the bonding between layers and in consequence the mechanical properties of the printed part.

In this paper a study on the influence of printing temperature on mechanical properties of 3D printed parts with PLA material is presented. More precise a series of parts were 3D printed with the same printing variables at different printing temperatures and mechanically tested to obtain their mechanic properties.

The structure of the paper is as follows. The experimental method and details are described in Section II. Experimental results are presented in Section III. Finally, the conclusions are drawn in Section IV.

2. EXPERIMENTAL SETUP

Figure 1. The computer-aided design (CAD) model of the used 3D printer during experiments

The general use open-source 3D printers often have belts for OX and OY axis movements. Also, there can be 3D printed parts included in the printer mechanical system which can worn out in time and introduce displacement errors of the heating head. These errors can induce gaps or layer misalignment which affects the overall mechanical performance of the 3D parts. As such we developed a 3D printer (fig. 1) after the models of open-sources ones found on market.

In the design we took in consideration and applied methods to minimize the backlash and hysteresis as much as possible to improve the repeatability and the reduction of printing errors in the printed parts. Some of the modifications are the replacements of the belts with screws, the usage of anti-backlash nuts, good linear guides and high-performance stepper motor drivers. This way we can be sure that during the production of the 3D printed experimental parts we have the same printer mechanical parameters and less errors.

The printer has the following printing volume 150 mm×110 mm×75 mm. The obtained positional accuracy of the device is under 15μm on all axis.

The printer framework is made from high pressure laminate (HPL) of 2 cm thickness in order to remove the flexing and vibrations caused by inertia forces during the printing operations. A steel bottom plate was added to

increase stability of the structure and the entire frame was designed to keep the center of gravity as close as possible to the center line of the printer.

A cooling fan was used to cool the heatsink of the heating head to eliminate the heat creep that can induce unwanted clogs and uneven extrusion. Part of the airflow can also be used to cooldown the printed part to remove warping and to allow an even print without many internal strains du to thermal stress.

During the printing operation of the experimental samples an Ambiental temperature of 21° C was maintained and the only temperature variations were caused by the printer itself. In this way we can better understand the influences of temperature during the printing process on the bonding between the layers of the printing part.

The printer parameters used in the printing process of the experimental samples were:

- Print speed: 80 mm/s
- Nozzle diameter: 0.4 mm
- Filament diameter: 1.75 mm
- Heat bed temperature: 60 ° C
- Shell thickness: 0.8 mm
- Top/bottom thickness: 0.6 mm
- Infill overlap: 30%
- Infill pattern: grid
- Infill percentage: 40%
- Layer height 0.3 mm

Figure 2. Printing orientations of the experimental sample

To test the bounding strength between layers and overall strength of the part we printed the samples in two orientations: flat (fig.2 left) and standing (fig. 2 right). The standing orientation will give a more accurate result on the bonding strength and the flat orientation will better describe the overall mechanical parameters of the printed part.

Figure 3. CAD design of the experimental sample

The shape and dimensions of 3D printed part can be observed in fig. 3. The shape was designed so that the vises of the tensile strength test machine will have a good grip on the tips of the experimental samples.

3. EXPERIMENTAL RESULTS

Figure 4. Tensile strength test machine during experiment

The first experiment consists of analysis on a tensile strength test machine (fig. 4) of 3D printed parts on flat orientation, using the fan to cool down the deposited layers, with the following printing temperatures: 190° C, 195° C, 200° C, 205° C, 210° C, 215° C and 220° C. The results can be observed in table 1.

Table 1. Experimental results for printed parts with flat orientation and cooling active

Temperature (° C)	Tensile load (kN)	Tensile strength (kN/mm ²)	Modulus (MPa)
190	0.329	0.008	465.585
195	0.375	0.009	504.879
200	0.409	0.010	570.914
205	0.420	0.010	577.755
210	0.442	0.011	625.559
215	0.437	0.010	547.926
220	0.532	0.012	523.931

As the results show at lower temperature the bonding between layers is not strong enough and the part easily breaks. At higher temperatures the printed part becomes brittle.

The second experiment is similar with the previous experiment but in this case no cooling was applied. The results can be observed in table 2.

Table 2. Experimental results for printed parts with flat orientation and without cooling

Temperature (° C)	Tensile load (kN)	Tensile strength (kN/mm ²)	Modulus (MPa)
190	0.380	0.009	527.413
195	0.448	0.011	580.548
200	0.474	0.011	589.847
205	0.507	0.012	576.082
210	0.513	0.012	590.945
215	0.499	0.012	561.972
220	0.523	0.012	597.146

These results show that the printing temperature has influenced the tensile strength property of the part and the higher the temperature the better is the bond between layers. From the data we can observe that the modulus seems more irregular which means that due to the uneven cooling areas with different values of elasticity can appear within the part.

The first two experiments are made to observe the overall mechanical properties of the part in different printing temperature conditions. The next experiment is made on samples printed on standing orientation to better understand the influence of printing temperature on the bonding between layers. In this orientation the test machine will pull the layer apart and the break will happen on the weakest bond. The results can be observed in figure 5.

Figure 5. Stress versus strain on samples printed in standing orientation

The obtained results demonstrate the influence of temperature on the bonding between layers. At low temperature the bonding is weak (190° C, 195° C, 200° C, 205° C) and uneven (195° C). On the 195° C sample the break happened in two different places and the material between them was stretched until the complete break. At higher temperature the printed part is more elastic and is more durable. As it can be seen the best result, in terms of stress, is at 215° C but at 210° C we obtain the best elasticity and a good stress performance.

4. CONCLUSION

A study on the effect of printing temperature on the tensile strength of 3D printed parts with PLA material was carried out. The study also showed the effect of the cooling of the material during the 3D printing operation.

The experimental data proved that prove that the cooling of the part during the printing process will result in more even bonding between layers. Also, the temperature greatly affects the mechanical properties of the part. At lower temperature the bonding between layer is weak and at higher temperature the part becomes brittle. The best temperature that the data has shown, for 3D printing with PLA, is 210° C.

An analysis on samples printed on standing orientation was held to better understand the printing temperature influence on the bonding between layers. The results show that a good bonding between layers with good elasticity is obtained at 210° C.

5. REFERENCES

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