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Influence of Annealing Time on Tensile Strength and Change of Dimensions of PLA Samples Produced by Fused Filament Fabrication

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Abstract

Annealing is a well-known technology of heat treatment, which is commonly used for metallic materials. Nowadays, with the growth of 3D printing technologies, the first experiments with annealing of plastic prints are starting to appear. One of the most important parameters of plastic annealing is the annealing time. This article deals with the experimental determination of the influence of annealing time on tensile strength and change of dimensions of printed samples from PLA. The samples were annealed in the industrial oven for 15, 30, 45, 60 and 240 minutes at 110 °C. After gradual cooling in air, they were measured and tested on a tensometer, which produces stress-elongation curves. The measurement results showed that all annealed samples changed in size depending on the position at which they were printed. For all different annealing times, the deformations of the annealed samples were approximately the same. The tensile strength of all annealed samples increased compared to the non-annealed ones. Also, no dependence between tensile strength and annealing time was found.

Introduction

Additive Manufacturing currently plays one of the key roles in design [1]. The most commonly used Additive Manufacturing technologies are Fused Filament Fabrication (FFF) or Fused Deposition Modeling (FDM)[2]. Both of these technologies are identical, but FDM is a registered trademark of Stratasys, so other printer manufacturers cannot use it and use the FFF designation. This technology is also currently the most widespread in the area of hobby 3D printers, whose prices are decreasing rapidly. This is due to the expiration of protection patents for this technology, and so the production of these printers has increased [3].

Although production by FFF technology is relatively simple, it is necessary to have good knowledge of the parameters and capabilities of both the technology and the materials itself to achieve the desired outcome [4]. There are many materials available for 3D printing on the market today. Each of them has different properties and therefore is suitable for different purposes. They also behave differently before, during and after printing [1]. In some cases, the prints are further processed after printing (post-processing). By doing so, for example, improved surface quality, required dimensions, and geometric accuracy, or desired material properties can be achieved [5].

Polylactic acid (PLA) is one of the most widely used materials for FFF [6]. It is a non-toxic (suitable for use in the human body) bioabsorbable polymer. According to the United States Food and Drug Administration, it is classified as a safe material and can be used in the food industry as well as in medical industry [7]. In FFF technology, it is mainly used because it is easy to print, has good mechanical properties, and low cost. After the object is printed, it can be heat-treated, which changes its properties. One of the heat treatment processes is annealing.

Annealing is a process whereby a printed plastic part is heated to a specific temperature, then maintained at that temperature for some time and then allowed to cool to room temperature in air. This process reduces the internal stress in the plastic part, that has been generated by thermal expansion during printing [8] and improves the resulting strength of the part [9].

Several researches about the PLA annealing process were already conducted, which has shown that the annealed samples are reaching greater strength than the non-annealed ones. [1,9,10]. This article adds to those studies [1,9,10] with an experimental determination of the influence of the time of annealing on the resulting tensile strength of the printed samples and the change in their dimensions. The samples were printed by FFF method from PLA material.

Among other things, the results of the experiment will help in the application of 3D printing in several robotics systems such as snake robotic devices [11], walking robotic devices [12] and modular systems [13] which are being developed in our department, where annealing of printed parts could help to improve the parameters of these devices.

Description of Experiments

All the samples were made by FFF technology on ORIGINAL PRUSA I3 MK3S printer from Prusament PLA [14]. The used basic printing parameters are shown in Table 1.

Table 1: The used basic printing parameters

Nozzle width [mm]	Layer height [mm]	Infill [%]	Number of perimeters [-]	Nozzle temperature [°C]	Bed temperature [°C]
0.4	0.2	100	2	215	60

All samples were printed in the same position as shown in Fig.1 on the left. The dimensions of the test samples are shown in Fig. 1 on the right.

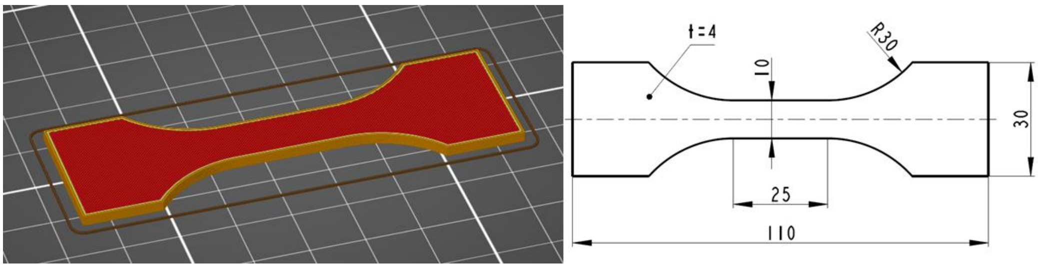

Fig. 1: Left – sample position on the bed, Right – sample dimensions

A total of 60 samples were printed. The basic dimensions of each sample were measured after printing and cooling it to room temperature. Then, they were annealed in the sets of 10 pieces in a Memmert UN 30 dryer over a period of 15, 30, 45, 60 and 240 minutes to 110 ° C, which is the recommended annealing temperature for PLA [10]. After they cooled to room temperature, the basic dimensions were re-measured to determine the formed deformation.

The samples were tested for tensile strength on a Testometric M500 / 50CT at room temperature. In addition to the annealed samples, 10 pieces of non-annealed samples were tested for subsequent comparison. Fig. 2 shows a test machine with tearing test sample.

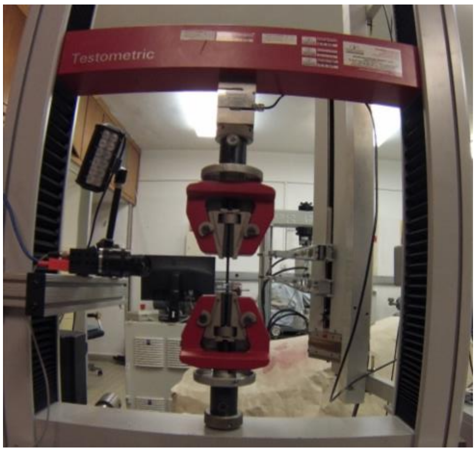

Fig. 2: Test machine Testometric M500/50CT with tearing test sample

Results

The experiment focused on detecting the change in sample's dimensions. The change in sample's geometric shape was not measured. The dimensions changed for all annealed samples. Dimensions were measured at the locations shown in Fig. 3. After annealing, the height (H1) of all samples has increased and all other dimensions decreased.

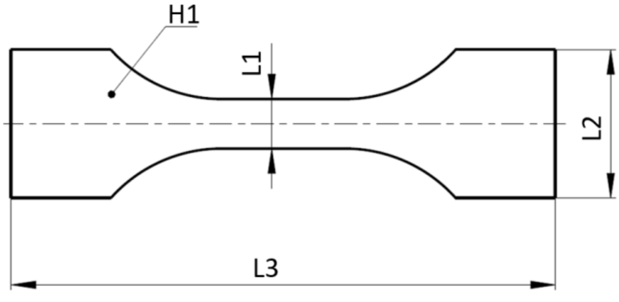

Fig. 3: Measured dimensions

Table 2 shows the average percentage change in dimension by annealing time.
From the table values, it can be seen that the average difference in dimension change between different annealing times for H1 is 1.05% and that for all other dimensions it does not exceed 0.5%. Thus, the annealing time has almost no effect on the resulting dimension change. On average, at all different annealing times, H1 increased by 12.14%, L1 decreased by 3.73%, L2 decreased by 5.80% and L3 decreased by 6.47%. Fig. 4 shows the influence of annealing time on dimension change.

Table 2: Average percentage change in dimension by annealing time

Annealing time [min]	ΔH1 [%]	ΔL1 [%]	ΔL2 [%]	ΔL3 [%]
15	12.10	-3.85	-5.84	-6.69
30	11.69	-3.78	-5.83	-6.46
45	11.93	-3.75	-6.03	-6.51
60	12.74	-3.39	-5.57	-6.26
240	12.25	-3.88	-5.72	-6.44

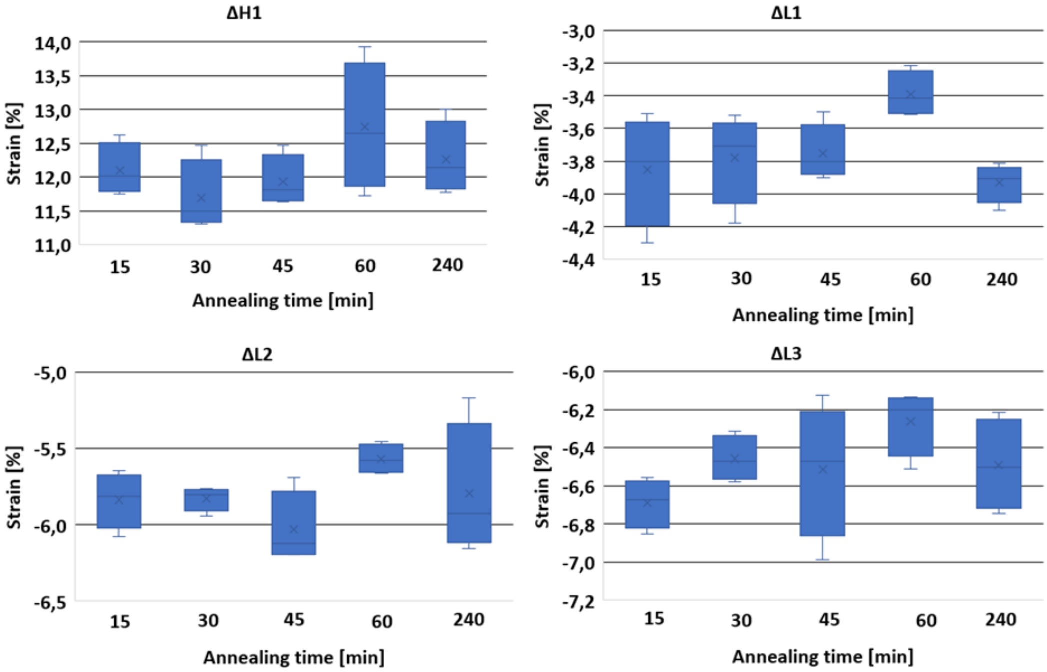

Fig. 4: Boxplots of the influence of annealing time on dimension change

Individual samples were then tested for tensile strength on a test machine. Fig. 1. 5 shows selected stress-elongation curves for individual annealing times. The curves show an increase in the strength value of the annealed samples.

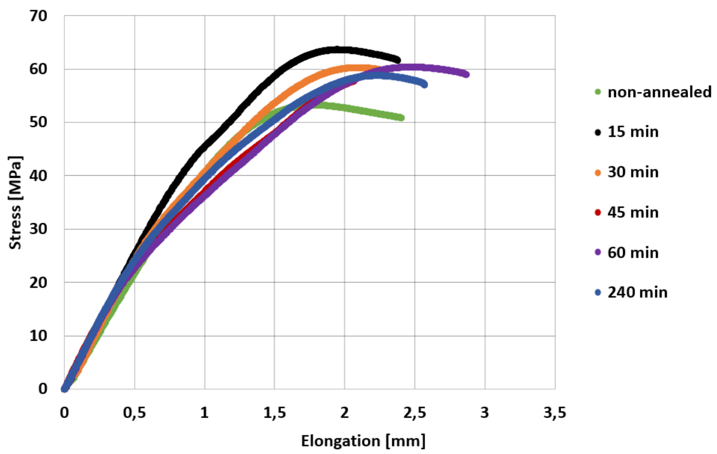

Fig. 5: Stress – elongation curve

Table 3 shows the average values of the tensile strength and the percentage increase in strength (compared to non-annealed samples). The experiment showed that annealing increases the tensile strength by approximately 10% and that the change of annealing time had minimal impact on it.

Table 3: Average values of the tensile strength and the percentage increase in strength

Annealing time [min]	Tensile strength [MPa]	Percentage increase in strength [%]
Non-annealed	53.86	-
15	61.15	13.54
30	59.03	9.59
45	59.89	11.20
60	62.28	15.63
240	60.51	12.34

Fig. 6 shows the influence of annealing time on tensile strength.

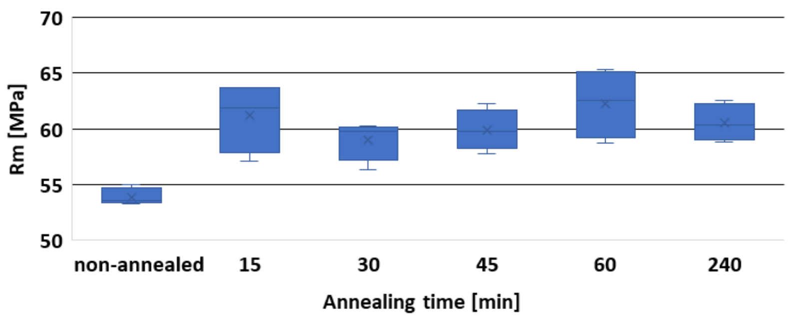

Fig. 6: Boxplots of tensile strength

Conclusions

All annealed samples have changed their dimensions as shown in Tab. 2 and FIG. 4. These dimension changes are dependent on the position at which the samples were printed. In the direction perpendicular to the printing surface (dimension H1 in Fig. 3), the dimensions of the test samples increased by an average of 12.14%. In other directions, the dimensions were reduced. The experiment did not prove the influence of the annealing time on the amount of deformation. It should be noted that the annealing time must be long enough for the entire material to be heated to a given temperature. Thereafter, the annealing time has no effect on the dimension change.

All annealed samples showed higher values of tensile strength as shown in Tab. 3, FIG. 5 and FIG. 6. On average, the tensile strength was increased by 10%. The experiment did not prove any influence of the annealing time on the tensile strength, once the entire material was heated to a given temperature.

The results of this work will be used for further research in the field of annealing of plastic materials for FFF technology.

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