Improving the Impact Resistance through Annealing in PLA 3D Printed Parts

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ABSTRACT

This study conducts an experimental exploration and thorough analysis of the influence of annealing on the impact resistance of PLA 3D-printed components. The investigation extends its scope to encompass the influence of printing parameters, specifically layer thickness and infill percentage. The research highlights that the impact resistance of annealed 3D printed PLA components is predominantly influenced by the infill percentage, with the highest impact energy observed at a full 100% infill. It is noticeable that the application of annealing post-processing heat treatment results in a remarkable, up to threefold, increase of the impact energy highlighting its potential efficacy as a viable technique for enhancing the mechanical integrity of PLA 3D printed products. Consequently, this study establishes annealing as a promising methodology, particularly for PLA 3D printing applications that encounter significant mechanical loads.

Keywords-3D printing; FDM; annealing; Charpy test; PLA

I. INTRODUCTION

The impact resistance of polylactic acid (PLA) is a critical parameter that significantly influences its practical applications. PLA, while widely appreciated for its biodegradability and compatibility with additive manufacturing techniques like 3D printing, does exhibit a notable limitation in impact strength [1], making PLA-based products susceptible to fracture or failure under certain mechanical loadings. Therefore, improvements in this direction are of significant industrial and technological importance [2]. In the context of its various applications, PLA's impact resistance plays a crucial role in determining its suitability for specific uses. For instance, in applications where structural integrity and robustness are dominant, such as in engineering components or load-bearing parts, PLA's inherent brittleness might impose constraints on its effective application. The low impact strength could lead to premature failure or reduced durability in applications involving dynamic loading or impact events [3-9]. Efforts to enhance PLA's impact resistance are of considerable interest from both industrial and technological perspectives. Various strategies, including material modifications, blending with impact modifiers, and processing optimization, are explored to address this limitation.

Annealing, serving as a heat treatment technique, stands out as a primary method of PLA modification, due to its cost-effectiveness [2, 11-13]. Annealing involves subjecting the polymer to a specific temperature range between the glass transition and the melting point, and maintaining this temperature for a specified duration. Other factors, such as printing parameters, can have a great influence on the mechanical behavior of 3D printed parts [13-22]. Charpy tests were performed in [1], on 3D-printed samples made of PLA and ABS, investigating the influence of layer thickness and infill percentage on their impact resistance. In [23], an impact test was executed to quantify the absorbed energy in the plastic deformation within 3D printed PLA components, encompassing diverse combinations of infill patterns and densities. The findings derived from the experimental assessment using the Izod impact test indicated that the highest energy absorption is achieved when the infill density reaches 85% across all infill patterns. The experimental investigation in [24] provides insights into the impact performance of PLA and PETG specimens manufactured through additive processes, revealing that PLA specimens generally experienced higher impact forces during testing. Authors in [25] focused on the influence of varying layer thicknesses (0.10, 0.20, 0.30, 0.40, 0.50 mm) and different print orientations (upright, flatwise, edgewise) on the impact strength of ABS, PLA, PET-G, and PC produced through additive manufacturing. Remarkably, the modification of layer thickness was found to exert the most pronounced effect on PC, followed sequentially by PET-G, ABS, and PLA. Polycarbonate PC demonstrated the highest impact strength, particularly when employing a layer thickness of 0.30 mm. On the other hand, PLA exhibited the least resistance to impact forces. It was also found that the upright print orientation yielded the lowest impact strength results among the evaluated orientations. The experimental results of [12] highlight the significant influence of carbon fiber reinforcement and infill density on the impact strength of annealed PETG and CFPETG. At 100% infill density, the annealing process increased the impact strength by 5.5% (for PETG samples) and 12% (for CFPETG samples). Following the heat treatment process at 80 °C and 90 °C, a substantial enhancement in impact strength was achieved in [2], with increases of 97.80% and 133.20% compared with as-built PLA specimens. Authors in [26] assessed how the impact performance of 3D printed nylon composites reinforced with continuous carbon, glass, and Kevlar fibers, produced using the FDM technique, is influenced by build orientation, layer thickness, and fiber volume content.

From the literature review presented above, it can be observed that a limited number of studies focused on the impact behavior of 3D printed parts, even less regarding the influence of post processing heat treatment. The aim of this paper is to analyze, in an innovative manner, the influence of annealing heat treatment correlated with printing parameters, such as layer thickness on impact resistance of PLA 3D printed parts. By meticulously investigating how annealing interacts with the printing parameters, the study sheds light on a previously unexplored dimension of optimizing impact resistance in PLA 3D printed parts.

II. MATERIALS AND METHODS

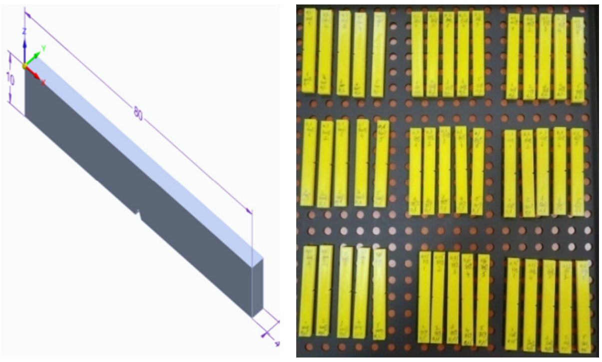
The technical specifications (Table I) were provided from the Raise filament producer through data sheets. A Raise E2 3D printer was used with a volume capacity of 330 × 240 × 240 mm. The printing parameters are presented in Table II. The samples dimensional characteristics can be seen in Figure 1(a). A notch type A was included in the design of the sample with radius $r_N = (0.25 \pm 0.05)$ mm.

TABLE I. 3D PRINTED SAMPLE CHARACTERISTICS

Parameters	Material specifications
Nozzle diameter	0.40 mm
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	45°-135°
Extruder temperature	210°C
Heated bed temperature	60 °C
Default printing speed	70 mm/s
Cooling fans	On
Filament diameter	1.75 mm
Filament density	1.24 g/cm^3

TABLE II. 3D PRINTING PARAMETERS

Constant parameters	Variable parameters
Build orientation X-Y	Layer thickness, L_t = 0.10 mm/0.15 mm/0.20 mm
Print speed – 80 mm/s	Infill percentage, I_p = 50%/75%/100%
Deposition temperature – 210 °C	
Infill model- lines, 45° orientated	



(a) (b)

Fig. 1. The samples used for experiments: (a) dimensions, (b) actual samples subjected to annealing.

The annealing procedure involved subjecting the samples to a temperature of 75 °C (slightly above the glass transition temperature of PLA) for 3 hr, followed by a gradual and controlled cooling process (Figure 1(b)). The samples were uniformly cooled together in the oven of Figure 2. The impact testing was done at the Liea laboratory, within ISIM Timișoara, on an Instron Pendulum Charpy tester (Figure 3), according to ISO 179-1:2010(E) [27].

Fig. 2. The oven used for the heat treatment.

Fig. 3. Impact testing machine.

III. RESULTS AND DISCUSSION

We aimed to examine how printing parameters and annealing heat treatment affect the impact resistance of PLA 3D printed parts, assessing the combined influence of these variables. For every specific group of process parameters, a set of five specimens was prepared. The outcome of the mechanical test was determined based on the average impact strength values derived from these specimens. The values of maximal energy absorbed for each combination of printing parameters, both for annealed and as-built PLA evaluated samples can be seen in Table III. The total absorbed energy of the impact is calculated by [26]:

$$E_T = mg\left(h_0 - h_f\right) \pm 0.2\ (\mathrm{J}) \qquad (1)$$

where E_T is the total absorbed energy, m is the mass, g is the gravitational acceleration, h_0 is the original height, and h_f is the final height.

TABLE III. AVERAGE VALUES OF PLA IMPACT ENERGY

Lt [mm]	*Ip* [%]	Energy [J] Annealed samples	Energy [J] As-built samples	Difference %
0.10	50	0.162	0.072	125.07
	75	0.228	0.088	157.62
	100	0.220	0.078	181.29
0.15	50	0.167	0.078	114.10
	75	0.235	0.075	213.63
	100	0.311	0.081	283.72
0.20	50	0.190	0.076	148.97
	75	0.202	0.080	152.84
	100	0.278	0.082	238.82

Figure 4 depicts the average impact energy values in relation to the printing parameters (layer thickness and infill percentage) both for as-built specimens and for annealed specimens, providing a clear understanding of the influence of the different factors.

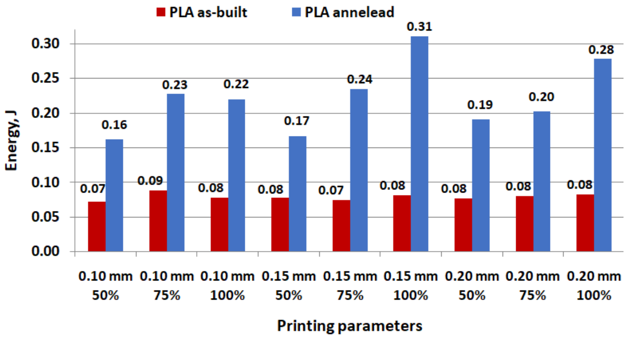


Fig. 4. Comparative values of impact energy obtained for as-built and annealed PLA samples.

The difference percentage between the impact energy of annealed and as-built samples for each combination of printing parameters is shown in Figure 5, in order to better visualize the influence of heat-treatment on the impact behavior of 3D printed parts. It can be observed that the impact energy increases by 125.10% and 283.70% (corresponding to the best optimal combination of printing parameters, namely 0.15 mm layer thickness and 100% infill percentage). A similar significant increase (from 97.80% to 133.20%) of PLA impact strength was obtained in [2].

For each layer thickness, the smallest increase of impact strength for the annealed specimens compared with the as-built ones was obtained at 50% infill percentage, while the greater influence of annealing treatment was observed at 100% infill percentage. This finding implies that annealing can be a highly effective method for increasing the impact resistance of PLA 3D printed parts.

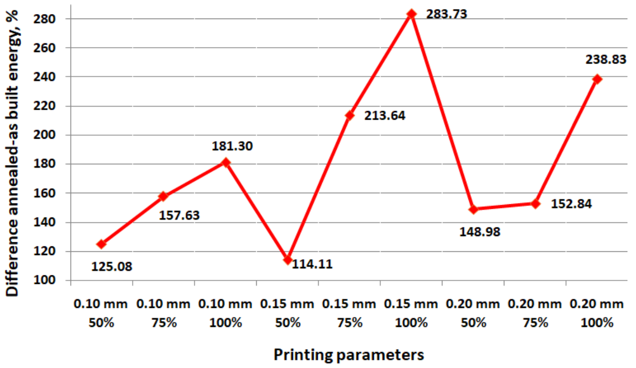


Fig. 5. The percentage variation of impact energy after annealing treatment.

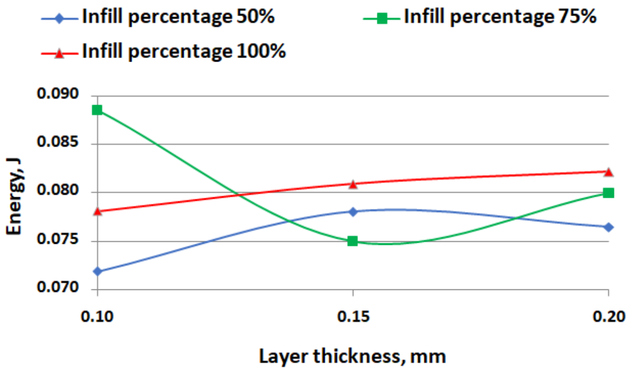


Fig. 6. The influence of printing parameters on impact energy for as-built samples.

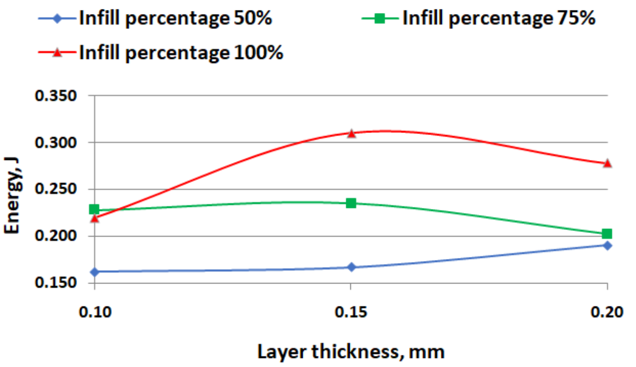


Fig. 7. The influence of printing parameters on impact energy for annealed samples.

For the as-built samples, the maximum impact energy value was obtained at 75% infill percentage and 0.1 mm layer thickness, while the minimum value corresponds to 50% infill percentage and 0.10 mm layer thickness (Figure 6). For the annealed samples, the maximum impact energy value was obtained at 100% infill percentage and 0.15 mm layer thickness, while the minimum value corresponds to 50% infill percentage and 0.10 mm layer thickness (Figure 7). It can be also observed that the impact energy of annealed PLA 3D printed parts increases with infill percentage and for each infill percentage the maximum value of impact energy is obtained for a layer thickness of 0.15 mm.

IV. CONCLUSION

This study innovatively investigates experimentally the previously unexplored relationship between annealing heat treatment, printing parameters (particularly layer thickness and infill percentage), and impact resistance in PLA 3D printed parts, addressing a significant research gap and providing valuable insights for optimizing mechanical performance.

It is noteworthy to emphasize that the impact energy of PLA printed components can be highly influenced by multiple variables, encompassing printing parameters (which were investigated in this study through changes in layer height and infill percentage) [26], and post-processing heat treatments.

The main factor influencing the impact resistance of annealed 3D printed parts is the infill percentage, the maximum impact energy corresponding to 100% infill percentage.

Since the impact energy increased up to three times due to the annealing treatment, it can be concluded that annealing is a suitable methodology to be applied for PLA 3D printing products used in applications that involve high mechanical loads.

The findings highlight the practicality and versatility of annealing as a cost-effective and efficient method for enhancing the mechanical integrity of PLA 3D printed products, which can have widespread applications in various industries [2].

Further studies will be performed to explore the effect of different annealing temperatures and durations on the impact resistance to determine the most effective annealing parameters. Thermogravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC) analysis will be applied in order to assess 3D printed PLA and heat treatments stems from their capacity to offer complementary data. TGA primarily concentrates on tracking the material's weight loss and how it decomposes under heating conditions, while DSC sheds light on shifts in the material's heat capacity and transitions between phases. When investigating the impact of heat treatments on 3D printed PLA, employing both techniques in unison will grant a holistic comprehension of how the material reacts to elevated temperatures. For instance, TGA will reveal the temperature at which substantial decomposition takes place, while DSC can accentuate alterations in the material's thermal transitions. These combined analyses will prove instrumental in refining heat treatments processes for specific purposes or gauging the material's adaptability to particular thermal settings.

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