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# Study on the influence of heat treatment on the mechanical tensile characteristics of parts additively manufactured by thermoplastic extrusion of PETG

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***Abstract*—The paper presents the results of research on the influence of heat treatment on the mechanical tensile characteristics of parts manufactured additively by thermoplastic extrusion of PETG. For the study, 27 tensile specimens were made from PETG filament on the Anycubic 4Max Pro 2.0 3D printer, using layer height values Lh of 0.10; 0.15 and 0.20 mm and filling percentages Ip of 50%, 75% and 100%. The printed specimens were subjected to a heat treatment at 75 °C for 180 minutes. Subsequently, they were tested in tension on the Barrus White 20 kN universal machine. The results showed that the heat treatment generated an increase in tensile strength with values ranging between 5.90% and 17.88% compared to PETG specimens manufactured additively without heat treatment.**

***Index Terms*—FDM; heat treatment; experimental study; tensile strength.**

## I. Introduction

THE technical performance of parts plays a crucial role in the smooth running of production processes, [1-7]. Increasing the technical performance of parts without significantly impacting the production cost is a continuous challenge in product development and innovation processes, and additive manufacturing technologies have created new opportunities in terms of efficient manufacturing, [8 – 16]. Additive manufacturing technology by extrusion of plastic masses is one of the most versatile additive technologies due to its simplicity in use, the range of materials and the low operating costs, [17 - 21]. Given the need to increase the technical performance and operational safety of additively manufactured parts, a bibliographic study was carried out that led to the appropriate solution for applying heat treatments to additively manufactured parts by thermoplastic extrusion. Heat treatments are used to modify the properties of materials and are mainly used for metallic materials, however, there is research that highlights the fact that the application of heat treatments on plastic materials brings improvements in durability and ductility, [22 - 29]. In the paper [26] Authors applied an annealing heat treatment on the specimens for the 3-point bending test made of additively manufactured PLA. The results of the study show that the annealing heat treatment resulted in an improvement in the 3-point bending strengths of the PLA specimens by (11 – 17)%. The study presented in the paper [27] demonstrates the viability of using the annealing heat treatment as a solution for improving the mechanical performance of additively manufactured parts made of PETG-CF. In the paper [28] the study on the influence of heat treatment on the impact strengths of additively manufactured PLA specimens is presented. The research results show that the impact resistance of heat-treated parts is (125.10 – 283.70)% higher than the impact resistance of non-heat-treated parts. Considering the promising results of studies conducted by other researchers, but also the gaps identified in the specialized literature, the authors conducted the present study, the novelty of which consists in evaluating the influence of thermoplastic extrusion parameters ($L_h$ – layer height deposited in one pass and $I_p$ – filling percentage) and heat treatment on the mechanical tensile characteristics of parts additively manufactured by thermoplastic extrusion of PETG filament.

## II. Of the Influence of Heat Treatment on the Tensile Characteristics of Specimens Additively Manufactured From Petg Filament

### *A. Additive manufacturing of tensile specimens by thermoplastic extrusion of PETG filament*

Using the CAD software Solidworks 2022, the 2D sketch of the tensile specimen was made according to the ISO 527-

1:2019 standard, subsequently the 2D sketch was transformed into a 3D model, and in the last stage the 3D model was converted into STL (Standard Triangle Language) format. Figure 1 shows the 2D model of the tensile specimen.

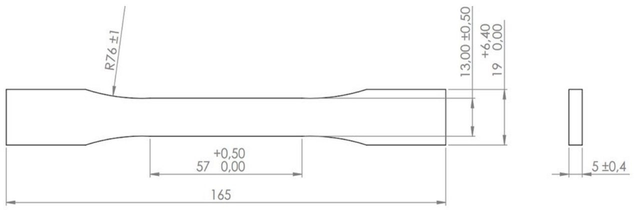



Fig. 1. 2D sketch of tensile sample.

The STL file of the tensile specimen was imported in Cura Slicer software. The thermoplastic extrusion parameters were set according to the data presented in Table 1. Based of these settings, 9 G-Code files were generated, each containing the neccessary instruction for additive manufacturing of the specimens using PETG filament. The G-Code files were transferred to the Anycubic 4 Max Pro 2.0 3D printer, where a total of 27 tensile specimens were produced by extruding Everfil PETG filament.

TABLE I. THERMOPLASTIC EXTRUSION PARAMETERS FOR ADDITIVE MANUFACTURING OF PETG FILAMENT TENSILE SPECIMENS

| Constant parameters | | Variable parameters | | Material |
|---|---|---|---|---|
| | | **Layer height** | **Infill percentage** | **PETG** |
| | | **$L_h$** | **$I_p$** | - |
| Part orientation, $P_o$ | X-Y | (mm) | (%) | (pieces) |
| | | 0.10 | 100 | 27 |
| Extruder temperature, $E_t$ (°C) | 250 | | 75 | |
| | | | 50 | |
| Platform temperature, $B_t$ (°C) | 70 | 0.15 | 100 | |
| | | | 75 | |
| | | | 50 | |
| Print speed, $P_s$ (mm/s) | 30 | 0.20 | 100 | |
| | | | 75 | |
| Filling pattern, $F_p$ | Grid | | 50 | |

Figure 2 shows the 27 tensile specimens additively manufactured on the Anycubic 4 Max Pro 2.0 3D printer by thermoplastic extrusion of PETG filament.

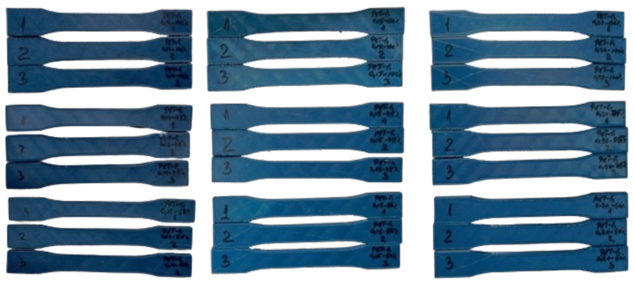


Fig. 2. Additive manufactured tensile samples by thermoplastic extrusion of PETG filament on 3D printer Anycubic 4 Max Pro 2.0.

*B. Heat treatment of tensile specimens manufactured additively by thermoplastic extrusion of PETG filament*

The 27 tensile specimens fabricated from PETG filament were placed in the ATS FAAR S110 FTE/D electric oven, where they were subjected to the annealing heat treatment. The parameters of the heat treatment applied to the tensile specimens fabricated from PETG filament are: temperature, T = 75 °C and duration, d = 180 minutes. Figure 3 shows the ATS FAAR S110 FTE/D electric oven, used to perform the heat treatment on the tensile specimens fabricated from PETG filament.

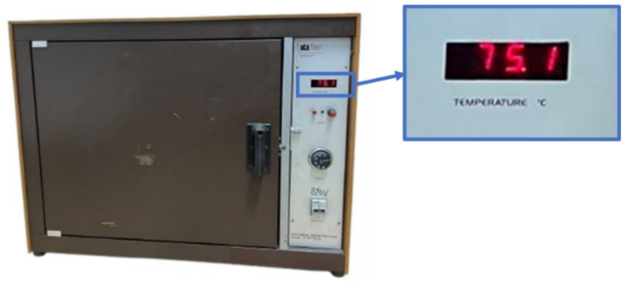



Fig. 3. Electrical convection oven ATS FAAR S110 FTE/D, used for heat treatment of tensile specimens made of PETG filament.

*C. Impact of heat treatment and thermoplastic extrusion parameters on the tensile strength of additively manufactured specimens from PETG filament*

The tensile specimens shown in Figure 2, made by thermoplastic extrusion of PETG filament on the Anycubic 4 Max Pro 2.0 printer, were tested on the Barrus White 20 kN testing machine (Fig. 4). Tensile tests were performed according to ISO 527-1:2019 standard, at a traverse speed of 5 mm/min [30].

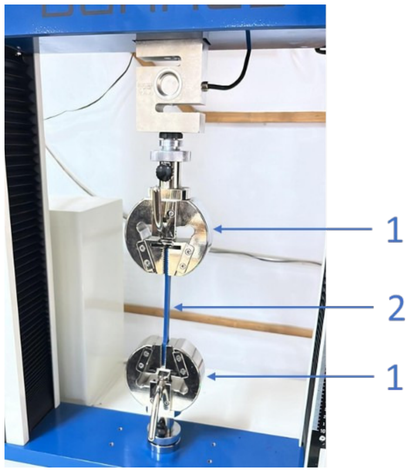



Fig. 4. Tensile testing of annelead samples on Barrus White 20 kN machine: 1 – grips; 2 – sample.

Figure 5 shows the 27 tensile specimens that underwent heat treatment after tensile testing on the Barrus White 20 kN machine.

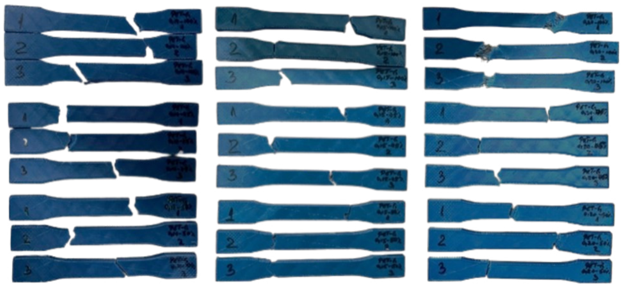
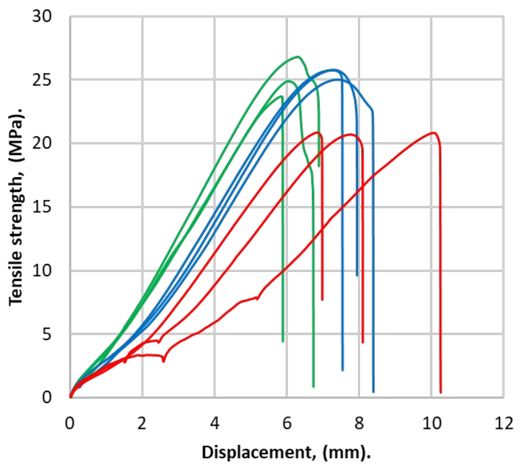


Fig. 5. Additive manufactured annealed tensile samples by thermoplastic extrusion of PETG filament on 3D printer Anycubic 4 Max Pro 2.0 after tensile testing on Barrus White 20 kN machine.

Figures 6 - 8 show the breaking strengths obtained for tensile specimens manufactured by thermoplastic extrusion of PETG filament and heat treated.

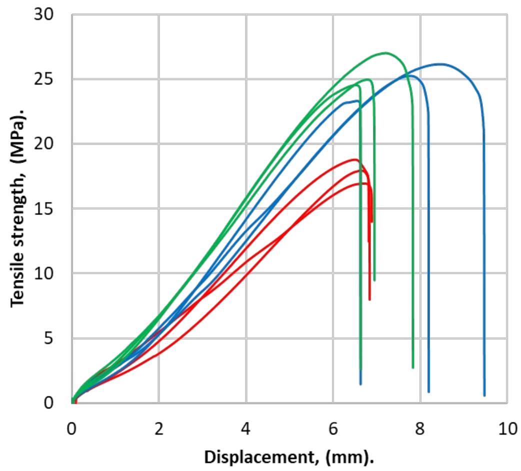



| Lh (mm) | Ip (%) | Sample 1 | Sample 2 | Sample 3 | Average (MPa) |
|---|---|---|---|---|---|
| 0.10 | 50 | 20.69 | 20.86 | 20.83 | **20.79** |
| | 75 | 25.78 | 25.02 | 25.76 | **25.52** |
| | 100 | 23.69 | 24.92 | 26.80 | **25.13** |

Fig. 6. Breaking strength values for annealed PETG samples with $L_h$=0.10 mm and $I_p$ = (50; 75; 100) %.

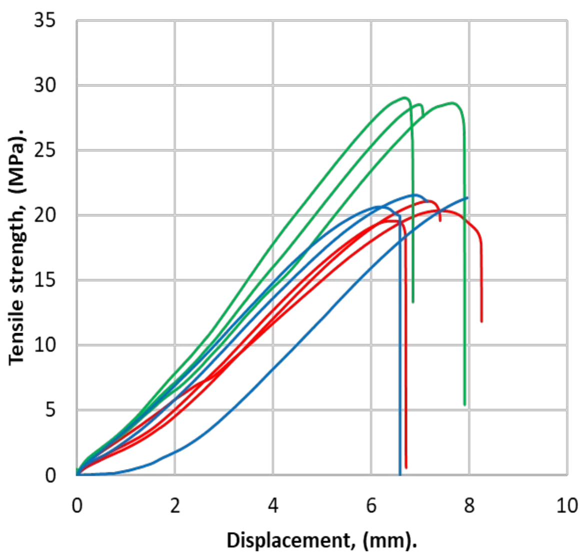
Analyzing the graph in Figure 6, it is possible to observe the influence of the filling percentage on the tensile strength of the specimens additively manufactured from PETG filament and subsequently heat-treated, using a constant layer height ($L_h$) of 0.10 mm. The maximum tensile strength of 25.52 MPa was recorded at a filling of 75%. Reducing the filling to 50% led to a loss of strength of 18.52%, and increasing it to 100% led to a slight reduction of 1.50%.

Analyzing figure 7, it can be observd how the filling percentages influence the tensile strengths of heat-treated and additively manufactured tensile specimens made PETG filament with $L_h$ = 0.15 mm. The maximum average value of the tensile strengths (25.50 MPa) was recorded for the specimens manufactured with $I_p$ = 100%. A reduction in the infilling percentage from 100% to 75% led to a 2.36% decrease in tensile strengths, while a reduction from 75% to 50% resulted in a tensile strength decrease of 28.17%.




| Lh (mm) | Ip (%) | Sample 1 | Sample 2 | Sample 3 | Average (MPa) |
|---|---|---|---|---|---|
| 0.15 | 50 | 18.78 | 17.94 | 16.94 | **17.89** |
| | 75 | 26.14 | 25.24 | 23.31 | **24.90** |
| | 100 | 27.00 | 24.54 | 24.96 | **25.50** |

Fig. 7 Breaking strength values for annealed PETG samples with $L_h$ = 0.15 mm and $I_p$ = (50; 75; 100) %.




| Lh (mm) | Ip (%) | Sample 1 | Sample 2 | Sample 3 | Average (MPa) |
|---|---|---|---|---|---|
| 0.20 | 50 | 20.34 | 21.08 | 19.55 | **20.32** |
| | 75 | 21.39 | 20.64 | 21.54 | **21.19** |
| | 100 | 29.03 | 28.62 | 28.51 | **28.72** |

Fig. 8. Breaking strength values for annealed PETG samples with $L_h$ = 0.20 mm and $I_p$ = (50; 75; 100) %.

Examining the graph in figure 8, we see the effects of filling percentages on the tensile strengths of thermally treated and additively manufactured tensile samples made from PETG filament with $L_h$ = 0.20 mm. The highest average tensile strength value (28.72 MPa) was observed for the specimens produced with $I_p$ = 100%. The reduction in the filling percentage from 100% to 75% led to a 26.21% decrease in tensile strengths, while the reduction from 75% to 50% resulted in a 4.09% decrease in tensile strengths

Employing Minitab software, the tensile strength results of the tensile specimens produced from PETG filament with $L_h$ = (0.10; 0.15; 0.20) mm and $I_p$ = (50; 75; 100) %, followed by heat treatment, led to the creation of the Pareto chart in figure 8 and the contour chart in figure 9, illustrating the impact of the variable parameters of thermoplastic extrusion on tensile strengths, [31].

Examining the graphs in figures 9 and 10, we note that of the two parameters assessed, ($A = L_h$ and $B = I_p$), the parameter that considerably affects the tensile strength results of the specimens produced from PETG filament and subjected to heat treatment is the parameter $B = I_p$.

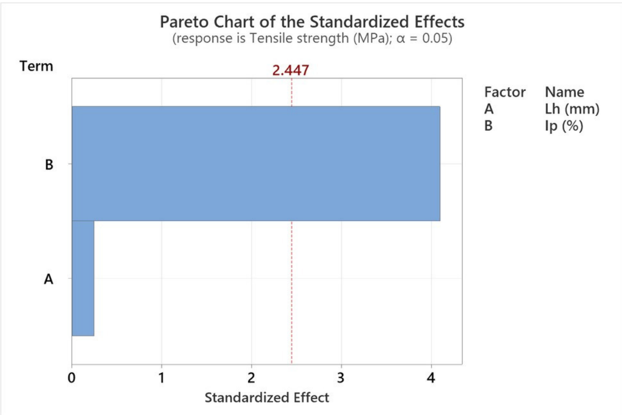



Fig. 9 . Pareto chart for influence of $A = L_h$ and $B = I_p$ on breaking strengths.

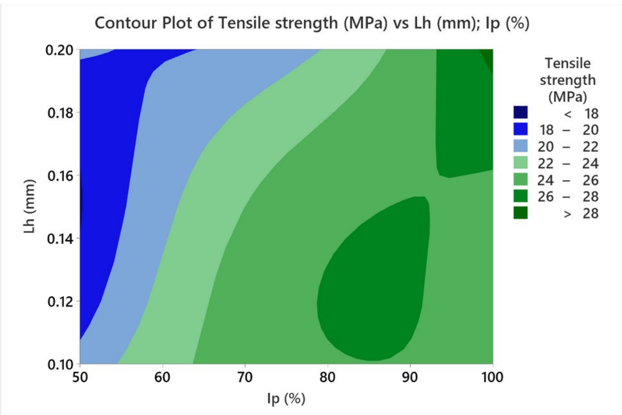



Fig. 10 . Contour plot for influence of $A = L_h$ and $B = I_p$ on breaking strengths.

### D. *Influence of heat treatment and thermoplastic extrusion parameters on the percentage elongation at break of additively manufactured specimens from PETG filament*

Figure 11 graphically represents the average values corresponding to the percentage elongations at break of tensile specimens additively manufactured from PETG filament with $L_h$ = (0.10; 0.15; 0.20) mm and $I_p$ = (50; 75; 100)% and heat treated.

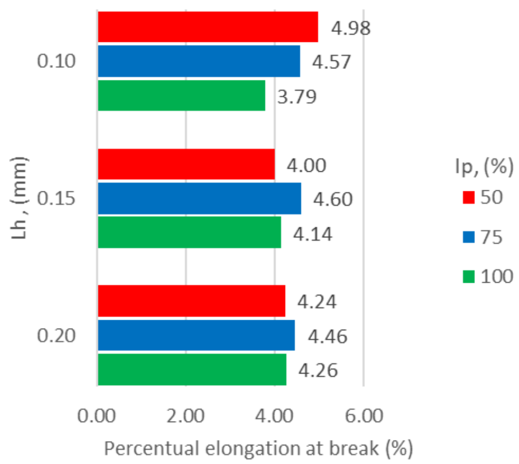



Fig. 11. Average percentual elongation at break of annealed tensile samples made by thermoplastic extrusion of PETG filament.

The highest average value related to the percentage elongation at break of tensile specimens made from PETG filament (4.98)%, was observed for the group of specimens produced with $L_h$ = 0.10 mm and $I_p$ = 50%. For an identical height of the layer applied in one pass, raising $I_p$ from 50% to 75% resulted in a reduction of the percentage elongation at break by 8.32%, while increasing Ip from 75% to 100% led to a decrease in the percentage elongation at break by 16.99%

By utilizing Minitab software, the graphs from figures 12 and 13 was generated, which show the influence of variable parameters of thermoplastic extrusion on the percentage elongations at break for tensile specimens made from PETG and subsequently subjected to heat treatment. The Pareto chart depicted in figure 12 illustrates the impact of the variable parameters of thermoplastic extrusion ($A = L_h$ and $B = I_p$) on the percentage elongations at break of tensile specimens that were additively manufactured from PETG and then subjected to heat treatment. Based on the graph in figure 12, factor $B = I_p$ shows a much stronger effect than factor $A = L_h$, yet statistically, both factors do not affect the percentage elongations at break values.

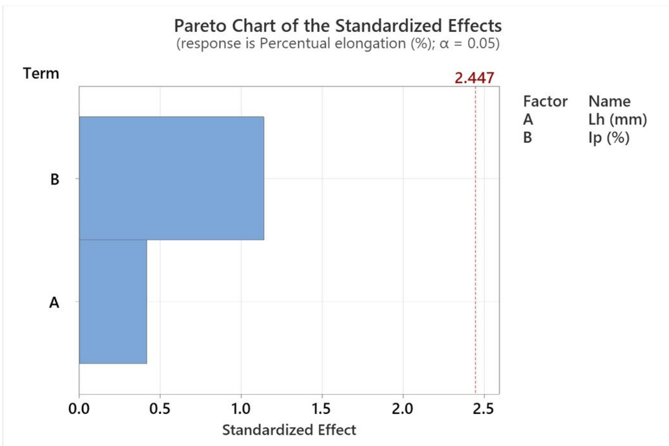



Fig. 12 Pareto chart for influence of $A = L_h$ and $B = I_p$ on percentual elongations at break.

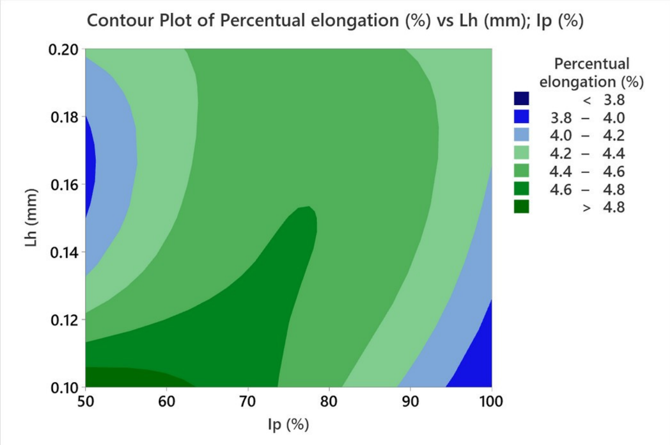



Fig. 13. Contour plot for influence of A = $L_h$ and B = $I_p$ on percentual elongations at break.

The contour plot in Figure 13 expresses the influence of thermoplastic extrusion parameters on the percentage elongations at break of tensile specimens additively manufactured from PETG filament and subsequently heat treated.

*E. Influence of heat treatment and thermoplastic extrusion parameters on the elastic modulus of additively manufactured PETG filament specimens*

Figure 14 graphically represents the average values of the elastic modulus corresponding to tensile specimens additively manufactured from PETG filament with $L_h$ = (0.10; 0.15; 0.20) mm and $I_p$ = (50; 75; 100)% and subsequently heat treated.

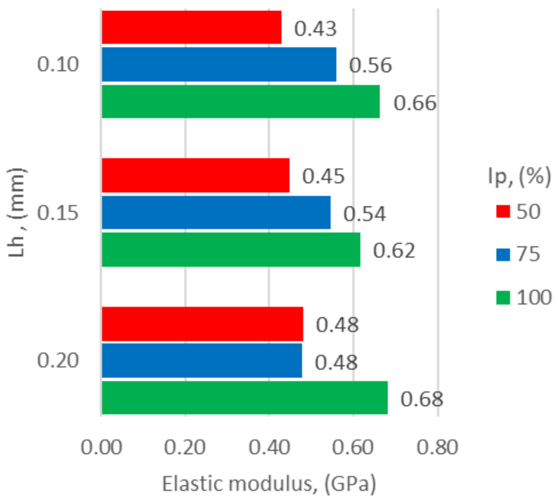



Fig. 14. Average elastic modulus of annealed tensile samples made by thermoplastic extrusion of PETG filament.

The maximum average values of the elastic modulus were recorded for the specimens manufactured with Ip = 100%, (0.62 – 0.68) GPa. The decrease of $I_p$ from 100% to 75% generated a decrease of the elastic modulus by (13.14 – 42.83)%, and the reduction of $I_p$ from 75% to 50% caused the decrease of the elastic modulus by up to 30.50%.

With the elastic modulus values and process parameters, the Pareto chart in Figure 15 was created in Minitab. This outlines the effect of extrusion parameters on the mechanical characteristics of PETG specimens produced through additive manufacturing and subsequently heat treated.

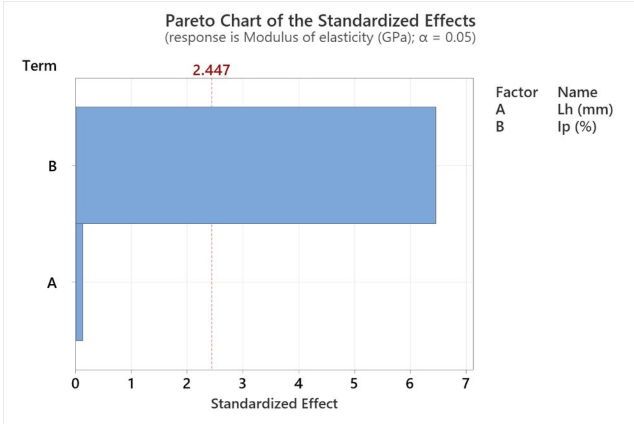



Fig. 15. Pareto chart for influence of A = $L_h$ and B = $I_p$ on modulus of elasticity.

Analyzing the Pareto chart in figure 15, we can see that the parameter B = $I_p$ has an overwhelming influence on the elastic modulus of the samples additively manufactured from PETG filament and heat treated, the same being demonstrated by the contour chart in figure 16.

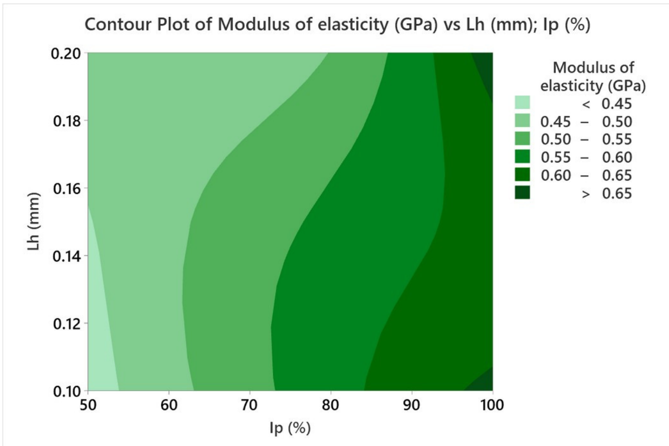



Fig. 16. Contour plot for influence of A = $L_h$ and B = $I_p$ on modulus of elasticity.

To maximize the tensile strength of annealed 3D printed specimens from PETG, was determined the optimal thermoplastic extrusion parameters. The resulting optimization graphs are shown in Figure 17.

Analyzing the optimization graphs in Figure 17, we observe that the optimal thermoplastic extrusion parameters for additive manufacturing of PETG tensile specimens are $L_h$ = 0.10 mm and $I_p$ = 100%.

## III. CONCLUSIONS

This paper show the research on the effects of annealing heat treatment on the tensile mechanical properties of sam-

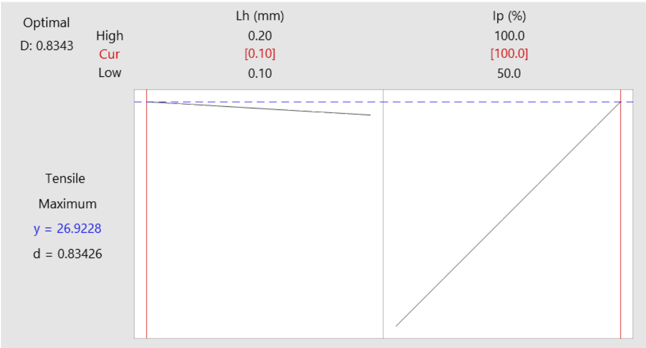



Fig. 17. Optimization plots of thermoplastic extrusion parameters ($L_h$ and $I_p$) for maximizing of breaking strenghts of PETG tensile samples.

ples produced through thermoplastic extrusion of PETG filament. To realize the study, employing the thermoplastic extrusion settings, the layer height , $L_h$ = (0.10; 0.15; 0.20) mm and the infill percentage, $I_p$ = (50; 75; 100) %, 27 tensile samples were additively produced through thermoplastic extrusion of PETG filament on the Anycubic 4 Max Pro 2.0 3D printer. The 27 tensile specimens underwent an annealing heat treatment that involved placing them in the ATS FAAR S110 FTE/D electric oven preheated to 75 ºC, holding the specimens in the oven at 75 ºC for 180 minutes, and then gradually cooling the parts. All 27 heat-treated samples underwent tensile testing on the Barrus White 20 kN machine, where the next tensile properties were determinated: tensile strength, elongation percentage at failure, and modulus of elasticity

The lowest average tensile strength values of the additively manufactured samples from PETG filament and heat-treated were recorded for the specimens made with $L_h$ = 0.15 mm and $I_p$ = 50%, while the highest average tensile strength values were recorded for the specimens made with $L_h$ = 0.20 mm and $I_p$ = 100%

The lowest average percentage elongation at break of the additively produced PETG filament and heat-treated samples was noted for those produced with $L_h$ = 0.10 mm and $I_p$ = 100%, whereas the highest average percentage elongation at break was noted for the samples made with $L_h$ = 0.10 mm and $I_p$ = 50%.

The lowest average value of the elastic modulus for the tensile specimens made from PETG filament and heat treated was recorded for the specimens produced with $L_h$ = 0.20 mm and the = 100%, while the highest average value of the elastic modulus was recorded for the specimens created with $L_h$ = 0.10 mm and the = 50%

The average breaking strength of the 27 tensile specimens additively manufactured from PETG and heat treated is 23.33 MPa, which is 10.50% higher than the average breaking strength of the tensile specimens manufactured from PETG, but not heat treated, in the study [32]. The annealing heat treatment has beneficial effects on the additively manufactured parts, through which the defects generated by the poor adhesion between the layers are remedied.

The results of this study demonstrate that heat treatment of additively manufactured parts made of PETG filament represents a solution for increasing mechanical tensile performance, which is (5.90 – 17.88)% higher compared to those of specimens manufactured from the same material, using identical parameters, but not heat treated.

The authors aim to study the effect of heat treatment on other mechanical characteristics (compression, 3-point bending, impact), but also on other types of materials.

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