A Study on the Influence of FDM Parameters on the Tensile Behavior of Samples made of PET-G

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ABSTRACT

This experimental study investigated the influence of FDM 3D printing parameters on the tensile behavior of PET-G-made parts. In this context, 27 test specimens were produced using FDM on the Anycubic 4 Max Pro 2.0 printer with layer heights applied in one pass L_h = 0.10/0.15/0.20 mm and filling percentages I_d = 50/75/100 %. All these samples were tensile tested on the Barrus White 20 kN universal testing machine. The experimental results determined maximum tensile strength, elongation percentage at break, and Young's modulus. The two parameters considered, I_d and L_h, influence the maximum tensile strength, the elongation percentage at break, and Young's modulus. The findings demonstrated that the filling percentage has a strong influence on the maximum tensile strength and the elongation percentage at break of the PET-G samples, and L_h has a decisive influence on Young's modulus.

Keywords-FDM parameters; PET-G; tensile strength; percent elongation; modulus of elasticity

I. INTRODUCTION

Additive manufacturing technologies have revolutionized a part of the manufacturing processes, introducing a new concept of adding material in overlapping layers. The former have been adopted worldwide by key industries, such as aerospace, energy, medical, automotive, and manufacturing [1-3]. Additive manufacturing technologies emerge over conventional manufacturing technologies (subtractive and formative technologies) with the following main advantages: the ability to change the shape of the finished product without constraints, ease of use, energy efficiency, and environmental impact [2, 4-10]. However, additive manufacturing technologies have certain limitations, namely printing speed, part surface quality, and mechanical characteristics that are inferior to parts made with conventional technologies [11-13].

The mechanical features of the parts are of great importance and it is necessary to optimize the printing parameters to obtain their maximum values. The main FDM parameters that contribute to the mechanical characteristics of parts are the height of the layer applied in one pass (L_h), the filling percentage (I_d), the printing speed (P_s), the filling pattern (I_p), the part orientation, the extruder temperature (E_t), and the table temperature (B_t) [14-26].

In [14], the influence of the FDM parameters (height of the layer applied in one pass and filling percentage) on the tensile strength and hardness of PLA parts was studied. The outcomes showed that better results were obtained with an increase in the filling percentage. In [15], the influence of the height of the layer applied in one pass and the color of the filament on the dimensional accuracy and tensile strength of FDM PLA parts was studied. According to the findings, the tensile strength decreases with increasing L_h and the color of the filament has an impact on tensile strength, as the FDM-made specimens from gray and red colored filaments had better mechanical characteristics compared to those made with black and natural colored filaments. In [16], a study on the optimization of FDM printing parameters to improve the tensile properties of parts produced from ABS and nylon was presented, varying three parameters: I_p (tri-hexagonal, triangular, octet), I_d (10/50/100%) and P_s (60/65/70 mm/s). The results exhibited that among the three parameters studied, I_d had a strong influence on tensile strength since it increased with a higher I_d. In [27], the mechanical and durability performance of concrete with different doses of bacteria were investigated. The results disclosed that bacteria can improve the physical properties of cement concrete. In [28], the effect of different gradations of coarse aggregates on the mechanical properties of No-Fines Concrete (NFC) was studied, showing that the aggregate gradation significantly affects the compressive, splitting tensile, and flexural strength of NFC. In [29], an experimental study was carried out on NFC with a fixed proportion of cement-to-aggregate (c-a) of 1:6 with a 0.40 water/cement (w/c) ratio. It was discovered that the aggregate classification, the c-a ratio, and the w/c ratio have a significant impact on compressive strength. In [30], the influence of FDM process parameters (air gap, extruder temperature, layer thickness, infill density, and raster angle) on the tensile strength of parts printed with PLA material was investigated. The findings demonstrated that layer thickness and infill density have a direct impact on tensile strength and percentual elongation, and the best result for tensile strength was for the sample with the highest infill density.

This study aims to determine the influence of FDM on the tensile behavior of samples made of PET-G and to present the optimal combination of parameters for the best tensile strength results. Statistical analysis was performed on the findings using Minitab for a better understanding of the effects of FDM parameters on the tensile behavior of PET-G-made samples. The samples were produced and tested in laboratories of the Faculty of Mechanical and Electrical Engineering of the Petroleum-Gas University of Ploiești.

II. EXPERIMENTAL METHOD

Figure 1 illustrates the steps of the method used to investigate the influence of FDM parameters on the tensile behavior of PET-G parts. Solidworks 2023 [31] was used to create the 2D and then the 3D model of the tensile specimen, shown in Figure 2. The 3D model of the specimen was converted from SLD to STL format. The STL file, which corresponds to the specimen depicted in Figure 2, was processed in Cura Slicer software [32] by choosing the PET-G material and entering the FDM printing parameters from Table I, followed by the generation of the G-Code file.

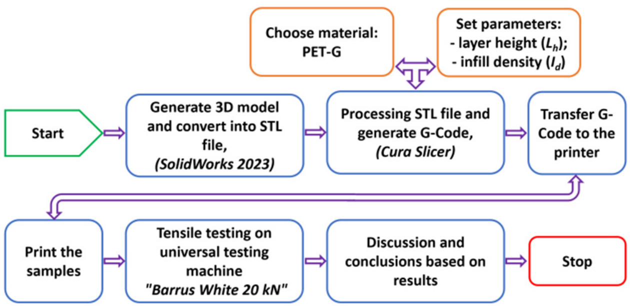


Fig. 1. The steps of the method used to investigate the influence of FDM parameters on the tensile behavior of PET-G parts.

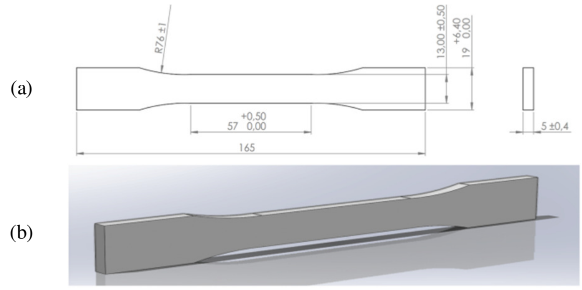


Fig. 2. Tensile test specimen models in SolidWorks 2023: (a) 2D, (b) 3D.

TABLE I. FDM PRINTING PARAMETERS FOR TENSILE SPECIMENS

Constant parameters	Variable parameters		Material
	Layer height	Infill density	PET-G
	L_h	I_d	-
Part Orientation: X-Y Extruder Temperature, E_t = 250 °C Table Temperature, B_t = 70 °C Printing Speed, P_s= 30 mm/s Filling Pattern I_p: Grid	(mm)	(%)	(pieces)
	0.10	100	3
		75	3
		50	3
	0.15	100	3
		75	3
		50	3
	0.20	100	3
		75	3
		50	3

Figure 3 displays the PET-G tensile specimen made in Cura Slicer software with constant parameters from Table I and L_h = 0.20 mm and I_d = 50%. The G-Code file was transferred to the Anycubic 4 Max Pro 2.0 3D printer. The latter has a print volume of 270×210×190 mm, on which the 27 tensile specimens presented in Figure 4 were fabricated using Everfill brand PET-G filament with 1.75 mm diameter. The 27 were tensile tested on the "Barrus White 20 kN" universal testing machine, according to the ASTM D638-14 standard, utilizing a speed of 5 mm/min [33].

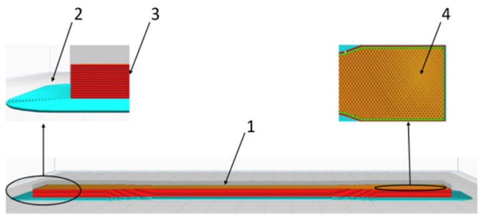


Fig. 3. Tensile test specimen in Cura Slicer software: (1) specimen, (2) specimen holder, (3) overlapping layers, (4) filling pattern.

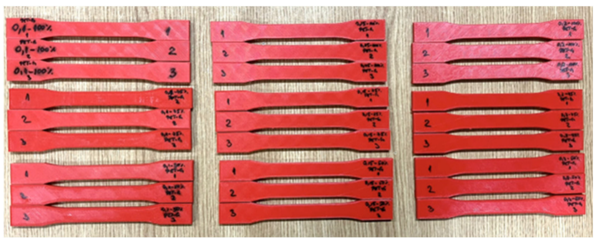
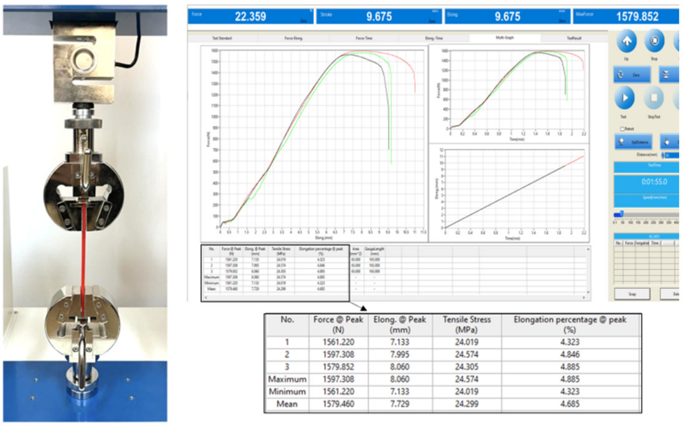


Fig. 4. PET-G tensile test specimens manufactured by FDM on Anycubic 4 Max Pro 2.0 printer.



(a) (b)

Fig. 5. Tensile test on Barrus White 20 kN machine: (a) Tensile test, (b) results of tensile test for L_h = 0.20 and I_d = 100%.

III. RESULTS AND DISCUSSION

Tensile strength, percentage elongation at break, and Young modulus are the mechanical characteristics determined from tensile tests on the 27 specimens portrayed in Figure 4. Figure 5 presents the 27 specimens of PET-G after tensile testing.

A. Influence of FDM Parameters on the Tensile Strength of PET-G Tensile Specimens

Figure 7 illustrates the mean tensile strength values obtained from testing the specimens. As can be seen, I_d has a major influence on the tensile strength of PET-G specimens. The best results, 24.29-28.25 MPa, were obtained for specimens having filling percentage I_d = 100%. By increasing I_d from 50 to 75%, the tensile strength of the specimens increased by 19.55-20.93%, while by rising I_d from 75 to 100%, tensile strength increased by 24.64-29.75%. The Pareto chart opserved in Figure 8 was plotted using Minitab [30] and indicates that the filling percentage (B = I_d) has a decisive influence on the tensile strength of PET-G FDM specimens.

By utilizing Minitab software [34] and the FDM parameters in Table I, L_h = 0.10/0.15/0.20 mm and I_d = 50/75/100%, the contour plot of the tensile strength of PET-G tensile specimens, pinpointed in Figure 10, was plotted [5]. Analysing the contour plot in Figure 10 led to an observation of how the L_h and I_d parameters of the FDM affect the specimen tensile strength. By increasing the filling percentage (I_d) it can be observed that this augmentation has a significant impact on the increase in tensile strength of PET-G tensile specimens.

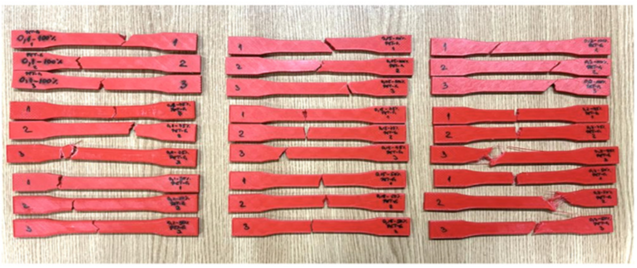


Fig. 6. PET-G specimens after tensile testing.

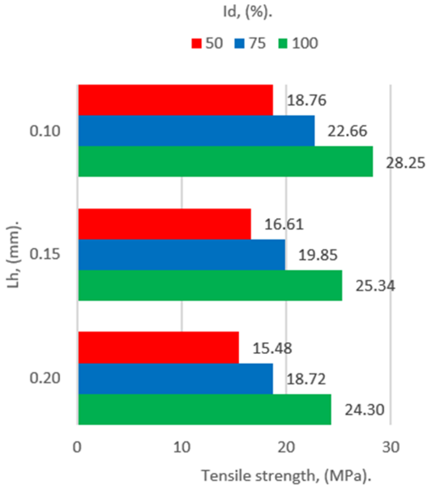


Fig. 7. Mean values of the tensile strength of PET-G specimens.

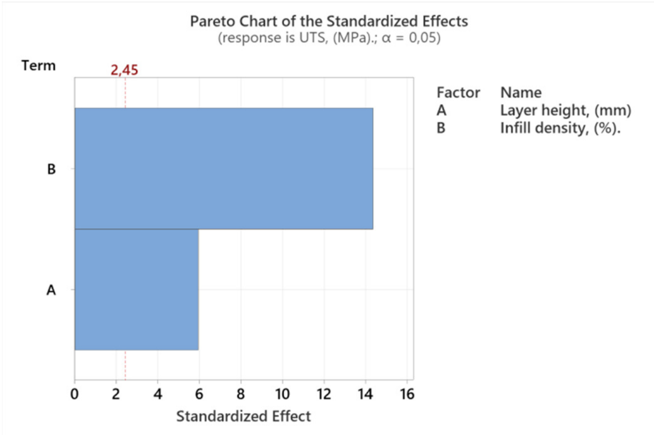


Fig. 8. Pareto chart of the influence of the parameters A = L_h and B = I_d on the tensile strength of PET-G tensile specimens.

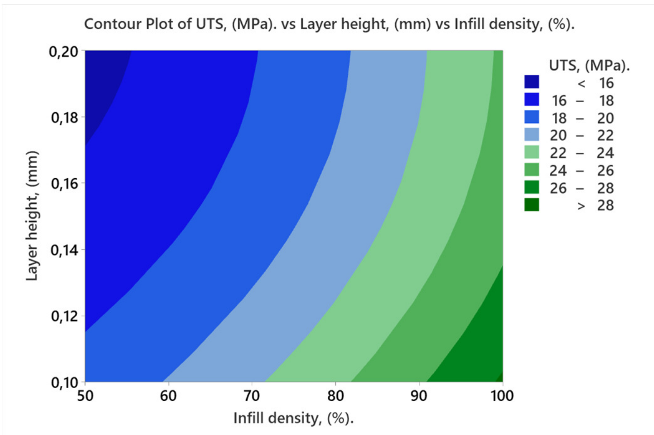


Fig. 9. Contour plot of the tensile strength of PETG tensile specimens.

B. Influence of FDM Parameters on the Elongation Percentage at Break of PET-G Tensile Specimens

Figure 10 presents the average values of the elongation percentage at break acquired from the tensile testing of the specimens. Filling percentage (I_d) influences the elongation percentage at break of PET-G tensile specimens. The best results, 4.59-4.68%, were obtained for specimens with I_d = 100%. By increasing I_d from 50 to 75%, the elongations at break of PET-G tensile specimens rose by 0.53-17.51%, while by increasing I_d from 75 to 100% the elongations at break rose by 15.91-33.43%.

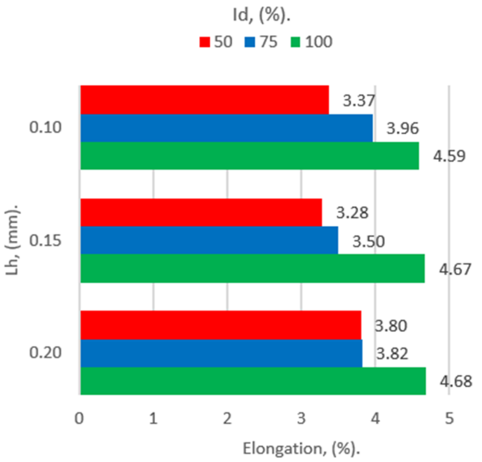


Fig. 10. Mean values of elongation percentage at break of PET-G specimens.

The Pareto chart shown in Figure 11 was plotted using Minitab and demonstrates that the filling percentage ($B = I_d$) strongly influences the elongation percentage at break of PET-G-made specimens.

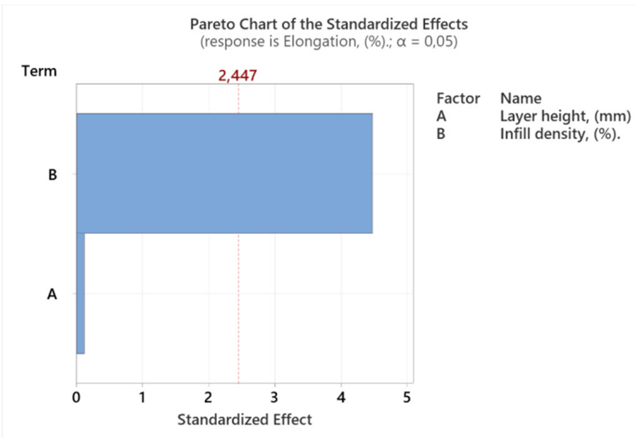


Fig. 11. Pareto chart showing the influence of the parameters A = L_h and B = I_d on the percentage elongation at break of PETG tensile specimens.

Figure 12 exhibits a contour plot of the elongation percentage of the specimens. It can be observed how the L_h and I_d of the FDM influence the elongation percentage at specimen break. Increasing I_d has the main influence on increasing the elongation percentage at break of PET-G tensile specimens.

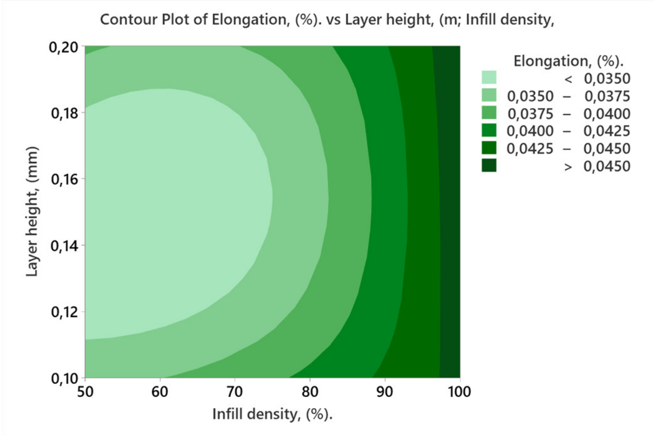


Fig. 12. Contour plot of percentage elongations at break of PET-G tensile specimens.

C. *Influence of FDM Parameters on Young Modulus Values Obtained in the Tensile Test of PET-G Specimens*

Figure 13 displays the average Young modulus values obtained from tensile testing of the specimens. The FDM parameters affect the Young modulus values. The best result, 0.62 GPa, was acquired for specimens with I_d = 100% and the height of the layer applied at one pass L_h = 0.10 mm. By increasing I_d from 50 to 75%, the Young modulus values increased by 11.93-21.08 %, and by increasing I_d from 75 to 100%, the Young modulus values increased by 5.31-7.67%. When decreasing the L_d applied from 0.20 to 0.15 mm, the Young modulus values increased by 4.33-24.04%, and when decreasing from 0.15 to 0.10 mm, the Young modulus values increased by 0.56-13.65%.

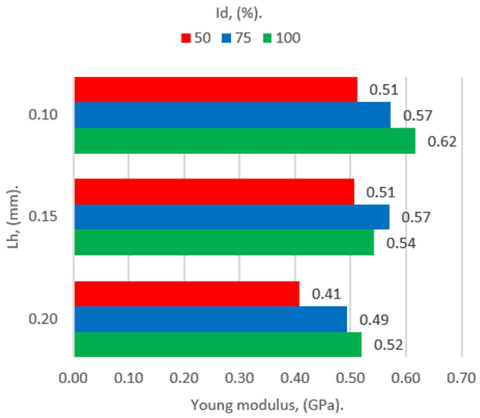


Fig. 13. Average values of Young modulus obtained in tensile test of PET-G specimens.

Figure 14 depicts a Pareto chart, indicating that the height of the layer applied at one pass ($A=L_h$) has the greatest influence on the Young modulus values obtained in the tensile test of PET-G specimens. Figure 15 portrays a contour plot of the Young modulus values acquired in the tensile test of PET-G specimens. It can be observed how increasing I_d and decreasing L_h determine an increase in the Young modulus values obtained in the tensile test of PET-G specimens.

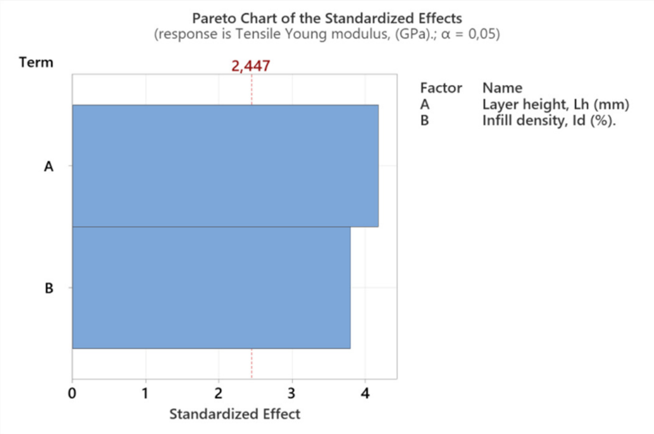


Fig. 14. Pareto chart of the influence of the parameters $A = L_h$ and $B = I_d$ on the Young modulus values obtained in the tensile test of PET-G specimens.

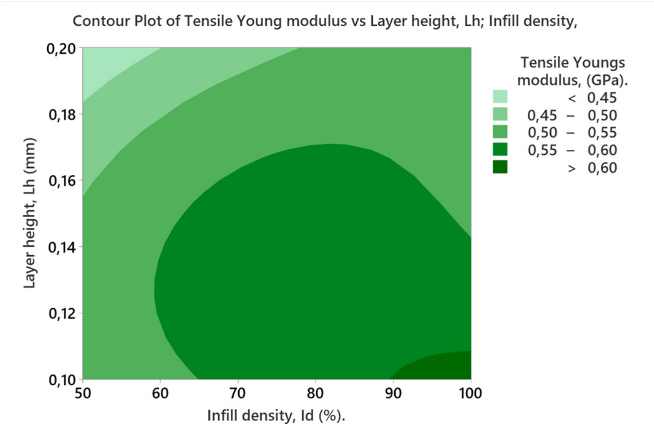


Fig. 15. Contour plot of Young modulus obtained in tensile test of PET-G specimens.

IV. CONCLUSIONS

The study investigated the influence of 3D FDM printing parameters on the tensile behavior of parts made of Everfill brand PET-G. In this context, 27 FDM-made specimens on the Anycubic 4 Max Pro 2.0 printer with layer heights applied at a pass L_h = 0.10/0.15/0.20 mm and filling percentage I_d = 50/75/100% were tensile tested on a Barrus White 20 kN universal testing machine. The parameters I_d and L_h influence the tensile behavior (tensile strength, percentage elongation at break, and Young modulus) of 3D-printed PET-G specimens. Increasing the filling percentage (I_d), increases the break strength of the specimens. This agrees with the results of [14, 16, 30]. By comparing the outcomes of this study to [14], the tensile strength of PET-G for I_d = 50/75/100% is less than the tensile strength of PLA with the same fill density with 31.10-56.22/16.50-44.05/18/60-58.14%. The minimum value of the tensile strength of the PET-G FDM specimens, 15.48 MPa, was recorded when using L_h = 0.20 mm and I_d = 50%, and the maximum value of the tensile strength, 28.25 MPa, was recorded for L_h = 0.10 mm and I_d = 100%.

Increasing the filling percentage (I_d) increased the elongation percentage of the specimens made by PET-G FDM. The minimum value of elongation percentage at break of PET-G FDM specimens (3.28%) was recorded when using L_h = 0.15 mm and I_d = 50%, while the maximum value (4.68%) was recorded for L_h = 0.20 mm and I_d = 100%. Increasing the filling percentage (I_d) and decreasing the height of the layer applied in one pass (L_h) increased the tensile Young modulus values obtained in the tensile test of the PET-G FDM specimens. The minimum value of the Young modulus (0.41 GPa) was recorded when using L_h = 0.20 mm and I_d = 50%, and the maximum value of the Young modulus (0.62 GPa) was documented in the case of L_h = 0.10 mm and I_d = 100%. Minitab was used to analyze the results from a statistical point of view, to better understand the effects of FDM parameters on the behavior of tensile strength, percentage elongation, and Young modulus. The applicability of this study is for creating 3D printed pieces by FDM from PET-G with the optimal parameters for the best mechanical proprieties and printing time. Future studies could investigate other materials, such as ASA and rPET-G, with different percentages of recycled material.

REFERENCES

[1] C. Jianu, S. I. Spiridon, and G. Ionita, "Tehnologia de fabricație aditivă 3D: Inovație și aplicabilitate în domeniul ingineriei," *Buletinul AGIR*, vol. 3-4, pp. 102–107, 2020.

[2] "Innovation trends in additive manufacturing," European Patent Office, Munich, Germany, 2023.

[3] D. G. Zisopol, M. Tănase, and A. I. Portoacă, "Innovative Strategies for Technical-Economical Optimization of FDM Production," *Polymers*, vol. 15, no. 18, Jan. 2023, Art. no. 3787, https://doi.org/10.3390/polym15183787.

[4] D. G. Zisopol and A. Dumitrescu, *Materiale şi tehnologii primare. Aplicații practice și studii de caz*. Ploiesti, Romania: Universității Petrol-Gaze din Ploiești, 2005.

[5] D. G. Zisopol and A. Dumitrescu, *Ecotehnologie. Studii de caz*. Ploiesti, Romania: Editura Universității Petrol-Gaze din Ploiești, 2020.

[6] D. G. Zisopol, A. Dumitrescu, and C. N. Trifan, *Ecotehnologie: Noțiuni teoretice, aplicații și studii de caz*. Ploiesti, Romania: Editura Universității Petrol-Gaze din Ploiești, 2010.

[7] D. G. Zisopol and M. J. Săvulescu, *Bazele tehnologiei*. Ploiesti, Romania: Editura Universității din Ploiești, 2003.

[8] M. J. Săvulescu and D. G. Zisopol, *Tehnologii industriale şi de construcții*. Ploiesti, Romania: UPG Ploiesti Publishing House, 2002.

[9] D. Zisopol, *Tehnologii industriale și de construcții. Aplicații practice și studii de caz*. Ploiesti, Romania: Publisher: Editura Universității din Ploiești, 2003.

[10] M. J. Săvulescu, D. G. Zisopol, and I. Nae, *Bazele tehnologiei materialelor: Îndrumar de lucrări practice*. Ploiești, Romania: Editura Premier Ploiești, 1997.

[11] D. G. Zisopol, N. Ion, and A. I. Portoaca, "Comparison of the Charpy Resilience of Two 3D Printed Materials: A Study on the Impact Resistance of Plastic Parts," *Engineering, Technology & Applied Science Research*, vol. 13, no. 3, pp. 10781–10784, Jun. 2023, https://doi.org/10.48084/etasr.5876.

[12] D. G. Zisopol, A. I. Portoaca, and M. Tanase, "Improving the Impact Resistance through Annealing in PLA 3D Printed Parts," *Engineering, Technology & Applied Science Research*, vol. 13, no. 5, pp. 11768–11772, Oct. 2023, https://doi.org/10.48084/etasr.6281.

[13] D. G. Zisopol, I. Nae, A. I. Portoaca, and I. Ramadan, "A Statistical Approach of the Flexural Strength of PLA and ABS 3D Printed Parts," *Engineering, Technology & Applied Science Research*, vol. 12, no. 2, pp. 8248–8252, Apr. 2022, https://doi.org/10.48084/etasr.4739.

[14] D. G. Zisopol, I. Nae, A. I. Portoaca, and I. Ramadan, "A Theoretical and Experimental Research on the Influence of FDM Parameters on

Tensile Strength and Hardness of Parts Made of Polylactic Acid," *Engineering, Technology & Applied Science Research*, vol. 11, no. 4, pp. 7458–7463, Aug. 2021, https://doi.org/10.48084/etasr.4311.

[15] D. Frunzaverde *et al.*, "The Influence of the Layer Height and the Filament Color on the Dimensional Accuracy and the Tensile Strength of FDM-Printed PLA Specimens," *Polymers*, vol. 15, no. 10, 2023, https://doi.org/10.3390/polym15102377.

[16] C. Vălean, L. Marşavina, M. Mărghitaş, E. Linul, N. Razavi, and F. Berto, "Effect of manufacturing parameters on tensile properties of FDM printed specimens," *Procedia Structural Integrity*, vol. 26, pp. 313–320, Jan. 2020, https://doi.org/10.1016/j.prostr.2020.06.040.

[17] D. G. Zisopol, A. I. Portoaca, and M. Tanase, "Dimensional Accuracy of 3D Printed Dog-bone Tensile Samples: A Case Study," *Engineering, Technology & Applied Science Research*, vol. 13, no. 4, pp. 11400–11405, Aug. 2023, https://doi.org/10.48084/etasr.6060.

[18] D. G. Zisopol, I. Nae, A. I. Portoaca, and I. Ramadan, "A Theoretical and Experimental Research on the Influence of FDM Parameters on Tensile Strength and Hardness of Parts Made of Polylactic Acid," *Engineering, Technology & Applied Science Research*, vol. 11, no. 4, pp. 7458–7463, Aug. 2021, https://doi.org/10.48084/etasr.4311.

[19] D. G. Zisopol, D. V. Iacob, and A. I. Portoaca, "A Theoretical-Experimental Study of the Influence of FDM Parameters on PLA Spur Gear Stiffness," *Engineering, Technology & Applied Science Research*, vol. 12, no. 5, pp. 9329–9335, Oct. 2022, https://doi.org/10.48084/etasr.5183.

[20] D. G. Zisopol, M. Minescu, and D. V. Iacob, "A Theoretical-Experimental Study on the Influence of FDM Parameters on the Dimensions of Cylindrical Spur Gears Made of PLA," *Engineering, Technology & Applied Science Research*, vol. 13, no. 2, pp. 10471–10477, Apr. 2023, https://doi.org/10.48084/etasr.5733.

[21] D. G. Zisopol, M. Minescu, and D. V. Iacob, "A Study on the Evaluation of the Compression Behavior of PLA Lattice Structures Manufactured by FDM," *Engineering, Technology & Applied Science Research*, vol. 13, no. 5, pp. 11801–11806, Oct. 2023, https://doi.org/10.48084/etasr.6262.

[22] D. G. Zisopol, M. Minescu, and D. V. Iacob, "A Study on the Influence of aging of the Butt-welded PE100 SDR11 on Shore A Hardness and Tensile Strength," *Engineering, Technology & Applied Science Research*, vol. 14, no. 1, pp. 12722–12727, Feb. 2024, https://doi.org/10.48084/etasr.6635.

[23] S. Subramonian *et al.*, "Artificial Neural Network Performance Modeling and Evaluation of Additive Manufacturing 3D Printed Parts," *Engineering, Technology & Applied Science Research*, vol. 13, no. 5, pp. 11677–11684, Oct. 2023, https://doi.org/10.48084/etasr.6185.

[24] B. Belarbi, M. E. A. Ghernaout, and T. Benabdallah, "Implementation of a New Geometrical Qualification (DQ) Method for an Open Access Fused Filament Fabrication 3D Printer," *Engineering, Technology & Applied Science Research*, vol. 9, no. 3, pp. 4182–4187, Jun. 2019, https://doi.org/10.48084/etasr.2689.

[25] D. G. Zisopol, I. Nae, and A. I. Portoaca, "Compression Behavior of FFF Printed Parts Obtained by Varying Layer Height and Infill Percentage," *Engineering, Technology & Applied Science Research*, vol. 12, no. 6, pp. 9747–9751, Dec. 2022, https://doi.org/10.48084/etasr.5488.

[26] D. G. Zisopol, A. I. Portoaca, I. Nae, and I. Ramadan, "A Comparative Analysis of the Mechanical Properties of Annealed PLA," *Engineering, Technology & Applied Science Research*, vol. 12, no. 4, pp. 8978–8981, Aug. 2022, https://doi.org/10.48084/etasr.5123.

[27] A. S. Buller, A. M. Buller, T. Ali, Z. A. Tunio, S. Shabbir, and M. A. Malik, "Experimental Characterization of Bacterial Concrete Against Mechanical and Durability Performance," *Engineering, Technology & Applied Science Research*, vol. 11, no. 1, pp. 6703–6707, Feb. 2021, https://doi.org/10.48084/etasr.3983.

[28] A. S. Buller, Z. A. Tunio, F. U. R. Abro, T. Ali, and K. A. Jamali, "Influence of Coarse Aggregate Gradation on the Mechnical Properties of Concrete, Part II: No-Fines Vs. Ordinary Concrete," *Engineering, Technology & Applied Science Research*, vol. 9, no. 5, pp. 4623–4626, Oct. 2019, https://doi.org/10.48084/etasr.3021.

[29] Z. A. Tunio, F. U. R. Abro, T. Ali, A. S. Buller, and M. A. Abbasi, "Influence of Coarse Aggregate Gradation on the Mechnical Properties of Concrete, Part I: No-Fines Concrete," *Engineering, Technology & Applied Science Research*, vol. 9, no. 5, pp. 4612–4615, Oct. 2019, https://doi.org/10.48084/etasr.3046.

[30] V. Ambade, S. Rajurkar, G. Awari, B. Yelamasetti, and S. Shelare, "Influence of FDM process parameters on tensile strength of parts printed by PLA material," *International Journal on Interactive Design and Manufacturing (IJIDeM)*, Aug. 2023, https://doi.org/10.1007/s12008-023-01490-7.

[31] "3D CAD Design Software", *Solidworks*, https://www.solidworks.com.

[32] "UltiMaker Cura," *UltiMaker*. https://ultimaker.com/software/ultimaker-cura/.

[33] "ASTM D638-14: Standard Test Method for Tensile Properties of Plastics." https://doi.org/10.1520/D0638-14.

[34] "Data Analysis, Statistical & Process Improvement Tools." https://www.minitab.com/en-us/.