A Study on the Influence of FDM Parameters on the Compressive Behavior of PET-G Parts

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ABSTRACT

This article presents the results of a study on the influence of Fused Deposition Modeling (FDM) 3D printing parameters on the compressive behavior of test specimens made of PET-G. In this context, 45 test specimens, made by FDM on the Anycubic 4 Max Pro 2.0 printer, were compressive tested on a universal testing machine Barrus White 20 kN, with the height of the layer applied in one pass being L_h = 0.10/0.15/0.20 mm and filling percentage I_d = 50/75/100%. The two considered variable parameters, L_h and I_d influence the compression resistance of the PET-G parts, with I_d having a more significant influence. The scope and novelty of this work is to find the optimal parameters for maximum compressive strength (C_s) of PET-G samples made of FDM.

Keywords-FDM parameters; PET-G; compressive stress; experimental tests

I. INTRODUCTION

Additive manufacturing is the process of producing parts by adding material in overlapping layers according to the 3D model profiles of the part [1-2]. Additive manufacturing technologies have continuously evolved since their emergence, this evolution being remarkable for new methods and materials used, improvement of mechanical and material quality characteristics of 3D manufactured parts, etc. [3-10]. One of the most widely used additive manufacturing technologies is Fused Deposition Modeling (FDM), which is characterised by the wide range of materials used for printing, such as PLA (polylactic acid), PET-G (polyethylene terephthalate glycol), ASA (acrylonitrile styrene acrylate), ABS (acrylonitrile butadiene styrene), TPU (thermoplastic polyurethane), and nylon, its ease of use, and the advantageous price of materials and equipment [11, 23-29]. However, in order to maximize the mechanical and qualitative characteristics of the parts produced by FDM, it is necessary to perform an optimization of the process parameters, i.e. the height of the layer applied in one pass L_h, the filling percentage I_d, the filling pattern I_p, the part orientation, the printing speed P_s, the extruder temperature E_t, and the table temperature B_t, [7-20]. In [2], a comparative study of the impact of FDM parameters, (part orientation, L_h, I_d, and P_s) on the mechanical properties of PLA, ABS, PEEK, and PET-G is presented. Out of the 4 parameters studied, I_d has the most decisive influence on the mechanical properties of the studied FDM parts. In [7], the compressive behavior was studied by varying I_d and L_h of FDM parts made of PLA, ABS, and heat-treated PLA. Heat treatment of PLA parts was performed by holding the parts in an oven at a temperature of 75°C for a 3-hour period. The results show that among the two varied parameters, I_d had higher impact on the compressive behavior, with the compressive strength increasing with increasing filling percentage. At the same time, it is observed that PLA parts which were heat treated, had 8.20% higher compressive strength on average than the not heated PLA parts. In [8], a study on the effects of printing parameters on the mechanical characteristics and mathematical modeling of FDM printed PET-G parts is presented. The best compressive results were obtained for parts made of PET-G with triangle filling pattern and the highest filling percentage. The obained results for triangle are higher by 6.45 – 35.16% than other filling patterns (grid, rectilinear, honeycomb, concentric).

The aim and novelty of this work are the determination of the influence of the FDM parameters (height of the layer applied in one pass L_h and filling percentage I_d) on the compressive behavior of parts made from PET-G in order to find the optimum parameters for the best mechanical proprieties. Specimens were manufactured and tested in compression in the laboratories of the Faculty of Mechanical and Electrical Engineering of the Petroleum – Gas University of Ploiești.

II. DETERMINATION OF THE INFLUENCE OF FDM PARAMETERS ON THE TENSILE BEHAVIOR OF PARTS MADE OF PET-G

A. Methodology

Figure 1 presents the steps of the work methodology in studying the influence of FDM parameters on the compressive behavior of PET-G parts.

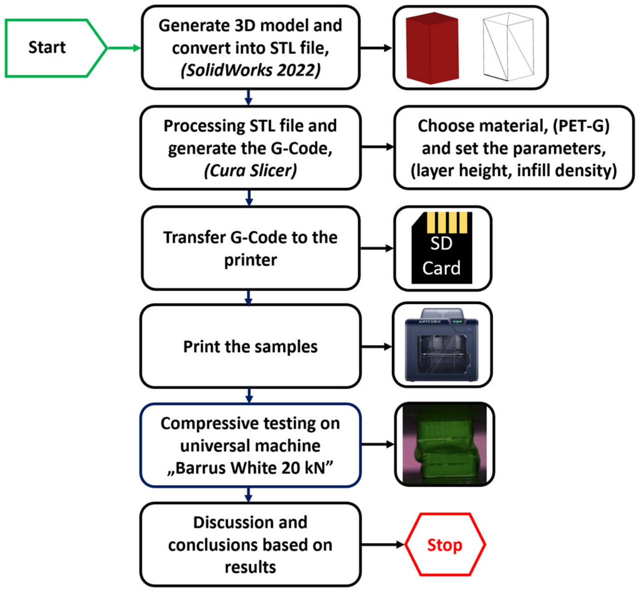

Fig. 1. Steps of the work methodology.

Using Solidworks 2022 software [31], we produced the 2D sketch and 3D model of the specimen for compression, converting it from SLD to STL format (Figure 2).

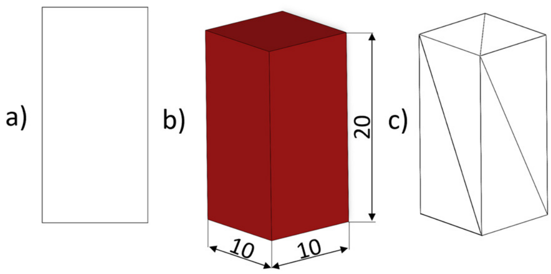

Fig. 2. Specimen for compressive testing in Solidworks 2022 software: (a) 2D model, (b) 3D model, (c) STL model.

The file in STL format, corresponding to the specimen shown in Figure 2, was processed in the Cura Slicer program, in which we set the PET-G material, entered the parameters shown in Table I and generated the G-Code file.

TABLE I. FDM PRINTING PARAMETERS FOR PET-G COMPRESSION SPECIMENS

Constant parameters		**Variable parameters**		**Material**
		Layer height in one pass	**Filling percentage**	**PET-G**
		L_h	**I_d**	-
Part orientation	X-Y	(mm)	(%)	(parts)
		0.10	100	5
Temperature of the extruder E_t	250 °C		75	
			50	
Temperature of the table B_t	70 °C	0.15	100	
			75	
Printing speed P_s	30 mm/s		50	
		0.20	100	
Filling pattern I_p	Grid		75	
			50	

Figure 3 depicts the rendering of the PET-G specimen for compression, made in Cura Slicer [32] with constant parameters from Table I and L_h = 0.10 mm, I_d = 100%. The G-Code file of the compression specimen illustrated in Figure 3 contains 40187 command lines, its structure being as shown in Figure 4 [32].

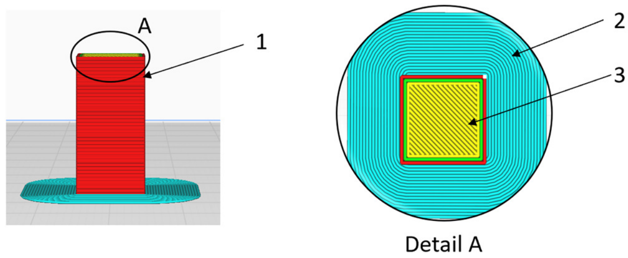

Fig. 3. PET-G specimen for compressive testing in Cura Slicer software: 1 - specimen made layer by layer, 2 - specimen holder, 3 - filling pattern.

```
;LAYER_COUNT:198
;LAYER:0
M107
M204 S300
M205 X8.18 Y8.18
G0 F2400 X99.372 Y99.567 Z0.3
M205 X3 Y3
;TYPE:SKIRT
G1 F1500 E0
G1 F1200 X100.749 Y98.458 E0.08821
G1 X102.725 Y97.474 E0.19834
G1 X104.358 Y97.244 E0.28061
G1 X115.619 Y97.2 E0.84243
G1 X117.676 Y97.623 E0.9472
G1 X119.55 Y98.681 E1.05457
G1 X120.433 Y99.372 E1.11051
G1 X121.542 Y100.749 E1.19872
```

Fig. 4. G-Code file structure of PET-G compression specimen.

The G-Code file shown in Figure 4 was transferred to the Anycubic 4 Max Pro 2.0 3D printer (Figure 5), on which 45 compression specimens shown in Figure 6 were manufactured using Everfill 1.75 mm PET-G filament. The 45 specimens presented in Figure 6, manufactured using the parameters in Table I, were tested for compression on the Barrus White 20 kN universal testing machine (Figure 7), according to the ISO 604:2002, with a speed of 10 mm/min [30].

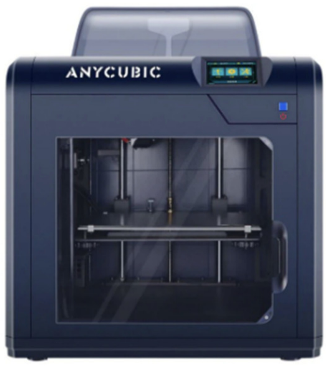

Fig. 5. Anycubic 4 Max Pro 2.0 printer, used for FDM manufacturing of PET-G specimens for compression.

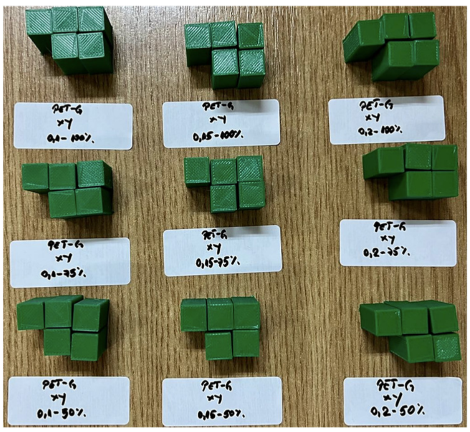

Fig. 6. Compression specimens made of PET-G by FDM.

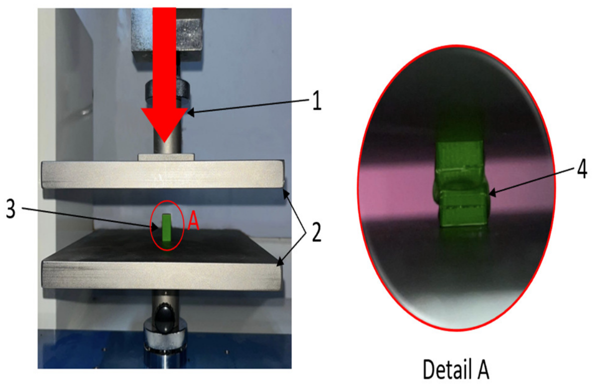

Fig. 7. Compression test on Barrus White 20 kN machine: 1 - loading direction, 2 - machine plates, 3 - specimen before compression test, 4 - specimen after compression test.

B. Results and Discussion

The results of the compression tests on the 45 specimens are summarized in Tables II-IV and plotted in Figures 8-10. An analysis of Figure 8 shows that the compressive strength (C_s) increases with increasing I_d. The best results, 29.79 MPa - 30.84 MPa, were obtained for specimens having I_d = 100%. By increasing the I_d from 50% to 75%, the compressive strength values increased by 38.78% - 46.94%, and by increasing the I_d from 75% to 100% they increased by 47.66% - 56.30%.

TABLE II. RESULTS OF COMPRESSION TESTS FOR PET-G WALLS WITH L_h = 0.10 mm

Infill I_d (%)	Compressive stress C_s (mpa)					
	Specimen					
	1	2	3	4	5	Average
50	14.20	13.73	14.00	14.16	14.21	14.06
75	19.17	19.06	19.76	20.29	20.88	19.83
100	29.79	30.84	30.02	30.47	30.54	30.33

TABLE III. RESULTS OF COMPRESSION TESTS FOR PET-G WALLS WITH L_h = 0.15 mm

Infill I_d (%)	Compressive stress C_S (MPa)					
	Specimen					
	1	2	3	4	5	Average
50	11.82	12.25	12.47	12.18	12.24	12.20
75	20.05	18.58	20.61	21.12	20.74	20.22
100	30.61	30.41	30.73	30.64	30.47	30.57

TABLE IV. RESULTS OF COMPRESSION TESTS FOR PET-G RIVERS WITH L_h = 0.20 mm

Infill I_d (%)	Compressive stress C_S (MPa)					
	Specimen					
	1	2	3	4	5	Average
50	11.10	10.65	10.65	11.86	12.07	11.27
75	20.39	19.74	19.73	19.10	20.12	19.82
100	28.67	29.55	29.06	29.30	29.41	29.20

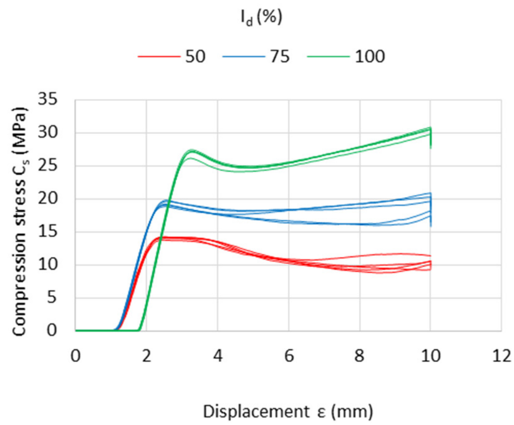

Fig. 8. Average compressive strength values for PET-G specimens with L_h = 0.10 mm and I_d = 50/75/100 %.

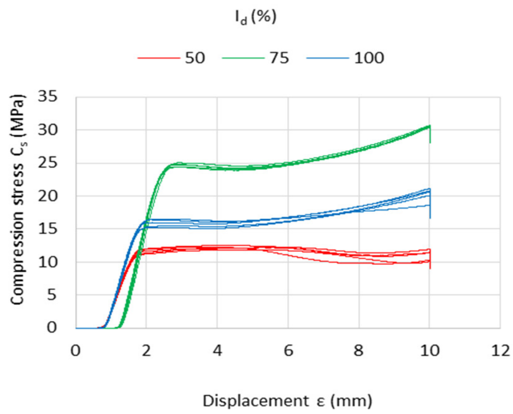

Fig. 9. Average compressive strength values for PET-G specimens with L_h = 0.15 mm and I_d = 50/75/100 %.

It is observed in Figure 9 that the compressive strength is decisively influenced by the filling percentage. The best results, 30.41 MPa - 30.73 MPa, were obtained for specimens having I_d = 100%. By increasing the filling percentage from 50% to 75%, the compressive strength valuess increased by 57.13% - 69.28%, whereas by increasing filling percentage from 75% to 100%, they increased by 45.52% - 63.70%. Looking at Figure 10, it can be observed that C_s is strongly influenced by I_d. The best results, 28.67 MPa - 29.55 MPa, were obtained for specimens with I_d = 100%. By increasing the filling percentage from 50% to 75%, the compressive strength valuess increased by 68.89% - 79.32%, while by increasing the filling percentage from 75% to 100%, they increased by 44.89% - 50.11%.

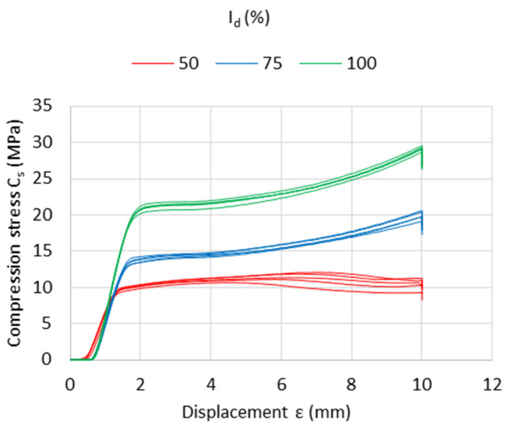

Fig. 10. Average compressive strength values for PET-G specimens with L_h = 0.20 mm and I_d = 50/75/100 %.

Based on the average compressive strength results (see Tables II-IV), the graph in Figure 11 was plotted with Minitab software [33]. The Figure illustrates how the variable parameters L_h and I_d of the FDM influence the Cs of PET-G specimens [33].

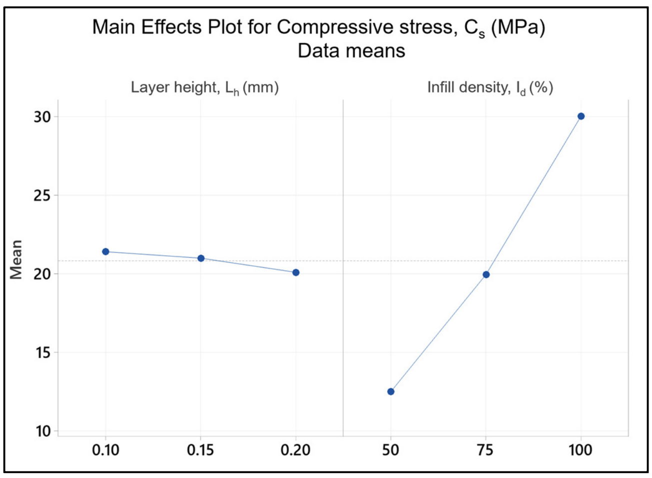

Fig. 11. Influence of variable FDM parameters L_h and I_d on the Cs of PET-G specimens.

According to Figure 11, out of the two variable parameters, I_d has the highest impact on the C_s of PET-G specimens, whereas the second variable parameter L_h, has an insignificant influence. The same conclusions can be drawn from an analysis of the Pareto chart in Figure 12. The Pareto chart shows that the filling percentage (B = I_d) has a strong influence on the compressive strength values obtained from compression tests of PET-G specimens on the Barrus White 20 kN universal testing machine (Figure 7). Using Minitab [33] and the FDM parameters in Table I, L_h = 0.10/0.15/0.20 mm and I_d = 50/75/100 %, the contour graph of compressive strengths for PET-G specimens was plotted, as shown in Figure 13.

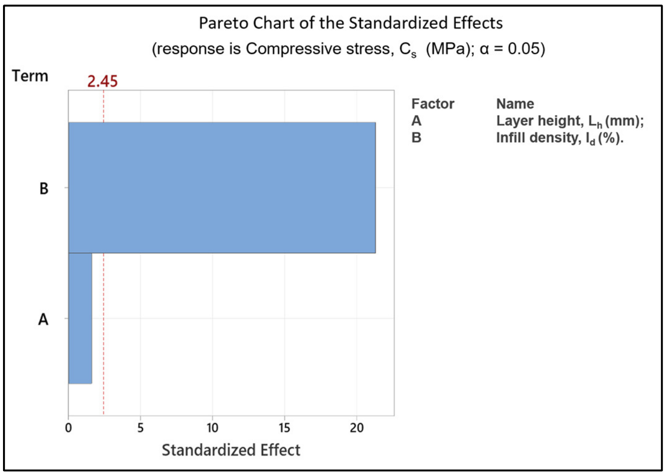

Fig. 12. Pareto plot of the influence of the variable parameters A = L_h and B = I_d of FDM on the compressive strength of PET-G specimens.

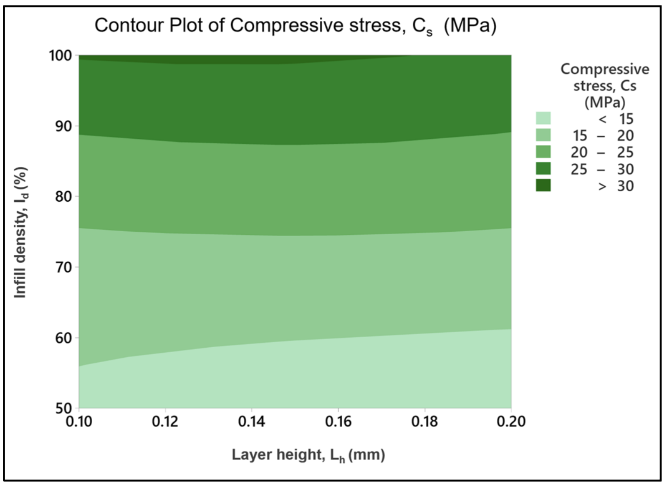

Fig. 13. Contour plot of the compressive strength of PET-G specimens manufactured by FDM.

Analyzing the contour plot in Figure 13, the way the variable parameters L_h and I_d of the FDM influence the compressive strength of the specimens can be concluded. Increasing I_d has a significant influence on the increase of the compressive strength of the specimens.

III. CONCLUSIONS

This paper presents the results of the research on the influence of FDM 3D printing parameters (see Table I) on the compression behavior of Everfill PET-G parts.

In this context, 45 specimens were produced on the Anycubic 4 Max Pro 2.0 printer, with layer height having values L_h = 0.10/0.15/0.20 mm and filling percentage having values I_d = 50/75/100 %. The specimens were compression tested on a Barrus White 20 kN universal testing machine.

Increasing the filling percentage (I_d) increases the compressive strength of the specimens made by FDM from PET-G, in accordance with the findings in [2, 7, 8]. The minimum value of the compressive strength of the specimens, i.e. 11.27 MPa, was recorded for parameter values L_h = 0.20 mm and I_d = 50%, and the maximum, i.e. 30.57 MPa, was recorded for L_h = 0.15 mm and I_d = 100%. The obtained results for PLA samples in [7] are bigger by 131.56 – 187.24% than the ones of this study for PET-G samples with the same parameters. For the same parameters for ABS samples, the obtained results are bigger by 99.12 – 104.65% than our own. When comparing with the findings in [8], our results for the same parameters, but for different filament brand are smaller by 7.09%.

Our study can be applied in the manufacturing process of parts by FDM from PET-G using optimal parameters to acquire the best mechanical proprieties. In addition, with this work, we filled knowledge gaps by investigating the effects of two crucial parameters (L_h and I_d) of 3D printing by FDM and opportunities for future research were found. It is recommended to extrapolate the study to other materials such as ASA, recycled PET-G, and ASA with varying percentages of the recycled material.

REFERENCES

[1] S. Valvez, A. P. Silva, and P. N. B. Reis, "Compressive Behaviour of 3D-Printed PETG Composites," *Aerospace*, vol. 9, no. 3, Mar. 2022, Art. no. 124, https://doi.org/10.3390/aerospace9030124.

[2] M. Algarni and S. Ghazali, "Comparative Study of the Sensitivity of PLA, ABS, PEEK, and PETG's Mechanical Properties to FDM Printing Process Parameters," *Crystals*, vol. 11, no. 8, Aug. 2021, Art. no. 995, https://doi.org/10.3390/cryst11080995.

[3] I. M. Alarifi, "Mechanical properties and numerical simulation of FDM 3D printed PETG/carbon composite unit structures," *Journal of Materials Research and Technology*, vol. 23, pp. 656–669, Mar. 2023, https://doi.org/10.1016/j.jmrt.2023.01.043.

[4] A. Yankin *et al.*, "Optimization of Printing Parameters to Enhance Tensile Properties of ABS and Nylon Produced by Fused Filament Fabrication," *Polymers*, vol. 15, no. 14, Jan. 2023, Art. no. 3043, https://doi.org/10.3390/polym15143043.

[5] A. Kholil, E. Asyaefudin, N. Pinto, and S. Syaripuddin, "Compression Strength Characteristics of ABS and PLA Materials Affected by Layer Thickness on FDM," *Journal of Physics: Conference Series*, vol. 2377, no. 1, Aug. 2022, Art. no. 012008, https://doi.org/10.1088/1742-6596/2377/1/012008.

[6] S. Skere, A. Zvironiene, K. Juzenas, and S. Petraitiene, "Optimization Experiment of Production Processes Using a Dynamic Decision Support Method: A Solution to Complex Problems in Industrial Manufacturing for Small and Medium-Sized Enterprises," *Sensors*, vol. 23, no. 9, Jan. 2023, Art. no. 4498, https://doi.org/10.3390/s23094498.

[7] 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.

[8] R. Kumaresan, M. Samykano, K. Kadirgama, A. K. Pandey, and Md. M. Rahman, "Effects of printing parameters on the mechanical characteristics and mathematical modeling of FDM-printed PETG," *The International Journal of Advanced Manufacturing Technology*, vol. 128, no. 7, pp. 3471–3489, Oct. 2023, https://doi.org/10.1007/s00170-023-12155-w.

[9] 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.

[10] 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.

[11] 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.

[12] 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.

[13] D. G. Zisopol, M. Tanase, and A. I. Portoaca, "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.

[14] 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.

[15] 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.

[16] 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.

[17] 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.

[18] M. Tanase, D. G. Zisopol, and A. I. Portoaca, "A Study regarding the Technical-Economical Optimization of Structural Components for enhancing the Buckling Resistance in Stiffened Cylindrical Shells," *Engineering, Technology & Applied Science Research*, vol. 13, no. 5, pp. 11511–11516, Oct. 2023, https://doi.org/10.48084/etasr.6135.

[19] 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.

[20] A. Dinita, A. Neacsa, A. I. Portoaca, M. Tanase, C. N. Ilinca, and I. N. Ramadan, "Additive Manufacturing Post-Processing Treatments, a Review with Emphasis on Mechanical Characteristics," *Materials*, vol. 16, no. 13, Jan. 2023, Art. no. 4610, https://doi.org/10.3390/ma16134610.

[21] 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.

[22] D. Zisopol, M. Minescu, and D. Iacob, "A Study on the Influence of FDM Parameters on the Tensile Behavior of Samples made of PET-G," *Engineering, Technology and Applied Science Research*, vol. 14, pp. 13487–13492, Apr. 2024, https://doi.org/10.48084/etasr.6949.

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

[24] D. G. Zisopol and A. Dumitrescu, *Ecotehnologie. Studii de caz*. Ploiesti, Romania: Editura Universității Petrol-Gaze din Ploiești, 2021.

[25] D. G. Zisopol, A. Dumitrescu, and C. N. Trifan, *Ecotehnologie: Noţiuni teoretice, aplicaţii şi studii de caz*. Ploiesti, Romania: Editura Universității Petrol-Gaze din Ploiești, 2010.

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

[27] M. J. Săvulescu and D. G. Zisopol, *Tehnologii industriale şi de construcţi*. Ploiesti, Romania: Editura Universității Petrol-Gaze din Ploiești, 2002.

[28] D. G. Zisopol, *Tehnologii industriale şi de construcţii, Aplicații practice şi studii de caz*. Ploiesti, Romania: Editura Universității Petrol-Gaze din Ploiești, 2003.

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

[30] *ISO 604:2002 Plastics: Determination of compressive properties*. ISO, 2002.

[31] "3D CAD Design Software," SOLIDWORKS. https://www.solidworks.com/home-page-2021.

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

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