Proceedings of the International Conference on Engineering, Technology and Applied Science Innovations pp. 15–20 DOI: 10.15439/2025I24 ISSN 2300-5963 ACSIS, Vol. 46

Study on the optimization of FDM parameters for the manufacture of flexural specimens from recycled ASA in the context of the transition to the circular economy

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Abstract—**This paper investigates how variable 3D printing parameters by fused deposition modeling (FDM) influence the mechanical properties of 3-point bending specimens made from recycled acrylonitrile styrene acrylate (rASA) filament. Using variable thermoplastic extrusion parameters [layer height Lh = (0.10, 0.15, 0.20) mm and fill percentage Ip = (50, 75, 100)%], 45 3-point bending specimens were additively fabricated from Everfil rASA filament on the QIDI Q1 Pro 3D printer. All fabricated specimens were subjected to 3-point bending tests on the Barrus White 20 kN universal testing machine. The analysis shows that both selected parameters (Lh and Ip) contribute to the changes in the maximum flexural stress (σf) of the rASA filament additive manufacturing specimens. Of the two, the filling percentage shows a significantly stronger effect, exceeding the influence of the layer height by 55.89%.**

Index Terms—**FDM; flexural; experimental study; FDM parameters.**

I. Introduction

GIVEN climate change, the continuous increase in plastic production and the negative impact of plastic waste, the need to decrease the quantity of plastic waste and adopt a circular economy is becoming increasingly urgent. In this context, extensive action plans have been developed at the European Union level to ensure that all plastic packaging is fully recyclable by 2030, [1]. Given the extraordinary advantages offered by additive manufacturing technologies (low manufacturing costs, efficient use of materials. Consequently, the application of the circular economy concept in the domain of additive manufacturing through thermoplastic extrusion engenders novel opportunities for the management of plastic waste, [2-13]. In this context, there are studies that investigate the impact of using recycled plastics in the field of additive manufacturing technologies through plastic extrusion, [14-30], however, certain branches have been found that have not yet been exploited, and through the present study the authors address a topic that has not yet been researched. In the paper [31], the authors demonstrate the viability of using recycled polycarbonate (PC) and acrylonitrile butadiene styrene (ABS) materials as raw materials for the manufacture of parts by thermoplastic extrusion of plastic granules. In the paper [32] a comparative study was carried out between the performances of parts additively manufactured from virgin carbon fibers (vCF) and recycled carbon fibers (rCF), the research results show that the bending strengths of the samples additively manufactured from rCF are 12.73% higher than the bending strengths of the samples manufactured from vCF. The findings of the study demonstrate that the utilisation of recycled carbon fibres (rCF) in the domain of additive manufacturing technologies through plastic extrusion constitutes an efficient and sustainable solution for the management of waste from this material.

In the paper [33], the study on the influence of the filling pattern and the filling percentage on the mechanical properties of tensile and dynamic stresses of sandwich structures additively manufactured from recycled polyethylene terephthalate glycol (rPET) is presented. The conclusions of the study show that the smallest dimensional deviations from the CAD model were obtained for the parts manufactured using the Concentric filling pattern and the filling percentage of 25%. In terms of mechanical performance, the parts additively manufactured using the Concentric filling pattern and the filling percentage of 50%, obtained the best tensile characteristics (tensile strength, elongation at break), but also the best ratio between strength and mass of the part.

In this study, the authors propose a sustainable approach for the recovery of acrylonitrile styrene acrylate (ASA) waste in the framework of additive manufacturing technologies by extrusion of plastics. The proposed solution is highlighted by reducing ASA waste, increasing the life span of the material, and reducing production costs. In the study, a statistical analysis is performed on the influence of process parameters on 3-point bending strengths, and subsequently the optimization of process parameters is performed in order to maximize 3-point bending strengths. In order to predict the values of 3-point bending strengths depending on the values of the thermoplastic extrusion parameters (L_h and I_p), the regression equation was generated.

II. Determination of the Influence of FDM Parameters on the 3-Point Bending Behavior of Specimens Manufactured Additive From Recycled ASA Filament

A. *Additive manufacturing of 3-point bending specimens by thermoplastic extrusion of rASA filament*

The basis of the additive manufacturing process is the digital model in STL format (Standard Triangle Language), which contains the dimensional information of the part in the form of surface approximations using a network of triangles. In this context, using the CAD software Solidworks 2022, the technical drawing of the specimen in 2D format was created (fig. 1, a), and subsequently based on it the 3D model of the specimen was generated (fig. 1, b), this being the basis for creating the digital model in STL format, (fig. 1, c), [34].

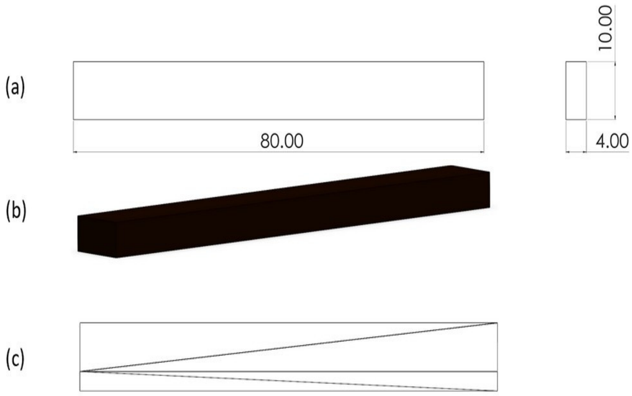

Fig. 1. 3 point bending sample: a) 2D model; b) 3D model; c) STL model.

The STL file of the 3-point bending sample was imported into the QIDI Slicer software. The thermoplastic extrusion parameters were setted were set in accordance with to the data in Table 1.

TABLE I. Parameters for Additive Manufacturing by Thermoplastic Extrusion of 3-Point Bending Specimens

Printing parameters	**QIDI Q1 Pro**
Material, Mat	rASA
Part orientation, P_o	X-Y
Extruder temperature, T_e	250 °C
Platform temperature, P_t	90 °C
Print speed, P_s	30 mm/s
Fill pattern, F_p	Grid
Layer height, L_h	0.10; 0.15; 0.20 mm
Fill percentage, I_p	50; 75; 100 %

Using the STL model corresponding to the 3-point bending specimen and the thermoplastic extrusion parameters from Table 1, 9 G-Code files (one file for each combination of parameters) were generated in the QIDI Slicer software, which contain the work instructions for the additive manufacturing of the 3-point bending specimens from rASA filament from the Everfil brand. Figure 2 shows the 3-point bending specimens in the QIDI Slicer software, [35].

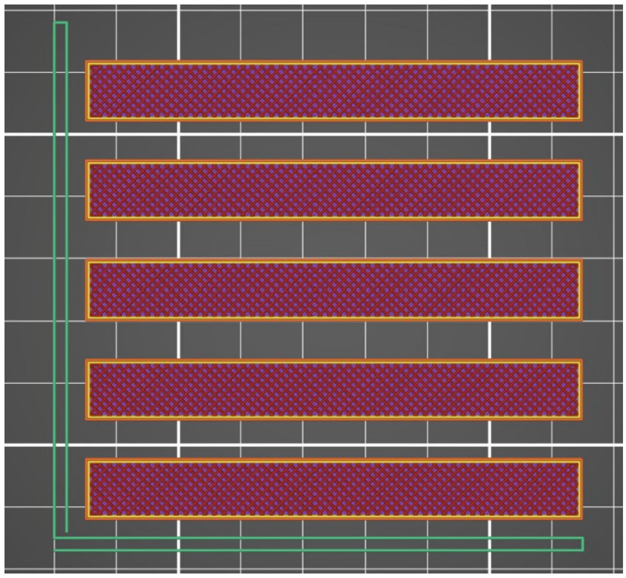

Fig. 2. 3-point bending specimens in QIDI Slicer.

The 9 G-Code files containing the work instructions for the additive manufacturing of 3-point bending specimens through thermoplastic extrusion of rASA filament were transferred to the QIDI Q1 Pro 3D printer. A total of where 45 specimens were manufactured for 3-point bending testing, (Fig. 3).

Fig. 3. 3-point bending specimens additively manufactured from rASA filament.

B. *Evaluation of the influence of FDM parameters on the 3-point bending strengths of additively manufactured specimens from rASA filament*

The 45 3-point bending samples samples, manufactured by means of additive manufacturing using thermoplastic extrusion of rASA filament, were tested for 3-point bending using the Barrus White 20 kN universal testing machine

(Fig. 4). The testing was conducted in accordance with the ISO 178:2019standard, with a speed of 5 mm/min, [36].

Fig. 4. 3-point bending test on the Barrus White 20 kN machine.

As demonstrated in Figure 5, the 45 specimens were subjected to the three-point bending test using the Barrus White 20 kN machine.

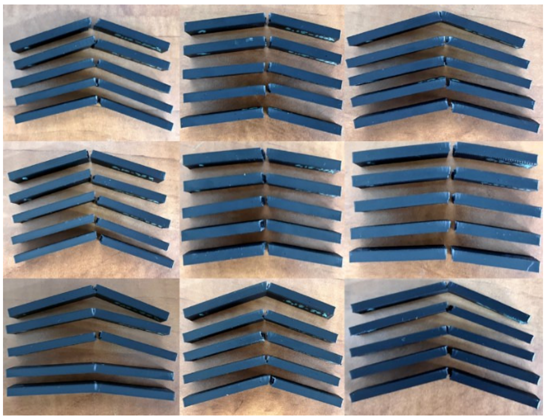

Fig. 5. Additively manufactured specimens on the QIDI Q1 Pro 3D printer, after performing the three-point bending test on the Barrus White 20 kN machine

Table 2 presents a summary of the 3-point bending strengths of the samples that were manufactured using additive manufacturing through thermoplastic extrusion of rASA filament.

Figure 6 graphically represents the average values of the 3-point bending strengths of the samples additively manufactured by thermoplastic extrusion of the rASA filament.

Figure 7 shows the graph expressing the influence of the variable parameters of thermoplastic extrusion (FDM) on the bending strengths of the additively manufactured samples from rASA filament. Analyzing the data in Table 2, it can be seen that the maximum value of the three-point flexural strength was obtained for sample 1 from the set manufactured with L_h = 0.20 mm and I_p = 100%. The lowest value of the flexural strength for the additively manufactured rASA filament specimens was obtained for sample 1 from the set produced with L_h = 0.10 mm and I_p = 50%.

TABLE II RESULTS OF 3-POINT BENDING TESTS OF SPECIMENS MANUFACTURED FROM rASA.

L_h, (mm)	I_p, (%)	FLEXURAL STRENGTH, σ_f					
		Sample number					
		1	2	3	4	5	Average
0.10	50	38.72	39.31	39.19	39.31	38.83	39.07
	75	44.01	45.07	44.72	44.48	44.48	44.55
	100	63.19	64.61	62.61	64.49	63.55	63.69
0.15	50	43.90	44.60	44.37	44.01	44.95	44.37
	75	44.01	45.07	44.72	44.48	44.48	44.55
	100	64.14	64.84	63.55	64.37	66.02	64.58
0.20	50	48.72	47.31	48.60	49.07	48.37	48.41
	75	59.90	60.37	59.90	59.55	59.90	59.92
	100	67.67	67.20	65.67	67.31	66.72	66.91

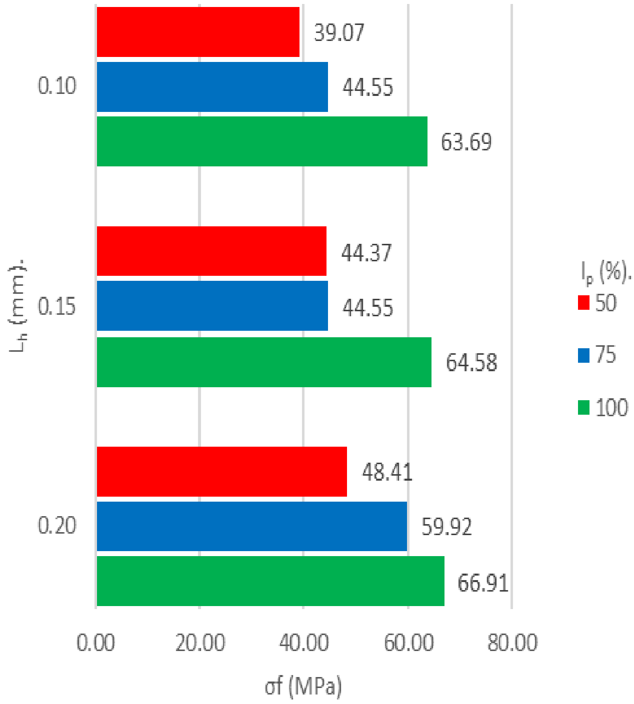

Fig. 6 Average flexural strength of rASA 3-point bending specimens.

The maximum average flexural strength, of 66.91 MPa, was obtained for the set of printed specimens with L_h = 0.20 mm and I_p = 100%. Increasing the filling percentage from 50% to 75% led to an improvement in the average flexural strength with values ranging from 0.42% to 23.77%. Increasing the filling level from 75% to 100% resulted in an additional increase in flexural strength ranging from 11.67% to 44.95%.

Minitab software was used to analyze the influence of FDM parameters (L_h and I_p) on the flexural behavior of specimens made on the QIDI Q1 Pro 3D printer by extruding rASA filament [37]. Figure 7 shows the diagram that highlights how these variable parameters of the thermoplastic extrusion process influence the flexural strength of additively manufactured rASA specimens.

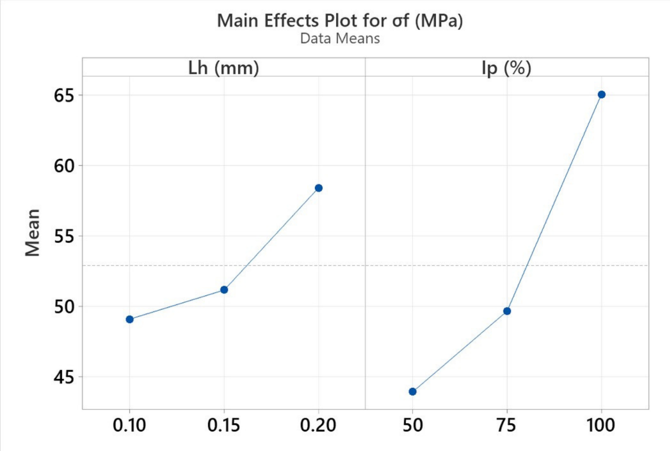

Fig 7. Influence of variable parameters of FDM on flexural strengths of samples made of rASA filament.

Analyzing the graph from figure 7, it can be seen tat the variable parameters of the 3D printing through thermoplastic extrusion L_h = (0.10, 0.15, 0.20) mm and I_p = (50, 75, 100)%, influence the flexural strength values of the specimens additively manufactured from rASA filament.

Figure 8 presents the Pareto chart, which illustrates how the variable parameters of thermoplastic extrusion (A = L_h and B = I_p) affect the flexural strength of the specimens obrained by additive manufacturing from rASA filament.

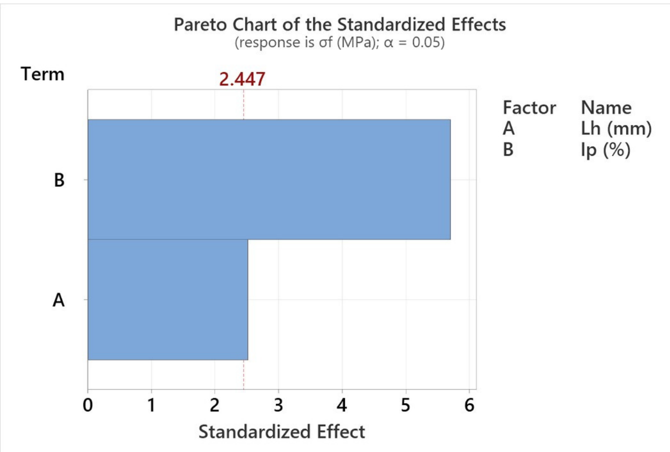

Fig. 8. Pareto chart regarding the influence of variable parameters of the FDM process (A = L_h and B = I) on the bending strength of specimens manufactured from rASA filament."

From the analysis of Figure 8, it appears that both variable parameters of thermoplastic extrusion influence the flexural strength of specimens additively manufactured from rASA filament, but the effect of the factor (B = I_p) is 55.89% greater than that of the factor (A = L_h).

Figure 9 presents the contour plot, which highlights how the variable parameters of the extrusion process (L_h and I_p) affect the values of the three-point flexural strength of specimens obtained by additive manufacturing from rASA filament.

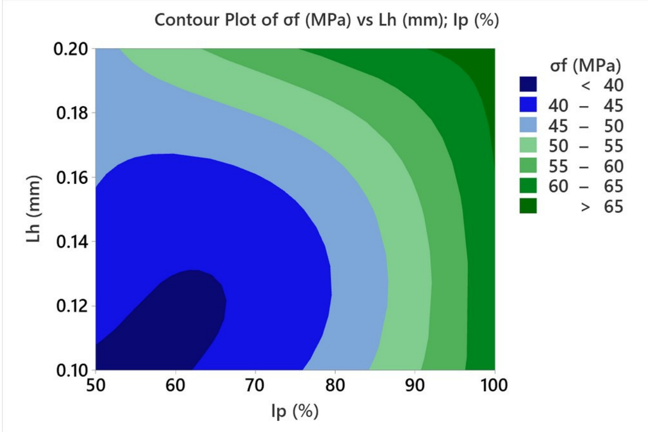

Fig. 9. Contour plot of the influence of variable FDM parameters (L_h and I_p) on the bending strengths of specimens manufactured from rASA filament.

Based on the contour diagram in Figure 9, it is observed that an increase in both the height of the layer (L_h) and the filling percentage (I_p) leads to higher values of three-point bending strength.

Using the statistical software Minitab, based on the variable parameters of the thermoplastic extrusion process (presented in Table 1) and the three-point flexural strength values for the additively manufactured samples of rASA filament (Table 2), optimization graphs of these parameters were generated, with the objective of obtaining maximum flexural strength values.

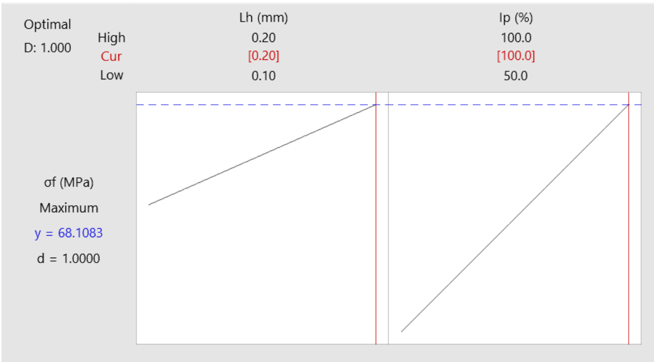

Fig. 10. Optimization graphs of variable thermoplastic extrusion parameters (L_h and I_p) for maximizing 3-point bending strengths.

According to the optimization graphs in Figure 10, it is concluded that the optimal thermoplastic extrusion (FDM) parameters for additive manufacturing of 3-point bending specimens from rASA are L_h = 0.20 mm and I_p = 100%.

In order to predict the 3-point bending strength depending on the values of the variable parameters of thermoplastic extrusion (L_h and I_p), using Minitab, the following regression equation was obtained:

$$\sigma f\ (MPa) = 7.26 + 93.1 \cdot L_h(mm) + 0.4222 \cdot I_p$$

III. Conclusions

This paper presents the results of research on the optimization of thermoplastic extrusion (FDM) parameters for the additive manufacturing of three-point bending test specimens from rASA filament, in the context of the transition to a circular economy. For the purpose of this study, 45 specimens were 3D printed on the QIDI Q1 Pro printer, using layer height values, L_h = (0.10, 0.15, 0.20) mm and filling percentages I_p = (50, 75, 100)%. Subsequently, all 45 specimens were tested for three-point bending on the Barrus White 20 kN universal testing machine, at a speed of 5 mm/min, according to the requirements of the ISO 178:2019 standard.

After performing the 45 experimental three-point bending tests on the Barrus White 20 kN machine, the following bending strength values were obtained:

- minimum average 3-point bending strength: 39.07 MPa;
- maximum average 3-point bending strength: 64.58 MPa;
- 3-point bending strength of the 45 specimens: 52.92 Mpa.

Using Minitab, the statistical influence of the influence of the variable parameters of thermoplastic extrusion (L_h and I_p) on the 3-point bending strengths of the specimens additively manufactured by thermoplastic extrusion of rASA filament was evaluated. The result of the analysis showed that both parameters have an influence on the 3-point bending strengths, but the influence of the I_p parameter is 55.89% greater than the influence of the L_h parameter.

Based on statistical analysis and the results obtained from three-point bending tests for additively manufactured rASA filament specimens, the optimization of the variable parameters of the thermoplastic extrusion process was carried out, with the aim of increasing the bending strength. The set of parameters identified as optimal is: L_h = 0.20 mm and I_p = 100%.

In order to predict the values of the bending resistance of the additively manufactured rASA filament specimens, depending on the values of the variable parameters, the regression equation 1 was generated.

Comparing the values of the 3-point bending strengths of specimens manufactured from rASA with L_h = (0.10, 0.15, 0.20) mm and I_p = 100% with those of specimens manufactured from virgin ASA using identical parameters, we conclude the following:

- for L_h = 0.10 mm, the 3-point bending strength of rASA is lower by 5.47%;
- for L_h = 0.15 mm, the 3-point bending strength of rASA is lower by 5.32%;
- for L_h = 0.20 mm, the 3-point bending strength of rASA is higher by 5.63%.

This study demonstrates that recycled materials can be a worthy alternative for additive manufacturing of parts with engineering applications.

By using optimal manufacturing parameters, material and equipment are efficiently utilized, superior mechanical characteristics are achieved, and the scrap rate is minimized.

The authors plan to extend the research to other types of materials as well as other types of mechanical tests.

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