



TESTING THE DEGREE OF INFLUENCE ON TENSILE STRENGTH OF 3D PRINTING PARAMETERS IN CARBON FIBER REINFORCED PETG

Prodromos Minaoglou¹, Anastasios Tzotzis², Sahaya Dennish Babu George³,
Panagiotis Kyratsis⁴

^{1,2,4}University of Western Macedonia, Department of Product and Systems Design Engineering, 50100 Kila Kozani, Greece
³Chettinad College of Engineering and Technology, Department of Physics, Karur, Tamil Nadu, India. Pin - 639114

Corresponding author: Panagiotis Kyratsis, pkyratsis@uowm.gr

Abstract: Several factors affect a 3D printed geometry's strength at the same time. The strength of the printed geometry depends on a number of factors, including the material, printing settings, geometry shape, and orientation. In this research the magnitude of influence from specific printing settings, defined by the slicer software on the tensile strength of 3D printed specimens was examined. The printer used was of the FFF (Fused Filament Fabrication) type. The composite material chosen for the test was a PETG (Polyethylene Terephthalate Glycol) strengthened with carbon-fiber NEEMA3D™ CARBON: PLUS. The material comprises 20% carbon fiber and 80% PETG polymer. The FFF 3D printer belongs to the closed type category with a large size, as a result of which it can print all the specimens simultaneously and with stable environmental conditions. More specifically, the printer is the CreatBot™ D600 Pro with dimensions 600mm × 600mm × 600mm. The Flow Rate, the Printing Speed and the Nozzle Temperature were the three parameters selected for the experiments, since all three of them affect the fluidity of the material, in other words its ability to pass easily and quickly through the interior of the printing nozzle. The change in the value of each parameter was divided into three symmetrical values, i.e. three levels. The variation in the Flow was: 85%, 100%, 115%, the Speed was: 25mm/s, 35mm/s, 45mm/s and the Temperature was: 235°C, 245°C, 255°C. The three parameters and the three value levels generate 27 different combinations. Using the Box-Behnken design, 15 out of the 27 specimens were fabricated and tested.

Key words: 3D printing; Tensile; Box and Behnken; Carbon Fiber Reinforced Polymer; Fused Filament Fabrication; Polyethylene Terephthalate Glycol

1. INTRODUCTION

The composition of two or more different materials can create a new material called a composite material. This composition has the ability to incorporate different properties between them. In many cases, there is a need to create a new material that satisfies specific properties that do not exist in a single traditional material. The synthesis of basic materials can be carried out in various ways. One of them is the addition of a small percentage of fibers into a material in order to strengthen it. Another way is to mix two materials at a point under specific ambient temperatures. The most common and recyclable way to reinforce polymers is the addition of carbon fibers [1]. Polymer materials are generally used in the field of 3D printing. The main disadvantage of polymer materials is their low mechanical properties. The incorporation of fibers into polymers can significantly increase their mechanical properties. Blok et al. examined how the shape and size of the fibers affect the properties related to mechanics of the composite material [2]. A material's mechanical properties can be altered by 3D printing parameters. Numerous published research has used composites made using 3D printers and tested with tensile testing apparatus. The outcomes of the mechanical properties vary depending on the values of the different printing parameters. Some of the parameters that can be changed are the printing direction, the layer height and the nozzle temperature [3, 4]. The effect of certain 3D printing conditions such as flow, wall and layer thickness on the strength of carbon fiber reinforced PET-G (Polyethylene Terephthalate Glycol) was investigated. The results of the study showed that the layer height affected the tensile strength to a greater extent. More specifically, the reduction of the value caused a greater tensile strength of the material [5]. Similar studies have been concerned with the search for the optimal values of printing parameters [6]. Manavis et al. evaluated the degree of influence of the printing parameters filling percentage, speed and filling type on the PETG polymer [7]. Also, evaluation is often done on 3D printer materials that are recyclable [8]. Mazen et al. investigated the effects of five parameters in tensile and impact tests. Using the fractional factorial method and printing 16 specimens, it emerged that part

orientation was the only statistically significant factor with maximum strength and hardness values [9]. In the context of tensile strength, Kechagias et al. evaluated the efficacy of the Full Factorial Design (FFD) approach against the Box-Behnken Design (BBD) method. PA12-based 3D-printed specimens were employed in the investigation. Based on the filling angle, layer height, and nozzle temperature, the two design techniques were compared. The results showed that, in terms of the tensile strength of 3D printed geometries, the BBD method and the FFD approach showed comparable indicators [10]. In the present study, the impact of definite 3D printing parameters on the tensile strength is investigated. In the context of the study, the printing parameters Flow, Nozzle Speed and Nozzle Temperature were selected. For each parameter, three control values were set: 85%, 100% and 115% for Flow, 25 mm/s, 35 mm/s and 45 mm/s for Nozzle Speed and finally 235 °C, 245 °C and 255 °C for Nozzle Temperature. The study used the Box-Behnken method for designing the experiments, from which 15 specimen combinations resulted. The specimens were tested in a tensile machine and the data were recorded and organized. The test results showed that increasing Flow significantly increases the specimen tension. Conversely, increasing the printing speed gradually reduces the tension.

2. METHODS AND MATERIALS

2.1. Experimental Setup

In the current research presented, additive manufacturing (3D printing) and tensile testing specimens were used. Each specimen was printed with specific printing conditions/settings and then its strength was measured using a tensile tester machine. Therefore, the test results were organized in tables and conclusions were drawn using statistical methods. More precisely, an empirical mathematical formula for estimating the strength at all values within the range of variables was created using the Box–Behnken design for the response surface method (RSM). The study can use more parameters because the Box–Behnken design significantly lowers the number of tests that must be run. This study is divided into four main phases (Figure 1):

- First phase: Determining the settings and printing the specimens.
- Second phase: Organizing and categorizing the samples with names.
- Third phase: Using a tensile machine and checking the mechanical properties of each sample.
- Fourth phase: Data analysis and final conclusions.

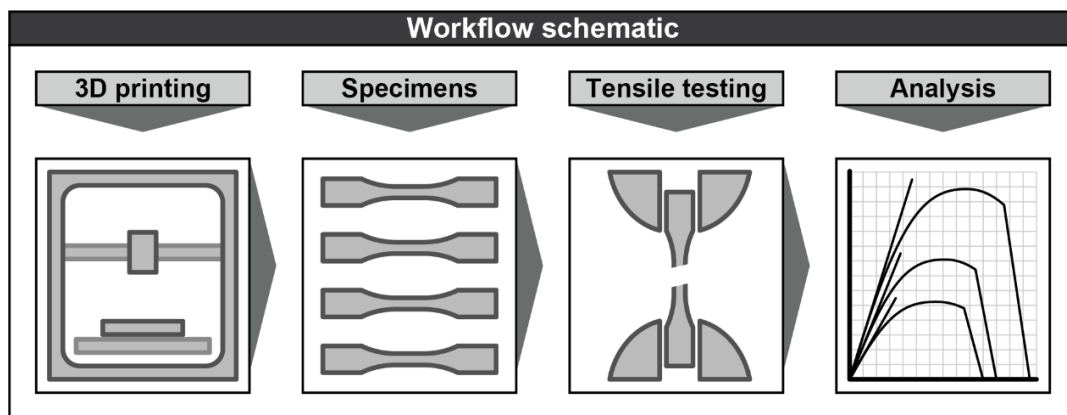


Fig. 1. Workflow schematic: 3D printing, Specimens, Tensile testing and Analysis.

The 3D printer chosen for printing the specimens was the FFF (Fused Filament Fabrication) technology. More specifically, it is the CreatBot™ D600 Pro 3D printer. The size of the useful print of the CreatBot™ D600 Pro is 600 × 600 × 600 mm. The two main advantages of this printer are: a) the large size (the specimens are printed simultaneously) and b) the enclosure type (maintaining the same environmental conditions during printing). The filament used was NEEMA3D™ CARBON: PLUS which is a composite material of PET-G and carbon fibers in a ratio of 80:20. Based on the manufacturer's data sheet, some of the properties of the filament are: a) relative density: 1190 kg/m³, b) Elastic modulus: 3.8 Kn/mm², c) Strain at break: 8%, d) Izod impact strength: 3.8 kJ/m² and e) Heat deformation: 80 °C [11]. The tensile machine used is called Instron™ 3345 (Norwood, MA, USA). Some of the features of Instron™ 3345 are the maximum tensile force, which is 5 kN and the dimensions of the useful area which is 1123 × 100 mm. In the present study, using 3 different print settings and 3 levels (values for each setting), 15 out of 27 total resulting combinations (3³ = 27) were printed and tested. The three settings selected were Flow, Nozzle Speed and Nozzle Temperature. The table below presents the selected settings along with their information Table 1.

Table 1. Description and range of parameters

Parameters	Typical range	Unit	Description
Flow	85 – 115	%	Flow controls the amount of material that will be printed. The initial value of the parameter is 100%. Increasing and decreasing Flow increases and decreases the percentage amount that passes through the nozzle.
Nozzle Speed	25 – 45	mm/s	The speed of the nozzle in the OX and OY axes, or nozzle speed, regulates the printing speed. mm/s is the unit of measurement. The Nozzle Speed parameter has a direct impact on the printing time. The 3D printer and the filament both restrict the range of values for this parameter.
Nozzle Temperature	235 - 255	°C	Nozzle Temperature controls the temperature of the nozzle in °C to melt the material.

Figure 2 presents the experimental setup used in this study. The three photographs show: the 3D printer, the tensile testing piece of equipment and the material used. At the same time, under each photograph there are the basic characteristics of the both pieces of equipment and the material. Finally, the settings that were chosen and the three values for each setting are presented.

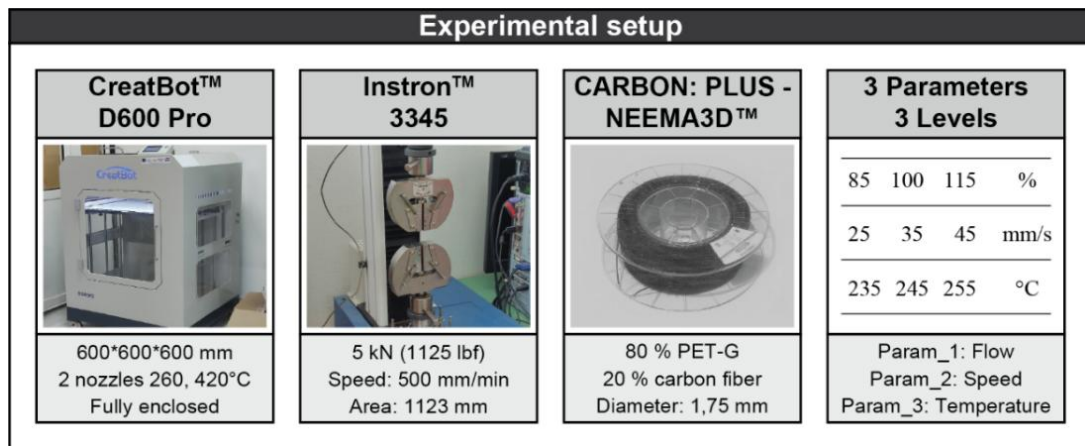


Fig. 2. Experimental setup: 3D printer, Tensile machine, Filament and Parameters

Apart from the variable settings Flow, Nozzle Speed and Nozzle Temperature the other settings remained constant. The Bed temperature was set to 60 °C and the layer Thickness was set to 0.2 mm. The filling of the specimens was set to 100% i.e. each specimen was completely filled with material. Two outer wall passes were made on each specimen. Finally, the nozzle and material diameters were 0.6 mm and 1.75 mm severally. Table 2 presents all the variable and fixed printing settings used.

Table 2. Variable and constant parameters

Settings/Parameters	Variable/Constant Settings	Unit	Values			
Flow	Variable Settings	%	85	100	115	
Nozzle Speed		mm/s	25	35	45	
Nozzle Temperature		°C	235	245	255	
Bed Temperature	Constant Settings	°C	60			
Layer Thickness		mm	0.2			
Infill		%	100			
Wall Lines / Thickness		mm	1.2			
Nozzle Diameter		mm	0.6			
Filament Diameter		mm	1.75			
Fan Speed		%	100			

The ASTM D638 standard, which is designed to assess the tensile strength of plastics, was applied in this investigation [12]. Both unreinforced and reinforced plastics, or composite materials like the one used in this

study, can be examined. The sample measures 115 x 19 x 3.6 mm. Conversely, the specimen's central crucial area A measures 33 x 6 x 3.6 mm. The surface A according to which the tensile strength was calculated, results from the operation $6 \text{ mm} \times 3.6 \text{ mm} = 21.6 \text{ cm}^2$. Figure 3 shows the top and side views of the specimen. The pattern illustrated inside represents the paths that the 3D printer followed. The walls are horizontal in blue, while the infill is light blue.

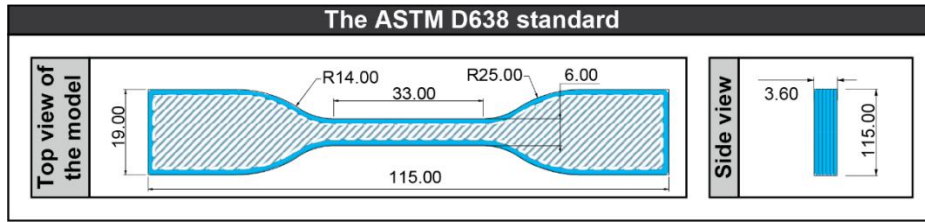


Fig. 3. 3D model of specimen and dimension

The Box-Behnken design in statistics is a response surface methodology (RSM). The main advantage of the methodology is the reduction of experiments with respect to the full factorial design. For example, if three factors are selected and each factor has three value levels, the full factorial design would require 27 experiments ($3^3 = 27$). On the other hand, using the Box-Behnken methodology, the number of experiments is reduced to 15, which requires less time and resources [13, 14, 15, 16]. Figure 4 presents two tables: Full Factorial Design and Box-Behnken Design. The Full Factorial Design table presents all possible combinations between the 3 factors and the 3 levels. On the contrary, the Box-Behnken Design table presents the experiments that the Box-Behnken method selects to test. Looking at the selected samples, it is observed that the method selects all samples with an even serial number. Also, the specimen with order 12 is selected 3 times for testing as the levels of each product are at their average value. The terms “Flow”, “Speed” and “Temp” refer to the respective value that will be defined in the Flow, Nozzle Speed and Nozzle Temperature parameters respectively. The term “R_Ord” (Run Order) defines the order in which the sample experiments should be executed. The term “S_Ord” (Standard Order) defines the standard order of the levels when they are created by the Box-Behnken method. These specific numbers have not been randomized as they indicate the order of creation as a reference. The term “FF_Ord” (Full Factorial Design Order) defines the order of the levels in the full factorial design. The order in which the levels are arranged is according to FF_Ord for easier understanding of the graph.

At this point in the study, the specimens were subjected to tensile testing. The specimens resulting from the Box-Behnken method were printed 2 times each, i.e. $15 + 15 = 30$. With the second printing and performance of the experiments, it is ensured that the results will be more reliable. Below in Figure 5, three images of the experiment are presented. Before the test, the samples were separated into the two groups in the left image. One of the samples undergoing the tensile test is depicted in the middle image. Lastly, the specimens' tensile test results are displayed in the right image.

Lists of variable parameters - Box-Behnken Design																											
Full Factorial Design																											
N	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
Flow (%)	85	85	85	100	100	100	115	115	115	85	85	85	100	100	100	115	115	115	85	85	85	100	100	100	115	115	115
Speed (mm/s)	25	35	45	25	35	45	25	35	45	25	35	45	25	35	45	25	35	45	25	35	45	25	35	45	25	35	45
Temp (°C)	235	235	235	235	235	235	235	235	235	245	245	245	245	245	245	245	245	245	255	255	255	255	255	255	255	255	255
R_Ord	10	1	13	7	4	9	6	8	15	3	12	5	2	11	14												
S_Ord	5	9	10	6	1	3	13	14	15	2	4	7	11	12	8												
FF_Ord	2	4	6	8	10	12	14	14	14	16	18	20	22	24	26												
Flow (%)	85	85	100	100	100	115	85	85	100	100	100	85	85	115	115												
Speed (mm/s)	35	25	45	25	35	45	25	35	45	25	35	45	25	35	45	25	35	45	25	35	45	25	35	45	25	35	
Temp (°C)	235	235	235	235	235	235	245	245	245	245	245	245	245	245	245	245	245	245	255	255	255	255	255	255	255	255	
Box-Behnken Design																											
R_Ord: Run Order S_Ord: Standard Order FF_Ord: Full Factorial Design Order																											

Fig. 4. Full Factorial and Box-Behnken Design

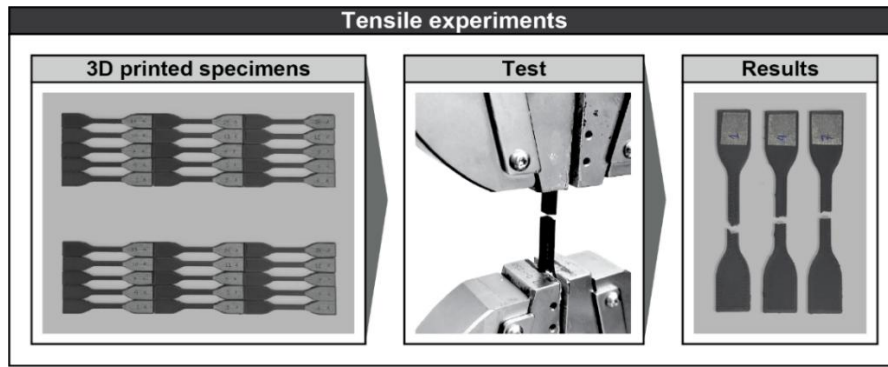


Fig. 5. 3D printed specimens, test and results

3. RESULTS AND DISCUSSION

Table 3 presents the variable settings of each test along with the measured strength σ in MPa. The strength was calculated according to the measured force exerted in kN by the vertical surface A (in mm²) of the specimen ($\sigma = \text{kN/A}$). The results presented were obtained from the average value of each pair of specimens. Also, the order in which they are presented is based on the run order defined by the Box-Behnken method. According to the table, the maximum value of strength was measured in specimen 3 with value: $\sigma = 52.95$ MPa, which has Flow = 115%, Speed = 25 mm/s and Temp = 245 °C. On the other hand, the minimum strength was measured in specimen 10 with value: $\sigma = 33.57$ MPa which has Flow = 85%, Speed = 35 mm/s and Temp = 235 °C.

Table 3. Results of experiments and parameters

Run_Ord	Std_Ord	FF_Ord	Flow (%)	Speed (mm/s)	Temp (°C)	σ (MPa)
1	9	4	100	25	235	49.53
2	11	22	100	25	255	52.71
3	2	16	115	25	245	52.95
4	1	10	85	25	245	37.00
5	7	20	85	35	255	38.33
6	15	14	100	35	245	48.97
7	6	8	115	35	235	43.88
8	13	14	100	35	245	48.97
9	3	12	85	45	245	34.31
10	5	2	85	35	235	33.57
11	12	24	100	45	255	47.43
12	4	18	115	45	245	37.82
13	10	6	100	45	235	39.20
14	8	26	115	35	255	50.65
15	14	14	100	35	245	48.97

The results of the analysis of variance (ANOVA) of the model were investigated in order to evaluate the performance of the model created Table 4. The value 0.05 was used as the confidence level. The model is statistically significant as the values of F-Value and P-Value are 196.15 and 0.000 respectively, while at the same time the R-sq is 99.72%. According to the results, the variables Flow, Speed, Temp, and the interactions Flow², Speed², Flow \times Speed and Speed \times Temp have P-Value less than 5%, which is the confidence level, therefore they are statistically significant. On the other hand, the interactions Temp² and Flow \times Temp have P-Value greater than 5% and as a result they are not statistically significant. It is further indicated that the terms Flow and Flow² provide most to the tensile strength, with percentages 12.46% and 10.26%, separately, while the terms Speed and Temp follow with percentages equal to 7.86% and 3.70%, respectively.

The residual analysis graphs are presented in Figure 6. The results of the graphs illustrate that the residuals follow a gaussian distribution. Also, there is no systematic error in the Residual - Fitted Value and Residual - Observation Order graphs as the residuals are scattered randomly and uniformly in the space of the graph. Finally, in Frequency

- Residual the residuals follow a normal distribution without any asymmetry or pattern being observed. According to the residual analysis graphs, the model successfully describes the relationships between the variables, while at the same time the predictions of the model with high probabilities are reliable.

Table 4. Data analysis of variance results

Source	Degree of Freedom	Sum of Squares	Mean Square	F-Value	P-Value	Contribution %
Regression	9	658.562	73.174	196.15	0.000	
Error	3	1.865	0.622			
Total	14	660.427				
R-sq = 99.72% R-sq(adjusted) = 99.21% R-sq(predicted) = 95.48%						
Term						
Flow	1	221.451	221.451	593.64	0.000	12.46
Speed	1	139.770	139.770	374.68	0.000	7.86
Temp	1	65.797	65.797	176.38	0.000	3.70
Flow ²	1	182.365	182.365	488.86	0.000	10.26
Speed ²	1	7.418	7.418	19.88	0.007	0.42
Temp ²	1	0.405	0.405	1,09	0.345	0.02
Flow × Speed	1	38.660	38.660	103.63	0.000	2.17
Flow × Temp	1	1,000	1,000	2.68	0.162	0.06
Speed × Temp	1	6.388	6.388	17.12	0.009	0.36

The 2nd order polynomial mathematical model is presented below. The equation consists of linear, quadratic and cross terms. The prediction values that can be used in the variable parameters should be within the range of 85-115% for Flow, 25-45 mm/s for Speed and 235-255 °C for Temp. The equation:

$$\sigma = -457 + 6.334 \times \text{Flow} - 0.457 \times \text{Speed} + 1.24 \times \text{Temp} - 0.03123 \times \text{Flow}^2 - 0.00630 \times \text{Speed}^2 - 0.00331 \times \text{Temp}^2 - 0.01382 \times \text{Flow} \times \text{Speed} + 0.00333 \times \text{Flow} \times \text{Temp} + 0.00842 \times \text{Speed} \times \text{Temp}$$

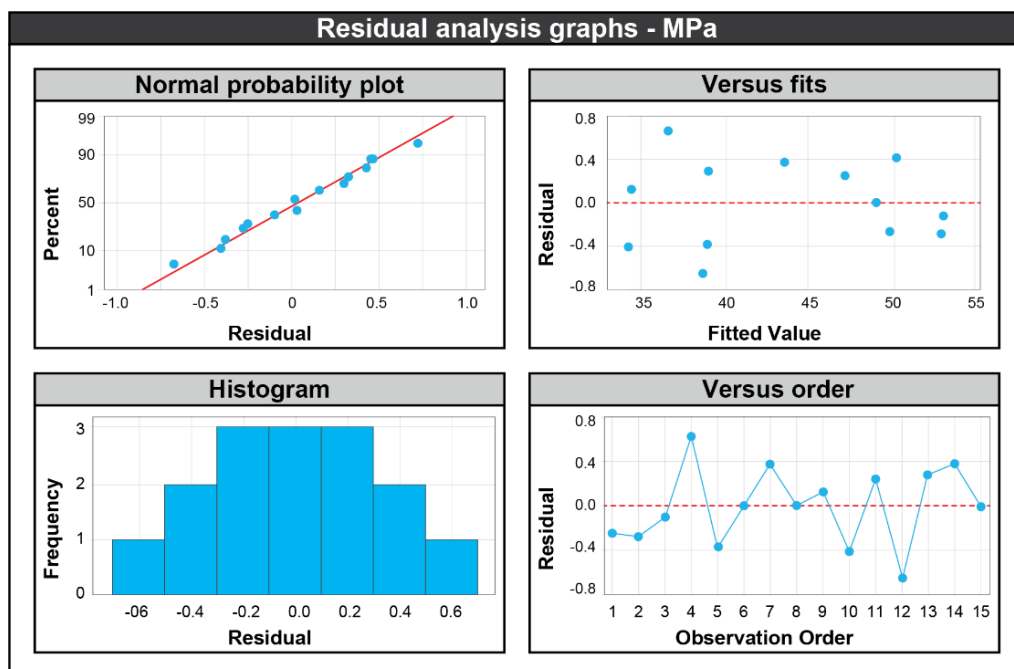


Fig. 6. Residual analysis graphs

In the Pareto Chart of the Standardized Effects (Figure 7), all variables and their interactions are presented in order of influence in the model. Specifically, it is confirmed that the interactions of the variables Flow × Temp and Temp² are behind the 2.57 which is the reference line. At the same time, the effects that the remaining variables and interactions are displayed in descending order.

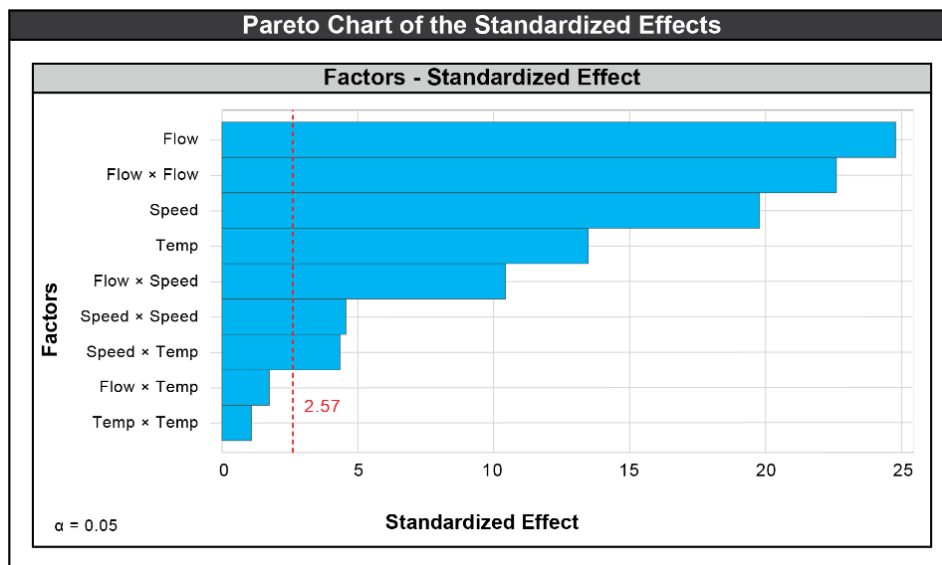


Fig. 7. Pareto Chart (Factors - Standardized Effect)

At the end of the study, the values of the variables were optimized. More specifically, the values of the variables Flow, Speed and Temp that give the highest strength were searched for. The results of the optimization showed that the maximum strength that can occur is equal to 55.8 MPa with parameters Flow = 109.54%, Speed = 25 mm/s and Temp 255 °C. Also, as shown schematically in Figure 8, where the maximum strength is located in each variable as well as the degree to which the strength is affected for each increase or decrease in each variable. For example, in Flow it is observed that as its value increases, the strength increases, but after the value 109.54% a decrease in strength is observed. At the same time, it is understood that the variable Flow affects strength to a greater extent, while Speed follows and finally Temp. The variable Speed, when increased, significantly reduces the strength of the material, in contrast to Temp, which increases the strength with its value.

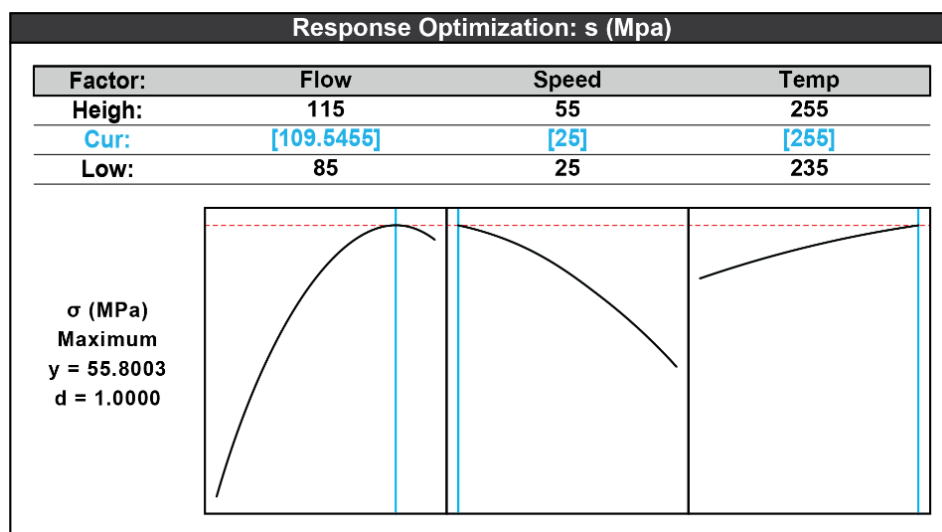


Fig. 8. Response Optimization graph

4. CONCLUSIONS

In the presented research, the amount of influence of 3D printing parameters on the tensile strength of 3D printed specimens was examined. The filament chosen was a composite polymer PETG strengthened with carbon-fiber. The 3D printing parameters varied were the Flow, Speed Nozzle and Temperature Nozzle. The values given for each parameter are Flow (85%, 100%, 115%), Speed Nozzle (25 mm/s, 35 mm/s, 45 mm/s) and Temperature Nozzle (235 °C, 245 °C, 255 °C). The ASTM D638 standard and the Box-Behnken statistical method were used in the study. The test results showed that:

- Flow significantly affects the specimen strength. Increasing the Flow value increases the material strength up to 109.54% and then begins to decrease it.
- The faster the specimen is printed, the lower its strength. When increasing the Speed Nozzle value this reduces

the material strength.

-Increasing the Temperature Nozzle value increases the strength at a slower rate than the other two parameters.

-Finally, through the search for the optimal values for each variable, the combination of Flow = 109.54%, Speed = 25 mm/s and Temp 255 °C was found, which presents the maximum strength in the material.

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