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Statistical Analysis and Optimization of Variables Affecting Tensile and Impact Behavior of Printed PETG Samples Using Fused Deposition Modeling

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Abstract

Fused deposition modeling (FDM) is known as one of the additive manufacturing methods of polymer parts. In this process, the workpiece is printed based on the deposition of melted filament. In this research, using the FDM process and based on the response surface methodology, standard samples for tensile and impact tests were produced from PETG filament under the certain settings of input variables including: layer height, nozzle temperature and printing speed. In the following, by performing measurement tests and statistical analysis, the tensile and impact behavior of the printed samples were evaluated. The results of ANOVA showed that the square of printing speed, the square of nozzle temperature and the product of layer height and nozzle temperature respectively have the greatest effect on yield strength, failure strength and impact strength of polymer samples. In addition, the high values of the coefficient of variation obtained from the statistical analysis showed that the regression models for predicting the tensile and impact behavior of the printed samples have high accuracy and ability. In the end, using the desirability method, the optimal combination of input variables of the FDM process was determined with the aim of maximizing the tensile and impact properties of polymer samples.

Keywords: Fused Deposition Modeling, Tensile, Impact, PETG, Statistical Analysis.

1. Introduction

Rapid prototyping technologies have emerged for the immediate and direct production of products. These technologies have significantly improved manufacturing methods across various industries. One of the most common rapid prototyping methods is additive manufacturing [1]. This process is based on the layer-by-layer deposition of materials with small thicknesses and is controlled by numerical control programs generated directly from computer-aided three-dimensional models. In recent years, 3D printing technology has played a crucial role in producing low-cost products in a short time. Among these, Fused Deposition Modeling (FDM) is one of the most efficient and cost-effective techniques in the field of 3D printing [2]. This process is introduced as one of the additive manufacturing methods for polymer products based on the extrusion of melted filament. The main advantages of FDM technology include reduced costs, high speed, and process simplicity. The mechanical properties of products manufactured through the FDM process largely depend on the precise selection of process variables. Therefore, identifying the parameters of this process that significantly influence the quality of the produced products is essential.

Gurrala and Regalla [3] investigated the variable "deposition orientation" using ABS-P430 filament and found that to achieve the maximum tensile strength, the deposition orientation should be aligned with the loading direction. Raut et al. [4] printed standard tensile and bending samples from ABS-P400 according to ASTM standards. The results showed that applying a zero-degree printing angle improved tensile strength and reduced printing time and costs.

Tezel et al. [5] evaluated the impact strength of four polymer products manufactured using the FDM process. They used four types of filaments: PLA, ABS, PC, and PET. The results showed that the highest impact strength was associated with PC (polycarbonate) with a layer thickness of 0.3 mm, and overall, the impact strength of the parts was directly related to the printing direction and layer thickness. Wang et al. [6] examined the effects of nozzle temperature and layer thickness on the mechanical and tribological properties of polyamide (PA) printed using the FDM process. The results indicated that the mechanical properties of PA improved, but the wear rate decreased as the nozzle temperature increased from 240°C to 260°C. Additionally, increasing the layer thickness from 0.1 mm to 0.3 mm reduced mechanical properties and increased the friction coefficient.

A review of previous research reveals that most studies in the FDM domain have focused on using PLA and ABS filaments, with less attention paid to printing polymer parts from PETG. Additionally, the effects of process variables on the tensile and impact behavior of printed samples have been examined separately or in a limited scope. Moreover, given the diversity of FDM process variables and the residual stresses caused by heat and layer arrangement, determining the tensile and impact behavior of printed samples is crucial. Therefore, this study investigates the effects of input variables in the FDM process, such as layer height, nozzle temperature, and printing speed, on the yield strength, failure strength, and impact strength of PETG-printed samples. For this purpose, the experimental design was based on Response Surface Methodology (RSM) and the Box-Behnken Design (BBD). Regression equations were derived to predict the tensile and impact behavior of the samples based on ANOVA. Furthermore, the optimal combination of input variables was determined to achieve maximum tensile and impact properties of the polymer samples.

2. Materials and Methods

In this study, the yield strength, failure strength, and impact strength of FDM-printed samples were examined as response parameters. Additionally, three variables (layer height, nozzle temperature, and printing speed) were selected as input process variables, each evaluated at three levels: low, medium, and high (Table 1).

Table 1. Factors and Range of Input Variables

Variable	Symbol	Level
Layer Height	H (mm)	0.1, 0.2, 0.3
Nozzle Temperature	T (°C)	225, 235, 245
Printing Speed	S (mm/s)	25, 35, 45

The experimental tests were designed based on Response Surface Methodology (RSM) and the Box-Behnken Design (BBD). This study used a second-order approximation function as follows [7]:

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_i \sum_j \beta_{ij} x_i x_j + \varepsilon \qquad (1)$$

Here, β_0 is the constant coefficient, β_i is the linear coefficient, β_{ii} is the quadratic coefficient, β_{ij} is the interaction coefficient, k is the number of independent variables, and ε is the observed error in the response. The experimental design was performed using Design-Expert software [8] with 15 runs, ensuring repeatability at the medium level (Table 2).

Table 2. Design of Experimental Tests

Test No.	Input Variables			Response Parameters		
	H (mm)	T (°C)	S (mm/s)	Yield Strength (MPa)	Failure Strength (MPa)	Impact Strength (kJ/m²)
1	0.1	245	35	7.50	16.40	2.23
2	0.2	235	35	7.50	17.03	2.62
3	0.3	235	25	8.00	17.69	2.75
4	0.2	235	35	7.50	17.03	2.62
5	0.1	225	35	9.00	16.27	3.90
6	0.3	235	45	9.11	14.16	2.64
7	0.2	235	35	7.50	17.03	2.62
8	0.1	235	45	8.85	17.83	3.18
9	0.1	235	25	9.29	13.89	3.43
10	0.3	245	35	7.44	14.40	3.13
11	0.2	245	25	9.95	16.62	2.98
12	0.2	225	45	8.60	12.69	2.78
13	0.2	245	45	9.45	11.38	3.58
14	0.2	225	25	8.30	10.32	3.48
15	0.3	225	35	8.13	10.25	1.93

The geometric and dimensional specifications of the tensile test samples were determined according to ASTM D638 (Type I). The impact test samples were designed in compliance with ASTM D256. Subsequently, CAD files were exported in STL format for the FDM printer. PETG filament was selected as the material for printing the samples.

3. Results and Discussion

The data analysis in this study was performed using

Analysis of Variance (ANOVA). Additionally, regression analysis was employed to establish mathematical functions between response parameters and the effective variables in the process. A confidence level of 0.05 was used for the analysis. The regression equations for yield strength, failure strength, and impact strength as functions of the input process variables were derived in coded form as follows:

$$\begin{aligned} Yield\ Strength = {} & 7.5 - 0.245\ H + 0.039\ T + 0.059\ S \\ & + 0.202\ HT + 0.388\ HS \\ & - 0.2\ TS + 0.128\ H^2 + 0.39\ T^2 \\ & + 1.18\ S^2 \end{aligned} \tag{2}$$

$$\begin{aligned} Failure\ Strength = {} & 17.03 - 0.986\ H + 1.16\ T \\ & - 0.308\ S + 1.01\ HT - 1.87\ HS \\ & + 1.90\ TS + 0.22\ H^2 - 2.92\ T^2 \\ & - 1.36\ S^2 \end{aligned} \tag{3}$$

$$\begin{aligned} Impact\ Strength = {} & 2.62 - 0.286\ H - 0.021\ T \\ & - 0.058\ S + 0.718\ HT \\ & + 0.035\ HS + 0.325\ TS \\ & - 0.014\ H^2 + 0.191\ T^2 \\ & + 0.394\ S^2 \end{aligned} \tag{4}$$

The R^2 values obtained from the ANOVA for yield strength, failure strength, and impact strength were 70.99%, 90.17%, and 97.83%, respectively. Thus, a strong correlation was established between the measured data and the predicted responses from the regression equations. The results showed that the residuals in the normal probability plot generally followed a straight line, with no evidence of non-normal data (Figure 1).

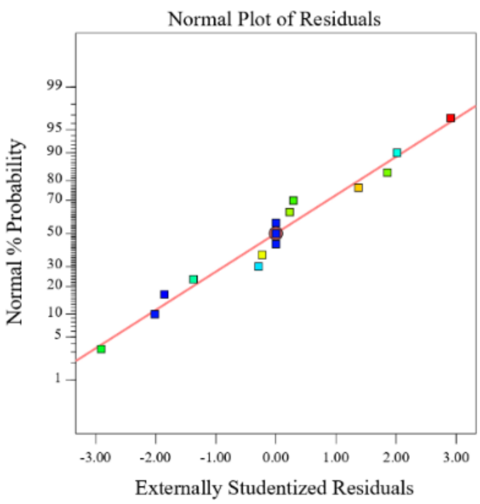


Figure 1. Normal Probability Plot (Yield Strength)

As seen in Figure 2, the residuals were randomly distributed around the zero axis, and the residuals plot showed no discernible pattern, confirming the reliability and suitability of the impact strength regression model.

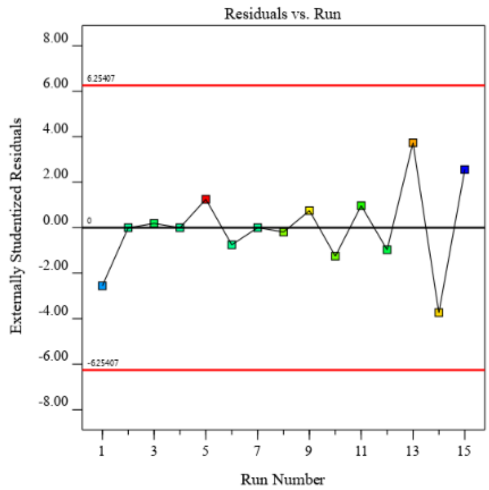
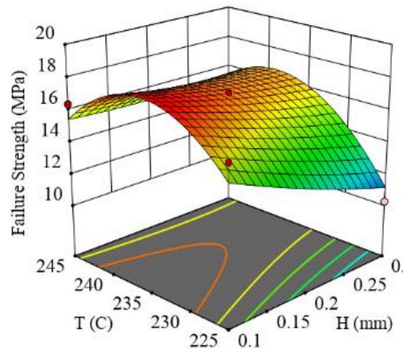
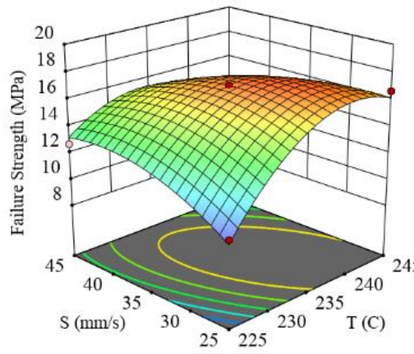


Figure 2. Residuals Plot (Impact Strength)

The interaction effects of nozzle temperature and layer height and the interaction effects of printing speed and nozzle temperature on failure strength are shown in Figure 3. As observed, failure strength increased as layer height decreased. Additionally, setting nozzle temperature and printing speed at medium levels maximized failure strength.



(a) Effect of nozzle temperature and layer height



(b) Effect of printing speed and nozzle temperature

Figure 3. Effects of Input Variables on Failure Strength

In Figure 3-a, failure strength increased as layer height decreased. Thinner layers improved interlayer adhesion and reduced structural weaknesses, enhancing failure strength. Nozzle temperature also played a significant role, with medium temperatures (e.g., 235°C) yielding the highest failure strength. Extremely high or low temperatures could reduce interlayer adhesion and failure strength. In Figure 3-b, medium printing speeds (e.g., 35 mm/s) maximized failure strength. Very high speeds could reduce interlayer adhesion, while medium nozzle temperatures (e.g., 235°C) had the most positive effect on failure strength.

4. Optimization

In this study, the desirability method was used to optimize the input variables of the FDM process. Since the goal was to maximize the tensile and impact properties of the printed samples, desirability was defined as follows [9]:

$$d = \begin{cases} 0 & y < L \\ \left(\dfrac{y-L}{U-L}\right)^r & L \le y \le U \\ 1 & y > U \end{cases} \tag{5}$$

In this equation, L and U are the lower and upper limits of the response value y, respectively. The weight value (r) was set to 1. In this method, a desirability function is defined for each response, with values ranging from 0 (undesirable) to 1 (fully desirable). The maximum mechanical properties of PETG-printed samples obtained through optimization were as follows: yield strength of 9.812 MPa, failure strength of 18.291 MPa, and impact strength of 4.315 kJ/m². Maximum yield strength, fracture strength, and impact strength were achieved with desirability values of 94.5%, 100%, and 100%.

5. Conclusion

In this study, FDM process was employed based on the response surface methodology and under specific combinations of input process variables to manufacture standard samples from PETG polymer filament. After performing measurement tests, the tensile and impact behavior of the printed samples were analyzed and evaluated. The key findings of this study are as follows:

- The ANOVA results showed that the square of printing speed (S^2) significantly affects yield strength. Additionally, the interaction terms (product of layer height and printing speed (HS), product of nozzle temperature and printing speed (TS), and square of nozzle temperature (T^2)) were identified as significant factors influencing failure strength.
- The ANOVA results indicated that the first-order term for layer height (H), the interaction term for layer height and nozzle temperature (HT), the interaction term for nozzle temperature and printing speed (TS), the square of nozzle temperature (T^2), and the square of printing speed (S^2) significantly affect impact strength.
- Regression equations for yield strength, failure strength, and impact strength as functions of the input variables of the FDM process were extracted in coded form.
- Yield strength increases as layer height and printing speed decrease.
- Failure strength increases as layer height decreases. Additionally, setting nozzle temperature and printing speed at intermediate levels leads to increased failure strength.
- Impact strength increases as layer height, nozzle temperature, and printing speed decrease.
- The optimal combinations of input variables to achieve maximum yield strength, failure strength, and impact strength were determined with desirability values of 94.5%, 100%, and 100%, respectively.

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