Taguchi optimization of fused deposition modeling process parameters on mechanical characteristics of PLA + filament material

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Abstract. This study attempts to investigate the effect of Fused Deposition Modeling (FDM) process parameters on mechanical characteristics with Taguchi optimization method. Three different FDM process parameters including filling structures (rectilinear, triangular, and full honeycomb), occupancy rates (10, 30, and 50%), and table orientation (0, 60, and $-45°$) were specified as variable parameters for experiments. Other parameters kept fixed for each tensile and izod impact test samples were printed in line with the ISO 527-Type IV and ISO 180-Type I standards. The results found tensile strength and izod impact values to be directly proportional to the occupancy rate. The difference between the estimation model and the results of experiments did not exceed the maximum value of 1.8%. Thus, by using the equations derived from this optimization, printing parameters can be determined for the desired tensile strength and izod impact values. By improving the material properties using modified PLA+ filament material as observed in the results, it is possible to provide support for researchers, design engineers, and manufacturer to optimize raw-material usage and margin.

1. Introduction

In every sector of manufacturing, technological innovations play a significant role in keeping companies competitive by shortening the release time of products to the market [1]. Recently, use of Rapid Prototyping (RP) technologies in industrial applications is increasing. Three-Dimensional (3D) printers, known as one of Additive Manufacturing (AM) methods, are used in both academic and industrial areas [2]. This technology allows producing a preliminary prototype of the design easily and quickly [3]. Production with 3D printing

has become a focus of interest in many fields such as automotive, civil aviation, medical devices, and dental applications. In addition, the use of tissues and implants in the fields of medicine and denistry is becoming widespread with 3D printing [4]. 3D printing is the process of producing deposition materials layer by layer to produce parts from computer-aided designed models instead of subtractive manufacturing methods [5]. 3D printing is characterized by major advantages including the reduction of both process time and raw material. There are many methods in this technology and the differences between them are generally related to how the materials are formed. Stereolithograhpy (SLA), Selective Laser Sintering (SLS), and Digital Light Processing (DLP) are among the most applied methods for 3D printing [6]. 3D printing uses heat-formable thermoplastic materials in this method (PLA, ABS,

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etc.) [7]. FDM technology is a complex process that is affected by many parameters. Generally, filament material, build orientation, extrusion temperature, layer thickness, raster width, and raster angle are preferred as effective parameters in mechanical properties.

Another study employed FDM method in conjunction with ABS material to examine layer thickness, build orientation, filling structure, and occupancy rate parameters and optimize the effect of process parameters on compressive strength. According to the results of this study, it was stated that the 3D printed product with an occupancy rate of 80%, gryoid filling structure, and 90° built orientation parameters yielded very close results to the fully filled product [8].

Another study investigated the effects of filling structures on 3D printed parts. Five filling structures (honeycomb, solid, grid, wiggle, and linear) were combined to investigate their effect on tensile strength analysis. PLA material samples were produced in two different directions: straight and edge. They stated that grid and honeycomb filling structures had the highest strength; their weight was lighter than solid; and the power was reduced by increasing the construction orientation in the study [9].

A research study targeted PLA material based on the experimental design. In addition, other process parameters including layer thickness, material deposition speed, occupancy rate, and filling structures were taken into account. It was found that layer thickness parameter significantly affected the tensile properties [10].

In similar studies, the relationships between mechanical properties and surface roughness values and system vibrations were investigated. The occupancy rate of 50% was fixed in the form of rectilinear filling from Polyethylene Terephthalate Glycol (PET-G) material for different raster angles and printing speeds. As a result, it was demonstrated that the printing speed of 3600 mm/s with raster angles of 60° and 30° was optimum in terms of mechanical properties and vibration [11,12].

In similar studies on mechanical properties, PET-G filament material was used. In addition, in different filling types (grid, rectilinear, wiggle, triangular, and honeycomb), the results mainly reported the effects of printing patterns on the product strength. The strength values obtained for the products manufactured as rectilinear filling were approximately 15% higher than those for other filling structures. In addition, it is reported that honeycomb filling style has greater elongation than other filling structures [13–15].

Scientists adopt the process of optimization to reduce the number of changes in a product by controlling the parameters and features related to product design and development. The selected input parameters affect the final performance of a product without a doubt. Many methods including Taguchi's Orthogonal Array and Response Surface Methodology (RSM) are generally adopted by scientists to establish the experimental setup and the experimental data are further analyzed to obtain the optimum and significant parameters that have maximum effect over final results for study [16,17].

In another study, mechanical properties and product cost were examined; layer thickness (0.15, 0.20, and 0.25 mm), raster angles (15°, 45°, and 75°), and table orientations (flat, horizontal, and vertical) were selected as effective parameters. In addition, the results were subjected to Taguchi optimization. The results reported that the raster angle of 45° had the highest mechanical properties. They reported that optimum 3D printing process parameters for product cost included horizontal table orientation, layer thickness of 0.25 mm, and raster angle of 75° [18].

The effects of ABS and Nylon materials on the tensile strength values and dimensional accuracy of parameters by 3D printing were examined in another study. The chosen effective parameters include part orientation on table, layer height, and shell numbers. To reduce the number of experiments, different combinations and levels of different parameters were determined using the Taguchi's L_9 orthogonal array. They reported that the orientation angle of part and shell numbers had a significant effect on tensile strength and moderately affected dimensional accuracy [19].

In a separate research, the mechanical properties of composites consisting of flexible plastic and natural fibers were studied. The impact strength and tensile strength values of the samples obtained from fiber and rubber in layers were examined. For decision-making, multi-objective optimization methods were employed [20].

A detailed review study reports that the reduction of the layer thickness does not yield a practical result as it extends the production time excessively. Many studies have analyzed the effects of parameters including printing speed, filling structures, and occupancy rate on mechanical properties. Contrary to the other studies reviewed, maximizing the occupancy rate does not increase the strength much after 50% occupancy rate and, also, makes the printing time difficult to apply in practice. Another issue addressed in these studies is that the filling structure, which gives the best mechanical properties according to the type of material, varies. In fact, different filling structures are recommended for improving different mechanical properties according to type of filament material. On the other hand, fused deposition modeling is a complicated process that has many affective parameters for product quality and material properties. According to the reported results, in terms of mechanical properties, the use of optimization is an important requirement that has arisen and is strictly dependent on the material and how it is applied [21].

In the literature, filling structure, occupancy rate, and table orientation are the most effective 3D printing parameters for the strength of products with 3D printing method [16–25].

Generally, the examined studies address the tensile strength values of ABS material and there is no study that examines the effects of the most important 3D printing process parameters (filling structure, occupancy rate, and table orientation) for the new modified PLA + material. In addition, in general, izod impact values for PLA + material are not mentioned in the studies [17,26]. In the literature, research studies have focused on tensile strength, ultimate strength, and percentage elongation. This study aimed to present the damping ability of the parts experimentally and statistically, which worked in impact environments where impact resistance tests were performed in order to set an example for the industry employees.

In this context, test samples were produced from PLA + material with three different filling structures, different occupancy rates, and table orientations using the FDM method. Within the scope of the study, experimental and statistical analyses were carried out by applying the Taguchi methodology to maximize strength, percent elongation, and Izod impact values. Effects of FDM process parameters on mechanical characteristics were examined by Taguchi optimization of process parameters. Thanks to the derived equations of optimization results, an attempt was made to provide the people active in this field to predict the tensile strength and izod impact values upon changes in the effective parameters.

2. Material and method

In this study, mechanical characteristics of the 3D printed PLA filament material samples were investigated experimentally and statistically. PLA filament material used in the scope of the study is manufactured by ESUN and can be found under the trade name PLA + with 1.75 mm diameter. The mechanical properties of this filament material, which is suitable for use with 3D printing, are given in Table 1. The main reason for using PLA within the scope of the research is that this plastic material has more advantages than ABS [27]. PLA is a biodegradable thermoplastic polyester material derived from cleaner sources that contains lower toxicity and requires lower temperatures

with 3D printing, thus positively influencing the energy consumption. PLA+ based tensile and Izod test samples were produced on a Cartesian 3D printer. The 3D printer has a 0.4 mm nozzle diameter that has open-source software as a commercial device. In this study, test samples were prepared for tensile tests according to ISO 527 and Izod impact tests according to ISO 180 standards. For this purpose, the solid model of test samples was created using SolidWorks design software and converted into STL file format for 3D printer slicing operation. The solid models of the samples were converted to Geometric Code (G-code) files using Simplfy3D slicing software and made ready for production.

2.1. Experimental design and optimization

The mechanical properties of the produced samples are related to the decision of process parameters by the FDM method. Occupancy rate is the most effective parameter for determining the strength of the product. Of course, the type of filament material used affects the strength. In 3D printing, the dimensions of the gaps from 30-40% to 100% change insignificantly. For this reason, the occupancy rate of 50% is sufficient to produce high-strength models with less material. Therefore, in our study, the occupancy rates were determined as 10%, 30%, and 50%. Filling structure is the shape of the material inside a 3D printed part. By ranging from lines to geometric shapes, filling structures can affect mechanical properties, weight, and printing time directly. Similar to the occupancy rate, some filling structures are better than the others. Depending on the slicing software used, there are different types of filling structures; yet, the three most used ones (rectilinear, triangular, and full honeycomb) appear in all slicing programmes. The table orientation points to the direction in which the part is positioned on the printing table along the X and Y axes. The table orientation angle and the filling structure of the part determine the shape of the inner structure. 3D prints are created layer by layer; however, how the layers are created has a large impact on mechanical properties.

In this context, three different occupancy rates (10, 30, and 50%) and filling structures (triangular, rectilinear, and full honeycomb) as well as three different table orientation angles (0, 60, and $-45°$) were determined and the Taguchi L9 experimental design was applied to printing test samples. All 3D printing parameters used in this experimental study are given in Table 2.
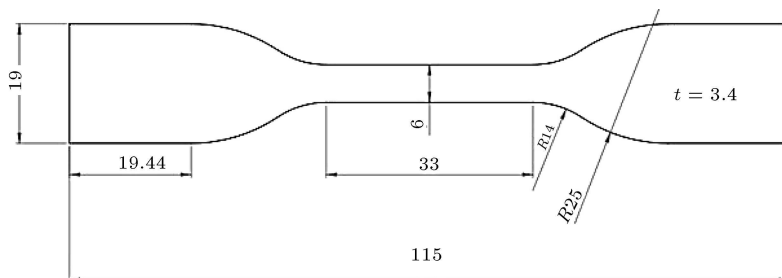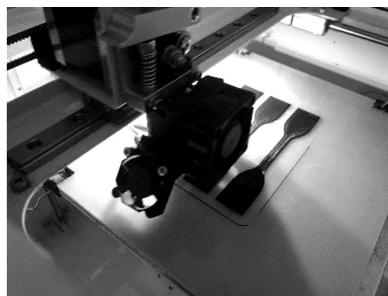
Table 1. Properties of PLA+ filament material [28].

Printing temperature ($°$C)	Density (g/cm^3)	Maximum service temperature ($°$C)	Ultimate strength (MPa)	Elongation at break (%)	Flexural strength (MPa)	Izod impact strength (kJ/m^2)
190-220	1.24	60	45.6	6	103	5.1

Table 2. FDM process parameters and 3D printer features.

Features	Values
Nozzle diameter (mm)	0.40
Extruder temperature (°C)	205
Table temperature (°C)	60
Extrusion width (mm)	0.35
Layer height (mm)	0.2
Printing speed (mm/min)	3600
Idle running (mm/min)	4800
Ambient temperature (°C)	24 ± 1
Model	Rigid3D Zero2
Printing volume	200*200*200 mm
Machine dimension	390*460*460 mm
Tolerance	0.05-0.1 mm
Power	600 W
Extruder nozzle	1
Processor	Arduino processor

For each test, three samples were produced at the same time. Detailed images of 3D printing process and dimensions of the IS0 527-Type IV sample are given in Figure 1. Tensile strength value is an important physical specification of material in any application. FDM process parameters and levels of test samples are given in Table 3.

Figure 2. IS0 180-Type I test sample dimensions (mm).

Dimensions of the ISO 180-Type I sample are given in Figure 2. Cross-sectional images of different filling shapes (rectilinear, triangular, and full honeycomb) and table orientation of samples are given in Figure 3.

Tensile tests were conducted using a 10-tonne tensile testing device (UTEST brand) at Düzce University, Mechanical Engineering Laboratory. The tensile test process is given in Figure 4. The tensile test speed of 5 mm/min was chosen in line with ISO 527 test standard and all tests were carried out under equal conditions.

Izod tester is given in Figure 5. The tests were repeated three times in line with ISO 180 test standard.

Izod test device has Joule pendulum's energy of 2.75, movement angle of 150 degrees, width of 4 mm, and notch thickness of 2 mm.

In order to minimize experimental errors, three tests were repeated for each condition and the obtained evaluations averaged the tensile strength values. In the last stage of this study, statistical analysis and optimization were carried out depending on tensile strength of the 3D printing parameters with PLA + material. In this context, ANOVA was applied at a

Figure 1. Printing process of samples and ISO 527-Type IV test sample dimensions (mm).

Table 3. Printing process parameters and levels (Taguchi L_9).

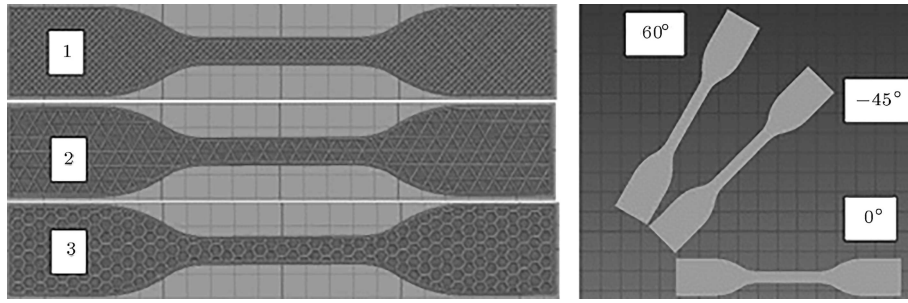| Factors	Unit	Levels	Output
Filling structures	—	1. Full Honeycomb 2. Rectilinear 3. Trianglular	Tensile strength values (MPa), Percentage elongation at break (%), Izod impact values
Occupancy rates	%	10, 30, 50	
Table orientation	°	0, 60, −45	

Figure 3. Filling structures. 1: Rectilinear, 2: Triangular, and 3: Full honeycomb. Table orientations: 60°, −45°, and 0°.
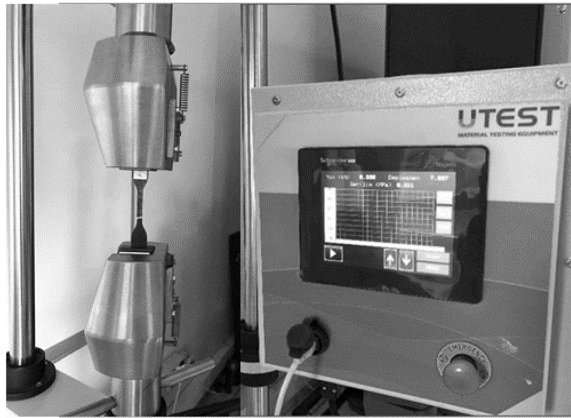

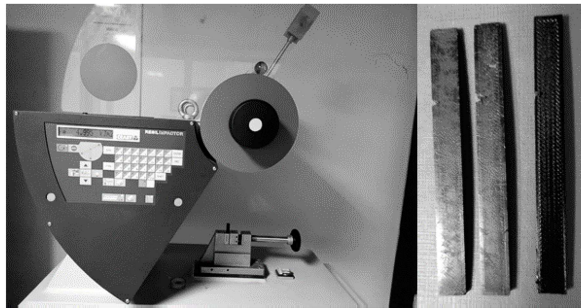**Figure 4.** Tensile testing device and tensile test process.

Figure 5. Izod impact test device and test sample.

confidence level of 95% ($\alpha = 0.05$) to the experimental results, and the effect levels of the filling structure, occupancy rate, and table orientation with respect to the tensile strength were defined.

Maximum tensile strength value, elongation value, and izod impact values as performance characteristics are required for the FDM method. The "larger is better" function of Taguchi was used in optimization, as shown in Eq. (1). Taguchi determines the goal function of Signal/Noise (S/N) ratio to illustrate the effect of the levels of printing parameters [29].

$$S/N = -10 \log \left(\frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2} \right). \tag{1}$$

3. Assessment of experimental and statistical results

3.1. Tensile and Izod test results of experiments

Taguchi L_9 experiment layout and signal to statistical results are given in Table 4. Tensile strength and elongation data obtained from tensile tests are given in Table 5.

Table 5 shows that the average tensile strength increases proportionally as the occupancy rate increases with each filling structure. The largest average tensile strength value was provided in Sample 6. Further, the highest average percentage elongation value was provided in Sample 6. The least average tensile strength value was provided in Sample 1. The lowest average percentage elongation value was observed in Sample 5. In addition, the average percentage elongation of full honeycomb filling structure remained unaffected by other parameters.

Table 6 shows that the average Izod impact values increase proportionally as the occupancy rate with triangular and full honeycomb filling structures increases. The highest average Izod impact value was acquired in Sample 6. The lowest average Izod impact value was observed in Sample 7. Rectilinear filling structure and Izod impact values vary independently of parameters. In applications whose Izod impact values are significant, it is not appropriate to work at an occupancy rate of 30% or below.

3.2. Statistical results

Results of variance analysis are shown in Table 7. Figure 6 shows the main signal-to-noise plot for the effects and levels of the 3D printing parameters. In order for the strength and impact values to be at the highest, the larger-is-better optimization function for the signal-to-noise ratio was determined using Minitab18 program. The optimized 3D printing parameters and their equivalent values are shown in Tables 8 and 9. R^2 regression coefficient was calculated at 96.96% and standard deviation at 0.256661. Linear regression equation is given in the following for estimation of tensile strength, percentage elongation at break, and

Table 4. Taguchi L$_9$ experiment layout and statistical results.

Samples	Filling structures	Occupancy rate (%)	Table orientation (°)	Signal to Noise (S/N)	Mean value
1	RC	10	0	-29.2087	8.9300
2	RC	30	60	-29.6540	10.2500
3	RC	50	-45	-28.3809	11.9943
4	TA	10	60	-28.7850	10.7437
5	TA	30	-45	-30.1238	11.4523
6	TA	50	0	-27.2702	14.0220
7	FH	10	-45	-28.3814	9.7180
8	FH	30	0	-28.3806	10.0687
9	FH	50	60	-28.3805	11.3603

Table 5. Tensile strength values and percentage elongation values of tensile tests.

Samples	Tensile strength (MPa)				Elongation at break (%)			
	1. Test	2. Test	3. Test	Average	1. Test	2. Test	3. Test	Average
1	25.60	24.76	24.59	24.98	0.020	0.023	0.020	0.021
2	28.58	28.66	28.08	28.44	0.020	0.021	0.018	0.019
3	35.06	33.44	33.62	34.04	0.024	0.020	0.023	0.022
4	29.11	31.22	30.95	30.42	0.021	0.022	0.021	0.021
5	31.77	32.26	33.61	32.54	0.018	0.017	0.019	0.018
6	37.62	38.89	38.92	38.47	0.023	0.030	0.022	0.025
7	27.40	28.44	27.27	27.70	0.021	0.023	0.024	0.022
8	29.36	25.02	28.10	27.49	0.021	0.024	0.021	0.022
9	31.31	29.95	31.68	30.81	0.023	0.026	0.019	0.022

Table 6. Izod impact test results.

Samples	Izod impact values (kJ/m^2)			
	1. Test	2. Test	3. Test	Average
1	1.692	1.987	1.692	1.790
2	2.336	2.390	2.148	2.291
3	1.520	1.799	2.444	1.921
4	1.826	1.584	1.960	1.790
5	1.638	2.014	1.745	1.799
6	4.001	4.377	2.336	3.571
7	1.504	1.369	1.423	1.432
8	2.121	3.625	2.336	2.694
9	4.001	3.840	1.907	3.249

Table 7. Variance analysis values.

Source	DF	Adj SS	Adj MS	F-value	P-value
Regression	3	111.191	37.064	8.94	0.019
Occupancy rate	1	68.141	68.141	16.44	0.010
Table orientation	1	3.369	3.369	0.81	0.409
Filling structures	1	39.681	39.681	9.57	0.027
Error	5	20.722	4.144		
Toplam	8	243.104			

Izod impact values at a confidence interval of 95%. Upon the application of the extracted equations instead of filling structure, the following numerical data are obtained: the numbers 1 for full honeycomb, 2 for rectilinear, and 3 for triangular, as shown in Table 3. Linear regression equation used in the estimation of tensile strength values:

$$\text{Tensile strength (MPa)} = 20.42 + 0.1685$$
$$\times \text{ Occupancy rate} - 0.0142 \times \text{Table orientation}$$
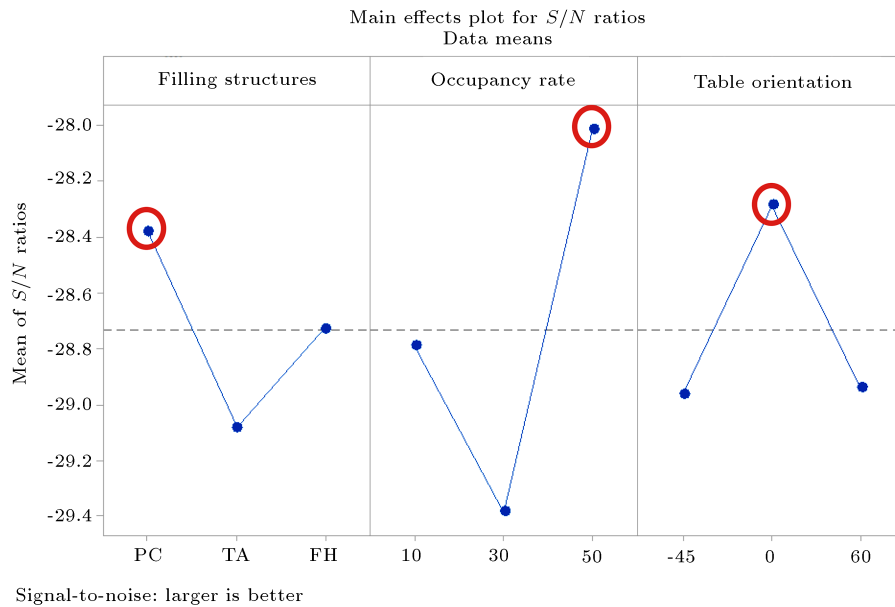$$+ 2.572 \times \text{Filling structure}. \tag{2}$$

Main effects plot for S/N ratios
Data means

Signal-to-noise: larger is better

Figure 6. S/N ratios of parameters for optimum 3D printing process parameters.

Table 8. Signal-to-noise ratios according to "larger is better" criterion.

Level	Filling structures	Occupancy rate (%)	Table orientation (°)
1	−28.38	−28.79	−28.96
2	−29.08	−29.39	−28.29
3	−28.73	−28.01	−28.94
Delta	0.70	1.38	0.68
Rank	2	1	3

Linear regression equation used in the estimation of tensile elongation at break:

Elongation at break (%) = 0.02040 + 0.00005

$\times$ Occupancy rate − 0.000002

$\times$ Table orientation − 0.000333

$\times$ Filling structure.   (3)

Linear regression equation used in the estimation of izod impact value:

Izod impact value (kJ/m^2) = 1.39 + 0.0311

$\times$ Occupancy rate − 0.00632

$\times$ Table orientation − 0.036 $\times$ Filling structure.   (4)

As seen in Table 7, when the P values are examined, only the value of the table orientation parameter is above 0.05. This situation shows that the effect of table orientation on mechanical properties is very lower than those of other parameters.

Table 8 shows the responses for signal-to-noise ratios. Such optimum 3D printing process parameters as rectilinear filling structure, 50% occupancy rate, and 0° table orientation with PLA+ filament were obtained. In a similar study, an optimization study was conducted in terms of compression strength. However, instead of the rectilinear filling structure that yields the best results, a gyroid filling method was preferred and ABS material was preferred as the material. The occupancy rate of 80% was suggested, which may not be effective in terms of printing speed and production costs. Our study selected the tensile and impact strength values as the most important mechanical characteristics obtained from 3D printed parts, constituting the condition for multi-criteria optimization. Our findings revealed the most suitable parameters in terms of printing cost for the most suitable modified filament for manufacturers [30].

Using Eqs. (2)–(4), the tensile strength, percentage elongation, and izod impact value were calculated for the proposed optimum process parameters, and the average test results of 3 test samples produced in these optimum parameters were compared. Thus, the results

Table 9. Comparison of verification test results and calculated results for optimum parameters.

Output	Estimated values	Verifying test results
Tensile strength (MPa)	33.99	33.15
Elongation (%)	0.024	0.023
Izod impact value (kJ/m^2)	3.017	2.82

Table 10. Comparison of the measured and estimated signal-to-noise and mean values using Taguchi method.

Sample no.	Signal to noise (S/N)	Mean value	Predicted signal to noise (S/N)	Predicted mean value
1	−29.2087	8.9300	-28.7005	9.2979
2	−29.6540	10.2500	-29.9483	9.8688
3	−28.3809	11.9943	-28.5949	12.0076
4	−28.7850	10.7437	-28.9990	10.7569
5	−30.1238	11.4523	-29.6156	11.8203
6	−27.2702	14.0220	-27.5645	13.6408
7	−28.3814	9.7180	-28.6756	9.368
8	−28.3806	10.0687	-28.5946	10.0819
9	−28.3805	11.3603	-27.8723	11.7283

obtained in this study were verified, as shown in Table 9. Accordingly, high convergence values of 97.53% for tensile strength, 95.88% for percentage elongation, and 93.47% for izod impact value were obtained. In this context, it is noteworthy that the difference between the results of the verification experiment and those obtained from the Taguchi approach is negligible. Based on these results, it is possible that Taguchi optimization be successfully applied at a significance level of 0.05. In addition, in an optimization study of tensile strength and material weight for the unmodified PLA material, the MPa tensile strength of 37, which is the strength obtained at an occupancy rate of 80%, can be obtained at an occupancy rate of 50% using the modified PLA + material and the parameters optimized in our study [31].

Table 10 shows that the difference between the estimation model and the experimental one did not exceed the maximum value of 1.8%. In new studies, the optimization proposed for future works was taken into consideration and the mechanical characteristics of the newly modified PLA material and the optimum operating parameters to be used by the manufacturers were examined. In addition, another future study suggested in the review studies is that in addition to the selected parameters, practical equations were obtained for the strength values if different degrees were selected [32]. Similar results to those existing in the literature were obtained [33].

4. Conclusion

Results of the experiments were conducted for occupancy rate, filling structure, and table orientation, which were selected as 3D printing parameters, and their effects on mechanical characteristics were examined with the help of Taguchi optimization. The following main results are listed below:

- Statistical calculations required for the optimum selection of tensile strength values, percentage elongation and Izod impact values, rectilinear filling structure, 50% occupancy rate, and 0° table orientation were determined. This study selected the tensile strength and impact strength, which are the most important mechanical characteristics of Taguchi optimization, and revealed the most suitable parameters in terms of printing cost for the most suitable modified PLA filament for manufacturers;

- In addition to the selected parameters, practical equations were obtained for the strength values if different degrees were selected. As a result of this study, the difference between the estimation equation and experimental results did not exceed the maximum value of 5%.

- The average tensile strength increased proportionally as the occupancy rate increased with each filling structure. The average percentage elongation of

full honeycomb filling structure was not affected by other parameters, and the most effective parameter for the mechanical characteristic was the rate of occupancy;

- The average Izod impact values increased proportionally as the occupancy rate increased with triangular and full honeycomb filling structures, unlike the rectilinear filling structure. Rectilinear filling structure and Izod impact values varied independently of the parameters. In applications whose Izod impact values are significant, it is not appropriate to work at an occupancy rate of 30% or below.

Acknowledgements

Nomenclature

3D	Three-dimensional
ABS	Acrylonitrile Butadiene Styrene
AM	Additive Manufacturing
ANOVA	Analysis Of Variance
CAD	Computer Aided Design
DLP	Digital Light Processing
FDM	Fused Deposition Modelling
G-code	Geometric code
ISO	International Organization for Standardization
PET-G	Polyethylene Terephthalate Glycol
PLA	Polylactic acid
RMS	Root Mean Square
RP	Rapid Prototyping
S/N	Signal/Noise
SLA	Stereolithography
SLS	Selective Laser Sintering
STL	Standard Tessellation Language

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