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Original Article

An Experimental Analysis of 3D Printed Poly-Lactic Acid (PLA) Specimens as per ASTM Standard Using Taguchi and Analysis of Variance (ANOVA) Approach

Manoj Kumar Poddar[1], Saroj Kumar Sarangi[2]

[1,2]*Department of Mechanical Engineering, National Institute of Technology Patna, Bihar, India.*

[1]*Corresponding Author : manojp.phd19.me@nitp.ac.in*

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Abstract *- Fused Deposition Modeling (FDM) is a fast-growing 3D printing technique because of its capacity to produce functional components with complicated shapes. The mechanical characteristics of 3D printed components are influenced by many process factors of FDM 3D printers. The present research examined the optimum settings for FDM 3D printers to use with Polylactic Acid (PLA) materials. The printed PLA specimens were subjected to tensile and flexural testing in accordance with ASTM standards to assess their mechanical qualities. The experiments were carefully planned using the Taguchi method of an* L_9 *orthogonal array with four factors at three levels each. Infill pattern, printing speed, printing temperature, and layer thickness were selected as four factors to optimize. Regression modeling, Analysis of Variance (ANOVA), and the Taguchi S/N ratio are used to analyze the data from tensile and flexural testing. The findings suggest that the mechanical strength is significantly influenced by the interactions among Infill patterns, printing speed, layer thickness, and printing temperature.*

Keywords *- FDM, Polylactic Acid (PLA), 3D printing, Taguchi method, DOE, ANOVA.*

1. Introduction

FDM is a widely used 3D printing process for thermoplastic materials. Using this process, semi-molten filaments are deposited to build an object with several overlapping layers as per CAD design data [1]. The ability to manufacture complicated and particular forms is a big benefit of using FDM technology. The method is now used in bioengineering, primarily for the production of tissue engineering scaffolds [2, 3].

Furthermore, the automobile industry uses this technique to manufacture small components [4]. Various printing factors, including layer thickness, infill density, build orientation, infill pattern, raster angle, raster width, feed rate, and air gap, greatly influence the quality and performance of components produced using FDM [5, 6, 7]. The evaluation of the products' mechanical properties is a critical aspect of FDM additive manufacturing [10]. PLA is a biodegradable thermoplastic substance often utilized in 3D printing. It is made from renewable natural sources such as cornstarch or sugarcane and has been regarded as an ecologically beneficial alternative to petroleum-based polymers in recent decades [8]. PLA is mechanically and aesthetically versatile, biodegradable via enzymatic activity and hydrolysis, and biocompatible; it can be engineered to suit a vast array of applications [9].

PLA's role in the COVID-19 worldwide pandemic has bolstered its usefulness as a 3D-printed biopolymer. Possible applications include the rapid production of medical equipment like the PPE needed to keep healthcare workers safe during the pandemic [11]. PLA experiences a physical change both during the 3D printing process and while it is in service as a result of temperature variation. These changes include the glass transition, which takes place between 50°C and 70°C, and other thermal transitions [12].

The FDM input factors were optimized using a number of Design Of Experiments (DOEs), such as fuzzy logic, ANOVA, complete factorial design, Taguchi technique, and Response Surface Methodology (RSM) [13]. The method known as Taguchi's design of experiments was frequently employed to enhance the setting of FDM factors due to its robustness and ability to control dimensions [14]. The regression analysis for Flexure strength and Tensile Strength are obtained by using Statistical Software Minitab-2022 [15].

Recent research has focused on studying the mechanical characteristics of 3D-printed PLA and its composite materials with the FDM process. Ahmad et al. [16] investigated the mechanical characterization of printed parts of oil palm fiber composite materials using FDM. They found the optimum setting of the printing process based on the S/N ratio was 0.4

mm layer thickness and 50% infill density, with a printing speed of 10 mm/sec. Manu Srivastava et al. [17] examined the correlation between model material volume and process parameters, suggested ideal combinations using the Taguchi approach, and performed regression analysis to determine a linear connection between mechanical properties and process factors.

J.M. Chacon et al. [18] investigated the 3D printing of PLA samples in accordance with ASTM standards and found that mechanical qualities are influenced by build orientation, layer thickness, and feed rate; tensile and flexural strength increased as layer thickness increased and decreased as the feed rate increased. V. Durga Prasada Rao et al. [19] study found that the tensile strength of Carbon fibre PLA parts produced by FDM is primarily influenced by layer thickness and extrusion temperature. Marzio Grasso et al. [20] found that temperature has an impact on the tensile strength of PLA 3D-printed specimens; with the temperature rising from 40°C to 50°C, stiffness decreases by 16%.

Roberto Spina [21] examined the compression testing of FFF parts made from two commercial PLA materials of various colours. The findings revealed that colour additive has a strong impact on mechanical qualities. Yu Zhao et al. [22] studied the impact of printing angle and layer thickness on tensile strength and Young's modulus in FDM PLA materials, developing theoretical models. S. K. Dhinesh et al. [23] investigated to check the strength of the FDM-printed composite of PLA and ABS in various proportions; the result shows the mechanical properties are enhanced when ABS and PLA are sandwiched together.

J.A. Travieso-Rodriguez et al. [24] analysed the flexural strength of ABS specimens printed through FDM; increasing the nozzle diameter and decreasing the layer height both increase the stiffness and strength of ABS components. M. Damous Zandi et al. [25] found that wood-reinforced PLA material printed through FDM with a 0.2 mm layer height, 0.7 mm nozzle diameter, and 75% infill density provides optimal mechanical strength.

K.N. Gunasekaran et al. [26] found that the flexural and tensile strengths of PLA printed specimens were enhanced when the infill density was raised from 25% to 100%. Salvatore Brischetto et al. [27] found no significant differences in the tensile and compressive behavior of PLA specimens printed using the FDM technique, indicating the 3D printing procedure is good for both types. Tianyun Yao et al. [28] found that when the layer thickness lowers from 0.3 mm to 0.1 mm, the tensile failure strength of PLA specimens printed using the FDM method goes up, even when the printing angles stay the same. Meena Pant et al. [29] investigated the influence of FDM process factors on the wear rate of printed PLA samples; the experimental result shows that orientation is the most influential factor in designing experiments. The wear analysis of PLA materials helps industries related to the biomedical field. Samykano [30] investigated mechanical properties and developed a model for PLA specimens printed using the FDM technique and found that infill percentage significantly affects ultimate tensile strength.

Lionel Aufray et al. [31] studied the impact of various FDM process factors on PLA material's elastic mechanical properties; experimental results demonstrate that infill density, infill pattern, printing speed, and printing orientation were the most relevant factors affecting mechanical strength and Young's modulus. Adnan Rasheed et al. [32] studied the optimum FDM process factors setting for 3D printed PLA-ABS composite material specimens; experimental results show that the optimal conditions include 75% infill density, 20 mm sec^{-1} printing speed, and 100°C printing platform temperature.

Recent publications still lack experimental data on 3D printed components, and further research is needed to increase our understanding of optimum process parameter settings and mechanical characterisation of printed components. The current study examined how FDM process factors impact the tensile and flexural properties of printed specimens. There is a lack of information about the detailed correlation between FDM parameters and tensile and flexural characteristics.

A novel approach using Taguchi design experiment techniques is presented to analyze the mechanical properties of FDM-printed PLA specimens. The present study aims at the mechanical characterization of PLA specimens according to ASTM standards printed using the FDM technique by taking into account several factors such as infill pattern, layer thickness, printing speed, and extrusion temperature. For optimization, the Taguchi S/N ratio technique was utilized, and experiments were planned using the Taguchi method of the L9 orthogonal array for four factors and three levels each. The tensile and flexural tests were performed to analyze the mechanical properties of PLA specimens printed using the FDM technique, and the findings were analyzed using ANOVA and a regression model.

2. Materials and Methods

2.1. PLA Materials

The material utilized in FDM based 3D printer for making test specimens was PLA (Poly-lactic acid) plastic filament of 1.75 mm diameters with a dimensional accuracy of ± 0.02 mm; manufactured by WOL3D India Pvt. Ltd. PLA material is an environmentally friendly thermoplastic manufactured using renewable resources, most often from plant-based materials like maize starch or sugarcane [8]. The study technique begins with the printing of tensile and flexure specimens, followed by the use of DOE and ANOVA and the performance of mechanical tests. Properties of PLA materials are shown in Table 1.

Table 1. Properties of PLA materials supplied by WOL3D

Properties	Value
Density (g/cm³)	1.24
Extrusion Temperatures Range (°C)	190-220
Preheating Heating Temperatures (°C)	60-80
Tension (kgf)	11-16

Fig. 1 PLA filament supplied by WOL3D

2.2. Experimental Method

Experiments were conducted using an FDM-based 3D printer. The workpiece material used is Poly-lactic Acid (PLA). The present study examined the mechanical characterization of PLA specimens according to ASTM standards printed using the FDM technique by taking into account several factors such as infill pattern, layer thickness, printing speed, and extrusion temperature using the Taguchi method and ANOVA analysis.

Three levels of process parameters were taken for an experiment, as given in Table 3. The constant process factors for 3D printing are shown in Table 2. For further expansion of experiment trials, the Taguchi technique was used to develop the experiment design for four factors at three levels. The array chosen was L9, which has 9 rows with 4 columns at three levels, as seen in Table 4.

The factors are allocated to the columns based on their levels. The plan of experiments is made up of nine tests, with each column designated for a specific variable: infill pattern (A), layer thickness (B), printing speed (C), and extrusion temperature (D). To optimize process parameters, Taguchi's design of trials was utilized [13, 14].

The responses to be analyzed for the studies are the tensile strength and flexure strength of PLA specimens. The S/N ratio is a quality indicator used to analyze the influence of input factors on responses. The current study's output responses are of the "larger the better" kind. The signal-to-noise ratio (S/N) value was estimated using Equation (1) for the responses.

$$S/N=-10\log_{10}\left(\frac{1}{n}\sum\frac{1}{y^2}\right) \quad (1)$$

Where (S/N) is signal-to-noise, n is the number of repeated experiments, y is the output value.

After that, a linear regression method is used to identify the relationship between the responses and the process parameter, i.e. the mathematical model is developed between responses and process parameters with the help of Statistical Software Minitab-2021 and Microsoft Excel 2013 within the given range of process parameters [15].

Table 2. Constant factors of FDM 3D printer

Parameters/factors	Unit	Values
Nozzle Diameter	mm	0.4
Infill Density	---	100%
Cooling Fan Speed	---	100%
Bed Temperature	°C	60

Table 3. Process parameters and their levels

Symbol	Parameters/Factors	Unit	Level 1	Level 2	Level 3
A	Infill Pattern	---	Line	Triangles	Tri-Hexagon
B	Layer Thickness	mm	0.12	0.16	0.20
C	Printing Speed	mm/s	40	50	60
D	Extrusion Temperature	°C	195	200	205

Table 4. Experimental plan (Taguchi L9) and observed responses

Exp. No.	Infill Pattern	Layer Thickness (mm)	Printing Speed (mm/s)	Extrusion Temperature (°C)	Responses		Signal-to-Noise (S/N) Ratio (in dB)	
					Tensile Strength (TS) (MPa)	Flexural Strength (FS) (MPa)	Tensile Strength (TS)	Flexural Strength (FS)
1	Line	0.12	40	195	22.15	69.68	26.91	36.86
2	Line	0.16	50	200	19.78	65.95	25.92	36.38
3	Line	0.20	60	205	36.69	63.55	31.29	36.06
4	Triangles	0.12	50	205	23.04	45.87	27.25	33.23
5	Triangles	0.16	60	195	20.77	45.07	26.35	33.08
6	Triangles	0.20	40	200	26.75	46.34	28.55	33.32
7	Tri-Hexagon	0.12	60	200	22.48	48.05	27.04	33.63
8	Tri-Hexagon	0.16	40	205	24.29	48.37	27.71	33.69
9	Tri-Hexagon	0.20	50	195	22.93	43.84	27.21	32.84

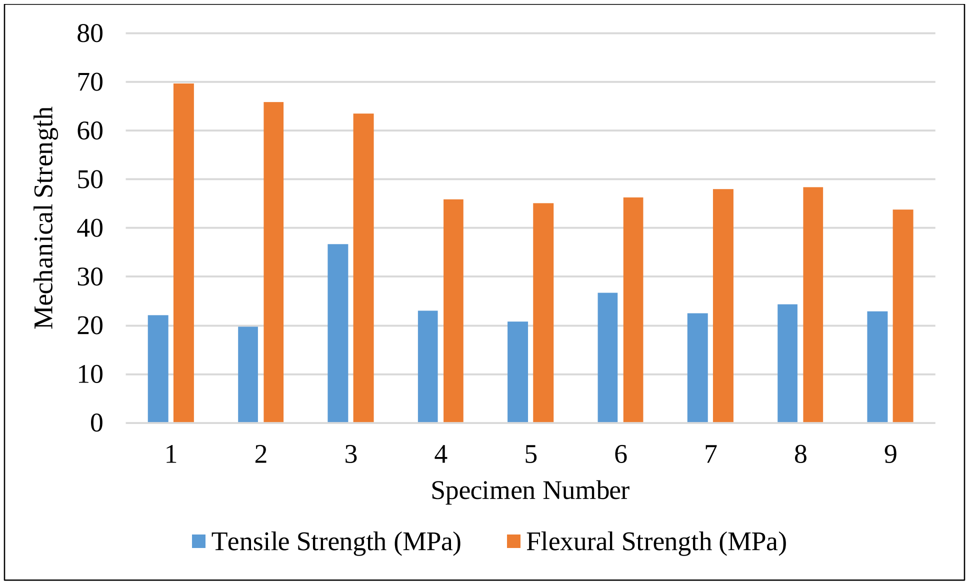


Fig. 2 Tensile and Flexure Strength of 3D printed PLA specimens

2.3. 3-D Printer

Polylactic Acid (PLA) specimens were printed using a Creality Ender-3 V2 desktop FDM 3D printer (as shown in Figure 3) according to ASTM standards. It is a low-cost desktop printer that uses PLA material in filament form with a 0.4 mm nozzle diameter in the present study. The open-source slicing program Ultimaker Cura 4.10.0 was used to command and manage all process settings, as well as to produce G-code files from CAD design data. PLA specimens for tensile and flexural tests were printed according to ASTM D638 [33] and D790 [24] standards as per the experimental plan, as shown in Figures 4 and 5.

The CAD model of PLA specimens was created using Autodesk Fusion 360 software, an open-source software free for students and educators. The infill pattern of tensile specimens is shown in Figure 6. The CAD model file is saved in .STL format. The .STL file was then imported into Ultimaker Cura 4.10.0, slicing software that translates the model into G-code, the language understood by 3D printers. To print the tensile and Flexural specimens as per ASTM standard, PLA filament of 1.75 mm diameter was loaded into the printer. The printer followed the G-code instructions to build the specimens layer by layer according to the experimental plan Table 4.

Fig. 3 Creality ender-3 V2 desktop 3D printer

Table 5. FDM 3D printer detail specifications

Model	Creality Ender-3 V2
Print Size	220 x 220 x 250mm
Number of Nozzles	1
Recommended Layer Thickness	0.1mm - 0.4mm
Stock Nozzle Diameter	0.4mm
Filament Diameter	1.75mm
File Format	.gcode
Power Specification	Input: AC 115/230V 50/60Hz Output: DC 24V
Build Plate Temperature	≤100°C
Nozzle Temperature	≤250°C
Print Speed	≤180 mm/s
Resume Printing	Yes, after Manual pause or Power failure

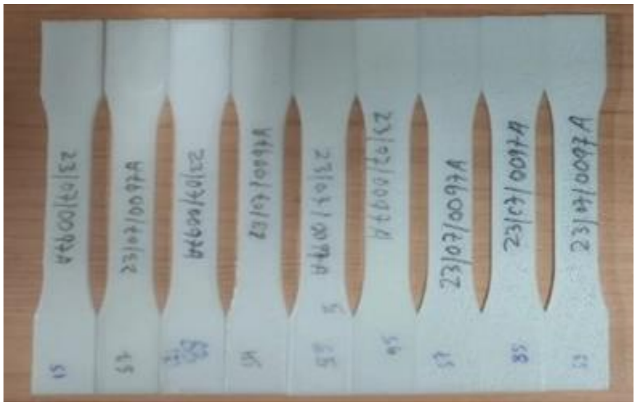


Fig. 4 Printed tensile specimens (ASTM D 638)

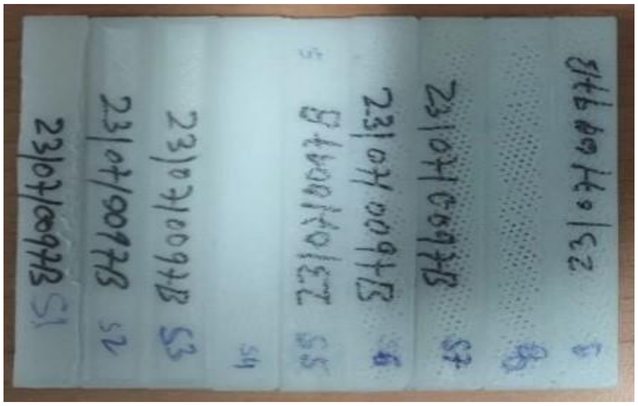


Fig. 5 Printed flexural specimens (ASTM D790)

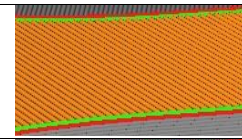
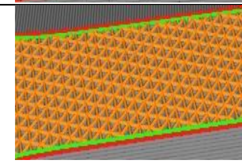
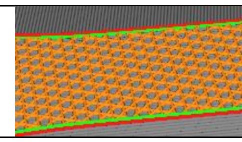
Infill Pattern	3D Printing of Tensile Specimens (Simulation Picture of Ultimaker Cura Software)	Infil Pattern Views in Printed Specimens
Line		
Triangles		
Tri-Hexagon		

Fig. 6 Simulation picture of 3D printing of tensile specimens and respective infill pattern views

Fig. 7 UTM with loaded test specimens

2.4. Tensile and Flexure Testing

The tensile characteristics of the printed specimens were evaluated using an ASTM D-638 standard [33]. Tensile strength measurements were performed using a Universal Testing Machine (UTM) from Dak System Inc., Series 7200, equipped with a 50 KN load cell and operated at a consistent crosshead speed of 5 mm/min, as shown in Figure 7.

The strength during the bending of PLA-produced specimens using FDM was assessed using a flexural test. The materials' flexural characteristics were examined using the ASTM D-790 standard technique [24]. Flexural tests were performed using a universal testing machine from Dak System Inc., Series 7200, that had a constant crosshead speed of 2 mm/min and a 50 KN load cell.

3. Results and Discussion

3.1. Optimization

The experimental results obtained for 3D printing of PLA specimens as per the Taguchi experimental design are summarised in Table 3. The printed specimens exhibited flexural strengths ranging from 43.84 to 69.68 MPa and tensile strengths ranging from 19.78 to 36.69 MPa, as seen in Figure 2. Taguchi optimization using the S/N ratio method is used to determine the best combination of process factors.

The primary purpose of the research is to increase the mechanical properties, the S/N ratio was used to determine to be "larger is better." Calculating the mean S/N ratios for each response at each level determines the optimum value; a higher S/N ratio indicates better quality.

Table 6 displays the response table for the signal-to-noise ratio of tensile strength. The result shows the rank of layer thickness is one (delta = 2.35) and is followed by extrusion temperature (delta =1.93, printing speed (delta = 1.43), and infill pattern (delta = 0.72). The rank is employed to determine which variable significantly impacts the responses. The optimum printing parameters for tensile strength of printed specimens based on S/N ratios were line infill pattern, 0.20 mm layer thickness, 60 mm/s printing speed and 205°C extrusion temperature. Table 7 displays the response table for the S/N ratio of Flexural strength. The result shows the rank of the infill pattern is one (delta = 3.23) and is followed by layer thickness (delta = 0.50), printing speed (delta = 0.47), and extrusion temperature (delta = 0.19). The optimum printing parameters for the flexural strength of printed specimens based on S/N ratios were line infill pattern, 0.12 mm layer thickness, printing speed of 60 mm/s, and extrusion temperature of 205°C.The major effects graphs for the S/N ratios of tensile and flexural strength with regard to 3D printing parameters, such as printing temperature, speed, infill pattern, and layer thickness, are shown in Figures 8 and 9, respectively.

Table 6. Response table for S/N ratios of tensile strength

Level	Infill Pattern	Layer Thickness	Printing Speed	Extrusion Temperature
1	28.04	27.06	27.72	26.82
2	27.38	26.66	26.79	27.17
3	27.32	29.02	28.23	28.75
Delta	0.72	2.35	1.43	1.93
Rank	4	1	3	2

Table 7. Response table for S/N ratios of Flexural Strength

Level	Infill Pattern	Layer Thickness	Printing Speed	Extrusion Temperature
1	36.44	34.58	34.62	34.26
2	33.21	34.38	34.15	34.45
3	33.39	34.07	34.26	34.33
Delta	3.23	0.50	0.47	0.19
Rank	1	2	3	4

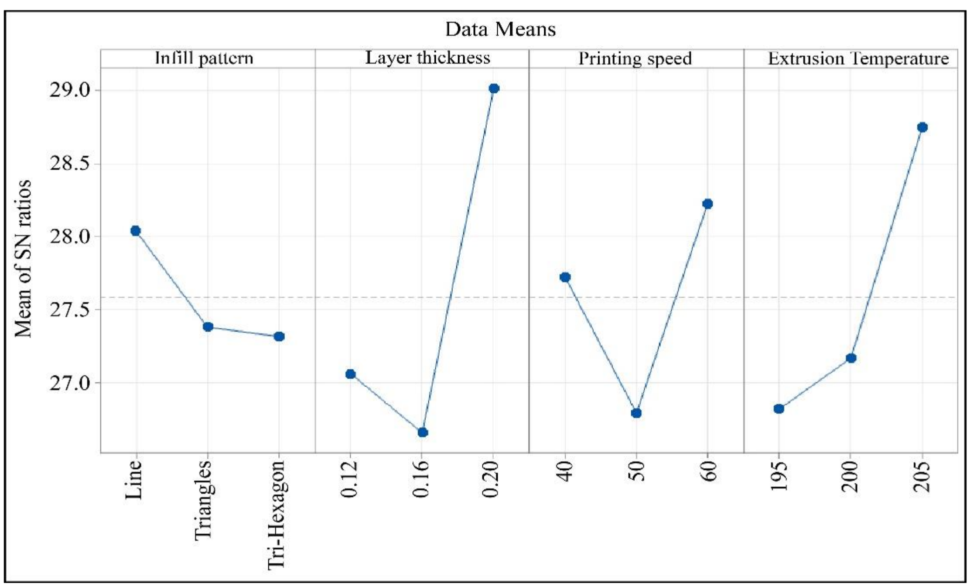


Fig. 8 Main effect plot for S/N ratio of tensile strength

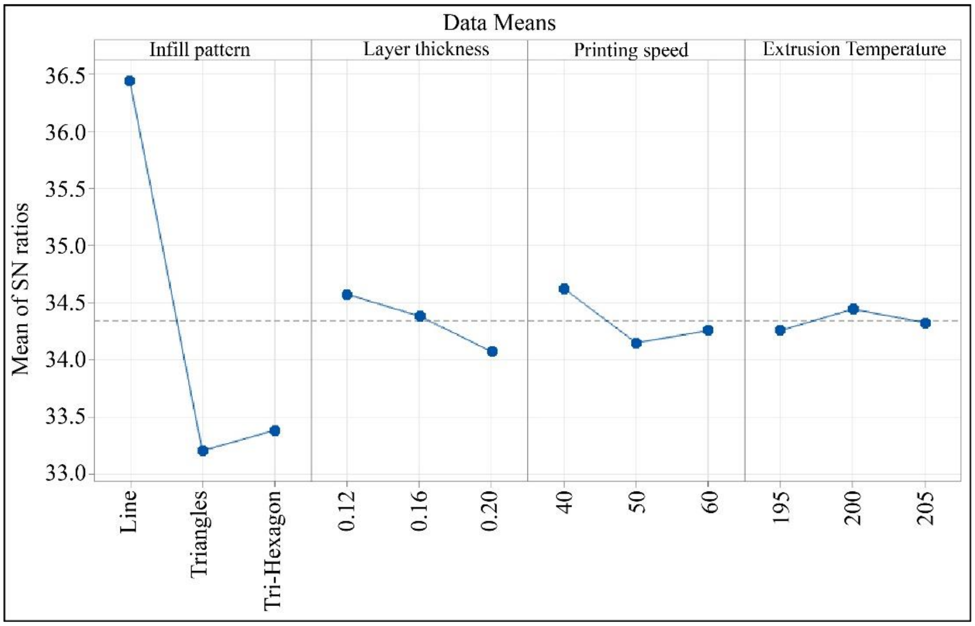


Fig. 9 Main effect plot for S/N ratio of Flexural Strength

3.2 Analysis of Tensile and Flexural Strength

The current research includes interaction graphs depicting how four process factors, printing speed, extrusion temperature, layer thickness, and infill pattern, correlate to tensile and flexural strength. Figures 10 and 11 display these graphs. An interaction plot Graphs demonstrate that lines are not parallel to each other, indicating a strong link between the FDM process factors and the values of tensile and flexural strength. An ANOVA analysis was conducted to examine the main impact of FDM process factors on responses with a 95% confidence level. Tables 8 and 9 represent the ANOVA findings for tensile and flexural strength, respectively. This analysis revealed that the infill pattern, accounting for 96.13% of the variance, had the greatest impact on flexural strength. On the other hand, characteristics like layer thickness, printing speed, and extrusion temperature had the least effect on flexural strength. The layer thickness (28.6%) and the extrusion temperature (27%) had the largest impact on tensile strength; other parameters, like infill pattern and printing speed, had the least effect on tensile strength.

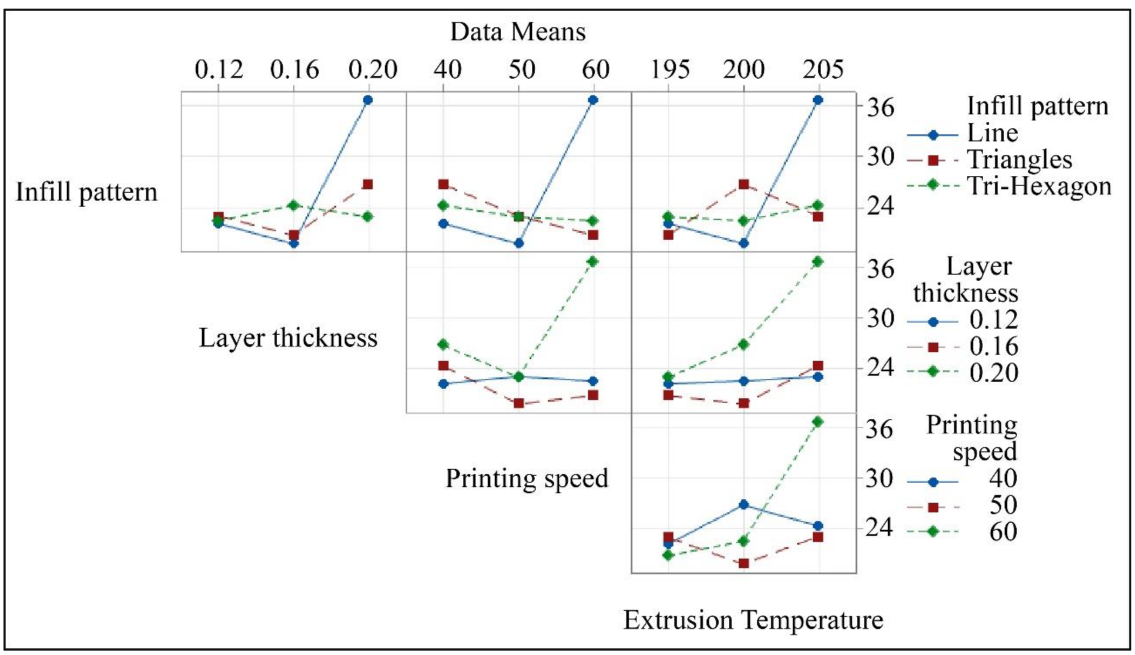


Fig. 10 Interaction plots for tensile strength

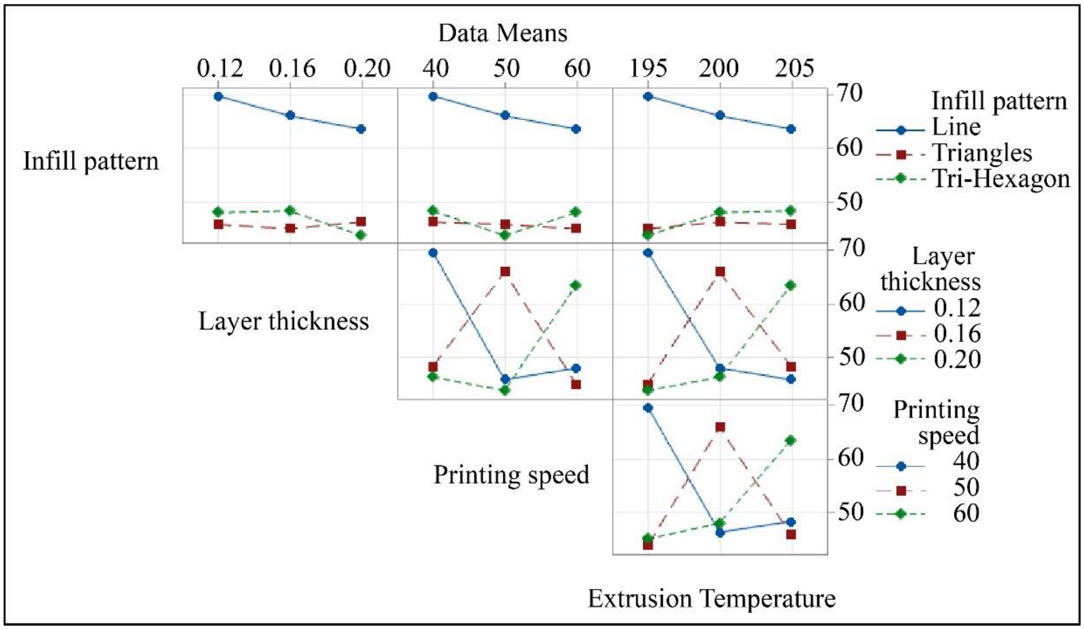


Fig. 11 Interaction plots for flexural strength

Table 8. ANOVA for the tensile strength

Response	Variables	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Tensile Strength	Regression	5	137.041	67.24%	137.041	27.408	1.23	0.460
	Layer Thickness	1	58.282	28.60%	58.282	58.282	2.62	0.204
	Printing Speed	1	7.594	3.73%	7.594	7.594	0.34	0.600
	Extrusion Temperature	1	55.025	27.00%	55.025	55.025	2.47	0.214
	Infill Pattern	2	16.141	7.92%	16.141	8.071	0.36	0.723
	Error	3	66.760	32.76%	66.760	22.253		
	Total	8	203.802	100.00%				

Table 9. ANOVA for the Flexural Strength

Response	Variables	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Flexural Strength	Regression	5	838.727	99.24%	838.727	167.745	78.45	0.002
	Layer Thickness	1	16.236	1.92%	16.236	16.236	7.59	0.070
	Printing Speed	1	9.933	1.18%	9.933	9.933	4.65	0.120
	Extrusion Temperature	1	0.107	0.01%	0.107	0.107	0.05	0.838
	Infill Pattern	2	812.451	96.13%	812.451	406.225	189.99	0.001
	Error	3	6.414	0.76%	6.414	2.138		
	Total	8	845.141	100.00%				

Where DoF- Degree of Freedom, Adj SS- Adjusted Sum of Square, Adj MS- Adjusted Mean Square

3.3. Regression Analysis for Flexural and Tensile Strength

The regression equations for Flexure strength and Tensile Strength are obtained by using Statistical Software Minitab-2021 and Microsoft Excel 2013 within the given range of process parameters [15]. Equation (2, 3, 4) and Equation (5, 6, 7) represent a mathematical model between FDM printing process factors and the resulting flexural and tensile strength, respectively. These expressions are useful for determining the characteristics of the response variable for certain input process parameters of an FDM 3D Printer when producing the components.

The deviation between the experimentally observed responses obtained using the Taguchi approach and the predicted outcomes is seen in Figures 12 and 13. It provides a comparison graph illustrating the experiment and mathematical model data for flexural and tensile strength, respectively.

The coefficient of determination (R-Sq) quantified the extent to which change in the process factors account for the variance in the predicted values and output responses. A greater coefficient of determination (R-Sq) value indicates a favourable correlation with a mathematical model.

Table 8 shows that the coefficient of determination (R-sq) value for flexural strength is 0.9924, indicating that 99.24% of the variation in the output response can be explained by the process factors. The coefficient of determination (R-sq) value accurately predicts 93.01% of the model's outcomes. We may use a similar idea to anticipate additional printing responses and forecast the model outcomes.

Table 10. Regression equation for Flexural Strength (FS)

Infill Pattern	Regression Equation	Equation No.
Line	FS = 84.7 - 41.1 B - 0.1287 C - 0.027 D	(2)
Triangles	FS = 64.1 - 41.1 B - 0.1287 C- 0.027 D	(3)
Tri-Hexagon	FS= 65.1 - 41.1 B - 0.1287 C- 0.027 D	(4)

Where B = Layer Thickness, C= Printing Speed, D= Extrusion Temperature, FS= Flexure Strength in Mpa, MPa= Mega Pascal

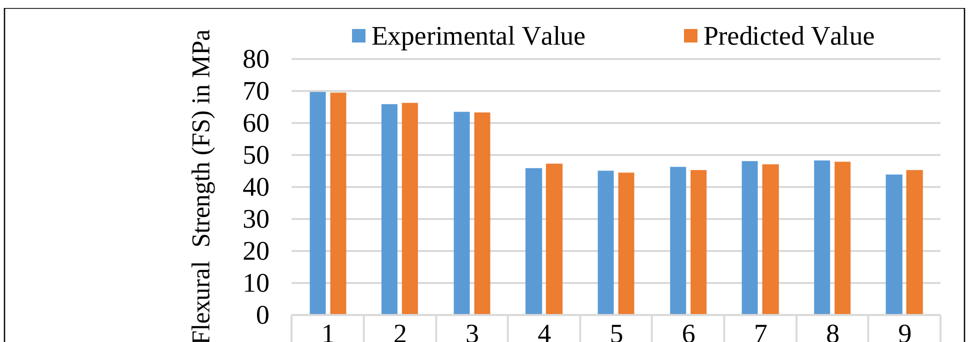
Table 11. Model summary Flexure Strength

S	R Square	R Square (adj)	Press	R Square (pred)
1.46224	99.24%	97.98%	59.0567	93.01%

Table 12. Regression equation for tensile strength

Infill Pattern	Regression Equation	Equation no.
Line	TS = -113.0 + 77.9 B + 0.112 C+ 0.606 D	(5)
Triangles	TS = -115.7 + 77.9 B + 0.112 C+ 0.606 D	(6)
Tri-Hexagon	TS = -116.0 + 77.9 B + 0.112 C+ 0.606 D	(7)

Where TS= Tensile Strength in Mpa



	1	2	3	4	5	6	7	8	9
Experimental Value	69.68	65.95	63.55	45.87	45.07	46.34	48.05	48.37	43.84
Predicted Value	69.46	66.39	63.33	47.27	44.61	45.40	47.11	47.91	45.24

Fig. 12 Regression fit plot of experimental vs. Predicted values for Flexural Strength

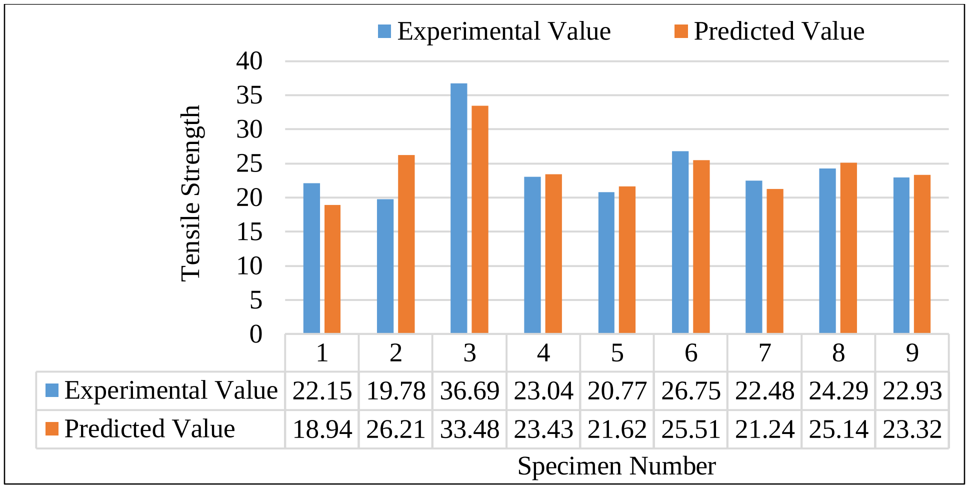


Fig. 13 Regression fit plot of experimental vs. Predicted values for tensile strength

4. Conclusion

The experimental study aimed to examine the tensile and flexural properties of FDM-printed PLA specimens and determine the best combination of input factors to improve their mechanical characteristics. Printed PLA specimens were examined according to the ASTM standard for tensile and flexural tests. Various process factors, including the infill pattern, layer thickness, extruder temperature, and printing speed, were taken into account throughout the investigation.

For optimization, the Taguchi S/N ratio technique was utilized, and experiments were planned using the Taguchi method of the L9 orthogonal array for four factors and three levels each. The obtained findings were then analyzed using ANOVA analysis and a regression model. The printed specimens exhibited a variety of tensile strength values, ranging from 19.78 to 36.69 MPa.

Similarly, the flexural strength of the specimens varied from 43.84 to 69.68 MPa. The optimum printing parameters for the flexural strength of printed specimens based on S/N ratios were line infill pattern, 0.12 mm layer thickness, printing speed of 60 mm/s, and extrusion temperature of 205 °C. The best printing settings for tensile strength of printed specimens based on S/N ratios were line infill pattern, 0.20 mm layer thickness, 60 mm/s printing speed, and 205 °C extrusion temperature. The ANOVA analysis revealed that the infill pattern, accounting for 96.13% of the variance, had the greatest impact on flexural strength. On the other hand, characteristics like layer thickness, printing speed, and extrusion temperature had the least effect on flexural strength. The layer thickness (28.6%) and the extrusion temperature (27%) had the largest impact on tensile strength; other parameters, like infill pattern and printing speed, had the least effect on tensile strength.

A linear model was used to establish mathematical equations between the mechanical properties and process parameters of a 3D printer. According to regression analysis R-square value for flexural strength is 0.9924, indicating that 99.24% of the variation in the output response can be explained by the process factors. The R-square value accurately predicts 93.01% of the model's outcomes. The present study may be extended to include these findings directly in Computer-Aided Design (CAD) models, resulting in optimal 3D-printed PLA components of desired mechanical properties with minimal wastage.

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