ITM Web of Conferences **74**, 03010 (2025) https://doi.org/10.1051/itmconf/20257403010
ICCPCI-2024

Optimization of Process Parameters for Maximizing Tensile Strength in 3D-Printed ASTM Specimens: A Comparative Study of Black PLA and Carbon PLA

Devesh Singh*, Ajay Verma

Department of Mechanical Engineering, KIET Group of Institutions, Ghaziabad, Uttar Pradesh, India

Abstract: The increasing need for additive manufacturing technologies generally Fused Deposition Modeling (FDM) demands parameter optimization strategies for producing better mechanical components. The study evaluated the tensile strength between ASTM standard specimens constructed utilizing black PLA and carbon PLA filament materials. The authors used regression methods to establish mathematical models that optimized FDM process parameters for maximizing tensile strength levels. Testing confirmed carbon PLA exhibits superior tensile strength than black PLA. The research-established optimized input parameter range succeeded in producing optimal tensile strength measurements. The discovered results create essential comprehension for bettering FDM-printed parts performance by selecting materials alongside process parameter optimization.

Keywords: 3D printing, FDM, PLA, Testing, Optimization

1. Introduction

Additive Manufacturing (commonly referred to as 3D printing) represents a transformative technology that facilitates the production of complex geometries at lower material consumption and shorter lead times. Fused Deposition Modeling (FDM) is one of the many AM techniques because of its simplicity, affordability, and versatility. Only the choice of material and the optimization of process parameters influence the mechanical performance of FDM printed parts, however, such improvements require systematic studies[1-6].

For use in FDM, Polylactic Acid (PLA) is a widely used thermoplastic polymer because it biodegrades, is cheap and easy to process. Nevertheless, its low mechanical strength prevents its use in load-bearing environments. To overcome this limitation, the work of researchers has also examined composite variants of PLA, such as carbon fiber reinforced PLA (carbon PLA) that features improved tensile strength and stiffness through the incorporation of carbon fibers.

*Email: deveshsinghbsr24@gmail.com

Studies in previous works have pointed out that process parameters like extrusion temperature, print speed, layer thickness, and infill density affect the mechanical properties of FDM printed components. As an example, Rajpurohit et al. (2018) [7] showed that plasma-treated PLA specimens with higher infill densities and optimized extrusion temperatures tend to demonstrate higher tensile strength. Similarly, Hikmat et al. [8] found that surface quality and mechanical performance are compromised relative to balanced conditions particularly when the layer is thinner. These studies then point out that optimal outcomes are achievable only if multiple parameters are optimized simultaneously.

Studies on carbon PLA have improved mechanical properties. Garg et al. (2015) [9]carried out a comparative study of PLA and CPLYA, and the latter was found to be superior in their tensile strength because of the reinforcing power of the carbon fibres. However, there is an ongoing investigation of the interplay between material properties and process parameters. Although several studies have investigated the effects of thermoplastic and shrinkage for FDM, very few have systematically optimized FDM parameters to maximize the tensile strength of FDM carbon PLA, leaving a critical gap.

To bridge this gap this study will first do a comparative analysis between black PLA and carbon PLA, optimizing FDM process parameters to improve tensile strength. The research employs regression analysis to correlate tensile strength and process parameters of a regime using ASTM D638 Type I specimens. Then, experimental testing validates the optimized settings to have a robust framework for improving the performance.

This research contributes to accumulating knowledge on additive manufacturing and is expected to provide practical detail on material selection and parameter optimization.

2. Proposed Methodology:

This study follows a three-phase approach to optimize FDM conditions for maximizing the tensile strength of Black PLA and Carbon PLA specimens as shown in Fig.1 :
Phase 1: Initial Phase
Material Selection: Carbon and Black PLA filament are utilized and are high quality.
Process Parameters:

- Extrusion Temperature: Optimized based on material datasheets.
- Layer Thickness: Tested between 0.1–0.3 mm.
- Print Speed: Evaluated from 30–100 mm/s.
- Infill Density: Assessed at 20–80%.

Printer Configuration: Calibrated for consistent performance, a standard FDM printer.
Phase 2: Specimen Printing and Testing
Design of Experiments (DoE): Framework exploring parameter combinations systematically in temperatures, layer thicknesses, speeds, and infill densities.
Specimen Printing: The tensile specimens are printed under controlled temperature and humidity ASTM standards.
Testing: All parameter variations are threaded on a universal testing machine (UTM) and tensile strength and elongation are measured.
Phase 3: Data Analysis and Optimization
Comparative Analysis: Black PLA and Carbon PLA specimens are compared in terms of the difference in tensile strength and surface finish.
Modeling and Optimization: With experiments, regression models identify optimal parameters, which validate the reliability of the models.

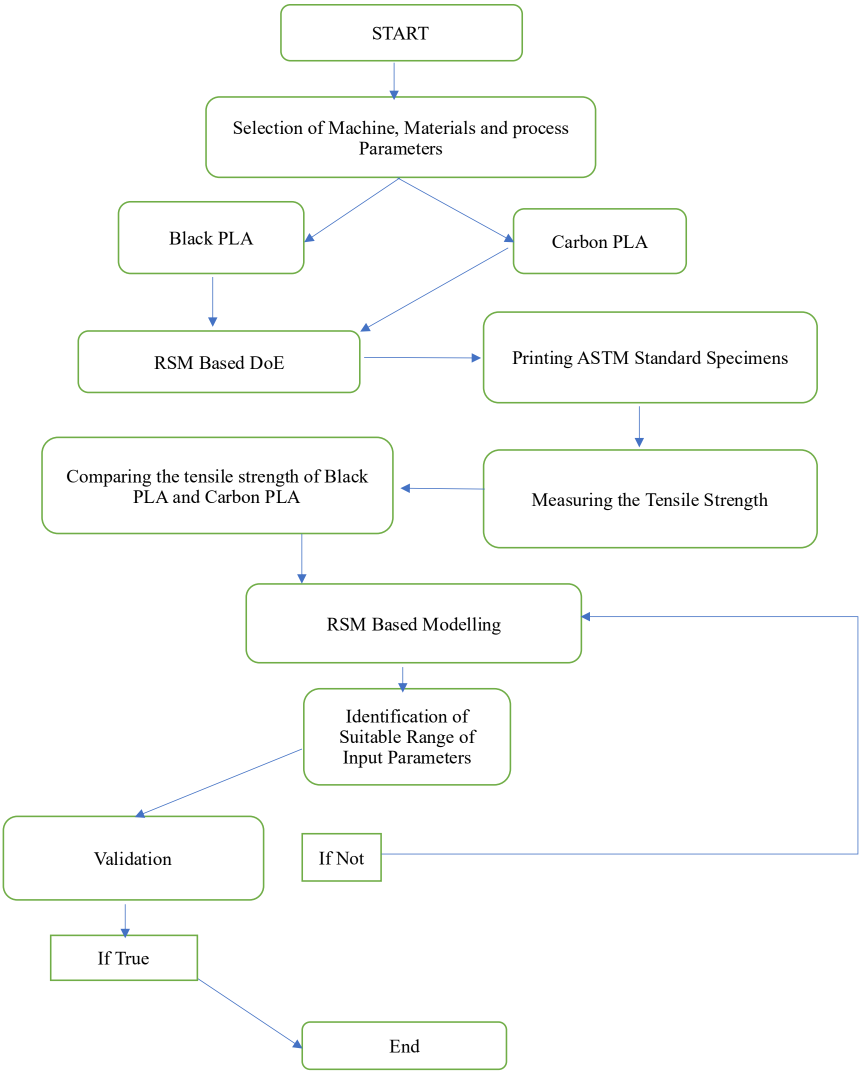

Figure 1. Proposed Methodology

3. 3D PRINTING AND TESTING OF SPECIMENS

In the present work, the process parameters have been selected based on the literature review and pilot experiments. The selected input parameters and their respective levels have been listed in Table 1. Moreover, the printer specifications have been listed in Table 2.

Table 1 Process Parameters and Levels

Process Parameters / Levels	Level 1	Level 2	Level 3	Level 4
Extrusion temp. (°C)	190	200	210	220
Layer Thickness (microns)	150	200	250	300
Print Speed (mm/s)	30	45	60	75
Infill Density (%)	85	90	95	100

Table 2 Printer Specifications

Printing parameters	Range
Make	Flash Forge Dreamer NX
Extruder temperature	0°c to 248°c
Print speed	10 mm/sec to 200 mm/sec
Layer thickness	0.1 mm to 0.4 mm
Infill density	10% to 100%
Orientation	X, Y, Z axis
Resolution	Low, Standard, High
First layer height	0.2-1.00 mm
Perimeter shells	2,3,5
Bottom solid layer	2,3,5
Fill pattern	Hexagon, line, triangular
Travel speed	10-100
Platform temperature	10-200°c

After the selection of process parameters, the DoE has been generated. In the present work, DoE has been generated based on an orthogonal array. The DoE has been shown in Table 3[10].

Table 3 Orthogonal array-based DoE.

Specimen No.	A	B	C	D
1	190	150	30	85
2	190	200	45	90
3	190	250	60	95
4	190	300	75	100
5	200	150	45	95
6	200	200	30	100
7	200	250	75	85
8	200	300	60	90
9	210	150	60	100
10	210	200	75	95
11	210	250	30	90
12	210	300	45	85
13	220	150	75	90
14	220	200	60	85
15	220	250	45	100
16	220	300	30	95

Fabrication of the specimens has been done based on the DoE shown in Table 3. Some of the fabricated specimens are shown in Fig.2. After the fabrication of the test specimens tensile testing was done. Tensile testing has been done. The obtained results are listed in Table 4. Moreover, after the testing of the specimens, mathematical models for both materials have been generated using Regression.

Figure 2. Some of the Printed Specimens

Table 4 Tensile testing results for Black PLA

Specimen No.	A	B	C	D	Material Required (grams)	Filament Length (mm)	Print Time (min)	No. of Layers	BLACK PLA Tensile Strength (MPa) Area=41.6mm^2	CARBON PLA Tensile Strength (MPa) Area=41.6 mm^2
1	190	150	30	85	14.26	4.78	101	24	55.865	61.2019
2	190	200	45	90	14.61	4.90	72	20	61.177	64.0144
3	190	250	60	95	14.89	4.99	54	17	74.134	81.4423
4	190	300	75	100	15.22	5.10	35	15	93.918	82.0673
5	200	150	45	95	14.76	4.95	90	24	65.7211	75.6490
6	200	200	30	100	15.22	5.10	84	20	97.0673	115.6971
7	200	250	75	85	14.53	4.87	49	17	67.5961	75.3846
8	200	300	60	90	14.82	4.97	46	15	54.4711	88.3725
9	210	150	60	100	15.21	5.10	59	24	97.0673	120.9615
10	210	200	75	95	14.81	4.96	59	19	73.6057	93.1490
11	210	250	30	90	14.72	4.93	74	17	64.2067	82.8125
12	210	300	45	85	14.67	4.92	51	15	72.6202	90.0721
13	220	150	75	90	14.52	4.87	77	24	45.4326	83.9663
14	220	200	60	85	14.38	4.82	63	20	65.7932	72.1153
15	220	250	45	100	15.22	5.10	52	17	98.2451	116.5144
16	220	300	30	95	14.96	5.02	67	15	82.2355	102.6682

4. MATHEMATICAL MODELLING

Taguchi is a process/product optimization method that is based on 8 steps of planning, conducting, and evaluating results of matrix experiments to determine the best levels of control factors. The primary goal is to keep the variance in the output very low even in the presence of noise inputs [11-16]. Table 5 shows the ANOVA for black PLA. Moreover, Table 6, shows the model summary for black PLA.

Equation 1 shows the generalized equation for the tensile strength of black PLA.

Table 4. Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	4	2724.68	681.17	5.58	0.011
Extrusion Temperature	1	22.56	22.56	0.18	0.676
Layer Thickness	1	192.25	192.25	1.57	0.236
Print Speed	1	49.24	49.24	0.40	0.538
Infill Density	1	2460.63	2460.63	20.14	0.001
Error	11	1343.79	122.16		
Total	15	4068.47			

Table 6. Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
11.0527	66.97%	54.96%	28.45%

Regression Equation

$$\text{Tensile Strength} = -162.4 + 0.106\ \text{Extrusion Temperature} + 0.0620\ \text{Layer Thickness} - 0.105\ \text{Print Speed} + 2.218\ \text{Infill Density} \quad (1)$$

Similarly, Table 7 shows the ANOVA for Carbon PLA and Table 8 shows the Model summary. Equation 2, shows the generalized equation of tensile strength for carbon PLA

Table 7. Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	4	3643.69	910.92	8.03	0.003
Extrusion Temperature	1	1062.20	1062.20	9.36	0.011
Layer Thickness	1	71.03	71.03	0.63	0.445
Print Speed	1	55.77	55.77	0.49	0.498
Infill Density	1	2454.69	2454.69	21.64	0.001

Error	11	1247.69	113.43
Total	15	4891.38	

Table 8. Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
10.6502	74.49%	65.22%	42.09%

Regression Equation

$$\text{Tensile Strength} = -269.1 + 0.729\ \text{Extrusion Temperature} + 0.0377\ \text{Layer Thickness} - 0.111\ \text{Print Speed} + 2.216\ \text{Infill Density} \quad (2)$$

Comparison between the results obtained:
The tensile strength results for Black PLA and Carbon PLA printed ASTM specimens at various input settings, as modeled using the Response Surface Methodology (RSM)[17-22], reveal significant differences in how process parameters influence the mechanical properties of each material. Below is a detailed comparison:

1. Sensitivity to Extrusion Temperature

Black PLA: Tensile strength increases by 0.106 units per degree of extrusion temperature.

Carbon PLA: Tensile strength increases significantly more, by 0.729 units per degree.

Conclusion: Carbon PLA is much more sensitive to extrusion temperature, suggesting that fine-tuning this parameter is critical for optimizing tensile strength in Carbon PLA.

2. Sensitivity to Layer Thickness

Black PLA: Tensile strength increases by 0.062 units per unit increase in layer thickness.

Carbon PLA: Tensile strength increases by a smaller margin, 0.0377 units per unit increase in layer thickness.

Conclusion: Layer thickness has a more pronounced effect on Black PLA tensile strength compared to Carbon PLA.

3. Sensitivity to Print Speed

Black PLA: Tensile strength decreases by 0.105 units per unit increase in print speed.

Carbon PLA: Tensile strength decreases by 0.111 units per unit increase in print speed.

Conclusion: Both materials show a similar sensitivity to print speed, with Carbon PLA showing a slightly higher reduction in tensile strength at higher speeds.

4. Sensitivity to Infill Density

Black PLA: Tensile strength increases by 2.218 units per unit increase in infill density.

Carbon PLA: Tensile strength increases by 2.216 units per unit increase in infill density.

Conclusion: Both materials exhibit nearly identical sensitivity to infill density, indicating their crucial role in enhancing tensile strength.

5. Base Strength

The experimental baseline tensile strength values for both materials were determined through intercept measurements (-162.4 for Black PLA and -269.1 for Carbon PLA). The lower intercept of Carbon PLA demonstrates that achieving high tensile strength demands precise adjustments of its input parameters.

Overall Observations

The high sensitivity of Carbon PLA to extrusion temperature turns optimization into a struggle while still providing better strength results through precise temperature maintenance.

The tolerance to layer thickness changes among Black PLAprinter models implements the greatest effect on product quality.

The two materials demonstrate equivalent responses to printing factors such as speed and density yet require constant management of these variables.

When manufacturing ASTM standard specimens it becomes essential to customize printing parameters based on each material type. The greater tensile strength strength of Carbon PLA depends on precise extrusion temperature management although Black PLA functions best during layer thickness variations.

The Available RSM models enable analysis to identify proper parameter settings resulting in optimal tensile strength outcomes for Black PLA as well as Carbon PLA. These models show how each input parameter modifies tensile strength values. Below is a step-by-step approach to identifying the optimal range for each parameter:

Black PLA Model

Tensile Strength = -162.4 + 0.106 (Extrusion Temperature) + 0.0620 (Layer Thickness) - 0.105 (Print Speed) + 2.218 (Infill Density)

Optimal Parameter Ranges:

Extrusion Temperature:

A positive coefficient (0.106) suggests that increasing the temperature enhances tensile strength.

Optimal range: Near the upper limit of the printer's recommended extrusion temperature for Black PLA (e.g., 200°C to 220°C).

Layer Thickness:

A positive coefficient (0.0620) indicates that a higher layer thickness increases tensile strength.

Optimal range: Upper practical limits of the printer's capability for Black PLA (e.g., 0.2 mm to 0.3 mm).

Print Speed:

A negative coefficient (-0.105) means tensile strength decreases with higher speeds.

Optimal range: Lower speed range for precise and strong layer bonding (e.g., 40 mm/s to 60 mm/s).

Infill Density:

A positive coefficient (2.218) shows that higher infill density improves tensile strength.

Optimal range: Near 100% infill for maximum strength.

Carbon PLA Model

Tensile Strength = -269.1 + 0.729 (Extrusion Temperature) + 0.0377 (Layer Thickness) - 0.111 (Print Speed) + 2.216 (Infill Density)

Optimal Parameter Ranges:

Extrusion Temperature:

High sensitivity with a coefficient of 0.729, suggests that maximizing extrusion temperature significantly enhances strength.

Optimal range: Upper range of Carbon PLA’s extrusion temperature (e.g., 210°C to 230°C). Avoid exceeding limits to prevent degradation.

Layer Thickness:

Positive but smaller effect (0.0377).

Optimal range: Mid-to-high values (e.g., 0.2 mm to 0.25 mm) to balance strength and print quality.

Print Speed:

Negative coefficient (-0.111), meaning lower speeds are better for layer adhesion.

Optimal range: Low to moderate speed (e.g., 40 mm/s to 50 mm/s).

Infill Density:

Similar influence as Black PLA (2.216).

Optimal range: Near 100% for maximum tensile strength.

Table 9 shows the summary of optimal ranges.

Table 9. Summary of Optimal Ranges

Parameter	Black PLA	Carbon PLA
Extrusion Temperature	200°C to 220°C	210°C to 230°C
Layer Thickness	0.2 mm to 0.3 mm	0.2 mm to 0.25 mm
Print Speed	40 mm/s to 60 mm/s	40 mm/s to 50 mm/s
Infill Density	~100%	~100%

These ranges should be validated experimentally, as interactions between parameters can affect the actual optimal settings. Fine-tuning within these ranges using confirmation experiments will ensure the best results.

Validation

To validate the identified ranges of input parameters for achieving maximum tensile strength in both Black PLA and Carbon PLA, the following procedure was employed. The table below outlines the chosen parameter combinations within the proposed ranges for both materials, which were used to print and test specimens. Table 10 shows the selected printing settings for validation. Moreover, Table 11, shows the measured tensile strength at validation settings.

Table 10. Selected Printing Settings for Validation

Material	Specimen No.	Extrusion Temperature (°C)	Layer Thickness (microns)	Print Speed (mm/s)	Infill Density (%)
Black PLA	1	200	200	45	100
Black PLA	2	220	250	30	100
Black PLA	3	210	300	40	95
Carbon PLA	4	210	150	60	100
Carbon PLA	5	220	200	30	100
Carbon PLA	6	200	250	45	95

Table 11. Measured Tensile Strength at Validation Settings

Material	Specimen No.	Measured Tensile Strength (MPa)
Black PLA	1	95.432
Black PLA	2	91.327
Black PLA	3	85.614
Carbon PLA	4	120.751
Carbon PLA	5	115.398
Carbon PLA	6	110.612

5. CONCLUSION

RSM models show the tensile strength of ASTM standard specimens printed using Black PLA, Carbon PLA, and two other PLA formulations to be significantly affected by process parameters. Also, the tensile strength of Black PLA is improved by extrusion temperature and layer thickness, and that of Carbon PLA mainly depends on extrusion temperature. Both materials show a similar dependence on print speed and infill density with near 100% infill being the most arable and the best performing and negative correlation with print speed to highlight the need for slower printing speeds to improve layer adhesion.

The identified optimal ranges for maximizing tensile strength are:

Black PLA: 200°C to 220°C Extrusion temperature, 0.2 mm to 0.3 mm Layer thickness, 40 mm/s to 60 mm/s print speed and near 100% Infill Density.

Carbon PLA: Extrusion temperature at 210°C to 230°C, layer thickness around 0.2mm to 0.25mm, print speed at 40 mm/s to 50 mm/s, and nearly 100% infill density.

This underlines the inherent importance of material-specific optimization for its designer maximization of tensile strength for 3D printed components. Black PLA is more forgiving, but its proof (less) comes in weaker form across parameters. Carbon PLA is stronger but not if the extrusion temperature is not chosen correctly. These findings need to be first validated experimentally, and subsequent interactions between parameters on the model should be explored to further improve the models' predictive accuracy.

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