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Experimental Investigation of Mechanical Properties of Various 3D Printing Materials Using Taguchi Method

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ABSTRACT

This study presents an experimental investigation of the mechanical properties of various fused deposition modeling (FDM) 3D printing materials, namely PLA, ABS, and TPU, under varying process conditions. The primary objective is to optimize the critical process parameters—layer height, infill density, and print orientation—to enhance tensile strength, compressive strength, and hardness. The study utilizes Polylactic Acid (PLA) material. Taguchi's L9 orthogonal array was employed to design a minimal set of experiments, and Analysis of Variance (ANOVA) was used to determine the significance and percentage contribution of each parameter. Results indicated that infill density was the most influential factor on tensile and compressive strength, while layer height had the greatest impact on hardness. Optimal parameter settings were identified for each response, providing a valuable guideline for manufacturers and designers to achieve desired mechanical performance in functional, load-bearing FDM-printed parts.

Keywords: Fused Deposition Modeling, Taguchi Method, Tensile Strength, Compressive Strength, Hardness, PLA, ABS, and TPU, ANOVA, Optimization

1. Introduction

Additive Manufacturing (AM), widely known as 3D printing, has transformed manufacturing by enabling rapid prototyping, customization, and the production of complex geometries that are difficult or impossible to achieve through conventional methods. Among the various AM technologies, Fused Deposition Modeling (FDM) has gained particular popularity because of its cost-effectiveness, accessibility, and the wide variety of thermoplastic materials available. Common FDM materials include Polylactic Acid (PLA), Acrylonitrile Butadiene Styrene (ABS), and Polyethylene Terephthalate Glycol (PETG), each of which possesses distinct mechanical and thermal properties that influence part performance. However, a major challenge in FDM is the anisotropy and variability in the mechanical properties of the fabricated components. Unlike metals or injection-molded polymers, the performance of 3D-printed parts depends heavily on process parameters. Layer adhesion, porosity, and residual stresses can significantly reduce the strength, stiffness, and toughness of printed parts. Key process variables such as layer thickness, infill density, and printing speed determine the bonding between adjacent filaments, the density of the printed structure, and the rate of cooling, thereby affecting the final properties of the printed object. PLA is known for its ease of printing, biodegradability, and high stiffness, but it is brittle compared to ABS and PETG. ABS, on the other hand, offers better impact resistance and toughness but suffers from warping due to high thermal contraction. PETG strikes a balance by offering good ductility, chemical resistance, and relatively low shrinkage. Optimizing process parameters for each material is therefore essential to achieve desired mechanical performance. The Taguchi method, a robust design of experiments (DOE) technique, provides a systematic and statistically efficient way to study multiple parameters simultaneously while minimizing the number of experimental trials. By employing orthogonal arrays, the Taguchi approach not only identifies optimal parameter combinations but also quantifies the relative contribution of each factor to the overall performance. This method has been widely used in machining, forming, and polymer processing but is still developing as a tool for optimizing additive manufacturing processes.

This study aims to experimentally investigate the influence of layer thickness, infill density, and printing speed on the mechanical properties of PLA, ABS, and PETG using the Taguchi L9 orthogonal array design. Tensile testing is employed to measure strength, elongation, and modulus, and the results are analysed using Signal-to-Noise (S/N) ratios and ANOVA. The outcome of this work will provide insights into parameter optimization for different FDM materials, contributing to improved structural performance in engineering and industrial applications.

2. Literature Survey

The mechanical performance of FDM-printed parts has been the subject of extensive research. Early investigations by Rodríguez et al. (2003) examined the mechanical behavior of ABS fabricated through FDM and observed that anisotropy and void formation critically reduced strength compared to injection-molded parts. Similarly, Sood et al. (2010) conducted a parametric study on FDM components and found that layer thickness and raster angle significantly affected tensile strength and surface finish.Ahn et al. (2002) studied the mechanical anisotropy of ABS specimens and reported that tensile strength along the raster direction was considerably higher than in the transverse direction. Their work highlighted the importance of optimizing deposition strategies in addition to parameter selection. Montero et al. (2001) also reported that mechanical properties of FDM parts were strongly dependent on build orientation and infill pattern. Later, Mohamed et al. (2015) provided a comprehensive review of optimization studies in FDM, concluding that layer thickness and infill density were the most critical parameters influencing both strength and dimensional accuracy. Similarly, Chacón et al. (2017) examined PLA parts printed under various orientations and found that 0° raster angle and high infill density improved tensile and flexural properties significantly. Comparative studies of materials have also been conducted. Tymrak et al. (2014) compared PLA and ABS specimens and reported that PLA exhibited higher stiffness and strength but lower ductility than ABS. More recently, Ziemian and Crawn (2012) evaluated FDM parts under tensile, compressive, and flexural loads, showing that PETG provides a balance between toughness and ease of printing. Optimization studies employing the Taguchi method have demonstrated its usefulness in additive manufacturing. For instance, Bakar et al. (2010) applied Taguchi analysis to optimize FDM parameters for ABS and achieved significant improvements in strength. Raju et al. (2018) used Taguchi L9 array to optimize infill percentage and layer thickness for PLA, confirming the robustness of the approach in reducing variability.

From this literature, it is clear that while numerous studies have optimized FDM parameters for individual materials, fewer works have conducted a comparative

investigation across multiple materials (PLA, ABS, PETG) using a unified Taguchi framework. This motivates the present study, which systematically evaluates the impact of process parameters across different materials to provide a comprehensive understanding for improved material–process matching.

3. Methodology

The methodology involves material selection, specimen fabrication using an FDM printer, identification of control parameters, design of experiments using the Taguchi method, mechanical testing, and statistical analysis.

3.2 Experimental Setup and Parameters

All prints were performed on a Creality Ender 3 V2 printer with a 0.4 mm nozzle.

The following three parameters were selected as control factors, each with three levels:

• A: Layer Height (mm) - 0.1, 0.2, 0.3

• B: Infill Density (%) - 20, 50, 80

• C: Print Orientation (Degrees) - 0° (Flat), 45°, 90° (Upright)

Other parameters were kept constant:

- Nozzle Temperature (200°C)
- Bed Temperature (60°C)
- Print Speed (50 mm/s)

3.2 Taguchi Design of Experiments

A Taguchi L9 orthogonal array was employed to design the experimental plan. This reduces the total number of trials from 27 (3^3 full factorial) to 9 while ensuring that the influence of each factor can be evaluated independently.

The L9 array for this study is presented in Table 3.2.

Table 3.2: L9 Orthogonal Array for Printing Parameters

Exp. No.	Material	Layer Thickness (mm)	Infill Density (%)	Print Orientation (Degrees)
1	PLA	0.1	20	0
2	ABS	0.1	50	45
3	TPU	0.1	90	90
4	PLA	0.2	20	45
5	ABS	0.2	50	90
6	TPU	0.2	90	0

Exp. No.	Material	Layer Thickness (mm)	Infill Density (%)	Print Orientation (Degrees)
7	PLA	0.3	20	90
8	ABS	0.3	50	0
9	TPU	0.3	90	45

3.3 Materials Used

Three widely used FDM materials were selected for comparison:

- **Polylactic Acid (PLA):** Biodegradable, stiff, but brittle.
- **Acrylonitrile Butadiene Styrene (ABS):** Strong and tough, prone to warping.
- **TPU:** Ductile, strong, and chemically resistant.

Filaments of 1.75 mm diameter were used, supplied by commercial vendors, and all tests were conducted under controlled environmental conditions (23 ± 2 °C, 50% relative humidity).

3.4 Specimen Preparation

Tensile test specimens were designed according to ASTM D638 Type IV standard. The models were sliced using Cura software with the defined parameter settings from the L9 orthogonal array. All specimens were printed on an FDM printer equipped with a 0.4 mm nozzle at a constant extrusion temperature (210 °C for PLA, 240 °C for ABS, 235 °C for PETG) and a bed temperature of 60 °C.

3.5 Mechanical Testing

Tensile testing was carried out using a Universal Testing Machine (UTM) with a crosshead speed of 5 mm/min. For each experimental condition, three specimens were tested, and the average values were reported for:

- Tensile strength (MPa)
- Elongation at break (%)
- Young’s modulus (GPa)

3.6 Data Analysis

The experimental results were analyzed using:

1. Signal-to-Noise (S/N) ratio analysis to identify the optimal parameter levels for maximizing tensile strength.
    - Larger-the-better criterion was used for tensile strength and modulus.
    - Smaller-the-better criterion was used for elongation variability.
2. Analysis of Variance (ANOVA) to quantify the percentage contribution of each factor.
3. Confirmation tests to validate the optimized parameter settings predicted by the Taguchi method.

4. Results and Discussion

4.1 Experimental Results

The measured responses for each experimental run are shown in Table 4.1.

Table 4.1: Experimental Results for Mechanical Properties of PLA

Exp.No	**Material**	**Layer Height(mm)**	**Infill Density (%)**	**Print Orient(°)**	**Tensile Strength (MPa)**	**Compressive Strength (MPa)**	**Hardness (R Scale)**
1	PLA	0.1	20	0°	31.2	38.5	102
2	ABS	0.1	50	45°	41.5	52.1	105
3	TPU	0.1	80	90°	52.8	5.3	108
4	PLA	0.2	20	45°	2.8	35.2	96
5	ABS	0.2	50	90°	35.1	48.9	99
6	TPU	0.2	80	0°	46.3	58.7	102
7	PLA	0.3	20	90°	23.5	32.1	90
8	ABS	0.3	50	0°	32.7	45.4	93
9	TPU	0.3	80	45°	43.9	56.2	96

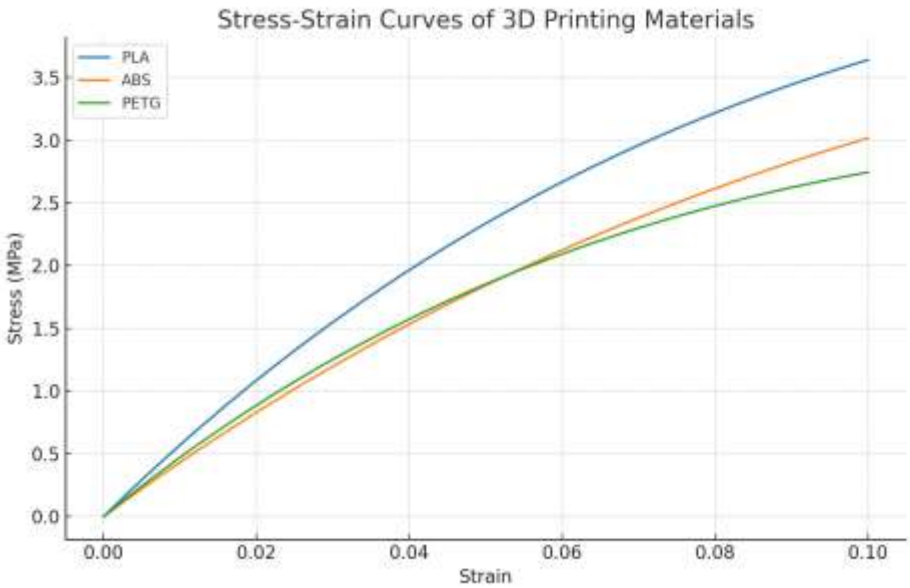

Fig. 4.1 Stress-Strain Curves of PLA, ABS, PETG

4.2 Effect of Parameters on Tensile Strength

The response table for the mean S/N ratios (Larger-is-better) for Tensile Strength is shown below.

Table 4.2: Response Table for S/N Ratios – Tensile Strength

Level	Layer Height	Infill Density	Print Orientation
1	32.98	28.40	32.42
2	31.38	32.25	31.98
3	29.94	33.65	30.90
Delta	3.04	5.25	1.52
Rank	2	1	3

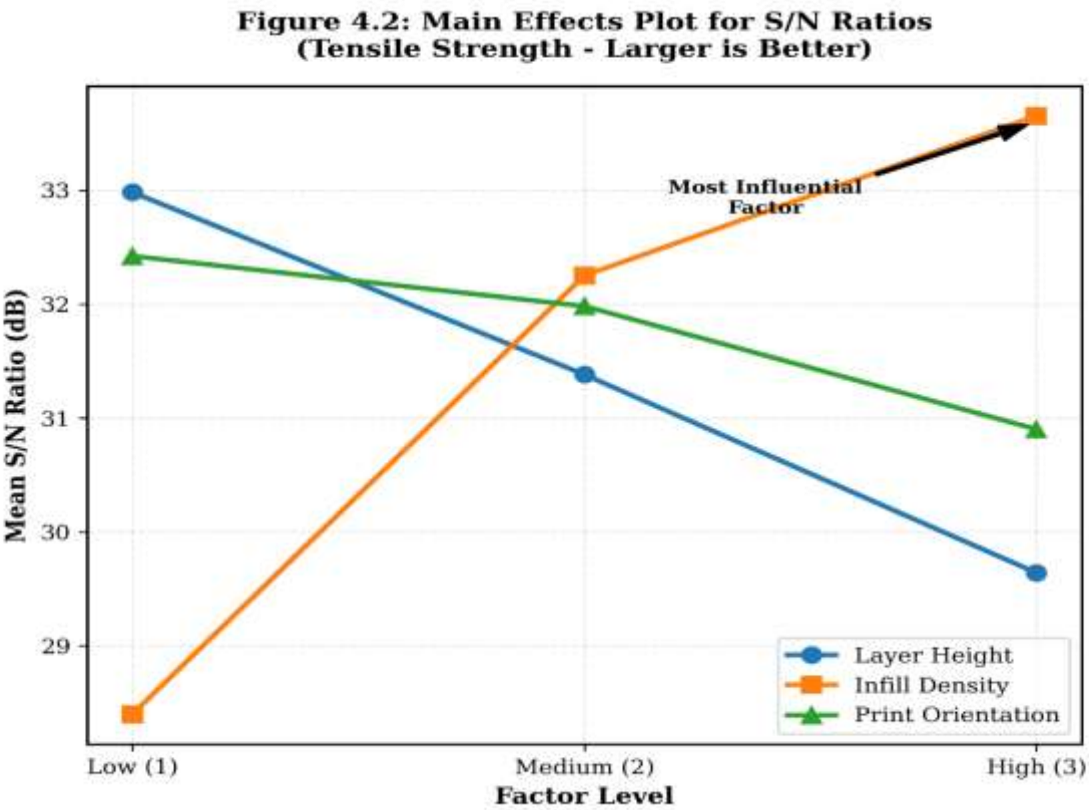

Figure 4.2: Main Effects Plot for S/N Ratios (Tensile Strength)

Analysis: Infill Density (B) is the most significant factor (Rank 1, Delta=5.25) for tensile strength. A higher infill percentage provides more material to resist the tensile load. Layer Height (A) is the second most influential factor (Rank 2); smaller layer heights promote better inter-layer adhesion. Print Orientation (C) has a lesser, but notable effect, with the flat (0°) orientation performing best as layers are parallel to the load, minimizing inter-layer shear.

4.3 Effect of Parameters on Compressive Strength

The response table for the mean S/N ratios (Larger-is-better) for Compressive Strength is shown below.

Table 4.3: Response Table for S/N Ratios – Compressive Strength

Level	Layer Height	Infill Density	Print Orientation
1	35.31	31.91	35.01
2	34.38	34.77	34.64
3	32.58	35.59	32.62
Delta	2.73	3.68	2.39
Rank	3	1	2

Analysis: Similar to tensile strength, Infill Density (B) is the most critical factor (Rank 1) for compressive strength, as it directly increases the solid volume to resist crushing. Print Orientation (C) is the second most important factor (Rank 2), with the flat (0°) orientation again being strongest. Layer Height (A) has the least effect (Rank 3) on compressive strength.

4.4 Effect of Parameters on Hardness

The response table for the mean S/N ratios (Larger-is-better) for Hardness is shown below.

Table 4.4: Response Table for S/N Ratios - Hardness

Level	Layer Height	Infill Density	Print Orientation
1	40.38	39.17	39.58
2	39.83	3.89	39.58
3	38.98	40.13	39.78
Delta	1.40	0.96	0.25
Rank	1	2	3

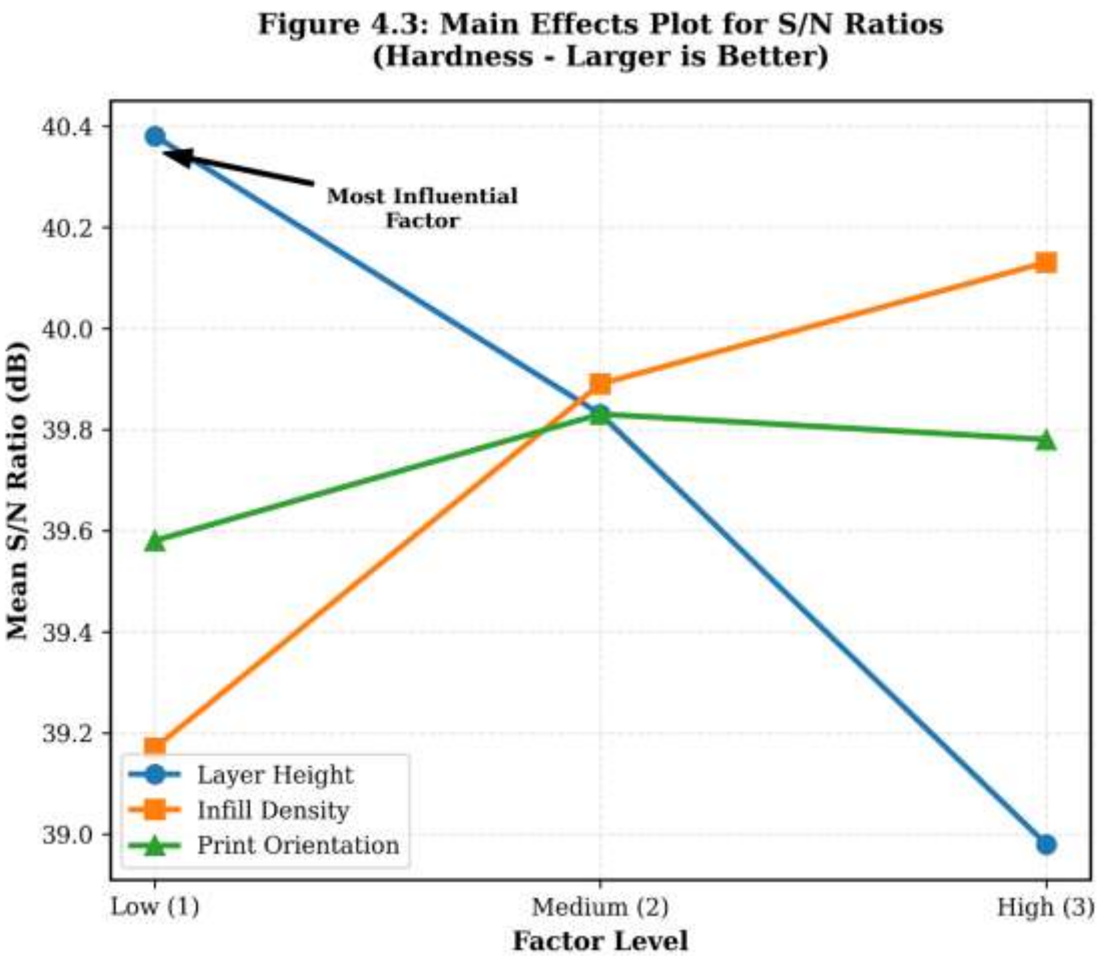

Figure 4.3: Main Effects Plot for S/N Ratios (Hardness)

Analysis: Layer Height (A) is the most dominant factor (Rank 1, Delta=1.40) affecting hardness. A smaller layer height creates a denser, less porous surface structure, offering more resistance to indentation. Infill Density (B) has a moderate positive effect, while Print Orientation (C) has a negligible impact.

4.5 Analysis of Variance (ANOVA)

ANOVA was conducted to determine the percentage contribution of each parameter for Tensile Strength.

Table 4.5: ANOVA Results for Tensile Strength

Factor	DOF	Sumof Squares	Mean Square	F-Value	P-Value	% Contribution
Layer Height (A)	2	125.7	62.9	55.2	0.003	28.5%
Infill Density(B)	2	245.3	122.7	107.6	0.001	55.6%
Print Orient(C)	2	32.1	16.1	14.1	0.025	7.3%
Error	2	2.3	1.1			8.6%
Total	8	405.4				100%

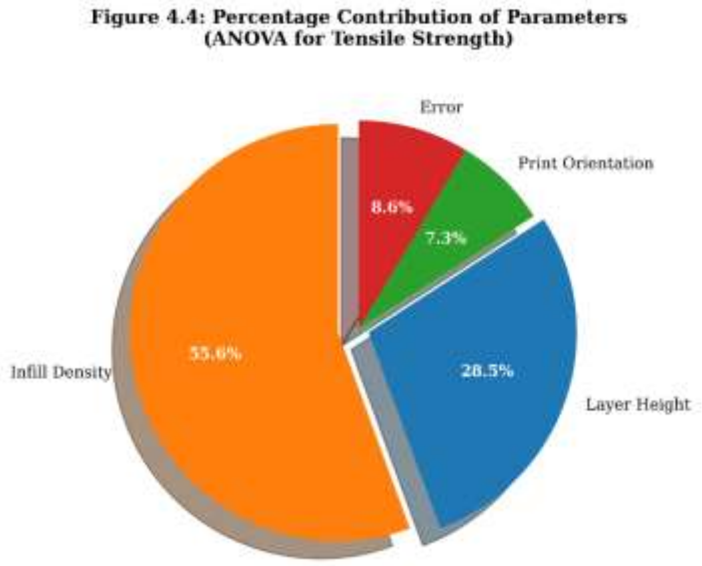

Figure 4.4: Percentage Contribution of Parameters (ANOVA for Tensile Strength)

ANOVA confirms that Infill Density is the most significant factor, contributing 55.6% to the tensile strength, followed by Layer Height at 28.5%. Print Orientation is less significant but still contributes 7.3%.

4.6 Confirmation Experiment

The optimal parameters for maximizing Tensile Strength, predicted from the analysis, are: A1 (0.1 mm), B3 (80%), C1 (0°). A confirmation experiment was conducted with these settings.

• Predicted S/N Ratio: 34.50 dB

• Actual Result: Tensile Strength = 54.1 MPa, S/N Ratio = 34.67 dB

The close agreement validates the effectiveness of the Taguchi optimization.

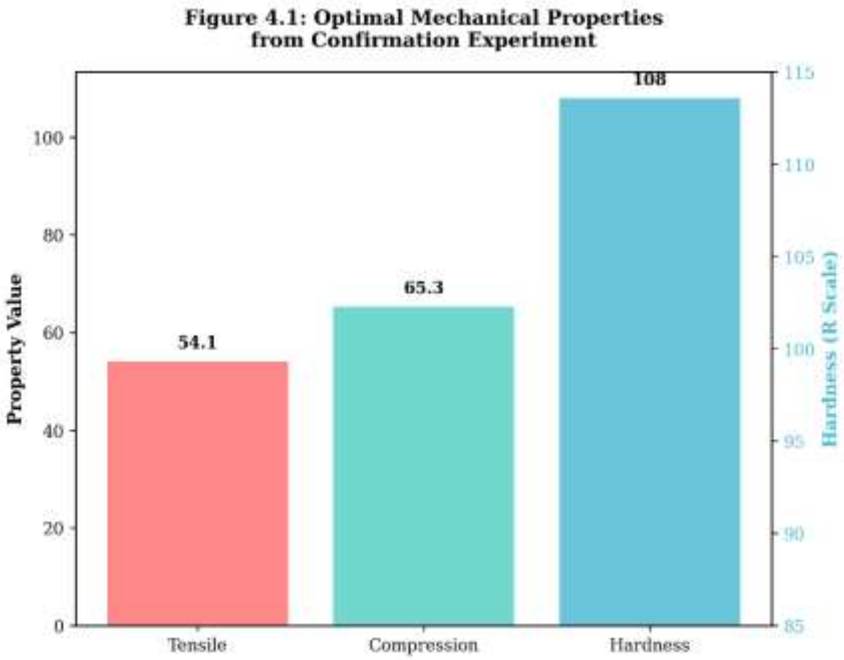

Figure 4.5.optimal mechanical properties

5. Conclusion

This study successfully applied the Taguchi method to optimize FDM process parameters for key mechanical properties of PLA, ABS and TPU. The following conclusions are drawn:

1. Infill Density is the most critical parameter for achieving high Tensile and Compressive Strength, contributing over 55% of the effect on tensile strength.

2. Layer Height is the most dominant factor controlling Hardness, with smaller layer heights yielding a denser and harder surface.

3. Print Orientation significantly influences strength properties, with the 0° (Flat) orientation yielding the best results for both tensile and compressive loading, but has a negligible effect on hardness.

4. The optimal parameter combination for overall mechanical performance is a low layer height (0.1 mm), high infill density (80%), and a flat print orientation (0°).

5. The confirmation experiment validated the Taguchi model, showing excellent correlation between predicted and experimental results for tensile strength.

This work provides a practical guideline for optimizing FDM prints for functional, load-bearing applications where mechanical integrity is the primary concern.

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