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Original Article

Mechanical Behavior of FDM-Printed CF-Nylon/Nylon Hybrid Composites: A Taguchi L27 Orthogonal Array Study

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Abstract *- Dual-material additive manufacturing is a feasible approach for fabricating composite structures that combine the advantages of two materials within a single printed component. This study investigates a 1:1 layered composite of Carbon Fiber Reinforced Nylon (CF-Nylon) and Nylon produced using the material extrusion process. The influence of five key printing conditions, namely Thickness of Layers, Print Speed, Nozzle Temperature, Shell Layers, and Bed platform Temperature, on the mechanical properties of the hybrid composites is evaluated using a Taguchi L27 orthogonal array. Tensile strength and Yield strength are measured using a Universal Testing Machine. The results show that the mechanical response of the layered structure is strongly influenced by the selected print conditions. The maximum tensile strength among the investigated conditions was 34.94± 0.39 MPa. Taguchi signal-to-noise ratio analysis and ANOVA of the tensile-strength data identify layer thickness as the main parameter, contributing to 54.31% of the total variation in tensile strength, and as the only statistically significant factor. The study demonstrates that appropriate selection of extrusion parameters enhances the mechanical performance of Nylon/ CF-Nylon layered composites. These findings provide useful guidelines for optimizing dual-material additive manufacturing processes and support the application of hybrid polymer composites in engineering components requiring improved mechanical performance.*

Keywords *- Carbon Fiber Reinforced Nylon (CF-Nylon), Hybrid composites, Material extrusion, Mechanical properties, Tensile strength.*

1. Introduction

In the aerospace, automotive, and biomedical sectors, Additive Manufacturing (AM) has been widely employed to fabricate complex geometries while significantly reducing material waste. Fused Deposition Modelling (FDM) is a popular AM technique, because it is easy to use, low in cost, and can work with a wide range of thermoplastics [1, 5]. Neat Nylon exhibits high toughness and flexibility but relatively low stiffness and strength, whereas Carbon-fiber-reinforced Nylon offers superior stiffness and strength at the expense of toughness and flexibility [1, 6].

Hybrid printing makes use of the complementary properties of both materials within a single printed part. Previous studies have focused on improving the reinforcement structure and printing conditions in a single material [1-3], rather than on the deliberate pairing of two different materials (neat Nylon and CF-Nylon) within one part. Although multi-material FDM has been investigated for other material combinations, the effect of key FDM processing parameters on the tensile properties and interface of a Nylon/ CF-Nylon hybrid structure has not been systematically investigated. Evaluating the tensile response, identifying suitable parameter levels within the studied range, assessing the relative influence of the parameters using ANOVA, and discussing the possible factors affecting the observed trends are the specific objectives of this study. The contribution of this work lies in experimentally establishing the tensile response and relative influence of selected FDM processing parameters for a 1:1 CF-Nylon/Nylon layered structure.

In this configuration, the effects of the investigated parameters on tensile performance are evaluated using ANOVA, and the observed tensile trends are discussed in relation to the possible influence of the interface between the two dissimilar layers. Thus, this study provides insight into a relationship between the process-property for a Nylon/CF-Nylon system and addresses a less- explored aspect of multi-material FDM.

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2. Literature Review

In response to demand for lighter and stronger components, research on additively manufactured fiber-reinforced polymer composites has grown rapidly. El Essawi et al. [1] reported that orientation of fiber and density affect the tensile performance of continuous CF-Nylon, while Radzuan et al. [3] and Sanei and Popescu [5] reported that mechanical properties get better with fiber reinforcement.

Printing conditions also have an important role in determining the mechanical behavior of FDM composites. Moradi et al. [4] found that extrusion temperature and speed of printing affect the flow of polymer and bonding within CF-Nylon layers, with excessive temperature causing material degradation. Haque et al. [9] similarly reported significant role of layer thickness, nozzle speed while printing, and material selection on mechanical response.

The quality of the microstructure of the material is related to the variations in deposition conditions. Microstructural studies further identified porosity, misalignment of fiber, and weaker filament interfaces as major causes of reduction in strength and premature failure [6, 8]. D'Andrea et al. [2] also demonstrated that appropriately made CF-Nylon can exhibit desirable fatigue performance. These findings indicate that mechanical performance is governed by the combined effects of fiber distribution, processing variables and manufacturing-induced defects.

While considerable research has focused on single-material and fiber-reinforced systems, multi-material fused modelling introduces additional challenges associated with bond integrity between dissimilar materials. Rasheed et al. [13] demonstrated the usefulness of Taguchi optimization to bi-layered PLA-ABS structures, whereas Richter and Wu [14] showed that adhesion in different thermoplastics depends strongly on the material combination. These findings highlight the importance of investigating the hybrid structures as a whole rather than considering the constituent materials independently. Anand Sankar et al. [7] and Clarke et al. [10] further demonstrated that fiber architecture and fiber-matrix interaction can substantially govern the mechanical response of additively manufactured composites.

Since print parameters can control material deposition, defects, and mechanical behavior, statistical optimization approaches provide an effective means of identifying influential parameters and suitable processing conditions. The Taguchi method uses orthogonal experimental designs and signal-to-noise value to evaluate the effects of many factors [11]. Ahmad et al. [12] demonstrated the usefulness of the Taguchi method for improving FDM parameters in oil-palm-fiber-reinforced thermoplastic composites, while Rasheed et al. [13] applied a it to a bi-layered system. These studies establish the suitability of Taguchi methodology for both reinforced polymer composites and layered multi-material structures. However, the trend observed for other material systems cannot necessarily be transferred to CF-Nylon/Nylon because carbon-fiber reinforcement introduces additional effects related to fiber distribution

Despite the extensive research on Fused-fabricated Nylon, Carbon-fiber-reinforced polymers, parameter optimization, and multi-material additive manufacturing, limited attention has been given to these layered structures combining CF-Nylon and unreinforced Nylon. Most existing CF-Nylon studies have focused on single-material components, while dual-material studies have mainly examined combinations such as PLA-ABS or other dissimilar thermoplastics. As a result, the role of print conditions on the behavior of Nylon/ CF-Nylon layered structures under tension remains insufficiently understood. In particular, the combined effects of layer thickness, printing speed, extrusion temperature, shell layer and bed temperature on the tensile performance of this system have not been systematically established. Therefore, the present study addresses this gap by employing a L27 experimental design to determine the tensile response and relative influence of process variables and evaluate their effects on the tensile performance of Nylon/ CF-Nylon layered components.

3. Materials and Methods

3.1. Materials

SUNLU PA12-CF filament containing 20% Carbon and neat Nylon filaments, each of diameter - 1.75 mm were used as the feedstock material for the study. A fixed 1:1 layer ratio was maintained throughout the fabrication. Both the filaments were dried before printing to reduce the effect of absorbed moisture on the print quality. The dried filaments were stored in airtight containers with desiccants between printing sessions to prevent moisture absorption.

3.2. Specimen Design and Fabrication

The tensile-specimens were designed using SolidWorks, as per the ASTM D638 standard, and then sliced with Simplify3D. Fabrication was performed using an AKAR 600 PRO FDM printer that supports dual extrusion. It was equipped with a 0.6 mm nozzle for printing both CF-Nylon and Nylon specimens. Layer thickness of 0.20, 0.30, and 0.36 mm were taken at 100% infill density. Printed parts were allowed to cool naturally.

The specimen thickness was 3.60 mm. Varying the thickness of layers changed the number of deposited layers. However, the alternating layer sequence was maintained throughout the specimen thickness, with one Nylon layer followed by one CF-Nylon layer. They were fabricated in a horizontal orientation, with their longitudinal axis parallel to the build platform. Each of the 27 experimental conditions

had three test specimens produced, thus providing repeatability and statistical reliability of results. The specimen's geometry is depicted in Figure 1, the dual-extrusion fabrication process is shown in Figure 2, and the fabricated hybrid specimens are shown for the various parameter combinations in Figure 3.

3.3. Selection of Process Parameters

Key findings from the literature survey indicate that Print Speed and Thickness of Layers affect the material deposition rate and layer bonding, respectively [5, 9]. Nozzle Temperature governs the viscosity and adhesion between composite layers [4, 5], while temperature of bed contributes to dimensional stability [5, 9]. Therefore, five parameters-Nozzle Temperature (NT), Bed platform Temperature (BT), Number of Shell Layers (SL), Print Speed (PS), and Thickness of Layer (LT)-were selected for the study. Three distinct levels were considered for each parameter, as shown in Table 1.

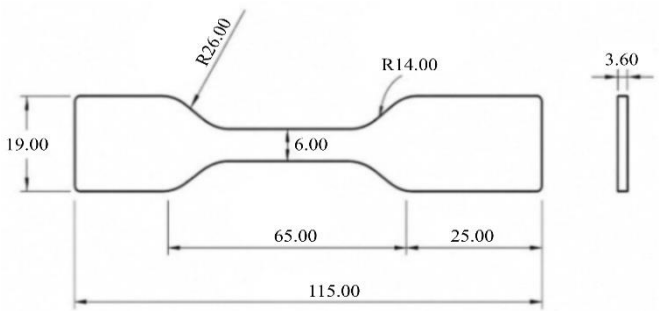


Fig. 1 Tensile specimen geometry designed in accordance with ASTM D 638. All dimensions are in mm.



Fig. 2 Dual-Extrusion fabrication of hybrid CF-Nylon/Nylon composite specimens on the AKAR 600 PRO FDM printer

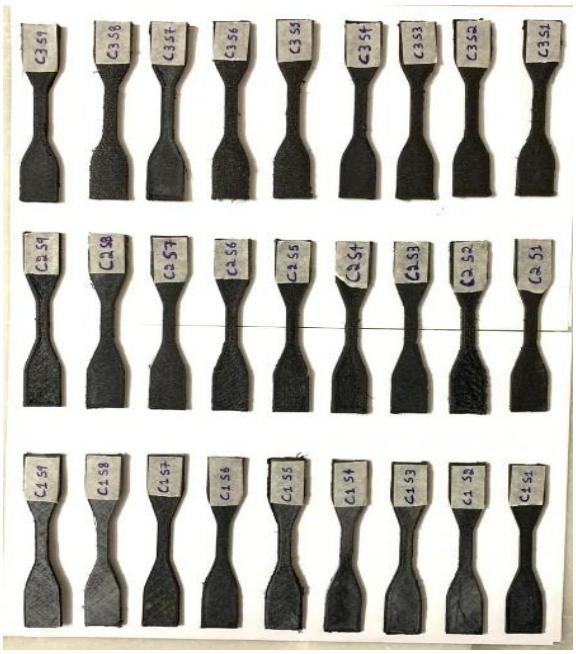


Fig. 3 Fabricated CF-Nylon/Nylon tensile specimens

Table 1. Process conditions and levels used in the Taguchi L27 design

Conditions	1st Level	2nd Level	3rd Level
LT (mm)	0.20	0.30	0.36
PS (mm/s)	55	60	65
NT (CF-Nylon/Nylon) (°C)	245/230	250/235	255/240
SL	2	3	4
BT (°C)	90.0	95.0	100.0

3.4. Taguchi Design of Experiments

An L27 array was used to determine the effect of five experimental conditions on the tensile properties of the hybrid composites in a structured manner. Using the Taguchi method, multiple factors can be studied, with fewer experimental runs than required by a full factorial design. This is suitable for multi-parameter optimization [11, 12]. To increase the reliability of the results, all three specimens that were fabricated for each run were tested.

The best parameter combination and the ranks of each parameter were identified by Signal to Noise (S/N) analysis according to the larger is better concept. The experimental results were then subjected to an ANOVA, to evaluate the Sum of the Squares (SS), Degrees of Freedom (DOF), Mean-Square (MS), F value, p value and contribution percentage of each factor associated with tensile strength.

3.5. Mechanical Testing

The mechanical testing was done using a Universal Testing Machine (UTM) (TTS Industrial Solutions & Test Tek-100 kN / HK-2B-100 kN) as per ASTM D638 standards as illustrated in Figure 4. Tensile- Strength (TS), and Yield-Strength (YS) were used as response variables.

3.6. Experimental Results

The data from the 27 experimental runs are shown in Table 2. Results are represented in the form of mean ±Standard Deviation (SD). This result was further analyzed by Taguchi techniques, and the findings are discussed in the following sections.

4. Results and Discussion

4.1. Mechanical Performance

The Tensile Strength varied between 22.50 ± 0.57 MPa (Run 8) and 34.94 ± 0.39 MPa (Run 25), while the yield strength ranged from 15.42 ± 0.32 MPa to 27.61 ± 0.88 MPa. A representative stress–strain curve for one specimen from Run 26 is shown in Figure 5. The wide spread indicates that the mechanical characteristics of Nylon/ CF-Nylon depends on the processing conditions selected. The highest tensile value of strength was obtained in Run 25 (LT = 0.36 mm, PS = 65 mm/s, NT = 250/235°C, SL = 2, BT = 90°C). The effect of individual -parameters on these properties is discussed in subsequent sections.



Fig. 4 Universal Testing Machine (UTM) setup used for tensile testing of hybrid CF-Nylon/Nylon specimens in accordance with ASTM D638

4.2. Effect of Processing Conditions

4.2.1. Thickness of Layers

The Thickness of Layers exhibited the most pronounced impact on tensile strength among the investigated parameters. The mean tensile strength was 26.86 MPa at 0.20 mm, which decreased slightly to 26.23 MPa at 0.30 mm, and increased to 31.25 MPa at 0.36 mm.

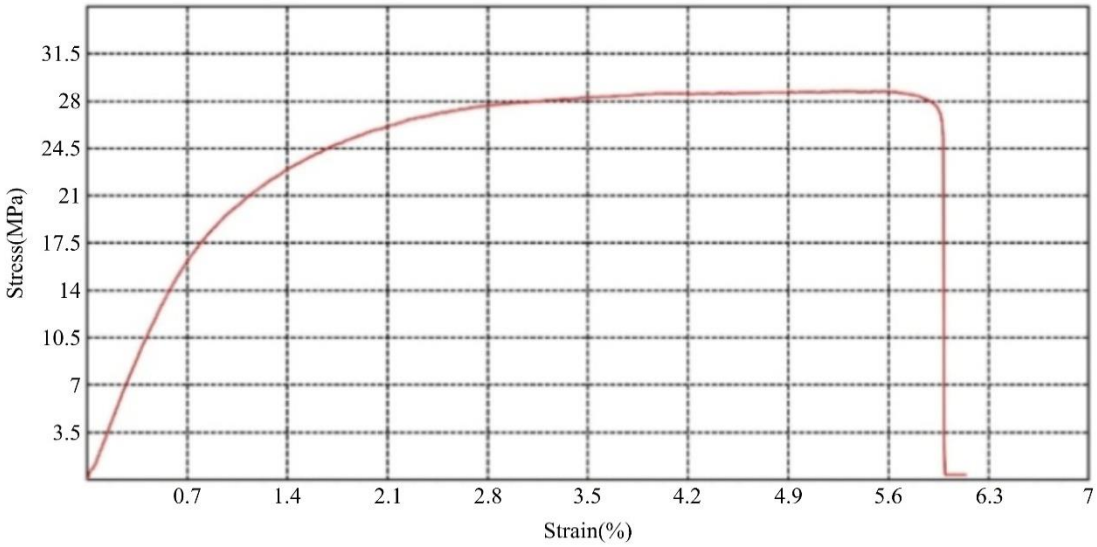


Fig. 5 Representative stress-strain curve of a specimen from run 26

4.2.2. Nozzle Temperature

The nozzle temperature (245/230°C for CF-Nylon/Nylon) yielded the highest average tensile strength among the investigated levels. The mean tensile strength was 28.53 MPa at 245/230°C, 28.26 MPa at 250/235°C and 27.54 MPa at 255/240°C. The differences between the temperature settings were relatively small.

4.2.3. Print Speed

In comparison to thickness, the Print Speed had a comparatively minor effect on tensile strength.

Strength variations were noted at the different printing speeds investigated, but they were not as prominent.

4.2.4. Shell Layers

Shell layers showed a relatively small variation in tensile strength compared with layer thickness. The mean tensile strength was 28.68 MPa for two shell layers, decreased to 27.36 MPa for three shell layers, and increased slightly to 28.08 MPa for four shell layers. The highest mean tensile strength was obtained at two shell layers. The S/N ratio response also indicated two shell layers as the preferred level.

4.2.5. Bed Platform Temperature

Bed platform Temperature showed variation in tensile strength within the investigated range. The mean tensile strength was 28.10 MPa at 90°C, increased to 28.70 MPa at 95°C, and decreased to 27.53 MPa at 100°C. The S/N response also showed the highest value at 95°C, indicating this as the preferred bed temperature level.

4.3. Taguchi S/N Ratio Analysis

The response tables for Tensile Strength (see Figure 6) and Yield Strength (see Figure 7) present the average S/N ratios, mean values at each parameter level, delta values, and parameter rankings. The mean tensile-strength plot (Figure 8) and the S/N plot for yield strength (Figure 9) illustrate the variation in the responses across the three levels of each process parameter. The response tables and plots consistently showed that thickness of layer was the most significant factor for both tensile and yield strength, with a delta rank of 1 for both of these analyses. Overall, the results indicate that thickness of the printed layers is the dominant variable affecting the tensile characteristics of the specimens. From the S/N criterion, the predicted combination set for maximizing strength was LT = 0.36 mm, PS = 60 mm/s, NT = 245/230°C, SL = 2, and BT = 95°C. This combination was found by choosing the levels with the highest average S/N values and it does not correspond to an individual experimental trial in the L27 orthogonal array. The highest experimentally observed tensile strength was obtained in Run 25 (34.94 ± 0.39 MPa), which differed from the predicted optimum combination. Based on the mean tensile-strength values at the selected combinations of the five FDM factors, the predicted strength was estimated to be 33.25 MPa. A validation experiment using three specimens at the selected parameter combination yielded a tensile strength of 35.21 ± 0.48 MPa, giving a prediction error of 5.91%.

S/N Ratio Response Analysis Table					
Larger the better					
Level	**LT**	**NT**	**PS**	**SL**	**BT**
1	28.56	29.08	28.84	29.09	28.92
2	28.35	28.97	29.06	28.85	29.11
3	29.88	28.74	28.88	28.84	28.75
Delta	1.52	0.34	0.22	0.25	0.36
Rank	1	3	5	4	2
Mean value Response Table					
Level	**LT**	**NT**	**PS**	**SL**	**BT**
1	26.86	28.53	27.82	28.68	28.10
2	26.23	28.26	28.53	27.36	28.70
3	31.25	27.54	27.98	28.08	27.53
Delta	5.02	0.99	0.71	1.32	1.17
Rank	1	4	5	2	3

Fig. 6 Taguchi table for S/N and means for Tensile Strength (TS) versus LT, NT, PS, SL, and BT

S/N Ratio Response Analysis Table					
Level	**LT**	**NT**	**PS**	**SL**	**BT**
1	26.15	26.58	26.16	26.52	26.34
2	25.50	26.33	26.45	26.33	26.44
3	27.53	26.27	26.57	26.34	26.41
Delta	2.03	0.32	0.41	0.19	0.10
Rank	1	3	2	4	5
Mean value Response Table					
Level	**LT**	**NT**	**PS**	**SL**	**BT**
1	20.37	21.39	20.58	21.42	20.84
2	18.92	20.97	21.12	20.83	21.18
3	23.84	20.78	21.43	20.88	21.11
Delta	4.92	0.61	0.85	0.59	0.33
Rank	1	3	2	4	5

Fig. 7 Taguchi table for S/N and means for Yield Strength (YS) versus LT, NT, PS, SL, and BT

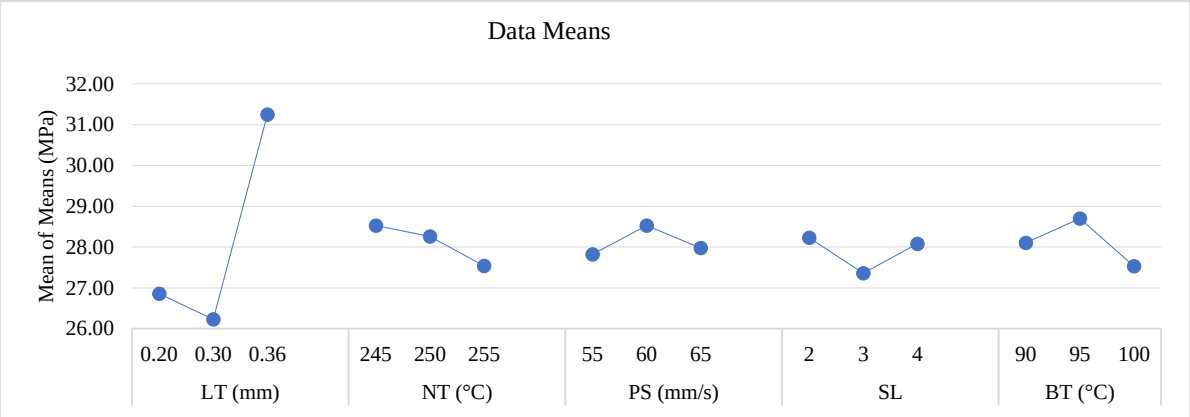


Fig. 8 Mean tensile-strength plot showing the influence of each process parameter across three levels

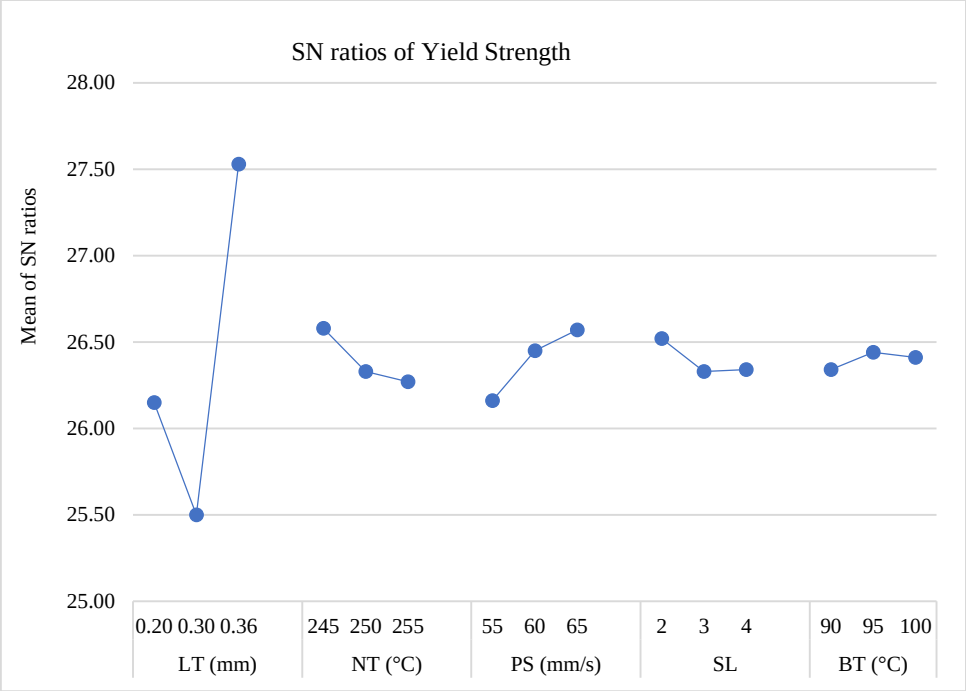


Fig. 9 S/N ratio plot for yield strength showing the influence of each process parameter across three levels

Table 2. Tensile properties of CF-Nylon/Nylon hybrid composites from the Taguchi L27 experimental design

Run	LT (mm)	PS (mm/s)	NT (°C) CF-Nylon/Nylon	SL	BT (°C)	TS (MPa)	YS (MPa)
1	0.20	55	245/230	2	90	28.73 ±0.38	21.00 ±0.82
2	0.20	55	245/230	3	95	26.79 ±0.42	19.31 ±0.58
3	0.20	55	245/230	4	100	26.31 ±0.26	20.46 ±0.38
4	0.20	60	250/235	2	95	28.61 ±0.55	21.11 ±0.96
5	0.20	60	250/235	3	100	29.57 ± 0.71	23.37 ±0.73
6	0.20	60	250/235	4	90	26.47 ± 0.47	20.06 ±0.21
7	0.20	65	255/240	2	100	26.29 ± 0.66	21.10 ±0.31
8	0.20	65	255/240	3	90	22.50 ±0.57	17.39 ±0.52
9	0.20	65	255/240	4	95	26.44 ±0.32	19.53 ±0.66
10	0.30	55	250/235	2	100	23.40 ±0.92	15.42 ±0.32
11	0.30	55	250/235	3	90	26.36 ±0.86	18.65 ±0.79
12	0.30	55	250/235	4	95	25.27 ±0.35	17.63 ±0.75
13	0.30	60	255/240	2	90	27.24 ±0.75	19.46 ±0.25
14	0.30	60	255/240	3	95	28.73 ±0.69	18.84 ±0.19
15	0.30	60	255/240	4	100	23.13 ±0.28	17.92 ±0.59
16	0.30	65	245/230	2	95	26.21 ±0.46	19.90 ±0.36
17	0.30	65	245/230	3	100	28.42 ±0.78	21.09 ±0.26
18	0.30	65	245/230	4	90	27.28 ±0.29	21.41 ±0.97
19	0.36	55	255/240	2	95	32.80 ±0.64	27.61 ±0.88
20	0.36	55	255/240	3	100	30.09 ±0.58	22.87 ±0.52
21	0.36	55	255/240	4	90	30.63±0.39	22.32 ±0.66
22	0.36	60	245/230	2	100	29.87 ±0.27	22.75 ±0.69
23	0.36	60	245/230	3	90	28.73 ±0.62	22.92 ±0.31
24	0.36	60	245/230	4	95	34.44 ±1.02	23.64 ±0.85
25	0.36	65	250/235	2	90	34.94 ±0.39	24.42 ±0.76
26	0.36	65	250/235	3	95	29.01 ±0.45	23.05 ±0.42
27	0.36	65	250/235	4	100	30.72 ±0.76	25.01 ±0.92

4.4. ANOVA Results

ANOVA was performed using the tensile-strength measurements of all 81 specimens as shown in Table 3. LT was the dominant and only statistically significant factor ($F = 49.411$, $p < 0.001$) contributing 54.31% of the total variation. NT, SL, and BT were not statistically significant ($p > 0.05$), while PS was pooled with the error term because its F-value was below 1. The pooled error accounted for 39.57% of the total variation. The replicate measurements allowed pure error and lack of fit to be assessed separately. The Taguchi S/N analysis was used to identify parameter levels within the investigated range.

LT, which had the largest S/N delta, was identified as the dominant parameter. The conclusions are limited to the parameter ranges investigated.

4.5. Future Scope

Future work will include Scanning Electron Microscopy (SEM) or optical microscopy to examine the fracture surfaces, voids, and interfacial bonding between the CF-Nylon and Nylon layers.

Future studies may use RSM or similar methods to study parameter interactions and develop predictive models.

Table 3. ANOVA results for tensile strength of CF-Nylon/Nylon hybrid composites

Parameter	DOF	SS	MS	F value	p value	% Contribution (each factor)
LT	2	404.076	202.038	49.411	<0.001	54.31
NT	2	14.214	7.107	1.738	0.183	1.91
SL	2	13.023	6.512	1.592	0.211	1.75
BT	2	18.369	9.185	2.246	0.113	2.47
Pooled error (PS+ residual)	72	294.401	4.089			39.57
Total	80	744.082				100

5. Conclusion

This study investigated the effects of five FDM process parameters -Thickness of Layers, Print Speed, Nozzle Temperature, Shell Layers, and Bed platform Temperature - on the tensile behaviour of CF-Nylon/Nylon hybrid composites using a Taguchi L27 orthogonal array. Tensile Strength ranged from 22.50 ±0.57 to 34.94±0.39 MPa and Yield Strength from 15.42 ±0.32 to 27.61 ± 0.88 MPa across the experimental runs.

ANOVA and S/N ratio analyses identified Layer Thickness as the key factor, accounting for 54.31% of the variation in tensile strength. The selected parameter combination (LT = 0.36 mm, PS = 60 mm/s, NT = 245/230°C, SL = 2, BT = 95°C) gave a predicted tensile strength of 33.25 MPa, which was confirmed experimentally at 35.21 ± 0.48 MPa corresponding to a prediction error of 5.91%.

Overall, the results demonstrate the importance of Thickness of Layers in controlling the tensile performance of the investigated CF-Nylon/Nylon layered configuration within the studied parameter ranges.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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