

Optimization of FFF Process Parameters for Tensile and Flexural Performance of ABS/Graphene Nanocomposites

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Abstract

Additive manufacturing, specifically fused filament fabrication (FFF), has transformed the manufacture of complex thermoplastic components. Melt blending and extrusion were used to prepare ABS/GNP composite filaments with different concentrations (0.5, 1 and 1.5 wt). The key parameters such as the layer thickness, build orientation, infill pattern, and infill density. Performance was determined by the use of mechanical testing as per the ASTM standards. The findings indicate that 1 wt% GNP is optimal in terms of mechanical properties. The combination of parameters, that is the 0.19 mm layer thickness, on-long-edge orientation, grid infill pattern, and 90% infill density, yielded the highest tensile and flexural strengths of 40.1 MPa and 56.9 Mpa, respectively, with the prediction error of less than 3%. ANOVA was used to determine that infill density (36.8%) was the most significant strength determining factor.

Keywords: Fused filament fabrication; Graphene Nano platelets; Tensile strength; Flexural strength; Taguchi method.

1. Introduction

Additive manufacturing has become a significant technology in contemporary engineering [1-3]. However, standard ABS parts manufactured through FFF generally exhibit anisotropic mechanical properties, weak layer bonding, and limited structural performance [4, 5]. Mechanical properties of FFF-printed parts are very dependent on the choice of process parameters [6-9]. Defects that can be caused by improper parameter selection include voids, poor interlayer adhesion and dimensional errors, which eventually affect tensile and flexural performance [10, 11].

The optimization of the FFF process parameter is important in additive manufacturing to improve the tensile and flexural properties of the ABS/graphene nanocomposite. Several researchers have indicated that both the composition of a material and the condition in which it is processed can greatly influence its ultimate performance. Joynal et al. (2021) [12] & Chowdhury et al. (2023) [13] showed that adding graphene improved the strength of the material. Tambrallimath et al. (2021) [14] & Bhaskar et al. (2022) [15] found that by adding graphene to the matrix, there was a significant increase in both tensile and flexural properties compared to those of the composite without graphene. Wang et al. (2021) [16] reported considerable improvement in flexural performance by using functionalized GNPs. Research conducted by ZISOPOL et al. (2022)[17] and Tyagi et al. (2023)[18] have also focused on the process parameters that influence the combination of the polymer and graphene. Bashir et al. (2024) [19], TG et al. (2025) [20] have demonstrated that adding graphene at loadings greater than 1 wt% actually contributed to the brittleness of the end product.

2. Materials and Methods

Materials: ABS reinforced with GNP was used as the basic material of the test specimens in this study. Table 2 lists the graphene nanoplatelets manufacturer-provided specifications.

Table 2: Graphene Nonoplatelets Specifications (Manufacturer’s Datasheet)

Specification	Value	Unit
Thickness	6–8	nm
Lateral Size	5 (± 3%)	µm
Avg. No. of Layers	1–3	-
Purity	99.5	%
Density	2.3	g/cm ³

3.1 Preparation of ABS/GNP Composite Filament: A melt blending and extrusion procedure was used to prepare the ABS/graphene nanoplatelet composite filament. The weight percentages of GNP (0.5wt, 1wt, and 1.5wt) required were first dry-mixed using a mechanical mixer to achieve preliminary dispersion with pellets of ABS. A single-screw extruder was then used to process the mixture at a temperature of between 220 and 240°C.

3.2 Process Parameters and Experimental Design: Based on their impact on mechanical qualities, four crucial fused filament fabrication (FFF) process parameters were chosen: Thickness of layer (LT),Construct orientation (O) ,Pattern of infill (IP) ,Density of infill (ID). Table 3 illustrates the three levels at which each parameter was examined.

Table 3: Process Parameters and Their Levels

Parameter	Level 1	Level 2	Level 3
Layer Thickness (mm)	0.19	0.29	0.39
Orientation	Flat	On Long Edge	On Short Edge
Infill Pattern	Linear	Grid	Honeycomb
Infill Density (%)	50	70	90

A Taguchi L27 orthogonal array was used to design the experiments to enable a systematic study of the effects of the parameters with reduced experimental runs. To provide uniformity and reproducibility, all the experiments are maintained in critical printing parameters. The parameters are as follows (as seen in Table 4):

Table 4 :Fixed Printing Parameters Used for Specimen Fabrication

Parameter	Value	Remarks
Nozzle Temperature	240 ± 5	Optimized for proper melting of ABS/GNP composite
Bed Temperature	90 ± 5	Ensures good adhesion and reduces warping
Printing Speed	50	Maintains balance between quality and build time
Nozzle Diameter	0.4	Standard nozzle size
Filament Diameter	1.75 ± 0.05	Maintained during extrusion
Cooling Fan Speed	50	Applied after initial layers
Raster Angle	±45	Default setting for balanced strength

These parameters were selected based on preliminary trials and literature recommendations to ensure proper melting, extrusion stability, and interlayer bonding of ABS/GNP composites.

3.3 Specimen Fabrication: Each specimen was 3D printed on a Creality K2 Plus FFF 3D printer with a filament drying mechanism to control the amount of moisture content in the material during printing, as shown in figure 3(a). The printing process was carried out under well-observed conditions to ensure a consistency in the quality of the specimens. Three upper layers and three lower layers ,Two wall loops (perimeters) ,Improved bonding with regulated filament drying



Figure 1: (a) ABS Creality K2 Plus 3D printer with multi-filament CFS unit; (b) ASTM D638/D7209 tensile specimens fabricated using graphene-reinforced

3.4 Mechanical Testing

There were three repetitions (n = 3) of each experimental condition to make it repeatable and statistically reliable. Standard testing methods were used to assess the mechanical performance of manufactured specimens, as seen in fig. 2(b):

Table 5: Tensile Test & Flexural Test Results

Sr. No.	Tensile Strength				Flexural Strength			
	Pure ABS	Graphene 0.5%	Graphene 1 Wt%	Graphene 1.5%	Pure ABS	Graphene 0.5%	Graphene 1 Wt%	Graphene 1.5%
1	21.89	22.61	20.71	17.57	29.64	33.19	38.21	37.9
2	22.19	22.67	16.62	21.93	32.01	37	35.27	37.07
3	20.21	22.25	21.63	20.97	30.38	36.23	36.95	38.85
4	26.34	40.63	36.76	40.36	40.45	52.29	46.72	59.63
5	25.23	39.39	40.06	39.73	39.66	52.16	48.06	55.3
6	26.60	39.78	37.88	38.5	39.49	53.07	47.14	55.15
7	5.01	7.78	10.66	7.5	12.63	42.63	37.56	35.2
8	6.16	9.88	9.26	7.11	11.47	44.17	38.62	29.66
9	6.36	10.9	11.45	7.9	12.63	45.55	37.74	32.18
10	26.61	27.62	24.47	26.11	35.19	39.08	41.39	37.05
11	23.68	26.33	25.18	26.31	39.28	38.53	41.44	37.68
12	22.87	26.64	25.91	26.53	37.33	40.85	42.61	38.33
13	23.98	25.38	23.05	23.84	31.88	35.58	37.88	41.97
14	21.44	24.2	21.96	23.57	30.52	37.53	38.21	41.4
15	22.07	24.07	22.61	24.12	31.48	36.12	38.9	41.44
16	8.89	7.03	6.17	6.06	12.31	38.57	32.49	30.1
17	8.40	8.67	10.04	5.14	14.21	36.51	32.03	29.13
18	7.63	6.84	5.45	5.56	12.52	37.09	30.84	28.91
19	16.98	27.18	25.84	27.55	21.15	42.33	33.6	30.61
20	17.35	28.59	26.81	27.23	20.06	40.69	30.1	31.29
21	16.66	26.71	26.63	28.24	20.09	40.22	33.53	31.36
22	20.54	31.78	28.54	31.44	33.6	47.05	48.19	44.04
23	20.63	27.97	28.78	26.8	35.3	45.84	45.79	47.87
24	20.85	30.3	29.81	28.24	33.96	46.33	46.46	45.06
25	8.40	4.98	5.58	3.65	13.16	21.97	18.5	24.56
26	9.63	6.49	4.8	3.99	13.56	22.02	14.95	23.87
27	9.03	4.25	5.47	2.99	14.74	21.71	16.58	22.92

3.5 Taguchi Design and Optimization Procedure

In order to maximize tensile and flexural strength, the Taguchi method was used to assess the impact of process factors. To investigate four parameters at three levels, an L27 orthogonal array was chosen. The larger-the-better quality feature was chosen because the study's goal is to maximize mechanical strength. The expression for the signal-to-noise (S/N) ratio is: $S/N = -10 \log \left(\frac{1}{n} \sum y_i^2 \right)$ where y_i represents the observed response and n is the number of observations. Higher S/N ratio values indicate improved performance with reduced variability.

4. Results and Discussion

4.1 Effect of Process Parameters on Tensile Strength

The combined main effects plot of signal-to-noise ratios are shown in Figure 2. Data from ABS reinforced with 0.5–1.5 weight percent graphene nanoplatelets and ABS reinforced with pure ABS were combined to make this plot.

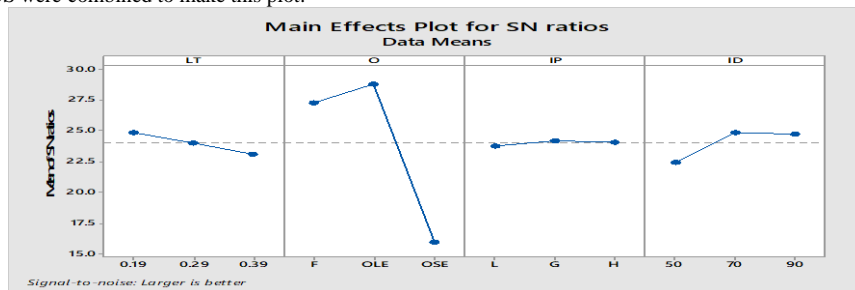


Fig. 2: Combined effect plot of Pure ABS, 0.5 % to 1.5% of Graphene Nanoplatelets for global influence of process parameters on tensile strength

Build orientation continues to be the primary factor influencing tensile strength for pure ABS (Figure 3(a)), with the on-long-edge (OLE) orientation producing the highest S/N ratio. Layer thickness has a moderate impact; performance is somewhat better at an intermediate value of 0.29 mm. While infill density has a comparatively small and non-monotonic effect, the grid infill pattern shows superior load distribution when compared to linear and honeycomb constructions.

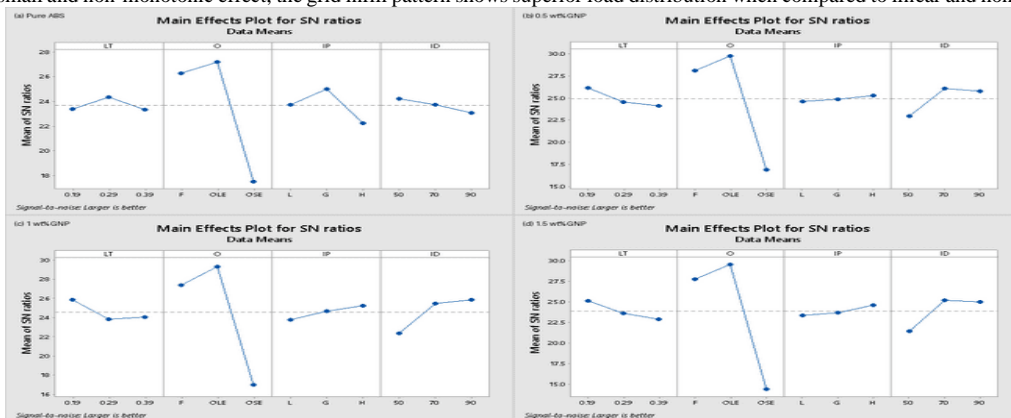


Figure 3: Material-wise main effects plots of signal-to-noise ratios (larger-the-better) for tensile strength: (a) Pure ABS, (b) ABS/0.5 wt% graphene nanoplatelets (GNP), (c) ABS/1 wt% GNP, and (d) ABS/1.5 wt% GNP.

4.2 ANOVA Table

ANOVA results show that infill density (36.8%) is the most significant parameter affecting tensile strength, followed by build orientation (24.8%) and infill pattern (21.9%). These parameters have high F-values (50.74, 34.24, and 30.29, respectively) and statistically significant p-values ($p < 0.001$), thus confirming strong

impacts on mechanical performance. Layer thickness contributes very little (0.07%) with a high p-value as it does not become statistically significant in this range; hence it can be ignored for practical purposes since its contribution to variance is negligible at such a high figure of 0.771. The error contribution being low at 16.6% indicates good experimental reliability overall; this analysis further confirms that parameters related to internal structure control tensile behavior where infill density clearly appears as the main parameter controlling strength enhancement in ABS parts made by FFF process.

Table 6: ANOVA Results for Tensile Strength

Source	Sum of Squares (SS)	DOF	F-value	p-value	Contribution (%)
Layer Thickness (LT)	2.25	1	0.087	0.771	0.07%
Orientation (O)	888.21	1	34.24	<0.001	24.8%
Infill Pattern (IP)	785.80	1	30.29	<0.001	21.9%
Infill Density (ID)	1316.43	1	50.74	<0.001	36.8%
Error	596.71	23	—	—	16.6%
Total	3589.39	—	—	—	100%

4.3 Effect of Process Parameters on Flexural Strength

The combined main effects plot of S/N ratios is used to assess the impact of FFF process parameters on flexural performance (Fig. 4). Build orientation is found to be the most important parameter, similar to tensile behavior, followed by infill density and infill pattern, while layer thickness exhibits relatively moderate sensitivity.

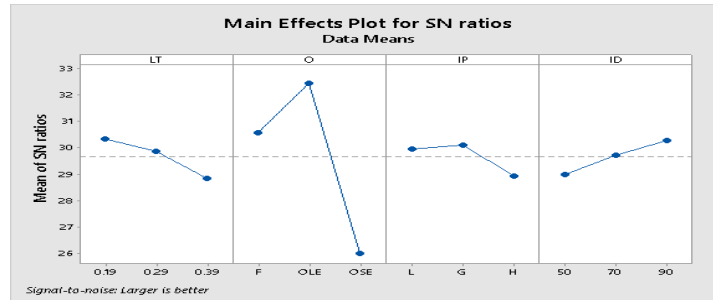


Figure4: Combined effect plot of Pure ABS, 0.5% to 1.5% of Graphene Nanoplatelets for global influence of process parameters on flexural strength.

Because there is less void formation and better interlayer fusion, a thinner layer improves flexural performance. Higher densities (70–90%) offer better resistance to bending loads by enhancing internal material continuity and decreasing structural weaknesses. Infill density exhibits a distinct upward trend.

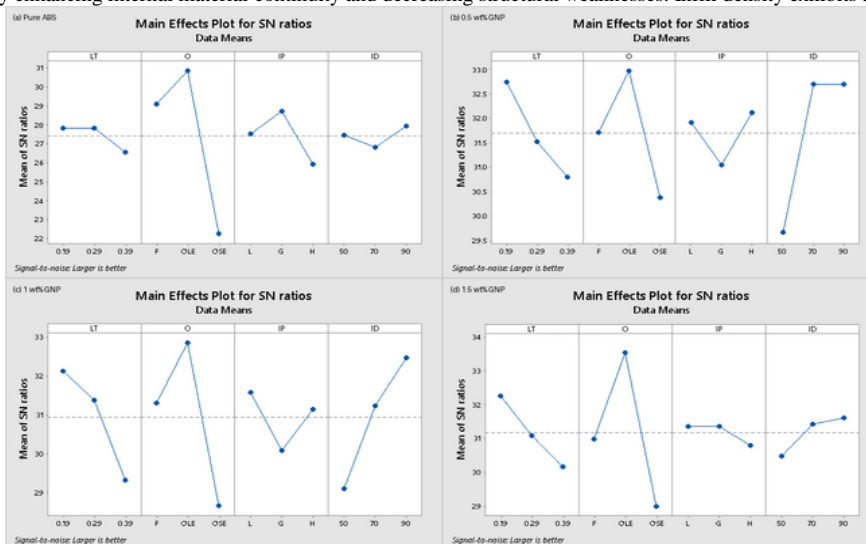


Figure 5: Material-wise main effects plots of signal-to-noise ratios (larger-the-better) for flexural strength: (a) Pure ABS, (b) ABS/0.5 wt% graphene nanoplatelets (GNP), (c) ABS/1 wt% GNP, and (d) ABS/1.5 wt% GNP.

4.4 Mean Strength Analysis and Taguchi-Optimized Performance

The tensile/flexural compression strength distribution of pure ABS and GNP-reinforced composite products for the 27 Taguchi experiments is illustrated in Figures 6 and 7.

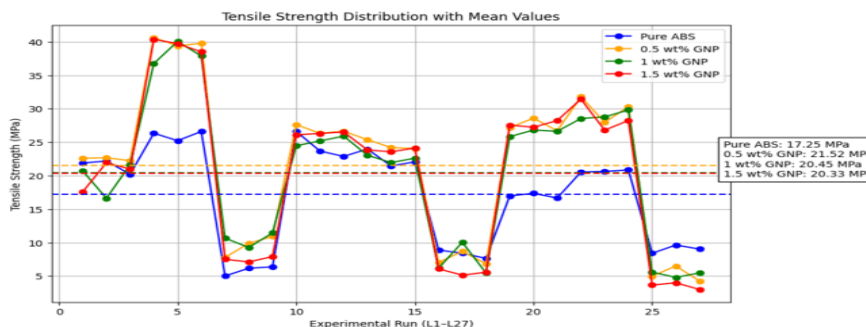


Figure 6: Tensile Strength distribution graph

Each figure presents an assessment of the entire mechanical performance range for all combinations of material types based on mean bending/compressive strengths in addition to the actual experimental data.

The effect of graphene nanoplatelets on tensile strength is evident when compared with that of pure ABS, as shown in Fig. 6. There is a significant increase in tensile strength with the addition of graphene nanoplatelets. The mean tensile strength for pure ABS is about 17.25 MPa, while that for 0.5 wt% GNP is 21.52 MPa, 1 wt% GNP is 20.45 MPa, and 1.5 wt% GNP is 20.33 MPa. The composition with 1 wt% GNP shows more consistent peaks compared to 0.5 wt%, although their means are nearly the same.

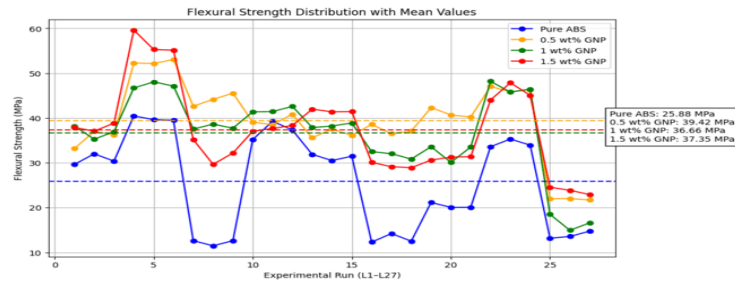


Figure 7: Flexural Strength distribution graph

In the same way, as observed in figure 7, the use of graphene as a reinforcement is shown to be an effective way to improve the distribution of flexural strength values. The mean flexural strength increased from 25.88 MPa for virgin ABS to 39.42 MPa for 0.5% GNP with the maximum value of 36.66 MPa for 1% GNP, then decreased slightly at 37.35 MPa at 1.5% GNP. The greater mean for these two samples as well as their consistently greater responses at 1% GNP show the effectiveness of this material to support bending loads.

4.5 Interaction Effects Analysis

Figures 8 (a) and 8 (b) present the interaction of key process variables and the tensile and flexural strength of ABS reinforced with 1 weight per cent graphene nanoplatelets (GNP). These figures show the interdependence of factors in the fused filament fabrication (FFF) and provide insight into the mechanical performance of altering parameters together. These results demonstrate the value of multi-parameter optimization and confirm the Taguchi method's efficacy in determining the best processing conditions for improved mechanical performance.

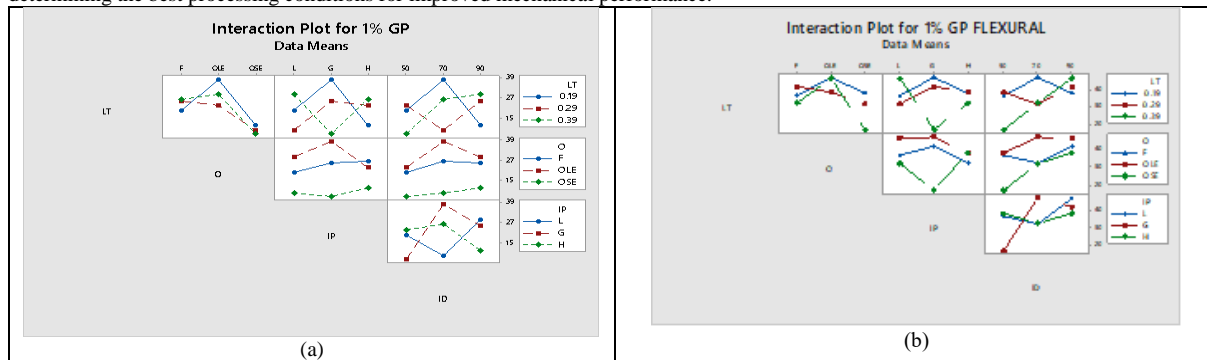


Fig. 8 (a) and 8 (b): Interaction effect plot of 1% ABS/Graphene Nanoplatelets for tensile strength and flexural strength.

4.6 Surface and Contour Analysis

Response surface and contour plots are used to further examine the impact of process parameters on flexural strength for ABS reinforced with 1 wt% graphene nanoplatelets (GNP), as illustrated in Figs. 9(a) and 9(b). These figures make it possible to determine the ideal processing settings by clearly showing the combined impact of layer thickness (LT) and infill density (ID) on mechanical performance.

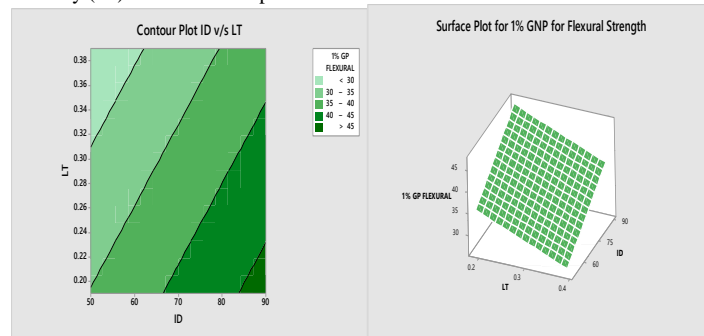


Fig. 9: Contour plot (Flexural, 1% GNP) and Surface plot (Flexural, 1% GNP)

4.7 Microstructural Analysis and Fractography

The SEM images of ABS reinforced with 1 wt% graphene nanoplatelets (GNP) under tensile and flexural loading conditions are presented in Fig. 10(a-d), illustrating the microstructural features responsible for the observed mechanical behavior.

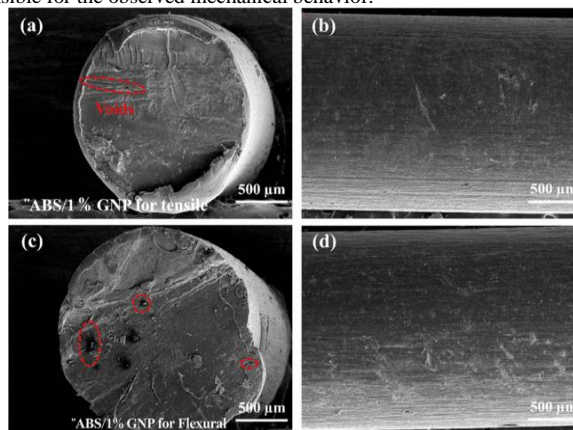


Fig. 10: SEM images of ABS/1 wt% graphene nanoplatelet (GNP) composites: (a) Tensile fracture cross-section showing voids and interlayer structure (b) Tensile fracture surface morphology (c) Flexural fracture cross-section showing voids and crack initiation sites (d) Flexural surface morphology showing raster structure and fracture features

Overall, the SEM analysis shows that 1 weight percent GNP provides the optimum interfacial bonding and dispersion, which reduces void content, improves layer adhesion, and increases resistance to fracture propagation. These microstructural features are directly related to the improved tensile and flexural properties mentioned in earlier sections. The SEM observations verify that the improved mechanical performance at 1 weight percent GNP is mostly due to greater interfacial bonding and decreased defect concentration inside the printed structure.

5. Conclusion

This study improves tensile and flexural properties of FFF-printed ABS using process parameter optimization and graphene nanoplatelet (GNP) reinforcement. ABS/GNP filaments (0.5, 1, 1.5 wt%) were prepared via melt blending and extrusion, and specimens were fabricated using FFF. A Taguchi L27 design evaluated layer thickness, build orientation, infill pattern, and infill density. Mechanical testing and ANOVA identified significant factors. Results showed 1 wt% GNP provided optimal performance due to better dispersion. Infill density (36.8%) was most influential. Optimal parameters achieved tensile strength of 40.1 MPa and flexural strength of 56.9 MPa with <3% error.

6. Acknowledgements

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Conflict of Interest:

There was no relevant conflict of interest regarding this paper.

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