The Optimization of Infill Pattern and FFF Printing Parameters for Improving Flexural Strength for Carbon Fiber Reinforced Nylon

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Abstract. This study investigates the flexural strength of Carbon Fiber Reinforced Nylon (CFRN) produced via Fused Filament Fabrication (FFF) about key printing parameters: extrusion temperature, printing speed, and infill pattern. While CFRN is known for its enhanced mechanical properties, the specific impact of these parameters on flexural strength still needs to be explored. Using a Taguchi orthogonal array L9 (3^3) design, experiments were conducted with extrusion temperatures of 260°C, 280°C, and 300°C, printing speeds of 40, 70, and 100 mm/s, and infill patterns of triangle, grid, and honeycomb, all set at an infill percentage of 20%. Analysis of variance (ANOVA) was applied to assess the significance of each parameter and their interactions with flexural strength. The results revealed that the infill pattern and printing parameters significantly influence flexural strength, with the highest value of 60.2 MPa observed using a honeycomb infill, a printing speed of 100 mm/s, and an extrusion temperature of 260°C. These findings suggest that optimizing print settings, including infill pattern, can greatly improve the mechanical performance of CFRN components in FFF applications.

Keywords: Flexural Strength, FFF 3D printing, Taguchi, Anova, Carbon Fiber Reinforced Nylon, Printing parameters.

1 INTRODUCTION

3D printing, or additive manufacturing, offers significant advantages: less material waste, the ability to create complex shapes and integrated assemblies, and the potential for highly customized products. These benefits have contributed to the 3D printing market's explosive expansion in recent years [1.,2.]. 3D printing, also known as additive manufacturing, has transformed the way we make complex and customized parts, especially in fields like aerospace, automotive engineering, and medicine [1.]. Among various 3D printing techniques, FFF stands out for its cost- effectiveness and versatility

M. A. Muflikhun et al. (eds.), *Proceedings of the 10th International Conference on Science and Technology (ICST 2024)*, Advances in Engineering Research 268,
https://doi.org/10.2991/978-94-6463-772-4_34

various 3D printing techniques, FFF stands out for its cost- effectiveness and versatility in material usage [3.]. Recent advancements have introduced composite materials such as CFRN, which offer enhanced mechanical properties compared to traditional filaments. These composites are particularly valued for their high strength-to-weight ratio and durability, making them ideal for functional parts subjected to mechanical stress [4.,5.].

Flexural strength is a critical measure of the performance of a 3D-printed part. Flexural testing, which determines its value, is quite common among other mechanical property tests. Depending on the application—like making prototypes or structural parts different levels of stiffness might be needed in a 3D- printed object. Some infill patterns make the part stiffer, while others create more flexible ones [6.,7.]. Infill patterns like triangles, grids, and honeycombs are selected based on their lightweight nature, high stiffness-to-weight ratio, and effective energy absorption [8.].

Parts produced using the FFF technique exhibit anisotropic properties, with their mechanical characteristics heavily influenced by the process parameters employed [9.]. Typically, operators choose parameters based on intuition and experience, but they need more information to select the optimal manufacturing parameters. Moreover, the default printing process parameters provided by filament and printer manufacturers do not ensure the quality of the printed products [10.,11.]. However, optimizing the mechanical properties of these materials requires a thorough understanding of the printing parameters. Extrusion temperature, printing speed, and infill pattern significantly affect the quality of the final 3D- printed part [1.,12.-15.]. Additive manufacturing processes often involve numerous parameters and can be expensive to optimize fully. The Taguchi method provides a valuable alternative to full factorial experiments, allowing more efficient exploration of process parameters to optimize product design [16.].

Previous studies have extensively explored the optimization of 3D printing parameters such as extrusion temperature, printing speed, and infill pattern to enhance the mechanical properties of various materials, including demonstrating the significant impact of processing parameters on the flexural strength of 3D printed CFRN. Christodoulou et al. (2024) investigated how various 3D printing settings (infill pattern, density, line multiplier, and speed) affect the tensile, compressive, and bending strength of Nylon-CF. Their analysis revealed that infill pattern (34.13%), infill density (16.92%), and infill line multiplier (48.58%) were the most influential factors, with minimal unexplained variation (0.41%) [17.]. Ramesh et al. (2021) investigated the influence of FDM parameters on Nylon parts, highlighting the role of ANOVA analysis in understanding these relationships [18.]. Research by Kumar et al. (2023) explored the effects of machine parameters on the strength of carbon fiber reinforced PETG, a related material, emphasizing the importance of parameter optimization for achieving desired mechanical properties [19.]. Furthermore, Miguel Araya et al. (2018) also looked into how reinforcement patterns and printing orientation affect the mechanical behavior of continuous fiber-reinforced composites, highlighting the intricate interplay of factors that affect these materials' strength [20.]. A study by Maryam et al. (2023) found that layer thickness and fill angle are significant factors affecting the strength of parts produced by FFF 3D printing [21.]. Abas et al. (2023) showed that by optimizing 3D printing process parameters, surface roughness can be reduced, leading to improved mechanical properties [22.].

While past research has shown that extrusion temperature, printing speed, and infill pattern are all important for the strength of a 3D-printed part, no one has examined how these factors work together when using CFRN filament. This study is the first to investigate their combined effects [17.-22.].

This study aims to address this gap by investigating the influence of extrusion temperature, printing speed, and infill pattern on the flexural strength of CFRN. By employing the design of experiments of Taguchi orthogonal array L_9 (3^3), this research seeks to identify optimal printing conditions, providing valuable insights for enhancing the performance of 3D-printed composite materials. Understanding these interactions is critical for advancing the application of FFF in high-performance sectors

2 MATERIAL AND METHOD

In general, this research was conducted with a flow such as shown in Fig.1.

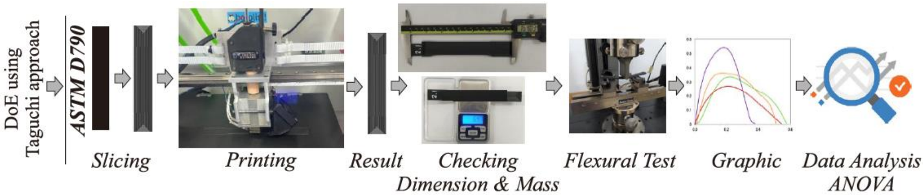

Fig. 1. Steps of experiment.

Shenzhen Esun Industrial Co. Ltd. provided the FFF CFRN (ePA-CF) used to create the samples. It consists of nylon 6/66 copolyester with the addition of 20% carbon fiber. This enhances strength, rigidity, and hardness, allowing for the replacement of metals in various applications. The filament featured a 1.75 mm diameter and a printing temperature specification of 260 to 300 °C [23.].

The DIY 3D printing machine was one of the main tools used to produce CFRN specimens. Fig. 2 and Table 1 show the machine and its specifications. This machine uses the FFF principle to transform polymer filaments into three dimensional shapes.

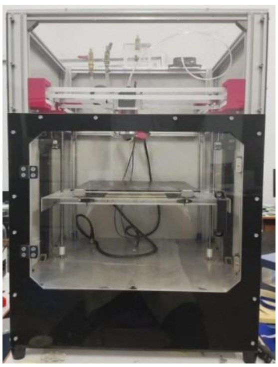

Fig. 2. DIY 3D printer.

Table 1. 3D printer specification.

Items	Specification
Machine Dimensions	530 x 490 x 780 mm
Main Controller	Bigtree Tech SKR V1.4
Motor Driver	TMC 2209
Bed Mechanism	Core XY
Internal Room Temp.	Max. 70°C
Nozzle Heater Temp.	Max. 300°C
Bed Heater Temp.	Max. 100°C
Nozzle Material	Hardened Steel
Nozzle Diameter	0.4 mm

The 3D printer employs a water cooling system to ensure that heat generated by the nozzle does not affect the extruder roller. It is designed with a cover to protect against external air exposure.

The extrusion temperature, printing speed, and infill pattern all had major impacts on the material properties examined in this study.

Temperature settings significantly impact mechanical strength, with research indicating that higher nozzle temperatures enhance filament bonding (24.). Print speed also influences the fusion and hardening of filament, affecting extrusion rates and product quality. Adjusting print speeds can improve layer bonding and mechanical strength (25.). Infill patterns are crucial for creating lighter, cost-effective, and mechanically sound hollow structures. Correctly adjusting these patterns allows for optimal tensile strength and elasticity. Different infill designs, such as triangles, grids, and honeycombs, provide varying rigidity levels, making them suitable for applications like prototyping or structural components (26.).

The material manufacturer suggested using an extrusion temperature between 260 and 300 °C and a printing speed between 40 and 100 mm/s. Since these parameters fell within these ranges, the best values were selected for this work. Table 2 shows the parameters and levels that were tested in this research.

Table 2. Printing parameters and their levels.

Parameter	Extrusion Temperature °C	Printing Speed mm/s	Infill Pattern
Level 1	260	40	Triangle
Level 2	280	70	Grid
Level 3	300	100	Honeycomb

This study used a smart experimental approach (a hybrid Taguchi method) to determine how three key 3D printing settings—extrusion temperature, printing speed, and infill pattern—affect the final product's properties. These settings were changed to see how they impacted the results. From Table 2, L_{27} (3^3) was obtained, ideally resulting in 27 trials with different parameter combinations. However, due to the relatively high cost of filament material and the significant risk of nozzle damage caused by abrasive filaments, it was decided that the chosen orthogonal array design would be L_9 (3^3), consisting of 9 parameter combinations. Printing will be repeated five times according to the requirements of the ASTM D790-17 standard testing protocol to determine the magnitude of deviation in the printing results, followed by analysis to obtain accurate outcomes. The number of specimens printed is 45 for flexural tests.

The research was initiated by designing a 3D model of the specimen tested in this study. As illustrated in Fig. 3, flexural testing followed ASTM D790-17 standard procedures, using a three-point bending method and standardized specimens.

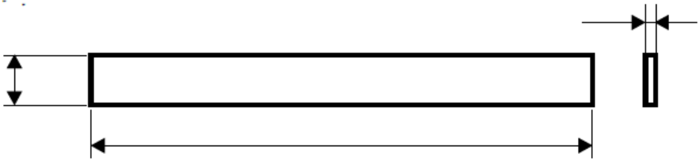

Fig. 3. Specimen shape and dimensions.

After obtaining the 3D model in STL format, the Prusa Slicer was used to the slicing process. The slicing results showing the infill pattern are displayed in Fig. 4.

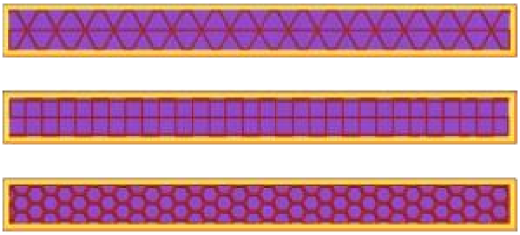

Fig. 4. CAD model sliced into layers infill pattern: a. triangle b. grid c. honeycomb.

During the generation of the g-code, several fixed parameters were implemented alongside the three parameters under investigation. These fixed printing parameters are detailed in Table 3.

Table 3. Fixed printing parameters.

Fix Printing Parameter	Values
Build plate Temperature	80 °C
Room Temperature	25-30 °C
Filament Diameter	1.75 mm
Nozzle Diameter	0.4 mm
Printing Angle	0 °
Wall Thickness	4 layers
Top-Bottom Thickness	4 layers
Infill Density	20%
Top & bottom Fill Pattern	Concentric

The flexural tests were performed using a Zwick Roell Universal Testing Machine (UTM), specifically the Z020 model, operating at a loading speed of 2 mm/min, see Fig. 5.

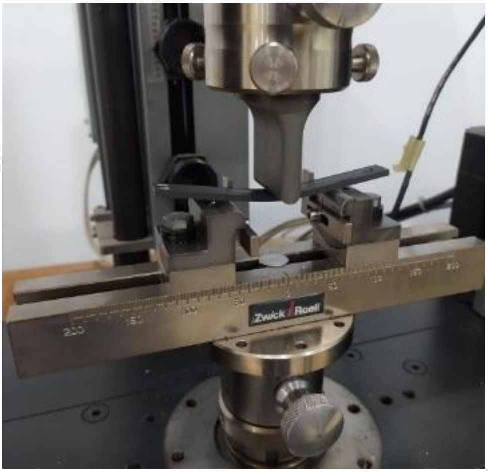

Fig. 5. Flexural testing method.

3 RESULTS AND DISCUSSIONS

The results of the flexural strength tests on the CFRN specimens printed using FFF are shown in Fig. 6.

Fig. 6. Flexural test's impact on the specimen.

Fig. 6 from the bend test results indicate that the samples did not break when subjected to bending loads. This suggests the tested material possesses ductile properties with sufficiently strong interlayer bonds. When this material is subjected to bending loads, its constituent layers do not experience delamination or separation from one another (27.).

The Design of Experiment (DoE), flexural strength values and standard deviations are shown in Table 3. Previous studies that highlight the significant effects of extrusion temperature, printing speed, and infill pattern on the mechanical properties of 3D-printed materials lend credence to these findings. For instance, a study by Ansari and Kamil (2021) demonstrated that high print speeds can enhance mechanical properties and reduce build time [28.], while the studies by Tajarernmuang et al. (2019) and Khan et al. (2024) showed that infill density and pattern significantly influence the flexural properties of 3D printed part [29.,30.]. The provided data in Table 4 and Fig. 7 present the results of a comprehensive flexural test on CFRN specimens fabricated using FFF 3D printing. The key findings reveal that samples printed at 260°C with a honeycomb infill pattern and 100 mm/s printing speed exhibited the highest mean flexural strength of 60.20 MPa with a low standard deviation, indicating consistent performance. In contrast, samples printed at 260°C with a triangle infill and 40 mm/s speed showed the lowest mean flexural strength of 45.92 MPa.

It can be seen from Fig. 8 that the average flexural strength values for materials made of 3D printed CFRN filament ranged from 45.92 to 60.2 MPa. With extrusion temperature and infill pattern varied, specimens 3, 6 and 9 showed the highest flexural strengths once printed at a speed of 100 mm/s

Table 4. DoE for flexural strength and test results.

Specimen No.	Extrusion Temp.	Printing Speed	Infill Pattern	Flexural strength (MPa)					FS Mean	STDev
	°C	mm/s	type	1	2	3	4	5	*MPa*	
1	260	40	Triangle	47.3	40.4	47.3	48.8	45.8	45.92	2.92
2	260	70	Grid	47.3	48.4	48.3	44.3	49.5	47.56	1.77
3	260	100	Honeycomb	58.1	61.2	60.6	60.9	60.2	60.20	1.10
4	280	40	Grid	47.5	47.2	49.4	47	50.6	48.34	1.42
5	280	70	Honeycomb	51.9	54	58.1	54.2	55.4	54.72	2.03
6	280	100	Triangle	57.5	56.3	58.8	56.6	57.6	57.36	0.88
7	300	40	Honeycomb	46.2	52.2	52.7	54.1	52.2	51.48	2.73
8	300	70	Triangle	56.9	57	57.4	55.4	53.2	55.98	1.55
9	300	100	Grid	55.2	56.3	58.7	57.6	57.4	57.04	1.19

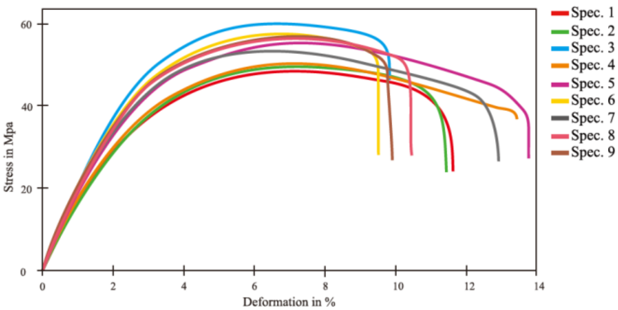

Fig. 7. The stress-deformation diagram obtained from the flexural test.

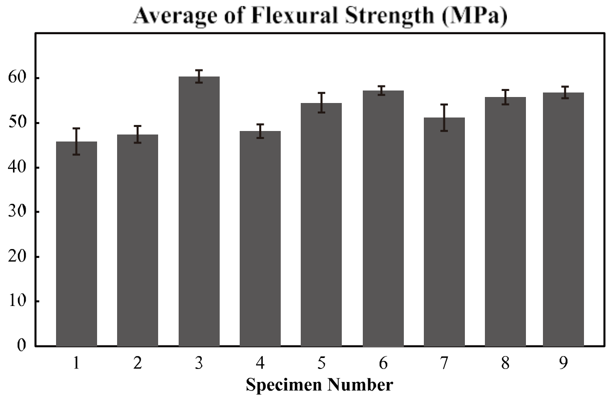

Fig. 8. The average flexural strength of the specimen tested in this research.

To evaluate the significance of each process parameter and their interactions, the ANOVA method was employed. This analysis utilized all 45 test results obtained from 9 specimens, each with 5 samples, allowing for a more robust and accurate assessment of the effects of these parameters on flexural strength [31.]. The ANOVA results are presented in Table 5 based on this comprehensive dataset. Specifically, the analysis examined the significance of each parameter, their influences, and their interactions, providing insights into the quality of the model. The data were analyzed through this rigorous statistical approach to draw meaningful conclusions regarding the factors affecting flexural strength.

Table 5. Analysis of Variance.

Source	D F	Seq SS	Contri- bution	Adj SS	Adj MS	F-Value	P-Value
Extrusion Temp	2	99.53	8.52%	99.53	49.763	8.64	0.001
Print Speed	2	698.14	59.79%	698.14	349.068	60.63	0.000
Pattern	2	151.16	12.95%	151.16	75.582	13.13	0.000
Error	38	218.77	18.74%	218.77	5.757		
Lack-of- Fit	2	63.53	5.44%	63.53	31.766	7.37	0.002
Pure Error	36	155.24	13.30%	155.24	4.312		
Total	44	1167.60	100.00%				

The ANOVA results in Table 5 indicate that the printing speed had the most significant impact on the flexural strength, contributing 59.79% to the total variability. This was consistent with the previous studies that showed that high print speeds enhanced the mechanical properties of 3D printed materials by reducing the time available for defects to form during the printing process [32.,33.]. In the FFF process, layers were deposited sequentially, with each layer adhesion significantly influencing the product performance. At a printing speed of 40 mm/s, the longer cooling time between layers resulted in poor adhesion of the semi-solidified material to the next layer, leading to a lower flexural strength. The behaviors observed in the study corresponded to the characteristics of thermoplastic materials, where the model became more brittle with the increasing print speed. The results from the 3-point bending test indicated that the more brittle specimens exhibited a higher flexural modulus [34.,35.]. This finding was supported the results presented in Fig. 8, which shows that specimens 3, 6 and 9 with a printing speed of 100 mm/s exhibited higher flexural strength with an average test result exceeding 57 MPa, but with low deformation ranging from 9-10%.

The extrusion temperature also showed a less effect to the flexural strength value than the printing speed, with a contribution of only 8.52% to the total variability. The material structure of CFRN is stable and less influenced by changes in extrusion temperature. The material exhibits good stability, with changes in extrusion temperature not significantly altering its mechanical properties. The stable interaction between carbon fibers and nylon polymer is also less influenced by changes in extrusion temperature. This is evident from studies showing that variations in extrusion temperature do not significantly affect the flexural strength of the material [36.].

Despite having a modest contribution of 12.95%, the infill pattern still played a crucial role in determining the specimens' flexural strength. The previous studies had shown that infill patterns affect the mechanical properties of 3D-printed materials. Some patterns, like the honeycomb and grid, perform better than the triangle [12.,31.]. Cojocaru et al. (2023) obtained the performance of various infill patterns in 3D printing, such as honeycomb and grid, compared to triangular patterns, which can be attributed to their structural properties and mechanical behaviour. Honeycomb and grid patterns demonstrate higher compressive strength and better resistance to deformation due to their stable and rigid frameworks, which evenly distribute stress. These patterns also achieve material efficiency by reducing mass and consumption while maintaining or improving mechanical properties, making them suitable for applications requiring weight reduction without compromising strength. Furthermore, their symmetrical nature minimizes stress concentrations, making them ideal for mechanical components with changing forces. While triangular patterns offer good mechanical properties, they are less efficient in terms of material usage and stress distribution compared to honeycomb and grid patterns, which can potentially affect their overall performance in specific applications [31.].

In Table 5, higher percentages in the contribution column indicate a greater influence on response variance. The contribution rates are extrusion temperature at 8.52%, print speed at 59.79%, infill pattern at 12.95%, and error at 18.74%. The ANOVA table shows that the pure error term accounts for 13.30% and lack-of-fit terms account for 5.44%. That is 18.74% of the total variation observed in the flexural strength data. This pure error component represents the inherent, unexplained variability in the experimental measurements, which may arise from uncontrolled factors, measurement errors, or other sources of randomness not captured by the model. This pure error component suggests that even when the FFF process parameters (nozzle temperature, printing speed, and infill pattern) are carefully controlled, a certain level of variability will still be present in the flexural strength results

A large F-value signifies significant factor effects compared to error variance, with larger values indicating greater importance. The ANOVA table ranks factors by their F-values: print speed with 60.63, infill pattern with 13.13, and extrusion temperature with 8.64. The p-values for extrusion temperature, print speed, and infill pattern are 0.001, 0.000, and 0.000, respectively, all less than 0.05. Therefore, all factors are statistically significant.

In Table 5, the ANOVA table ranks factors by their F-values: print speed with 60.63, infill pattern with 13.13, and extrusion temperature with 8.64. The p-values for extrusion temperature, print speed, and infill pattern are 0.001, 0.000, and 0.000, respectively, all less than 0.05. Therefore, all factors are statistically significant. This aligns with the discussion conducted by Christodoulou et al. (2024) [17].

The main effects plot reveals the individual impacts of the FFF process parameters on the flexural strength of the CFRN specimens. See Fig. 9.

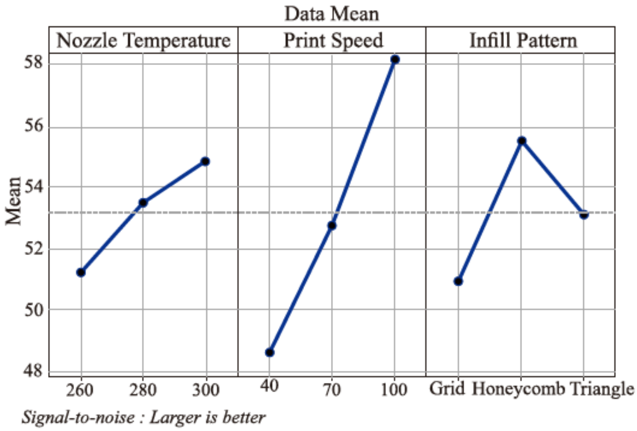

Fig. 9. Main effects plot for flexural strength.

As the nozzle temperature increases from 260°C to 300°C, the mean flexural strength steadily improves, indicating a positive effect of higher temperatures. The printing speed shows an optimal range, with the flexural strength initially increasing from 40 mm/s to 100 mm/s. This suggests that higher printing speeds, up to 100 mm/s, positively affect the flexural strength of the CFRN specimens fabricated using the FFF method. Notably, the choice of infill pattern emerges as a crucial factor, with the honeycomb pattern consistently exhibiting the highest flexural strength, followed by the triangle and grid patterns.

ANOVA analysis suggests that certain FFF process parameters—specifically, a nozzle temperature of 300°C, a printing speed of 100 mm/s, and a honeycomb infill pattern can enhance the flexural strength of CFRN specimens. However, this specific combination of parameter settings was not included in the original DoE and, therefore, has not been experimentally verified. Therefore, further investigation is necessary to validate the efficacy of these optimized parameters through assessments of the mechanical characteristics of CFRN components fabricated via FFF under this defined setting.

The interaction plot, as shown in Fig. 10, reveals the complex relationships between the three key FFF process parameters and their combined effects on the flexural strength of the CFRN specimens.

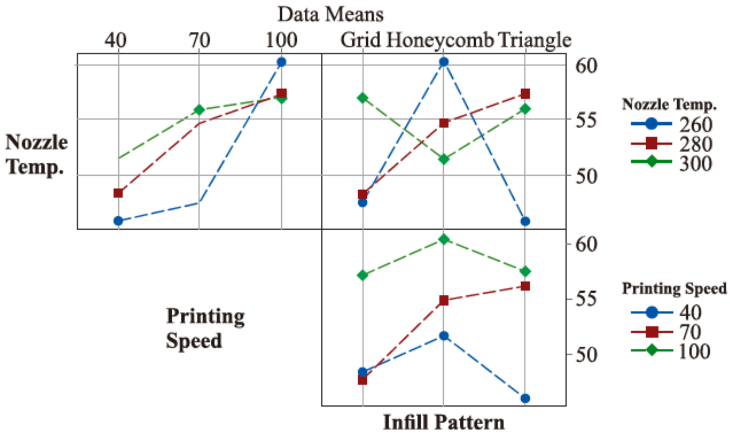

Fig. 10. Interaction plot for flexural strength.

As the nozzle temperature increases from 260°C to 300°C, the flexural strength generally improves, with the effect being more pronounced at higher temperatures. Printing speed also plays a significant role, with the flexural strength initially increasing from 40 mm/s to 100 mm/s. The choice of infill pattern emerges as a crucial factor, with the honeycomb pattern consistently exhibiting the highest flexural strength across the tested temperature and speed ranges, in contrast to the more variable performance of the grid and triangle infill patterns. The plot highlights the importance of considering the interactive effects of these parameters, as the influence of one factor can be amplified or diminished depending on the settings of the other two, underscoring the need for a comprehensive approach to optimizing the FFF process for enhanced mechanical properties of CFRN components.

4 CONCLUSION

This study investigated the relationship between 3D printing process parameters (extrusion temperature, printing speed, and infill pattern) and the flexural strength of CFRN, using ASTM D790 standard test methods. This understanding is crucial for optimizing the mechanical performance of these materials. To reduce the number of experiments, a three-level fractional factorial design, using the L_9 (3^3) Taguchi orthogonal array, was employed. The results revealed that the apparent flexural strength varied significantly, ranging from 45.92 to 60.20 MPa. Notably, the contribution rates of each parameter were distinct: extrusion temperature accounted for 8.52%, print speed dominated with 59.79%, infill pattern contributed 12.95%, and error made up 18.74%. This analysis highlighted a significant interaction among extrusion temperature, printing speed, and infill pattern. The study recommends setting the extrusion temperature at 260°C, maintaining a printing speed of 100 mm/s, and utilizing a honeycomb infill pattern to maximize flexural strength.

Acknowledgments. This research was funded by Polytechnic ATMI Surakarta.

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