UDC 621.767 **doi: 10.20998/2078-7405.2024.100.11**

# AN EXPERIMENTAL INVESTIGATION OF THE MECHANICAL PROPERTIES OF FUSED FILAMENT FABRICATED NYLON-CARBON FIBER COMPOSITES

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**Received: 28 March 2024 / Revised: 26 April 2024 / Accepted: 28 May 2024 / Published: 15 June 2024**

**Abstract.** *Additive Manufacturing (AM) is a rapidly growing field in both the researching and the industrial world, as it produces highly customized and geometrically complex objects. The most well-known AM technology for plastics is Fused Filament Fabrication (FFF), in which a thermoplastic filament is melted and extruded through a nozzle on the printing bed. A wide variety of printing parameters affect the quality of the printed objects, such as printing speed, infill density, infill pattern, build orientation, layer height, etc. In literature, there is already extended research of the impact of the printing parameters on the mechanical properties of the most common thermoplastics, such as ABS and PETG. However, the development of advanced thermoplastic materials, such as Nylon composites reinforced with carbon fibers (Nylon-CF), requires a further investigation of the effect of the printing parameters on those advanced composites. In the current study, an in-depth correlation of all the major printing parameters (infill pattern, infill density, dual line infill and printing speed) with all the major mechanical properties (tensile strength, compressive strength and bending strength) of Nylon-CF is carried out.*

**Keywords:** *Fused Filament Fabrication (FFF); Nylon-Carbon Fiber (Nylon-CF); tensile strength; compressive strength; bending strength.*

## 1. Introduction

Additive Manufacturing (AM) has become a very popular field for both the researching and the industrial world, due to its ability to give lightweight products with high customization and geometrical complexity [1]. In AM, the final product is fabricated with layer-by-layer deposition of melted material on a printing bed. According to the printing material, different AM technologies have been developed, such as Laser Powder Bed Fusion (LPBF) for metals and developed, such as Laser Powder Bed Fusion (LPBF) for metals and Stereolithography (SLA) and Fused Filament Fabrication (FFF) for thermoplastics [2].

Specifically, in Fused Filament Fabrication (FFF), a thermoplastic filament is melted and then extruded through a nozzle on the printing bed [3]. In order to control the quality of the printed object, several printing parameters should be fine-tuned. Such parameters are printing speed, infill density, infill pattern, build orientation, layer height, raster angle, extrusion temperature, nozzle diameter and air gap, etc. [4].

Most of the papers in literature investigate the effect of these parameters on the mechanical properties of the most conventional thermoplastic materials, such as ABS and PETG. Es-Said et al. [5] printed with FFF ABS samples with different raster angles. They observed that the highest strength is achieved for $0^o$, whereas $45^o$ and $90^o$ lead to layers delamination. Ashtankar et al. [6] examined the effect of building orientation on the tensile and compressive strength of FFF-produced ABS samples. They observed that by increasing the orientation from $0^o$ to $90^o$, both tensile and compressive strength are reduced. Baich et al. [7] studied how infill density (low density, high density and double density) affects tensile, compressive and bending strength of FFF-printed ABS specimens. Higher strength is achieved by the high-density samples, whereas higher compressive and bending strength is achieved by double-density samples. Durgashyam et al. [8] fabricated with FFF PETG samples and observed that a combination of low layer height, high infill density and medium feed rate leads to higher tensile strength, whereas a combination of low infill density, low layer height and medium feed rate results in the best flexural properties. Yadav et al. [9] fabricated with FFF ABS, PETG and 50%ABS-50%PETG specimens. The results showed that the tensile strength is, mostly, affected by the extrusion temperature and the infill density. Srinivasan et al. [10] showed that in case of FFF-printed PETG specimens, increased infill density, increases tensile strength and decreases surface roughness.

Although there is, in literature, an in-depth investigation of the effect of printing parameters to the mechanical properties of the most well-known thermoplastic materials, such as ABS and PETG, there is a need to extent these mechanical properties investigations and into more advanced thermoplastic materials, which have started to gain a significant space into the industry, due to their superior mechanical properties. Such a material is the Nylon-Carbon Fiber (Nylon-CF). Nylon-CF is a composite filament of nylon polymer, blended with carbon fibers and demonstrates enhanced strength, stiffness and durability properties. These properties make Nylon-CF appropriate for multiple applications, such as prototyping, tooling and end-use products for aerospace and automotive industries. For this reason, researchers have started to study the mechanical properties of Nylon-CF

FFF-printed products. De Toro et al. [11] carried out experiments with FFF-printed Nylon-CF and showed that infill density has the most crucial role in both tensile and bending properties, whereas infill pattern affects mainly the bending behaviour. León-Becerra et al. [12] investigates the effect of build orientation on the roughness of FFF-fabricated Onyx (short carbon-filled fiber nylon) samples. The lowest roughness was observed in the flat print orientation. Sedlacek et al. [13] developed with FFF and compared pure PA6 nylon and PA6 with short carbon fibers. They showed that carbon fibers affect the strength and the heat deflection of the specimens. The research, till now, regarding FFF-fabricated Nylon-CF is very interesting, but it is not so extended like in other more conventional materials. So, in order to better understand the mechanical behaviour of FFF-fabricated Nylon-CF, all the major printing parameters should be correlated with all the major mechanical properties of Nylon-CF.

The target of this paper is to correlate and optimize all the major printing parameters (infill pattern, infill density, dual line infill and printing speed) with all the major mechanical properties (tensile strength, compressive strength and bending strength) of Nylon-CF.

## 2. Experimental Methods

The Nylon-CF samples were fabricated by the FFF-printer FlashForge® Creator 3 (Zhejiang Flashforge 3D Technology Co., Ltd.). The Nylon-CF filament was the Ultrafuse® PAHT CF15 (BASF 3D Printing Solutions BV), which is a high-performance 3D printing filament. The samples were fabricated and tested according to the ASTM D638-14, ASTM D695-15 and ASTM D790-15 standards for tensile strength, compressive strength and flexural strength tests, respectively. All the mechanical tests were carried out on an Instron® 4482 machine, which has a maximum loading capacity of 100 [kN].

For the Design of Experiments (DOE), Taguchi method was implemented, as shown in the Tables 1 (tensile strength) and Table 2 (compressive and flexural strength), below:

Table 1 Design of Experiments (DOE) for the tensile strength tests.

| Factor / Run | Infill Pattern | Infill Density (%) | Infill Line Multiplier |
|---|---|---|---|
| 1 | Grid | 5 | 1 |
| 2 | Grid | 15 | 2 |

| | | | |
|---|---|---|---|
| 3 | Grid | 25 | 3 |
| 4 | Lines | 5 | 2 |
| 5 | Lines | 15 | 3 |
| 6 | Lines | 25 | 1 |
| 7 | Triangular | 5 | 3 |
| 8 | Triangular | 15 | 1 |
| 9 | Triangular | 25 | 2 |

Table 2 Design of Experiments (DOE) for the compressive and flexural strength tests.

| Factor / Run | Infill Pattern | Infill Density | Printing Speed | Infill Line Multiplier |
|---|---|---|---|---|
| 1 | Grid | 5 | 25 | 1 |
| 2 | Grid | 15 | 50 | 1 |
| 3 | Grid | 25 | 75 | 1 |
| 4 | Triangular | 5 | 25 | 1 |
| 5 | Triangular | 15 | 50 | 1 |
| 6 | Triangular | 25 | 75 | 1 |
| 7 | Lines | 5 | 50 | 1 |
| 8 | Lines | 15 | 75 | 1 |
| 9 | Lines | 25 | 25 | 1 |
| 10 | Grid | 5 | 75 | 2 |
| 11 | Grid | 15 | 25 | 2 |
| 12 | Grid | 25 | 50 | 2 |

| | | | | |
|---|---|---|---|---|
| 13 | Triangular | 5 | 50 | 2 |
| 14 | Triangular | 15 | 75 | 2 |
| 15 | Triangular | 25 | 25 | 2 |
| 16 | Lines | 5 | 75 | 2 |
| 17 | Lines | 15 | 25 | 2 |
| 18 | Lines | 25 | 50 | 2 |

According to the aforementioned standards, 5 samples, for each one of the experiments in Tables 1 and 2, were tested and the mean value of these 5 samples was extracted as a result.

The rest printing parameters were fixed for all the experiments (Table 3):

Table 3 Fixed printing parameters.

| **Printing Parameter** | **Fixed Value** |
|---|---|
| Nozzle Diameter | 0.6 [mm] |
| Layer Height | 0.32 [mm] |
| Printing Temperature | 270 [$^o$C] |
| Part Orientation | Horizontal |
| Shells | 2 |
| Build Plate Temperature | 130 [$^o$C] |

## 3. Results and Discussion

This study systematically investigates the mechanical properties of Nylon-Carbon Fiber composites fabricated using Fused Filament Fabrication (FFF) under varied printing parameters. The results highlight distinct trends across tensile, compressive, and flexural strengths, which are essential for optimizing the use of Nylon-CF in engineering applications.

<ins>Tensile Tests:</ins>

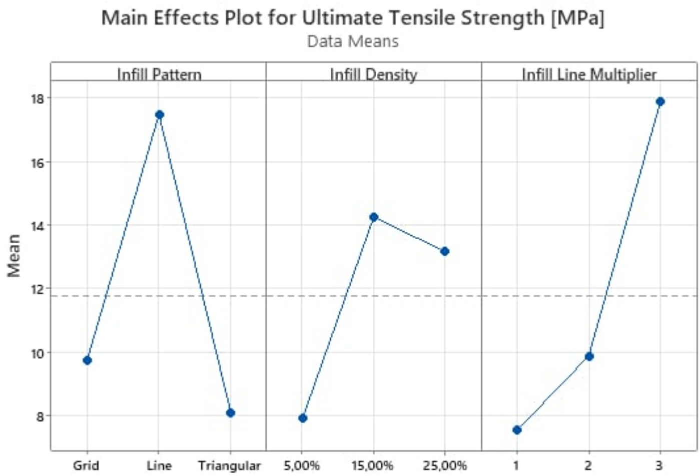


Figure 1. Main Effects Plot for Ultimate Tensile Strength

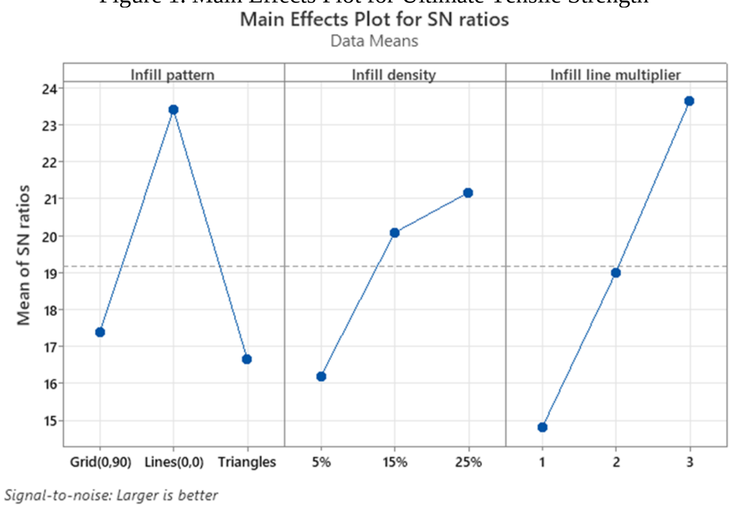


Figure 2. SN plots for Main Effects

The analysis of the tensile strength of Nylon-Carbon Fiber composites fabricated using Fused Filament Fabrication (FFF) reveals critical insights into the influence of printing parameters on mechanical performance. Given Figure 1, notably, the main effects plots indicate that the 'lines' infill pattern yields the highest tensile strength. This outcome is intuitive, given that the lines were aligned with the direction of the tensile force during testing, thereby enhancing the load-bearing capacity of the composite. Surprisingly, the optimal infill density for maximizing tensile strength is found to be 15%, rather than the denser 25% option. This suggests a balance between material density and structural integrity, where too much density might introduce flaws or stress concentrations. Additionally, the infill line multiplier of 3 emerges as the most beneficial, significantly improving strength by adding two extra lines to the infill, thus reinforcing the composite structure. These findings underscore the complex interplay of infill pattern, density, and line multiplier in optimizing the tensile properties of FFF-manufactured Nylon-CF composites, offering valuable directions for tailoring material properties through precise control of printing parameters. The analysis of the Signal-to-Noise (S/N) ratios for the tensile strength of the Nylon-Carbon Fiber composites further, as showed in Figure 2, corroborates the findings from the main effects plot. The S/N ratios, which emphasize the robustness and reliability of the tensile strength under various experimental conditions, also highlight the lines infill pattern as particularly effective. This consistency between the S/N ratios and the main effects plot underscores the strength stability provided by the line orientation, which aligns with the tensile force direction. Furthermore, the optimal infill density at 15% and the superior performance of the three-line multiplier in the S/N analysis echo the main effects findings, demonstrating that these settings not only enhance mean strength but also minimize variability in performance.

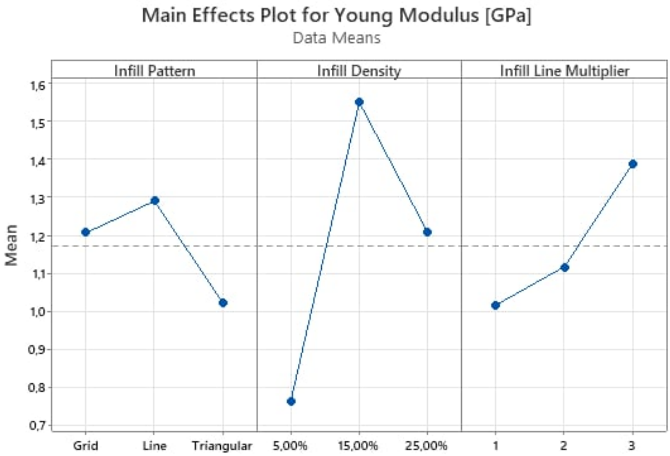


Figure 3. Main Effects Plot for Young Modulus

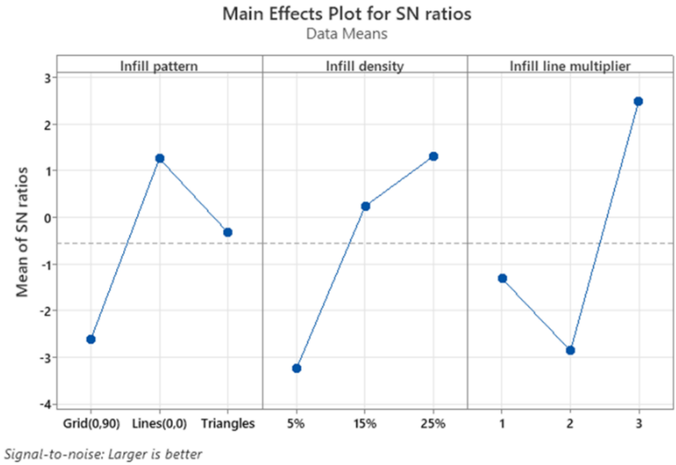


Figure 4. Main Effects Plot for SN ratios (Young modulus)

The examination of Young's Modulus for the tensile properties of Nylon-Carbon Fiber composites fabricated via Fused Filament Fabrication (FFF) presents intriguing results that align with trends observed in tensile strength. The main effects plot distinctly shows that the 'lines' infill pattern is superior, achieving an impressive modulus of 13 MPa. This pattern likely provides more continuous load-bearing paths along the tensile test direction, effectively improving the elastic response of the material. Furthermore, similar to the findings for tensile strength, an infill density of 15% is identified as optimal for maximizing Young's Modulus. This suggests that a medium density facilitates a balance between flexibility and rigidity, which is crucial for optimizing the elastic properties of the material. Additionally, the three-line multiplier once again proves to be most effective, likely due to its enhancement of the composite's internal structure, making it more resistant to elastic deformation. Consistently, the Signal-to-Noise (S/N) ratios for Young's Modulus reinforce these conclusions. The S/N plots follow the same patterns as the main effects, demonstrating that the 'lines' infill pattern, 15% infill density, and three-line multiplier not only maximize the mean modulus but also ensure stability and consistency across test conditions. These findings confirm the robustness of these parameter settings in enhancing the elastic properties of the composites, providing a reliable basis for parameter selection in the fabrication of FFF-manufactured Nylon-CF composites.

ANOVA Analysis:

Table 3. Analysis of Variance for Ultimate Tensile Strength

| Source | Seq SS | Contribution | Adj SS | Adj MS | F-Value | P-Value |
|---|---|---|---|---|---|---|
| Infill Line Multiplier | 117.076 | 48.54 % | 117.076 | 58.5378 | 119.36 | 0.008 |
| Infill Patterns | 82.324 | 34.13 % | 82.324 | 41.1622 | 83.93 | 0.012 |
| Infill Percentage % | 40.821 | 16.92 % | 40.821 | 20.4104 | 41.62 | 0.023 |
| Error | 0.981 | 0.41 % | 0.981 | 0.4904 | | |
| Total | 241.202 | 100.00% | | | | |

Contribution: displays the percentage that each factor (Source) in the ANOVA table contributes to the total sequential sum of squares (Seq SS). Higher percentages indicate that the factor contributes more to the response variance. In the ANOVA table, the contribution rate of "infill pattern" factor is 34.13%, "infill density" factor is 16.92% and "infill line multiplier" factor is 48.58%, the contribution rate of "Error" factor is 0.41%.

F-value: A large F-value means that the effect of this factor is large compared to the variance of the error. Also, the larger the value, the more important this factor is in influencing the process response. Thus, F values can be used to classify the factors. An F value less than one means that the effect of the factor is less than the model error. An F value greater than two means that the factor is not small enough, while greater than four means that the effect of the factor is quite large. In the ANOVA table, the F values for the factors in order of ranking their effect from largest to smallest are "infill line multiplier" with an F value of 119.36, "infill pattern" with 83.93 and "infill density" with 41.62 respectively.

P-value: P-value is a probability that measures the evidence against the null hypothesis. Lower probabilities provide stronger evidence against the null hypothesis. To determine whether the relationship between the response and each term in the model is statistically significant, the P-value of the term is compared to the significance level for the null hypothesis evaluation. The null hypothesis asserts that there is no relationship between the term and the response. Typically, a significance level of $\alpha=0.05$ works well. A significance level of 0.05 indicates a 5% risk of concluding that a relationship exists when in fact it does not.

P-value $\leq 0.05$: The relationship is statistically significant.

If the p-value is less than or equal to the significance level, we can conclude that there is a statistically significant relationship between the response variable and the term.

P-value > 0,05: The relationship is not statistically significant

If the p-value is greater than the significance level, we cannot conclude that there is a statistically significant relationship between the response variable and the term. The model can be re-fitted without the term.

In the ANOVA table the P value of the factor "infill line multiplier" is 0.008 < 0.05, the factor " infill pattern" is 0.012 < 0.05 and the factor "infill density" is 0.023 < 0.05 therefore we conclude that all the factors are statistically significant.

Table 4. Analysis of variance for Young Modulus

| Source | Seq SS | Contribution | Adj SS | Adj MS | F-Value | P-Value |
|---|---|---|---|---|---|---|
| Infill Line Multiplier | 45.352 | 44.00% | 45.352 | 22.6761 | 46.99 | 0.021 |
| Infill Patterns | 22.799 | 22.12% | 22.799 | 11.3995 | 23.62 | 0.041 |
| Infill Percentage % | 33.953 | 32.94% | 33.953 | 16.9763 | 35.18 | 0.028 |
| Error | 0.965 | 0.94% | 0.965 | 0.4825 | | |
| Total | 103.069 | 100.00% | | | | |

From Table 2, on the other hand, for maximizing the elasticity measure, the contribution of infill density comes second after the infill line multiplier factor, while all factors have a large effect and are statistically significant.

Compression Tests:

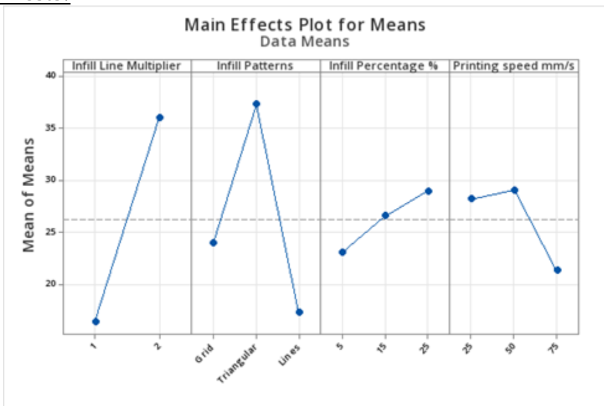


Figure 5. The primary effects of the processing parameters on the compressive strength of the produced specimens were analyzed using Taguchi's L18 array DOE. The average compressive strength of the fabricated specimens is represented by the dashed gray line.

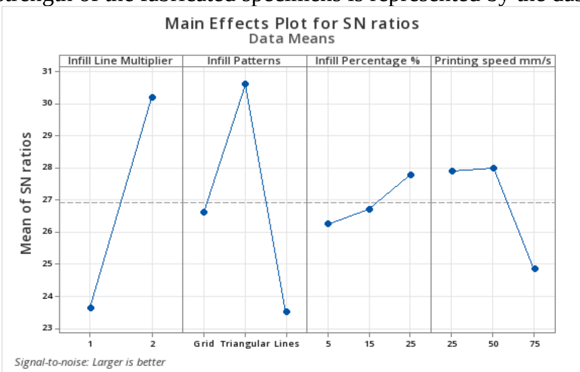

Figure 6. The graphs demonstrate the primary impacts of the processing factors on the compressive strength signal-to-noise ratio. The dashed gray line indicates the average signal-to-noise ratio of all the manufactured specimens

The study examines how different processing factors of Fused Deposition Modeling (FDM) affect the compressive strength of the specimens. Figure 5 shows the graphs of each processing parameter. The findings suggest that the percentage of infill and printing speed have a minimal impact on the resultant compressive strength of the specimens. Augmenting the infill % leads to a marginal augmentation in the compressive strength of the specimen, in line with the anticipated linear correlation, since it provides additional material to counteract the applied stress. Similarly, there is a nearly direct correlation between printing speed and compression strength of the specimens, where an increase in printing speed results in a decrease in compression strength. This phenomenon can be explained by the potential of greater printing speeds to diminish material deposition, leading to a subsequent decrease in adhesion between the layers. The infill pattern is identified as the parameter that has the most significant influence on the compression strength. More precisely, the triangle infill design produces the greatest compression strength values, whilst the grid and linear infill patterns produce the lowest values. The infill line multiplier has the second highest impact on the resultant compression strength. Augmenting the infill line multiplier leads to a proportional augmentation in the infill percentage of the specimen, resulting in a bigger mass of the specimen. This setting enhances the rigidity of the infill material. In order to optimize the Signal-to-Noise (S/N) ratio and improve the consistency of compression strength measurements for the specimen, it is advisable to utilize a double infill line, a triangle infill pattern, a 25% infill percentage, and a printing speed of 50 mm/s. The parameters described are anticipated to result in the greatest level of consistency in the compression strength of the specimens, as shown in Figure 6.

For Compressive Yield Strength, the Figures 7 and 8 are presented below,

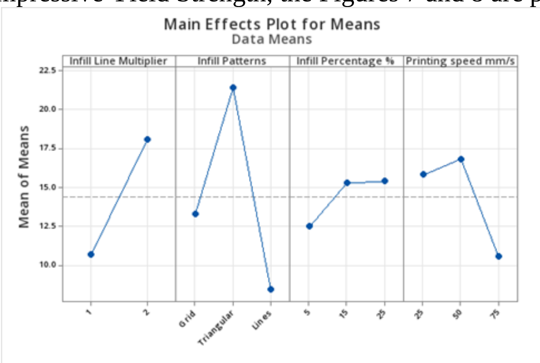

Figure 7. Plots of the main effects of the processing parameters on the compressive yield strength of the fabricated specimens investigated using Taguchi's L18 array DOE, the dashed gray line represents the average compressive yield strength of the fabricated specimens

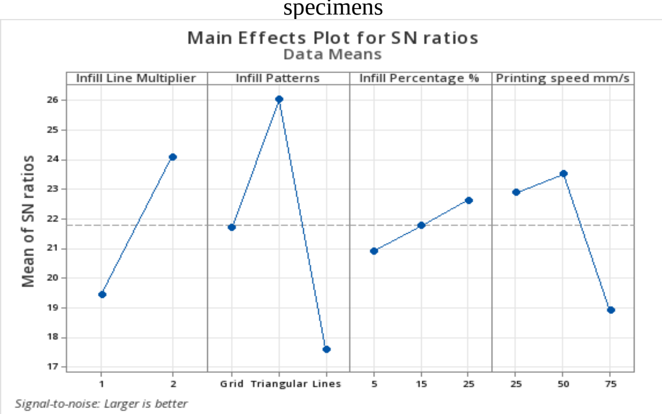


Figure 8. Plots of the main effects of the processing parameters on compressive yield strength S/N ratio, the dashed gray line represents the average S/N ratio of all the fabricated specimens.

The findings suggest that the processing factors have a comparable effect on the yield strength as they do on the compression strength. Infill patterns have an equal impact on both the yield strength and compression strength, as well as on the elastic modulus. The triangle infill pattern achieved the highest maximum yield strength, as shown in Figure 7. The strength of the material improves proportionally with the increase in infill percentage. However, there is no substantial further improvement in the yield strength beyond a 15% infill percentage. In contrast, increased printing speeds have an adverse impact on the strength of the material. According to Figure 8, the Signal-to-Noise (S/N) ratio for yield strength is maximized when the same processing parameters are used.

Table 5. Analysis of Variance for Compressive strength

| Source | Seq SS | Contribution | Adj SS | Adj MS | F-Value | P-Value |
|---|---|---|---|---|---|---|
| Infill Line Multiplier | 193.120 | 41.04% | 193.120 | 193.120 | 24.11 | 0.001 |
| Infill Patterns | 151.497 | 32.19% | 151.497 | 75.748 | 9.46 | 0.005 |
| Infill Percentage % | 7.334 | 1.56% | 7.334 | 3.667 | 0.46 | 0.645 |
| Error | 80.103 | 17.02% | 80.103 | 8.010 | | |
| Total | 470.601 | 100.00% | | | | |

Table 6. Analysis of variance for compressive yield strength

| Source | Seq SS | Contribution | Adj SS | Adj MS | F-Value | P-Value |
|---|---|---|---|---|---|---|
| Infill Line Multiplier | 96.902 | 21.16% | 96.902 | 96.902 | 15.15 | 0.003 |
| Infill Patterns | 213.444 | 46.61% | 213.444 | 106.722 | 16.69 | 0.001 |
| Infill Percentage % | 8.870 | 1.94% | 8.870 | 4.435 | 0.69 | 0.522 |
| Error | 63.943 | 13.96% | 63.943 | 6.394 | | |
| Total | 457.919 | 100.00% | | | | |

Contribution: This indicates the proportionate contribution, expressed as a percentage, of each factor (source) in the ANOVA table to the overall sequential sum of squares (Seq SS). Greater percentages indicate a higher level of contribution from the factor to the variation in the response. The ANOVA table displays the contribution percentages of the components as follows: "Infill line multiplier" contributes 41.04%, "Infill patterns" contributes 32.19%, "Infill percentage" contributes 1.56%, "Printing speed" contributes 8.19%, and the remaining 17.02% is attributed to mistake.

The ANOVA table displays the F-values for the components, listed in descending order of their influence: "Infill line multiplier" has the greatest F-value of 24.11, followed by "Infill patterns" with 9.46, "Printing speed" with 2.41, and "Infill percentage" with 0.46. The ANOVA table shows that the P-value for the factor "Infill line multiplier" is 0.001 and for "Infill patterns" is 0.005. Both of these values are less than the significance level of 0.05, showing that both factors are statistically significant. The remaining factors have P-values exceeding 0.05, indicating that they lack statistical significance.

<u>3-point Bending Test:</u>

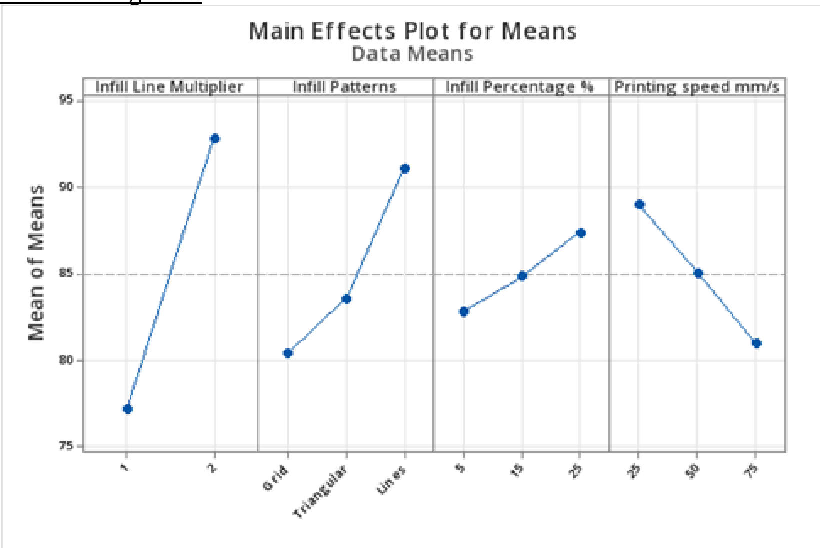

Figure 9. Plots illustrating the impact of processing factors on the flexural strength of the fabricated specimens were analyzed using Taguchi's L18 array Design of Experiments (DOE). The dashed gray line indicates the average flexural strength of the fabricated specimens.

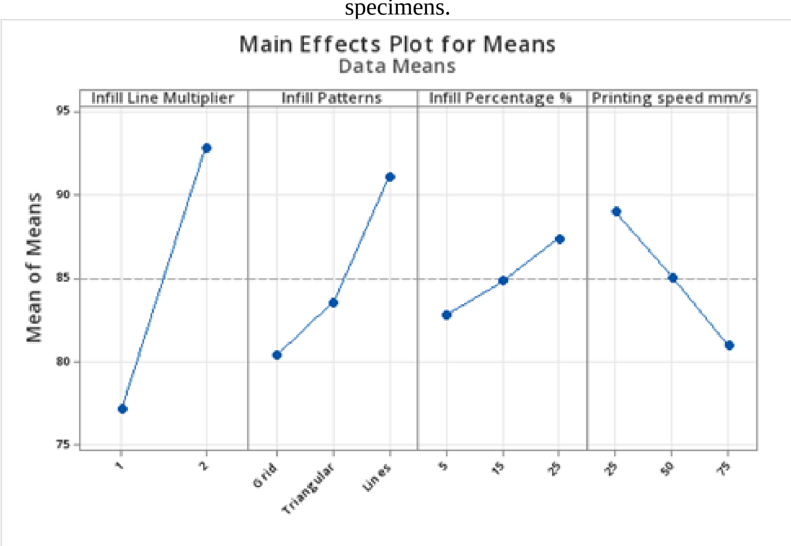


Figure 10. The plots illustrate the primary impacts of the processing factors on the flexural strength signal-to-noise (S/N) ratio. The dashed gray line indicates the average S/N ratio of all the produced specimens.

The flexural test results are presented in Figure 9, displaying the mean values obtained from each of the five repeated specimens. The parameters examined in this study include the flexural fracture stress and flexural strength, Flexural Strength, and the energy required to produce the specimens. For the signal-to-noise ratio, a bigger value is preferable. The signal-to-noise ratio (S/N ratio) is employed to maximize these desired mechanical properties.

The study examines how different processing factors of Fused Deposition Modeling (FDM) affect the flexural strength of the specimens. Figure 9. The charts of each processing parameter are shown. The findings suggest that the impact of the infill percentage and printing speed on the flexural strength of the specimens is less significant compared to the other parameters. Higher infill percentages lead to a proportional increase in the flexural strength of the specimen, since it introduces additional material to withstand the applied load. Similarly, there is a nearly direct correlation between printing speed and compression strength of the specimens, where an increase in printing speed results in a decrease in compression strength.

This phenomenon is ascribed to the potential that increased printing velocities could diminish the amount of material being deposited, leading to a subsequent decline in the bonding between the layers.

The parameter that has the greatest influence on the flexural strength is the infill line multiplier. More precisely, the double infill line produces the highest flexural strength numbers, whilst the infill line multiplier 1 produces the lowest values. The infill patterns have the second highest impact on the final flexural strength. Utilizing a lines design yields superior flexural strength, while a grid pattern exhibits the lowest values of flexural strength. The triangle pattern is in between these two extremes.

In order to optimize the Signal-to-Noise (S/N) ratio and improve the consistency of flexural strength measurements, it is advisable to employ a double infill line, a lines infill pattern, a 25% infill percentage, and a printing speed of 25 mm/s. The parameters described are anticipated to result in the greatest level of consistency in the flexural strength of the specimens, as shown in Figure 10.

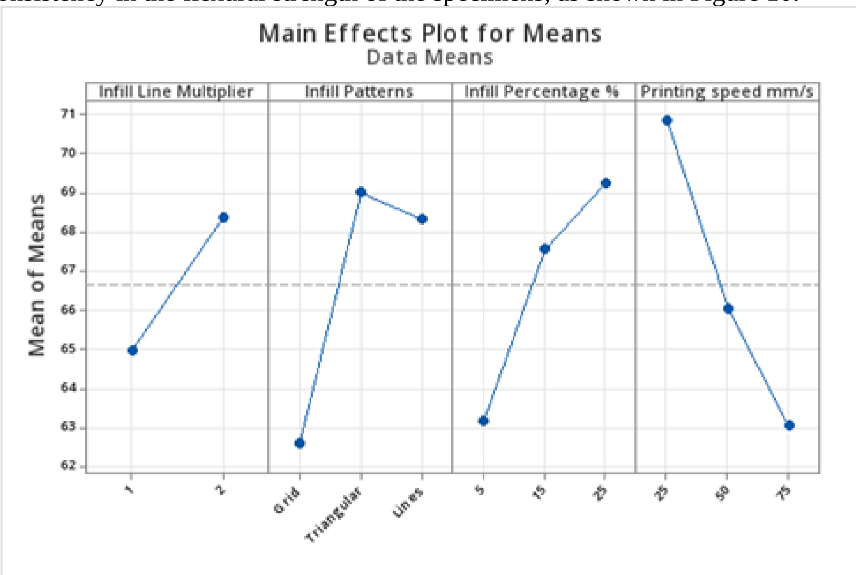


Figure 11. The primary effects of the processing factors on the flexural break stress of the produced specimens were analyzed using Taguchi's L18 array DOE. The average flexural break stress of the fabricated specimens is represented by the dashed gray line.

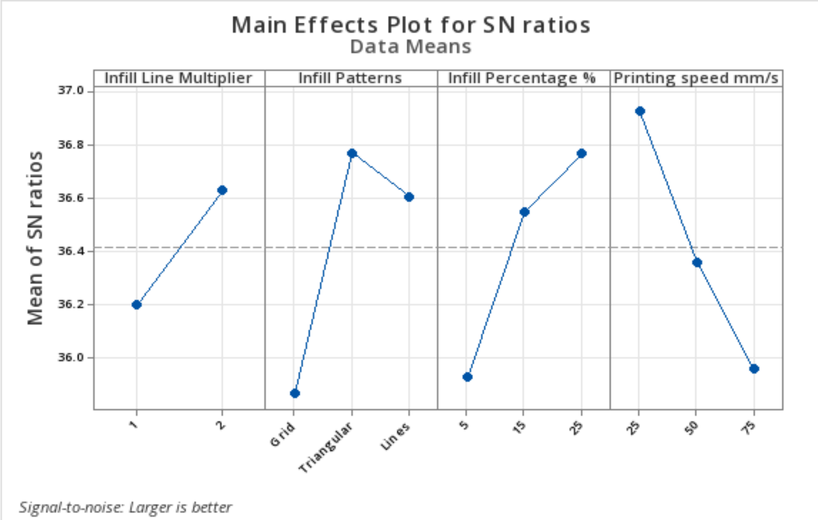


Figure 12. The graphs demonstrate the primary impacts of the processing parameters on the flexural break stress S/N ratio. The dashed gray line indicates the average S/N ratio of all the fabricated specimens.

The findings suggest that the flexural break stress is affected by the processing factors in a manner that is comparable to their impact on flexural strength. The printing speed has an equal impact on both the flexural break stress and flexural strength, as well as on the elastic modulus. It is worth mentioning that the printing speed of 25 mm/s achieved the highest maximum flexural break stress, as shown in Figure 11. The flexural fracture strength rises proportionally with the increase in the percentage of infill. The triangular infill design appears to produce superior results in terms of flexural break stress, whilst the lines pattern exhibits nearly identical performance. The grid infill pattern reduces the flexural break stress values. The infill line multiplier has a comparable impact on flexural strength, but it is the least significant factor. According to Figure 12, in order to get the highest Signal-to-Noise (S/N) ratio for flexural break stress, the processing parameters need to remain the same, except for the infill pattern which should be triangular.

Table 7. Analysis of Variance for Flexural Strength

| Source | Seq SS | Contribution | Adj SS | Adj MS | F-Value | P-Value |
|---|---|---|---|---|---|---|
| Infill Line Multiplier | 12.4723 | 49.24% | 12.4723 | 12.4723 | 20.01 | 0.001 |
| Infill Patterns | 4.3362 | 17.12% | 4.3362 | 2.1681 | 3.48 | 0.071 |
| Infill Percentage % | 0.5338 | 2.11% | 0.5338 | 0.2669 | 0.43 | 0.663 |
| Printing speed mm/s | 1.7562 | 6.93% | 1.7562 | 0.8781 | 1.41 | 0.289 |
| Error | 6.2335 | 24.61% | 6.2335 | 0.6233 | | |
| Total | 25.3320 | 100.00% | | | | |

Table 8. Analysis of Variance for Flexural break stress

| Source | Seq SS | Contribution | Adj SS | Adj MS | F-Value | P-Value |
|---|---|---|---|---|---|---|
| Infill Line Multiplier | 0.8326 | 4.23% | 0.8326 | 0.8326 | 0.76 | 0.404 |
| Infill Patterns | 2.7621 | 14.03% | 2.7621 | 1.3811 | 1.26 | 0.325 |
| Infill Percentage % | 2.2813 | 11.58% | 2.2813 | 1.1406 | 1.04 | 0.389 |
| Printing speed mm/s | 2.8519 | 14.48% | 2.8519 | 1.4260 | 1.30 | 0.315 |
| Error | 10.9642 | 55.68% | 10.9642 | 1.0964 | | |
| Total | 19.6921 | 100.00% | | | | |

The Analysis of Variance (ANOVA) for flexural strength and flexural break stress provides significant insights into the influence of various printing parameters on the mechanical properties of Nylon-Carbon Fiber composites. In the flexural strength analysis, the most critical factor proved to be the infill line multiplier, which showed a substantial contribution of 49.24% to the model with an F-value of 20.01, indicating a highly significant effect (P-value = 0.001). This suggests that the infill line multiplier greatly influences the composite's ability to resist bending forces, which is crucial for applications requiring high flexural strength. Conversely, other factors such as infill patterns, infill percentage, and printing speed demonstrated less impact. Infill patterns and printing speed showed some influence with F-values of 3.48 and 1.41, respectively, but their contributions were not statistically significant at conventional levels (P-values of 0.071 and 0.289, respectively). The infill percentage contributed minimally to flexural strength variations, as reflected by a low F-value of 0.43 and a non-significant P-value of 0.663, indicating that changes in percentage infill do not considerably alter the flexural strength within the tested range. For flexural break stress, the ANOVA results indicated a more evenly distributed but generally non-significant influence across all tested parameters. The highest contribution came from printing speed, contributing 14.48% with an F-value of 1.30 (P-value = 0.315), followed closely by infill patterns and infill percentage, which showed similar contributions and non-significant P-values. The infill line multiplier, despite being a significant factor in flexural strength, showed a minimal and non-significant effect on flexural break stress (P-value = 0.404). These findings suggest that while certain parameters significantly affect flexural strength, such as the infill line multiplier, their impact on flexural break stress is less pronounced. This differentiation in parameter influence highlights the complexity of 3D printing settings on material properties, underscoring the need for careful selection and optimization of parameters based on the specific mechanical property requirements of the final product.

## 4. Conclusion

This study provides a detailed analysis of the mechanical properties of Nylon-Carbon Fiber composites manufactured using Fused Filament Fabrication (FFF). By examining tensile, compressive, and flexural strengths under various printing parameters, significant insights were gained into the optimization of these properties for industrial applications.

The tensile tests showed that the 'lines' infill pattern, when combined with a 15% infill density and a three-line multiplier, produced the highest tensile strength, enhancing the load-bearing capacity of the material. This configuration led to an optimal tensile strength of up to 18 MPa and a Young's modulus of 1.58 GPa, demonstrating that precise control over the infill parameters can lead to substantial improvements in performance. The consistency and reliability of these settings were validated by the Signal-to-Noise ratios, ensuring that the enhancements in mechanical properties are both significant and dependable.

In compressive strength tests, while the infill pattern and line multiplier impacted strength, their effects were less pronounced than in tensile strength tests. The optimal settings that favored higher infill percentages and specific infill patterns still provided a modest increase in compressive strength, with the best configurations achieving up to 35 MPa, indicating improved rigidity and load-bearing capacity under compression.

Flexural strength testing highlighted the critical role of the infill line multiplier, which substantially influenced the material's ability to resist bending forces. The best settings, involving a double infill line and specific speeds and patterns, led to a maximum flexural strength of 94 MPa. These parameters were crucial in distributing stress and strain across the composite during bending tests, thereby enhancing its structural integrity under flexural loads.

In summary, this research has systematically explored how the adjustment of key printing parameters can manipulate the mechanical properties of Nylon-Carbon Fiber composites in targeted ways. Each set of mechanical tests—tensile, compressive, and flexural—has its own set of optimal print settings, highlighting the need for a nuanced approach to the 3D printing of advanced composite materials. Future studies could further refine these findings by exploring the interaction effects between parameters and extending the analysis to include dynamic loading conditions and long-term material behavior. This would provide even deeper insights into the practical applications of FFF technology in producing high-performance parts for aerospace, automotive, and other demanding industrial sectors.

**References: 1.** *M. S. Alsoufi, A. El-Sayed, and A. E. Elsayed,* How Surface Roughness Performance of Printed Part Manufactured by Desktop FDM 3D Printer with PLA+ is Influenced by Measuring Direction, Am. J. Mech. Eng., vol. 5, no. 5, pp. 211–222, 2017, doi: 10.12691/ajme-5-5-4. **2.** *A. Rashid,* Additive Manufacturing Technologies, CIRP Encycl. Prod. Eng., pp. 1–9, 2019. **3.** *S. Vyavahare, S. Teraiya, D. Panghal, and S. Kumar,* Fused deposition modelling: a review, Rapid Prototyp. J., vol. 26, no. 1, pp. 176–201, 2020, doi: 10.1108/RPJ-04-2019-0106. **4.** *K. Rajan, M. Samykano, K. Kadirgama, W. S. W. Harun, and M. M. Rahman*, Fused deposition modeling: process, materials, parameters, properties, and applications, vol. 120, no. 3–4. Springer London, 2022. doi: 10.1007/s00170-022-08860-7. **5.** *O. S. Es-Said, J. Foyos, R. Noorani, M. Mendelson, R. Marloth, and B. A. Pregger*, Effect of layer orientation on mechanical properties of rapid prototyped samples, Mater. Manuf. Process., vol. 15, no. 1, pp. 107–122, 2000, doi: 10.1080/10426910008912976. **6.** *K. M. Ashtankar, A. M. Kuthe, and B. S. Rathour*, IMECE 2013-63146, pp. 1–7, 2016. **7.** *L. Baich, G. Manogharan, and H. Marie*, Study of infill print design on production cost-time of 3D printed ABS parts, Int. J. Rapid Manuf., vol. 5, no. 3/4, p. 308, 2015, doi: 10.1504/ijrapidm.2015.074809. **8.** *K. Durgashyam, M. Indra Reddy, A. Balakrishna, and K. Satyanarayana*, Experimental investigation on mechanical properties of PETG material processed by fused deposition modeling method, Mater. Today Proc., vol. 18, pp. 2052–2059, 2019. **9.** *D. Yadav, D. Chhabra, R. Kumar Garg, A. Ahlawat, and A. Phogat*, Optimization of FDM 3D printing process parameters for multi-material using artificial neural network, Mater. Today Proc., vol. 21, pp. 1583–1591, 2020, doi: 10.1016/j.matpr.2019.11.225. **10.** *R. Srinivasan, W. Ruban, A. Deepanraj, R. Bhuvanesh, and T. Bhuvanesh*, Effect on infill density on mechanical properties of PETG part fabricated by fused deposition modelling, Mater. Today Proc., vol. 27, pp. 1838–1842, 2020, doi: 10.1016/j.matpr.2020.03.797. **11.** *E. V. De Toro, J. C. Sobrino, A. M. Martínez, and V. M. Eguía*, Analysis of the influence of the variables of the fused deposition modeling (FDM) process on the mechanical properties of a carbon fiber-reinforced polyamide, Procedia Manuf., vol. 41, pp. 731–738, 2019, doi: 10.1016/j.promfg.2019.09.064. **12.** *J. León-Becerra, M. Á. Hidalgo-Salazar, J. P. Correa-Aguirre, O. A. González-Estrada, and A. D. Pertuz*, Additive manufacturing of short carbon filled fiber nylon: effect of build orientation on surface roughness and viscoelastic behavior, Int. J. Adv. Manuf. Technol., vol. 130, no. 1–2, pp. 425–435, Jan. 2024, doi: 10.1007/s00170-023-12503-w. **13.** *F. Sedlacek and V. Lašová*, Additive Manufacturing of PA6 with Short Carbon Fibre Reinforcement Using Fused Deposition Modelling, Mater. Sci. Forum, vol. 928, pp. 26–31, Aug. 2018, doi: 10.4028/www.scientific.net/MSF.928.26.

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# ЕКСПЕРИМЕНТАЛЬНЕ ДОСЛІДЖЕННЯ МЕХАНІЧНИХ ВЛАСТИВОСТЕЙ КОМПОЗИТІВ НЕЙЛОН-ВУГЛЕЦЕВЕ ВОЛОКНО, ВИГОТОВЛЕНИХ ІЗ ПЛАВКИХ НИТОК

**Анотація.** *Адитивне виробництво (АМ) – це галузь, яка швидко розвивається як у дослідницькому, так і в промисловому світі, оскільки дозволяє виробляти дуже індивідуальні та геометрично складні об'єкти. Найвідомішою технологією АМ для пластмас є виробництво з плавленої нитки (Fused Filament Fabrication, FFF), в якій термопластична нитка розплавляється і видавлюється через сопло на друкарську пластину. На якість надрукованих об'єктів впливають різноманітні параметри друку, такі як швидкість друку, щільність заповнення, малюнок заповнення,* *орієнтація побудови, висота шару тощо. У літературі вже існують ґрунтовні дослідження впливу параметрів друку на механічні властивості найпоширеніших термопластів, таких як ABS і PETG. Однак розробка сучасних термопластичних матеріалів, таких як нейлонові композити, армовані вуглецевими волокнами (Nylon-CF), вимагає подальшого дослідження впливу параметрів друку на ці композити. У даному дослідженні проведено поглиблену кореляцію всіх основних параметрів друку (малюнок заповнення, щільність заповнення, дворядкове заповнення і швидкість друку) з усіма основними механічними властивостями (міцність на розрив, міцність на стиск і міцність на вигин) нейлону з вуглецевим волокном (Nylon-CF). Випробування на розтягнення показали, що "лінійна" структура заповнення в поєднанні з 15% щільністю заповнення і трилінійним мультиплікатором забезпечує найвищу міцність на розтягнення, підвищуючи тримальну здатність матеріалу. Така конфігурація дозволила досягти оптимальної міцності на розрив до 18 МПа і модуля Юнга 1,58 ГПа, демонструючи, що точний контроль параметрів заповнення може призвести до значного поліпшення експлуатаційних характеристик. Послідовність і надійність цих налаштувань були підтверджені співвідношенням сигнал/шум, яке гарантує, що покращення механічних властивостей є значним і надійним. Таким чином, це дослідження системно вивчило, як регулювання ключових параметрів друку може цілеспрямовано впливати на механічні властивості композитів з нейлон-вуглецевого волокна. Для кожного набору механічних випробувань - розтягування, стиснення та згинання - є свій набір оптимальних параметрів друку, що підкреслює необхідність нюансованого підходу до 3D-друку передових композитних матеріалів. Майбутні дослідження можуть уточнити ці висновки, вивчивши ефекти взаємодії між параметрами і розширивши аналіз, включивши в нього динамічні умови навантаження і довгострокову поведінку матеріалу. Це дало б ще глибше розуміння практичного застосування технології FFF у виробництві високопродуктивних деталей для аерокосмічної, автомобільної та інших відповідальних галузей промисловості.*

**Ключові слова:** *виробництво плавких ниток (FFF); нейлон-вуглецеве волокно (Nylon-CF); міцність на розрив; міцність на стиск; міцність на вигин.*