# Optimization of an Aerospace Bracket by Additive Manufacturing with Continuous Fiber Reinforced Plastics

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**Abstract -** Fused Deposition Modelling (FDM), one of the most widely used methods of Additive Manufacturing Technique known as 3D Printing, is a popular technique used to produce different engineering components using common engineering fibre. Carbon fibre filament. This study presents an experimental study examining the effect of printing parameters on the mechanical properties of components produced with Carbon fibre filaments. The effects of the printing parameters determined as infill pattern, infill density and nozzle temperature on the mechanical strength parameter determined as tensile strength and flexural strength of Carbon fibre samples produced in standard sizes were investigated experimentally. The experimental design was carried out in accordance with the Taguchi L9 orthogonal array, and the relationship between the printing parameters and the mechanical strength parameters was modelled mathematically. The predicted strength values calculated using mathematical models were compared with the experimental test results. The results showed that the tensile strength and flexural strength values were directly proportional to the infill density. Experiments have shown that the most effective 3D printing parameter on the mechanical strength parameters is the infill density parameter with a contribution ratio of 62.09% for tensile strength and 72.83% for flexural strength. As a result of the RSM optimization, it was determined that the infill density 60%, the nozzle temperature value 265 C° and the infill pattern type lines to maximize the flexural strength and tensile strength values.

***Key Words*:** Sustainable Material, 3D Printing Parameters, Mechanical Strength Optimization, Response Surface Methodology.

## 1. INTRODUCTION

Three-dimensional production technique has become increasingly popular due to its advantages such as ease of use, economic accessibility and fast production process. One of the most important factors in the spread of this technique is the easy accessibility of this technology. In addition, researchers can produce prototypes of the designs they have developed with this technique without the need for complex and experience-requiring production techniques and they can make design changes when necessary. The production of products with complex geometry has also become possible with this method.

The Fused Deposition Technique (FDM) is the most common production technique known in additive manufacturing technology. A printer working with the FDM technique heats the filament material until it becomes semi-molten using a heater extruder and follows the tool path created by the software, stacking the layers on top of each other from the bottom up to form a three-dimensional object. In the FDM technique, printing parameters can be easily changed and optimized.

Different filament materials have been developed by considering factors such as the melting point and extrudability of the material to be used in the FDM technique. Carbon fiber reinforced with Onyx is a versatile and high-performance material used in additive manufacturing for various applications requiring strength, durability, and lightweight properties. Its uses span across industries such as aerospace, automotive, medical, sports, and robotics, making it a valuable material for both prototyping and end-use parts.

Academic studies carried out in recent years have focused on examining the effect of printing parameters on different mechanical properties. Optimization of printing parameters for ideal properties determined by different application areas is an important issue for the final use of the product. There is still a deficiency in the literature examining the mechanical properties of filaments developed with different filling materials. Optimization of the mechanical properties of biomaterials is important in terms of increasing the use of sustainable materials.

In this study, the effect of 3D printing parameters on the mechanical properties of samples produced using Carbon Fibre with Onyx filament was investigated. The effects of the production parameters determined as infill type, infill density and nozzle temperature on the tensile strength and flexural strength of the samples produced according to the Taguchi L9 experimental design were investigated. Response Surface Methodology was used to determine the effect of each printing parameter on the output values and to determine the optimum printing parameters.

## 2. LITERATURE REVIEW

In this study **(Basim El Essawi et al., 2024)** conducted an experimental investigation that the position of the carbon fiber layer has comparatively less effect on the final mechanical properties of 3D printed parts, with a contribution of 10.12%. To facilitate the optimization, the outcomes will be helpful for designing and manufacturing 3D printed carbon-fiber reinforced nylon composite parts.

In this study **(Erman Zurnacı 2023)** conducted a numerical and experimental investigation in which the results showed that the tensile strength and flexural strength values were directly proportional to the infill density. Experiments have shown that the most effective 3D printing parameter on the mechanical strength parameters is the infill density parameter with a contribution ratio of 63.09% for tensile strength and 73.83% for flexural strength. As a result of the RSM

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optimization, it was determined that the infill density 60%, the nozzle temperature value 202.62 C° and the infill pattern type lines to maximize the flexural strength and tensile strength values.

In this study **(Gurcan Atakok et al., 2022)** conducted a numerical and experimental investigation demonstrates the possibility of 3DP with Re-PLA filament and environmental awareness was noted by using recycled filament. The study demonstrates the possibility of 3DP with Re-PLA filament and environmental awareness was noted by using recycled filament. The research shows that 3D printing with Re-PLA is feasible.

In this study **(Mustafa Gunay 2019)** conducted a numerical investigation in which it was determined that the increase in the printing speed decreased the tensile and bending strength proportionally. Between the results obtained from the mathematical models developed with multiple regression analysis and experimental results, an average deviation of 3% for tensile strength and 2% for bending strength were found.

## 3. MATERIAL AND METHODS

### 3.1. Printing Material and Parameters:

**Properties of Carbon Fiber with Onyx Filament:**

**Mechanical Properties:**

1. **Tensile Strength**: High, significantly higher than standard 3D printing materials.
2. **Flexural Strength**: High, providing excellent resistance to bending.
3. **Young's Modulus**: High, indicating the material's stiffness and resistance to elastic deformation.
4. **Impact Resistance**: Good, able to absorb energy from impacts without fracturing.
5. **Compressive Strength**: High, resists crushing forces effectively.

**Thermal Properties:**

1. **Heat Deflection Temperature:** High, can withstand elevated temperatures without deforming.
2. **Thermal Expansion:** Low, maintaining dimensional stability under temperature changes.

**Physical Properties:**

1. **Density:** Low, providing a high strength-to-weight ratio.
2. **Surface Finish:** Smooth, professional finish reducing the need for extensive post-processing.
3. **Dimensional Stability:** Excellent, with minimal warping or shrinkage.

**Chemical Properties:**

1. **Chemical Resistance:** Good, resists degradation from exposure to various chemicals and solvents.

**Specific Properties for Mark forged Onyx with Carbon Fiber Filament:**

1. **Tensile Strength:** 800 MPa (with continuous carbon fibre reinforcement)
2. **Flexural Strength:** 540 MPa
3. **Young's Modulus:** 51 GPa
4. **Density:** 1.2 g/cm³
5. **Heat Deflection Temperature:** 145°C

These properties make Carbon Fiber with Onyx filament a highly desirable material for applications demanding high strength, stiffness, and thermal stability, while also benefiting from a lightweight and durable structure.

For experimental tests, tensile test specimens were designed in accordance with ASTM D638-IV and three-point bending test specimens ASTM D790 test standards. Three-dimensional models of the samples were created with CATIA solid modeling software.

### 3.2. Experimental Design:

The printing parameters are an effective factor on the mechanical strength criteria of the samples produced with the FDM technique. Three different printing parameters were used in the production of the samples produced with Carbon Fiber with Onyx filament: infill pattern, infill density and nozzle temperature. Taguchi optimization technique is a frequently used method in the literature to determine optimum mechanical parameters by reducing product development costs. Experimental design was carried out in accordance with the Taguchi L9 orthogonal array with the printing parameters and levels given in Table 1. The cross-sectional views of the tensile specimens converted to STL format for different printing parameters are given in Figure 1.

**Table 1.** Taguchi design factors and levels

| Factors | Units | Level 1 | Level 2 | Level 3 |
|---|---|---|---|---|
| Infill Pattern | - | Lines | Triangles | Cubic |
| Infill Density | % | 20 | 40 | 60 |
| Nozzle Temp | °C | 265 | 270 | 280 |

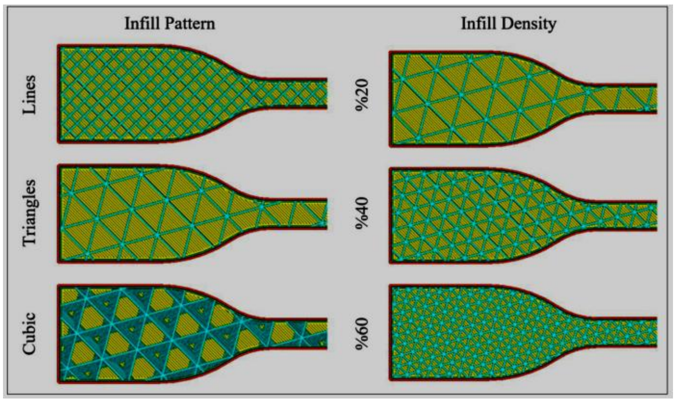



**Figure 1.** Infill pattern and infill density cross section views

### 3.3. Production of Experimental specimens:

Experimental test samples based on Carbon Fiber with Onyx were produced at room temperature in a mark forged mark two printer at Government Engineering College, Bargur, which produces with FDM technique. In the mechanical tests, the number of upper and lower layers was limited to three layers in order to make the effect of the printing parameters on the mechanical properties more evident. Thus, it is aimed to increase the effect of infill pattern and infill density parameters on mechanical properties. In order not to deteriorate the dimensional stability of Carbon Fiber with Onyx filaments by being affected by thermal changes, support was created for the samples in the production of the first layer. The printing parameters used in the production of experimental test samples are given in Table 2. In order to ensure the experimental measurement accuracy.

**Table 2.** FDM printing parameters

| Item Descriptions | Category | Technical Specification |
|---|---|---|
| PRINTER | Process | Continuous Fiber Reinforced Plastics |
| | Build Volume | 320 x 132 x 154 mm (12.6 x 5.2 x 6 in) |
| | Weight | 16 kg (35 lbs) |
| | Machine Footprint | 584 x 330 x 355 mm (23 x 13 x 14 in) |
| | Print Bed | Flat to within 160 um - Kinematic coupling |
| | Power | 100-240VAC, 150W (2A peak) |
| PART PROPERTIES | Layer Height | 100um default, 200um maximum |
| | Ultimate Tensile Strength | 700 MPa (22.6x ABS, 19.4x Onyx) |
| | Max Flexural Stiffness | 51 GPa (24.8x ABS, 17.6x Onyx) |
| | Infill | Closed Cell Infill: Multiple geometries available |
| SOFTWARE | Supplied Software | Markforged Software - Cloud Storage, Local Storage, or |
| | Security | Two Factor Auth, Org Admin Access, Single Sign On |
| MATERIALS | Plastics Available | Onyx |
| | Fibers Available | Carbon Fiber, Fiberglass, Kevlar, High Strength/High Temp Fiberglass |

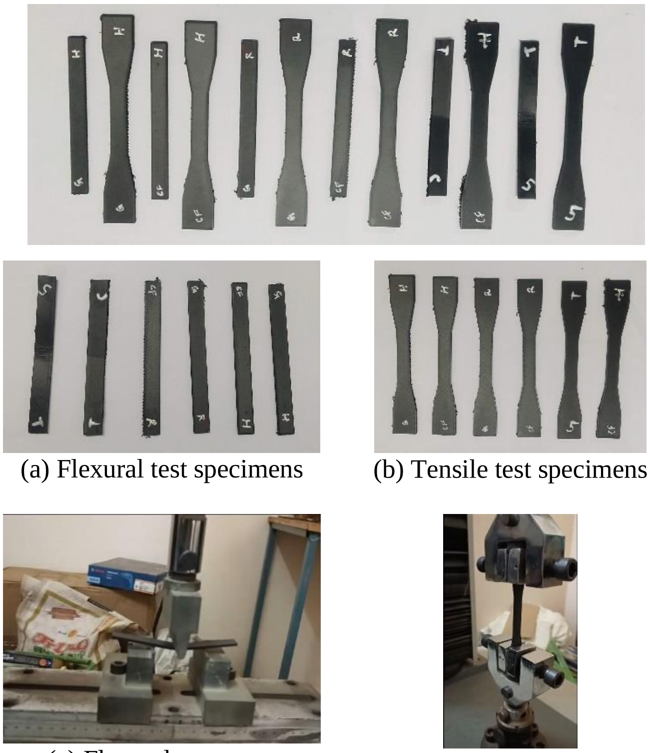
## 4. EXPERIMENTAL STUDY

### 4.1. Tensile Test Setup:

Tensile test specimens were produced in accordance with ASTM D638-IV test standard. The tests were carried out in the 100 kN capacity Schimadzu Autograph AGS-X tensile testing device in L.M.P.R&D Laboratory, Pallipalayam, Erode. Tensile tests were carried out with reference to the literature at a speed of 2.0 mm/min and the tests were continued until the specimens fractured. Tests for each sample were performed at room temperature in triplicate. As a result of the experiments, the tensile strength values of the samples were determined.

### 4.2. Flexural Test Setup:

The flexural test specimens were produced in accordance with the ASTM D790 test standard (Figure 2a) and the specimens were tested using a three-point bending test apparatus in the device used for the tensile test (Figure 2b). Tests for each sample were carried out at a speed of 2.0 mm/min with reference to the literature, and the test was terminated after 5% deflection occurred in the samples. Three point bending test apparatus loading span diameter of 10 mm and a support roller with a diameter of 30 mm with supporting span length of 51.2 mm were used for the flexural tests. Bending load-displacement curves were recorded from the experimental tests. Experimental specimens and test setup is shown in Figure 2.



(a) Flexural test specimens (b) Tensile test specimens

(c) Flexural test setup (d) Tensile test setup

**Figure 2.** Flexural and Tensile specimens & test setup

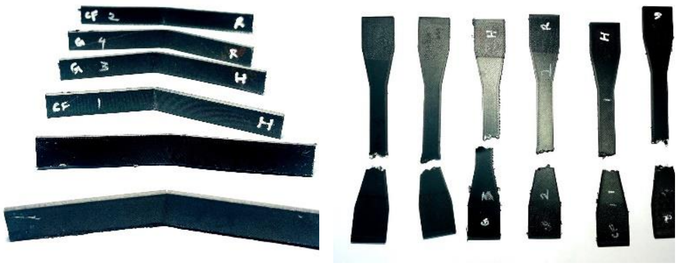
## 5. RESULTS AND OPTIMIZATION

### 5.1. Experimental Results:

In this study, the effect of 3D printing parameters on the mechanical properties of Carbon Fiber with Onyx material samples was investigated. As a result of the experiments carried out with test samples, the tensile strength and flexural strength values of the samples were obtained. The arithmetic means of the test results performed three times for each sample was calculated. Experimental test results are given in Table 3. The post-test images of the tensile test specimens are shown in Figure 3.

**Table 3.** L9 Taguchi orthogonal array and experimental results

| | Infill Pattern | Infill Density (%) | Nozzle Temp. (°C) | Tensile Strength (MPa) | Flexural Strength (MPa) |
|---|---|---|---|---|---|
| 1 | Triangles | 20 | 265 | 69.573 | 105.871 |
| 2 | Triangles | 40 | 270 | 66.345 | 100.435 |
| 3 | Triangles | 60 | 280 | 69.690 | 97.075 |
| 4 | Rectangle | 20 | 270 | 62.710 | 84.391 |
| 5 | Rectangle | 40 | 280 | 60.050 | 75.235 |
| 6 | Rectangle | 60 | 265 | 63.602 | 66.331 |
| 7 | Hexagonal | 20 | 280 | 78.120 | 122.871 |
| 8 | Hexagonal | 40 | 265 | 81.400 | 124.435 |
| 9 | Hexagonal | 60 | 270 | 83.430 | 130.330 |



(a) Flexural test specimens (b) Tensile test specimens

**Figure 3.** Image of Flexural and Tensile Test Specimens after Testing

### 5.2. Response Surface Methodology:

In order to produce Carbon Fiber with Onyx samples with the best mechanical strength properties, optimization of 3D printer printing parameters is required. Response Surface Methodology (RSM) is a method that optimizes output parameters according to the determined objective function by calculating the statistical relationship between input parameters and output parameters. In this study, RSM was used to determine the relationship between 3D printing parameters and tensile strength and flexural strength output parameters. Optimization calculations were performed using Minitab 21.2 software. The maximize objective function was determined for both output variables as the optimization criterion (Figure 4).

| Factor | Name | Low | High |
|---|---|---|---|
| A | Flexural Stre | 66.33 | 130.43 |
| B | Tensile Stren | 60.05 | 83.43 |

**Figure 4.** RSM optimization parameters

Analysis of variance (ANOVA) at the 95% confidence interval was applied on experimental test results to determine the contribution of 3D printing parameters on output parameters. When the results of the ANOVA analysis were examined, it was determined that the most effective 3D printing parameter on tensile strength was infill density with an additive ratio of 62.09%. The infill pattern parameter, on the other hand, was calculated as the second most effective parameter on tensile strength with a contribution rate of 25.85% (Table 4). The R2 value of the ANOVA analysis for the tensile strength parameter was calculated as 0.89. This value shows that the regression equations are highly successful in explaining the predicted tensile strength.

When the results of the ANOVA analysis performed for the flexural strength parameter are examined; it was determined that the most effective 3D printing parameter on flexural strength was the infill density parameter with an additive rate of 71.83%. The infill pattern parameter, on the other hand, was calculated as the second most effective parameter on flexural strength with a 16.42% contribution rate (Table 5). The R2 value of the ANOVA analysis for flexural strength was calculated a 92.00%. This value shows that the regression equations are highly successful in explaining the predicted flexural strength value.

Regression equations to be used to optimize the output variables were created in accordance with the objective function determined by RSM. The regression equations for the factors are presented in Equations 1-6, respectively, to predict the responses of tensile strength and flexural strength. Since the infill pattern is a categorical variable, the constant coefficients of the regression equations change for different infill patterns. For this reason, the regression equations for the infill pattern were given separately. Using these regression equations, the predicted output parameters for the experimental design parameters were calculated (Table 6). In addition, a graph showing the relationship between the predicted output values and the experimental test results is given in Figure 5.

**Table 4.** Results of ANOVA for tensile strength

| Source | DF | Seq SS | Contribution | Adj SS | Adj MS | F Value | P Value |
|---|---|---|---|---|---|---|---|
| Regression | 4 | 24.3637 | 87.00% | 566.415 | 141.604 | 40.83 | 0.002 |
| Infill Density | 1 | 17.2721 | 62.09% | 6.655 | 6.655 | 1.92 | 0.238 |
| Nozzle Temp | 1 | 0.0148 | 0.05% | 7.868 | 7.868 | 2.27 | 0.206 |
| Infill Pattern | 2 | 7.0769 | 25.85% | 551.893 | 275.946 | 79.56 | 0.001 |
| Error | 4 | 3.0125 | 11.00% | 13.873 | 3.468 | | |
| Total | 8 | 27.3762 | 100.00% | 580.28 | | | |
| $R^2$ | | | 87.00% | | | | |

**Table 5.** Results of ANOVA for flexural strength

| Source | DF | Seq SS | Contribution | Adj SS | Adj MS | F Value | P Value |
|---|---|---|---|---|---|---|---|
| Regression | 4 | 214.363 | 92.00% | 3957.7 | 989.43 | 35.34 | 0.002 |
| Infill Density | 1 | 173.721 | 72.83% | 107.5 | 107.5 | 3.84 | 0.122 |
| Nozzle Temp | 1 | 8.0148 | 0.05% | 15.23 | 15.23 | 0.54 | 0.502 |
| Infill Pattern | 2 | 37.769 | 16.42% | 3834.98 | 1917.49 | 68.5 | 0.001 |
| Error | 4 | 13.125 | 11.00% | 111.97 | 27.99 | | |
| Total | 8 | 257.762 | 100.00% | 4069.68 | | | |
| $R^2$ | | | 92.00% | | | | |

| Infill Pattern | | Regression Equations | |
|---|---|---|---|
| Triangles | Tensile Strength (MPa) = | 107.2+0.0527 Infill Density - 01499 Nozzle Temp. | (1) |
| Rectangle | | 100.7+0.527 Infill Density - 0.00390.1499 Nozzle Temp. | (2) |
| Hexagonal | | 119.6+0.0527 Infill Density - 0.1499 Nozzle Temp. | (3) |
| Triangles | Flexural Strength (MPa) = | 166.3-0.212 Infill Density -0.209 Nozzle Temp. | (4) |
| Rectangle | | 140.4-0.212 Infill Density-0.209 Nozzle Temp. | (5) |
| Hexagonal | | 191-0.212 Infill Density -0.209 Nozzle Temp. | (6) |

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**Table 7.** Experimental test results and predicted output values in accordance with the experimental design parameters

| | Infill Pattern | Infill Density (%) | Nozzle Temp. (°C) | Tensile Strength (MPa) | Predicted Tensile Strength (MPa) | Difference ratio (%) | Flexural Strength (MPa) | Predicted Flexural Strength (MPa) | Difference ratio (%) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Triangles | 20 | 265 | 69.573 | 69.273 | -2.29 | 105.871 | 105.371 | -1.55 |
| 2 | Triangles | 40 | 270 | 66.345 | 65.945 | 2.94 | 100.435 | 102.435 | 2.46 |
| 3 | Triangles | 60 | 280 | 69.690 | 69.590 | -0.78 | 97.075 | 98.075 | -1.05 |
| 4 | Rectangle | 20 | 270 | 62.710 | 62.410 | -1.05 | 84.391 | 84.091 | -1.49 |
| 5 | Rectangle | 40 | 280 | 60.050 | 60.150 | -2.43 | 75.235 | 74.235 | -1.45 |
| 6 | Rectangle | 60 | 265 | 63.602 | 63.902 | 2.88 | 66.331 | 67.331 | 2.65 |
| 7 | Hexagonal | 20 | 280 | 78.120 | 78.420 | 3.17 | 122.871 | 124.871 | 3.18 |
| 8 | Hexagonal | 40 | 265 | 81.400 | 81.300 | -0.89 | 124.435 | 129.435 | -1.33 |
| 9 | Hexagonal | 60 | 270 | 83.430 | 83.130 | -1.72 | 130.330 | 125.330 | -1.20 |

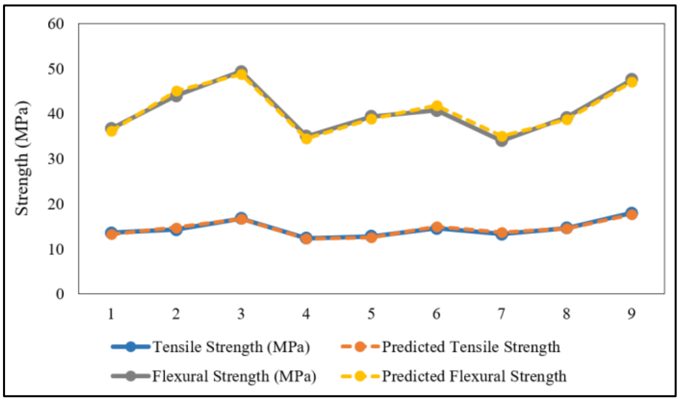
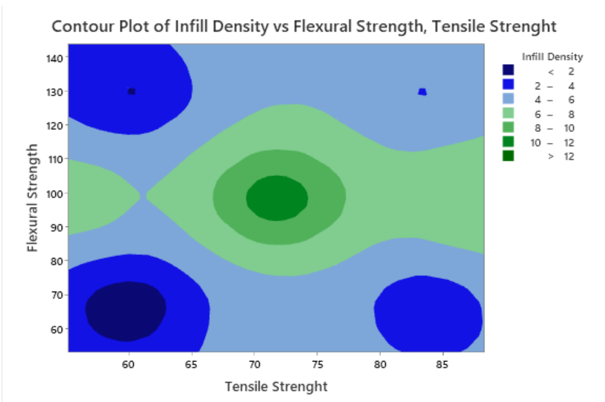



**Figure 5.** Comparison of experimental and predicted mechanical strength results

Contour plots graphs are very useful for examining the relationship between a response variable and two factors. In a contour plot graph, the factor values that affect the response variable are shown on the x and y axes, and the values of the response variable are represented by shaded regions called contours. A contour plots graphs is similar to a topographic map, using coordinates instead of longitude, latitude, and elevation. Contour plot graphs obtained as a result of the optimization performed with the RSM method show the relationship between 3D printing parameters and output parameters. In the contour plot graphs were given in Figure 6, the relationship between two different 3D printing parameters and output variables is shown for the factor levels of the categorical 3D printing parameter infill pattern.



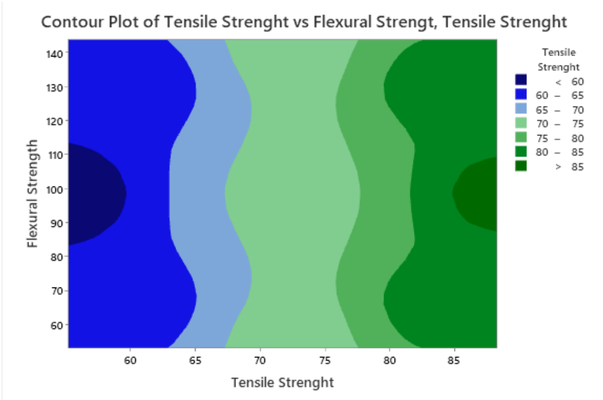




**Figure 6.** Contour Plot graphs of the relationship between printing parameters and mechanical strength criteria

As a result of RSM optimization, necessary factor levels were calculated to maximize flexural strength and tensile strength values. The response optimizer graph shown in Figure 7 gives 3D printing parameters that can optimize flexural strength and tensile strength values together. When the results were interpreted, it was determined that in order to maximize flexural strength and tensile strength values, infill density value should be 60%, nozzle temperature value should be 265.00 °C and infill pattern type should be lines categorical parameters. The predicted flexural strength value to be obtained as a result of the selection of these parameters was calculated as 125.33 MPa and the predicted tensile strength value was calculated as 83.13 MPa.

The response optimizer graph also calculates the composite desirability. This value represents the value of countervailing the objective function of the optimization and varies between 0 and 1. The composite desirability value calculated for this optimization is 0.93. This shows that the determined factor values are 93% successful in countervailing the objective function.

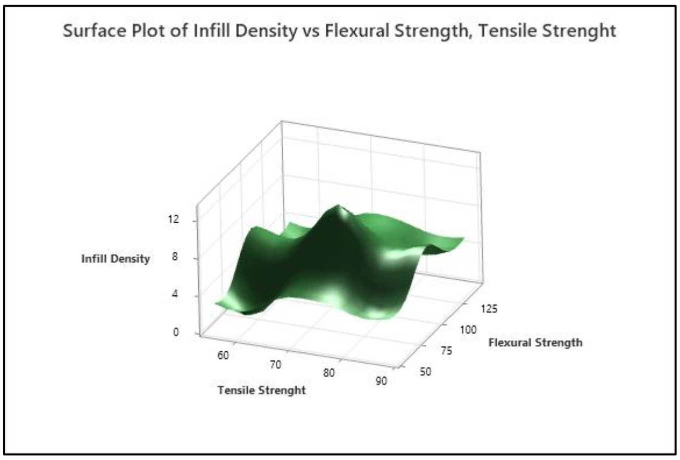



**Figure 7.** Response optimizer surface graph

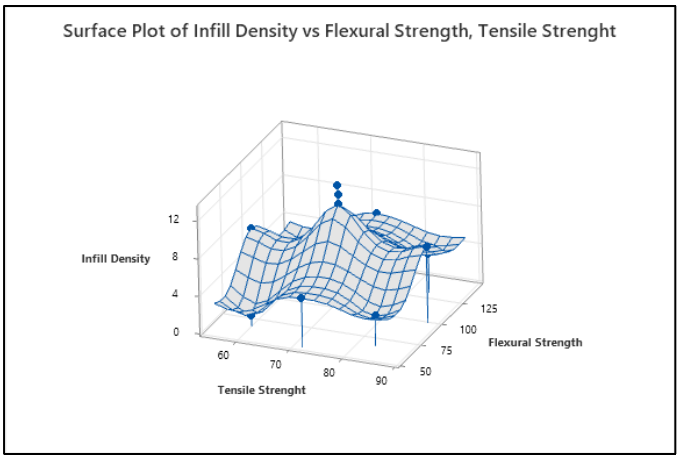



**Figure 8.** Response optimizer wireframe graph

## 6. CONCLUSIONS

In this study, statistical analysis and optimization of 3D printing parameters affecting the mechanical properties of samples produced from Carbon Fiber with Onyx material were performed using Response Surface Methodology. Regarding experimental tests and statistical analysis, the following conclusions can be drawn:

- Changes in 3D printing parameters are effective on the mechanical properties of the samples, and the mechanical properties can be improved by parameter optimization.
- ANOVA analysis results show that the most effective parameter among the tested parameter values in improving the mechanical properties of the samples produced from Carbon Fiber with Onyx material is the infill density parameter. The second most effective parameter is the infill pattern, and the effect of nozzle temperature on mechanical properties is too low to be considered.
- The low difference (less than 4%) between the experimental test results and the predicted test results confirms the accuracy and precision of the optimization procedure to determine the optimized combination of input variables.
- The optimal values of the input variables were determined so that the samples produced from Carbon Fiber with Onyx material could provide maximum tensile strength and flexural strength.

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