Graphene/Carbon Powder Reinforced Polycarbonate Composites for Additive Manufacturing: Taguchi–ANOVA Optimization of Hardness and Flexural Strength

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**Abstract:** This study investigates that the hardness and flexural strength of a 3D-printed composite composed of 90% polycarbonate, 5% graphene, and 5% carbon powder are influenced by three important Fused Deposition Modelling (FDM) process parameters: nozzle temperature, printing speed, and bed temperature. Nine experimental runs were carried out to assess the impact of each parameter using the Taguchi technique (L9 orthogonal array). Mechanical testing was done in accordance with ASTM D790 for flexural strength and ASTM D785 for hardness. According to the findings of the ANOVA, the most important factor was the nozzle temperature, which contributed 72.19% to hardness and 70.00% to flexural strength. The maximum hardness (87.6 D Shore) and flexural strength (107 MPa) were obtained using the ideal parameter combination of 210°C nozzle temperature, 15–20 mm/s printing speed, and 80°C bed temperature. Despite having lower predicted R2 values, regression models showed good fits, with R2 Coefficient of correlation values of 95.81% for flexural strength and 95.30% for hardness. Additionally, contour plots demonstrated that better mechanical performance is achieved with higher bed temperatures and moderate nozzle temperatures. The significance of process optimization in improving the mechanical characteristics of polycarbonate-based composites for FDM applications is highlighted by this study.

**Keywords:** Polycarbonate, Graphene, Powder, Fused Deposition modelling, Hardness and Flexural strength, ASTM standard, Orthogonal array, ANOVA, Regression model, Contour plot.

# Introduction

Additive manufacturing is one of the better technologies in the industrial sector is 3D printing, which produces things quickly, allows for three degrees of freedom in design, and creates unthinkable styles [1]. One thermoplastic engineering polymer is polycarbonate, Graphene is a substance that has a high degree of heat resistance and is essentially creating a high level of strength [2]. In the material sector, it has the toughest material. The resisting capability of carbon powder is enormous [3]. This resistance capability can withstand any type of stress. It has the capacity to support a large weight without breaking [4]. because this carbon powder substance is being used by several industries. These materials are used in the fabrication of several tiny and large parts for watches, computers, toys, televisions, and other devices in order to improve the design's strength, structure, and functionality [5]. The combination of polycarbonate, graphene, and carbon powder provides excellent strength, fire resistance, surface resistance, environmental hazard resistance, quality, and good compact resistance. In essence, this combination results in increased productivity [6]. Greater flexibility and high sustainability are provided by this three-way combo. Printing the samples is quite difficult with this combined combination. alter the printer head, clean the printer often, and turn off the fans in the surrounding area [7]. Changing the bed temperature, printing temperature, and nozzle head often. These three factors need to be adjusted often. Then, only the combination of the three ingredients is producing precise printing [8]. Prior research has not thoroughly examined the combination of polycarbonate, graphene, and carbon powder for printing samples in accordance with ASTM standards for hardness and flexural tests [9]. This combination has not been thoroughly discussed in prior research. Although there is a great deal of uniqueness in this combination, prior scholars have not given this combination their full attention [10].

Since all three of these materials are industrial grade, extremely durable, and sturdy. Due to the high cost of building this mix of three materials and the significant difficulties in printing the samples, previous research has not focused on this topic. High strength is provided by this combination [11]. The gap in the literature for this work is Carbon powder, graphene, and polycarbonate were used to create printed samples; no previous research had been done on this combination. This combination of printed samples for hardness and flexural strength according to ASTM standards has not been covered in previous research. The trials for these three parameters were designed for nine studies utilizing the Taguchi technique L9 experimental orthogonal array. These three materials do not mention the Taguchi technique in previous investigations. For instance, carbon powder, graphene, and polycarbonate [12-29]. This area of study has not been covered in previous research. Hardness and flexural strength are two properties in the signal ratio that have not been previously discussed in this three-merged combination using the Taguchi method. The previous study work did not do Taguchi analysis for nine experiments for Nozzle temperature, Bed temperature, Printing speed, Hardness, Flexural strength, Signal to Noise Ratio, Signal to Noise Ratio 1, FITS, and FITS 1 for nine levels of experiment design. The prior study did not include an analysis of variance for the flexural strength and hardness contributions over 1% [20-25]. The prior research for these three combined combinations did not verify a coefficient of correlation over 95% of hardness and flexural strength. Previous research has not discussed regression models for enhancing mechanical behavior for hardness and flexural strength for these three combined combinations. In the earlier work, the contour plot displaying the maximum hardness and flexural strength was not covered. The previous study did not address the Taguchi method's capacity to determine the optimal nozzle temperature range, bed temperature range, or printing speed. It can also determine the highest flexural strength and high hardness strength. This three-way combo is producing a great deal of new material. The Objective of this research to achieve 90% polycarbonate, 5% carbon powder, and 5% graphene. For printing flexural strength and hardness samples, three combined combinations following the ASTM standard were used. Using the Taguchi approach, the L9 experiments orthogonal array is used to design three levels of experiments for bed temperature, printing speed, and nozzle temperature [26-30].

Every parameter is providing a unique value. additional signal to noise ratio for flexural strength and hardness for printing speed, bed temperature, and nozzle temperature for three testing levels. The optimal ranking delta may be found with the use of these three signals to noise ratio levels. Nozzle temperature is ranked as the best delta. Bed temperature comes in at number two. The printing speed for the hardness and flexural strength samples is the last lowest ranking [31-35]. The variance analysis to determine the coefficient of correlation and contribution for both attributes, ANOVA is utilized. It denotes hardness and flexural strength. The coefficient of correlation value and contribution are shown by this ANOVA. In general, a coefficient of correlation value greater than 95% indicates the best mechanical behavior for both the hardness and flexural strength samples. Additionally, the contribution value must be greater than 1% before the research's results are considered satisfactory. It is typical for both hardness and flexural samples. The regression model can determine the precise values of hardness surface resistance and flexural strength. For maximum strength and medium strength and lowest strength a contour plot is utilized to determine the precise color and strength. For both the flexural strength and the hardness sample, each strength level is visually represented by showing the appropriate route, including color in the contour pot for both properties. The mechanical behavior strength may be enhanced using this Taguchi approach to reach the next level of innovation. Using the Taguchi approach, these three combined printing samples can generate a high level of strength for this study [36-40].

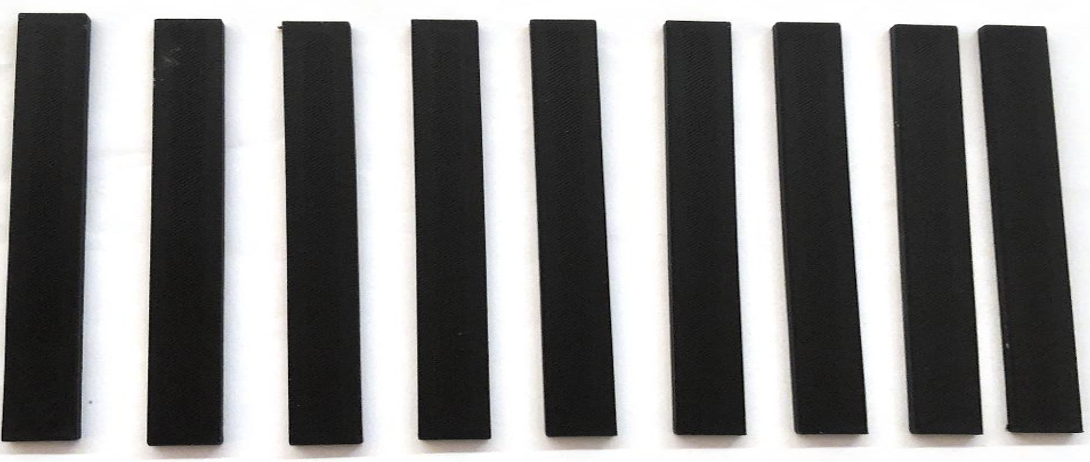
# Materials and Methods

## Materials

The experiment's printed samples for the material combination of 90% polycarbonate, 5% graphene, and 5% carbon powder are displayed in Figure 1 (a and b). This combined printed sample combines hardness and flexural strength. With the aid of a 3D printing machine from the Pro Bundle category, samples of hardness and flexural strength are created. The flexural strength and hardness of these samples meet ASTM standard for hardness and flexural strength are D785 and D790, respectively [41-43].



(a)

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**(b)**

**Figure 1:** (a) Polycarbonate composite Hardness sample **(b) Polycarbonate composite Flexural strength samples**

**In this work, table 1 shows the parameters and level for Hardness and flexural strength, In this parameters level 1 for Printing speed is 15 mm/s, Level 2 printing speed is 20 mm/s and level 3 printing speed is 25 mm/s. In this parameter level 1 for Bed temperature is 60 degree Celsius, Level 2 Bed temperature is 70 degree Celsius, Level 3 Bed temperature 80 degree Celsius. In this parameter level 1 for Nozzle temperature is 200, Level 2 Nozzle temperature is 210 degree Celsius and Level 3 Nozzle temperature is 220 degree Celsius [44-48].**

**Table 1: Parameters and Level for Hardness and Flexural strength**

|  |  |  |  |
| --- | --- | --- | --- |
| **Factor** | **Level 1** | **Level 2** | **Level 3** |
| **Printing speed** | **15** | **20** | **25** |
| **Bed Temperature** | **60** | **70** | **80** |
| **Nozzle Temperature** | **200** | **210** | **220** |

## ****Experimental Design****

**In this work, Table 2 shows Experimental design for Hardness and Flexural strength of first experiment design for Printing speed is 15 mm/s, Bed temperature is 60 degree Celsius and Nozzle temperature is 200 degree Celsius. Second experiment design for Printing speed is 20 mm/s, Bed temperature is 70 degree Celsius and Nozzle temperature is 200 degree Celsius.Third Experimental design for Printing speed is 25 mm/s, Bed temperature is 80 degree Celsius, Nozzle temperature is 200 degree Celsius. Fourth experimental design for Printing speed is15mm/s, Bed temperature is 70 degree Celsius and Nozzle temperature is 210 degree Celsius. Fifth experimental design for Printing speed is 20 mm/s, Bed temperature is 80 degree Celsius and Nozzle temperature is 210 degree Celsius. Sixth experimental design for Printing speed is 25 mm/s, Bed temperature is 60 and Nozzle temperature is 210 degree Celsius. Seventh experimental design for Printing speed is 15 mm/s,Bed temperature is 80 degree Celsius and Nozzle temperature is 220 degree Celsius. Eight experimental design for Printing speed is 20 mm/s, Bed temperature is 60 degree Celsius and Nozzle temperature is 220 degree Celsius. Nineth Experimental design for Printing speed of 25mm/s, Bed temperature is 70 degree Celsius and Nozzle temperature is 220 degree Celsius.**

**Table 2: Experimental design for Hardness and Flexural strength**

|  |  |  |  |
| --- | --- | --- | --- |
| **Exp. no** | **Printing speed mm/s** | **Bed Temp** | **Nozzle temp** |
| 1 | 15 | 60 | 200 |
| 2 | 20 | 70 | 200 |
| 3 | 25 | 80 | 200 |
| 4 | 15 | 70 | 210 |
| 5 | 20 | 80 | 210 |
| 6 | 25 | 60 | 210 |
| 7 | 15 | 80 | 220 |
| 8 | 20 | 60 | 220 |
| 9 | 25 | 70 | 220 |

## ****Response Measurement****

**This experiment examines the hardness and flexural strength of printed samples that include carbon powder, graphene, and polycarbonate. The hardness and flexural strength of this print adhere to ASTM standards. The ASTM standards for flexural strength are D790 and hardness are D785. The larger value in the signal to noise ratio is the optimal value in this work.**

# ****Result and Discussion****

## ****Taguchi analysis****

**In this work, table 3 shows the Taguchi analysis for three parameters, Flexural strength, Hardness, Signal to noise ratio and FITS. In this experiment 1 Taguchi analysis for Nozzle temperature is 200 degree Celsius, Printing speed is 15 mm/s, Bed temperature is 60 degree Celsius, Flexural strength is 103 MPa, Hardness is 83.9 D shore, Signal to noise ratio is 40.256, Signal to noise ratio 1 is 38.47, FITS is 103.22 and FITS 1 is 84.51. In this experiment 2 Taguchi analysis for Nozzle temperature is 200 degree Celsius, Printing speed is 20 mm/s, Bed temperature is 70 degree Celsius, Flexural strength is 104 MPa, Hardness is 84.9 D shore, Signal to noise ratio is 40.34, Signal to noise ratio 1 is 38.57, FITS is 104.56 and FITS 1 is 85.211. In this experiment 3 Taguchi analysis for Nozzle temperature is 200 degree Celsius, Printing speed is 25 mm/s, Bed temperature is 80 degree Celsius, Flexural strength is 105 MPa, Hardness is 85.9 D shore, Signal to noise ratio is 40.42, Signal to noise ratio 1 is 38.67, FITS is 104.22 and FITS 1 is 84.97.**

**Table 3: Taguchi analysis for three parameters, Signal to noise ratio,Flexural strength, Hardness and FITS**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Experimental no** | **Nozzle temp** | **Printing speed** | **Bed Temp** | **Flexural strength** | **Hardness** | **S/N Ratio for Flexural strength** | **S/N Ratio for Hardness** |
| 1 | 200 | 15 | 60 | 103 | 83.9 | 40.25674449 | 38.47523922 |
| 2 | 200 | 20 | 70 | 104 | 84.9 | 40.34066679 | 38.5781538 |
| 3 | 200 | 25 | 80 | 105 | 85.9 | 40.42378598 | 38.67986328 |
| 4 | 210 | 15 | 70 | 106 | 87.6 | 40.50611731 | 38.85008212 |
| 5 | 210 | 20 | 80 | 107 | 86.9 | 40.58767555 | 38.78039553 |
| 6 | 210 | 25 | 60 | 102 | 82.8 | 40.17200344 | 38.36060674 |
| 7 | 220 | 15 | 80 | 101 | 81.9 | 40.08642748 | 38.26567804 |
| 8 | 220 | 20 | 60 | 100 | 79.8 | 40 | 38.04005783 |
| 9 | 220 | 25 | 70 | 98 | 77.9 | 39.82452151 | 37.83074915 |

**In this experiment 4 Taguchi analysis for Nozzle temperature is 210 degree Celsius, Printing speed is 15 mm/s, Bed temperature is 70 degree Celsius, Flexural strength is 106 MPa, Hardness is 87.6 D shore, Signal to noise ratio is 40.50, Signal to noise ratio 1 is 38.85, FITS is 105.22 and FITS 1 is 86.67. In this experiment 5 Taguchi analysis for Nozzle temperature is 210 degree Celsius, Printing speed is 20 mm/s, Bed temperature is 80 degree Celsius, Flexural strength is 107 MPa, Hardness is 86.9 D shore, Signal to noise ratio is 40.58, Signal to noise ratio 1 is 38.78, FITS is 107.22 and FITS 1 is 87.51. In this experiment 6 Taguchi analysis for Nozzle temperature is 210 degree Celsius, Printing speed is 25 mm/s, Bed temperature is 60 degree Celsius, Flexural strength is 102 MPa, Hardness is 82.8 D shore, Signal to noise ratio is 40.172, Signal to noise ratio 1 is 38.36, FITS is 102.55 and FITS 1 is 83.11.**

**In this experiment 7 Taguchi analysis for Nozzle temperature is 220 degree Celsius, Printing speed is 15 mm/s, Bed temperature is 80 degree Celsius, Flexural strength is 101 MPa, Hardness is 81.9 D shore, Signal to noise ratio is 40.08, Signal to noise ratio 1 is 38.26, FITS is 101.55 and FITS 1 is 82.211. In this experiment 8 Taguchi analysis for Nozzle temperature is 220 degree Celsius, Printing speed is 20 mm/s, Bed temperature is 60 degree Celsius, Flexural strength is 100 MPa, Hardness is 79.8 D shore, Signal to noise ratio is 40, Signal to noise ratio 1 is 38.04, FITS is 99.22 and FITS 1 is 78.87. In this experiment 9 Taguchi analysis for Nozzle temperature is 220 degree Celsius, Printing speed is 25 mm/s, Bed temperature is 70 degree Celsius, Flexural strength is 98 MPa, Hardness is 77.9 D shore, Signal to noise ratio is 39.82, Signal to noise ratio 1 is 37.83, FITS is 98.22 and FITS 1 is 78.51.**

## ****Hardness and Flexural strength response for signal to noise ratio****

### **Hardness**

**The signal to noise ratio is displayed in Table 4 for this Hardness. The signal to noise ratio for level 1 is 38.58 degree Celsius for the nozzle temperature, 38.53 mm/s for the printing speed, and 38.29 degree Celsius for the bed temperature. Printing speed is 38.47mm/s, bed temperature is 38.42 degree Celsius, nozzle temperature is 38.66 degree Celsius, and signal to noise ratio is Level 2. Nozzle temperature, printing speed, and bed temperature are 38.05 degree Celsius, 38.29 mm/s, and 38.58 degree Celsius, respectively, for the level 3 signal to noise ratio.**

**Table 4: Signal to noise ratio for Hardness**

|  |  |  |  |
| --- | --- | --- | --- |
| **Level** | **Nozzle temp** | **Printing speed** | **Bed Temp** |
| 1 | 38.58 | 38.53 | 38.29 |
| 2 | 38.66 | 38.47 | 38.42 |
| 3 | 38.05 | 38.29 | 38.58 |
| Delta | 0.62 | 0.24 | 0.28 |
| Rank | 1 | 3 | 2 |

**The Hardness curve for the signal to noise ratio is displayed in Figure 2 of this experiment. When comparing this Nozzle temperature to the other parameters, the delta value of 0.62 is the greatest. The second-highest score is 0.28 for the bed temperature delta. 0.24 is the lowest rating printing speed.**



**Figure 2: Hardness plot for Signal to noise ratio**

### **Flexural strength**

**The signal to noise ratio is displayed in Table 5 for this Flexural strength. The signal to noise ratio for level 1 is 40.34 degree Celsius for the nozzle temperature, 40.28 mm/s for the printing speed, and 40.14 degree Celsius for the bed temperature. Printing speed is 40.31 mm/s, bed temperature is 40.22 degree Celsius, nozzle temperature is 40.42 degree Celsius, and signal to noise ratio is Level 2. Nozzle temperature, printing speed, and bed temperature are 39.97 degree Celsius, 40.14 mm/s, 40.37 degree Celsius respectively, for the level 3 signal to noise ratio.**

**Table 5 Signal to noise ratio for flexural strength**

|  |  |  |  |
| --- | --- | --- | --- |
| **Level** | **Nozzle temp degree Celsius** | **Printing speed mm/s** | **Bed Temp degree Celsius** |
| 1 | 40.34 | 40.28 | 40.14 |
| 2 | 40.42 | 40.31 | 40.22 |
| 3 | 39.97 | 40.14 | 40.37 |
| Delta | 0.45 | 0.17 | 0.22 |
| Rank | 1 | 3 | 2 |

**The Flexural strength curve for the signal to noise ratio is displayed in Figure 3 of this experiment. When comparing this Nozzle temperature to the other parameters, the delta value of 0.45 is the greatest. The second-highest score is 0.22 for the bed temperature delta. 0.17 is the lowest rating printing speed.**



**Figure 3: Flexural strength plot for signal to noise ratio**

## Analysis of Variance (ANOVA)

### Hardness

In this experiment, table 6 shows the ANOVA analysis for the hardness of a Polycarbonate (90%) + 5% Graphene + 5% Carbon powder composite, revealing that Nozzle Temperature is the most influential parameter, contributing 72.19% of the variation in hardness with a high F-value of 15.37, though its P-value of 0.061 is just above the 0.05 significance level, indicating it is marginally significant. Bed Temperature and Printing Speed contribute 13.30% and 9.81%, respectively, but have low F-values (2.83 and 2.09) and high P-values (0.261 and 0.324), indicating that they are statistically insignificant. The model explains most of the variation in the hardness data, as indicated by its high R-squared value of 95.30% for the coefficient of correlation and 81.21% for the modified R-squared, which takes the number of predictors into account. The model's poor generalization to new data is evidenced by the expected R-squared of only 4.88%. The prediction error sum of squares (PRESS) is 80.235, while the standard error is 1.40752.

Table 6: Hardness ANOVA

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Source | DF | Seq SS | Contribution | Adj SS | Adj MS | F-Value | P-Value |
| Nozzle temp | 2 | 60.896 | 72.19% | 60.896 | 30.448 | 15.37 | 0.061 |
| Printing speed | 2 | 8.276 | 9.81% | 8.276 | 4.138 | 2.09 | 0.324 |
| Bed Temp | 2 | 11.216 | 13.30% | 11.216 | 5.608 | 2.83 | 0.261 |
| Error | 2 | 3.962 | 4.70% | 3.962 | 1.981 |  |  |
| Total | 8 | 84.349 | 100.00% |  |  |  |  |

The residual plots in Figure 4 demonstrate the hardness and imply that the regression model is typically suitable. The normal probability plot indicates that residuals are roughly normally distributed, with slight deviations. The vs fits plot shows a random scatter around zero, indicating continuous variance. The histogram indicates a very symmetric distribution of residuals, however the against order plot shows some cyclic fluctuation, implying non-random error or process tendencies. Overall, the model assumptions are adequately met; however, modest tweaks might increase dependability.



Figure 4: Residual Plots for Hardness

### Flexural strength

In the ANOVA table 7 shows that flexural strength of the composite consisting of 90% polycarbonate, 5% graphene, and 5% carbon powder, indicating that nozzle temperature is the most important process parameter. It accounts for 70.00% of the overall variation in flexural strength, with a high F-value of 16.69 and a P-value of 0.057, which is somewhat higher than the conventional significance threshold of 0.05, implying that it is marginally statistically insignificant but likely important. Bed Temperature and Printing Speed contribute 15.81% and 10.00%, respectively, with F-values of 3.77 and 2.38, and P-values of 0.210 and 0.295, suggesting that they are not statistically significant in this investigation. The residual error contributes just 4.19%, indicating that the specified parameters explain the majority of the variation. The model summary shows a strong fit, with a coefficient of correlation (R²) of 95.81% and an adjusted R² of 83.23%. This suggests that the model explains a significant percentage of the variation while accounting for the number of factors. However, the anticipated R² is 15.08%, indicating little predictability for fresh or unknown data. The standard error (S) is 1.20185, and the prediction error sum of squares (PRESS) is 58.5.

Table 7: Flexural strength ANOVA

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Source | DF | Seq SS | Contribution | Adj SS | Adj MS | F-Value | P-Value |
| Nozzle temp | 2 | 48.222 | 70.00% | 48.222 | 24.111 | 16.69 | 0.057 |
| Printing speed | 2 | 6.889 | 10.00% | 6.889 | 3.444 | 2.38 | 0.295 |
| Bed Temp | 2 | 10.889 | 15.81% | 10.889 | 5.444 | 3.77 | 0.21 |
| Error | 2 | 2.889 | 4.19% | 2.889 | 1.444 |  |  |
| Total | 8 | 68.889 | 100.00% |  |  |  |  |

The residual plots in Figure 5 for flexural strength indicate that the regression model is typically acceptable. The normal probability plot reveals that the residuals typically follow a straight line, suggesting approaching normality. The vs fits plot shows a random dispersion around zero, which supports the assumption of constant variance. The histogram indicates a fairly symmetrical distribution, albeit slightly clustered. The vs order plot indicates certain cyclic tendencies, indicating that the trial sequence may not be random. Overall, the model is statistically sound, although tiny deviations indicate that more validation or data may increase robustness.



Figure 5: Residual Plots for Flexural strength

## Regression model

### Hardness

The hardness regression equation shows that the ideal processing conditions for the composite are 210°C nozzle temperature, 15 mm/s printing speed, and 80°C bed temperature, with positive contributions of +2.256, +0.956, and +1.389, respectively. Higher nozzle temperature (220°C), quicker printing speed (25 mm/s), and lower bed temperature (60°C) all had negative effects on hardness, with values of −3.644, −1.311, and −1.344, indicating thermal deterioration and poor layer bonding. The basic hardness value at reference levels is 83.511, with intermediate values such as 200°C nozzle and 20 mm/s speed providing moderate enhancements.

|  |  |  |
| --- | --- | --- |
| Hardness | = | 83.511 + 1.389 Nozzle temp\_200 + 2.256 Nozzle temp\_210 - 3.644 Nozzle temp\_220 + 0.956 Printing speed\_15 + 0.356 Printing speed\_20 - 1.311 Printing speed\_25 - 1.344 Bed Temp\_60 - 0.044 Bed Temp\_70 + 1.389 Bed Temp\_80 |

### Flexural strength

The regression equation for flexural strength suggests that the ideal printing parameters for the polycarbonate composite are a nozzle temperature of 210°C, a printing speed of 20 mm/s, and an 80°C bed temperature. These settings provide positive contributions to flexural strength with coefficients of +2.111, +0.778, and +1.444. Higher nozzle temperatures (220°C), quicker printing rates (25 mm/s), and lower bed temperatures (60°C) all have a detrimental impact on strength, indicating material deterioration or inadequate interlayer bonding. The reference level base flexural strength is 102.889 MPa.

|  |  |  |
| --- | --- | --- |
| Flexural strength | = | 102.889 + 1.111 Nozzle temp\_200 + 2.111 Nozzle temp\_210 - 3.222 Nozzle temp\_220 + 0.444 Printing speed\_15 + 0.778 Printing speed\_20 - 1.222 Printing speed\_25 - 1.222 Bed Temp\_60 - 0.222 Bed Temp\_70 + 1.444 Bed Temp\_80 |

## Contour plot

The hardness of the polycarbonate composite is revealed by the contour plot in Figure 6, which illustrates the interaction between the nozzle and bed temperatures. Higher bed temperatures (75–80°C) and lower nozzle temperatures (200–205°C) are concentrated in the darkest green area (hardness >86), suggesting that these two temperatures together yield the greatest hardness values. The lightest green regions indicate values below 78, indicating a considerable loss in hardness when the nozzle temperature rises over 215°C, particularly when the bed temperature is also low (60–65°C). The figure shows that the highest surface hardness is achieved by combining higher bed temperatures with lower nozzle temperatures throughout. The contour plot The flexural strength in Figure 6 shows how the bed and nozzle temperatures influence the mechanical performance of the composite. The ideal range for increasing flexural strength is shown by the darkest green region (flexural strength >106 MPa), which appears at a nozzle temperature of 205–210°C and a bed temperature of 75–80°C. Lighter green zones with values below 98 MPa indicate a noticeable loss in strength when the nozzle temperature rises to 220°C or the bed temperature falls to 60–65°C. This implies that better flexural performance and stronger interlayer bonding are encouraged by higher bed temperatures and moderate nozzle temperatures.



1. (b)

Figure 6: Contour plot for Hardness and Flexural strength

# Conclusion

This study examined the influence of nozzle temperature, printing speed, and bed temperature on the hardness and flexural strength of a composite material made from 90% polycarbonate, 5% graphene, and 5% carbon powder using the Taguchi method. The ANOVA results revealed that nozzle temperature had the most significant effect on both properties, contributing 72.19% to hardness and 70.00% to flexural strength. In order to achieve a maximum hardness of 87.6 D Shore and a flexural strength of 107, the ideal set of process parameters was determined to be 210°C nozzle temperature, 15–20 mm/s printing speed, and 80°C bed temperature. These results were validated by regression analysis, which showed that the regression model for flexural strength had good model fits with an R2 of Coefficient of correlation is 95.81% and an adjusted R2 of 83.23%, while the regression model for hardness had an R2 Coefficient of Correlation is 95.30% and an adjusted R2 of 81.21%. The expected R2 values, however, were quite low (4.88% for hardness and 15.08% for flexural strength), indicating a limited capacity for prediction and the necessity of further data or validation to improve generalizability. Contour plots supported these findings, demonstrating that the highest mechanical performance was obtained at higher bed temperatures (75–80°C) and moderate nozzle temperatures (205–210°C). Overall, the study shows that precisely adjusting process variables greatly improves the mechanical characteristics of composites made of polycarbonate for use in 3D printing.

# References

1. Anand et al., (2024). A comprehensive analysis of small-scale building integrated photovoltaic system for residential buildings: Techno-economic benefits and greenhouse gas mitigation potential. Journal of Building Engineering, 82, 108232.
2. RAO, N. S., KUMAR, R., KAVITHA, N., PYDI, H. P., SHANKHYAN, A., SUBBIAH, R., & Singh, V. (2025). Analyse the mechanical property optimization for FDM/3D-printed polycarbonate using Taguchi and TOPSIS techniques. *Journal of Metals, Materials and Minerals*, *35*(1), e2196-e2196.
3. Grosious et al., (2024, June). Utilizing 3D printing in marine industries: innovations for enhanced ship and boat production. In International Conference on Medical Imaging, Electronic Imaging, Information Technologies, and Sensors (MIEITS 2024) (Vol. 13188, pp. 132-143). SPIE.
4. Mariya Louis et al., Multiresponse optimization and network-based prediction modelling for the WEDM of AM60B biomedical material. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 238(20), 10045-10066.
5. Grosious et al., (2024, June). Advancements in automotive production: exploring the role of 3D printing and selective laser sintering. In International Conference on Medical Imaging, Electronic Imaging, Information Technologies, and Sensors (MIEITS 2024) (Vol. 13188, pp. 403-415). SPIE.
6. Kaushal et al., (2024). Fault prediction and awareness for power distribution in grid connected res using hybrid machine learning. Electric Power Components and Systems, 1-22.
7. Kumar, J., Verma, R. K., Mondal, A. K., & Singh, V. K. (2021). A hybrid optimization technique to control the machining performance of graphene/carbon/polymer (epoxy) nanocomposites. Polymers and Polymer Composites, 29(9\_suppl), S1168-S1180.
8. Grosious et al., (2024, June). Impact of additive manufacturing on sports safety prevention and performance enhancement: a review. In International Conference on Medical Imaging, Electronic Imaging, Information Technologies, and Sensors (MIEITS 2024) (Vol. 13188, pp. 46-56). SPIE.
9. Balaji, S., Bharathiraja, G., Kaliappan, S., Veeman, D., & Mammo, W. D. (2021). Experimental investigation on mechanical properties of TiAlN thin films deposited by RF magnetron sputtering. Journal of Nanomaterials, 2021(1), 5943486.
10. Seeniappan and Neha Garg. Checking and supervisory system for calculation of industrial constraints using embedded system. 2023 4th International Conference on Smart Electronics and Communication (ICOSEC). IEEE, 2023.
11. P. Sakthivel et al. Mechanical and thermal properties of a waste fly ash-bonded Al-10 Mg alloy composite improved by bioceramic silicon nanoparticles. Biomass Conversion and Biorefinery, pp.1-12.
12. A. Baraniraj et al. 2023. Silicon Carbide Particle Enriched Magnesium Alloy (AZ91) Composite: Physical, Microstructural and Mechanical Studies. Silicon, 15(15), pp.6367-6374.
13. P. Chandramohan et al. Processing and Characteristics Evaluation of Polyester Resin Nanocomposite Synthesized with Natural Fiber. Journal of The Institution of Engineers (India): Series D, pp.1-5.
14. C. Angalaparameswari et al. Effective Utilization of Bast Fiber in High Density Polyethylene Nanocomposite Enriched by Alumina Nanoparticle: Mechanical Performance Evaluation. Journal of The Institution of Engineers (India): Series D, pp.1-5.
15. Sureshkumar, P., et al., Electrochemical corrosion and tribological behaviour of AA6063/Si3N4/Cu (NO3) 2 composite processed using single-pass ECAPA route with 120 die angle. Journal of Materials Research and Technology 16 (2022): 715-733.
16. M. Senthil Kumar. Influence of silicon carbide on tribological behaviour of AA2024/Al2O3/SiC/Gr hybrid metal matrix squeeze cast composite using Taguchi technique. Materials Research Express 6.12 (2020): 1265f9.
17. C. B. Priya et al. "Bio-degradable waste banana and neem fiber reinforced epoxy hybrid composites: characteristics study." Journal of Mechanical Science and Technology 38, no. 4 (2024): 1891-1896. <https://doi.org/10.1007/s12206-024-0322-7>
18. M. Aruna et al. "Alkali-Processed Flax Natural Made High-Density Polyethylene Waste Recycled Composites: Performance Evaluation." Journal of The Institution of Engineers (India): Series D (2024): 1-5. <https://doi.org/10.1007/s40033-024-00739-z>
19. M. Senthil Kumar, and Mukesh Chaudhari. Optimization of squeeze casting process parameters to investigate the mechanical properties of AA6061/Al2O3/SiC hybrid metal matrix composites by taguchi and anova approach. Advanced Engineering Optimization Through Intelligent Techniques: Select Proceedings of AEOTIT 2018. Singapore: Springer Singapore, 2019. 393-406
20. Pethuraj Manickaraj, and V. Sakthi Murugan. "Featuring with Nano Alumina Made Hybrid Epoxy/Carbon Fiber Nanocomposite: Performance Evaluation." Journal of The Institution of Engineers (India): Series D (2024): 1-5. <https://doi.org/10.1007/s40033-024-00754-0>
21. Suman, Turpati, et al., IoT based Social Device Network with Cloud Computing Architecture. 2023 Second International Conference on Electronics and Renewable Systems (ICEARS). IEEE, 2023.
22. S. Kaliappan. Mechanical Assessment of Carbon–Luffa Hybrid Composites for Automotive Applications. No. 2023-01-5070. SAE Technical Paper, 2023.
23. Muralidaran, V. Manivel, et al., Grape stalk cellulose toughened plain weaved bamboo fiber-reinforced epoxy composite: load bearing and time-dependent behavior. Biomass Conversion and Biorefinery 14.13 (2024): 14317-14.
24. K. Logesh et al. "Performance investigation of silicon nitride (SiNx) layer doped with twin thin films of gallium and zinc oxide for solar cell." Optical and Quantum Electronics 56, no. 7 (2024): 1-13.<https://doi.org/10.1007/s11082-024-07100-4>
25. R. Karthik et al. "Characteristics performance evaluation of AZ91-fly ash composite developed by vacuum associated stir processing." International Journal of Cast Metals Research (2024): 1-8.<https://doi.org/10.1080/13640461.2024.2364129>
26. Kaliappan, S., and Akshay Rajput. Sentiment Analysis of News Headlines Based on Sentiment Lexicon and Deep Learning. 2023 4th International Conference on Smart Electronics and Communication (ICOSEC). IEEE, 2023.
27. De Poures, Melvin Victor et al. "Sodium Hydroxide Processed Natural Sisal Fiber Made Polypropylene Composite: Characteristics Evaluation." Journal of The Institution of Engineers (India): Series D (2024): 1-5. <https://doi.org/10.1007/s40033-024-00761-1>
28. Josphineleela, R., and Upendra Mohan Bhatt. Intelligent Virtual Laboratory Development and Implementation using the RASA Framework. 2023 7th International Conference on Computing Methodologies and Communication (ICCMC). IEEE, 2023.
29. Vaishali, Kokila R., et al., Guided container selection for data streaming through neural learning in cloud. International Journal of System Assurance Engineering and Management (2021): 1-7.
30. Yogeshwaran, S., et al., Experimental investigation on mechanical properties of epoxy/graphene/fish scale and fermented spinach hybrid bio composite by hand lay-up technique. Materials Today: Proceedings 37 (2021): 1578-1583.
31. Khimsuriya, Yogeshkumar D., et al., Artificially roughened solar air heating technology–A comprehensive review. Applied Thermal Engineering 214 (2022): 118817.
32. Kumar, M. Senthil, et al., Experimental investigations on mechanical and microstructural properties of Al2O3/SiC reinforced hybrid metal matrix composite. IOP Conference Series: Materials Science and Engineering. Vol. 402. No. 1. IOP Publishing, 2018.
33. Yogeshwaran, S., et al. Mechanical properties of leaf ashes reinforced aluminum alloy metal matrix composites. International Journal of Applied Engineering Research 10.13 (2015): 11048-11052.
34. D. Dillikannan et al. 2024. An Approach of Nano-SiC-Filled Epoxy Nanocomposite Tensile and Flexural Strength Enriched by the Addition of Sisal Fiber. Journal of The Institution of Engineers (India): Series D, pp.1-5.
35. L. Kamaraj et al. 2024. Fabrication and Behavior Study of Natural Fiber Utilized Low-Density Polyethylene Nanocomposite via Injection Mold. Journal of The Institution of Engineers (India): Series D, pp.1-5.
36. Paranthaman et al., Influence of SiC particles on mechanical and microstructural properties of modified interlock friction stir weld lap joint for automotive grade aluminium alloy. Silicon 14.4 (2022): 1617-1627.
37. C. Devanathan et al. 2024. Significance of Hemp Fiber on Mechanical and Thermal Performance of Polypropylene Nanocomposite Developed by Compression Mould Technique. Journal of The Institution of Engineers (India): Series D, pp.1-5.
38. P. Sakthivel et al. Synthesis and Thermal Adsorption Characteristics of Silver-Based Hybrid Nanocomposites for Automotive Friction Material Application. Adsorption Science & Technology, 2023.
39. Chennai Viswanathan, Prasshanth, et al., Deep learning for enhanced fault diagnosis of monoblock centrifugal pumps: Spectrogram-based analysis. Machines 11.9 (2023): 874.
40. R. Anand, and S. Santhosh Kumar. Optimization of process parameters in TIG welding of AISI 4140 stainless steel using Taguchi technique. Materials today: proceedings 37 (2021): 1550-1553.
41. V. Vijayan et al. 2016. Performance Evaluation of Multipurpose Solar Heating System. Mechanics & Mechanical Engineering, 20(4).
42. I. J. Isaac Premkumar et al. Combustion analysis of biodiesel blends with different piston geometries. Journal of Thermal Analysis and Calorimetry, 142(4), pp.1457-1467.
43. M. Vivekanandan et al. 2021. Experimental and CFD investigation of helical coil heat exchanger with flower baffle. Materials Today: Proceedings, 37, pp.2174-2182.
44. V. Vijayan et al. CFD modeling and analysis of a two-phase vapor separator. Journal of Thermal Analysis and Calorimetry, 145(5), pp.2719-2726.
45. S. Baskar 2022, July. Thermal management of solar thermoelectric power generation. In AIP conference proceedings (Vol. 2473, No. 1). AIP Publishing.
46. Selvi, S., et al. Optimization of solar panel orientation for maximum energy efficiency. 2023 4th International Conference on Smart Electronics and Communication (ICOSEC). IEEE, 2023.
47. Sai, Samavedam Aditya, et al. Transfer learning based fault detection for suspension system using vibrational analysis and radar plots. Machines 11.8 (2023): 778.
48. M. V. Kumar et al. 2024. Development of Low-Density Polyethylene Nanocomposite with CNT Fibre Via Injection Moulding: Performance Study. Journal of The Institution of Engineers (India): Series D, pp.1-5.