Influence of Printing Parameters on Stiffness–Ductility Characteristics of Polycarbonate/Graphene Composites

R Endymion Grosious1, Natrayan Lakshmaiya1,a)

1Department of Mechanical Engineering, Saveetha School of Engineering, SIMATS, Chennai -602105, Tamil Nadu, India.

Corresponding authors: a)[natrayanphd@gmail.com](mailto:natrayanphd@gmail.com)

**Abstract:** This study investigates which the nozzle temperature (200–220 °C), printing speed (15–25 mm/s), and bed temperature (60–80 °C) of 95 percent polycarbonate and 5 percent graphene composite specimens made using FDM technology affect their tensile Young's modulus and tensile elongation. Nine experimental scenarios were carefully evaluated using a Taguchi orthogonal array technique, which was backed by regression modeling and ANOVA. According to the results, nozzle temperature had the most influence, accounting for 88.18% of the tensile Young's modulus and 87.63% of the tensile elongation. Printing speed and bed temperature had less of an impact, at around 8% and 2%, respectively. The best tensile Young's modulus (5000 MPa) and the lowest tensile elongation (20.00%) were obtained by combining the ideal nozzle temperature of 200 °C, printing speed of 15 mm/s, and bed temperature of 60 °C. According to contour plots, bed heating between 65 and 75 degrees Celsius and moderate nozzle temperatures (200–210 degrees Celsius) increase stiffness while reducing elongation. All things considered, this study offers a precise optimization framework for enhancing the mechanical performance and print quality of polycarbonate–graphene composites, directing the use of sophisticated functional FDM-printed materials in the future.

**Keywords:** Polycarbonate, Graphene, Tensile Elongation, Tensile Youngs modulus, Parameters and Taguchi analysis.

# Introduction

Additive manufacturing is extensively utilized in the electrical industry to produce additional electrical components. Additive manufacturing materials have enormous material characteristics, and additive manufacturing is capable of producing good design structures [1]. Polycarbonate and graphene materials are widely employed in the electrical sector. These two materials are used to make enclosures, switchboards, circuit boards, connectors, and a variety of electronic equipment [2]. Basically, these two materials have great electrical conductivity and can withstand any overheating or danger. This material combination primarily provides light weight, great strength, flexibility, precision, and an unfathomable additive manufacturing design structure [3]. These two materials are commonly used in electrical housing to mount boards, cables, and other interior components of many homes. This material is often used in various sectors such as malls, stores, residences, factories, transformers, and many other places [4]. Polycarbonate and graphene materials are usually used for electrical purposes. Every day, the market values has rising for this electrical business. this additive manufacturing technology is huge percentage level for controlling the electrical industries [5]. In this case, graphene and polycarbonate materials are used for electrical shielding in order to improve the quality and strength of the shield for communication devices with lightweight structures [6]. These two materials are being added for the construction of communication devices like 5G antennas and several other pieces of equipment, mobile phones, condensers, and others [7]. To increase the surface roughness of this device, light-emitting diodes are used in graphene and polycarbonate. The capacity to absorb and release heat is essentially a feature of materials with high thermal conductivity, such as graphene and polycarbonate [8]. This material is also used in battery modules, and heat sinks are constructed using same materials. Power modules also manufacturing for using Polycarbonate and graphene materials [9]. These polycarbonate and graphene materials are used in the production of circuits that are in good, flexible condition. They are also used in the production of inner parts for phone cameras [10]. These materials are used in the production of transparent film. Battery shells are manufactured utilizing this material at an exact level of structural design [11]. Lightweight, highly flexible, accurate, rigid, reliable, high-quality, and strong structures are typical characteristics of these printing parts. With the aid of graphene and polycarbonate materials, casting is also manufactured. device is also manufactured using these two materials [12].

Polycarbonate and graphene materials are commonly used in electric cars to manufacture numerous sections of electric bicycles. These two materials are used to create a lightweight battery casing with high quality and strength [13]. These two materials are commonly used in the energy industry to manufacture various high-quality handling parts and large products. It has the capacity to withstand any load throughout the materials handling time, which is why electrical industries primarily use these two materials to create numerous parts; they are extremely reliable materials in all sorts of conditions. This research present gap in the literature by examining polycarbonate and graphene merging combination printed samples for tensile elongation and tensile young's modulus [14-19]. The prior study does not go into depth on printed samples utilizing ASTM standards in this mix of materials. It refers to polycarbonate and graphene. This tensile elongation and young’s modulus employing different levels of parameters conditions checking for three separate stages in optimization are not mentioned in the earlier work for this materials combination for tensile elongation and tensile young’s modulus. and experiment analysis work for nine various levels of circumstances developed for three key Taguchi parameters. Nozzle temperature, bed temperature, and printing speed were not considered in the earlier work in these materials combinations. The previous study did not include Taguchi assessment for tensile elongation or tensile youthful modulus. Prior research on the coupling of polycarbonate and graphene materials have not examined the signal-to-noise ratio for tensile elongation or tensile young’s modulus. The previous study explored the analysis of variance for tensile elongation and tensile young modulus. The contribution and coefficient of correlation for tensile elongation and tensile young's modulus were not explored in the previous work for this polycarbonate and graphene material combination [20-26].

Prior research has not examined regression models for determining the optimal mechanical behavior and strength for tensile elongation and tensile young’s modulus. Contour plot for visualizing the optimum tensile elongation value and tensile Young's modulus is not discussed clearly in the prior studies for the combination of polycarbonate and graphene combination material [27-33]. The objective of this research is polycarbonate 95% and 5% graphene. Combined sample Printing for tensile elongation and tensile young’s modulus. These two materials were optimized using the Taguchi approach to get the best mechanical properties, stiffness, quality, and strength. Initially, parameters for three conditions must be developed, and nine distinct levels of experimental assessment are used to identify the category of circumstances. It refers to nozzle temperature, bed temperature, and printing speed [34-39]. These three conditions are essential to the overall process. Nine levels of investigations were designed to test the three conditions for tensile elongation and tensile young's modulus. Response measurement studies for tensile elongation and tensile young’s modulus the highest value is the best for tensile young’s modulus, while the lowest value is the best in tensile elongation. Optimization settings for tensile elongation, tensile elongation, sine to noise ratio, and FITS, as well as three conditions and nine levels, will be evaluated to determine the ideal strength condition. To determine the optimal circumstances, three criteria are used: signal to noise ratio, tensile elongation, and tensile young’s modulus [40-45]. Analysis of variation to determine the appropriate contribution level for this tensile elongation and tensile young’s modulus, The coefficient of correlation represents the capacity to determine the optimal output for this tensile elongation and tensile young’s modulus for these parameters. Regression model to calculate the precise strength of tensile elongation and tensile young’s modulus for these values. The contour plot graphically represents the tensile elongation and tensile young’s modulus for quality. it means highest tensile young’s modulus is the best result. tensile elongation lowest percentage value is the best. this an objective of this research work for the combination of polycarbonate and graphene material [46-50].

# Materials and Methods

## Materials

In this experiment figure 1 shows the samples according to ASTM standards for tensile elongation and tensile Youngs modulus. 95% polycarbonate and 5% graphene make up this material combination for tensile Young's modulus and tensile elongation. This content is both main and secondary. Samples of this material are printed using an Ultima Ker 3D printer.

In this work table 1 shows the tensile Youngs modulus and tensile elongation Categories and parameters for Level 3 for printing speed is 25 mm/s, Nozzle temperature is 220 degree Celsius and Bed temperature is 80 degree Celsius. Level 2 for Printing speed is 20 mm/s, Nozzle temperature is 210 degree Celsius and Bed temperature is 70 degree Celsius. Level 1 for Printing speed is 15 mm/s, Nozzle temperature is 200 degree Celsius and Bed temperature is 60 degree Celsius.

****

Figure 1: Composite tensile sample

Table 1: Process Parameter and levels

|  |  |  |  |
| --- | --- | --- | --- |
| Types of Parameters | Level 3 | Level 2 | Level 1 |
| Printing speed | 25 | 20 | 15 |
| Nozzle temperature | 220 | 210 | 200 |
| Bed temperature | 80 | 70 | 60 |

## Examination through experimentation

Table 2: Designing structures for main conditions

|  |  |  |  |
| --- | --- | --- | --- |
| Levels | Nozzle temp | Printing speed | Bed Temp |
| 1 | 200 | 15 | 60 |
| 2 | 200 | 20 | 70 |
| 3 | 200 | 25 | 80 |
| 4 | 210 | 15 | 70 |
| 5 | 210 | 20 | 80 |
| 6 | 210 | 25 | 60 |
| 7 | 220 | 15 | 80 |
| 8 | 220 | 20 | 60 |
| 9 | 220 | 25 | 70 |

In this experiment Table 2 shows nine levels of experimental settings for 3D printing experiments, including nozzle temperature, printing speed, and bed temperature. At Level 1, the nozzle temperature was 200 °C, printing speed was 15 mm/s, and bed temperature was 60 °C. At Level 2, the nozzle temperature remained at 200 °C, but the speed was increased to 20 mm/s and the bed temperature to 70 °C. Level 3 kept the nozzle at 200 °C, with a maximum speed of 25 mm/s and a bed temperature of 80 °C. Levels 4–6 saw a rise in nozzle temperature to 210 °C. Level 4 employed a low speed of 15 mm/s with a 70°C bed, Level 5 raised speed to 20 mm/s with an 80°C bed, and Level 6 increased speed to 25 mm/s but dropped the bed temperature to 60°C. Levels 7–9 increased the nozzle temperature to 220 °C, with Level 7 combining it with the lowest speed of 15 mm/s and an 80 °C bed, Level 8 using a 20 mm/s speed and a 60 °C bed, and Level 9 balancing the highest nozzle temperature with the fastest speed of 25 mm/s and a 70 °C bed. This structured design investigates how incremental changes in temperature and speed affect the printing process, providing a solid platform for assessing their impact on material behaviour.

## Response Measurement

The optimal value for the signal to noise ratio response for tensile Youngs modulus is the greatest value in this Taguchi method measurement for the response of the signal to noise ratio for tensile elongation and elastic Youngs modulus. The optimal value in this elongation for the Taguchi technique is the tensile elongation for the signal to noise ratio response.

# Result and discussion

## Orthogonal array methods analysis

In this work, Table 3 presents the orthogonal array method analysis for tensile Young’s modulus and tensile elongation. At Level 1 (200 °C nozzle, 15 mm/s printing speed, 60 °C bed), the material achieved the maximum tensile Young’s modulus of 5000 MPa with a corresponding elongation of 20.00%. The FITS and FITS\_1 values were 5006.67 and 0.1998, respectively, while the signal-to-noise ratios (SNRA and SNRA1) were 73.9794 and 13.9794. Increasing the bed temperature to 70 °C and printing speed to 20 mm/s at Level 2 improved elongation slightly to 20.08% but reduced modulus to 4980 MPa. At Level 3 (200 °C, 25 mm/s, 70 °C), elongation increased again to 20.16%, though the modulus dropped to 4970 MPa. These results indicate that while higher printing speeds at a constant nozzle temperature improved ductility, they also reduced material stiffness.

Table 3: Orthogonal array experiments

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Exp Nos** | **Nozzle temp** | **Printing speed** | **Bed Temp** | **Tensile Youngs modulus MPa** | **Tensile Elongation** | **S/N ratio for Tensile Youngs modulus** | **S/N ratio for Tensile Elongation** |
| 1 | 200 | 15 | 60 | 5000 | 20.00% | 73.97940009 | 13.9794 |
| 2 | 200 | 20 | 70 | 4980 | 20.08% | 73.94458686 | 13.944726 |
| 3 | 200 | 25 | 80 | 4970 | 20.16% | 73.92712777 | 13.910189 |
| 4 | 210 | 15 | 70 | 4910 | 20.41% | 73.82162984 | 13.80314 |
| 5 | 210 | 20 | 80 | 4800 | 20.83% | 73.62482475 | 13.626215 |
| 6 | 210 | 25 | 60 | 4850 | 20.62% | 73.71483477 | 13.714227 |
| 7 | 220 | 15 | 80 | 4750 | 21.05% | 73.53387219 | 13.534958 |
| 8 | 220 | 20 | 60 | 4600 | 21.74% | 73.25515663 | 13.254809 |
| 9 | 220 | 25 | 70 | 4700 | 21.28% | 73.44195716 | 13.440568 |

Raising the nozzle temperature to 210 °C led to more pronounced changes. At Level 4 (15 mm/s, 70 °C), elongation rose to 20.41%, while modulus fell to 4910 MPa. In Level 5 (20 mm/s, 80 °C), elongation reached 20.83%, but modulus dropped further to 4800 MPa, with FITS\_1 rising to 0.2081. Level 6 (25 mm/s, 60 °C) gave 20.62% elongation with modulus of 4850 MPa. At the highest nozzle setting of 220 °C, ductility peaked while stiffness declined sharply. Level 7 (15 mm/s, 80 °C) showed 21.05% elongation and 4750 MPa modulus, while Level 8 (20 mm/s, 60 °C) recorded the largest elongation of 21.74% but the lowest modulus of 4600 MPa. Finally, Level 9 (25 mm/s, 70 °C) partially recovered modulus to 4700 MPa with elongation at 21.28%. Overall, the pattern indicates that increasing nozzle temperature and printing speed enhances ductility but compromises stiffness. While FITS\_1 values rise slightly at higher settings, suggesting minor optimization gains, the decreasing FITS values confirm an inherent trade-off between tensile elongation (ductility) and Young’s modulus (stiffness).

## Response for Signal to noise ratio

### Tensile Elongation

In this work, table 4 shows the tensile elongation for signal to noise ratio for Level 1 Nozzle temperature is 13.94 degree Celsius, Printing speed is 13.77 mm/s and Bed temperature is 13.65 degree Celsius. Level 2 Nozzle temperature is 13.71 degree Celsius, Printing speed is 13.61 mm/s and Bed temperature is 13.73 degree Celsius. Level 3 for Nozzle temperature is 13.41 degree Celsius, Printing speed is 13.69 mm/s and Bed temperature is 13.69 degree Celsius.

Table 4: Tensile Elongation for signal to noise ratio

|  |  |  |  |
| --- | --- | --- | --- |
| **Level** | **Nozzle temp** | **Printing speed** | **Bed Temp** |
| 1 | 13.94 | 13.77 | 13.65 |
| 2 | 13.71 | 13.61 | 13.73 |
| 3 | 13.41 | 13.69 | 13.69 |
| Delta | 0.53 | 0.16 | 0.08 |
| Rank | 1 | 2 | 3 |

In this experiments figure 2 shows The signal to noise ratio graphic for tensile elongation. In this plot, the top graph line shows nozzle temperature with a delta value of 0.53, followed by printing speed with a delta value of 0.16, and the lowest graph line shows bed temperature with a delta value of 0.08.



Figure 2: SN ratio Plot for Tensile Elongation

### Tensile Youngs modulus

In this work, table 5 shows the tensile Youngs modulus for signal to noise ratio for Level 1 Nozzle temperature is 73.95 degree Celsius, Printing speed is 73.78 mm/s and Bed temperature is 73.65 degree Celsius. Level 2 Nozzle temperature is 73.72 degree Celsius, Printing speed is 73.61 mm/s and Bed temperature is 73.74 degree Celsius. Level 3 for Nozzle temperature is 73.41 degree Celsius, Printing speed is 73.69 mm/s and Bed temperature is 73.70 degree Celsius.

Table 5: Tensile Youngs modulus for signal to noise ratio

|  |  |  |  |
| --- | --- | --- | --- |
| **Level** | **Nozzle temp** | **Printing speed** | **Bed Temp** |
| 1 | 73.95 | 73.78 | 73.65 |
| 2 | 73.72 | 73.61 | 73.74 |
| 3 | 73.41 | 73.69 | 73.70 |
| Delta | 0.54 | 0.17 | 0.09 |
| Rank | 1 | 2 | 3 |

In this experiments figure 3 shows The signal to noise ratio graphic for tensile elongation. In this plot, the top graph line shows nozzle temperature with a delta value of 0.54, followed by printing speed with a delta value of 0.17, and the lowest graph line shows bed temperature with a delta value of 0.09.



Figure 3: SN ratio Plot for Tensile Youngs modulus

## Analysis of Variance (ANOVA)

### Tensile Elongation

The ANOVA findings for tensile elongation are shown in Table 6, which also indicates the impact of various process factors on the response. Nozzle temperature is the most important of the three variables, contributing 87.63% of the total variance (Seq SS = 0.000246, Adj MS = 0.000123). Its statistically significant influence is confirmed by its extremely high F-value of 45.9 and P-value of 0.021. While bed temperature had only a 2.07% contribution (Seq SS = 0.000006) with a low F-value of 1.08 and P-value of 0.48, demonstrating a negligible influence on elongation, printing speed contributed 8.39% (Seq SS = 0.000024) with an F-value of 4.4 and a P-value of 0.185, suggesting a minor but not statistically significant effect. The trustworthiness of the model is shown by the extremely low error term of 1.91%. This is further supported by the model summary, which shows that the projected R2 is 61.34%, indicating high predictive power, and the adjusted R2 is 92.36%, indicating excellent fit, with an R2 coefficient of correlation value of 98.09%. The low PRESS value (0.0001087) and extremely tiny standard deviation (S = 0.0016384) support the constructed model's statistical soundness and robustness, with nozzle temperature being the crucial component.

Table 6: Tensile Elongation ANOVA.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Source** | **DF** | **Seq SS** | **Contribution** | **Adj SS** | **Adj MS** | **F-Value** | **P-Value** |
| Nozzle temp | 2 | 0.000246 | 87.63% | 0.000246 | 0.000123 | 45.9 | 0.021 |
| Printing speed | 2 | 0.000024 | 8.39% | 0.000024 | 0.000012 | 4.4 | 0.185 |
| Bed Temp | 2 | 0.000006 | 2.07% | 0.000006 | 0.000003 | 1.08 | 0.48 |
| Error | 2 | 0.000005 | 1.91% | 0.000005 | 0.000003 |  |  |
| Total | 8 | 0.000281 | 100.00% |  |  |  |  |

The normal probability is often expressed in this plot graph for figure 4 ANOVA Tensile Elongation as having nice and constant dots for both directions in the standard residual level. This fitted value likewise shows acceptable standard deviation from the vs fits. For the frequency condition, the histogram displays a standard and constant bar chart. At the usual order of operation graph level, Versus order also provides good observation [51-53]..



Figure 4: Plots for ANOVA Tensile Elongation

### Tensile Youngs modulus

The ANOVA findings for tensile Young's modulus in this experiment are shown in Table 7, emphasizing how much 3D printing factors affect material stiffness. The most important element is nozzle temperature, which accounts for a huge 88.18% of the overall variance (Seq SS = 135,800; Adj MS = 67,900). It is statistically significant, as seen by its very high F-value of 72.75 and P-value of 0.014. With an F-value of 7 and a P-value of 0.125, printing speed explains 8.48% of the variation (Seq SS = 13,067; Adj MS = 6533.3), suggesting a considerable but not statistically significant influence. Bed temperature has a little impact, contributing just 2.12% (Seq SS = 3267; Adj MS = 1633.3) with a low F-value of 1.75 and P-value of 0.364. The dependability of the model is strengthened by the extremely low error term (1.21%). With a good R2 of correlation of 98.79% and an adjusted R2 of 95.15%, the model summary further illustrates its robustness, indicating that it explains almost all of the variability in tensile Young's modulus. The PRESS value (37,800) validates model stability, the standard deviation is minimal (S = 30.55), and the anticipated R2 is 75.45%, indicating high forecasting performance. Overall, the data demonstrates that the primary factor influencing tensile Young's modulus is nozzle temperature, with printing speed and bed temperature having less of an impact.

Table 7: Tensile Youngs modulus ANOVA

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Source | DF | Seq SS | Contribution | Adj SS | Adj MS | F-Value | P-Value |
| Nozzle temp | 2 | 135800 | 88.18% | 135800 | 67900 | 72.75 | 0.014 |
| Printing speed | 2 | 13067 | 8.48% | 13067 | 6533.3 | 7 | 0.125 |
| Bed Temp | 2 | 3267 | 2.12% | 3267 | 1633.3 | 1.75 | 0.364 |
| Error | 2 | 1867 | 1.21% | 1867 | 933.3 |  |  |
| Total | 8 | 154000 | 100.00% |  |  |  |  |

In this plot graph for figure 5 ANOVA Tensile young's modulus, the normal probability is commonly represented as having delightful consistent dots for both directions in the standard residual level. Additionally, the standard deviation of this fitted value from the versus fits is acceptable. The histogram shows a standard and consistent bar chart for the frequency condition. Versus order also offers a useful observation at the standard order of operation graph level.



Figure 5: Plots for ANOVA Tensile Youngs modulus

## Regression model

### Tensile Elongation

The regression equation below represents tensile elongation as a function of nozzle temperature, printing speed, and bed temperature, demonstrating how each parameter effects the output. The base constant is 0.206856, which represents the initial elongation value prior to any factor changes. The coefficients represent the influence of each setting: Nozzle temperature of 200 °C reduces elongation by -0.006056, while 210 °C decreases it somewhat (-0.000656). However, 220 °C increases elongation by +0.006711. Printing speed affects vary—Elongation decreases by -0.001989 at 15 mm/s, but increases by +0.001978 and +0.000011 at 20 and 25 mm/s, respectively, indicating a little improvement at higher speeds. Bed temperature is also an important factor. 60°C enhances elongation by +0.001011, 70°C decreases it by -0.000956, and 80°C produces a small reduction of -0.000056. The equation indicates that higher nozzle temperatures (220 °C) and moderate printing rates (20 mm/s) enhance tensile elongation, whereas lower nozzle settings and extremely low printing speeds limit it.

|  |  |  |
| --- | --- | --- |
| Tensile Elongation | = | 0.206856 - 0.006056 Nozzle temp\_200 - 0.000656 Nozzle temp\_210 + 0.006711 Nozzle temp\_220 - 0.001989 Printing speed\_15 + 0.001978 Printing speed\_20 + 0.000011 Printing speed\_25 + 0.001011 Bed Temp\_60 - 0.000956 Bed Temp\_70 - 0.000056 Bed Temp\_80 |

### Tensile Youngs modulus

The regression equation for Tensile Young's Modulus (MPa) shows how nozzle temperature, printing speed, and bed temperature influence material stiffness in 3D printing. The base value is 4840.0 MPa, which is the reference modulus before adjusting for factors. Setting the nozzle temperature to 200 °C adds +143.3 MPa, slightly boosting stiffness. 210 °C adds a small +13.3 MPa, and 220 °C dramatically lowers stiffness by -156.7 MPa, indicating that very high heat weakens the material. Printing speed affects modulus: 15 mm/s rises by +46.7 MPa, 20 mm/s decreases by -46.7 MPa, and 25 mm/s has a neutral impact (0.0 MPa). Bed temperature has a little impact on stiffness. At 60°C, modulus decreases slightly (-23.3 MPa), at 70°C, it improves (+23.3 MPa), and at 80°C, it remains unchanged (0.0 MPa). The equation shows that moderate nozzle temperatures (200-210 °C) and slower printing rates (15 mm/s) increase stiffness, whereas extremely high nozzle temperatures (220 °C) and mid-range speeds (20 mm/s) decrease the tensile Young's modulus.

|  |  |  |
| --- | --- | --- |
| Tensile Youngs modulus MPa | = | 4840.0 + 143.3 Nozzle temp\_200 + 13.3 Nozzle temp\_210 - 156.7 Nozzle temp\_220 + 46.7 Printing speed\_15 - 46.7 Printing speed\_20 - 0.0 Printing speed\_25 - 23.3 Bed Temp\_60 + 23.3 Bed Temp\_70 + 0.0 Bed Temp\_80 |

## Contour plot

The contour plot figure 6 shows the link between tensile elongation and the combined effects of nozzle temperature (200-220 °C) and bed temperature (60-80 °C) is shown using colour bands to illustrate elongation ranges [30]. The deep blue zones (≤ 0.2000) indicate excellent Strength conditions for lowering elongation, with lower nozzle temperatures (200 °C) and higher bed temperatures (75-80 °C). The colour changes from bright blue (0.2000-0.2050) to turquoise (0.2050-0.2100) to pale green (0.2100-0.2150), indicating a gradual rise in elongation. The dark green spots (> 0.2150) exhibit the maximum elongation levels, focused around 220 °C nozzle temperature and lower bed temperatures (60-65 °C). In general, the figure shows that the lowest tensile elongation (desired) is produced by cooler nozzle settings and somewhat higher bed temperatures, but the material behaviour shifts towards higher ductility when elongation is increased by hotter nozzle temperatures. The Tensile Youngs modulus,Higher values indicate greater performance. Figure 6's contour plot depicts how tensile Young's modulus (MPa) reacts to changes in nozzle temperature (200–220 °C) and bed temperature (60–80 °C). Mostly at mid-range bed temperatures (65–70 °C) and lower nozzle temperatures (about 200 °C), the dark green patches (> 4980 MPa) indicate the maximum stiffness. When the hues change to pale green (4800–4860 MPa) and lighter green (4860–4920 MPa), the modulus stays high but begins to slowly decrease, indicating moderately strong material behaviour. Particularly at higher nozzle temperatures (215–220 °C), stiffness significantly decreases as one moves into the blue zones (4740–4620 MPa). The dark blue sections (<4620 MPa) indicate the lowest tensile modulus and, thus, the least acceptable result. Overall, the plot reveals that **maintaining a lower nozzle temperature (200–210 °C) with moderate bed heating (65–75 °C)** is optimal for maximizing tensile Young’s modulus, while excessive nozzle heat at 220 °C tends to soften the material and diminish its stiffness.



(a)



(b)

Figure 6: (a) (b) Contour plot for Tensile elongation and Youngs modulus

# Conclusion

This study investigated the effect of nozzle temperature (200–220 °C), printing speed (15–25 mm/s), and bed temperature (60–80 °C) on the tensile Young’s modulus and tensile elongation of 95% polycarbonate and 5% graphene composite samples fabricated by FDM 3D printing using the Taguchi design of experiments. ANOVA results revealed that nozzle temperature is the most significant parameter, contributing 88.18% to the variation in tensile Young’s modulus and 87.63% to tensile elongation, followed by printing speed (8–9%) and bed temperature (≈2%). The experiments showed that the lowest tensile elongation value (20.00%)—the desired outcome for dimensional stability was achieved at 200 °C nozzle temperature, 15 mm/s printing speed, and 60 °C bed temperature (Level 1). The highest tensile Young’s modulus (5000 MPa) the target for maximum stiffness was also recorded under the same conditions. Conversely, at 220°C nozzle temperature, 20mm/s speed, and 60°C bed temperature (Level 8), the greatest elongation (21.74%) and the lowest modulus (4600MPa) were recorded, underscoring the detrimental impact of excessive heat. According to contour plots, a printing speed of 15 mm/s promotes greater structural integrity, while moderate nozzle temperatures (200–210 °C) and bed heating of 65–75 °C are ideal for preserving high stiffness and minimal elongation. Overall, this work shows that the key to maximizing mechanical performance is careful control of the nozzle temperature, which ensures minimal tensile elongation and high Young's modulus for better polycarbonate–graphene composite parts.

# 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. Malek‐Mohammadi, H., Majzoobi, G. H., & Payandehpeyman, J. (2019). Mechanical characterization of polycarbonate reinforced with nanoclay and graphene oxide. *Polymer Composites*, *40*(10), 3947-3959.
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. Sabet, M. (2023). The impact of graphene oxide on the mechanical and thermal strength properties of polycarbonate. *Journal of Elastomers & Plastics*, *55*(4), 511-525.
5. Jazani, O. M., Arefazar, A., Saeb, M. R., & Ghaemi, A. (2010). Evaluation of mechanical properties of polypropylene/polycarbonate/SEBS ternary polymer blends using Taguchi experimental analysis. *Journal of Applied Polymer Science*, *116*(4), 2312-2319.
6. Jadhav, V. D., Patil, A. J., & Kandasubramanian, B. (2021). Polycarbonate nanocomposites for high impact applications. *Handbook of consumer nanoproducts*, 1-25.
7. Dharmaraj, M. M., Chakraborty, B. C., & Begum, S. (2022). The effect of graphene and nanoclay on properties of nitrile rubber/polyvinyl chloride blend with a potential approach in shock and vibration damping applications. *Iranian Polymer Journal*, *31*(9), 1129-1145.
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. Jang, K. S. (2020). Low-density polycarbonate composites with robust hollow glass microspheres by tailorable processing variables. *Polymer Testing*, *84*, 106408.
10. Chen, X., Lu, S., Sun, C., Song, Z., Kang, J., & Cao, Y. (2021). Exploring impacts of hyper-branched polyester surface modification of graphene oxide on the mechanical performances of acrylonitrile-butadiene-styrene. *Polymers*, *13*(16), 2614.
11. 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.
12. 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.
13. 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.
14. 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.
15. S. Baskar 2022, July. Thermal management of solar thermoelectric power generation. In AIP conference proceedings (Vol. 2473, No. 1). AIP Publishing.
16. 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.
17. 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.
18. 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.
19. A. Baraniraj et al. 2023. Silicon Carbide Particle Enriched Magnesium Alloy (AZ91) Composite: Physical, Microstructural and Mechanical Studies. Silicon, 15(15), pp.6367-6374.
20. 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.
21. 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.
22. 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.
23. 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>
24. 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>
25. Khimsuriya, Yogeshkumar D., et al., Artificially roughened solar air heating technology–A comprehensive review. Applied Thermal Engineering 214 (2022): 118817.
26. 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.
27. 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.
28. S. Kaliappan. Mechanical Assessment of Carbon–Luffa Hybrid Composites for Automotive Applications. No. 2023-01-5070. SAE Technical Paper, 2023.
29. 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.
30. 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>
31. 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>
32. 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.
33. Sai, Samavedam Aditya, et al. Transfer learning based fault detection for suspension system using vibrational analysis and radar plots. Machines 11.8 (2023): 778.
34. P. Sakthivel et al. Synthesis and Thermal Adsorption Characteristics of Silver-Based Hybrid Nanocomposites for Automotive Friction Material Application. Adsorption Science & Technology, 2023.
35. Chennai Viswanathan, Prasshanth, et al., Deep learning for enhanced fault diagnosis of monoblock centrifugal pumps: Spectrogram-based analysis. Machines 11.9 (2023): 874.
36. 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.
37. V. Vijayan et al. 2016. Performance Evaluation of Multipurpose Solar Heating System. Mechanics & Mechanical Engineering, 20(4).
38. 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.
39. M. Vivekanandan et al. 2021. Experimental and CFD investigation of helical coil heat exchanger with flower baffle. Materials Today: Proceedings, 37, pp.2174-2182.
40. 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.
41. 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.
42. 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.
43. 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.
44. 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.
45. 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.
46. 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.
47. 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.
48. 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.
49. 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
50. 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>
51. 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>
52. 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.
53. 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.