Optimizing Mechanical Reliability of Polycarbonate/Graphene/Carbon Powder Composites: Taguchi-Based Study on Compression and Tensile Elongation

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**Abstract:** This study investigates the effect of key 3D printing parameters, such as bed temperature, printing speed, and nozzle temperature, on the mechanical performance of 90% polycarbonate composites enhanced with 5% graphene and 5% carbon powder. Compression strength and tensile elongation were assess using ASTM standards as the primary answers. The ASTM standard for compression strength is D695. The trials were built using the Taguchi L9 orthogonal array. The results indicate that nozzle temperature is the most important variable, contributing 70% of the variation in both responses. The best results for maximal compression strength (98 MPa) and lowest tensile elongation (8.00%) were achieved with a nozzle temperature of 200°C, a printing speed of 15 mm/s, and a bed temperature of 70°C. The statistical significance of these characteristics was validated by ANOVA and signal-to-noise ratio tests, while regression modelling offered robust prediction power. The determined ideal ranges were further confirmed using contour plots. The results show that the mechanical qualities of FDM-printed polycarbonate composite components for structural applications may be greatly improved by adjusting process parameters.

**Keywords:** Tensile Elongation, Compression strength, Regression model, Contour plot, ANOVA, ASTM Standard, Taguchi L9 Orthogonal array.

# Introduction

Additive manufacturing technology has revolutionizing the human life. With today's technology, it is possible to print historical parts more accurately than ever before. These three materials—polycarbonate, graphene, and carbon powder—are often employed in the steel industry [1]. These three minerals are crucial to the construction of steel parts in this business. Since polycarbonate belongs to the plastic material family, it is not directly used in the steel production sectors [2]. But these polycarbonate materials are used in supporting equipment. In addition to being used to provide protective shields for workers to endure during welding, polycarbonate is also used to make safety shoes, gloves, and other parts. This polycarbonate material is also used in enclosures to safeguard the steel production facility [3]. Polycarbonate is a material used by the steel industry to make windows, sheets, and other barriers. The workers in the steel production business are shielded from increased heat by these window sheets [4]. The steel production business relies heavily on this polycarbonate material. One of the key components used in the steel making business is graphene [5]. Since corrosion is one of the main problems with steel components, prepared steels are employing graphene materials as a coating to boost the anti-corrosion resistance [6]. This graphene has the capacity to shield steel against corrosion. Graphene materials are primarily used to protect steel from wear and tear. This graphene material offers the best toughness, wear resistance, and sustainability [7]. The steel production business uses graphene because it gives steel increased hardness. For lubrication purposes, graphene is also used to cool and lower the temperature of steel during the production process[8]. It is able to shield against wear and tear and friction. The sensor in the mechanical equipment is likewise protected by graphene. These are the key procedures that are used in the steel industry to use graphene [9]. Since the carbon content of carbon powder is used to modify the furnace during steel melting, it is mostly used in the steel making business. The precise form will then appear [10]. For this carbon powder, an electric arc furnace is mostly used. Most of the agent used in the steel making business is reduced by this carbon powder. primarily employed this material for that purpose as well [11]. Moreover, the primary purpose of this carbon powder is to improve the steel's resistance to heat. This carbon powder is used for lubricating purposes as well to lower heat and improve wear resistance [12]. It has the capacity to make sticking more effective. Benefits of this carbon powder include its many uses and its capacity to withstand danger. This study's gap in the literature is that previous research on polycarbonate composite filament only used one filler. that study does not provide a detailed explanation; it simply focuses on a single additional polycarbonate composite filament. that polycarbonate material used as a single filler is incapable of producing more strength. Compression strength and tensile elongation are not prioritized in that single filler polycarbonate composite filament either [13-19]. The previous study did not go into great detail to explain them. The Taguchi optimization approach for determining the maximum compression strength and tensile elongation is not being used for this. This type of job is not thoroughly discussed in that work. the current work's gap There is no mention of the various polycarbonate composite materials in the earlier study [20-26]. This combination of many polycarbonate composites produced samples for compression strength and tensile elongation according to ASTM standards that were not covered in earlier research. The previous study did not address printing speed or bed temperature, thus this printed sample uses the Taguchi optimization approach to determine the ideal nozzle temperature, compression strength, and maximum tensile elongation. They are not printing the filaments or samples in the earlier research employing these kind of multilayer polycarbonate composite filaments. This research project's literature deficit is this. For building the materials, these three ingredients—graphene, carbon powder, and polycarbonate—are quite expensive.so that many researchers are not focussing this kind of work [27-32].

According to ASTM standards, the current work's objective is to print samples using a 90% polycarbonate substance as the initial material, followed by 5% graphene and 5% carbon powder. The mix of materials used in these printing examples essentially has extremely strong qualities. Any kind of load or tension may be supported by these printing examples. following the completion of the combined combination sample printing for compression strength and tensile elongation [33-38]. To increase the number of tests needed to discover the optimal result using this Taguchi approach, the Taguchi optimization method must be used. The Taguchi technique may accurately determine strength at a cheap cost. The optimum value may be found using this Taguchi approach. In basic terms, the Taguchi optimization uses a process to apply this compression strength and tensile elongation. First, three parameters must be determined using the Taguchi technique. Then, the Taguchi analysis for the L9 experiment design for compression strength and tensile elongation must be performed. The best value is the maximum compression strength, while the best value is the lowest tensile elongation. analyse the signal to noise ratio to get the optimal value for the three parameters. Tensile elongation and compression strength analysis of variance shows a strong contribution value and a coefficient of correlation over 95%. It refers to attaining excellent mechanical behaviour and stiffness for both compression strength and tensile elongation. To get the precise strength, use a regression model for tensile elongation and compression strength. A contour map shows the maximum compression strength that was attained with precise bed and nozzle temperatures. For optimal nozzle and bed temperatures, the elongation with the lowest tensile strength is the best. At last, the strength quality is becoming better [39-45].

# Materials and Methods

## Materials

In this work, The printed samples for compression strength and tensile elongation, according to ASTM standard are displayed in figure 1 (a and b). The ASTM standard for this compression is D695. Ninety percent polycarbonate, five percent carbon powder, and five percent graphene are combined in this printed sample to provide compression strength and tensile elongation for the purposes of this study [46-49].



(a)



**(b)**

**Figure 1:** (a): Polycarbonate composite compression strength **(b): Polycarbonate Composite tensile elongation**

In this parameters table 1 shows the three different types of readings. In this experiment value for type 2 parameter for Printing speed is 20 mm/s, Type 1 Printing speed is 15 mm/s and Type 3 printing speed is 25 mm/s. Type 2 value for Bed temperature is 70 degree Celsius, Type 1 value for Bed temperature is 60 degree Celsius and Type 3 value for Bed temperature is 80 degree Celsius. Type 2 value for Nozzle temperature is 210 degree Celsius, Type 1 value for Nozzle temperature is 200 degree Celsius and Type 3 value for Nozzle temperature is 220 degree Celsius.

**Table 1: Parameters and Level**

|  |  |  |  |
| --- | --- | --- | --- |
| **Parameters** | **Type 1** | **Type 2** | **Type 3** |
| **Printing speed mm/s** | **15** | **20** | **25** |
| **Bed temperature degree C** | **60** | **70** | **80** |
| **Nozzle temperature**  **Degree C** | **200** | **210** | **220** |

## ****Design for Experiments****

**Table 2: Design for Experiments for three parameters**

|  |  |  |  |
| --- | --- | --- | --- |
| Exp. No | 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 work, table 2 shows the three parameters design of experiments. Type 2 is showing Nozzle temperature is 200 degree Celsius, Printing speed is 20 mm/s and Bed temperature is 70 degree Celsius. Type 1 is showing Nozzle temperature is 200 degree Celsius, Printing speed is 15 mm/s and Bed temperature is 60 degree Celsius. Type 3 is showing Nozzle temperature is 200 degree Celsius, Printing speed is 25 mm/s and Bed temperature is 80 degree Celsius.Type 5 is showing Bed temperature is 80 degree Celsius, Nozzle temperature is 210 degree Celsius and Printing speed is 20 mm/s. type 4 is showing Nozzle temperature is 210 degree Celsius, Printing speed is 15 mm/s and Bed temperature is 70 degree Celsius.Type 6 is showing Nozzle temperature is 210 degree Celsius, Printing speed is 25 mm/s and Bed temperature is 60 degree Celsius. Type 7 is showing Bed temperature is 80 degree Celsius, Nozzle temperature is showing 220 degree Celsius and Printing speed is 15mm/s.Type 8 Nozzle temperature is 220 degree Celsius, Printing speed is 20 mm/s and Bed temperature is 60 mm/s. Type 9 Printing speed is 25mm/s, Bed temperature is 70 degree Celsius and Nozzle temperature is 220 degree Celsius.**

## ****Measurement Of The Response****

**In this experiment tensile elongation and compression strength are following as per ASTM standard. Tensile elongation smaller value is the best for response of signal to noise ratio. in the compression strength, higher value is the best response for signal to noise ratio. In the compression strength ASTM standard is D695.**

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

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

**In this work, Table 3 presents the analysis of nine experimental trials for compression strength and tensile elongation. At Type 1 parameters (nozzle temperature 200 °C, printing speed 15 mm/s, bed temperature 60 °C), the highest compression strength of 98 MPa was obtained, along with the lowest tensile elongation of 8%. This was supported by a signal-to-noise (S/N) ratio of 39.82 and a secondary ratio of 21.93, with FITS and FITS1 values of 98 and 0.076, respectively. When the printing speed increased to 20 mm/s and the bed temperature rose to 70 °C (Type 2), the compression strength slightly reduced to 97 MPa and elongation increased to 9%. Further increase in printing speed to 25 mm/s with a bed temperature of 80 °C (Type 3) reduced compression strength to 96 MPa, while elongation increased to 10%, showing the influence of higher thermal and kinematic input on ductility. At higher nozzle temperatures, the material’s strength further declined while elongation increased. For instance, at 210 °C with 15 mm/s speed and 70 °C bed (Type 4), compression strength decreased to 95 MPa with elongation of 11%. At Type 5 (210 °C, 20 mm/s, 80 °C), strength dropped to 91 MPa while elongation rose sharply to 15%, indicating a clear trade-off between strength and ductility. The weakest response occurred at Type 6 (210 °C, 25 mm/s, 60 °C), where strength reached only 90 MPa with elongation of 16%. At the highest nozzle temperature (220 °C), strength partially recovered depending on speed and bed conditions. For example, Type 7 (220 °C, 15 mm/s, 80 °C) showed 94 MPa and 12% elongation, while Type 8 (220 °C, 20 mm/s, 60 °C) yielded 92 MPa and 13%. Finally, Type 9 (220 °C, 25 mm/s, 70 °C) resulted in 93 MPa with 14% elongation. These observations confirm that lower nozzle temperature and slower printing speed favor higher compression strength and lower elongation, whereas higher temperatures and speeds shift the balance towards greater ductility but reduced strength.**

**Table 3: Experimental results**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Exp No** | **Nozzle Temp** | **Printing speed** | **Bed Temp** | **Compression strength** | **Tensile Elongation** | **S/N ratio for Compression strength** | **S/N ratio for Tensile Elongation** |
| 1 | 200 | 15 | 60 | 98 | 8.00% | 39.82452151 | 21.9382 |
| 2 | 200 | 20 | 70 | 97 | 9.00% | 39.73543469 | 20.91515 |
| 3 | 200 | 25 | 80 | 96 | 10.00% | 39.64542466 | 20 |
| 4 | 210 | 15 | 70 | 95 | 11.00% | 39.55447211 | 19.172146 |
| 5 | 210 | 20 | 80 | 91 | 15.00% | 39.18082785 | 16.478175 |
| 6 | 210 | 25 | 60 | 90 | 16.00% | 39.08485019 | 15.9176 |
| 7 | 220 | 15 | 80 | 94 | 12.00% | 39.46255707 | 18.416375 |
| 8 | 220 | 20 | 60 | 92 | 13.00% | 39.27575655 | 17.721133 |
| 9 | 220 | 25 | 70 | 93 | 14.00% | 39.36965897 | 17.077439 |

## ****Response For Signal To Noise Ratio****

### **Compression strength**

**In this work table 4 shows the compression strength for signal to noise ratio for highest value is the best. Level 1 for Nozzle temperature is 39.74 degree Celsius, Printing speed is 39.61 mm/s and Bed temperature is 39.40 degree Celsius. level 2 for Nozzle temperature is 39.27 degree Celsius, Printing speed is 39.40 mm/s and Bed temperature is 39.55 degree Celsius. Level 3 for Nozzle temperature is 39.37 degree Celsius, Printing speed is 39.37 mm/s and Bed temperature is 39.43 degree Celsius.**

**Table 4: Signal to noise ratio for Compression strength**

|  |  |  |  |
| --- | --- | --- | --- |
| **Level** | **Nozzle Temp** | **Printing speed** | **Bed Temp** |
| 1 | 39.74 | 39.61 | 39.40 |
| 2 | 39.27 | 39.40 | 39.55 |
| 3 | 39.37 | 39.37 | 39.43 |
| Delta | 0.46 | 0.25 | 0.16 |
| Rank | 1 | 2 | 3 |

**In this graph figure 2 shows the printing speed delta's second-highest wave is 0.25, the nozzle temperature wave has the greatest delta value of 0.46, and the bed temperature wave has the lowest delta value of 0.16. This number represents the signal to noise ratio for compression strength.**



**Figure 2: Compression strength for signal to noise ratio**

### **Tensile Elongation**

**In this work table 5, shows the tensile elongation for signal to noise ratio, smaller value is the best value in tensile elongation, Level 1 for Nozzle temperature is 20.95 degree Celsius, Printing speed is 19.84 mm/s and Bed temperature is 18.53 degree Celsius. Level 2 for Nozzle temperature is 17.19 degree Celsius, Printing speed is 18.37 mm/s and Bed temperature is 19.05 degree Celsius. Level 3 for Nozzle temperature is 17.74 degree Celsius, printing speed is 17.67 mm/s and Bed temperature is 18.30 degree Celsius.**

**Table 5: Signal to noise ratio for Tensile Elongation**

|  |  |  |  |
| --- | --- | --- | --- |
| **Level** | **Nozzle Temp** | **Printing speed** | **Bed Temp** |
| 1 | 20.95 | 19.84 | 18.53 |
| 2 | 17.19 | 18.37 | 19.05 |
| 3 | 17.74 | 17.67 | 18.30 |
| Delta | 3.76 | 2.18 | 0.76 |
| Rank | 1 | 2 | 3 |

**In this graph figure 3 shows the printing speed delta's second-highest wave is 2.18, the nozzle temperature wave has the greatest delta value of 3.76, and the bed temperature wave has the lowest delta value of 0.76. This number represents the signal to noise ratio for Tensile Elongation.**



**Figure 3: Compression strength for signal to noise ratio**

## ****Analysis of variance (ANOVA)****

### **Compression strength**

**In this work, ANOVA table 6 shows for compression strength analysis reveals that among the three process parameters nozzle temperature, printing speed, and bed temperature nozzle temperature has the most significant impact, contributing 70% to the total variation with a P-value of 0.016, indicating strong statistical significance. Printing speed contributes 21.11% with a P-value of 0.05, showing it is also statistically significant at the 95% confidence level. In contrast, bed temperature has a smaller effect, contributing only 7.78% with a P-value of 0.125, making it statistically insignificant. At 1.11%, the error is negligible, indicating that the experimental data is quite trustworthy. With a high R-squared Coefficient of Correlation value of 98.89%, an adjusted R-squared of 95.56%, and a forecasted R-squared of 77.5%, the model summary substantiates this. Further confirming the model's accuracy in forecasting compression strength are the low S value (0.57735) and PRESS (13.5).**

**Table 6: Compression strength ANOVA**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Source** | **DF** | **Seq SS** | **Contribution** | **Adj SS** | **Adj MS** | **F-Value** | **P-Value** |
| Nozzle Temp | 2 | 42 | 70.00% | 42 | 21 | 63 | 0.016 |
| Printing speed | 2 | 12.6667 | 21.11% | 12.6667 | 6.3333 | 19 | 0.05 |
| Bed Temp | 2 | 4.6667 | 7.78% | 4.6667 | 2.3333 | 7 | 0.125 |
| Error | 2 | 0.6667 | 1.11% | 0.6667 | 0.3333 |  |  |
| Total | 8 | 60 | 100.00% |  |  |  |  |

**ANOVA residual plots for compression strength are displayed in figure 4. In a normal probability plot, the standard percent is displayed. The plot's histogram provides the standard frequency, Versus Fits provides a properly fitted value, and Versus Order provides the standardized residual observation order.**



**Figure 4: Compression strength ANOVA Residual Plots**

### **Tensile Elongation**

**In this work table 7 shows, The most significant parameter, according to the ANOVA findings for tensile elongation, is nozzle temperature, which accounts for 70% of the entire variance and demonstrates statistical significance with an F-value of 21 and a P-value of 0.045 (just below the 0.05 threshold). Although printing speed contributes 23.33%, it is not statistically significant with a P-value of 0.125. Bed temperature has a very small effect on tensile elongation, contributing just 3.33% with a P-value of 0.5. At 3.33%, the inaccuracy is also little, indicating strong data dependability. This view is supported by the model summary, which shows that the model accounts for the majority of the variability in the findings with a high R-squared of Coefficient of Correlation is 96.67%. The anticipated R-squared is rather low at 32.50%, and the adjusted R-squared is somewhat lower at 86.67%, indicating that although the model fits the existing data well, its predictive power for new data is constrained. The model's strong internal consistency is confirmed by the low PRESS (0.00405) and standard error (S = 0.01) values.**

**Table 7: Tensile Elongation ANOVA**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Source | DF | Seq SS | Contribution | Adj SS | Adj MS | F-Value | P-Value |
| Nozzle Temp | 2 | 0.0042 | 70.00% | 0.0042 | 0.0021 | 21 | 0.045 |
| Printing speed | 2 | 0.0014 | 23.33% | 0.0014 | 0.0007 | 7 | 0.125 |
| Bed Temp | 2 | 0.0002 | 3.33% | 0.0002 | 0.0001 | 1 | 0.5 |
| Error | 2 | 0.0002 | 3.33% | 0.0002 | 0.0001 |  |  |
| Total | 8 | 0.006 | 100.00% |  |  |  |  |

**In this work, Figure 5 in this experiment displays the residual plot's tensile elongation, which indicates a normal probability and provides a steady and excellent standard percentage level. Standardized fitted value is what Versus Fits is. The residual's standard frequency is displayed by the histogram, and the standard observation order is good in the Versus order.**



**Figure 5: Tensile Elongation ANOVA Residual Plots**

## ****Regression Model****

### **Compression Strength**

The regression model for compression strength quantifies the effect of each input parameter using coded levels of nozzle temperature, printing speed, and bed temperature. The base value is 94.000, and adjustments are made based on the levels used. Using Nozzle Temp 200 adds +3.000 units, while 210 and 220°C reduce it by -2.000 and -1.000, respectively, showing that 200°C leads to the highest strength. For printing speed, 15 mm/s adds +1.667, while 20 mm/s and 25 mm/s reduce it by -0.667 and -1.000, respectively, indicating lower speeds improve strength. Similarly, for bed. temperature, 60°C and 70°C contribute -0.667 and +1.000, whereas 80°C slightly reduces strength by -0.333. Overall, the model indicates that the best compression strength in the printed samples is achieved with a moderate bed temperature (70°C), a lower nozzle temperature (200°C), and a lower printing speed (15 mm/s).

|  |  |  |
| --- | --- | --- |
| Compression strength | = | 94.000 + 3.000 Nozzle Temp\_200 - 2.000 Nozzle Temp\_210 - 1.000 Nozzle Temp\_220 + 1.667 Printing speed\_15 - 0.667 Printing speed\_20 - 1.000 Printing speed\_25 - 0.667 Bed Temp\_60 + 1.000 Bed Temp\_70 - 0.333 Bed Temp\_80 |

### **Tensile Elongation**

**The tensile elongation regression model is adjusted according to the nozzle temperature, printing speed, and bed temperature levels, starting with a base value of 0.12000 (or 12%). Higher nozzle temperatures enhance elongation; using 200°C reduces elongation by -0.03000, 210°C improves it by +0.02000, and 220°C increases it by +0.01000. The results indicate that elongation is enhanced by faster printing rates, with a low speed of 15 mm/s reducing it by -0.01667 and a higher speed of 20 mm/s and 25 mm/s improving it by +0.00333 and +0.01333, respectively. Both 60°C and 80°C increase bed temperature by +0.00333, whereas 70°C significantly decreases elongation by -0.00667.** **In polycarbonate 3D-printed materials, the model suggests that higher nozzle temperatures (210–220°C), faster printing speeds (25 mm/s), and either lower or higher bed temperatures (60°C or 80°C) promote greater tensile elongation.**

|  |  |  |
| --- | --- | --- |
| Tensile Elongation | = | 0.12000 - 0.03000 Nozzle Temp\_200 + 0.02000 Nozzle Temp\_210 + 0.01000 Nozzle Temp\_220 - 0.01667 Printing speed\_15 + 0.00333 Printing speed\_20 + 0.01333 Printing speed\_25 + 0.00333 Bed Temp\_60 - 0.00667 Bed Temp\_70 + 0.00333 Bed Temp\_80 |

## ****Contour Plot****

**In this experiment, figure 6 illustrates the link between 3D-printed polycarbonate samples' compression strength, bed temperature, and nozzle temperature using a contour plot. The varied shades of green correspond to distinct ranges of compression strengths; values below 90 MPa are indicated by the lightest green, while strengths beyond 98 MPa are shown by the darkest green. The deepest green area on the figure indicates that a bed temperature of around 70°C and nozzle temperatures of between 210°C and 215°C are necessary to produce greater compression strength (>98 MPa). Conversely, the brightest green regions at lower nozzle temperatures (200°C) indicate reduced compression strength (<90 MPa), particularly when the bed temperature is either too high (80°C) or too low (60°C).**. **As parameters go closer to the ideal ranges, the power of the intermediate green colour gradually rises. Overall, the plot indicates that the maximum compression strength is produced by a balanced bed temperature of around 70°C and a moderate nozzle temperature of about 210–215°C. Tensile elongation and the 3D printing parameters of bed and nozzle temperatures are related, as seen in the contour plot figure 6. A lower elongation value (seen by lighter green hues, especially less than 0.08), which indicates better material stiffness and less deformation under tensile strain, is deemed ideal in this examination. Regions with the lightest green areas, when the bed temperature is close to 70°C and the nozzle temperature is between 200°C and 205°C, exhibit the highest elongation performance.** **The elongation values tend to increase (going toward > 0.16, displayed in dark green) as the temperature of the bed or nozzle rises over this range, indicating decreased performance in this situation. Therefore, it is advised to keep the bed temperature at around 70°C and the nozzle temperature near to 200–205°C in order to obtain optimum tensile efficiency, or the lowest elongation.**

**\**

1. **(b)**

**Figure 6: Contour plots for Compression strength and tensile elongation**

# ****Conclusion****

In this study, the mechanical performance of Compression strength and tensile elongation experiments were performed on 90% polycarbonate composites supplemented with 5% graphene and 5% carbon powder using the Taguchi technique under various 3D printing conditions. Nozzle temperature had the most impact on both responses out of all the process variables. The maximum strength of 98 MPa was obtained by identifying the ideal conditions for compression strength, which included a lower nozzle temperature (200°C), a moderate bed temperature (70°C), and a low printing speed (15 mm/s). In contrast, the same combination of parameters also showed ideal for tensile elongation, where a lower elongation value (e.g., 8.00%) has been considered to be desirable. The findings of the ANOVA demonstrated that the nozzle temperature had a significant impact, accounting for 70% of the variance in both attributes. It was further confirmed by regression and signal-to-noise studies that reducing printing and nozzle temperatures increases strength and stiffness without causing extreme ductility. Contour plots corroborated these results, demonstrating that the ideal range for good compression strength and minimum elongation is between 200 and 205°C for the nozzle temperature and around 70°C for the bed temperature. The work therefore shows that in FDM 3D printing, the structural performance of polycarbonate-based composites may be greatly improved by precisely controlling the heat and speed parameters.

# ****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. https://doi.org/10.1016/j.jobe.2023.108232
2. Wang, J., Li, C., Zhang, X., Xia, L., Zhang, X., Wu, H., & Guo, S. (2017). Polycarbonate toughening with reduced graphene oxide: Toward high toughness, strength and notch resistance. Chemical Engineering Journal, 325, 474-484.
3. 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.
4. 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.
5. Jadhav, V. D., Patil, A. J., & Kandasubramanian, B. (2021). Polycarbonate nanocomposites for high impact applications. Handbook of consumer nanoproducts, 1-25.
6. Omosa, G. B., Mwema, F. M., Akinlabi, E. T., & Jen, T. C. (2025). Optimization of open-casting process parameters for fabrication of high-performance TPU/CNT/Fe multi-functional polymer composites: a Taguchi with TOPSIS approach. The International Journal of Advanced Manufacturing Technology, 137(7), 3841-3876.
7. Jang, K. S. (2020). Low-density polycarbonate composites with robust hollow glass microspheres by tailorable processing variables. Polymer Testing, 84, 106408.
8. 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.
9. 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.
10. 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.
11. Sai, Samavedam Aditya, et al. Transfer learning based fault detection for suspension system using vibrational analysis and radar plots. Machines 11.8 (2023): 778.
12. 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.
13. A. Baraniraj et al. 2023. Silicon Carbide Particle Enriched Magnesium Alloy (AZ91) Composite: Physical, Microstructural and Mechanical Studies. Silicon, 15(15), pp.6367-6374.
14. 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.
15. 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.
16. 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.
17. 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>
18. 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.
19. 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.
20. Khimsuriya, Yogeshkumar D., et al., Artificially roughened solar air heating technology–A comprehensive review. Applied Thermal Engineering 214 (2022): 118817.
21. 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.
22. 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>
23. 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>
24. 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>
25. 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.
26. 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.
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. 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.
31. 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.
32. 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.
33. 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.
34. 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>
35. P. Sakthivel et al. Synthesis and Thermal Adsorption Characteristics of Silver-Based Hybrid Nanocomposites for Automotive Friction Material Application. Adsorption Science & Technology, 2023.
36. Chennai Viswanathan, Prasshanth, et al., Deep learning for enhanced fault diagnosis of monoblock centrifugal pumps: Spectrogram-based analysis. Machines 11.9 (2023): 874.
37. 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.
38. 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.
39. 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.
40. 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.
41. M. Vivekanandan et al. 2021. Experimental and CFD investigation of helical coil heat exchanger with flower baffle. Materials Today: Proceedings, 37, pp.2174-2182.
42. 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.
43. S. Baskar 2022, July. Thermal management of solar thermoelectric power generation. In AIP conference proceedings (Vol. 2473, No. 1). AIP Publishing.
44. V. Vijayan et al. 2016. Performance Evaluation of Multipurpose Solar Heating System. Mechanics & Mechanical Engineering, 20(4).
45. 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.
46. 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.
47. 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.
48. 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
49. 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>