



RESEARCH ARTICLE

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PARAMETRIC OPTIMIZATION AND EXPERIMENTAL VERIFICATION OF FLEXURAL AND IMPACT PERFORMANCE OF FDM PRINTED AUTOMOBILE JIG COMPONENT USING PA12CF.

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ABSTRACT

Fused deposition modeling (FDM) is one of the leading additive manufacturing methods, currently employed across different sectors to produce functional components using composite materials. This study investigates the influence of various process variables on the mechanical properties of 3D-printed Polyamide 12 containing 20% carbon fiber composite material. In this study, the layer height, infill density, and printing speed are the process parameters considered because of their significant impact on the mechanical properties of the product. The tensile strength, impact strength, and Flexural strength of PA12-CF specimens were evaluated using fused deposition modeling (FDM) in accordance with ASTM and ISO standards. Analysis of variance (ANOVA) was used to determine the importance of the process parameters in relation to the response parameters. Polyamide 12 carbon fiber (1.75 mm thickness) was used for 3D printing. Finally, as a multi-objective optimization technique, the TOPSIS and GRA method obtain an optimal set of FDM process parameters to fabricate the best parts with comprehensive mechanical properties. The proposed research ensures the successful fabrication of the Jig Component, which is used for LOGO Printing in the Automobile Industry, with reduced weight, cost of component and manufacturing process time as compared to traditional manufacturing processes and materials.



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I. INTRODUCTION

In the era of Industry 4.0, additive manufacturing (AM) has led to digital transformation. AM is considered one of the most pristine digital technologies because it eliminates the need for tools and fixtures, which minimizes waste and expenses, while fostering sustainable business models. By aiding in the digitization of inventory, AM methods contribute to conserving the warehouse space. Soon, AM technologies will evolve to be so fast and affordable that users might print their items with only a quick press of a button. Several possible advantages of utilizing AM methods over traditional alternatives includes reduced lead times, automated inventory, decreased waste, enhanced product quality, and the ability to create intricate shapes, along with other benefits [1].

Additive manufacturing (AM) is a method that denotes a process incorporating multiple advanced techniques, with the item created through 3D printing in layers[2]. Additive manufacturing (AM) is at the forefront of contemporary manufacturing and surpasses conventional machining methods. Conventional machining faces problems with internal stress and distortion, whereas additive manufacturing (AM) rapid prototyping provides accurate, economical, and efficient solutions. The widespread application of this method in producing complex patterns is the transformation of the industrial sector. A major challenge in 3D printing is their ability to work with various materials. 3D printing has become a transformative factor in the manufacturing and research of materials science. Its impressive capacity to create intricate items with customizable material traits has ignited innovative progress across multiple industries. Diligent optimization is essential to address these challenges and ensure the effective 3D printing of composite materials. [3]. Case studies on nanocomposites, short, and continuous fiber composites, highlighting their improvements in mechanical, thermal, and electrical properties

over neat polymers, are among the challenges that additive manufacturing faces when preparing composite feedstock filaments and printing processes for thermoplastic composites [4]. In the past few years, it has been developed to produce prototypes; however, its advantages have prompted researchers to deeply investigate and explore the possibility of manufacturing functional parts. The use of 3D-printed carbon fiber-reinforced thermoplastic composites shows the potential to replace metal parts with lightweight, strong, customizable components, and better mechanical properties [5].

As per the required specific mechanical properties and their applications, many researchers have studied and implemented different composite materials for the manufacturing of particular functional parts—that are currently manufactured using conventional methods. This study investigates the use of carbon fiber polymer composites in 3D printing for centrifugal pump impellers, and suggests that corrosion-resistant materials may eventually replace metal components in manufacturing applications. Pump parts that are resistant to corrosion can be fabricated from composite materials [6]. Because of their lightweight design and mechanical capabilities, 3D-printed fiber-reinforced composites have replaced metals and thermosetting polymers. The study evaluated 3D-printed nylon/carbon fiber composites, showing improved flexural strength and stiffness compared to metals, supporting the replacement of metal parts with 3D-printed carbon fibers. The nylon + CF composite exhibited increased deflection, lower flexural strength, and elastic carbon fiber behavior. The primary disadvantages of nylon composite material are fiber breakage, pull-out, and void formation [7].

Compared to their pure polymer equivalents, 3D-printed objects have greater mechanical strength, rigidity, and toughness owing to the use of composite materials. The study showed enhanced mechanical properties by integrating carbon fibers into fused deposition modeling (FDM) filaments, enabling the replacement of metal parts with 3D-printed carbon fiber components in various industries[8]. Composites are becoming increasingly important in a range of applications requiring high-performance materials and products in industries such as aircraft, marine, automotive, construction, missiles, and defense technology. Oriented fiber composites have garnered significant attention owing to their advantageous properties, which include a high strength-to-weight ratio and controllable anisotropy. The use of short, aligned fiber filaments in high-performance 3D-printed composites has demonstrated great potential for improving the mechanical and thermal properties of objects [9]. An important consideration in determining the quality of a finished product is the adjustment of the process parameters in accordance with the requirements.

The raster angle, print speed, layer thickness, repetitive heating and cooling, print platform temperature, infill speed, nozzle temperature, and nozzle diameter are the main factors that affect composites processed with AM. During processing, particular attention must be paid to the raster angle, the infill speed, the layer thickness, and the nozzle temperature. Young's modulus, toughness, ductility, and ultimate product strength are all directly affected by the raster angle and layer thickness. The on-edge and flat orientations showed the highest tensile and flexural strengths and stiffnesses, whereas the upright orientation had the lowest [10]. The placement of the carbon fiber layer can significantly improve the durability of the 3D-printed components. It is also evident that the carbon fiber layer can be strategically positioned to control the occurrence and spread of cracks. The fiber angle was the most influential parameter (54.13%) followed by the infill density (16.25%), and the carbon layer had a smaller effect on the mechanical properties. The optimum parameters were a 0° fiber angle and 80% infill density [11]. It can be said that the three infill patterns (triangular, grid, and line) that were examined performed similarly in the mechanical tests (three-point bending and tensile).

Therefore, it can be said that the three-point bending and tensile performance are not significantly affected by the core configuration and from a mechanical test perspective, the composite filaments containing 15% chopped carbon fiber demonstrated better results than regular filaments (ABS, PLA, PETG), which are currently used in 3D printing. The Core configuration did not significantly affect the performance of mechanical properties [12]. The average tensile strength of the specimen with the carbon fiber oriented at 0° was approximately 47.83% higher than that of the 90° sample. Following a tensile test, the specimen displayed distinct breaking areas; for example, the 90° direction specimen displayed breaking in the gauge length area, whereas the 0° direction specimen displayed fracture propagation in the curvature area. According to this, the printing path and post-processing are important because they may cause reduced fiber density and improper fiber orientation in some places, which would reduce the strength of such areas [13]. Studying the printing configurations for 3D printing indicated that, compared to the air gap, raster width, contour number, and contour width, the raster angle influences the majority of the mechanical qualities. After examining the effect of printing orientation at 0°, 45°, and 90° on the 3D printing of carbon fiber-reinforced polyamide,

The tensile strength of the material was enhanced by the 0° printing orientation, which led to a greater resistance to applied tensile loading [14]. PA12-CF showed the largest elongation of any composite material, a notably low roughness, and significantly greater tensile and bending strengths. In comparison to samples made of pure polymer, samples from PETG and PA12-CF appeared significantly more pleasant to touch [15]. To investigate the effects of printing parameters, such as extruder temperature and printing speed, on the mechanical properties of continuous carbon fiber-reinforced nylon matrix composites, a methodical experimental study was created and produced for Fused deposition modeling (FDM) components. The quality of 3D-printed components is affected by both the extruder temperature and printing speed [16]. The deflections, warpings, and residual stresses were significantly affected by CF reinforcement. The Higher residual stresses 14.53 MPa as opposed to 11.75 MPa in pure PA6 specimens were necessary to achieve better 3D printed specimen quality. By lowering the deflections and warpings, CF reinforcement greatly enhanced the 3DP manufacturing performance of PA6/(28%)CF composites [17].

The bed temperature (100 °C) was the most significant parameter compared with the infill density (20%), layer thickness (0.2 mm), extrusion temperature (240 °C), and printing speed (100 mm/s) for the Polyamide 12 (PA12) material [18]. The literature highlights recent trends in composite materials and additive manufacturing methods for improving performance and functional applications. Research indicates that composite materials exhibit high durability, tensile strength, impact strength, and flexural strength, which are suitable for absorbing shocks and functioning in dynamic environments. Additive manufacturing (AM) methods such as fused deposition modeling (FDM), are recognized for producing cost-effective, customized parts for functional industrial uses. This shows the significance of various effective printing parameters such as layer height, infill density, printing speed, raster angle, and other parameters, on the mechanical performance of 3D-printed composites. Studies have suggested that composite materials reduce material waste compared with traditional manufacturing. This study aims to investigate a perfect set of optimized parameters that can produce high-strength 3D-

printed functional parts using a minimum amount of material, reduce weight, excellent rigidity and strength, heat resistance, low warpage and low water absorption, which aligns with the selection of polyamide 12 with 20% carbon fiber (PA12/CF). It is the most suitable replacement material for tool steel materials when manufacturing certain automobile components like jigs and fixtures

II. EXPERIMENTAL DETAILS

As per a detailed study of the literature and the application of polyamide carbon fiber composite material for manufacturing functional parts, various process parameters, layer height, infill density, and printing speed have been considered to study their effect on tensile strength, impact strength, and flexural strength, whereas few parameters were kept constant as shown in Table 1. Flexural strength and impact strength are important for the manufacturing and application of jig components. Therefore, we did not give more importance to the tensile strength. In addition, the layer height, infill density and printing speed are three Key Parameters in the FDM Process. According to the research study and experiments, other parameters do not have a significant effect on the flexural and impact strengths. The levels and values of the selected fused deposition modeling (FDM) process parameters are presented in Table 2.

Table 1: Constant Process Parameters.

Printing Temperature	Bed Temperature	Wall Thickness	Top Layers	Bottom Layers	Raster Angle	Infill Pattern	Cooling Fan Speed
250°C	60°C	1.2 mm	3	3	0°	Cubic	100%

Source: Authors, (2025)

Table 2: Fused deposition modeling (FDM) Process Parameters and Levels

Parameter	Level 1 (Low)	Level 2 (High)
Layer height (mm)	0.1	0.3
Infill Density (%)	20	80
Printing speed (mm/sec)	40	100

Source: Authors, (2025)

II.1 MATERIALS AND EQUIPMENT

The material used in the present study was a polyamide carbon fiber (PA12-CF) filament of 1.75 mm diameter with 80% polyamide and 20% carbon fiber. Polyamide 12 (PA12) carbon fiber composites offer a balance of strength, durability, and dimensional stability owing to carbon fiber reinforcement. The key mechanical properties include high tensile strength, flexural strength, and impact resistance, particularly when reinforced with carbon fibers. The 3D printer used to manufacture the specimen is the Omega 300 3D printer with a stainless steel nozzle of 0.4 mm diameter. This 3D printer is capable of using a wide range of materials such as PLA, ABS, polycarbonate (PC), CPE (copolyester), nylon and composite materials. Product 3D modeling was performed on SolidWorks and -.stl files in the 3D printing software Cura Ultimaker. The properties of the filament material are listed in Table 3.

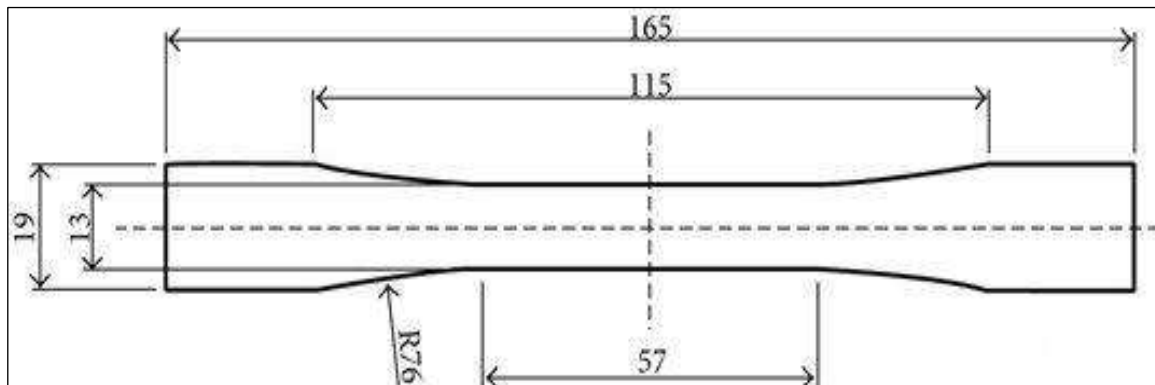
Table 3: Polyamide carbon fiber Material Properties.

Material	PA12-CF (80% Polyamide, 20% Carbon Fiber)
Filament Diameter (mm):	1.75
Density (g/cm ³):	1.2
Elongation at Break (%):	10.61
Melt Flow Index (g/10min):	8(250°C/5kg)
Dimensional Accuracy (mm):	170±0.1
Roundness Accuracy (mm):	±0.5
Melting Point (°C)	180

Source: Authors, (2025)

II.2 SAMPLE PREPARATION

The specimens used in this study to evaluate the layer height, infill density, and printing speed were designed in Solidworks based on ASTM D638 for tensile strength (Figure. 1), ASTM D256 for Izod impact (Figure. 2), and ISO 178 for flexural strength (Figure. 3).



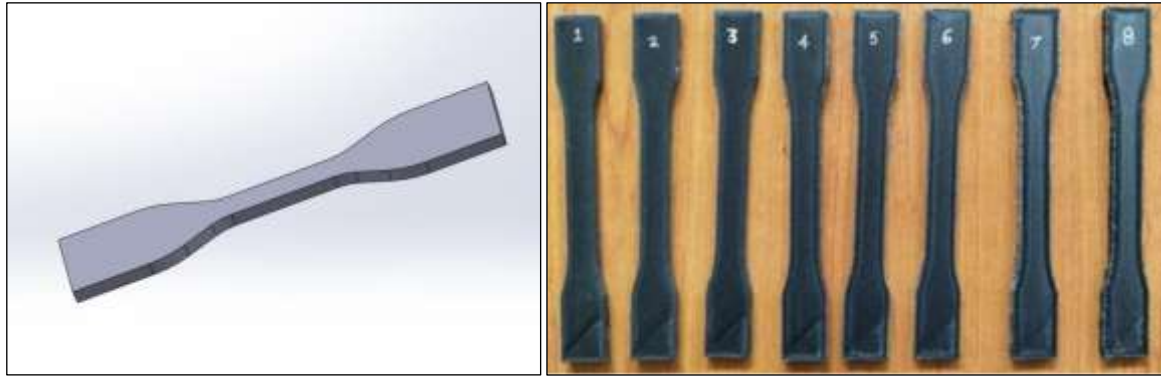


Figure 1: Tensile Strength testing Samples as per ASTM D638 Standard.
Source: Authors, (2025)

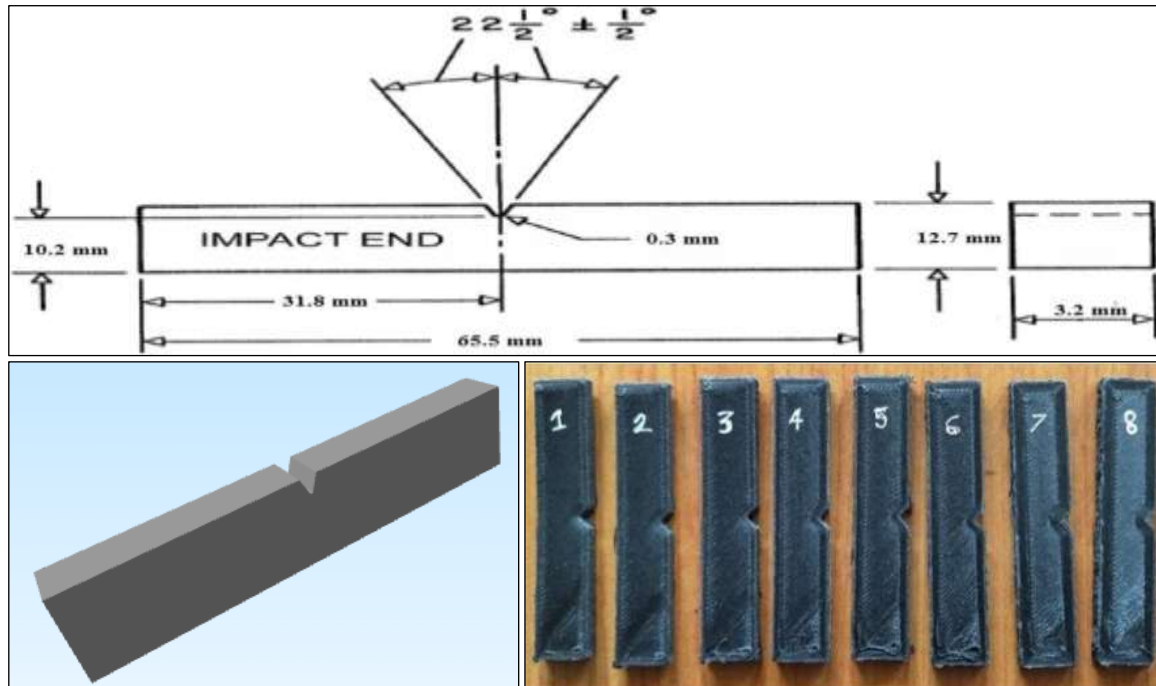


Figure 2: Impact Strength testing Samples as per ASTM D256 Standard.
Source: Authors, (2025)

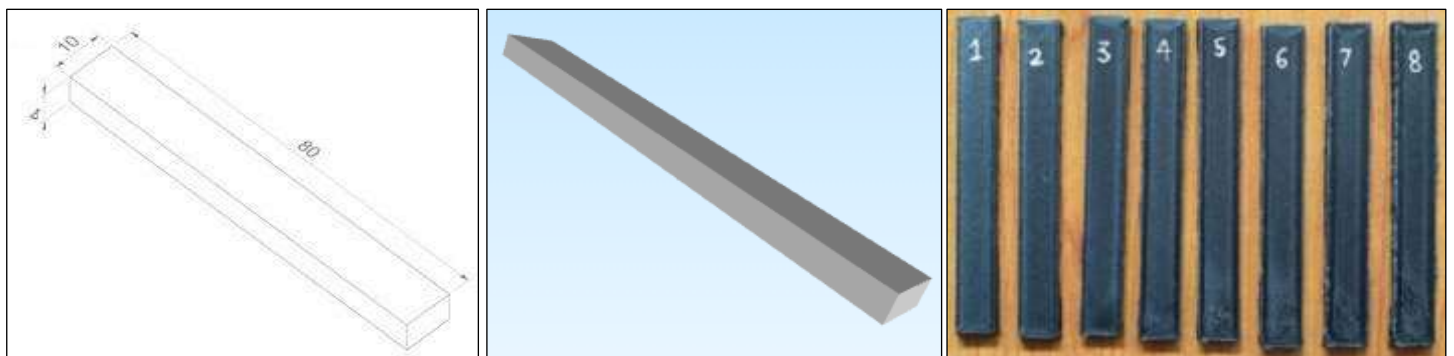


Figure 3 : Flexural Strength testing Samples as per ISO 178 Standard.
Source: Authors, (2025)

II.3 DESIGN OF EXPERIMENT (DOE) AND EXPERIMENTATION SETUP

Design of experiments (DOE) is a branch of statistics that aids in efficiently organizing, planning, and carrying out experiments while enhancing productivity. The focus of the literature is to study composite materials, which are useful for manufacturing functional parts with specific process parameters and better mechanical properties. As per the application, layer height, infill density, and printing speed were selected for this study. The layer height affects surface quality and mechanical performance. The infill density provides the strength and weight of the internal structure. The printing speed affects the production time and bonding quality.

The effects of these three parameters on the tensile, impact, and flexural strengths of the specimens were investigated independently. Tensile tests were performed using a universal testing machine (UTM) to the ASTM D638 standard. The Impact strength was tested using an Izod impact tester following the ASTM D256 standard. The flexural strength was tested using a 3-point bending test method following the ISO 178 standard. The values of the processing parameters listed in Table 4 were used to set an experiment plan to fabricate a total number of 8 samples for tensile, impact, and flexural tests.

Table 4: Design of Experiment.

Specimen	Layer Height(mm)	Infill Density (%)	Printing speed (mm/sec)
1	0.1	20	40
2	0.1	20	100
3	0.1	80	40
4	0.1	80	100
5	0.3	20	40
6	0.3	20	100
7	0.3	80	40
8	0.3	80	100

Source: Authors, (2025)

III. RESULTS AND DISCUSSIONS

The experimental setup for the tensile, impact, and flexural strengths is shown in Figure. 4. The tensile, impact, and flexural strengths of the specimens are listed in Table 5.

Table 5: Results for Tensile, Impact and Flexural Strength.

Specimen	Layer Height (mm)	Infill Density (%)	Printing Speed (mm/sec)	Tensile Strength (MPa)	Impact Strength (J/m)	Flexural (MPa)
1	0.1	20	40	10.66	132.16	16.25
2	0.1	20	100	9.15	190.4	13.47
3	0.1	80	40	17.52	294.6	23.41
4	0.1	80	100	21.3	327.93	23.56
5	0.3	20	40	12.49	163	16.83
6	0.3	20	100	11.01	114.21	14.25
7	0.3	80	40	18.61	190.08	25.22
8	0.3	80	100	16.23	186.73	19.72

Source: Authors, (2025)



Figure 4: Testing set-up for Specimen of Tensile, Impact and Flexural test.

Source: Authors, (2025)

III.1 TENSILE TEST

The tensile strength of the samples prepared using polyamide 12 carbon fiber material which was manufactured in a flat orientation, was tested using universal testing machines. All values were obtained with a 95% confidence interval. ANOVA analysis was performed using MINITAB software to identify the influence of various components on the tensile strength. The results of the ANOVA are presented in Table 6. The main and interaction effect plots for the tensile strength are shown in Figure. 5 and Figure. 6, respectively.

A higher infill density (80%) significantly improves the tensile strength. A higher printing speed (100 mm/sec) results in a maximum tensile strength of 21.3 MPa. Lower layer height (0.1 mm) tends to produce higher tensile strength compared to 0.3 mm for similar conditions. According to the results, the infill density has a greater contribution to increasing the tensile strength than the other selected parameters. Therefore, the combination of 0.1 mm layer height, 80% infill density, and 100 mm/sec printing speed maximizes the tensile strength (Specimen 4, Table 5).

Table 6: Analysis of variance table for tensile test results.

Source of Variation	Sum of Squares	DF	Mean Square	% contribution
Layer Height	0.0105	1	0.0105	0.01%
Infill Density	115.14	1	115.14	85.47%
Printing Speed	0.316	1	0.316	0.23%

Source: Authors, (2025)

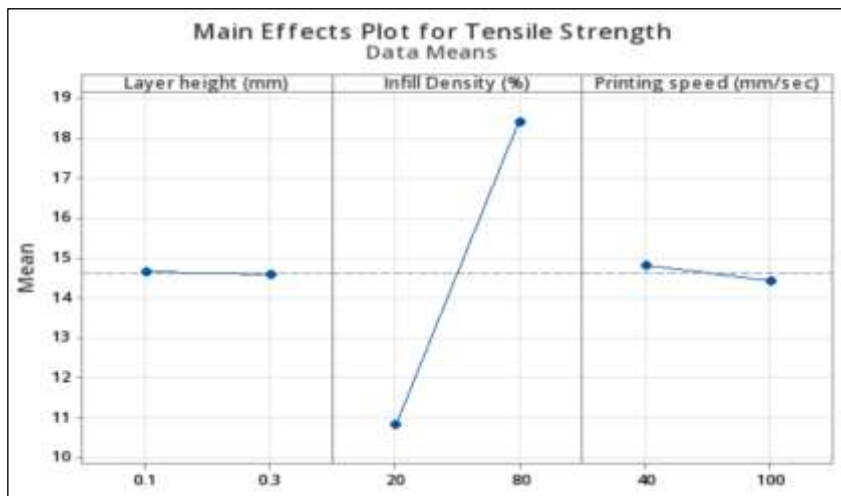


Figure 5: Main effects plot for Tensile strength.

Source: Authors, (2025)

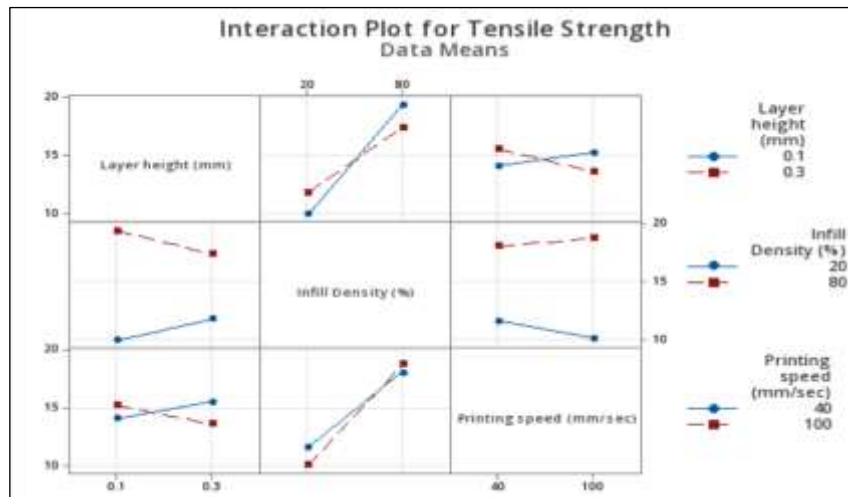


Figure 6: Interactions plot for Tensile strength.

Source: Authors, (2025)

III.2 IMPACT TEST

The impact strength of samples made of polyamide carbon fiber material was manufactured in a flat orientation and tested using the Izod impact test. The test results are listed in Table 5. All values were obtained with a 95% confidence interval. ANOVA was performed using MINITAB software to identify the influence of various components on the impact strength. The results of the ANOVA are presented in Table 7. The main and interaction effect plots for the tensile strength are shown in Figure. 7 and Figure. 8, respectively. A higher infill density (80%) significantly improves the impact strength. A higher printing speed (100 mm/sec) achieved a maximum impact strength of 327.93 J/m. A lower layer height (0.1 mm) provides a higher impact strength at a higher infill and higher speeds.

Therefore, the combination of 0.1 mm layer height, 80% infill density, and 100 mm/sec printing speed maximizes the impact strength (Specimen 4, Table 5).

Table 7: Analysis of variance table for Impact strength.

Source of Variation	Sum of Squares	DF	Mean Square	% contribution
Layer Height	10590.22	1	10590.22	27.15%
Infill Density	19957.02	1	19957.02	51.15%
Printing Speed	194.34	1	194.34	0.50%

Source: Authors, (2025)

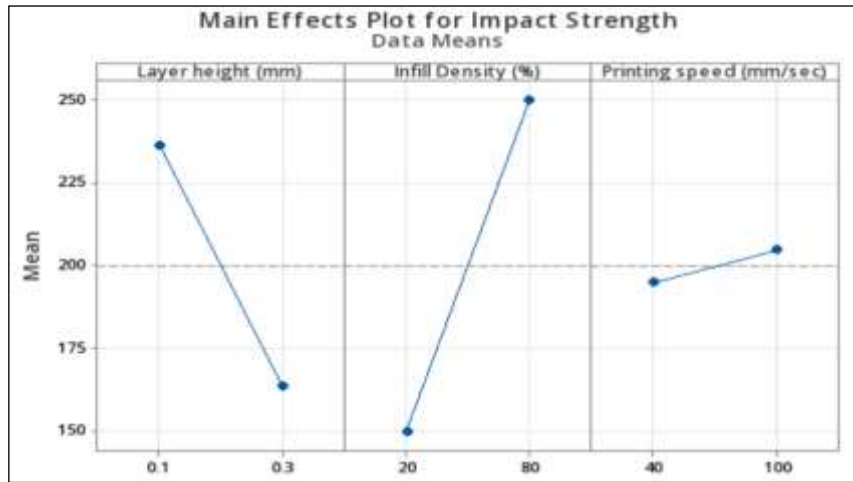


Figure 7: Main effects plot for Impact strength. Source: Authors, (2025)

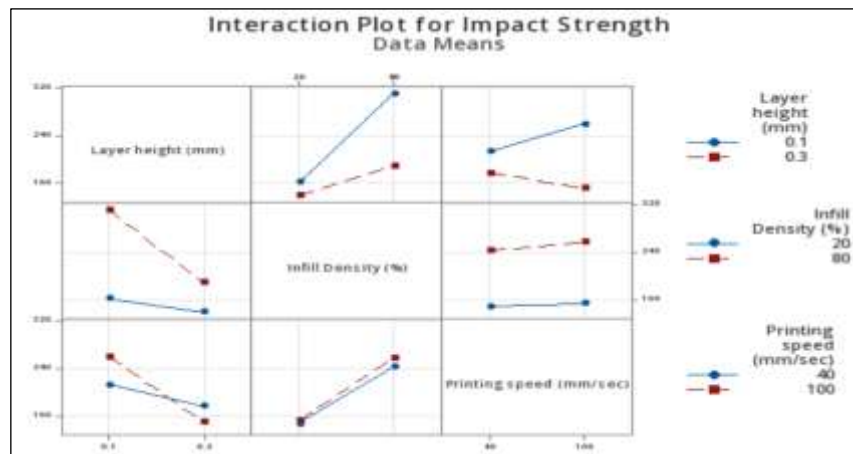


Figure 8: Interactions plot for Impact strength. Source: Authors, (2025)

III.3 FLEXURAL TEST

The flexural strength of the samples made of polyamide carbon fiber material was determined by a 3-point bending test and manufactured in the edge orientation according to the required application of the jig component. All values were obtained with a 95% confidence interval. ANOVA analysis was performed using MINITAB software to identify the influence of various components on the flexural strength. The results of the ANOVA are presented in Table 8. It was observed that the infill density had a significant effect on the flexural strength. The main and interaction effect plots for the flexural strength are shown in Figure. 9 and Figure. 10 respectively. A higher infill density (80%) improves the flexural strength. A lower printing speed (40 mm/sec) produced a higher flexural strength for most conditions. The combination of 0.3 mm layer height, 80% infill density, and 40 mm/sec printing speed maximized the flexural strength (Specimen 7, Table 5).

Table 8 Analysis of variance table for Flexural strength.

Source of variation	Sum of Squares	df	Mean Square	% contribution
Layer height	0.0561	1	0.0561	0.04%
Infill Density	120.98	1	120.98	83.55%
Printing Speed	14.34	1	14.34	9.90%

Source: Authors, (2025)

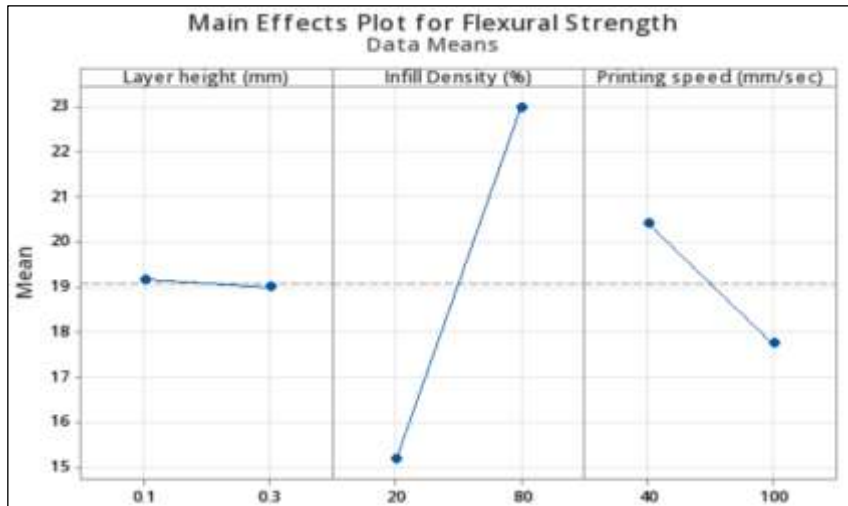


Figure 9: Main effects plot for Flexural strength.
Source: Authors, (2025)

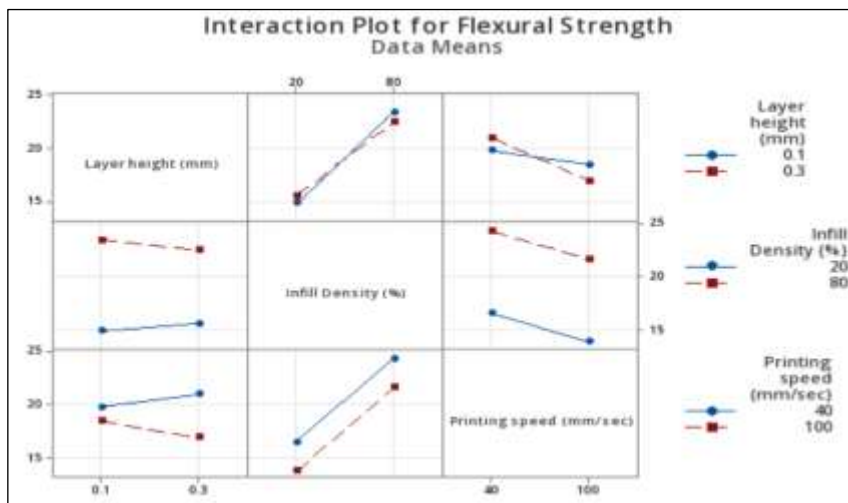


Figure 10: Interactions plot for Flexural strength.
Source: Authors, (2025)

IV. MULTI-OBJECTIVE OPTIMIZATION

IV.1 TOPSIS METHOD

TOPSIS (technique for order preferences by similarity to an ideal solution) is a method used to solve multiple-criteria decisions. TOPSIS can be easily expanded to involve more than two output responses; hence, it is a good statistical tool for multi-objective optimization problems, which is currently applied in the FDM process. The multi-objective optimization problems are transferred to multiple decision-making conditions and then coded to the single-objective problem in terms of relative closeness values. Simplicity, rationality, comprehensibility, computational efficiency, and ability to measure the relative performance of each alternative in a simple mathematical form.

Step 1: Construction of the decision matrix:

In the TOPSIS multi objective problem, the averaged output responses for each experiment are the inputs to be placed in a matrix form known as a decision matrix. A decision matrix is created:

$$D = \begin{matrix} A_1 \\ A_2 \\ A_m \end{matrix} \begin{bmatrix} X_{11} & X_{12} & \dots & X_{1n} \\ X_{21} & X_{22} & \dots & X_{2n} \\ X_{m1} & X_{m2} & \dots & X_{mn} \end{bmatrix}$$

Alternatives - A₁, A₂, and A_m.
 criteria based on which ranking is performed = C₁, C₂, ..., C_n
 qualification of alternative A_i with respect to criterion C_j = X_{ij}
 weight of criterion C_j = w_j

Step 2: Calculation of the normalized decision matrix:

This step changes various characteristic dimensions into non-dimensional characteristics that permit evaluation across criteria. The two criteria of functions are the benefit function (larger is better) and cost function (smaller is better). The decision matrix must be converted to a normalized scale using the following equation:

$$n_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^m x_{ij}^2}}$$

where, $i = 1, 2, \dots, m, j = 1, 2, \dots, n$.

Step 3: Calculation of the weighted normalized decision matrix:

It is done using equation:

$$v_{ij} = w_j \times \eta_{ij}, i = 1, 2, \dots, m; j = 1, 2, \dots, n.$$

where ,
weight response is represented using criterion

$$\sum_{j=1}^n w_j = 1$$

Step 4: Determination of the positive ideal and negative ideal solutions:

The ideal positive solution is the result of enlarging the benefit criteria and reducing the cost criteria whereas the negative ideal solution enlarges the cost criteria and reduces the benefit criteria.

The values are given by the following equation:

$$\begin{aligned} \text{Positive ideal solution, } A^+ &= (v_1^+, v_2^+, \dots, v_n^+) \\ &= ((\max_i v_{ij} | j \in I), (\min_i v_{ij} | j \in \mathcal{J})) \end{aligned}$$

$$\begin{aligned} \text{Negative ideal solution, } A^- &= (v_1^-, v_2^-, \dots, v_n^-) \\ &= ((\min_i v_{ij} | j \in I), (\max_i v_{ij} | j \in \mathcal{J})) \end{aligned}$$

Where.

I is correlated with Benefit Criteria and J is correlated with Cost Criteria.

Step 5: Calculate the segregation measures from the positive ideal solution (di+) and negative ideal solution (di-) using the following equations :

$$d_i^+ = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^+)^2}, i = 1, 2, \dots, m$$

$$d_i^- = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^-)^2}, i = 1, 2, \dots, m$$

Step 6: Calculate the segregation measures from the positive ideal solution (di+) and negative ideal solution (di-) using the following equations :

$$R_i = \frac{d_i^-}{d_i^- + d_i^+}, \text{ where } 0 \leq R_i \leq 1, i = 1, 2, \dots, m$$

Step 7: Rank the preference order:

The ranking order to be deployed with respect to the Ri value is in descending order from 0 to 1. The value closest to 1 attained the first rank, and that attribute should be selected as the best among multiple decision-making conditions. As per the TOPSIS method, the ranking of the specimens for tensile, impact and flexural strengths is listed in Table 9.

Table 9: Ranking of specimens According to Tensile, Impact and Flexural strength using TOPSIS analysis.

No.	Layer Height (mm)	Infill Density (%)	Printing Speed (mm/sec)	Tensile Strength (MPa)	Impact Strength (J/m)	Flexural Strength (MPa)	di+	di-	pi	Rank
1	0.1	20	40	10.66	132.16	16.25	0.28	0.14	0.333	7
2	0.1	20	100	9.15	190.4	13.47	0.28	0.22	0.439	4
3	0.1	80	40	17.52	294.6	23.41	0.33	0.36	0.526	2
4	0.1	80	100	21.3	327.93	23.56	0.36	0.41	0.536	1
5	0.3	20	40	12.49	163	16.83	0.27	0.18	0.397	6
6	0.3	20	100	11.01	114.21	14.25	0.28	0.12	0.294	8
7	0.3	80	40	18.61	190.08	25.22	0.26	0.21	0.445	3
8	0.3	80	100	16.23	186.73	19.72	0.27	0.21	0.438	5

Source: Authors, (2025)

di+ separation of each alternative from the positive ideal

di- separation of each alternative from the negative ideal

Pi - relative closeness to the ideal solution, a higher Pi corresponds to a higher rank

IV.2 GRA METHOD

Step 1: Grey relational generation (Normalization of Raw Data)

The experimental data obtained for the output responses can be normalized according to different requirements. There are three different normalization conditions: lower-the-better, higher-the-better and nominally the best criteria.

For lower-the-better: For higher-the-better:

$$X_i(k) = \frac{\max Y_i(k) - Y_i(k)}{\max Y_i(k) - \min Y_i(k)} \quad X_i(k) = \frac{Y_i(k) - \min Y_i(k)}{\max Y_i(k) - \min Y_i(k)}$$

where - Xi is the value obtained after grey relational generation.

Min Yi (k) is the smallest value of Yi and Max Yi (k) is the maximum value of Yi (k).

Step 2: Grey relational coefficient :

$$\gamma_i = \frac{\Delta_{\min} + \zeta \Delta_{\max}}{\Delta_{oi}(k) + \zeta \Delta_{\max}}$$

where γ is the Grey relational coefficient of the ith experiment for the kth response.

$\Delta_{oi} = |X_o(k) - X_i(k)|$ = difference between absolute value, ζ the distinguishing coefficient and it is defined in the range $0 < \zeta \leq 1$,

$\Delta_{\min} = \min |x_0(k) - x_j(k)|$ is the smallest value of Yj(k) and

$\Delta_{\max} = \max |x_0(k) - x_j(k)|$ is the largest value of Yj(k).

Step 3: Grey relational grade:

The grey relational grade was calculated by averaging the grey relation coefficients corresponding to each experiment. The overall response of multiple performance characteristic is based on the grey relational grade which is the objective function.

$$\alpha_i = \frac{1}{n} \sum_{k=1}^n \gamma_i(k)$$

A higher grade implies that the corresponding parameter combination is closer to the optimal set of input parameters. As per the GRA method, the ranking of the specimens for tensile, impact and flexural strengths is listed in Table 10.

Table 10: Ranking of specimens According to Tensile, Impact and Flexural strength using GRA Method.

No.	Layer Height (mm)	Infill Density (%)	Printing Speed (mm/sec)	Tensile Strength (MPa)	Impact Strength (J/m)	Flexural Strength (MPa)	Grey Relational Grade	Rank
1	0.1	20	40	10.66	132.16	16.25	0.5562	6
2	0.1	20	100	9.15	190.4	13.47	0.5520	7
3	0.1	80	40	17.52	294.6	23.41	1.0716	2
4	0.1	80	100	21.3	327.93	23.56	1.3898	1
5	0.3	20	40	12.49	163	16.83	0.8654	4
6	0.3	20	100	11.01	114.21	14.25	0.5267	8
7	0.3	80	40	18.61	190.08	25.22	1.0649	3
8	0.3	80	100	16.23	186.73	19.72	0.7462	5

Source: Authors, (2025)

IV.3 OPTIMUM PROCESS PARAMETER FOR TOPSIS AND GRA (RANK 1 TO 3)

As per the TOPSIS and GRA rankings and analysis, the optimum process parameters are identified and are similar for the Ranks 1 to 3, as mentioned in Table 11. Rank 1 Specimen was implemented for the 3D printing of Jig components.

Table 11: Optimum Process Parameters.

Method	Rank	Layer Height (mm)	Infill Density (%)	Printing Speed (mm/sec)	Tensile Strength (MPa)	Impact Strength (J/m)	Flexural Strength (MPa)
TOPSIS	1	0.1	80	100	21.3	327.93	23.56
GRA	1	0.1	80	100	21.3	327.93	23.56
TOPSIS	2	0.1	80	40	17.52	294.6	23.41
GRA	2	0.1	80	40	17.52	294.6	23.41
TOPSIS	3	0.3	80	40	18.61	190.08	25.22
GRA	3	0.3	80	40	18.61	190.08	25.22

Source: Authors, (2025)

IV.4 FDM 3D PRINTED FINAL PART

(Jig Component for LOGO Printing in Automobile Industry as per optimum Process Parameters Rank 1)

Based on the tested results and optimization of all the above mechanical properties, it is concluded that the polyamide 12 carbon fiber composite material is strongly recommended and used for tooling and functional prototypes in the automotive and engineering industries. It is used for manufacturing functional components that require a higher flexural strength in the edge orientation and a higher impact strength in a flat orientation. The density of the PA12CF Material was much lower than that of tool steel material used in conventional machining. Therefore, it can be used for the development of a tool for automobile assembly lines for the manufacture of Jig components which is used for LOGO Printing in the Automobile Industry, and it also reduces the weight, cost of components, and manufacturing process time. Therefore, it is recommended to use PA12 CF composite material for manufacturing 3D Printed parts which is required for specific applications with good mechanical properties such as flexural strength. It has been successfully implemented in real life applications in the automobile Industry for LOGO Printing. The design of jig components for LOGO Printing and the final 3D Printed components are shown in Figure. 11(a) and (b), respectively. Manufacturing and testing were performed in an authorized research institute /laboratory.



Figure 11: (a) Design of Jig component for LOGO Printing (b) 3D Printing Component.

Source: Authors, (2025).

V. FINAL CONCLUSION

In this study, three important process parameters—infill density, layer height, and printing speed—were selected for the fused deposition modeling (FDM) process. The effects of process parameters on the tensile, impact, and flexural strength of the specimens were investigated using L8 Taguchi orthogonal array and ANOVA approaches. The specimens were fabricated using a 3D printer according to ASTM and ISO standards.

This study examines the effect of fused deposition modeling (FDM) process parameters on the characteristics of functional parts and their application to specific requirements of higher flexural strength and impact strength. The experiment investigated the effect of the infill density, layer height, and printing speed on the mechanical properties of the parts. The following conclusions were drawn:

- 1) Infill density (80%) was the most critical factor for all three mechanical properties.
- 2) Printing speed has varying effects:
 - o A higher speed (100 mm/sec) favors tensile and impact strength.
 - o A lower speed (40 mm/sec) favors the flexural strength.
- 3) Layer Height has varying effects:
 - o A lower layer height (0.1 mm) is better for tensile and impact strength.

o A higher layer height (0.3 mm) was preferred for the flexural strength.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Rahul Patel, Dr. Suketu Jani.
Methodology: Rahul Patel, Dr. Suketu Jani.
Investigation: Rahul Patel, Dr. Suketu Jani.
Discussion of results: Rahul Patel, Dr. Suketu Jani.
Writing – Original Draft: Rahul Patel
Writing – Review and Editing: Rahul Patel, Dr. Suketu Jani.
Resources: Rahul Patel, Dr. Suketu Jani.
Supervision: Dr. Suketu Jani
Approval of the final text: Rahul Patel, Dr. Suketu Jani.

VII. REFERENCES

- [1] Divya Zindani , Kaushik Kumar, An insight into additive manufacturing of fiber reinforced polymer composite,International Journal of Lightweight Materials and Manufacture ,Volume 2, Issue 4, December 2019, 267-278,https://doi.org/10.1016/j.ijlmm.2019.08.004
- [2] Abdallah S, Ali S, Pervaiz S. Performance optimization of 3D printed polyamide 12 via multi jet fusion: a Taguchi grey relational analysis (TGRA). Int J Light Mater Manuf. 2023;6:72-81. doi:10.1016/j.ijlmm.2022.05.004
- [3] Hasan Rafsan Jania and Md Zillur Rahmanb, Modeling and simulation of additively manufactured composites, Comprehensive Materials Processing, 2024 https://doi.org/10.1016/B978-0-323-96020-5.00230-2
- [4] Pavan Kumar Penumakala , Jose Santo, Alen Thoma,A critical review on the fused deposition modeling of thermoplastic polymer composites , Composites Part B 201 (2020) 108336,https://doi.org/10.1016/j.compositesb.2020.108336
- [5] Nidhi Dixit, Prashant K. Jain, 3D printed carbon fiber reinforced thermoplastic composites: A review,Materials Today: Proceedings 43 (2021) 678–681. https://doi.org/10.1016/j.matpr.2020.12.609
- [6] Gabriel Mansour , Vasileios Papageorgiou ,Dimitrios Tzetzis, Carbon Fiber Polymer Reinforced 3D Printed Composites for Centrifugal Pump Impeller Manufacturing. Technologies 2024, 12, 48. https://doi.org/10.3390/technologies12040048
- [7] Ibrahim M. Alarifi, A performance evaluation study of 3d printed nylon/glass fiber and nylon/carbon fiber composite materials. Journal of Material Research and Technology 2022 https://doi.org/10.1016/j.jmrt.2022.09.085.
- [8] Antreas Kantaros , Evangelos Soulis , Florian Ion Tiberiu Petrescu ,Theodore Ganetsos, Advanced Composite Materials Utilized in FDM/FFF 3D Printing Manufacturing Processes: The Case of Filled Filaments. Materials 2023, 16, 6210. https://doi.org/10.3390/ma16186210.
- [9] Arunachalam Ramanathan, Varunkumar Thippanna, Barath Sundaravadivelan, Yuxiang Zhu, Abhishek Saji Kumar, Dharmeendar Ravichandran,| Sui Yang, Kenan Song, Highly loaded carbon fiber filaments for 3D-printed composites. J Polym Sci. 2024;62:2670–2682.DOI: 10.1002/pol.20230632.
- [10] Manickam Ramesh,Kanakaraj Niranjana,Ramasamy Bhoopathi, and Lakshminarasimhan Rajeshkumar, Additive manufacturing (3D printing) technologies for fiber-reinforced polymer composite materials: A review on fabrication methods and process parameters, e-Polymers 2024; 24: 20230114 https://doi.org/10.1515/epoly-2023-0114.
- [11] Basim El Essawi , Said Abdallah, Shafahat Ali , Abdallah Nassir Abdo Mohammed,Rahmat Agung Susantyoko, Salman Pervaiz Optimization of infill density, fiber angle, carbon fiber layer position in 3D printed continuous carbon-fiber reinforced nylon composite ,Results in Engineering 21 (2024) 101926, https://doi.org/10.1016/j.rineng.2024.101926.
- [12] M A Pop, S M Zaharia , L A Chicos, C Lancea, V M Stamate, G R Buican and I S Pascariu, Effect of the infill patterns on the mechanical properties of the carbon fiber 3D printed parts. IOP Conf. Series: Materials Science and Engineering 1235 (2022) 012006 doi:10.1088/1757-899X/1235/1/012006.
- [13] Nathathai Saithongkum, Karuna Tuchinda, Study of Properties of 3D Printed Short Carbon Fiber Key Engineering Materials ISSN: 1662-9795, Vol. 841, pp 182-187 doi:10.4028/www.scientific.net/KEM.841.182.
- [14] Nisa Naima Khalid,Nabilah Afiqah Mohd Radzuan,Farhana Mohd Foudzi,Abu Bakar Sulong,Nurul Najwa Abd Rahman, Interfacial Bonding of Polyamide -Reinforced Carbon fibre Via Additive Manufacturing, Materiali in tehnologije / Materials and technology 58 (2024) 5, 587–595.
- [15] Justyna Rybarczyk, Filip Górski, Wiesław Kuczko, Radosław Wichniarek , Sabina Siwiec , Nikola Vitkovic , Răzvan PăcurarMechanical Properties of Carbon Fiber Reinforced Materials for 3D Printing of Ankle Foot Orthoses , Advances in Science and Technology Research Journal 2024, 18(4), 191–215 https://doi.org/10.12913/22998624/188819.
- [16] Mahmoud Moradi, Zeinab Malekshahi Beiranvand,Nahid Salimi, Saleh Meiabadi and Jonathan Lawrence, Experimental Investigation on the 3D Printing of Nylon Reinforced by Carbon Fiber through Fused Filament Fabrication Process. Effects of Extruder Temperature, and Printing Speed.,International Journal of Polymer Science, Volume 2024, Article ID 1234797, 12 pages https://doi.org/10.1155/2024/1234797.
- [17] Ans AL RASHID, Hamid IKRAM, Muammer KOÇ, Effect of carbon fiber reinforcement on dimensional variations of 3D printed polyamide-6 composites: A simulation study,Turkish Journal of Chemistry,(2023) 47: 33-39 doi:10.55730/1300-0527.3513 .
- [18] Hussein Alzyod, Peter Ficzer,Optimizing fused filament fabrication process parameters for quality enhancement of PA12 parts using numerical modeling and Taguchi method ,Heliyon 9 (2023) e14445,https://doi.org/10.1016/j.heliyon.2023.e14445