JOURNAL OF MECHANICAL ENGINEERING, SCIENCE, AND INNOVATION
ITATS
Research Article

Optimization of Fused Deposition Modeling (FDM) Machine Parameters for Carbon Fiber Tensile Strength Using the Taguchi Method

Journal of Mechanical Engineering, Science, and Innovation
e-ISNN: 2776-3536
2024, Vol. 4, No. 1
DOI: 10.31284/j.jmesi.2024.v4i1.5987
ejurnal.itats.ac.id/jmesi

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Abstract

3D printing using Fused Deposition Modeling (FDM) technology has emerged as a promising approach for manufacturing components with composite materials such as carbon fiber. This study aims to optimize the parameters of FDM machines for carbon fiber tensile strength using the Taguchi Method. The optimized FDM machine parameters include nozzle temperature, infill density, printing speed, layer thickness, infill pattern, and orientation. Experiments were conducted based on the Taguchi experimental design with an L27 Orthogonal Array (3^6) matrix, resulting in 27 experiments with different parameter combinations. After printing was completed, tensile tests were performed to measure the tensile strength of the printed samples. The results of the analysis using the Taguchi Method show the optimal settings of the FDM machine parameters to achieve maximum tensile strength for carbon fiber material. The analysis results show that the parameters that can optimize the tensile test response are nozzle temperature at level 2 (230°C), infill density at level 3 (80%), printing speed at level 3 (100 mm/s), layer thickness at level 3 (0.3 mm), infill pattern at level 1 (line), and orientation at level 3 (30°) with the highest tensile test value of 27.7766 MPa. This study provides an important contribution to the development of 3D printing techniques with carbon fiber, by identifying the optimal settings that can improve the mechanical performance of printed components. It is expected that the results of this study can be used as a practical guideline for the 3D printing industry in optimizing FDM machine parameters for printing carbon fiber-based composite materials.

Keywords: *3D Printing, Carbon Fiber, Taguchi, Tensile Test, FDM*

Received: May 31, 2024; Received in revised: July 23, 2024; Accepted: July 25, 2024
Handling Editor: Afira Ainur Rosidah

INTRODUCTION

3D printing using Fused Deposition Modeling (FDM) has emerged as a popular method for producing components with various materials, including composite materials like carbon fiber. Carbon fiber has gained significant attention in the 3D printing process due to its high mechanical strength, lightweight properties, and corrosion resistance. Therefore, carbon fiber has become a prime choice for diverse applications ranging from aerospace to automotive industries [1][2]. The implementation of 3D printing on carbon fiber material has the potential to produce products with high accuracy and complex designs. However, to achieve optimal results in 3D printing with carbon fiber, the parameters of the FDM machine need to be precisely adjusted. Several 3D printing parameters that require optimization include nozzle temperature, bed temperature, layer thickness, wall thickness, perimeter, infill density, infill pattern, and printing speed [3].

Several researchers have conducted optimization studies on 3D printing manufacturing for various purposes. Logesh Kothandaraman [4] investigated the influence of 3D printing variables (nozzle temperature, layer height, printing speed) on the surface irregularities of 3D printed objects. Kapil Kumar [5] optimized FDM parameters to enhance mechanical properties. Naveen Kumar Suniya [6] performed FDM parameter optimization focusing on improving mechanical properties, reducing manufacturing time, enhancing component quality, dimensional accuracy, surface roughness, tensile strength, compressive strength, and cost-effectiveness. Emanuele Vaglio [7] analyzed the effect of FDM parameters (nozzle temperature, nozzle speed, and layer thickness) on the mechanical properties of PEEK. Vijaykumar S. Jatti [8] also analyzed FDM process parameters on tensile strength, impact strength, and flexural strength of PLA material.

Lee & Wu [9] employed five parameters with three levels to investigate how 3D printing parameters (angle orientation, infill thickness, bed temperature, nozzle temperature, and printing speed) affect the mechanical properties of Carbon Fiber-PLA filament. The results indicated that bed temperature significantly influences the tensile strength of specimens, while orientation emerged as the most significant factor affecting the tensile strength of specimens. Another study conducted by Prihadianto et al., [10] utilized two types of filament materials (nylon carbon fiber and PLA carbon fiber) with variations in infill density and printing temperature to examine their impact on tensile strength. The findings revealed that the tensile strength of nylon carbon fiber material ranged from 19.244 MPa to 23.899 MPa, with an average tensile strength value of 21.852 MPa. Meanwhile, PLA material exhibited a tensile strength ranging from 16.970 MPa to 26.681 MPa, with an average strain value of 20.372%.

This study aims to optimize the FDM machine parameters for carbon fiber printing to enhance its tensile strength. Improper settings can lead to structural weaknesses and reduced mechanical performance of the printed components. Therefore, optimizing FDM machine parameters is crucial to ensure the achievement of maximum tensile strength in the final product. In this research, the Taguchi method is employed as the optimization technique due to its proven effectiveness in identifying the optimal parameter combination with minimal testing. This approach enables the determination of the best parameters that can enhance tensile strength and minimize testing time and costs.

The outcomes of this study are anticipated to provide practical guidelines for the 3D printing industry in setting FDM machine parameters for carbon fiber material. Consequently, this technology can be more widely utilized in various engineering applications, such as manufacturing, automotive, aerospace, and other sectors that demand strong and durable components. Moreover, the study is also expected to offer deeper insights into the relationship between 3D printing process parameters and the mechanical properties of carbon fiber-based composites. This will contribute to the development of mechanically superior composite materials, expanding the possibilities for their use in various industrial applications.

METHODS AND ANALYSIS

The research methodology employed in this study is illustrated by the flowchart presented in Figure 1.

Selection of variables and parameters for FDM machines

Determination of Process Parameters and Experimental Levels The selection of process parameters and experimental levels was based on an evaluation of literature studies. The process parameters consist of six factors with three different levels for each factor. The process parameters and their corresponding level values are presented in Table 1 below.

Table 1. Factors and Levels or Process Parameters and Level Values

Parameter Proses	level		
	1	2	3
Nozzle Temperature	220°C	230°C	240°C
Infill Density	40%	60%	80%
Printing Speed	60 mm/s	80 mm/s	100mm/s
Layer Thickness	0,1 mm	0,2 mm	0,3 mm
Infill Pattern	Line	Triangle	Hexagon
Orientasi	0°	15°	30°

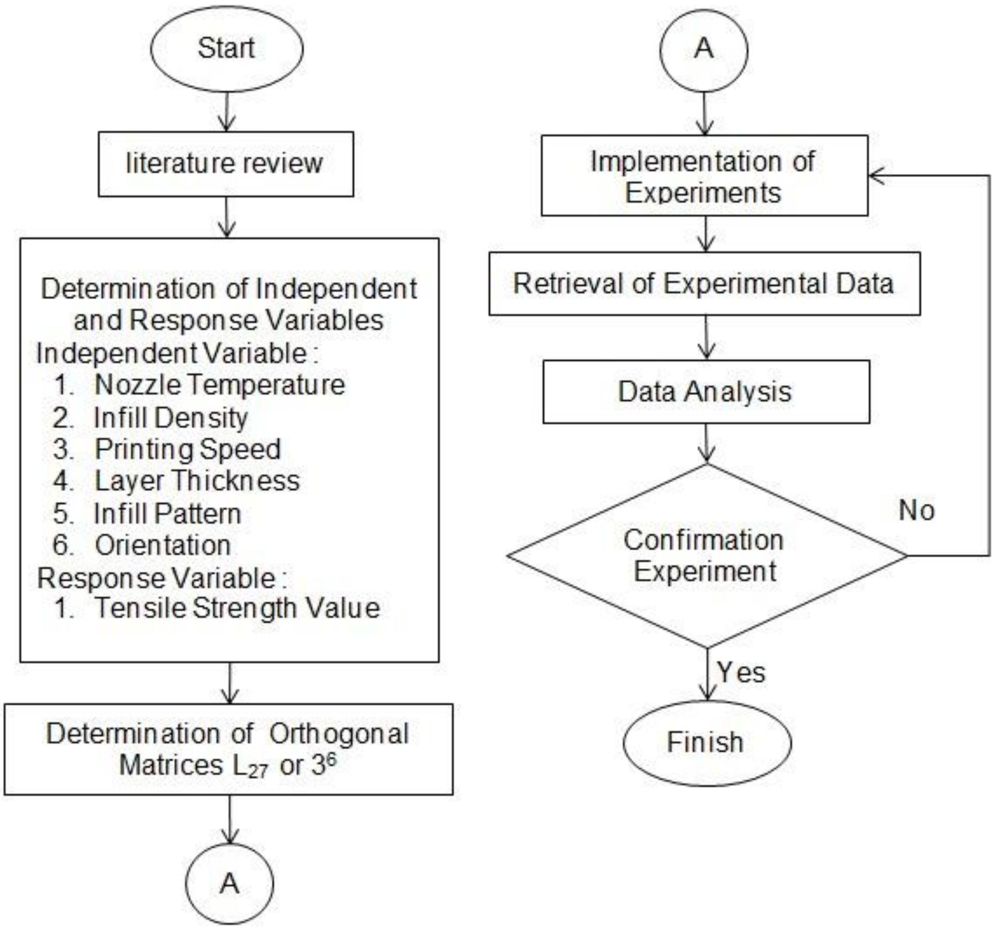

Figure 1. Research Flow Diagram

Experimental design

After determining the factors and levels, the next step is to select the appropriate Orthogonal Array (OA) matrix. This study utilizes the Taguchi L27 (36) method, as presented in Table 2.

Printing and Testing

The specimens to be printed are tensile test specimens in accordance with ASTM D638 standard [11] . The dimensional dimensions of the tensile test specimens can be seen in Figure 2. The specimens are then converted to STL format and transferred to FlashPrint software to configure the 3D printing parameters according to the OA matrix. The printing process is carried out using a FlashForge series II machine, as shown in Figure 3.

Tensile strength testing

This testing process aims to determine how strong or resistant an object is to tensile force before structural failure occurs. Tensile testing in this study was conducted using a

Table 2. Taguchi Design

Nozzle Temperature	Infill Density	Printing Speed	Layer Thickness	Infill Pattern	Orientasi
220	40	60	0.1	Line	0
220	40	60	0.1	Triangle	15
220	40	60	0.1	Hexagon	30
220	60	80	0.2	Line	0
220	60	80	0.2	Triangle	15
220	60	80	0.2	Hexagon	30
220	80	100	0.3	Line	0
220	80	100	0.3	Triangle	15
220	80	100	0.3	Hexagon	30
230	40	80	0.3	Line	15
230	40	80	0.3	Triangle	30
230	40	80	0.3	Hexagon	0
230	60	100	0.1	Line	15
230	60	100	0.1	Triangle	30
230	60	100	0.1	Hexagon	0
230	80	60	0.2	Line	15
230	80	60	0.2	Triangle	30
230	80	60	0.2	Hexagon	0
240	40	100	0.2	Line	30
240	40	100	0.2	Triangle	0
240	40	100	0.2	Hexagon	15
240	60	60	0.3	Line	30
240	60	60	0.3	Triangle	0
240	60	60	0.3	Hexagon	15
240	80	80	0.1	Line	30
240	80	80	0.1	Triangle	0
240	80	80	0.1	Hexagon	15

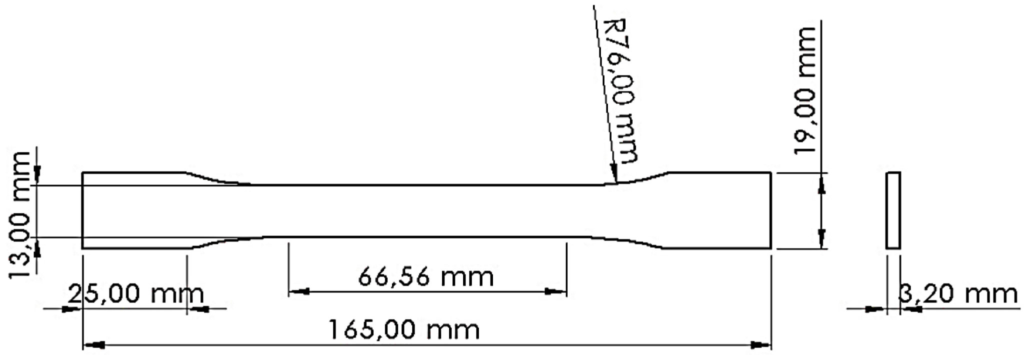

Figure 2. Tensile Test Specimen Design

Figure 3. FlashForge Series II 3D Printer

Zwickroell machine, as shown in Figure 4, with a pre-load of 0.5 MPa, a test speed of 50 mm/min, a gauge length of 50 mm, and standard travel of 50 mm.

Analysis of Results

Results analysis is conducted to evaluate the influence of independent variables on tensile strength and determine the optimal parameter combination. The experimental results are analyzed using Minitab 19 software to determine the S/N ratio and identify the most optimal parameters. This is followed by ANOVA analysis to determine the optimal parameter combination. The analysis data is then used in the confirmation test phase to validate the research findings.

(i). Calculation of S/N Ratio Values

The first step in the analysis is to calculate the Signal-to-noise ratio (SN Ratio) for each experiment. SN Ratio is used in the Taguchi Method to evaluate the relative performance of each parameter combination [11][12]. The main goal is to find the parameter combination that yields the highest SN Ratio, as a higher SN Ratio value indicates better or optimal performance. Tensile strength has a Larger-is-Better characteristic, and its value is obtained from the following equation (1).

$$S / N \text{ ratio} = -10 \log \left[\sum_{i=1}^{n} \frac{y_i = 1^2}{n}\right] \quad (1)$$

Where n is the number of repetitions and y_i is the i-th observation data (I = 1,2,3,....,n)

(ii). ANOVA

Furthermore, Analysis of Variance (ANOVA) is conducted to evaluate the statistical significance of each factor (variable) on tensile strength. ANOVA aids in identifying the factors that have a significant impact on the response (tensile strength) and which factors have a lesser influence.

(iii). Calculation of the predicted mean of the optimal S/N Ratio

The calculation of the predicted mean of the optimal S/N ratio is performed using the following equation (2) [13].

$$\mu_{prediction} = y_m + \sum_{i=1}^{n} (y_i - y_m) \quad (2)$$

Where y_m is the average value of the overall S/N ratio and y_i is average S/N Ratio optimal level condition.

(iv). Confidence Interval Calculation

Confidence intervals are employed for treatment conditions during the experiment. The confidence interval for the optimal condition can be calculated using the following equation (3-5) [14][15].

For prediction experiments :

$$CI_p = \sqrt{\frac{F_{a:d_{f1}:d_{f2}} \times MS_g}{n_{eff}}} \quad (3)$$

Where $F_{a:d_{f1}:d_{f2}}$ is F-ratio value from table, α is risk; level of confidence = 1- risk, d_{f1} is factor degrees of freedom, d_{f2} is error degrees of freedom, MSE is mean squared error, and Neff is the number of effective observations

$$n_{eff} = \frac{\text{total number of trials}}{1+\text{number of degrees of freedom}} \quad (4)$$

$$\mu_{prediction} - CI_k \leq \mu_{confirmation} \leq \mu_k + CI_p$$

For confirmation experiments :

$$CI_k = \sqrt{F_{a:d_{f1}:d_{f2}} \times MS_E \times \left[\frac{1}{n_{eff}} + \frac{1}{r}\right]} \quad (5)$$

$$\mu_k - CI_K \leq \mu_{confirmation} \leq \mu_k + CI_p$$

(v). Confirmation Experiment

Once the calculations are completed, the optimal parameter variations will be obtained. Next, the optimal parameter variations are used for confirmation testing by printing the test product samples and then measuring their roughness. Additionally, the roughness of the confirmation results is examined as the correct test result.

RESULTS AND DISCUSSIONS

Taguchi Analysis

Data collection for the experiment involves conducting tensile testing. The tensile test results from 27 experiments with three replications for each experiment are presented in Table 3. The average S/N ratio calculations for each level are detailed in Table 4. Additionally, the results of the S/N ratio calculations are presented in Table 5.

Based on the average S/N ratio calculations in Table 5, the optimum value is obtained at the largest average S/N ratio value for each process parameter. The parameters and levels that have the most influence on the tensile test response can be illustrated as shown in the graph in Figure 4.

Analysis of Varian (ANOVA)

Analysis of Variance (ANOVA) is employed to identify the parameters that have the most significant influence on the tensile test response and to determine the magnitude of their contribution. The ANOVA calculation results can be found in Table 6.

Table 3. Tensile Test Results

No.	Nozzle Tempe rature	Infill Density	Printing Speed	Layer Thick ness	Infill Pattern	Orien-tation	Tensile test results (MPa)			
							1	2	3	Mean
1	220	40	60	0.1	Line	0	12,62	13,05	14,51	13,393
2	220	40	60	0.1	Triangle	15	12,25	13	12,7	12,65
3	220	40	60	0.1	Hexagon	30	13,82	13,83	14,37	14,007
4	220	60	80	0.2	Line	0	18,12	18,59	18,45	18,387
5	220	60	80	0.2	Triangle	15	17,37	19,73	19,41	18,837
6	220	60	80	0.2	Hexagon	30	19,35	19,31	18,43	19,03
7	220	80	100	0.3	Line	0	27,76	27,97	27,6	27,777
8	220	80	100	0.3	Triangle	15	22,44	24,12	24,33	23,63
9	220	80	100	0.3	Hexagon	30	22,48	23,67	22,53	22,893
10	230	40	80	0.3	Line	15	18,97	20,25	19,11	19,443
11	230	40	80	0.3	Triangle	30	20,05	20,68	21,96	20,897
12	230	40	80	0.3	Hexagon	0	18,99	20,02	19,54	19,517
13	230	60	100	0.1	Line	15	17,18	15,95	16,25	16,46
14	230	60	100	0.1	Triangle	30	17,96	17,26	15,84	17,02
15	230	60	100	0.1	Hexagon	0	14,93	13,88	14,53	14,447
16	230	80	60	0.2	Line	15	24,68	23,98	24,07	24,243
17	230	80	60	0.2	Triangle	30	18,38	18,12	19,78	18,76
18	230	80	60	0.2	Hexagon	0	20,46	20,49	23,1	21,35
19	240	40	100	0.2	Line	30	15,69	16,01	16,29	15,997
20	240	40	100	0.2	Triangle	0	16	16,18	15,48	15,887
21	240	40	100	0.2	Hexagon	15	15,68	14,74	13,71	14,71
22	240	60	60	0.3	Line	30	19,33	18,09	19,05	18,823
23	240	60	60	0.3	Triangle	0	19,72	19,15	19,13	19,333
24	240	60	60	0.3	Hexagon	15	17,18	17,64	18,89	17,903
25	240	80	80	0.1	Line	30	16,67	17,5	16,27	16,813
26	240	80	80	0.1	Triangle	0	13,15	11,82	13,59	12,853
27	240	80	80	0.1	Hexagon	15	12,79	16,13	13,57	14,163

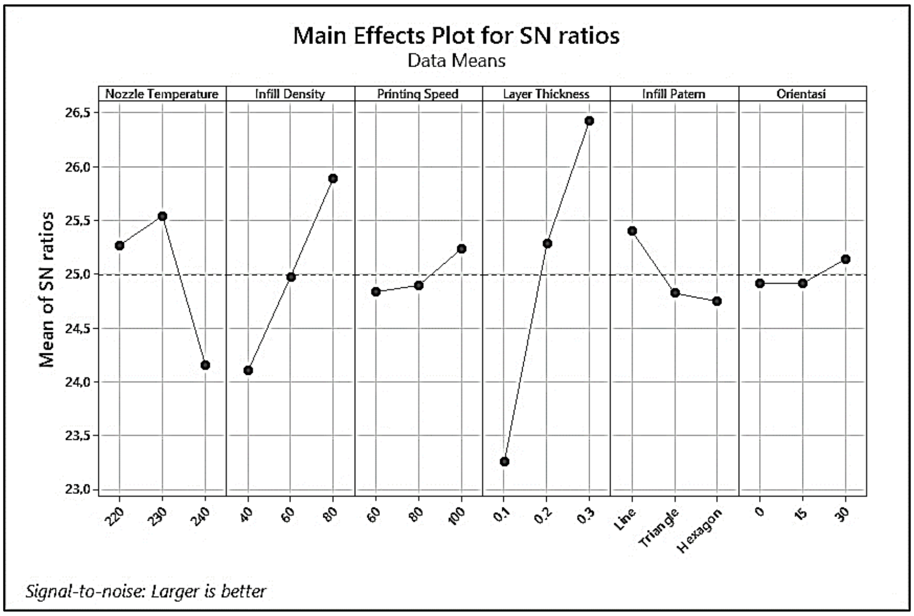

Figure 4. Influence of process parameters on tensile test response

Table 4. S/N Ratio of Tensile Test Response

No.	Nozzle Tempe rature	Infill Density	Printing Speed	Layer Thickness	Infill Pattern	Orien-tation	Tensile test results (Mean)	S/N Ratio
1	220	40	60	0.1	Line	0	13,3933	22,5378
2	220	40	60	0.1	Triangle	15	12,65	22,0418
3	220	40	60	0.1	Hexagon	30	14,0067	22,9267
4	220	60	80	0.2	Line	0	18,3867	25,2901
5	220	60	80	0.2	Triangle	15	18,8367	25,5001
6	220	60	80	0.2	Hexagon	30	19,03	25,5888
7	220	80	100	0.3	Line	0	27,7767	28,8736
8	220	80	100	0.3	Triangle	15	23,63	27,4693
9	220	80	100	0.3	Hexagon	30	22,8933	27,1942
10	230	40	80	0.3	Line	15	19,4433	25,7754
11	230	40	80	0.3	Triangle	30	20,8967	26,4015
12	230	40	80	0.3	Hexagon	0	19,5167	25,8081
13	230	60	100	0.1	Line	15	16,46	24,3286
14	230	60	100	0.1	Triangle	30	17,02	24,6192
15	230	60	100	0.1	Hexagon	0	14,4467	23,1954
16	230	80	60	0.2	Line	15	24,2433	27,6918
17	230	80	60	0.2	Triangle	30	18,76	25,4647
18	230	80	60	0.2	Hexagon	0	21,35	26,588
19	240	40	100	0.2	Line	30	15,9967	24,0806
20	240	40	100	0.2	Triangle	0	15,8867	24,0207
21	240	40	100	0.2	Hexagon	15	14,71	23,3523
22	240	60	60	0.3	Line	30	18,8233	25,4939
23	240	60	60	0.3	Triangle	0	19,3333	25,7261
24	240	60	60	0.3	Hexagon	15	17,9033	25,0587
25	240	80	80	0.1	Line	30	16,8133	24,5131
26	240	80	80	0.1	Triangle	0	12,8533	22,1803
27	240	80	80	0.1	Hexagon	15	14,1633	23,0233

Table 5. Average S/N ratio value (Large is better)

Level	Nozzle Temperature	Infill Density	Printing Speed	Layer Thickness	Infill Pattern	Orientation
1	25,27	24,1	24,84	23,26	25,4	24,91
2	25,54	24,98	24,9	25,29	24,82	24,92
3	24,16	25,89	25,24	26,42	24,75	25,14
Delta	1,38	1,78	0,4	3,16	0,65	0,23
Rank	3	2	5	1	4	6

The parameter with the largest contribution is layer thickness with a percentage contribution of 53.078%, followed by infill density 20.216%, nozzle temperature 12.694%, infill pattern 3.191%, printing speed 1.522%, and orientation 0.075%.

Table 6. ANOVA Calculation results

Source	DF	Seq SS	Contribution %	Adj MS	F	P
Nozzle Temperature	2	46,008	12,694	23,0041	9,64	0,002
Infill Density	2	73,272	20,216	36,6362	15,35	0,000
Printing Speed	2	5,517	1,522	2,7586	1,16	0,343
Layer Thickness	2	192,377	53,078	96,1886	40,29	0,000
Infill Patern	2	11,567	3,191	5,7834	2,42	0,125
Orientation	2	0,272	0,075	0,1359	0,06	0,945
Residual Error	14	33,424	9,222	2,3875		
Total	26	362,438	100			

Prediction of Optimum Response Means

Prediction of the average response at optimum parameter settings:

$$\mu_{\text{prediction}} = y_m + (A_2 - y_m) + (B_3 - y_m) + (C_3 - y_m) + (D_3 - y_m) + (E_1 - y_m) + (F_3 - y_m)$$

$$\mu_{\text{prediction}} = 24{,}99052 + (25{,}54 - 24{,}99052) + (25{,}89 - 24{,}99052) + (25{,}24 - 24{,}99052) + (26{,}42 - 24{,}99052) + (25{,}40 - 24{,}99052) + (25{,}14 - 24{,}99052)$$

$$\mu_{\text{prediction}} = 28{,}6774$$

The confidence interval of the predicted mean S/N ratio using a 95% CI can be calculated as follows.

$$n_{\text{eff}} = \frac{27\times3}{1+(2\times6)} = \frac{81}{13}$$

$$CI_p = \sqrt{\frac{3.7388918\times0{,}4777}{\frac{81}{13}}} = 0{,}5350$$

So :

$$28{,}6774 - 0{,}5350 \le \mu_{\text{prediction}} \le 28{,}6774 + 0{,}5350$$

$$28{,}1424 \le \mu_{\text{prediction}} \le 29{,}2124$$

Confirmation Experiment

Confirmation experiments were conducted five times under the optimal parameter conditions, which were: nozzle temperature 220 °C, infill density 80%, printing speed 100 mm/s, layer thickness 0.3 mm, infill pattern Line, and orientation 30°. The tensile test response measurements from the confirmation experiments are presented in Table 7 below.

Table 7. Data Confirmation Experiment Results

Tensile Test Confirmation Experiment							
Nozzle Tempe-rature (°C)	**Infill Density (%)**	**Printing Speed (mm/s)**	**Layer Thickness (mm)**	**Infill Pattern**	**Orientation (°)**	**Tensile Test Results (MPa)**	**S/N Ratio**
220	80	100	0,3	Line	30	29	29,24795996
220	80	100	0,3	Line	30	29,32	29,34327932
220	80	100	0,3	Line	30	27,12	28,6657937
220	80	100	0,3	Line	30	28,94	29,22997054
220	80	100	0,3	Line	30	28,84	29,19990512
			Mean			28,644	29,13738173

Based on the response values obtained from the confirmation experiments, the S/N ratio values are calculated. The S/N ratio values for the confirmation experiments are used to calculate the confidence interval for the mean S/N ratio of the confirmation experiments at a 95% confidence level, as follows.

$$n_{eff} = \frac{27\ x\ 3}{1+(2\ x\ 6)} = (\frac{81}{13})$$

$$\mathrm{CI_{confirmation}} = \sqrt{\mathrm{F_{a:d_{f1}:d_{f2}}} \times \mathrm{MS_E} \times \left[\frac{1}{\mathrm{n_{eff}}} + \frac{1}{\mathrm{r}}\right]}$$

$$\mathrm{CI_{confirmation}} = \sqrt{3.7388918 \times 0{,}4777 \times \left[\frac{1}{\frac{81}{13}} + \frac{1}{3}\right]} = 0{,}9454$$

So :

$$29{,}1373 - 2{,}09957 \leq \mu_{prediction} \leq 29{,}1373 + 2{,}09957$$

$$28{,}1919 \leq \mu_{prediction} \leq 30{,}0827$$

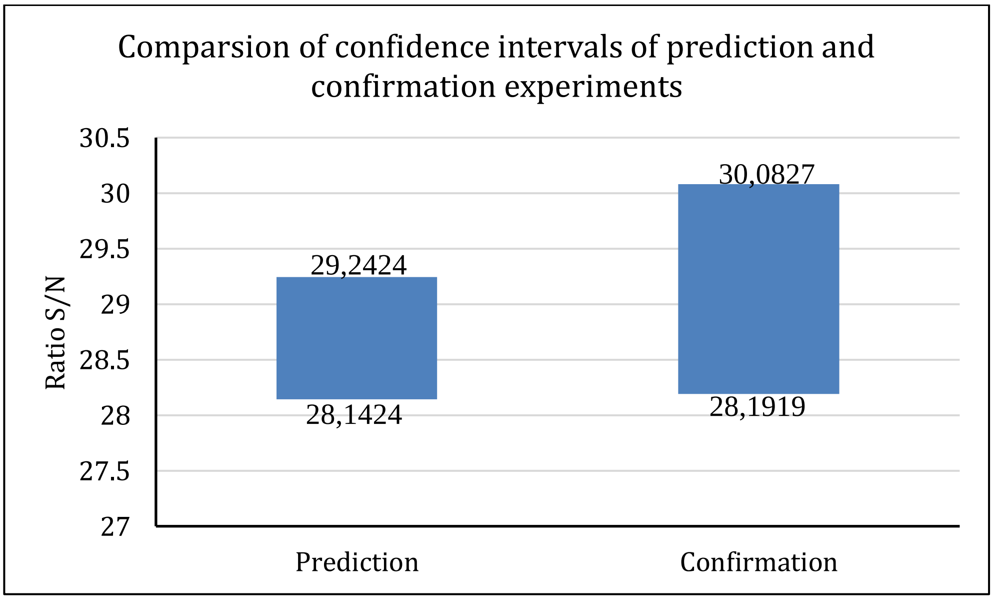

Figure 5. Comparison of confidence intervals of confirmation and prediction experiments

The confidence intervals for the prediction at a 95% confidence level are compared to the confidence intervals for the confirmation experiment at a 95% confidence level. These confidence intervals can be seen in Figure 5. Since the confidence interval of the confirmation experiment overlaps with the confidence interval of the prediction, it can be concluded that the tensile test response optimization has been successful. Therefore, the combination of process parameter settings for the prediction is also the combination of process parameter settings that produces the optimal response.

CONCLUSIONS

The percentage contribution of process parameters to tensile testing indicates that layer thickness is the most influential parameter on the tensile strength of carbon fiber material specimens, followed by infill pattern, infill density, printing speed, nozzle temperature, and orientation. Then for combination of parameter levels that can optimize the tensile test response is nozzle temperature at level 2 (230°C), infill density at level 3 (80%), printing speed at level 3 (100 mm/s), layer thickness at level 3 (0.3 mm), infill pattern at level 1 (line), and orientation at level 3 (30°) with the highest tensile test value of 27.7766 MPa. By refining the parameter settings of FDM machines based on the findings of this research, the 3D printing industry is expected to produce stronger and more reliable components using carbon fiber material. The use of the Taguchi Method in optimizing FDM machine parameters can also serve as a foundation for further research in this field.

In conclusion, this research provides valuable insights into the influence of FDM machine parameters on the tensile strength of carbon fiber material. By applying these findings, it is expected that the development of 3D printing technology with carbon fiber-based composite materials can continue to advance, supporting applications in various industries, including manufacturing, automotive, aerospace, and others.

ACKNOWLEDGEMENTS

This effort would not have been possible without my supervisor, Mrs. Wahyu Dwi Lestari, who helped write and complete this research.

DECLARATION OF CONFLICTING INTERESTS

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

FUNDING

The author(s) disclosed receipt of no financial support for the research, authorship, and/or publication of this article.

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