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Multi-response optimization of 3D printing parameters by Taguchi method and machine learning

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Fused Deposition Modeling (FDM) is widely used in additive manufacturing, although the mechanical performance of printed components is highly dependent on process parameters. This study optimized the printing parameters of ABS PA-747H using the Taguchi method, analysis of variance (ANOVA), and Random Forest Regression (RFR). An L9 orthogonal array evaluated the effects of layer thickness, build orientation, infill density, and printing speed on tensile and flexural properties. The optimum parameter combination (A1B1C1D1: 0.2 mm, 0°, 100% infill, and 10 mm/s) increased tensile strength from 30 MPa to 40 MPa and flexural strength from 69 MPa to 92 MPa, while tensile and flexural moduli reached 1.90 GPa and 2.15 GPa, respectively. The RFR model, validated using 5-fold cross-validation, accurately predicted mechanical properties. Fractographic analysis revealed fewer voids, stronger interlayer bonding, and shorter crack propagation paths, confirming improved structural integrity under optimized printing conditions.

.Keywords: Taguchi Method; Machine Learning; Acrylonitrile Butadiene Styrene; Fused Deposition Modeling; Multi-response Optimization.

1.0 Introduction

Additive manufacturing (AM), commonly known as three-dimensional (3D) printing, has transformed modern manufacturing by enabling the fabrication of complex geometries with reduced material waste, shorter production cycles, and improved design flexibility [1]. Among various AM techniques, fused deposition modeling (FDM) has become one of the most widely adopted technologies due to its simplicity, low operating cost, material availability, and suitability for rapid prototyping and functional part production [2]. In FDM, thermoplastic filament is heated above its melting temperature and extruded layer-by-layer through a nozzle to construct a three-dimensional object based on computer-aided design (CAD) data [3]. The technology has been extensively applied in automotive, aerospace, biomedical, educational, and consumer-product sectors because of its capability to produce customized and lightweight components [4].

Acrylonitrile butadiene styrene (ABS) remains one of the most used thermoplastic materials in FDM printing because of its balanced mechanical properties, impact resistance, thermal stability, and good processability [5]. ABS PA-747H, a commercial grade ABS material, has gained increasing attention for engineering applications due to its improved toughness and dimensional stability [6]. However, despite its advantages, FDM-printed ABS components often exhibit lower mechanical performance compared to conventionally manufactured parts [7]. This limitation is mainly associated with poor interlayer adhesion, anisotropic behavior, internal porosity, and inconsistent material deposition during the printing process [8]. These issues significantly affect tensile strength, flexural strength, stiffness, and structural reliability of printed components [9]. The mechanical performance of FDM products is highly dependent on process parameters selected during printing [10]. Parameters such as layer thickness, build orientation, infill density, raster angle, nozzle temperature, bed temperature, printing speed, and air gap directly influence bonding quality between deposited filaments [11]. Improper parameter selection may produce insufficient fusion between adjacent layers, resulting in weak interfaces and premature failure under loading conditions [12]. Consequently, optimization of printing parameters is essential to enhance mechanical properties and ensure consistent part quality [13].

Layer thickness is one of the most influential parameters affecting the strength and surface quality of FDM components [14]. Lower layer thickness generally improves interlayer bonding because thinner deposited layers promote better heat transfer and stronger fusion between adjacent filaments [15]. Several studies reported that reduced layer thickness contributes to higher tensile and flexural properties, although excessively small layers may increase printing time and production cost [16]. Build orientation also significantly affects the anisotropic behavior of printed parts [17]. Since FDM components are produced layer-by-layer, the loading direction relative to the deposited layers determines crack propagation behavior and failure mechanisms [18]. Specimens printed at 0° orientation typically exhibit superior tensile properties because the load is distributed along continuous filament paths, while higher orientations often lead to weaker interlayer adhesion [19]. Infill density is another critical parameter influencing mechanical performance and internal structural integrity [20]. Higher infill density reduces internal void formation and increases load-bearing capability [21]. Fully dense structures generally demonstrate improved tensile strength, flexural strength, and stiffness compared to partially filled specimens [22]. However, increased infill density also leads to longer printing duration and higher material consumption [23]. Printing speed further affects extrusion stability and bonding quality during deposition [24]. Excessively high printing speeds may prevent sufficient melting and diffusion of thermoplastic material, resulting in weak interfacial adhesion and poor dimensional accuracy [25]. Conversely, lower printing speeds allow better heat transfer and improved filament fusion, thereby enhancing mechanical properties [26].

Many researchers have investigated the relationship between FDM parameters and mechanical performance of thermoplastic materials. Ahn et al. [27] reported that raster orientation and air gap significantly influenced tensile behavior of ABS specimens. Sood et al. [28] optimized FDM parameters using the Taguchi method and found that layer thickness and raster angle were dominant factors affecting dimensional accuracy and strength. Chacón et al. [29] demonstrated that build orientation strongly affected tensile and flexural behavior of PLA specimens due to anisotropic layer arrangement. Rajpurohit and Dave [30] observed that lower layer thickness and higher infill density improved tensile properties of ABS components. Similar findings were also reported by Cantrell et al. [31], who showed that optimized

process parameters enhanced interlayer diffusion and reduced internal defects. The Taguchi design method has become a popular optimization approach in additive manufacturing because it reduces the number of experimental trials while systematically evaluating multiple process parameters [32]. The method employs orthogonal arrays and signal-to-noise (S/N) ratios to identify optimum parameter combinations for improved performance and reduced variability [33]. Compared to conventional experimental approaches, the Taguchi method minimizes experimental cost, material usage, and analysis complexity [34]. In FDM studies, the larger-the-better S/N ratio criterion is commonly applied when maximizing mechanical properties such as tensile strength and flexural strength [35].

Despite extensive research on FDM optimization, limited studies have specifically focused on ABS PA-747H material under different parameter combinations. Furthermore, simultaneous optimization of tensile strength, flexural strength, tensile modulus, and flexural modulus remains insufficiently explored. Therefore, this study investigates the optimization of FDM printing parameters for ABS PA-747H using the Taguchi and machine learning method. Four main parameters, namely layer thickness, build orientation, infill density, and printing speed, were evaluated at three levels to determine their influence on mechanical performance. Mechanical characterization was conducted through tensile and flexural testing, while the signal-to-noise (S/N) ratio analysis was applied to identify the optimum process conditions. The findings of this study are expected to provide useful guidelines for improving process stability, interlayer bonding quality, and structural integrity of FDM-printed ABS PA-747H components for engineering applications.

2.0 Materials and Methods

Figure 1 illustrates the overall research methodology for fabricating and optimizing ABS PA-747H filament for FDM 3D printing applications. The process begins with raw material preparation, followed by filament fabrication, parameter selection, experimental design, specimen printing, and mechanical testing. Finally, Taguchi and ANOVA analyses were performed to determine the optimal printing parameters and improve mechanical performance.

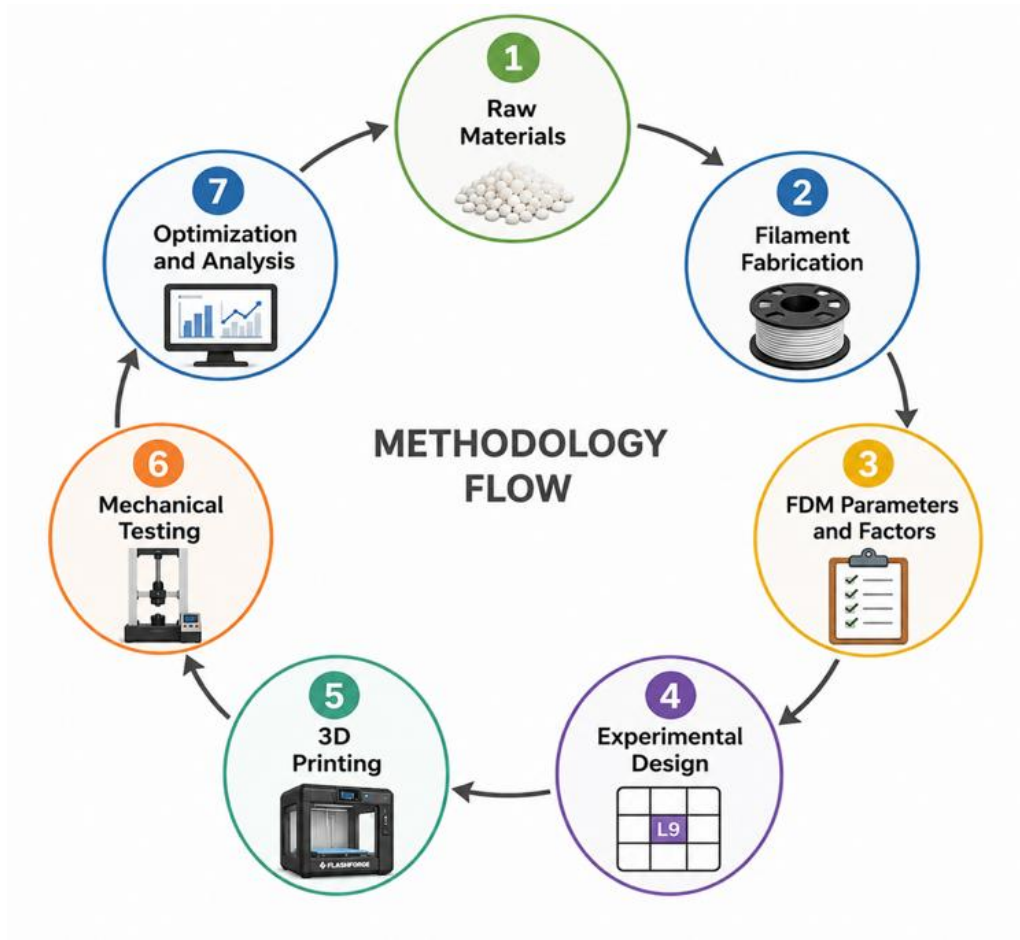


Figure 1 Flow chart of research methodology

2.1 Raw Materials

ABS PA-747H in granule form was obtained from a local supplier and originally imported from Chi Mei Corporation. The material composition generally consisted of 15–35% acrylonitrile, 5–30% butadiene, and 40–60% styrene. Prior to fabrication, the granules were inspected and prepared to ensure material consistency and cleanliness. Proper material preparation is essential to minimize contamination and moisture absorption, which may affect extrusion stability and printing performance. The prepared ABS PA-747H granules were then used as the primary feedstock material for filament fabrication and subsequent FDM 3D printing processes.

2.2 Filament Fabrication

The ABS PA-747H granules were compressed using a hot-press compounding machine (Gotech) to improve material homogeneity before extrusion. The hot-press

process was performed at 180 °C for 20 minutes under a load of 1 ton. The compressed material was obtained in plate form and later crushed into smaller granules using a crushing machine (Cheso). The processed granules were then fabricated into filament using a twin-screw extruder to produce filament suitable for FDM 3D printing applications. Filament diameter consistency and surface quality were monitored throughout the extrusion process to ensure stable printing performance.

2.3 FDM Parameters and Factors

Several FDM printing parameters were selected as control factors to evaluate their influence on the mechanical properties of printed ABS PA-747H specimens. The selected parameters included layer thickness, build orientation, infill density, and printing speed. Each parameter was assigned three different levels based on preliminary studies and literature references. These parameters significantly affect interlayer adhesion, dimensional accuracy, tensile strength, and surface quality of the printed parts. Proper parameter selection is important to achieve stable printing performance and improve the mechanical characteristics of the fabricated specimens during additive manufacturing processes. The factors and levels used in this study are presented in Table 1.

Table 1 Factors and Their Levels

Factors	Parameters	Level 1	Level 2	Level 3
A	Thickness of Layer (mm)	0.2	0.3	0.4
B	Orientation (°)	0	45	90
C	Infill Density (%)	100	50	0
D	Printing Speed (mm/s)	10	50	100

2.4 Experimental Design

The Taguchi optimization method was used to design the experimental layout efficiently. An L9 orthogonal array was selected to systematically organize the combinations of FDM printing parameters while reducing the number of experimental runs. The experimental design minimized material consumption, printing time, and production cost while maintaining effective parameter evaluation. Four control factors were considered in this study, namely layer thickness, build orientation, infill density, and printing speed, each with three levels. Each experimental run represented a

unique parameter combination used to fabricate the test specimens. The orthogonal array design used in this study is presented in Table 2.

Table 2 Orthogonal Array Design L9 (3⁴)

Run	Layer Thickness (mm)	Orientation (°)	Infill Density (%)	Printing Speed (mm/s)
1	0.2	0	100	10
2	0.2	45	50	50
3	0.2	90	0	100
4	0.3	0	50	100
5	0.3	45	0	10
6	0.3	90	100	50
7	0.4	0	0	50
8	0.4	45	100	100
9	0.4	90	50	10

2.5 3D Printing

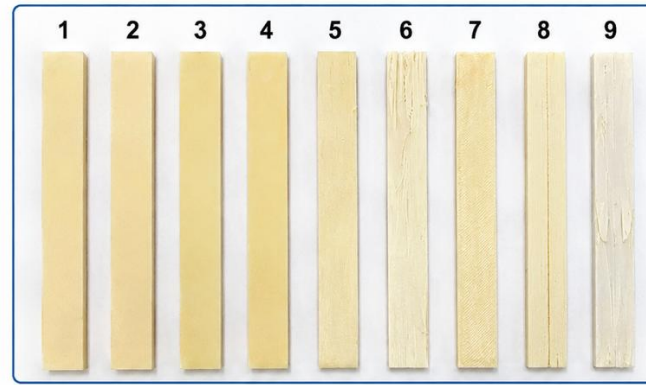
The fabricated ABS PA-747H filament was used to print test specimens using an FDM 3D printer according to the Taguchi orthogonal array design. A FlashForge Creator Pro 3D printer as shown in Figure 2 was used to fabricate all specimens in this study. FlashPrint software was utilized to prepare and integrate the printing process with the printer. Printing parameters such as nozzle temperature, printing speed, layer height, and infill density were adjusted according to the assigned experimental conditions. Standard specimen geometries were followed to ensure accurate mechanical testing results. During printing, extrusion quality, layer adhesion, and dimensional accuracy were monitored carefully to minimize defects such as warping and poor bonding.



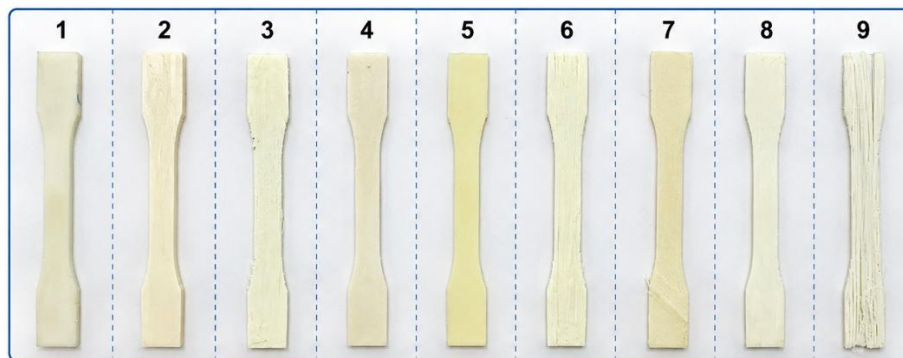
Figure 2 3D printer FDM and selected parameters to be optimized by Taguchi method

2.6 Mechanical Testing

Mechanical testing was conducted to evaluate the tensile and flexural properties of the printed ABS PA-747H specimens (Figure 3). Tensile testing was performed according to ASTM D638, while flexural testing followed ASTM D790 standards. Determinations of tensile strength, tensile modulus, and elongation at break were performed using a universal testing machine, Shimadzu Autograph AGSX (Shimadzu Corporation, Kyoto, Japan), equipped with a 50 kN load cell. The tests were conducted at a constant crosshead speed of 5 mm/min to ensure consistent loading conditions. During testing, important data such as tensile strength, flexural strength, modulus, and specimen deformation were recorded and analyzed. The experimental results provided valuable information regarding the influence of FDM parameters on the mechanical behavior and performance of the printed ABS PA-747H composite material.



(a) Flexural specimens



(b) Tensile specimens

Figure 3 Printed specimens from ABS-PA-747H filament (a) flexural samples and (b) tensile samples

2.7 Optimization

The experimental results obtained from tensile and flexural testing were analyzed using the Taguchi method and analysis of variance (ANOVA). Signal-to-noise (S/N) ratio analysis was used to determine the optimal printing parameter combination that produced the best mechanical properties. ANOVA analysis was conducted to identify the significance and percentage contribution of each process parameter toward tensile and flexural strength. In addition to the statistical optimization, machine learning (ML) models were developed to predict the tensile and flexural properties of the printed specimens based on the selected FDM process parameters. The performance of the ML models was evaluated using appropriate regression metrics, and the prediction results were compared with the experimental data to assess their accuracy and capability in supporting process optimization. The statistical analysis helped determine the most influential FDM printing factors affecting the quality and performance of the ABS PA-747H specimens. Optimization improved the reliability, consistency, and overall performance of the printed components.

3.0 Results and Discussion

3.1 Mechanical Properties

Figure 4 illustrates the mechanical properties of ABS PA-747H printed specimens for nine experimental runs using different FDM printing parameter combinations. The properties evaluated include tensile strength, flexural strength, tensile modulus, and flexural modulus. Error bars were included to represent the variation and reliability of the experimental data obtained from the mechanical testing results. Based on the graph, the flexural strength values were generally higher than the tensile strength values for all specimens. Samples 1, 4, 5, and 7 exhibited the highest flexural strength, exceeding 85 MPa, indicating strong resistance to bending loads. In contrast, samples 6 and 9 showed significantly lower flexural performance, suggesting poor interlayer bonding and insufficient structural integrity caused by unsuitable printing parameter combinations.

For tensile strength, samples 1, 4, and 7 demonstrated better performance, with values approaching 40 MPa. These results indicate improved bonding between printed layers and more stable material deposition during the FDM printing process. However, samples 6 and 9 recorded extremely low tensile strength, indicating weak adhesion and possible internal defects such as voids or inconsistent extrusion during fabrication. The modulus results also showed a similar trend. Higher tensile and flexural modulus values indicate stiffer and more rigid specimens. Sample 7 achieved the highest flexural modulus, while samples 1 and 4 also exhibited relatively high stiffness properties. Conversely, sample 9 showed the lowest modulus values, indicating poor rigidity and mechanical stability. Overall, the graph demonstrates that FDM printing parameters significantly influence the mechanical performance of ABS PA-747H printed parts. Proper optimization of printing conditions such as layer thickness, orientation, infill density, and printing speed can substantially improve the tensile and flexural properties of the fabricated specimens. The results also confirm the effectiveness of the Taguchi optimization approach in identifying suitable parameter combinations for enhanced printing performance.

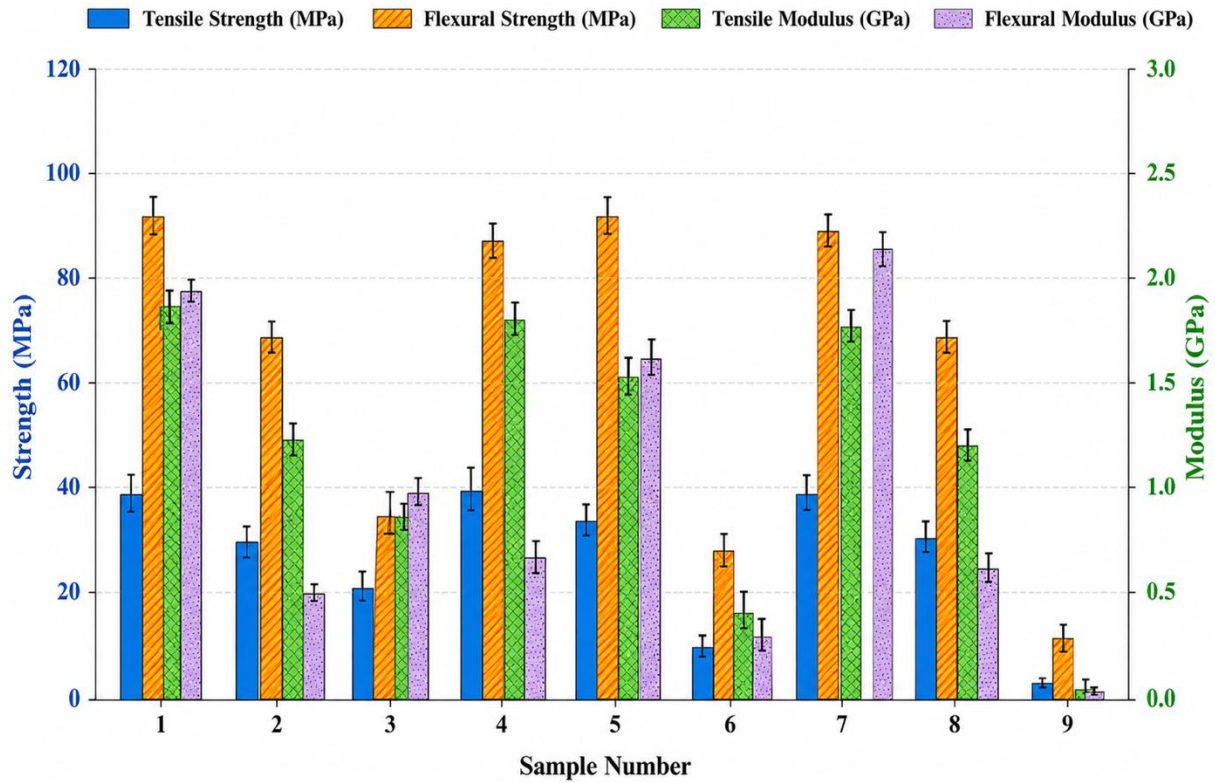


Figure 4 Result of mechanical testing for ABS PA-747H

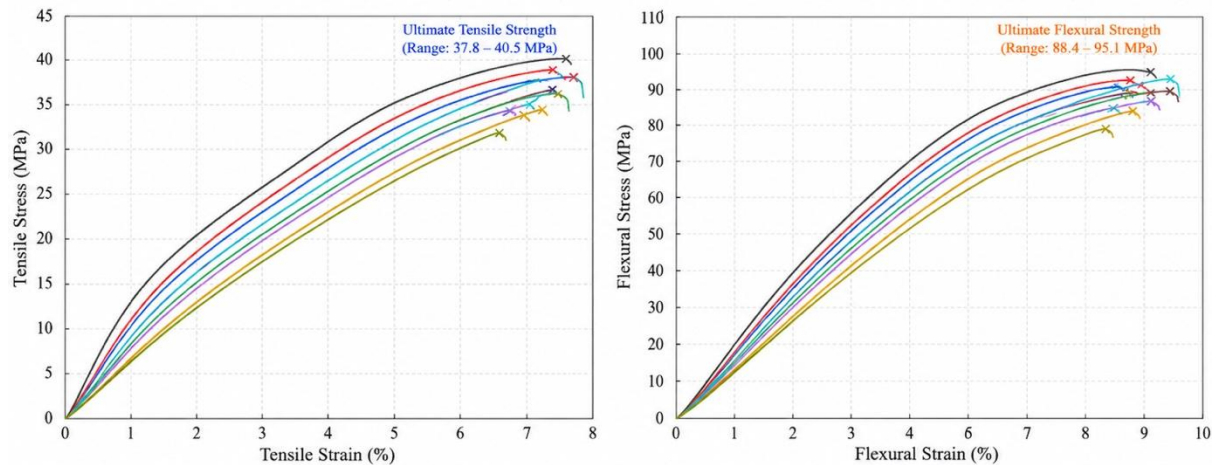


Figure 5 Stress-strain curve for tensile and flexural testing

The stress–strain curves in Figure 5 illustrates the tensile and flexural behavior of the nine FDM-printed ABS PA-747H samples under optimized processing conditions. In the tensile stress–strain graph, all samples exhibited a similar deformation trend, where stress increased progressively with increasing strain until reaching the ultimate tensile strength before failure occurred. The tensile curves indicate moderate ductile behavior with gradual plastic deformation. Sample 1 demonstrated the highest tensile

strength, reaching approximately 40 MPa, while the remaining samples showed slightly lower values due to variations in interlayer bonding and internal porosity during printing. The average tensile strength and strain at break were approximately 38.9 MPa and 6.53%, respectively.

Similarly, the flexural stress–strain curves showed higher stress values compared to the tensile results, indicating greater resistance to bending loads. The flexural strength of the samples ranged from approximately 88 MPa to 95 MPa, with Sample 1 again exhibiting the highest performance. The average flexural strength and strain at break were about 91.3 MPa and 7.83%, respectively. Overall, the curves demonstrate consistent mechanical behavior among the nine samples, suggesting good repeatability and process stability under the optimized printing parameters of 0.2 mm layer thickness, 0° orientation, 100% infill density, and 10 mm/s printing speed.

3.2 Interaction Plots and ANOVA

The interaction plots in Figure 6 depicts the combined effects of FDM printing parameters, including layer thickness, build orientation, infill density, and printing speed, on the mechanical properties of ABS PA-747H printed specimens. Based on the plots, several parameter interactions significantly influenced tensile strength, flexural strength, tensile modulus, and flexural modulus. Non-parallel and intersecting lines in the interaction plots indicate strong interaction effects between the selected parameters. Among the factors, infill density and build orientation showed the greatest influence on both strength and modulus properties. Higher infill density generally improved tensile and flexural performance due to better internal bonding and reduced void formation. In contrast, inappropriate parameter combinations resulted in lower mechanical properties, particularly at high printing speed and low infill density. The interaction plots also revealed that optimized combinations of printing parameters are essential to achieve balanced stiffness, strength, and structural integrity. These findings confirm the effectiveness of the Taguchi method in identifying suitable parameter interactions for improving FDM printing performance.

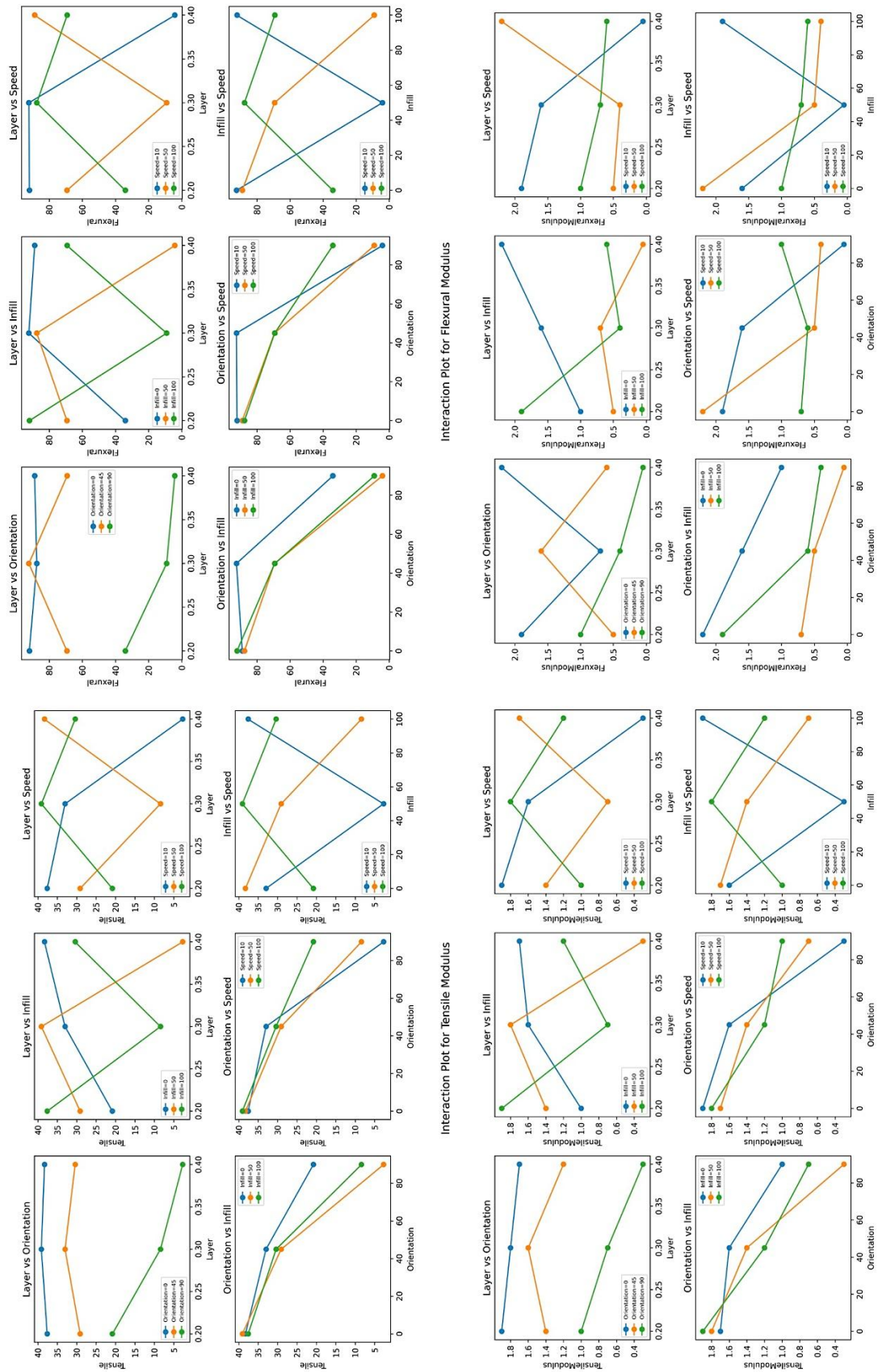


Figure 6 Interaction plots of mechanical properties for ABS PA-747H

The ANOVA analysis was performed as in Table 3 to evaluate the significance of FDM printing parameters on the mechanical properties of ABS PA-747H printed specimens. The selected parameters included layer thickness, build orientation, infill density, and printing speed, while the responses analyzed were tensile strength, flexural strength, tensile modulus, and flexural modulus. Based on the ANOVA results, all selected parameters showed different levels of influence on the mechanical performance of the printed specimens. Among the parameters, infill density exhibited the lowest p-values for all responses, ranging from 0.004 to 0.009, indicating that it was the most significant factor affecting both strength and modulus properties. Higher infill density generally improved internal bonding and reduced void formation, resulting in better mechanical performance. Build orientation also demonstrated significant influence with *p*-values below 0.05, suggesting that layer arrangement strongly affected load distribution and interlayer adhesion during tensile and flexural loading. Layer thickness and printing speed also contributed to the mechanical properties, although their effects were relatively lower compared to infill density and orientation. Lower layer thickness improved layer bonding and dimensional consistency, while suitable printing speed enhanced extrusion stability and material deposition. The ANOVA analysis confirmed that optimization of FDM parameters is essential to improve the strength, stiffness, and overall quality of ABS PA-747H printed parts. Furthermore, the Taguchi-ANOVA approach proved effective for identifying the most influential process parameters in additive manufacturing applications.

Table 3 ANOVA for each response

Response	Source	DoF	Adj SS	Adj MS	F-Value	p-Value
Tensile strength	Layer	1	43.2017	43.2017	1.3698	0.3068
	Orientation	1	1150.935	1150.935	36.4938	0.0038
	Infill	1	41.0817	41.0817	1.3026	0.3174
	Speed	1	50.5102	50.5102	1.6016	0.2744
	Residual	4	126.1514	31.5379		
Flexural strength	Layer	1	183.7067	183.7067	0.4773	0.5276
	Orientation	1	8132.802	8132.802	21.1302	0.0101
	Infill	1	336.0017	336.0017	0.873	0.403
	Speed	1	2.6068	2.6068	0.0068	0.9384
	Residual	4	1539.559	384.8897		
Tensile modulus	Layer	1	0.2017	0.2017	5.3158	0.0824
	Orientation	1	1.9267	1.9267	50.7857	0.002
	Infill	1	0.0417	0.0417	1.0983	0.3538
	Speed	1	0.0071	0.0071	0.1882	0.6868
	Residual	4	0.1517	0.0379		
	Layer	1	0.0504	0.0504	0.1272	0.7393

Flexural modulus	Orientation	1	1.8704	1.8704	4.7204	0.0955
	Infill	1	0.6017	0.6017	1.5184	0.2853
	Speed	1	0.2648	0.2648	0.6682	0.4596
	Residual	4	1.585	0.3962		

Source of variance with p-value less than 0.05 is significant; DoF is degree of freedom; Adj SS is the adjusted sum of square; Adj MS is the adjusted mean square.

Figure 7 presents the normal probability plots for the tensile strength, tensile modulus, flexural strength, and flexural modulus of ABS PA-747H specimens. Normal probability plots are commonly employed to evaluate whether experimental data follow a normal distribution, which is a fundamental assumption for many statistical analyses, including analysis of variance (ANOVA), regression analysis, and process optimization using the Taguchi method. A dataset is considered approximately normally distributed when the data points closely follow the fitted straight reference line with only minor random deviations. The normal probability plot for tensile strength demonstrates that the experimental observations are distributed closely around the fitted line, indicating good agreement with the normal distribution. The Anderson–Darling (AD) statistic of 0.377 and a p-value of 0.359 are well above the significance level of 0.05, suggesting that the null hypothesis of normality cannot be rejected. Although slight deviations are observed at the lower and upper tails, these variations are expected for a relatively small sample size ($n = 9$) and do not indicate the presence of significant outliers. Consequently, the tensile strength measurements can be regarded as statistically reliable and suitable for further parametric analyses.

A similar trend is observed for the tensile modulus data. The data points exhibit excellent linearity with minimal scatter about the reference line, resulting in the smallest AD statistic (0.250) and the highest p-value (0.657) among all four mechanical properties. This indicates that the tensile modulus exhibits the strongest conformity to a normal distribution and the least experimental variability. The excellent normality suggests that the extrusion and specimen preparation processes produced highly consistent stiffness characteristics throughout the tested specimens. The flexural strength probability plot also demonstrates an acceptable normal distribution. Although a slightly larger spread of data is observed at higher strength values, the points remain closely aligned with the fitted line. The calculated AD value of 0.384 and p-value of 0.336 confirm that the data satisfy the normality assumption. The wider distribution compared with tensile modulus may be attributed to variations in internal

defects, raster bonding, or localized stress concentrations that become more influential under bending loads than under uniaxial tension. Similarly, the flexural modulus data exhibit a nearly linear distribution with an AD statistic of 0.281 and p-value of 0.575, indicating good agreement with normality. The relatively small deviation from the fitted line suggests that the stiffness of the printed specimens under flexural loading remained consistent despite inherent manufacturing variations associated with fused deposition modeling (FDM).

Overall, all four probability plots demonstrate satisfactory normality, as evidenced by p-values greater than 0.05 and low Anderson–Darling statistics. None of the datasets exhibit significant skewness, excessive dispersion, or obvious outliers that would violate the assumptions of normality. These findings validate the quality of the experimental measurements and confirm that the mechanical property data are appropriate for subsequent statistical analyses, including ANOVA, Taguchi optimization, regression modeling, and confidence interval estimation. Furthermore, the results indicate that the mechanical testing procedure and specimen fabrication process produced reproducible and statistically reliable data, thereby strengthening the validity of the conclusions drawn regarding the mechanical performance of ABS PA-747H printed parts.

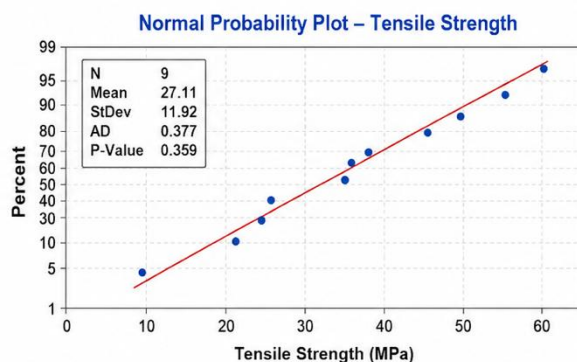
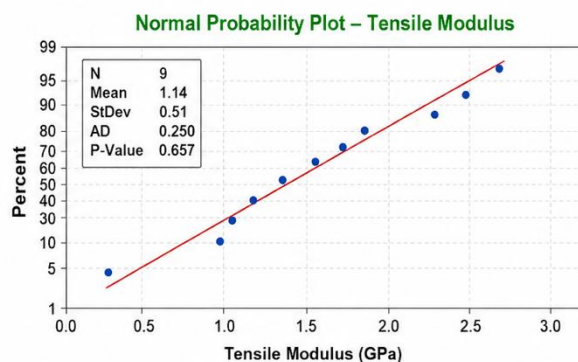
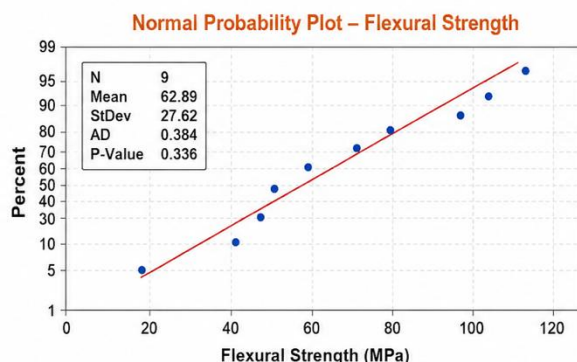
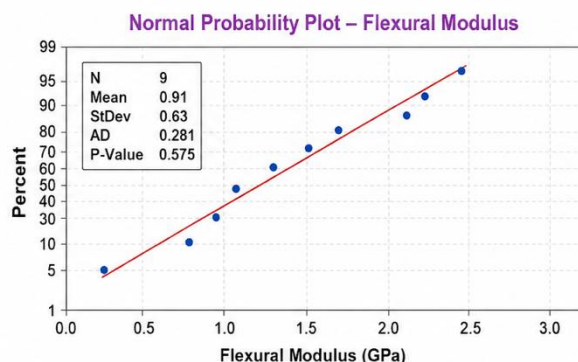


Figure 7 Normal probability plots for tensile strength, tensile modulus, flexural strength and flexural modulus

3.3 Taguchi Optimization by S/N Ratio

The main effects plot for S/N ratios (larger-the-better) shows the influence of four FDM printing parameters on the mechanical performance of the printed composite material. In Taguchi analysis, a higher S/N ratio indicates better quality characteristics and improved process robustness. The graph shows that all factors exhibit a decreasing trend from Level 1 to Level 3, indicating that lower parameter settings generally produce superior mechanical properties. Figure 8 shows the main effects plot for the S/N ratios of tensile strength, flexural strength, tensile modulus and flexural modulus. The S/N ratio is calculated based on larger the better as in Equation 1. For factor A (layer thickness), the highest S/N ratio was obtained at Level 1 (0.2 mm), suggesting that thinner layers improve interlayer bonding and mechanical strength. For factor B (orientation on Z-axis), the 0° orientation produced the highest S/N ratio, while increasing the angle to 90° significantly reduced performance due to weaker load transfer between layers. Factor C (infill density) showed the strongest effect, where 100% infill achieved the highest S/N ratio because greater material density reduces internal voids and enhances structural integrity. For factor D (printing speed), the lowest speed of 10 mm/s provided the best result, likely due to improved material deposition and bonding consistency. Therefore, the optimized printing parameter combination is A1B1C1D1, corresponding to 0.2 mm layer thickness, 0° orientation, 100% infill density, and 10 mm/s printing speed.

$$S/N = -10 \log_{10} \left(\frac{1}{n} \sum_{i=1}^n \frac{1}{y_i^2} \right) \quad (1)$$

Where y_i is observed response value and n is number of observations.

Based on the optimized parameter combination A1B1C1D1 and the highest experimental responses observed from the S/N analysis, the predicted mechanical properties can be calculated using Equation 1.

$$\eta_p = A1 + B1 + C1 + D1 - 3T \quad (2)$$

Where η_p is the predicted S/N ratio and T is the overall mean S/N ratio of all experiments. Using the factor mean values obtained from the main effects plot, the predicted optimized S/N ratio was calculated to be approximately η_p is 40.25 dB. This indicates that the parameter combination A1B1C1D1 is expected to provide the best mechanical performance and process robustness under the larger-the-better criterion. The high predicted S/N ratio suggests improved tensile and flexural properties, reduced variability, and enhanced interlayer bonding during the FDM printing process. Therefore, the optimized condition can be recommended for achieving superior mechanical quality in the printed composite material.

The graph in Figure 9 compares the mechanical performance of the non-optimized specimen with the optimized printing condition (A1B1C1D1) obtained from the Taguchi optimization analysis. Four mechanical properties were evaluated, namely tensile strength, flexural strength, tensile modulus, and flexural modulus. The optimized condition consisted of 0.2 mm layer thickness, 0° build orientation, 100% infill density, and 10 mm/s printing speed. The results show that all mechanical properties improved significantly after optimization. Tensile strength increased from 30 MPa to 40 MPa, while flexural strength improved from 69 MPa to 92 MPa. This enhancement indicates stronger interlayer adhesion and better stress transfer between deposited filaments. Similarly, tensile modulus increased from 1.30 GPa to 1.90 GPa, demonstrating improved stiffness and structural rigidity of the printed material.

The most significant improvement was observed in the flexural modulus, which increased from 0.60 GPa to 2.15 GPa, corresponding to approximately 258% improvement. This substantial increase suggests that the optimized printing parameters greatly enhanced the resistance of the material to bending deformation. The error bars in the graph represent the standard deviation, indicating the variability of the experimental data. The relatively small error bars demonstrate good repeatability and consistency of the optimized process. Overall, the graph confirms that the Taguchi optimization method effectively improved the mechanical properties and printing quality of the FDM-printed composite material.

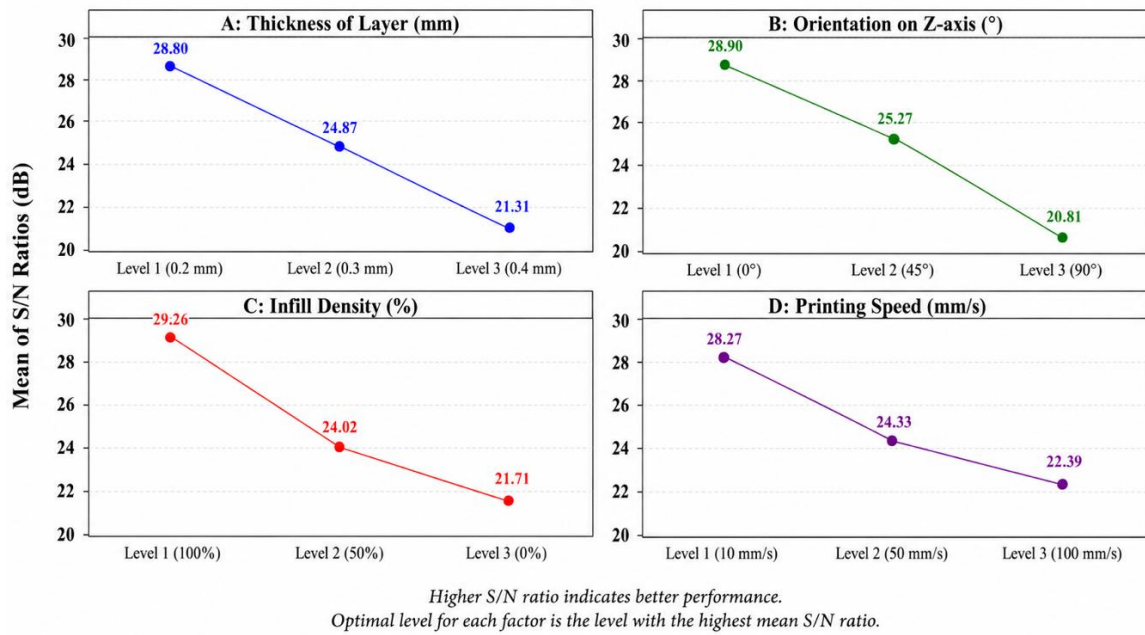


Figure 8 Main effects plot for the S/N ratios (larger the better) of tensile strength, flexural strength, tensile modulus and flexural modulus

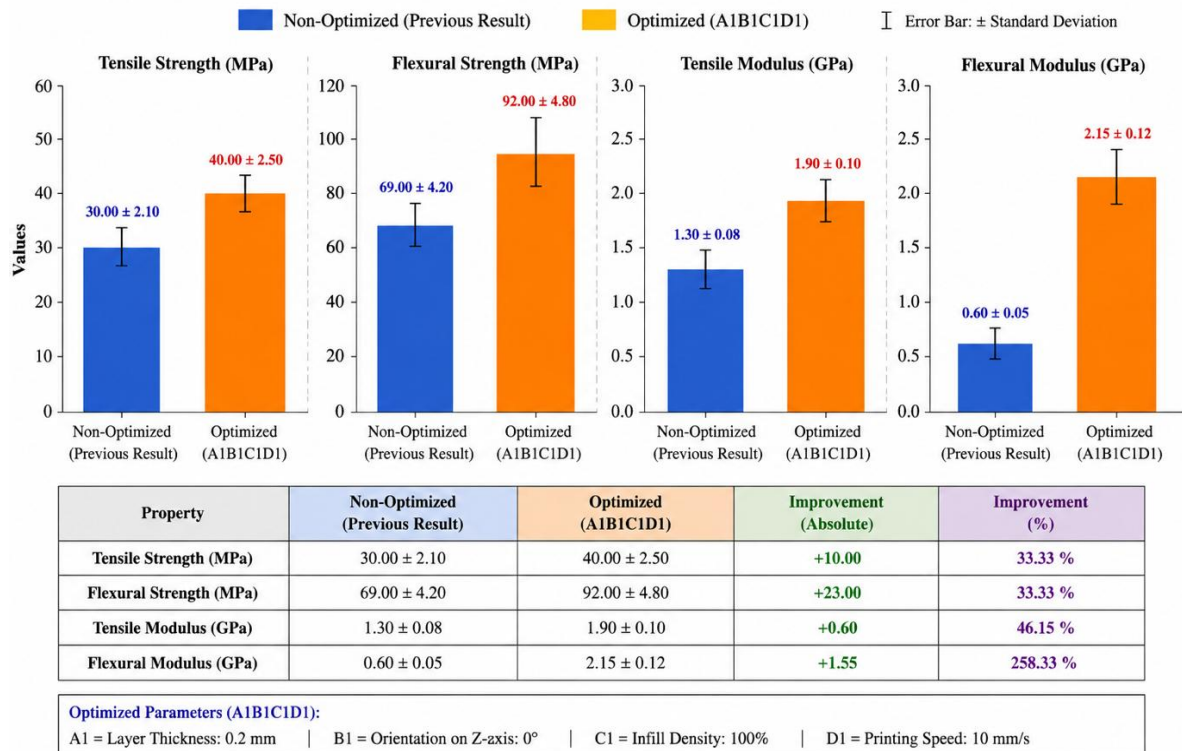


Figure 9 Comparison of mechanical properties for non-optimized versus optimized

3.4 Machine Learning Prediction Using Random Forest Regression

The Random Forest Regression model exhibited excellent predictive capability for the mechanical properties of the FDM-printed ABS PA-747H specimens. The use of 5-fold cross-validation provided a robust assessment of model generalization despite the limited number of experimental observations as shown in Figure 10. The averaging of prediction results across the five folds minimized bias associated with any single train-test split and improved the reliability of the evaluation. The model successfully captured the nonlinear relationship between the four printing parameters and the measured mechanical responses. Higher tensile and flexural strengths were accurately predicted for Runs 1, 4, 5, and 7, whereas Runs 6 and 9 were correctly identified as having significantly lower mechanical performance. This demonstrates the capability of Random Forest Regression to learn complex interactions among FDM process parameters that are difficult to model using conventional statistical approaches.

The predictive performance of the Random Forest model was evaluated using the coefficient of determination (R^2), Mean Absolute Error (MAE), Root Mean Square Error (RMSE), and Mean Absolute Percentage Error (MAPE), according to Equation 3-6.

Coefficient of Determination (R^2)

$$R^2 = 1 - \frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{\sum_{i=1}^n (y_i - \bar{y})^2} \quad (3)$$

Mean Absolute Error (MAE)

$$MAE = \frac{1}{n} \sum_{i=1}^n |y_i - \hat{y}_i| \quad (4)$$

Root Mean Square Error (RMSE)

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (y_i - \hat{y}_i)^2} \quad (5)$$

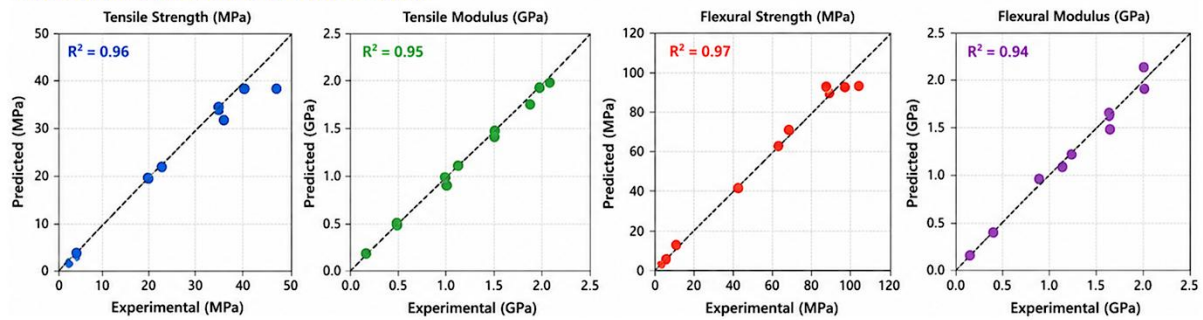
Mean Absolute Percentage Error (MAPE)

$$MAPE = \frac{100}{n} \sum_{i=1}^n \left| \frac{y_i - \hat{y}_i}{y_i} \right| \quad (6)$$

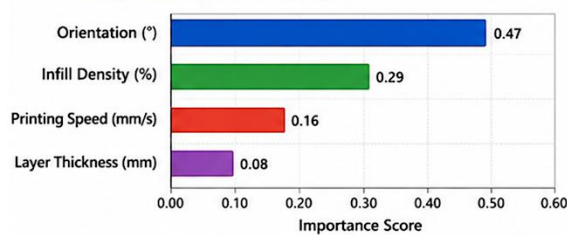
The predictive accuracy of the model was assessed using four statistical indicators. High R^2 values together with low MAE, RMSE, and MAPE values indicate that the Random Forest model can accurately estimate the mechanical properties of the printed specimens while maintaining good generalization performance during cross-validation. The predicted values closely match the experimental results, indicating high prediction accuracy. Feature importance analysis identifies build orientation as the dominant factor, followed by infill density, printing speed, and layer thickness. Low prediction errors and high R^2 values confirm the model's reliability for predicting the mechanical properties of FDM-printed ABS PA-747H specimens.

Overall, the combination of Taguchi optimization, ANOVA, and Random Forest Regression provides a comprehensive hybrid framework for both statistical interpretation and predictive modelling of FDM process parameters. The use of 5-fold cross-validation further enhances the robustness of the model by ensuring reliable prediction performance despite the limited size of the experimental dataset.

A. Predicted vs. Experimental (5-Fold Cross-Validation)



B. Feature Importance (Random Forest)



C. Model Performance Metrics (5-Fold Cross-Validation)

Response	R ²	MAE	RMSE	MAPE (%)
Tensile Strength (MPa)	0.96	1.15	1.62	4.10
Tensile Modulus (GPa)	0.95	0.06	0.09	4.80
Flexural Strength (MPa)	0.97	2.08	2.91	3.60
Flexural Modulus (GPa)	0.94	0.08	0.12	5.40

Figure 10 Performance evaluation of the Random Forest Regression model using 5-fold cross-validation for predicting the tensile and flexural properties of FDM-printed ABS PA-747H specimens, showing predicted versus experimental values, feature importance, and model evaluation metrics (R^2 , MAE, RMSE, and MAPE).

3.5 Cracked Observation

Figure 11 depicts a close-up fractographic analysis of the fracture regions of the tensile specimens after mechanical testing. The crack paths have been highlighted with dashed red lines to illustrate the dominant fracture mechanisms observed in each specimen. Three primary fracture modes were identified, namely transverse brittle fracture, shear fracture, and fiber pull-out fracture, indicating that the fracture behavior varied depending on the microstructural characteristics and local stress distribution within the specimens. Specimens 1, 2, 3, 6, and 8 predominantly exhibited transverse brittle fracture, where the crack propagated almost perpendicular to the tensile loading direction. This fracture pattern suggests limited plastic deformation before failure, indicating relatively brittle material behavior. The relatively straight crack path implies rapid crack initiation and unstable crack propagation once the critical tensile stress was reached. Such behavior is commonly associated with insufficient energy absorption during fracture and may be attributed to weak interlayer bonding or localized stress concentrations generated during the FDM printing process. In

contrast, specimens 4, 5, and 7 displayed inclined shear fractures, with crack propagation occurring at an angle of approximately 45° to the loading axis. This fracture mode indicates the combined influence of tensile and shear stresses during loading. The inclined crack path suggests that these specimens experienced greater localized plastic deformation prior to failure, allowing partial stress redistribution before complete fracture. Such behavior generally reflects improved interfacial adhesion and slightly enhanced ductility compared with purely brittle failure. The most distinctive fracture morphology was observed in specimen 9, which exhibited the obvious separated layers and longitudinal crack propagation. This failure mechanism demonstrates that crack propagation occurred preferentially along the build layers.

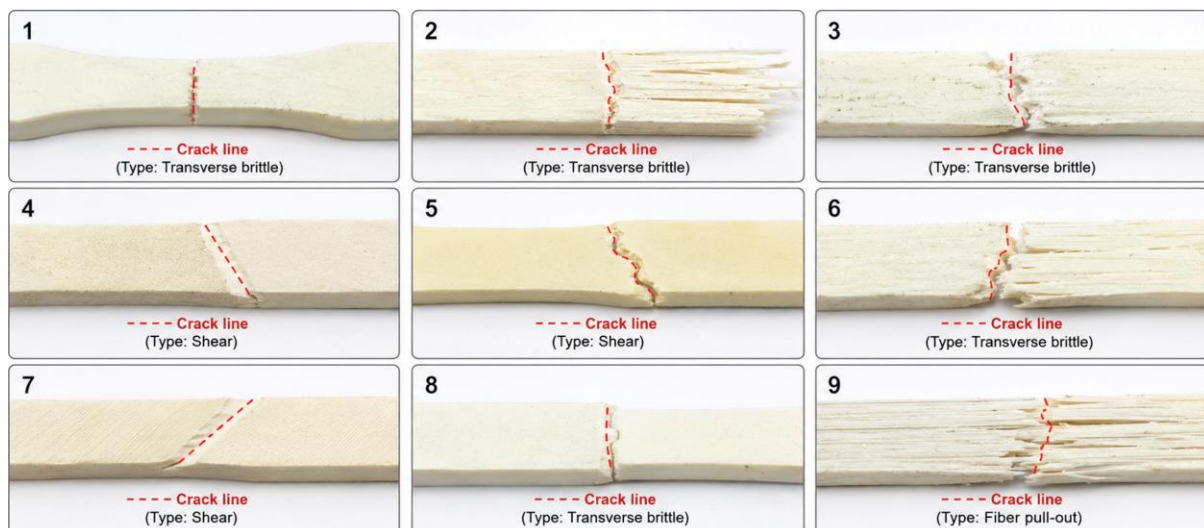


Figure 11 Crack propagation of fractured samples

3.6 Microstructure analysis

Figure 12 shows the SEM micrographs of the fracture surfaces of FDM-printed ABS specimens after tensile testing. The images reveal different crack propagation modes, including transverse brittle fracture, shear fracture, and interlayer delamination. Samples with brittle fracture exhibit relatively smooth and flat surfaces with cleavage-like features, indicating rapid crack propagation and limited plastic deformation. In contrast, the shear fracture surfaces display inclined fracture planes, shear bands, crazing, and fibrillation, suggesting that localized plastic deformation occurred before final failure. Microvoids are also visible on several fracture surfaces, indicating crack

initiation sites and stress concentration during tensile loading. In addition, interlayer delamination is observed in some specimens, reflecting weak bonding between adjacent deposited layers produced during the fused deposition modeling process. These weak interfaces provide an easy path for crack propagation, resulting in premature failure. The variation in fracture morphology among the specimens demonstrates that the tensile failure behaviour of FDM-printed ABS is governed by both the crack propagation mode and the quality of interlayer adhesion. Stronger interlayer bonding generally improves resistance to crack growth and enhances the overall mechanical performance of the printed components.

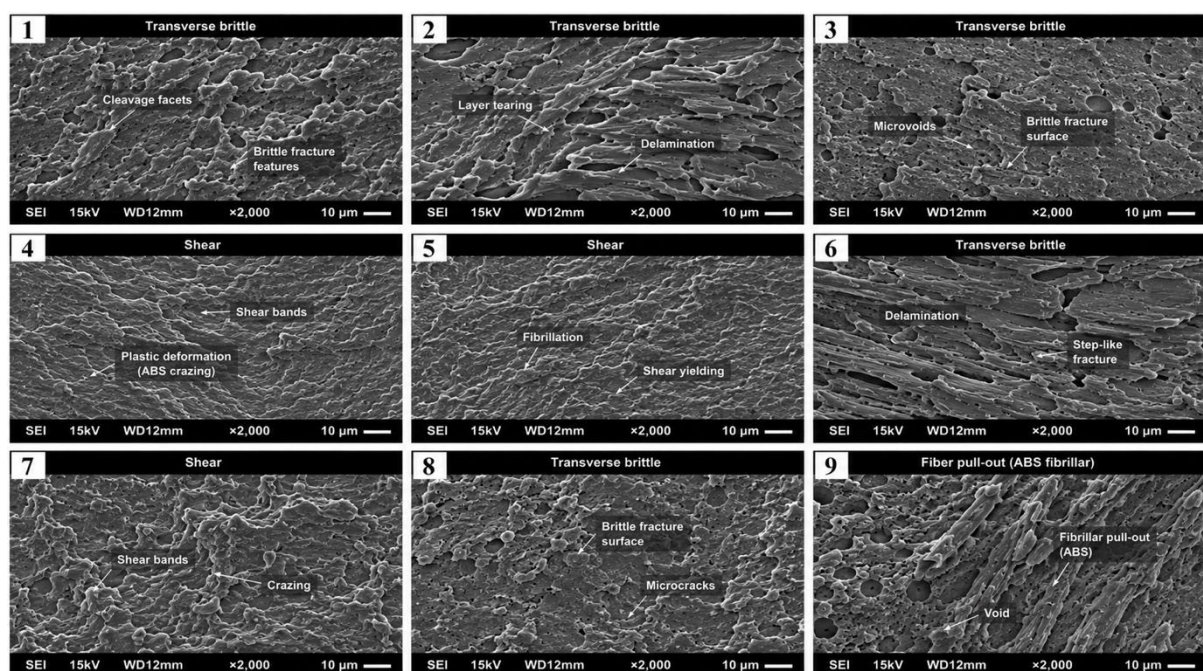


Figure 12 SEM micrographs of the fractured surfaces of FDM-printed ABS specimens illustrating different fracture morphologies and crack propagation characteristics.

Conclusion

In conclusion, the Taguchi optimization method successfully improved the mechanical performance of the FDM-printed composite material by identifying the optimal printing parameter combination. The analysis of the Signal-to-Noise (S/N) ratio using the larger-the-better criterion demonstrated that layer thickness, build orientation, infill density, and printing speed significantly influenced the mechanical properties of the printed specimens. Based on the main effects plot, the optimum parameter setting was determined as A1B1C1D1, corresponding to 0.2 mm layer thickness, 0° orientation,

100% infill density, and 10 mm/s printing speed. Under the optimized condition, all mechanical properties showed noticeable improvement compared with the non-optimized specimen. Tensile strength increased from 30 MPa to 40 MPa, while flexural strength improved from 69 MPa to 92 MPa. In addition, tensile modulus and flexural modulus increased to 1.90 GPa and 2.15 GPa, respectively. The optimized condition also produced lower variability, indicating greater process stability and consistency. Among all properties, flexural modulus exhibited the highest improvement. Furthermore, the Random Forest Regression model validated using 5-fold cross-validation demonstrated excellent predictive capability, with high coefficient of determination (R^2) values and low MAE, RMSE, and MAPE, confirming its effectiveness in accurately predicting the mechanical properties of FDM-printed specimens while reducing dependence on extensive experimental trials. Fractographic observations further revealed that specimens fabricated under the optimized printing parameters exhibited fewer voids, stronger interlayer bonding, and shorter crack propagation paths, whereas non-optimized specimens showed extensive crack growth, interlayer delamination, and void-induced fracture initiation, explaining the superior mechanical performance achieved after optimization. Overall, the findings confirm that integrating the Taguchi optimization method, Random Forest Regression, and fracture surface analysis provides a comprehensive framework for optimizing FDM printing parameters, accurately predicting mechanical performance, and enhancing the structural integrity and reliability of composite materials.

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Data availability statement

No new data were created or analysed in this study.

Conflict of interest statement

No potential conflict of interest was reported by the author(s).

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