Optimization of Mechanical Properties in 3D Printed ULTRA PLA Sandwich Structures: Effect of Infill Density, Printing Speed, and Layer Thickness

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Optimization of Mechanical Properties in 3D Printed ULTRA PLA Sandwich Structures: Effect of Infill Density, Printing Speed, and Layer Thickness

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Abstract: The present research aims to evaluate the effect of layer thickness, printing speed, and infill density on sandwich structures fabricated using 3D printing. The optimal parameter combination was determined using the Signal Noise (S/N) ratio. At the same time, analysis of Variance (ANOVA) was applied to determine the most significant parameters and quantify their impact on manufacturing time, flexural strength, elastic modulus, stiffness, and specific stiffness. The results reveal that specific stiffness is predominantly affected by infill density (76.53%), followed by layer thickness (13.88%), and printing speed (2.67%). The optimization results indicate that the combination of a 0.1 mm layer thickness, 10% infill density, and a printing speed of 120 mm/s as the optimal configuration. This study highlights the potential of 3D printing for enhancing the specific stiffness of sandwich structures and provides insight into the suitability of Ultra Polylactic Acid (ULTRA PLA) for engineering and structural optimization applications.

Keywords: 3D printing; Sandwich structures; Optimization

1. Introduction

Rapid prototyping technology is becoming more popular in the industry. 3D printing and other rapid prototyping techniques use multiple layers of material to create 3D objects[1)]. Additive manufacturing creates parts from 3D Computer-Aided Design (CAD) models by layering materials together. This method increases productivity while lowering costs. The most prevalent method of three-dimensional printing is Fused Deposition Modeling (FDM)[2)]. These technologies can save money by reducing waste and producing intricate shapes. In recent decades, they have received considerable attention[3)]. FDM 3D printing softens and molds thermoplastic materials into objects using heat. The material heats up and is printed in layers to form a 3D model[4)]. Polymers are the most common materials used in 3D printing[5)]. The type of polymer used is determined by the printing method and product[6–9)]. Polymers are classified into several categories, including thermoplastics and photopolymers[10)].

Nevertheless, 3D-printed polymers are rarely employed for structural or functional elements because they lack the necessary strength and ability to insulate electricity and heat. Researchers looked into 3D printing for polymer composites to improve mechanical performance[11)]. This has included the addition of nanoparticles as well as short or continuous fibers. Adding other materials to the polymers can increase the performance of 3D-printed polymer composites in certain applications[12)].

Materials with high specific strength, defined as great strength paired with low weight, are in high demand in aircraft, structural engineering, transportation, and machining industries. These materials usually have stretching-dominated structures and deform largely under uniaxial compression or tension[10)]. A composite sandwich construction is made up of two main components. The face sheet is the first component. It supports the sandwich structure's bending strains. Carbon, glass, and basalt fibers are the most frequent materials used in face sheets. The second component is the core. Sandwich structure cores come in four types: corrugated, honeycomb, balsa wood, and foam. The core carries the shear forces that operate on the sandwich panel. The core is selected based on its capacity to withstand stress and offer the required stiffness[13)]. Composites are widely employed in the automotive and marine industries because of their good corrosion resistance and high stiffness-to-weight ratios[14–17)]. Carbon fiber reinforced plastic (CFRP) is now used in aviation and aerospace instead of stainless steel and similar materials[18]. CFRP is strong, stiff, and resistant to corrosion. Its improved durability also contributes to this change[19].

Much research has lately been conducted to determine how different factors affect mechanical qualities. Infill density, layer thickness, and printing speed are used as inputs. Zandi et al. discovered that layer thickness was the most critical element in flexural strength for wood PLA composites[20]. Camargo et al. discovered that increasing layer height increased mechanical properties[21]. According to Rajpurohit et al, layer thickness has the greatest effect on flexural strength[22]. In Cho et al, the influence of layer thickness on the mechanical properties of PLA is explored. The findings reveal that an increase in layer thickness from 0.1 mm to 0.3 mm has a good effect on the impact property of PLA[23]. Hidayat et al[24] investigated the influence of printing parameters (nozzle diameter, layer height, nozzle temperature, and printing speed), geometric dimensions (wall thickness), and filament material on the impact crashworthiness performance of PLA multi-cell tubes. Shergill et al examine the effect of layer thickness on the mechanical characteristics of PLA and ABS. The findings reveal that raising layer thickness has a negative impact on the mechanical properties of both PLA and ABS, with PLA being more significantly affected[25].

This study investigates the effects of infill density, printing speed, and layer thickness on key performance metrics of 3D-printed ULTRA PLA sandwich structures, including manufacturing time, flexural strength, elastic modulus, stiffness, and specific stiffness. The sandwich structures were fabricated using ULTRA PLA with layer thicknesses of 0.1 mm, 0.2 mm, and 0.3 mm, infill density of 10%, 20%, and 40%, and printing speeds of 90 mm/s, 120 mm/s, and 150 mm/s. Employing the Taguchi method, this research optimizes the printing parameters to enhance the performance of the structures, while analysis of variance (ANOVA) provides insights into the percentage contribution of each parameter. This work provides a novel contribution by systematically exploring the combined effects of these parameters on the mechanical properties and manufacturing efficiency of ULTRA PLA sandwich structures, offering a foundation for further advancements in 3D-printed composite design.

2. Experimental Section

2.1 The filament

Creality ULTRA PLA filaments were used in this project. The filament had a diameter of 1.75 mm and was extruded using a 0.4 mm nozzle. ULTRA PLA has a density of 1238 kg/m³, tensile strength of 32.18 MPa, and Young's modulus of 2440 MPa[26].

2.2 The preparation of specimens

The experimental specimens employed in this study measured 100 mm x 38 mm x 10 mm, with a honeycomb sandwich core covered by two skins and varying core infill densities (10%, 20%, 40%). Figure 1 shows the CAD of the sandwich construction for visual representation reasons.

The ULTRA PLA specimens were manufactured with high precision accuracy using a Creality K1 3D printer, with each layer of the specimen exactly created horizontally. The Creality K1 is specifically designed as a high-speed printer capable of reaching up to 300 mm/s. This high-speed printer allows for a detailed exploration of the balance between reduced manufacturing time and potential trade-offs in the mechanical properties of printed structures. Given the increasing demand for faster production processes in various industries, this study aims to provide insights into optimizing these trade-offs for practical applications. The specimens were constructed with a 50ºC construction plate and a nozzle temperature of 200ºC. Throughout the study, all other Creality K1 3D printer parameters stayed at their default values.

2.3 Experimental methods

The Taguchi method helps make products and services better. Its primary purpose is to determine the optimal combination of components and their respective amounts to achieve the best results[27]. This study employed the Taguchi method to optimize the mechanical properties of ULTRA PLA sandwich structures. The experiments were designed with three input parameters: layer thickness, infill density, and printing speed. The layer thickness was varied at 0.1 mm, 0.2 mm, and 0.3 mm, while the infill density was set at 10%, 20%, and 40%. Printing speeds of 90 mm/s, 120 mm/s, and 150 mm/s were evaluated to investigate their influence on the manufacturing time, flexural strength, elastic modulus, stiffness, and specific stiffness. Table 1 presents an L-9 orthogonal array design, comprising nine specimens, each containing three samples. All specimens were evaluated using the ASTM C393 bending test. The S/N characteristics indicate that lower values are preferable for manufacturing time, while higher values are desirable for flexural strength, elastic modulus, stiffness, and specific stiffness. Regression equations and mathematical models were developed for each output response, including manufacturing time, flexural strength, elastic modulus, stiffness, and specific stiffness.

Table 1. Taguchi experiment design L-9.

Number of Experiment	Layer Thickness (mm)	Infill Density (%)	Printing Speed (mm/s)
L1	0.1	20	90
L2	0.1	40	120
L3	0.1	10	150
L4	0.2	20	120
L5	0.2	40	150
L6	0.2	10	90
L7	0.3	20	150

L8	0.3	40	90
L9	0.3	10	120

Table 2. Specimen process parameters.

Parameters	ULTRA PLA
Nozzle diameter	0.4 mm
Build orientation	Flat (0^0)
Top and bottom solid layers	20 layers
Core solid layers	30 layers
Contours (Perimeters)	2 layers
Internal fill pattern	Honeycomb
External fill pattern	Lines
Extruder temperature	200 °C
Bed temperature	50 °C
Filament diameter	1.75 mm
Filament density	1.24 g/cm^3

Bending testing and dimensions of sandwich specimens are as follows in Fig. 1. The experimental design was produced with AutoCAD and Creality Slicer software. This printing process produced nine specimens of the specified ULTRA PLA sandwich structure sample types, as shown in Table 2.

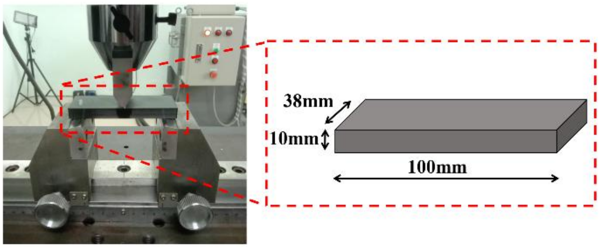


Fig. 1: 3-point bending test and specimen dimension.

Sandwich specimens were placed horizontally on two supports. The load was applied at the center of the specimen surface, with deflection measured from the position of the crosshead at a rate of 5 mm/min. The data obtained included elongation/δ and load/F values.

2.4 Sandwich Structure

The study intends to look at the effects of infill density, printing speed, and layer thickness on manufacturing time, flexural strength, elastic modulus, stiffness, and specific stiffness of 3D Printed ULTRA PLA Sandwich Structures. The printed specimens are evaluated for dimensional accuracy and weight. Measurements are taken to determine the averages and standard deviations of various measurements such as sandwich thickness, width, length, and weight. The collected data includes the dimensions and weight of each specimen. Here are the formulas for determining flexural strength, elastic modulus, stiffness, and specific stiffness in bending tests:

$$\sigma_{flexural} = \frac{PS}{2t(d+c)b} \quad (1)$$

Flexural strength is the deformation of the specimen gets to the point of maximum deflection[28]. Where σ_f = flexural strength (MPa); P = force (N); S = span length (mm); t = facing thickness (mm); d = sandwich thickness (mm); c = core thickness (mm); b = sandwich width (mm).

$$E = \frac{PS^3}{48I\delta} \quad (2)$$

Elastic modulus values have been examined in the elastic range using the previous infill and pattern variations at maximum load without breaking the specimen[29]. Where E = elastic modulus in bending (GPa); I = moment of inertia (mm^4); δ = deflection (mm).

$$D = E \times I \quad (3)$$

Stiffness is the measure of an object's resistance to deformation in response to an applied force. It's essentially the ratio of the applied load to the displacement produced by the load. D = stiffness (Nmm^2).

$$D_{specific} = \frac{D}{W} \quad (4)$$

Specific stiffness is the stiffness of a material divided by its density, providing a measure of how efficient the material is at resisting deformation relative to its weight. Where, $D_{specific}$ = specific stiffness (Nmm^2/gram); D = stiffness (Nmm^2); W = weight of the specimen (gram)

2.5 Determination of optimal treatments

The Taguchi method is used to optimize 3D printing parameters. ANOVA can be used to quantify the contribution of multiple process parameters to a single measured outcome[30], such as printing speed, infill density, and layer thickness. The ANOVA helps to determine the best combination of parameters for achieving the desired print quality, such as mechanical strength and dimensional accuracy while reducing manufacturing costs and time. In other words, ANOVA is a systematic and effective method for screening and prioritizing the factors that most influence the quality and efficiency of the 3D printing process. Before running the ANOVA, the Anderson-Darling tests were used to assess the normality of dimensions and weight.

3. Result and Discussion

3.1 Normality test

The dimensions and weight of each specimen were previously measured and utilized to populate the test data, which are presented in Fig. 2. Once the normality of the data regarding dimensions and weight had been established. The normality test was used to analyze the dimensions and weight of nine specimens, consisting of three samples each. Most dimensions had P values greater than 0.05, showing normal distribution and adherence to tolerances. The Process Capability Report also shows the distribution of data for length, width, thickness, and weight in bar form. The data is considered normal if it falls within the range of the Upper Specification Limit (USL) and Lower Specification Limit (LSL), calculated as the mean plus or minus 4 times the standard deviation. The process target line is placed in the center of the bar graph.

Figure 2 presents a process capability report for the length measurement (mm) with parameters of 0.1 mm layer thickness, 20% infill density, and 90 mm/s printing speed. The histogram depicts the distribution of measured lengths around a mean of 99.7453 mm. The process capability indices (Pp, Ppk, Cp, and Cpk) all equal 1.33, suggesting that the process is competent and has good precision and centering. The second figure shows normal distribution with a mean of 99.75 mm, a standard deviation of 0.03889 mm, and a p-value of 0.237 (more than 0.05), suggesting that the data do not depart significantly from normality.

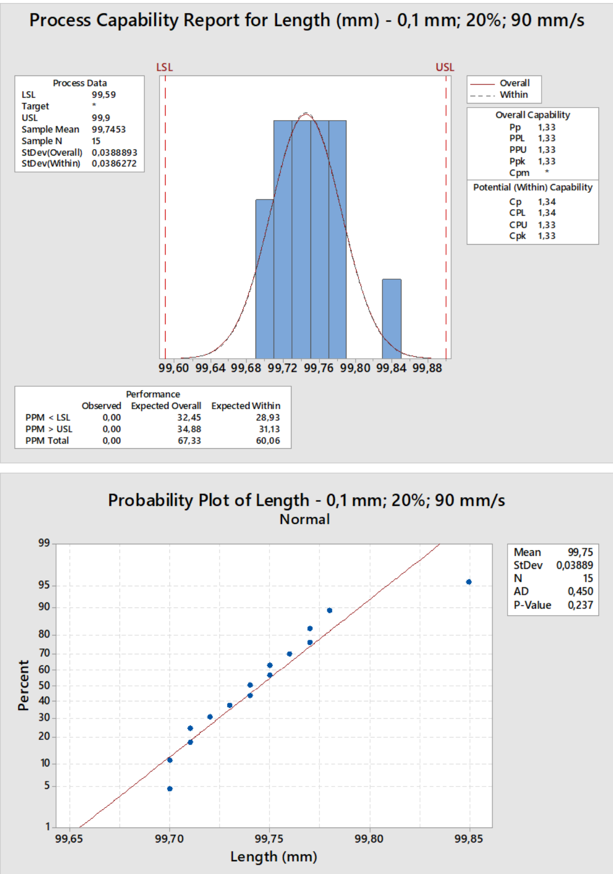


Fig. 2: Probability plot and process capability specimen.

3.2 Three-point bending test

Figure 3 presents the load-elongation curves for nine sandwich structure specimens made of ULTRA PLA, tested under varying parameters of infill density, printing speed, and layer thickness according to the Taguchi L9 Array, with factors of layer thickness (0.1 mm; 0.2 mm; 0.3 mm), infill density (10%; 20%; 40%), and printing speed (90 mm/s; 120 mm/s; 150 mm/s). The X-axis represents elongation (mm), which is the change in specimen length due to the bending force, while the Y-axis represents the load (N) applied to the specimens. The curves demonstrate how each specimen withstands the applied load until reaching its maximum point, followed by a decrease in load after the specimen fractures. Specimens with steeper gradients, such as L8 and L2, demonstrate higher stiffness, as they require greater force to achieve a given elongation.

Figure 4 depicts the comparison of maximum load capacity across 3d-printed sandwich structure specimens under three-point bending testing. The applied loads range from 1793 N and 2811 N, with corresponding elongations varying from 2.27 mm to 2.89 mm. Specimen L8 (0.3 mm layer thickness, 40% infill density, and 90 mm/s printing speed) exhibits the highest load of 2811 N with an elongation of 2.89 mm, while specimen L9 (0.3 mm layer thickness, 10% infill density, and 120 mm/s printing speed) shows the lowest load of 1793 N with an elongation of 2.55 mm.

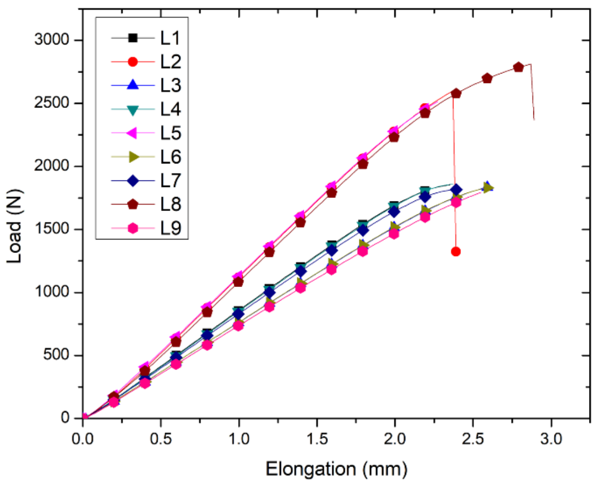


Fig. 3: Load-elongation curve of 3-point bending test.

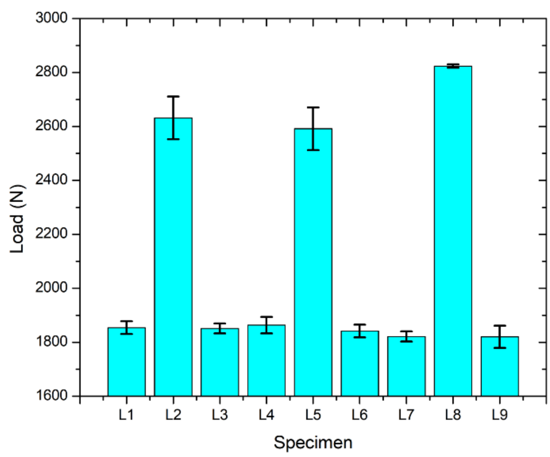


Fig. 4: Comparison of maximum load capacity across 3d-printed sandwich structure specimens under three-point bending testing.

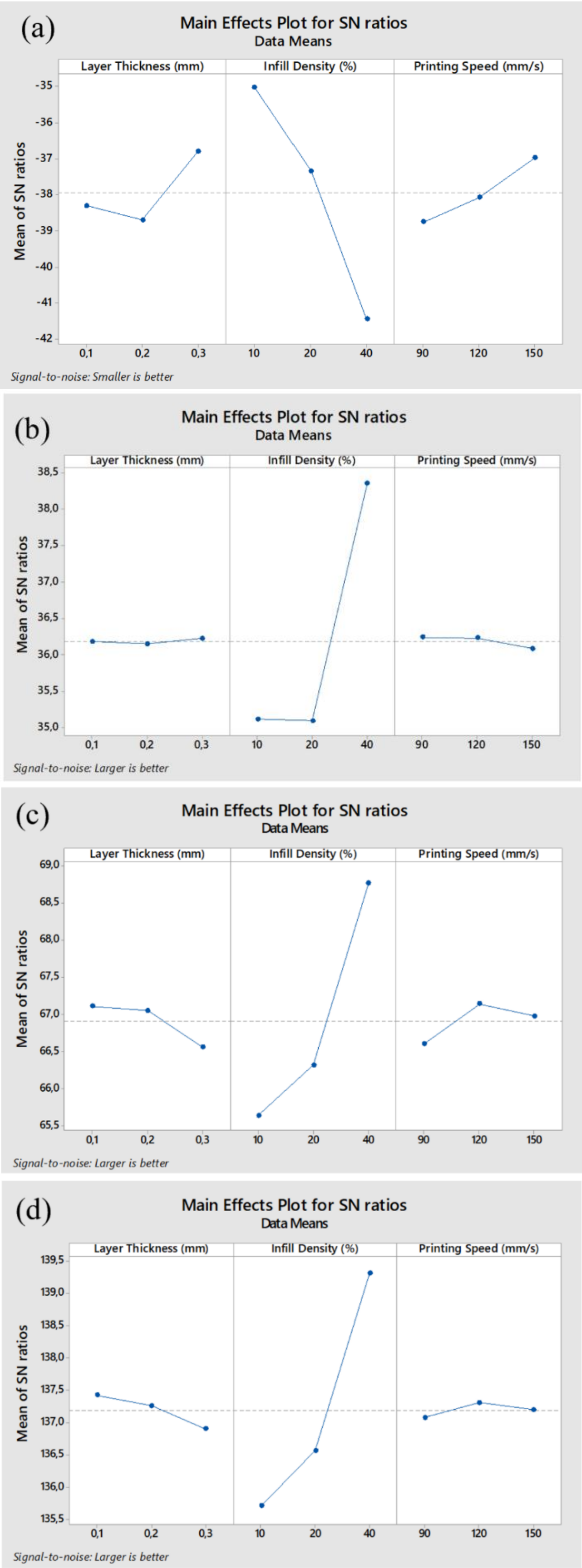
3.3 Analysis of S/N Ratio for 3d-printed ULTRA PLA sandwich structures

The 3-point bending test results (Table 3) show the variation in performance based on the printing parameters. The lowest value for manufacturing time was 49 minutes with a layer thickness of 0.1 mm, infill density of 10%, and printing speed of 150 mm/s in L3. The optimum flexural strength was obtained in experiment L8 at 84.74 MPa with layer thickness 0.3 mm, infill density 40%, and printing speed 90 mm/s. The highest elastic modulus was found in experiment L5, which amounted to 2.89 GPa with a layer thickness of 0.2 mm, infill density of 40%, and printing speed of 150 mm/s. The optimal stiffness was achieved in experiment L2 with a value of 9,615,737 Nmm^2, using a layer thickness of 0.1 mm, infill density of 40%, and printing speed of 120 mm/s. Meanwhile, the highest specific stiffness was achieved in experiment L3 at 224,612 Nmm^2/gram with layer thickness 0.1 mm, infill density 10%, and printing speed 150 mm/s.

Table 3. Experimental result for mechanical properties of 3d-printed ULTRA PLA sandwich structures.

No	Manufacturing Time (minutes)	σ_f (MPa)	E (GPa)	D (Nmm^2)	$D_{specific}$ (Nmm^2/g)
L1	89	56.74	2.10	6,968,639	204,515
L2	128	82.46	2.88	9,615,737	206,444
L3	49	57.09	1.92	6,116,623	224,612
L4	76	57.67	2.10	6,703,982	197,257
L5	122	80.75	2.89	9,508,986	203,157
L6	69	56.69	1.88	6,074,644	223,201
L7	59	56.06	2.00	6,521,288	192,664
L8	106	84.74	2.47	8,593,751	182,465
L9	53	57.08	1.94	6,106,076	223,061

From the results, it can be concluded that the combination of printing parameters results in variations in material strength. Higher infill density tends to produce materials with greater strength. In this study, an infill density of 40% gave the highest values for flexural strength, elastic modulus, and stiffness. This indicates that flexural strength, elastic modulus, and stiffness positively correlate with material density. In contrast, manufacturing time and specific stiffness are negatively related to infill density.



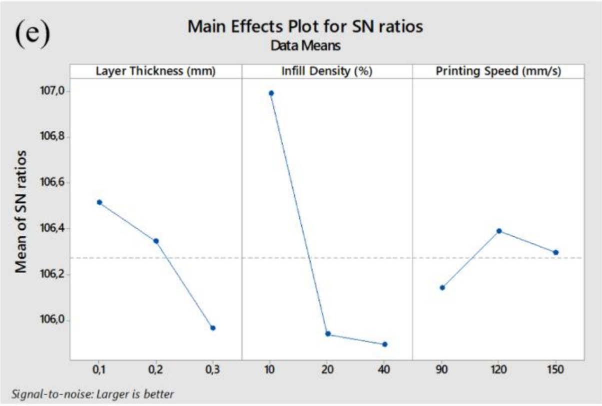


Fig. 5: Mean effect plots for S/N ratio for (a) manufacturing time, (b) flexural strength, (c) elastic modulus, (d) stiffness, and (e) specific stiffness obtained from the Taguchi method.

The Taguchi method decreases the number of experiments performed. The Taguchi technique determines the S/N ratio by evaluating how far a characteristic deviates from its set values[31]. The maximum value was plotted to determine the best level of each element. Figure 5 demonstrates that the best manufacturing time parameters are layer thickness of 0.3 mm, infill density of 10%, and printing speed of 150 mm/s. The best settings for flexural strength are 0.3 mm layer thickness, 40% infill density, and a printing speed of 90 mm per second. Layer thickness of 0.1 mm, infill density of 40%, and printing speed of 120 mm/s yield the best elastic modulus and stiffness results. The ideal combination for maximum specific stiffness is a layer thickness of 0.1 mm. an infill density of 10%, and a printing speed of 120 mm/s.

3.4 Analysis of Variance

Based on the ANOVA results (Table 4), the most significant influences on manufacturing time are infill density (86.61%), layer thickness (7.48%), and printing speed (3.08%), respectively. By optimizing these three parameters, the printing process can be enhanced by minimizing material used (infill density set at 10%), reducing the required number of layers (layer thickness 0.3 mm), and increasing the extruder motion speed to covers a larger area in less time (printing speed 150 mm/s). This optimized combination significantly reduces the overall manufacturing time. The research findings of Ćwikła[32] also corroborated these results.

Table 4. Analysis of variance of manufacturing time.

Source	Contribution	Adj SS	Adj MS	P-value
Layer Thickness	7.48%	522.9	261.44	0.274
Infill Density	86.61%	6050.9	3025.44	0.032
Printing Speed	3.08%	214.9	107.44	0.479
Error	2.83%	197.6	98.78	
Total	100.00%			

ANOVA analysis of the S/N ratio results (Table 5) confirmed that infill density had the largest impact on flexural strength, followed by printing speed and layer thickness. In the ANOVA analysis, the most significant influences on flexural strength were infill density (99.29%), printing speed (0.25%), and layer thickness (0.10%). A high infill density (40%) produces a denser and stronger structure that is better able to withstand flexural loads. In addition, the use of a low printing speed (90 mm/s) results in a more accurate shape and better surface quality, reducing defects that can become weak points when the material is subjected to bending loads[25].

Table 5. Analysis of variance of flexural strength.

Source	Contribution	Adj SS	Adj MS	P-value
Layer Thickness	0.10%	1.29	0.643	0.274
Infill Density	99.29%	1327.3	663.68	0.032
Printing Speed	0.25%	3.35	1.673	0.479
Error	0.36%	4.79	2.395	
Total	100.00%			

Table 6. Analysis of variance of elastic modulus.

Source	Contribution	Adj SS	Adj MS	P-value
Layer Thickness	3.79%	49511	24756	0.4
Infill Density	90.70%	11845	592247	0.03
Printing Speed	3.06%	39937	19968	0.45
Error	2.45%	31996	15998	
Total	100.00%			

The ANOVA results (Table 6) showed that infill density is the most significant contributor to elastic modulus, accounting for at 90.70%, followed by layer thickness at 3.79% and printing speed at 3.06%. A high infill density combined with a low layer thickness enhances the elastic modulus, as the denser structure and stronger interlayer bonds result in a stiffer material capable of withstanding flexural deformation more effectively[33]. This observation aligns with the finding reported by Nugroho et al[34].

Table 7. Analysis of variance of stiffness.

Source	Contribution	Adj SS	Adj MS	P-value
Layer Thickness	2.25%	3.9E+11	1.9E+11	0.38
Infill Density	95.76%	1.7E+13	8.3E+12	0.01

Printing Speed	0.62%	1.1E+11	5.3E+03	0.7
Error	1.38%	2.4E+11	1.2+11	
Total	100.00%			

In the ANOVA analysis (Table 7), infill density had the significant influences on stiffness at 95.76%, layer thickness at 2.25%, and printing speed at 0.62%. A high infill density (40%) increases the overall density and strength of the structure with more material inside. This distributes the load more evenly, reducing weak points that could cause deformation during bending. In addition, thinner layers (0.1mm) strengthen the bond between the layers, reducing the risk of delamination. These findings are consistent with research by Brischetto[35)].

Table 8. Analysis of variance of specific stiffness.

Source	Contribution	Adj SS	Adj MS	P-value
Layer Thickness	13.88%	2.4E+08	1.2E+08	0.333
Infill Density	76.53%	1.3E+09	6.7E+08	0.083
Printing Speed	2.67%	4.7E+07	2.3E+07	0.722
Error	6.92%	1.2E+08	6.1E+07	
Total	100.00%			

The ANOVA analysis (Table 8) reveals that infill density significantly impacts specific stiffness, contributing 76.53%, follow by layer thickness at 13.88% and printing speed at 2.67%. This means that the choice of the right infill density is a key factor in the optimization of the strength-to-weight ratio of the structure. This study has shown that a low infill density (10%) can increase the specific stiffness of the structure through a reduction in total weight, without sacrificing efficient material distribution for load bearing. This leads to a lighter structure with comparable strength, improving the strength-to-weight ratio. This finding is consistent with previous research by[25)].

3.5 Regression Analysis

This experiment investigates the effects of several parameters, namely layer thickness, infill density, and printing speed, on the outcomes of the 3D-printed ULTRA PLA sandwich structures. The results are utilized to develop regression equations and construct mathematical models for each output response, including manufacturing time, flexural strength, elastic modulus, stiffness, and specific stiffness. Using a general linear model, the printing parameters are treated as factors and analyzed with statistical software to derive predictive equations for these responses.

The manufacturing time was analyzed using regression analysis, and Equation (5) presents the best fit for it.

$$\begin{aligned} &\text{Manufacturing time} = 83.44 \\ &+ 5.22\ \text{Layer Thickness (mm)\_0.1} \\ &+ 5.56\ \text{Layer Thickness (mm)\_0.2} \\ &- 10.78\ \text{Layer Thickness (mm)\_0.3} \\ &- 26.44\ \text{Infill Density (\%)\_10} \\ &- 8.78\ \text{Infill Density (\%)\_20} \\ &+ 35.22\ \text{Infill Density(\%)\_40} \\ &+ 4.56\ \text{Printing Speed (mm/s)\_90} \\ &+ 2.22\ \text{Printing Speed (mm/s)\_120} \\ &- 6.78\ \text{Printing Speed (mm/s)\_150} \end{aligned} \tag{5}$$

The regression analysis is employed for the flexural strength, and Equation (6) presents the best fit for it.

$$\begin{aligned} &\text{Flexural strength} = 65.476 \\ &- 0.046\ \text{Layer Thickness (mm)\_0.1} \\ &- 0.439\ \text{Layer Thickness (mm)\_0.2} \\ &+ 0.484\ \text{Layer Thickness (mm)\_0.3} \\ &- 8.522\ \text{Infill Density (\%)\_10} \\ &- 8.652\ \text{Infill Density (\%)\_20} \\ &+ 17.174\ \text{Infill Density (\%)\_40} \\ &+ 0.581\ \text{Printing Speed (mm/s)\_90} \\ &+ 0.261\ \text{Printing Speed (mm/s)\_120} \\ &- 0.842\ \text{Printing Speed (mm/s)\_150} \end{aligned} \tag{6}$$

The elastic modulus was analyzed using regression analysis, and Equation (7) presents the best fit for it.

$$\begin{aligned} &\text{Elastic modulus} = 2243.1 \\ &+ 58.0\ \text{Layer Thickness (mm)\_0.1} \\ &+ 46.7\ \text{Layer Thickness (mm)\_0.2} \\ &- 104.7\ \text{Layer Thickness (mm)\_0.3} \\ &- 330.3\ \text{Infill Density (\%)\_10} \\ &- 174.8\ \text{Infill Density (\%)\_20} \\ &+ 505.1\ \text{Infill Density (\%)\_40} \\ &- 91.7\ \text{Printing Speed (mm/s)\_90} \\ &+ 64.5\ \text{Printing Speed (mm/s)\_120} \\ &+ 27.2\ \text{Printing Speed (mm/s)\_150} \end{aligned} \tag{7}$$

The regression analysis is employed for the stiffness, and Equation (8) presents the best fit for it.

$$\begin{aligned} &\text{Stiffness} = 7356637 \\ &+ 210364\ \text{Layer Thickness (mm)\_0.1} \\ &+ 72568\ \text{Layer Thickness (mm)\_0.2} \\ &- 282931\ \text{Layer Thickness (mm)\_0.3} \\ &- 1257522\ \text{Infill Density (\%)\_10} \\ &- 625333\ \text{Infill Density (\%)\_20} \\ &+ 1882855\ \text{Infill Density (\%)\_40} \\ &- 144292\ \text{Printing Speed (mm/s)\_90} \\ &+ 118629\ \text{Printing Speed (mm/s)\_120} \\ &+ 25663\ \text{Printing Speed (mm/s)\_150} \end{aligned} \tag{8}$$

The regression analysis is employed for the specific stiffness, and Equation (9) presents the best fit for it.

$$\begin{aligned} &\text{Specific stiffness} = 206375 \\ &+ 5482\ \text{Layer Thickness (mm)\_0.1} \end{aligned} \tag{9}$$

+ 1497 Layer Thickness (mm)_0.2
- 6978 Layer Thickness (mm)_0.3
+ 17250 Infill Density (%)_10
- 8230 Infill Density (%)_20
- 9020 Infill Density (%)_40
- 2981 Printing Speed (mm/s)_90
+ 2546 Printing Speed (mm/s)_120
+ 436 Printing Speed (mm/s)_150

The general equation correlating manufacturing time, flexural strength, elastic modulus, stiffness, and specific stiffness with the parameters of layer thickness, infill density, and printing speed was developed using ANOVA. The R^2 values for the responses are presented in Table 9. It can be observed that the flexural strength model exhibits the highest accuracy, while the specific stiffness model demonstrates the lowest accuracy.

Table 9. Significance of the coefficient of determination (R^2) in validating ANOVA.

Responses	R^2
Manufacturing time	0.9717
Flexural strength	0.9964
Elastic modulus	0.9755
Stiffness	0.9862
Specific stiffness	0.9308

Table 10. Optimal parameters for manufacturing time and mechanical properties of 3-printed ULTRA PLA Sandwich Structures.

Responses	Layer Thickness (mm)	Infill Density (%)	Printing Speed (mm/s)
Manufacturing time	0.3	10	150
Flexural Strength	0.3	40	90
Elastic modulus	0.1	40	120
Stiffness	0.1	40	120
Specific Stiffness	0.1	10	120

The optimal answer to the ULTRA PLA bending test using the Taguchi method is shown in the Table 10. The ideal layer thickness for manufacturing time was 0.3 mm, with 10% infill density and a printing speed of 150 mm/s. For flexural strength, the ideal layer thickness was 0.3 mm, with 40% infill density and a printing speed of 90 mm/s. The best combination for elastic modulus and stiffness was 0.1 mm layer thickness, 40% infill density, and 120 mm/s printing speed. Meanwhile, the best combination for specific stiffness was 0.1 mm layer thickness, 10% infill density, and a printing speed of 120 mm/s. For ULTRA PLA, these combinations produced the largest results in terms of manufacturing time, flexural strength, elastic modulus, stiffness, and specific stiffness.

4. Conclusion

This study optimizes the manufacturing time, flexural strength, elastic modulus, stiffness, and specific stiffness of ULTRA PLA sandwich specimens. The infill density significantly influences these parameters. Higher infill density result in stronger and stiffer specimens, while lower infill density lead to shorter manufacturing times and higher specific stiffness values. The shortest manufacturing time was 49 minutes in experiment L3 with parameters of 0.1 mm layer thickness, 10% infill density, and printing speed of 150 mm/s. The highest flexural strength (84.74 MPa) was observed in experiment L8 with parameters 0.3 mm layer thickness, 40% infill density, and a printing speed of 90 mm/s. Experiment L5 achieved the highest elastic modulus (2.89 GPa) using parameters of 0.2 mm layer thickness, 40% infill density, and a printing speed of 150 mm/s). The maximum stiffness (9,615,737 Nmm^2) was recorded in experiment L2 with parameters of 0.1 mm layer thickness, 40% infill density, and a printing speed of 120 mm/s. Meanwhile, the highest specific stiffness (224,612 Nmm^2/gram) was obtained in experiment L3 with parameters 0.1 mm layer thickness, 10% infill density, and a printing speed of 150 mm/s. Among these factors, infill density exhibited the most significant impact on all performance metrics. Notably, the highest specific stiffness was primarily influenced by layer thickness (13.88%), infill density (76.53%), and printing speed (2.67%). Based on ANOVA analysis, the optimal configuration for ULTRA PLA sandwich specimens was determined to be a layer thickness 0.1 mm, an infill density of 10%, and a printing speed of 120 mm/s.

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