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Optimization of 3D Printing Parameters for Compressive Strength of PLA Using the Taguchi Method

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Abstract: Fused Deposition Modeling (FDM) has significantly advanced in the additive manufacturing of complex geometrical and customized parts, particularly for thermoplastics like Polylactic Acid (PLA). The purpose of the present study is to optimize FDM process parameters to improve the compressive strength of 3D-printed PLA using the Taguchi method. Four process parameters such as infill density, printing speed, layer thickness, and infill pattern type are selected. Among these parameters applied, printing speed had a significant impact on compressive strength. Analysis of variance results revealed that printing speed was dominant, followed by layer thickness in analyzing the compressive strength, but the infill density and infill pattern were not significant. Confirmation tests were provided by Taguchi method. Further, it is found that the optimal compressive strength was achieved with a printing speed of 300 mm/s, a layer thickness 0.3 mm, an infill density of 10, and a pattern shape of grid. Therefore, trial 3 yielded the highest compressive strength results at approximately 42.45 MPa, which is slightly higher than those reported in prior studies.

Keywords: An additive manufacturing, Fused deposition modelling, Polylactic acid, Compressive strength, Taguchi method, Optimization

Introduction

Any type of products in additive manufacturing technique (3D printing) are given design flexibility, very precise dimension on components associated with complex geometries, which are quite hard to achieve using classical production methods (Abdallah et al., 2023). Due to having design flexibility prototyping and cost advantage, 3D printing approach has moved to various industries such as automotive, aerospace, medical and sports (Arifin et al., 2021). However, this process has some dis-advantages like irregular surface, poor mechanical property and indicating low accuracy. In order to produce good quality of mechanical parts, it is necessary to produce those parts with optimum combination of process parameters.

There are several various types of additive manufacturing techniques like Fused Deposition Modelling (FDM), Fused Filament Fabrication (FFF), Stereolithography (SLA), and Selective Laser Sintering (SLS). Each one has specific advantages, depending on the application (Kumaresan et al., 2023; Hikmat et al., 2021). Polylactic Acid (PLA) is a bio-plastic commonly used in FDM 3D printing, notable for its biodegradability and environmental friendliness. Its availability is significantly supported by its excellent processability and biocompatibility. PLA

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has higher tensile strength, low warp, and low ductility when compared to ABS (Kafle et al., 2021; Solomon et al., 2021). The fused deposition modeling (FDM) is an additive manufacturing (AM) process that is often used to fabricate geometrically complex shaped prototypes and parts. The many fundamental process parameters such as nozzle diameter/temperature, fill density/fill pattern, layer thickness/height, print speed and various patterns directly affect the quality of the manufactured parts and mechanical performance (Dey & Yodo, 2019). To avoid trial and error approach on experimental work on polymeric materials, Taguchi optimization is adopted in a more systematic way and efficiently, by testing the different printing parameters because of simple, easier/less cost in short period of time.

A large number of researchers analyzed different parameters to achieve desirable properties of parts (Hema et al., 2022; Myers et al., 2022; Özmen et al., 2023; Adanur et al., 2024; Oviedo et al., 2020; Evlen et al., 2019; Kadhum et al., 2023; Ramírez-Revilla et al., 2022; Abifarin et al., 2022; Kumar et al., 2023; Khalifah et al., 2025; John et al., 2023; Singh et al., 2022), and many other researchers have worked on optimizing process parameters using DoE (Sahoo et al., 2023; Gebrehiwot & Espinosa-Leal, 2022; Alviar & Basilia, 2024; Lokesh et al., 2022; Chinchanikar et al., 2024; Cui et al., 2024; Makwana, 2023; Patel et al., 2023). Hema et al. (2022) studied the effects of machine process parameters on the compressive and flexural strength of Polylactic Acid (PLA) material produced using FDM 3D printing by Taguchi design. For compressive strength, the optimal parameters were 100 µm layer height, 80% infill density and 80 mm/s printing speed. It was indicated that layer height was the most significant parameter for flexural strength (68.42% contribution), while infill density was the most significant parameter for compressive strength (62.18% contribution). Myers et al. (2022) aimed to analyze and optimize FDM additive manufacturing process parameters for cellular structures used in orthopedic scaffolds. The studied parameters included layer height (0.12, 0.16, 0.2 mm), flow rate (90%, 100%, 110%) and printing speed (40, 50, 60 mm/s). The best combination for geometric accuracy and time/cost optimization was 0.16 mm layer height, 50 mm/s printing speed, and 90% flow rate.

Özmen et al. (2023) examined the effect of infill pattern and orientation on the tensile strength of test specimens fabricated using FDM 3D printing and PLA. The different infill patterns and three infill angles (0°, 45°, 90°) were printed. Those with concentric 90° and zigzag 90° infill exhibited the highest tensile strength. The specific strength of the 30% infill concentric pattern sample was about 25% higher than that of the 100% infill sample. Adanur et al. (2024) investigated the effects of different infill patterns and angles on production time, weight and tensile and compressive strength of PLA samples. Results showed that 15% infill samples required four times less material and printing time than fully solid ones. The highest tensile strength occurred at a 45° printing angle. Among 15% infill samples, the Aligned Linear (B-0) pattern with a 0° angle had the highest strength. Oviedo et al. (2020) focused on the mechanical performance of commercial filaments based on ABS, PLA, and PLA/PHA and their corresponding 3D printed samples. Evlen et al. (2019) studied experimentally to determine the effect of infill ratio on the mechanical properties of PLA and PET materials. In PLA, tensile strength increased up to a 30% infill ratio (maximum 48 N/mm^2) but then declined at higher ratios (40–50%) due to notch effects and poor layer adhesion.

Kadhum et al. (2023) searched a comprehensive study assessing the effects of fourteen different infill patterns on the mechanical and surface characteristics of 3D-printed parts. PLA+ showed the highest average strength (14.7 MPa). Ramírez-Revilla et al. (2022) evaluated the compressive and tensile properties of FDM 3D-printed polymers exposed to saline solution. In compression, PLA and PC exhibited the highest compressive strength. After degradation, the tensile strength of PLA decreased most significantly (33.55% reduction). Abifarin et al. (2022) investigated the effects and optimization of manufacturing parameters on the tensile, compressive and flexural strength of 3D-printed Chitosan/PLA scaffolds by the Taguchi-Grey Relational Analysis methodology. The optimal parameters were obtained at 1% Chitosan, 100% infill density and 70°C annealing temperature. Kumar et al. (2023) investigated the effects of different concentrations of poly(ethylene glycol) (PEG) on the properties of PLA parts. The PLA/PEG blend containing 5% PEG showed optimal structural and mechanical properties.

Khalifah et al. (2025) studied that the Taguchi method/Analysis of Variance are selected in optimizing the fused filament fabrication process to produce PLA composites. The tensile strength increased to 40 MPa instead of 35 MPa. Among the parameters, only nozzle temperature and infill density had a significant impact on tensile strength. John et al. (2023) studied the influence of nozzle diameter, strain rate, and geometric patterns on the mechanical properties of PLA samples. Singh et al. (2022) applied a Taguchi-based DoE to optimize the layer height and infill pattern for PLA surgical equipment produced via FFF. They obtained a tensile strength of 42.6 MPa and an elasticity modulus of 32.74 MPa.

The literature surveys indicate that there are many studies carried out to optimize the mechanical properties of PLA/PEG/ASA through various methods, most of them concentrated on the effect of process parameters on tensile strength, and limited number of studies related to compressive property of PLA materials (Hema et al., 2022; Adanur et al., 2024; Ramírez-Revilla et al., 2022; Abifarin et al., 2022). The purpose of this study is to determine and optimize the process parameters infill density, printing speed, layer thickness and infill pattern on PLAs using the Taguchi method. Each parameter's effect on process performance will be searched in terms of the Taguchi L9 design due to becoming more systematic, saving time and costly. Experiments are made for validation to confirm the results of optimization.

Method

Taguchi Method

In this case, an orthogonal array like L9 (3^4), as indicated in Table 3, is quite applicable for 9 experimental trials with four factors at three levels each. This array provides a symmetrical and comprehensive assessment of the main effects while minimizing confounding, meaning that the effects of two or more factors cannot be distinguished. The use of the L9 array ensures that the effects of any factors are unbiased during estimation, allowing accurate and reliable conclusions to be drawn through this approach.

This technique is employed to determine the optimal machining parameters. The Signal-to-Noise Ratio (SNR) is utilized to evaluate the robustness of the process and analyze the system's response under varying conditions. There are three common types of SNR formulations: **Smaller-is-Better (SB), Larger-is-Better (LB) a**nd **Nominal-is-Best (NB).** In this study, **compressive strength (CS)** is considered a response to be maximized. Therefore, the LB characteristic is applied for CS using Eq. (1).

If LB is effective, Eq. (1) is used.

$$SNR\ (dB) = -10log\left(\frac{1}{n}\right)\sum_{i=1}^{n}\left(\frac{1}{y_{ij}^{2}}\right) \quad (1)$$

Where, n shows the number of replicates while Yij exhibits the outputs. Highest SNR will give an optimal solution.

Materials

PLA was the filament used to prepare the compressive specimens. Commercially available from Filament Company of 1.75 mm diameter (Shenzhen, China), some technical specifications of composite PLA are given in Table 1. Compressive test samples were produced using the Flashforger Guider IIs FFF technology-based 3D printer, in Beijing, China and modeled using CAD software with Solidworks 2020. Once the model is sliced through the Flashprint slicing software, G-code is generated. It is a set of commands telling a 3D printer how to print objects. Examples of information that G-code conveys are how the printer moves, at what speed, and the required temperature of the extruder. Sliced code is a code comprising directives along with both variables and constant parameters necessary for the slicing program.Table 1 presents some physical and mechanical properties of PLA filament, including tensile strength, elongation at break, density, melting temperature and glass transition temperature.

Table 1. Properties of Polylactic Acid (PLA) filament Property.

	Value	Units
Density	1.24	Kg / m^3
Elongation at break	6.3	%
Ultimate tensile strength	52.9	MPa
Tensile modulus	1146	MPa
Rockwell hardness	80	Hr
Melting temperature (Tm)	185	C^o
Glass transition temperature	62	C^o

The variable parameters set for the 3D printing process through FlashPrint software in the case of PLA are noted in Table 2 that are infill density (A), printing speed (B), layer thickness (C) and infill pattern (D), respectively.

Table 2. Variable parameters used in Flashprint software.

No	Process parameters	Levels			Units
		1	2	3	
1	Infill Density (A)	10	30	50	%
2	Printing Speed (B)	100	200	300	mm / s
3	Layer Thickness (C)	0.11	0.2	0.3	mm
4	Infill Pattern (D)	Honeycomb	Zigzag	Grid	-

The following Taguchi L9 orthogonal array (Table 2) was used for the design of the experiment, showing various combinations of the four process parameters: infill density, printing speed, layer thickness and infill pattern. This will systematically allow the study of multiple factors affecting the comprehensive strength of 3D-printed PLA.

Results and Discussion

Optimization of Process Parameters

The term noise factor actually designates a controllable variable analogous to levels of temperature and humidity in ambient air. The results of the compressive strength testing in Table 3 showed that process parameters such as printing speed and layer thickness had a significant impact on the mechanical properties of 3D-printed PLA. The printing speed was the single most influential factor that accounted for a 35.79% variation in compressive strength that improved internal bonding and structural integrity as its speed increased. Further improvement of compressive properties is attained through the establishment of the layer thickness at about 27.61%. The infill density and pattern type had less effective but still important roles in optimizing process and minimizing thermal degradation. These results are also given that the optimized parameter achieved a maximum compressive strength of 42.45 MPa, well above the normal tensile strength of standard PLA, which ranges from 30 to 35 MPa. This indicates the effectiveness of parameter optimization in improving the mechanical performance of 3D printing fabricated PLA products.

Table 3. Results of compressive strength testing and signal-to-noise (S/N) ratio analysis for 3D printed PLA specimens

	Basic factors applied in testing the compressive test				Mechanical properties (MPa)	
	Infill Density (%), A	Printing Speed (mm/s),B	Layer Thickness (mm),C	Pattern Type, D	PLA- Force, N	PLA,YS-2%
1	10	100	0.1	Honeycomb	2180.39	16.319
2	10	200	0.2	Zigzag	2951	21.788
3	10	300	0.3	Grid	5412.24	42.4513
4	30	100	0.2	Grid	1933.42	14.671
5	30	200	0.3	Honeycomb	2510.25	25.039
6	30	300	0.1	Zigzag	2735.58	19.38
7	50	100	0.3	Zigzag	2758.34	20.479
8	50	200	0.1	Grid	3046.12	22.995
9	50	300	0.2	Honeycomb	3082.09	23.01

Figure 2 further illustrates the graph of the mean effects plot of compressive test response or performance evaluations of materials in terms of SNR under given processing conditions. Based on the data presented in this figure and table 3, printing speed is the most influential parameter, changed more or less linearly with speed, followed by layer thickness and pattern. Both infill density and pattern firstly decreased up to medium point after that it started to increase linearly again. Further, our experimental results indicated that the optimum testing parameters are provided at the third trial of experiment because of using the A1, B3, C3, D3 level when tested compressive testing. In other words, the optimum condition can be obtained at infill density of 10, printing speed of 300 mm/s, layer thickness of 0.3 mm, and pattern type of grid.

Table 4 exhibites the results of compressive testing Response Table for SNR. It is indicated that factor B is the most significant factor affecting the SNR because it holds the topmost (rank 1), followed by layer thickness (rank 2), infill density (rank 2), infill pattern holds the least effect (rank 4).

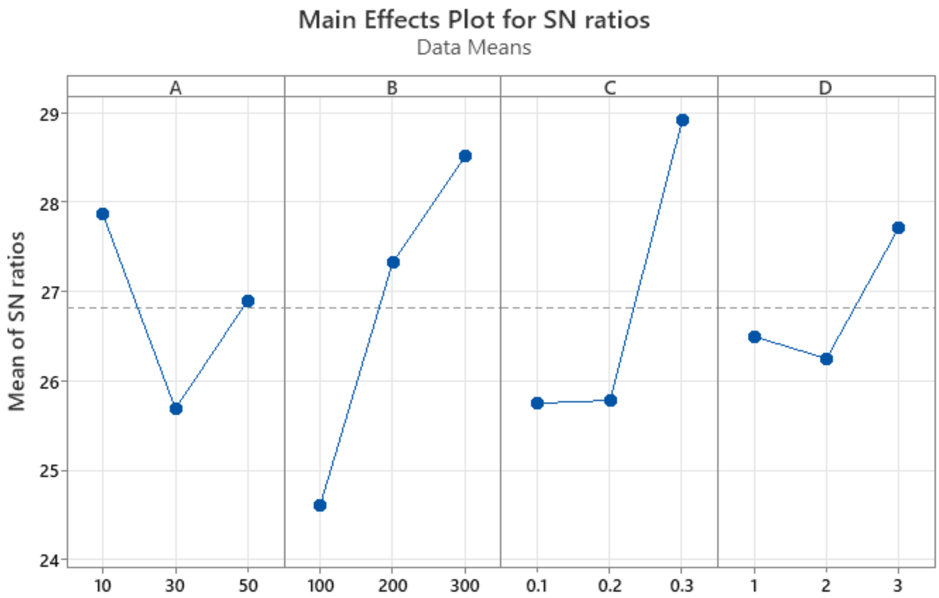

Figure 2. Main effect plot for SN ratio using Minitab software for six parameters.

Table 4. Response table for S/N ratio

Levels	Infill density (A)	Printing Speed (B)	Layer thickness (C)	Infill pattern (D)
1	27 .86	24.60	25.75	26.49
2	25.68	27.32	25.78	26.25
3	26.90	28.51	28.92	27.71
Delta (Δ)	2.18	3.91	3.17	1.46
Ranking	3	1	2	4

Analysis of Variance (ANOVA)

ANOVA is a computational method used to assess error variance and determine effect of process parameters on performance characteristics like compressive strength. Table 5 indicates the ANOVA analysis performed and the results are given here. The Fisher's ratio (F-value) is employed in the ANOVA. The calculated F-test is smaller than the critical F-table at α=0.05, derived from the null hypothesis i.e. $F_{0.05}$,1, 4 = 7.71, there is a no statistically significant relationship between the input factors and outputs. Among the four factors together in the model, infill density, printing speed, layer thickness, and pattern other factors were not found an effective because their p-values are 0.343, 0.064, 0.089, 0.296, respectively, which are higher than 0.05 value. Additionally, the contribution (%) is mostly comes from the factor B (35.79%), followed by factor C (27.61%), factor D (7.97%) and finally factor A (6.39%), respectively, when tested at compressive testing. Again, the layer thickness was the second most influential factor noted, accounting for 27.61% variation in compressive strength measurement. This means that while the choice of layer thickness becomes influenced, it is lesser than that of printing speed; it still remains a considerable force when considering an improvement in the mechanical integrity of printed material. On the other hand, the pattern had a small effect on compressive strength; therefore, pattern changes do not affect the strength properties of the material.

Table 5. Analysis of variance of the compressive strength of PLA

Source	DF	Adj SS	Contribution(%)	Adj MS	F-Value	F-table	P-Value
Regression	4	402.67	77.849	100.67	3.51		0.125
A	1	33.08	6.39	33.08	1.16		0.343
B	1	185.51	35.79	185.51	6.48	7.71	0.064
C	1	142.81	27.61	142.81	4.99		0.089
D	1	41.26	7.97	41.26	1.44		0.296
Error	4	114.57	22.15	28.64			
Total	8	517.24	100				

Figure 3 illustrates a Normal Probability Plot for a dataset for PLA samples. This data does not follow a normal distribution. P-value obtained is 0.019: In statistical analysis, we typically use an alpha level of 0.05. Since 0.019 value is less than 0.05, the hypothesis is rejected that the data is normal. In graph, AD (Anderson-Darling) shows the 0.828. This is a "goodness of fit" test. For a sample size this small (N=9), an AD value this high generally indicates a poor fit for the normal distribution. The single blue point far to the right (at approximately 43) can be outlier. The rest of the data is clustered between 15 and 25. This one "heavy" data point is pulling the mean up and is the primary reason the P-value is so low. If the data were perfectly normal, the blue dots would form a tight, straight line along the center red line. Instead, they follow an "S" shape, which suggests the distribution has skewness or heavy tails. While most points stay within the curved red lines (the 95% Confidence Interval), they are drifting toward the boundaries, particularly at the high end.

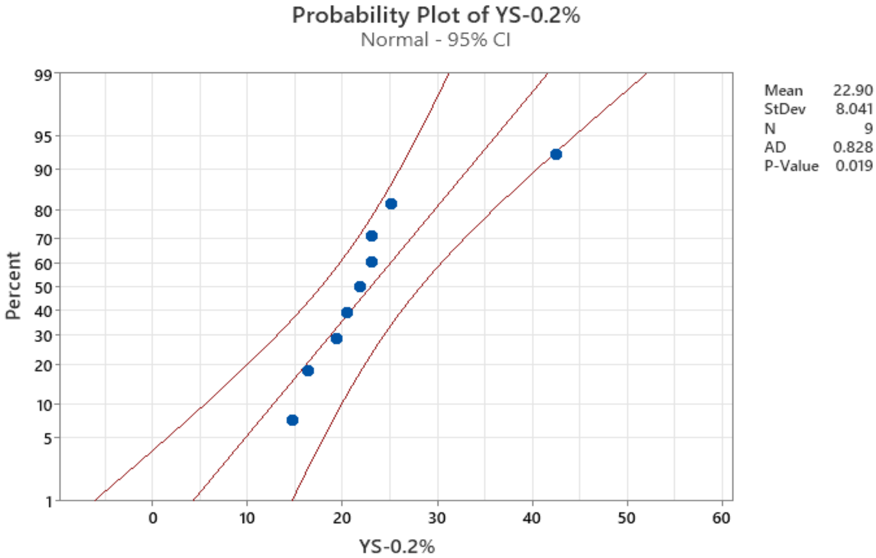

Figure 3. Normal probability plot.

Optimum Cutting Conditions

The optimal testing conditions for improved compressive strength can be obtained from main effects plot for mean data in terms of SNR, as shown in Fig. 2. The optimal values for the parameters were A1=10, B3 = 300 mm/s, D3 = 0.3 mm, and D3 = 3 (grid), as exhibited in the following response, as shown in Table 6.

Table 6. Optimum conditions for CS.

Parameter	Notation	Best level	Value
Infill density	A	1	10
Printing speed	B	3	300
Layer thickness	C	3	0.3
Fill pattern	D	3	3

Estimation of Optimum CS/Confirmation Tests

In the final step, it is necessary to perform a verification experiment in order to validate the precision of the optimization. The experiment was conducted using the optimal levels of the variables that were selected, as presented in Table 7 with two repeated tests. It is determined to be (A1-B3-C3-D3), as can be given in Eq. (3).

$$CS_{opt} = Y_m + (A_1 - Y_m) + (B_3 - Y_m) + (C_3 - Y_m) + (D_3 - Y_m) \quad (3)$$

where the variable Ym represents the mean value of performance attributes for CS, as indicated by all L9 measurements in Table 7. The CS*opt* denotes the anticipated average of the CS when subjected to ideal conditions. Based on the model, the optimal testing performance for CS is obtained at a first level of infill density, 3rd level of printing speed, 3rd level of layer thickness and 3rd level of pattern type as well. The response averages are computed and the resulting values are presented below. The CR values for Ym, A1, B3, C3 and D3 are 26.814

dB, 27.86 dB, 28.51 dB, 28.92 dB and 27.71 dB, respectively, and their corresponding values are 34.96, 10, 300, 0.3 and 3, respectively. Upon incorporation of the aforementioned values into Eq. (2), it is projected that the optimal magnitude of CS will manifest as 30.92 dB. It is reported that statistical analysis can only be deemed reliable if the error values remain below 20%.

Table 7. Confirmation test results.

	Taguchi method based on (Eq. 2)		
Level	Exper.	Predict.	Error (%)
A1B3C3D3 (Optimum)	34.03	32.558	4.44
A3B2C3D2 (Random)	28.5	25.81	10.42

Our results can be compared to more recent research works conducted at the tensile/compressive strengths of PLAs. For example, the research results of Lokesh et al. (2022), who recorded a 30 to 40 MPa confidence interval. Similar results were reported by John et al. (2023), Patel et al. (2023) provided confidence limits of 35 to 45 MPa, related to the effect of production processes on the tensile strength. The higher performance can be attributed to differences in sample preparation and printing techniques, various parameters and equipment. There were no full agreement on mechanical properties of polymeric materials among the previous studies. Some researchers indicated that infill density was the most significant parameter for compressive strength of PLAs (Özmen et al., 2023; Evlen et al., 2019; Abifarin et al., 2022), infill angle (Adanur et al., 2024), layer height (Hema et al., 2022) while others only nozzle temperature and infill density (Khalifah et al., 2025) and nozzle diameter (John et al., 2023) had a significant impact on tensile/compressive property of polymeric samples. Whereas, Singh et al. (2022) revealed that the layer height and infill pattern for PLA surgical equipment. Such variations in experimental study exhibited the need for process optimization with respect to material performance enhancement. It can be suggested that this approach can serve as a benchmark for future studies in this area.

Conclusion

The fused filament fabrication process is adopted to produce PLA materials under different conditions and is optimized through the Taguchi method and Analysis of Variance (ANOVA). Analysis of variance results indicated that printing speed was the first effective parameter, followed by layer thickness in analyzing the compressive strength, but the infill density and infill pattern were not significant. The experimental results revealed that the optimal compressive strength was achieved with a printing speed of 300 mm/s, a layer thickness of 0.3 mm, infill density of 10 and a pattern of grid. Furthermore, trial 3 yielded the largest strength results at approximately 42.45 MPa, which is higher than those reported in prior studies. Future works should be considered in examining additional parametric variations as well as different materials like PETG and ASA, and apply to multi-objective approach to further validate and refine the finding results here.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest.

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