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Optimization of mechanical properties in 3D-printed PLA parts with honeycomb and cubic infill patterns using taguchi method

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Abstract. 3D printing is a revolutionary manufacturing technology that provides previously unheard-of levels of efficiency and design freedom. Fused Deposition Modeling (FDM) is a popular method for creating complicated parts using thermoplastic materials like Polylactic Acid (PLA). Layer height, layup speed, and infill pattern are some of the process variables that have a major impact on the mechanical characteristics of PLA components that are FDM produced. The goal of this study was to maximize the mechanical performance of PLA components made with honeycomb and cubic infill patterns. The best combinations of layer height, layup speed, and infill density were found via Taguchi optimization. The findings showed that in terms of modulus and tensile strength, honeycomb infill designs continuously performed better than cubic patterns. Notably, a 40% infill density with a 0.3 mm layer height and a 60 mm/s layup speed yielded the best mechanical properties for honeycomb-patterned parts. The Taguchi study emphasized how important layer height and infill density are to mechanical performance. These results offer useful recommendations for producers looking to enhance FDM procedures in order to create long-lasting, premium PLA components. Tensile strength and modulus were found to be most significantly impacted by infill density and layer height when the Taguchi method was used to optimize the process parameters.

Introduction

3D printing has completely changed the manufacturing industry by making it possible to create intricate parts with remarkable accuracy and little waste of material [1,2]. Because of its affordability and adaptability, Fused Deposition Modeling (FDM) is one of the most widely used 3D printing technologies [3,4]. Layers of thermoplastic materials are extruded in FDM to create three-dimensional objects. A popular thermoplastic in FDM, polylactic acid (PLA) is perfect for both functional and prototyping applications because of its biodegradability, ease of processing, and reasonably good mechanical qualities [5]. Despite its low melting temperature, moderate mechanical strength, and outstanding printability, PLA products' mechanical performance is extremely susceptible to printing parameters including infill patterns, layer height, and layup speed [6]. For PLA components to have the appropriate mechanical qualities, these parameters must be optimized. The Taguchi approach is among the best ways to optimize industrial processes, including 3D printing. Using orthogonal arrays to systematically examine the effects of several variables with a small number of tests, this reliable statistical method streamlines experimentation [7]. The final mechanical qualities of printed objects are significantly impacted by process variables like as layer height, layup speed, and infill density in the context of FDM.

The qualities of the components and the efficiency of production are greatly influenced by a number of FDM process factors. Important process parameters include things like layer thickness,

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raster angle, build orientation, infill density, printing speed, infill pattern, raster width, etc. [8]. The results show that reducing the layer height enhances inter-layer adhesion, leading to improved mechanical strength. However, higher lay-up speeds may reduce strength by jeopardizing the bonding between layers, as the material lacks adequate time to cool and solidify properly [9]. An important factor in the FDM process is the infill pattern, which gives the 3D print inherent support as it is built layer by layer. The effects of various infill patterns on the mechanical characteristics of 3D-printed objects have been investigated by a number of researchers. In order to evaluate their effects, Aloyaydi et al. [10] and Dezaki et al. [11] looked at patterns like grid, rectilinear, wiggle, and honeycomb. Similarly, Parab and Zaveri [12] examined the impact of infill on the compressive strength of PLA components, while Srinivasan et al. [13] examined the effects of grid, triangle, and cubic patterns on Polyethylene Terephthalate Glycol-modified **[**PETG] parts. Current studies demonstrate how particular patterns can improve mechanical performance, highlighting how crucial pattern selection is to getting the best outcomes. The Taguchi method has proven to be an efficient approach for optimizing these parameters, significantly reducing the number of trials needed while effectively identifying the optimal conditions for achieving maximum mechanical strength [14].

The current research focuses on analyzing the mechanical characteristics such as tensile, compressive, and flexural strength for specific infill patterns like honeycomb and cubic. While both patterns demonstrate unique performance attributes, honeycomb infill excels in stiffness-to-weight efficiency at lower densities, making it suitable for lightweight applications. On the other hand, cubic infill consistently outperforms honeycomb in terms of structural strength, particularly at higher densities, making it ideal for load-bearing applications. Despite the wealth of data on these patterns, strong statistical tools like the Taguchi approach remain underutilized in systematically optimizing the influence of process parameters on these mechanical properties.

Materials & methods

Tensile specimens were printed using PLA material in accordance with Type 1 specifications as per ASTM D638 standards, as shown in Figure 1 [15].The fabrication parameters included three different layer heights 0.15 mm, 0.2 mm, and 0.3 mm with layup speeds of 40 mm/min, 60 mm/min, and 80 mm/min. The infill densities were varied across 20%, 40%, and 60%, with cubic and honeycomb structures used as the infill patterns to evaluate mechanical performance. PLA specimens were created using a low-cost desktop 3D printer using Fused Deposition Modeling (FDM) techniques.

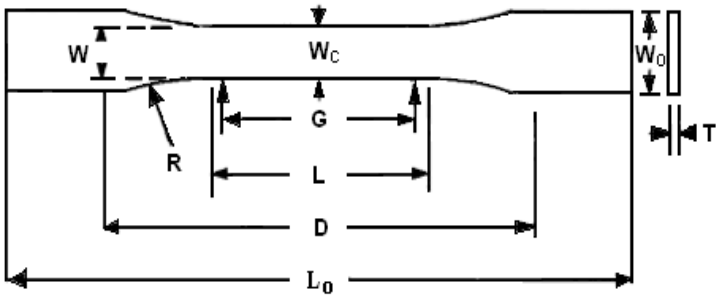


Figure 1 Tensile sample designed in 3D CAD program.

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Table 1 Specimen specifications

Sl. No.	Geometrical parameter	Dimensions(mm)
1	W-width of a narrow section	13
2	L- length of a narrow section	57
3	WO-width overall, minimum	19
4	LO-length overall, minimum	165
5	G-Gauge length	50
6	D-Distance between grips	115
7	R-Radius of fillet	76

On the Kapton Tape construction surface, a total of nine pieces of each honeycomb and cubic PLA are printed. For filament extrusion, the nozzle's temperature is kept at 190^0C, and the printer platform's temperature is kept at 60^0C. Table 2 displays the printing settings, such as layer height and lay-up speed density.

Table 2: Process parameter for 3D printer.

Printing Parameter	Particulars
Layer height (mm)	0.15, 0.2 & 0.3
Lay-up speed (mm/Min)	40, 60 & 80
Infill Density, %	20, 40 & 60
Infill Pattern	Honey comb & Cubic
Nozzle dia (mm)	0.6
PLA density	1.24g/cm3

First, CAD software was used to design the tensile specimens. PrusaSlicer software was then used to slice the 3D model so it could be printed. The file was sliced, then saved in .stl format before being sent to the 3D printer to be manufactured. As shown in Figure 1, the printer was configured to generate PLA specimens with the designated infill patterns cubic and honeycomb. Every pattern was selected in order to investigate its impact on the specimens' mechanical characteristics.

One important technique for characterizing materials is the tensile test, which evaluates a specimen's strength under a uniaxial tensile force and the experimental setup is shown in figure 2. In this investigation, a universal testing machine with a 10 kN load cell was used to evaluate specimens with both honeycomb and cubic infill patterns. A controlled load was applied to each specimen at a crosshead speed of 3 mm per minute while it was positioned between the machine's grips, as shown in Figure 3. Table 2 provides a summary of the tensile strength and elongation findings from these testing.

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Figure 2 Experimental setup for performing tensile test

The three-level control factors selected for the experimental analysis are detailed in Table 3. A Taguchi L9 orthogonal array was utilized to examine the effects of various factors on the mechanical properties of honeycomb and cubic infill patterns. The experimental design, based on Taguchi's method, was developed and analyzed using MINITAB 19. The optimal combination of control factors was determined by converting the experimental results into signal-to-noise (S/N) ratios. The larger is better feature can be used to indicate the S/N ratio for maximal Young's modulus and ultimate tensile strength. The Signal to Noise (S/N) ratio greater is better characteristic equation is displayed beneath Equation 1.

$$\frac{S}{N} = -10Log\left(\frac{\sum {}^{1}\!/_{Y^2}}{n}\right) \qquad Eq.1\ [16]$$

Where *n* is the number of observations and *y* is the observed data

Table 3. Control factors and levels used in the experiment.

Factors	Level 1	Level 2	Level 3
Layer height (mm)	0.15	0.2	0.3
Lay-up speed (mm/min)	40	60	80
Infill density (%)	20	40	60

Result & Discussion

Mechanical Properties

The process variables, such as layer height, layup speed, and infill density, affect the mechanical characteristics of the 3D printed items. The findings in Table 4 make it abundantly evident that 3D items printed at lower speeds and heights and with a higher infill density have better mechanical qualities than those printed at higher speeds and heights.

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Table 4. Representation of Tensile properties and control factors

Sample	Layer height (mm)	Lay-up speed (mm/Min)	Infill Density (%)	Honeycomb		Cubic	
				Young's Modulus (MPA)	Ultimate Tensile strength (MPA)	Young's Modulus (MPA)	Ultimate Tensile strength (MPA)
1	0.15	40	20	878	32.4	974	32.9
2	0.15	60	40	942	33.4	977	37.1
3	0.15	80	60	1176	35.6	1150	42.6
4	0.2	40	20	891	32.8	871	32.6
5	0.2	60	40	947	33.2	924	35.7
6	0.2	80	60	983	35.5	997	34.5
7	0.3	40	20	902	35.4	854	31.6
8	0.3	60	40	998	36.5	912	32.2
9	0.3	80	60	945	34.8	974	33.7

There is a strong correlation between process parameters and mechanical performance, according to the results in Table 4. Different performance trends influenced by layer height, lay-up speed, and infill density are revealed when comparing the Young's modulus of cubic and honeycomb infill patterns. Honeycomb infill has a slightly higher Young's modulus than cubic at lower infill densities (20%), indicating its greater stiffness-to-weight efficiency with less material consumption. Sample 1, for example, displays 878 MPa for honeycomb and 974 MPa for cubic. Nevertheless, cubic infill reaches competitive or superior stiffness when the infill density rises to 40% and 60%. Figure 3 shows a peak Young's modulus of 1150 MPa as opposed to 1176 MPa for honeycomb (Sample 3). These patterns show that cubic infill works better in situations demanding more structural strength at increasing densities, even though honeycomb is initially beneficial for lightweight designs.

Process variables such as layer height and lay-up speed are critical in determining the Young's modulus for both honeycomb and cubic infill patterns. A higher lay-up speed (80 mm/min) and a thinner layer height (0.15 mm) for cubic infill help to improve material consolidation, which raises stiffness. However, honeycomb infill performs quite consistently over a range of parameters, indicating that it is appropriate for applications with varying production conditions. Overall, honeycomb works well in lightweight designs that prioritize stiffness efficiency, whereas cubic infill provides a fair trade-off between strength and stiffness, making it perfect for applications needing both qualities.

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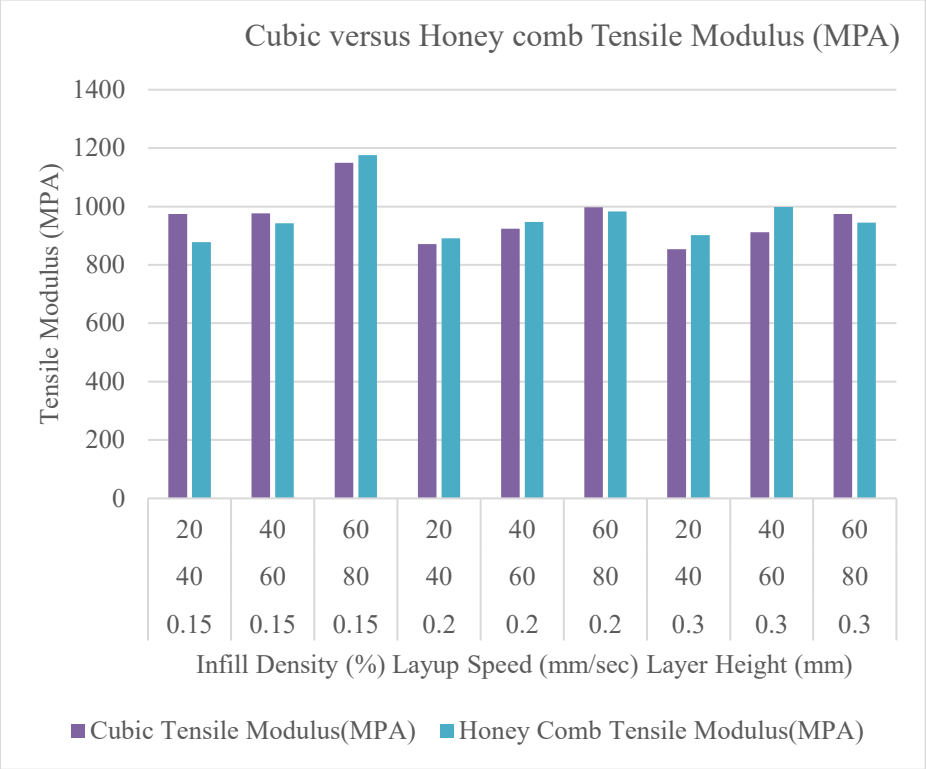


Figure 3 Cubic versus Honey comb Tensile Modulus (MPA)

Cubic infill continuously performs better than honeycomb in terms of ultimate tensile strength at different layer heights, lay-up speeds, and infill densities. With a maximum tensile strength of 42.6 MPa (Sample 3) compared to 36.5 MPa for honeycomb (Sample 8) in Figure 4, the superiority of cubic infill becomes even more noticeable at increasing infill densities. This pattern shows that cubic infill is the best option for load-bearing applications since it can sustain more loads before failing. Cubic infill's slight tensile strength advantage over honeycomb, even at lower densities (20%), emphasizes its structural integrity independent of material utilization.

The robustness of cubic infill is further highlighted by the impact of production factors. By guaranteeing tighter layer adhesion and less void formation, a lower layer height (0.15 mm) and a faster lay-up speed (60–80 mm/min) increase the tensile strength. Conversely, honeycomb infill exhibits modest gains in tensile strength as infill density rises, but it falls short of cubic infill in all circumstances. According to these results, cubic infill is the best alternative for situations where tensile performance is a top priority, while honeycomb is still a good choice for designs that prioritize material economy and moderate strength.

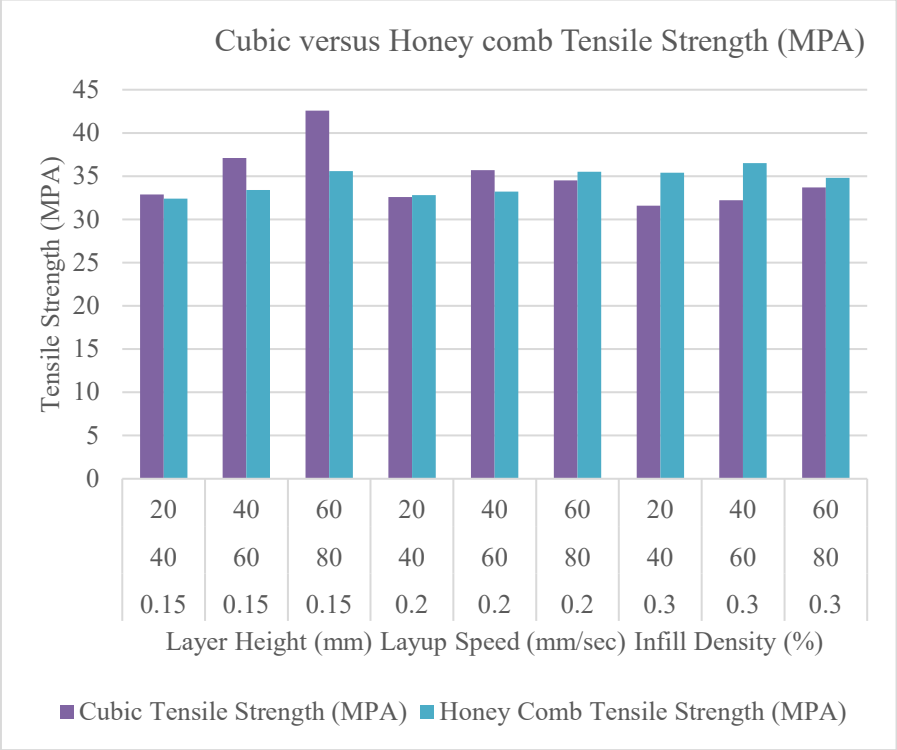


Figure 4 Cubic versus Honey comb Tensile Strength

The data show that PLA parts printed at lower layer heights and slower lay-up speeds consistently displayed superior mechanical properties compared to those printed at higher settings[17]. This improvement can be attributed to increased curing and settling time, which enhances layer bonding and structural integrity.

Analysis of Mechanical properties using Taguchi design of experiments

Tables 5 and 6 show the ultimate tensile strength and Young's modulus for the honeycomb and cubic infill patterns, as well as the related S/N ratios. The S/N ratio graphs for the several control factors influencing the ultimate tensile strength and Young's modulus of the honeycomb and cubic infill patterns are shown in Figures 5 and 6, respectively.

Table 5. Experimental design parameters for Honey Comb

Honeycomb							
Exp. No.	Layer height	Lay-up speed	Infill density	Young's modulus	S/N ratio	Ultimate tensile strength	S/N ratio
1	0.15	40	20	878	58.8699	32.4	30.2109
2	0.15	60	40	942	59.4810	33.4	30.4749
3	0.15	80	60	1176	61.4081	35.6	31.0290
4	0.20	40	40	891	58.9976	32.8	30.3175
5	0.20	60	60	947	59.5270	33.2	30.4228
6	0.20	80	20	983	59.8511	35.5	31.0046
7	0.30	40	60	902	59.1041	35.4	30.9801
8	0.30	60	20	998	59.9826	36.5	31.2459
9	0.30	80	40	945	59.5086	34.8	30.8316

Table 6. Experimental design parameters for Cubic

Cubic							
Exp. No.	Layer height	Lay-up speed	Infill density	Young's modulus	S/N ratio	Ultimate tensile strength	S/N ratio
1	0.15	40	20	974	59.77	32.9	30.34
2	0.15	60	40	977	59.80	37.1	31.39
3	0.15	80	60	1150	61.21	42.6	32.59
4	0.20	40	40	871	58.80	32.6	30.26
5	0.20	60	60	924	59.31	35.7	31.05
6	0.20	80	20	997	59.97	34.5	30.76
7	0.30	40	60	854	58.63	31.6	29.99
8	0.30	60	20	912	59.20	32.2	30.16
9	0.30	80	40	974	59.77	33.7	30.55

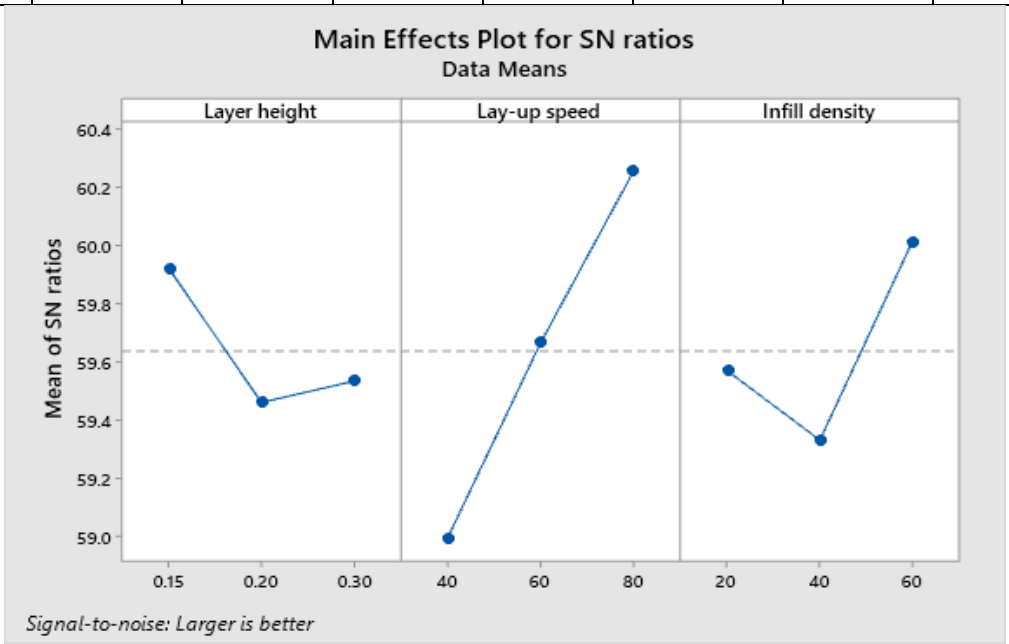


Figure 5. Effect of control factors on Young's modulus of honeycomb infill pattern

By analyzing these factors, one can effectively optimize the control parameters to achieve the maximum Young's modulus and ultimate tensile strength. This optimization is critical for tailoring the mechanical performance of printed components to specific application requirements. From Figure 5, it is evident that the combination of a 1.5 mm layer height, 80 mm/min lay-up speed, and 60% infill density produces the highest Young's modulus. This combination likely ensures optimal bonding between layers and efficient load distribution within the infill structure, enhancing stiffness. Additionally, the higher infill density provides better structural integrity and minimizes internal voids, further contributing to improved mechanical properties. This insight underscores the importance of precise parameter selection in achieving desired outcomes in 3D-printed parts.

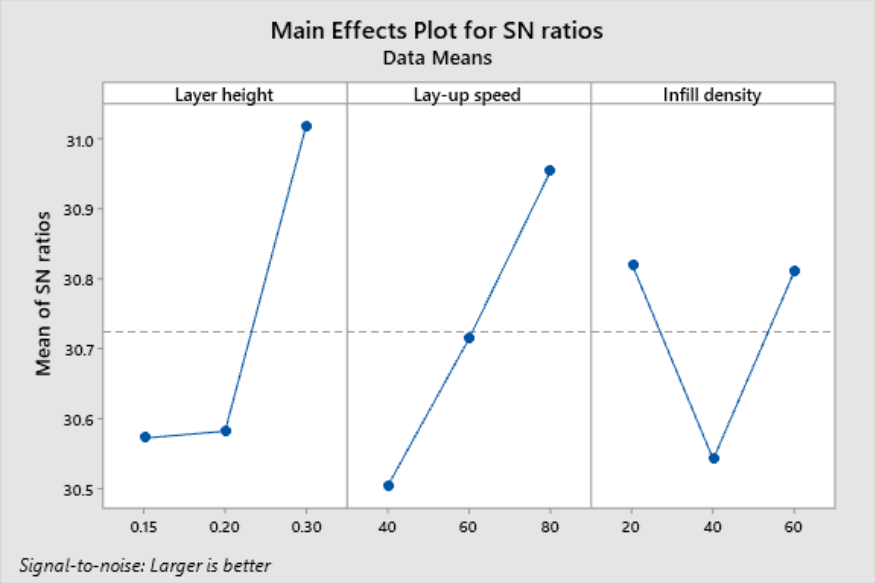


Figure 6. Effect of control factors on Ultimate tensile strength of honeycomb infill pattern

From the figure 6, it is clear that the factor combination of 0.3 mm layer height, lay-up speed of 80 mm/min and 20% of infill density yield maximum Ultimate tensile strength of honeycomb infill pattern.

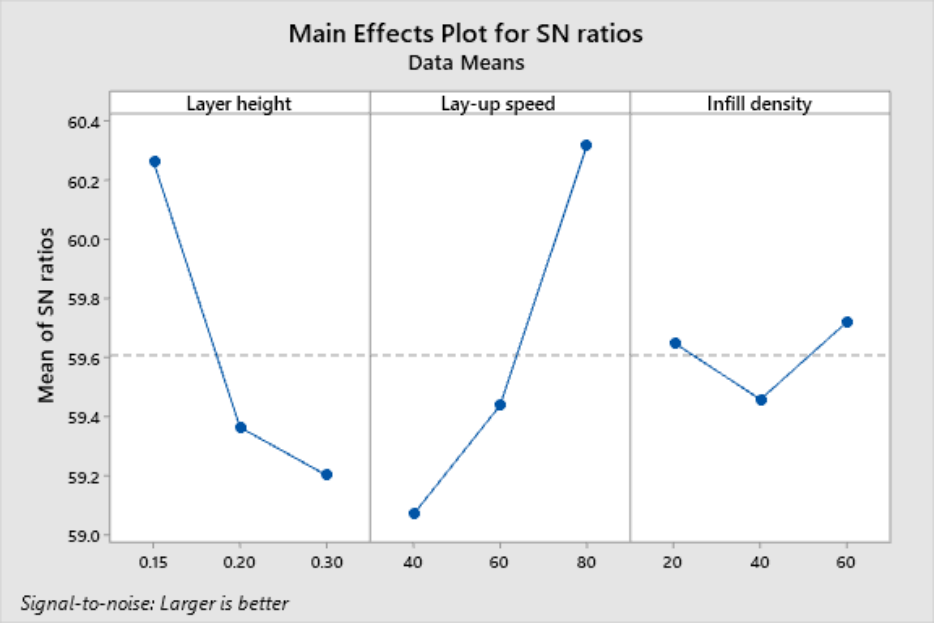


Figure 7. Effect of control factors on Young's modulus of cubic infill pattern

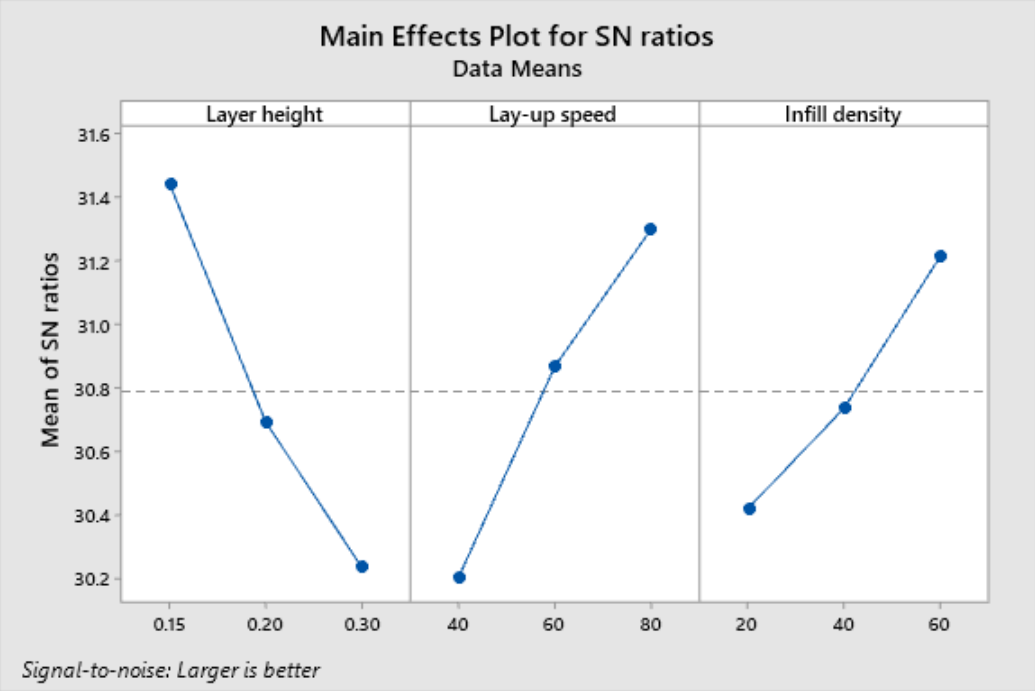


Figure 8. Effect of control factors on Ultimate tensile strength of cubic infill pattern

From Figures 7 and 8, it is evident that the control factor combination of a 0.15 mm layer height, 80 mm/min lay-up speed, and 60% infill density yields the maximum Young's modulus and ultimate tensile strength for the cubic infill pattern. This combination likely provides a fine balance between precision and structural integrity. The smaller layer height ensures better surface finish and stronger interlayer adhesion, which directly enhances tensile properties. The higher lay-up speed optimizes the deposition process, maintaining uniformity without compromising the bonding quality. Additionally, the 60% infill density provides sufficient internal support and minimizes voids, contributing to the superior mechanical performance. This combination highlights the significance of carefully chosen parameters for achieving optimal mechanical properties in cubic infill designs, making it suitable for applications requiring high strength and durability.

Conclusions

The comparison of cubic and honeycomb infill patterns makes it clear how process variables affect mechanical performance in 3D-printed PLA products. With a Young's modulus of 878 MPa as opposed to 974 MPa for cubic at 20% density, honeycomb infill performs exceptionally well in terms of stiffness-to-weight efficiency at lower infill densities. Nevertheless, cubic infill outperforms honeycomb at peak values of 1150 MPa and 1176 MPa, respectively, when infill density rises to 40% and 60%.

In terms of ultimate tensile strength, cubic infill routinely performs better than honeycomb at all density levels. Cubic achieves a tensile strength of 42.6 MPa at maximum infill density (60%), whereas honeycomb achieves 36.5 MPa.

Higher lay-up speeds (80 mm/min) and smaller layer heights (0.15 mm) enhance material consolidation, increasing stiffness and tensile strength. The 0.15 mm layer height, 80 mm/min lay-up speed, and 60% infill density for cubic infill were shown to be the best control factor combinations for optimizing both tensile strength and Young's modulus.

References

[1] A. Y. Alqutaibi, M. A. Alghauli, M. H. A. Aljohani, M. S. Zafar, Advanced additive manufacturing in implant dentistry: 3D printing technologies, printable materials, current applications and future requirements, Bioprint (2024) e00356. https://doi.org/10.1016/j.bprint.2024.e00356

[2] A. Jandyal, I. Chaturvedi, I. Wazir, A. Raina, M. I. U. Haq, 3D printing–A review of processes, materials and applications in industry 4.0, Sust. Oper. Comput. (2022) 33-42. https://doi.org/10.1016/j.susoc.2021.09.004

[3] K. B. Mustapha, K. M. Metwalli, A review of fused deposition modelling for 3D printing of smart polymeric materials and composites, Eur. Polym. J. 156 (2021) 110591. https://doi.org/10.1016/j.eurpolymj.2021.110591

[4] R. H. Risad, M. H. Ahmed, A. Basher, S. Rashid, M.M.A. Shishir, K.R. Hossain, FDM printing process and its Biomedical Application.Chem. Res. Technol. 1.3 (2024) 138-149. https://doi.org/10.22034/chemrestec.2024.467346.1021

[5] E. H. Tümer, H. Y. Erbil, Extrusion-based 3D printing applications of PLA composites: a review, Coatings 11.4 (2021) 390. https://doi.org/10.3390/coatings11040390

[6] V. Cojocaru, D. Frunzaverde, C. O. Miclosina, G. Marginean, The influence of the process parameters on the mechanical properties of PLA specimens produced by fused filament fabrication A review, Polymers 14.5 (2022) 886. https://doi.org/10.3390/polym14050886

[7] H. Radhwan, Z. Shayfull, S. M. Nasir, A.R. Irfan, Optimization parameter effects on the quality surface finish of 3D-printing process using taguchi method, IOP Conf. Ser.: Mater. Sci. Eng. Vol. 864. No. 1. (2020) DOI 10.1088/1757-899X/864/1/012143

[8] M. Q. Tanveer, G. Mishra, S. Mishra, R. Sharma, Effect of infill pattern and infill density on mechanical behaviour of FDM 3D printed Parts-a current review, Mater. Today: Proc. 62 (2022) 100-108. https://doi.org/10.1016/j.matpr.2022.02.310

[9] K. P. Aveen, F. Vishwanath Bhajathari, C. J. Sudhakar, 3D Printing & Mechanical Characteristion of polylactic acid and bronze filled polylactic acid components, IOP Conf. Ser. Mater. Sci. Eng. Vol. 376. No. 1. IOP Publishing (2018) DOI 10.1088/1757-899X/376/1/012042

[10] B. Aloyaydi, S. Sivasankaran, A. Mustafa, Investigation of infill-patterns on mechanical response of 3D printed poly-lactic-acid. Polym. Test. 87 (2020) 106557. https://doi.org/10.1016/j.polymertesting.2020.106557

[11] L. Dezaki, Mohammadreza, Mohd Khairol Anuar Mohd Ariffin. The effects of combined infill patterns on mechanical properties in fdm process, Polymers 12.12 (2020) 2792. https://doi.org/10.1016/j.matpr.2022.09.227

[12] P. Sanket, N. Zaveri, Investigating the influence of infill pattern on the compressive strength of fused deposition modelled PLA parts, Proceedings of: ICIMA 2020. Springer Singapore, (2020) https://link.springer.com/chapter/10.1007/978-981-15-4485-9_25

[13] R. Srinivasan, W. Ruban, A. Deepanraj, R. Bhuvanesh, T. Bhuvanesh, Effect on infill density on mechanical properties of PETG part fabricated by fused deposition modelling, Mater. Today: Proc.27 (2020) 1838-1842. https://doi.org/10.1016/j.matpr.2020.03.797

[14] K. Sharma, K. Kumar, K. R. Singh, M. S. Rawat, Optimization of FDM 3D printing process parameters using Taguchi technique, IOP Conf. Ser.: Mater. Sci. Eng. Vol. 1168. No. 1. IOP Publishing, 2021. DOI 10.1088/1757-899X/1168/1/012022

[15] K. P. Aveen, V. Bhajantri, R. D'Souza, N. V. Londe, S. Jambagi, Experimental analysis on effect of various fillers on mechanical properties of glass fiber reinforced polymer composites, AIP Conf. Proc. Vol. 2057. No. 1. (2019). https://doi.org/10.1063/1.5085615

[16] Tseng, Wan-Tsun, Chen-Nan Kuo, Li-Iau Su, Optimizing design parameters of a novel PM transverse flux linear motor, Trans. Can. Soc. Mech. Eng. 39.3 (2015) 443-454. https://doi.org/10.1139/tcsme-2015-0033

[17] U. V. Akhil, N. Radhika, B. Saleh, S. Aravind Krishna, N. Noble, L. Rajeshkumar, A comprehensive review on plant-based natural fiber reinforced polymer composites: fabrication, properties, and applications, Polym. Compos. 44.5 (2023) 2598-2633. https://doi/abs/10.1139/tcsme-2015-0033