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Research Article

Hybrid Layer Thickness Configurations for Enhanced Mechanical Performance and Energy Efficiency FDM-Printed PLA

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ABSTRACT

This study examines the impact of hybrid layer thickness configurations on the mechanical properties and energy consumption of 3D-printed polylactic acid (PLA) parts produced via Fused Deposition Modeling (FDM). PLA specimens with various combinations of outer and core layer thicknesses (0.08 mm, 0.16 mm, and 0.28 mm) were fabricated and tested for tensile strength, flexural strength, and flexural modulus, alongside measurements of energy consumption. The results revealed that hybrid structures incorporating 0.16 mm face layers and 0.08 mm core layers exhibited superior mechanical performance. In contrast, thicker core layers (0.28 mm) significantly reduced printing time and energy use. The highest tensile strength (53.57 MPa), flexural strength (90.68 MPa), and flexural modulus (2898.4 MPa) were obtained in the sample group of 0.16_0.08_0.16 mm layer thickness. Scanning Electron Microscopy (SEM) provided microstructural insights supporting these findings. The porosity and higher nozzle temperature may influence the material strength for thicker and thinner layer thicknesses, respectively. The sample group with the least energy consumption was 0.28 mm, followed by the sample group with the same layer thickness in both the face and core layers. The study highlights the potential of hybrid layering strategies to optimize performance-energy trade-offs in FDM printing, offering valuable guidance for material-efficient and functionally robust additive manufacturing.

1. Introduction

The optimization of 3D printing parameters is crucial to achieve high-quality printing in various applications. In recent advancements in 3D printing, especially Fused Deposition Modelling (FDM), comprehending and fine-tuning parameters such as layer thickness, nozzle temperature, printing speed, and infill density, raster orientation, building orientation, and infill pattern come into prominence to enhance the mechanical properties, printing efficiency, and surface quality of the printed component.

Layer thickness is one of the most crucial parameters because it directly affects mechanical properties, surface finish resolution, and printing time of the final products. [1] stated that optimizing layer thickness allows for better material performance in printing structures, especially when employed in biodegradable materials such as polylactic acid (PLA). A thinner layer provides better interlayer adhesion, which is essential for material strength for printed objects, but it increases printing time. On the contrary, printing time can be reduced with thicker layers; however, its mechanical properties may decrease owing to poor bonding quality between layers. Here, there is no restriction on parameter selection to increase the quality of printing. Figure 1 illustrates various layer thicknesses.

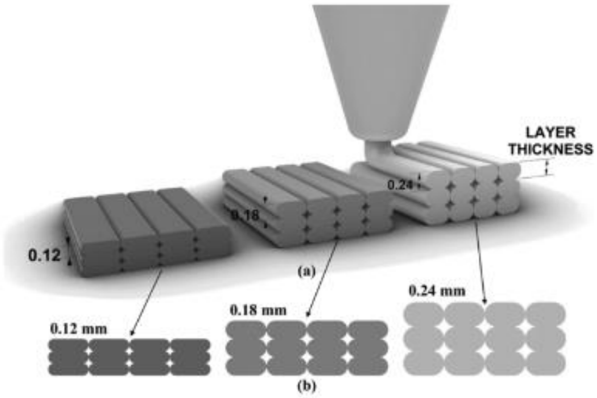

Figure 1: Layer thickness illustration in FDM [2].

Recent studies have been conducted to provide better solutions to inadequate interfacial adhesion by combining printing parameters, particularly the overlapping ratio. [3] found that increasing the overlap ratio provides higher interlayer adhesion, correspondingly, necking (Figure 2). Conversely, one of the primary issues associated with a higher overlapping ratio is the formation of air voids between layers; namely, voids could emerge owing to inadequate filling gaps, which can result from excessive material overlap during the extrusion process [4]. Therefore, each adjustment for printing parameters could be urged to combine parameters to influence printing performance negatively.

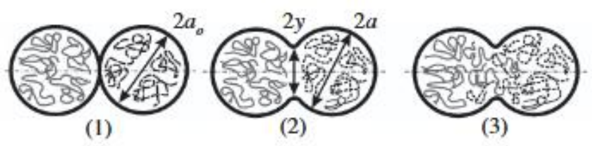

Figure 2: Bonding formation process between adjacent strands: (1) surface contacting, (2) neck growth, and (3) diffusion at the interface [5]

Based on the understanding of uniform layer thicknesses, the mechanical properties have been studied so far [6-7], but there is a notable gap related to hybrid layer thickness configuration in FDM 3D printing. The incomprehensibility associated with changing layer thickness during 3D printing of a single part has not been adequately examined. The intermediate 3D printing process can be achieved through a hybrid thickness layer in a single print, leveraging the advantages of both thinner and thicker layers to achieve the desired mechanical properties, surface quality, and printing time efficiency.

Hybrid layer thickness provides targeted optimization for overall performance, with an increase in mechanical properties, higher surface quality, and lower energy consumption, among other benefits. [8] stated that variations in layer thickness can significantly influence shear strength between strands. Besides, this variation can enhance the tribological performance of layers by impacting wear rates and friction in 3D printing parts [9]. Since the thicker and thinner layer thicknesses are combined in a single print, the interfacial adhesion ratio could be increased, thereby improving material strength by modifying layer thickness [10-11]. In doing so, facilitating robust structures could be printed under varying operational conditions to optimize material strength. A product can be obtained with superior results tailored to the required function in the application by strategically implementing various layer thicknesses in a single print.

In the realm of FDM 3D printing, layer thickness significantly influences both energy consumption and the efficiency of the printing process. The interplay between these factors is critical for optimizing 3D printing practices, particularly for sustainable production and mechanical quality. When considering layer thickness, thicker layers typically lead to reduced printing times as fewer layers are required to complete a part. However, this advantage comes with increased power requirements for the process, especially when managing the thermal dynamics of the printing material. For instance, energy consumption is markedly affected by layer thickness, with thicker layers generally requiring more energy for heating and extrusion due to their larger surface area exposed to the heating elements during printing [12]. In addition, increased layer height can exacerbate thermal gradients, impacting material bonding and mechanical properties, which may necessitate careful calibration to maintain material strength while optimizing energy usage. Conversely, thinner layers often result in lower energy consumption during individual prints, as they allow for finer resolution and potentially better inter-layer adhesion, which can contribute to reduced defects and voids in the produced parts. However, this advantage may be offset by the longer overall print time and increased complexity in the print path. Thinner layers can create intricate internal structures, causing higher energy demands to achieve uniform material deposition throughout the printing process [13].

This study aims to systematically investigate the influence of hybrid layer thickness configurations—where the outer and core layer thickness differs on the mechanical properties and energy consumption of PLA parts fabricated via FDM. The ultimate goal is to identify optimal hybrid layer strategies that balance mechanical performance and energy efficiency in additive manufacturing. To do this, the research objectives are to (i) fabricate PLA test specimens using FDM with uniform and hybrid layer thickness configurations comprising 0.08 mm, 0.16 mm, and 0.28 mm for face and core layers, respectively, (ii) measure and compare the tensile strength, flexural strength, and flexural modulus of the printed specimens in order to evaluate the mechanical performance of each layer configuration, (iii) quantify the energy consumption, printing time, and material usage for each specimen group by integrating slicing software outputs and energy consumption data of the 3D printer under controlled conditions, (iv) examine fracture surfaces using SEM to identify microstructural factors such as porosity and interlayer bonding that may influence mechanical properties, and (v) determine the coefficient of energy consumption per unit strength (MPa) for tensile, flexural strength, and flexural modulus, and (vi) to evaluate the trade-offs between mechanical performance and energy efficiency among different hybrid configurations.

2. Material and Methods

2.1. Material and Printing Parameters

In this study, an Esun PLA+ filament was used with a diameter of 1,75 mm. Polylactic acid (PLA) is the most widely utilized filament material in the Fused Deposition Modeling (FDM) production technique. As a biodegradable biopolymer derived from renewable resources such as corn starch and sugarcane, PLA is recognized for its environmentally friendly and user-safe characteristics. In addition to its sustainable origin, PLA exhibits favorable mechanical properties, including adequate stiffness and dimensional stability, which contribute to its widespread application in FDM-based additive manufacturing systems.

In the 3D printing, specimens for tensile and flexural properties were printed in the Bambu Lab P1S 3D printer. Specimen dimensions were used in ASTM D 638 [14] (Type IV) for tensile test specimens, and ASTM D 790 [15] was used for flexural test specimens. Three layer thicknesses were selected: 0.08 mm (extra fine), 0.16 mm (medium), and 0.28 mm (draft), as suggested in Bambu Studio Slicer. Under the purpose of the hybrid layer thickness, these layer thicknesses were rearranged in the slicer as 0.08-0.16-0.08 mm, 0.08-0.28-0.08 mm, 0.16-0.08-0.16 mm, 0.16-0.28-0.16 mm, 0.28-0.08-0.28 mm, and 0.28-0.16-0.28 mm (Figure 3). The printing parameters were given in Table 1.

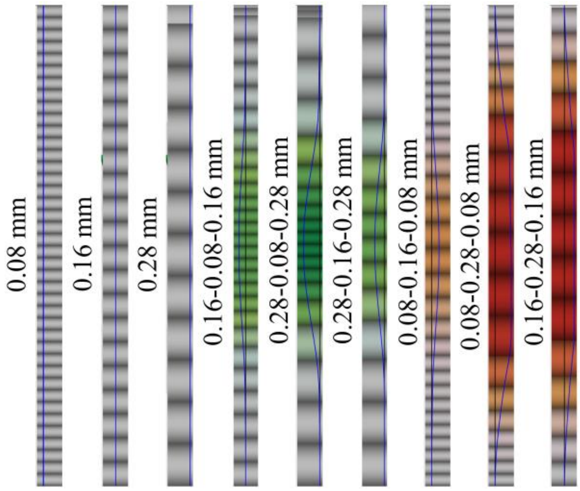

Figure 3: Layer thicknesses.

Table 1: Printing parameters.

Parameters	Values
Nozzle diameter	0.4 mm
Print speed	50 mm/s
Nozzle temperature	220 °C
Bed temperature	60 °C
Built orientation	Flatwise
Raster orientation	0°/0°
Infill pattern	Aligned rectilinear
Infill ratio	100%

Nine different sample groups were observed with three replications (27 specimens) for each tensile and flexural test specimen (Figure 4).

Figure 4: 3D printed test specimens.

2.2. Weight, Printing Time, and Energy Consumption of the Specimens

In this study, all specimens were weighed using a precision scale with a resolution of 0.0001 g. The printing time of each sample group was taken from the Bambu Studio Slicing software. The energy consumption of the Bambu Lab P1S 3D printers is 0.0238-0.031 kWh in 968 sec., while printing PLA. The average energy consumption was used (0.0274 kWh).

2.3. Tensile Strength and Flexural Properties

All specimens were tested using a SHIMADZU AG-IC universal test machine. Specimens were exposed to a static load applied parallel to the axis at a rate of 5 mm/min according to ASTM D 638 for the tensile test of the samples. The loading continued until the fracture load was reached on the specimens. In the *flexural strength test*, the specimens were subjected to a static vertical load at a rate of 5.2 mm/min according to ASTM D 790. After the loading reached the ultimate load on the specimens, the test continued until the load decreased to 80% of this ultimate value. In all tests, load-deformation curves were obtained. Tensile strength (σ_T), flexural strength (σ_F), and flexural modulus (E) were calculated according to equations 1, 2, and 3, respectively.

$$\sigma_T = \frac{F_{T,ult}}{w \times t} \quad (1)$$

$$\sigma_F = \frac{3 \times F_{F,ult} \times l}{2 \times w \times t^2} \quad (2)$$

$$E = \frac{\Delta F \times l^3}{4 \times \Delta d \times w \times t^3} \quad (3)$$

where, $F_{T,ult}$ is the ultimate load in tensile strength test (N), w is the width of the specimen (mm), t is the thickness of the specimen (mm), $F_{F,ult}$ is the ultimate load in flexural strength test, l is the span (mm), ΔF is the difference two load levels retrieved from the linear region of the load-deformation curve (N), and Δd is the difference of deformations at these load levels.

2.4. Fracture Surfaces Using SEM

Fracture surfaces will be examined using SEM. The Carl Zeiss/Gemini 300 device was used for this experiment. A thermal electron source was employed, and an acceleration voltage of 3.0 kV was preferred [16]. Before analysis, samples taken from the fracture surfaces of tensile specimens were coated with a platinum and gold mixture in the Leica/ACE600 device.

2.5. Statistical Analysis

Data were analyzed for statistical significance using one-way analysis of variance (ANOVA) and Tukey pairwise comparison in SPSS.

3. Results and Discussion

Results for weight, printing time, and energy consumption of the specimen are displayed in Table 2. According to the results, increasing layer thickness results in a lower specimen weight due to higher porosity between layers, as well as shorter printing time and reduced energy consumption in the 3D printing process. In the hybrid layered specimens, the same phenomenon was observed: a combination of thinner face layers and thicker core layers reduced them, or vice versa. For example, in the sample group of 0.08 mm tensile strength tests, they decreased by 23.95% and 51.52% when using 0.16 mm and 0.28 mm core layers, respectively. In the case of the 0.28 mm tensile strength test, these ratios increased by 26.66% and 62.01% with 0.16 mm and 0.08 mm core layers, respectively.

There is no linear relationship between increasing layer thickness and specimen weights in both tests. The layer thickness of 0.16 mm was more effective in increasing weight. Besides, in *tensile test specimens*, the specimen weight was 0.08 mm higher than that of the face layer thickness, which was statistically different from the others. This phenomenon is evident in flexural test specimens measuring 0.08 mm, but the weight of the sample group with dimensions of 0.08 and 0.08_0.16_0.08 mm did not show statistically significant differences. Table 2 demonstrates whether the sample groups were statistically different from each other or not. According to ANOVA results, layer thicknesses were statistically significant (Table 3)

.

Table 2: Printing processing values and weight of 3D-printed specimens.

Layer Thickness ($x10^{-2}$ mm)	Specimen Weight (g)		Printing Time (s)		Energy Consumption ($x10^{-3}$ kWh)	
	Tensile	Flexural	Tensile	Flexural	Tensile	Flexural
8	5.52 (0.71%) [d, e]	5.99 (0.42%) [c]	2789	2980	78.94	84.35
16	5.64 (0.31%) [g]	6.01 (0.27%) [c]	1490	1557	42.18	44.07
28	5.45 (0.83%) [c, d]	5.77 (0.11%) [b]	874	917	24.74	25.96
8_16_8	5.39 (0.36%) [c]	5.97 (0.20%) [c]	2121	2320	60.04	65.67
8_28_8	5.19 (0.19%) [a]	5.63 (0.22%) [a]	1352	1431	38.27	40.51
16_8_16	5.55 (0.28%) [e, f]	6.17 (0.13%) [e]	1931	2096	54.66	59.33
16_28_16	5.29 (0.29%) [b]	5.76 (0.36%) [b]	1050	1095	29.72	30.99
28_8_28	5.62 (0.59%) [f, g]	6.06 (0.20%) [d]	1416	1448	40.08	40.99
28_16_28	5.84 (0.45%) [h]	6.24 (0.15%) [f]	1107	1320	31.33	37.36

**Values in parentheses are the coefficient of variation. ** Same letters were not statistically different from each other according to Tukey analysis in each test (α = 0.05).*

The typical load–deformation curves for the tensile and flexural tests are presented in Figures 5 and 6, respectively. According to the curves, the highest average failure load in the tensile strength test was achieved by the sample group with a 0.28_0.16_0.28 mm layer thickness, reaching 1069.79 N with a standard deviation of 51.70 N. This was closely followed by the 0.28_0.08_0.28 mm group with 1065.26 N, the 0.16_0.08_0.16 mm group with 1049.58 N, and the uniform 0.16 mm group with 1046.51 N. The lowest tensile failure load was observed in the 0.08_0.28_0.08 mm group, which averaged 850.99 N and exhibited a standard deviation of 105.94 N.

In the flexural strength tests, the 0.28_0.16_0.28 mm configuration again yielded the highest average failure load at 155.85 N, accompanied by a low standard deviation of 1.24 N. Other high-performing groups included 0.16_0.08_0.16 mm with 152.95 N, 0.08_0.16_0.08 mm with 151.32 N, the uniform 0.08 mm group with 148.57 N, and the uniform 0.16 mm group with 147.05 N. The lowest flexural load was recorded in the uniform 0.28 mm group at 133.98 N.

Overall, the 0.28_0.16_0.28 mm configuration consistently demonstrated superior failure loads in both tensile and flexural tests. Additionally, specimens incorporating a 0.16 mm thickness—whether applied uniformly or as outer layers—tended to exhibit higher load-bearing capacity compared to other configurations.

Table 3: ANOVA results for the weight of specimens.

Source	Tests	Sum of Squares	df	Mean Square	F-value	p-value
Between Groups	Weight in tensile	0.934	8	0.117	157.703	≤ 0.001
	Weight in flexural	0.960	8	0.120	556.325	≤ 0.001

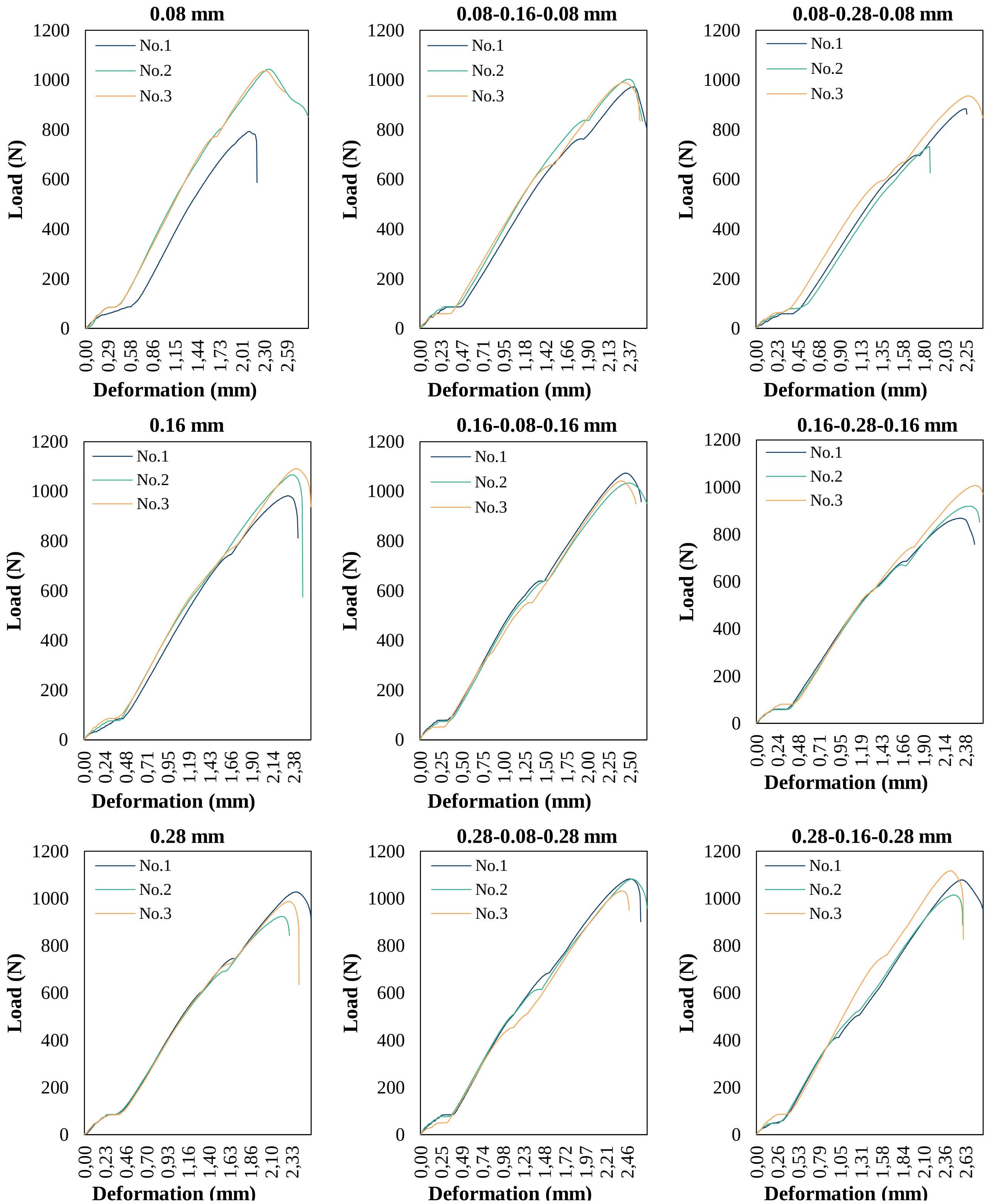

Figure 5: Load-deformation curves in tensile strength tests.

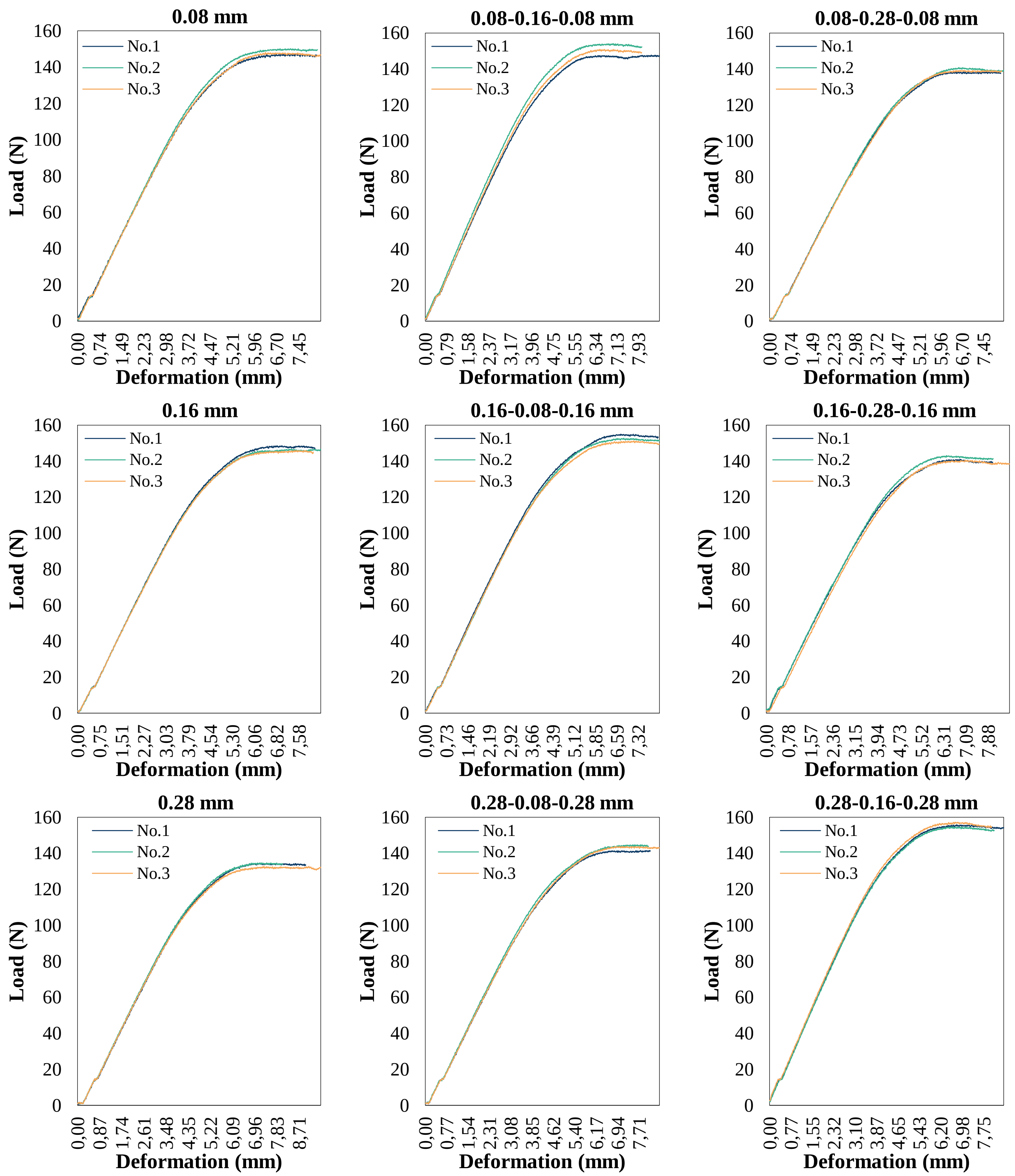

Figure 6: Load-deformation curves in tests for flexural properties.

The results for tensile strength, flexural strength, and flexural modulus are given in Figure 7. According to the results, the specimens printed with a 0.16 mm layer thickness exhibited superior mechanical performance, achieving a tensile strength of 52.49 MPa, a flexural strength of 90.16 MPa, and a flexural modulus of 2896.6 MPa—values notably higher than those obtained from specimens with 0.08 mm or 0.28 mm layer thicknesses. A thicker layer generally leads to a rougher surface, which affects the adhesion performance of the adhesive used between 3D-printed components, potentially promoting interfacial mechanical interlocking and enhancing shear strength [17]. However, the material strength of the sample group with a layer thickness of 0.08 mm is lower than those of 0.16 mm. While thinner layers, such as those at the 0.08 mm mark, promote finer detail and potentially better surface finishes, they can suffer from weaker interlayer adhesion due to rapid cooling, preventing optimal bonding between adjacent layers. The loss in strength when printing with smaller layer thicknesses is often due to weak interlayer bond strength and distortion caused by high temperature gradients during the printing process [18]. Employing thicker layers in FDM processes enhances tensile strength due to the increased diffusion of material between layers as they are deposited at higher temperatures. This facilitates stronger bonding, leading to greater tensile strength [19].

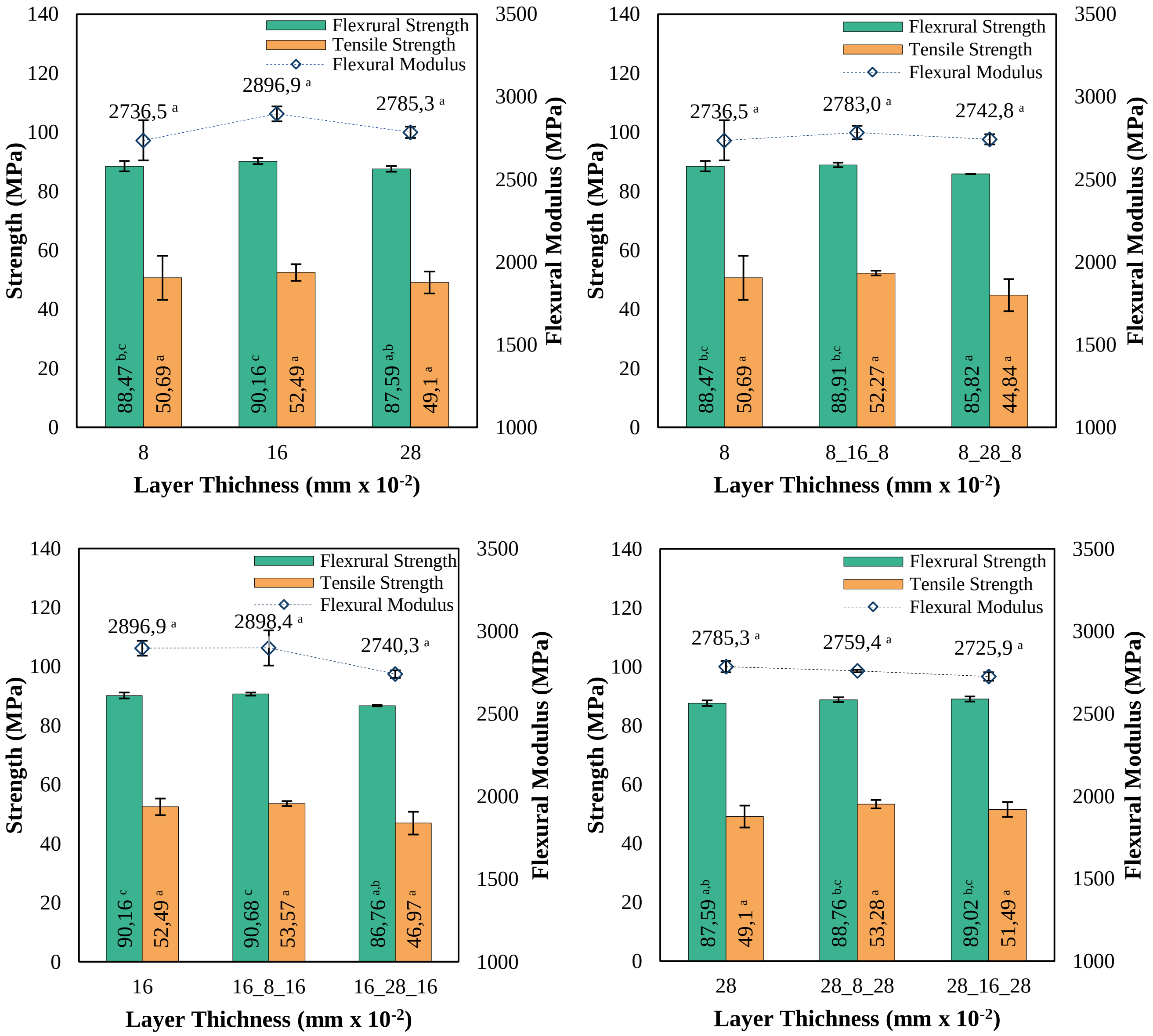

Figure 7: Flexural strength, tensile strength and flexural modulus of 3D-printed specimens (Same letters were not statistically different from each other according to Tukey analysis in each test ($\alpha = 0.05$).)

Additionally, the thermal energy provided to the thicker layers enables more effective melting and integration of the filament, resulting in improved mechanical properties. In the printing process, a nozzle temperature of 220 °C was used; namely, this temperature is the highest recommended temperature to print PLA+. Therefore, some distortion may occur during the printing of a sample group with a 0.08 mm layer thickness at such a high temperature.

In *hybrid layer thicknesses for 0.08 mm*, in the case of core layers increased to 0.16 mm, tensile strength, flexural strength, and flexural modulus enhanced to 52.27 MPa (3.1% improvement), 88.91 MPa (0.5% improvement), and 2783 MPa (1.7 % improvement), respectively. On the other hand, when the core layer thickness increased to 0.28 mm, the tensile and flexural strengths reduced by 11.5% and 3%, respectively, but the flexural modulus increased by 0.2%. In the case of *0.16 mm layer thicknesses*, mechanical properties slightly increased, and the specimens with a 0.16_0.08_0.16 mm hybrid layer configuration yielded the highest mechanical properties in the study, with a tensile strength of 53.57 MPa, a flexural strength of 90.68 MPa, and a flexural modulus of 2898.4 MPa. However, in the case of core layer thickness increased to 0.28 mm, those suddenly decreased by 10.5%, 3.8%, and 5.4%, respectively. In the case of *0.28 mm layer thicknesses*, tensile and flexural strength increased to 53.28 MPa and 88.76 MPa, but flexural modulus decreased to 2759.4 MPa while printing core layers with a thickness of 0.08 mm. Furthermore, in the case of core layers of 0.16 mm, flexural strength was enhanced to 89.02 MPa, but tensile strength and flexural modulus were reduced to 51.49 MPa and 2725.9 MPa, respectively. Here, 0.16 mm-layer thickness played a key role in material strength, regardless of whether it is in all cross-sections, core, or face layers.

Table 4: ANOVA results for the mechanical properties of 3D-printed specimens.

Source	Tests	Sum of Squares	df	Mean Square	F-value	p-value
Between Groups	Tensile strength	215.185	8	26.898	1.835	0.136
	Flexural strength	57.201	8	7.150	9.065	≤ 0.001

Figure 7 and Table 4 give the Tukey mean comparison and the ANOVA results, respectively. In tensile strength and flexural modulus, average values were not significantly different from each other. According to the ANOVA results, layer thickness did not have a significant effect on tensile strength, but they had a significant effect on flexural modulus and flexural properties. Besides, flexural strength with a layer thickness of 0.16 mm was significantly different from those of 0.28 mm. There is no statistical difference between the sample groups of 0.08 mm, 0.16 mm, and 0.28 mm separately. In *hybrid layer thickness*, the flexural strength of the sample groups with a layer thickness of 0.08 mm was statistically different from those of 0.08_0.16_0.08 mm. Still, there is no significant difference with those of 0.08_0.28_0.08. In the case of 0.16 mm, its flexural strength was not statistically different from those of 0.16_0.08_0.16 mm, but there is a significant difference with those of 0.16_0.28_0.16 mm. Furthermore, while core layer thickness decreased from 0.28 to 0.16 or 0.08 mm, the average flexural strength of the 3D-printed specimens was not statistically different from each other.

Figure 8 shows SEM images of specimens in tensile tests. In each image, the layer thickness distribution through cross-sections can be seen clearly. In specimens of 0.08 mm, layers cannot be seen on cross-section due to the fact that there were no breaks on the specimens at the end of the tests. Throughout the cross-sections, layer deposition varies for the hybrid layered sample groups. Porosity also decreased with layer thickness of 0.08 and 0.16 mm.

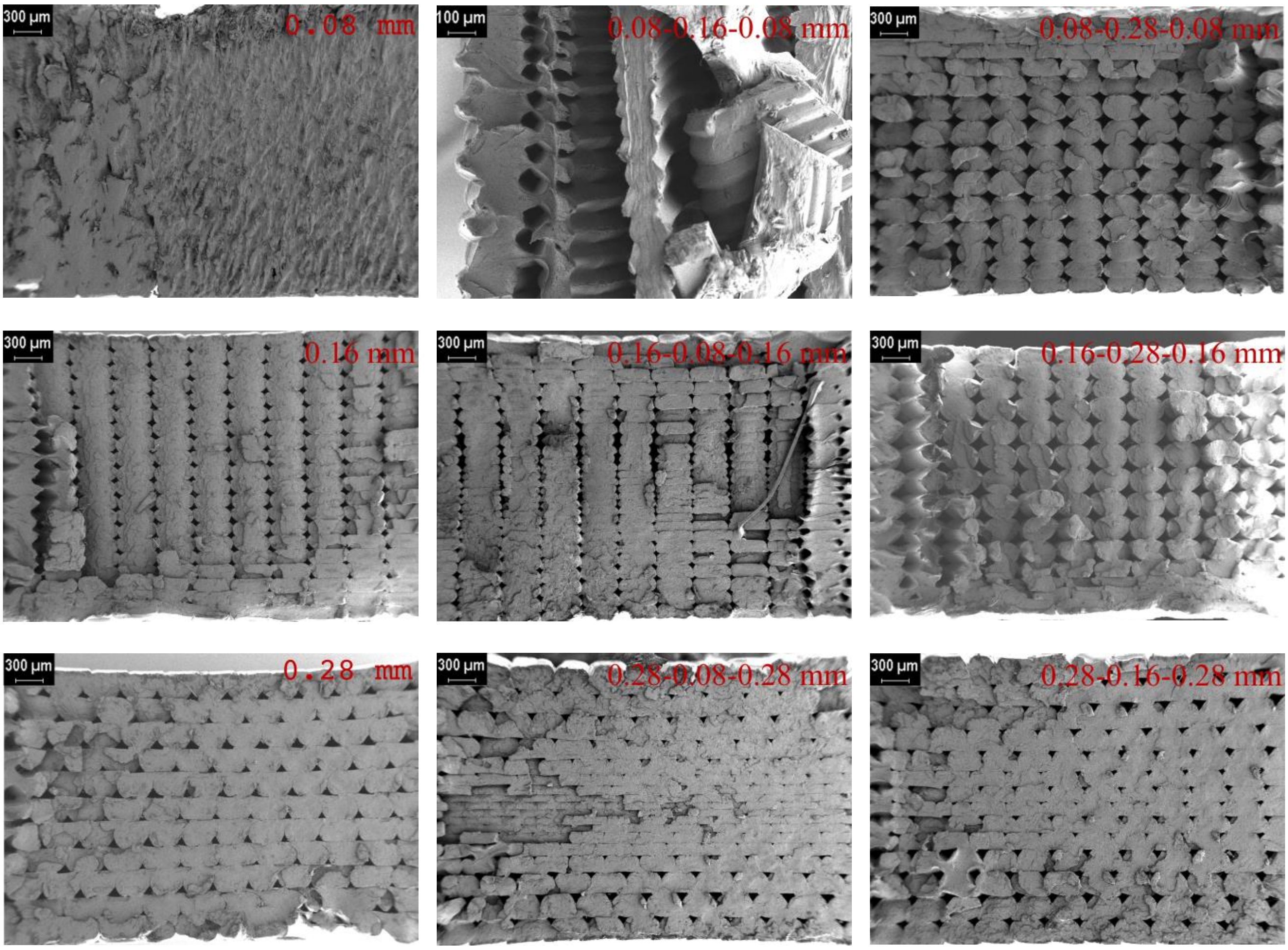

Figure 8: SEM images of fractured surfaces for tensile test specimens.

In Figure 9, layer thicknesses, layer width, height, and width of the deposition paths, and height of the neck between strands are shown. All SEM images showed that the proposed layer thicknesses were successfully deposited. In a higher layer thickness, porosity increased. High levels of porosity typically lead to a decrease in mechanical strength due to the presence of voids within the material structure. Variations in porosity directly corresponded to changes in tensile strength, with increased porosity resulting in lower tensile values [20]. The low tensile strength in the sample group of 0.08_0.28_0.08 mm occurred owing to these variations, which are inevitable in hybrid layered 3D printing. Even minor changes in porosity could lead to significant variations in strength, with lower porosity levels enhancing the stiffness and durability of materials [21]. The porosity in 3D printing can be controlled through careful management of printing parameters, such as layer height and print speed, which significantly influence the bonding between polymer layers and the overall integrity of the printed part [22]. The printing speed is also carefully investigated to achieve better bonding quality between layers, thereby controlling porosity and increasing overall integrity.

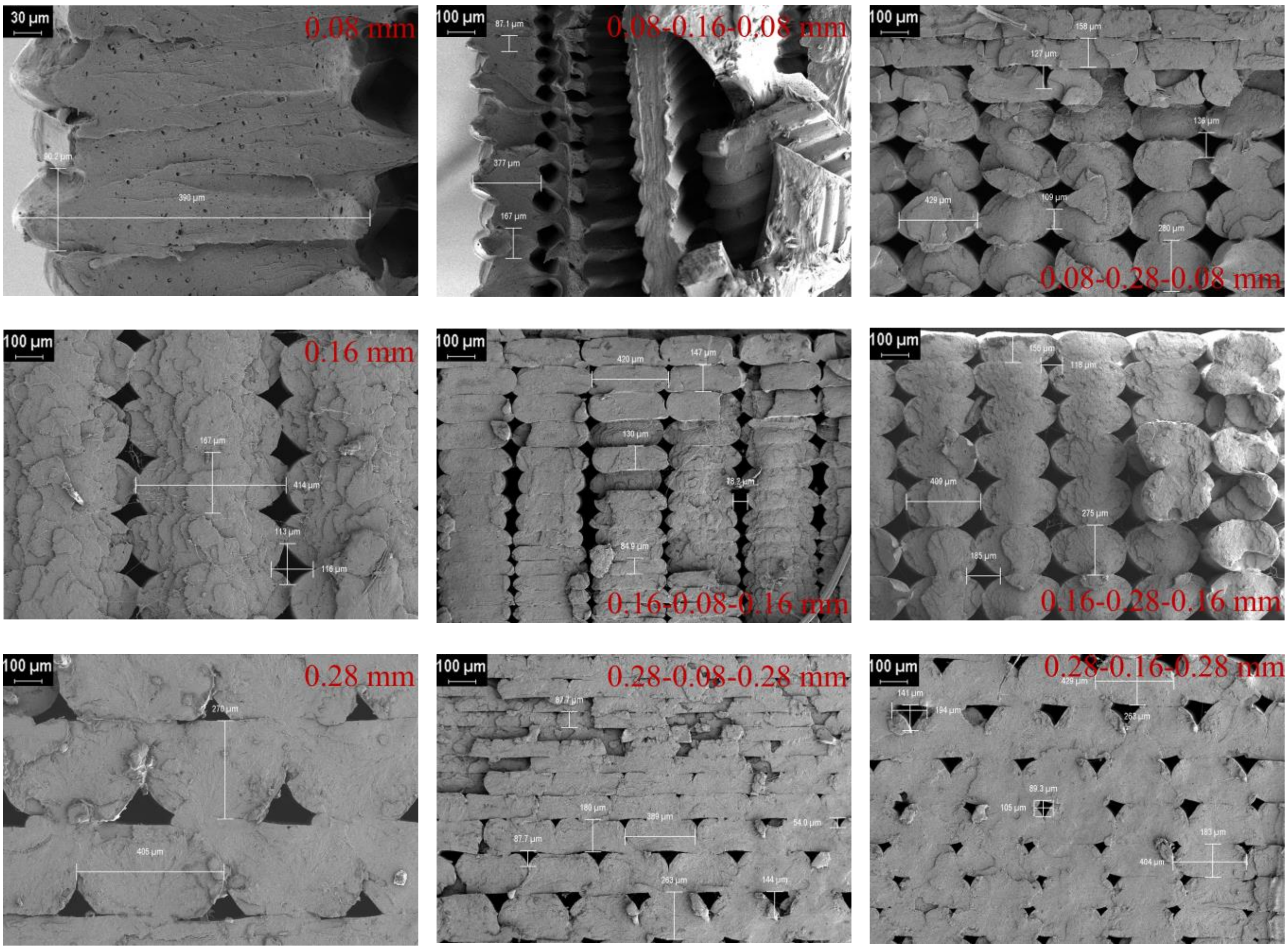

Figure 9: Deposited layer dimensions measured in SEM analysis.

Figure 10 presents the coefficient for the ratio of energy consumption to strength in the 3D printing process. Here, the appropriate amount of energy needed to produce tensile and flexural specimens with 1 MPa strength was discussed. The increase in layer thickness resulted in lower energy consumption due to reduced printing time. The coefficient in *flexural strength* decreased by 49.4% and 68.6% from 0.08 mm to 0.16 mm and 0.28 mm, respectively. In *tensile strength*, these changes were 47.1% and 67.9%, while they were 50.1% and 68.9% in *flexural modulus*. The changes in each increase for all strength values were relatively close to each other. Besides, average strength values for each mechanical property were statistically different from each other while changing the layer thickness.

In *the hybrid layer thickness, increasing core layer thickness reduced energy consumption or vice versa*, as expected. In the case of increasing core layer thickness from 0.08 to 0.16mm, changes in the coefficient for the ratio of energy consumption and strength were 35.1%, 28.7%, and 30.4% for tensile strength, flexural strength, and flexural modulus, respectively. Those of 0.28 mm were 44.6%, 50.6%, and 52.2%.

In the case of changing the core layer from 0.16 to 0.08 mm, energy consumption increased by 24.2%, 36%, and 36.9% to print specimens for tensile strength, flexural strength, and flexural modulus, respectively. On the other hand, an increase in layer thickness from 0.16 to 0.28 mm caused a reduction in tensile strength, flexural strength, and flexural modulus by 21.1%, 26.2%, and 24.2%, respectively. Furthermore, decreasing the layer thickness from 0.28 to 0.16 and 0.08 mm resulted in increased energy consumption coefficients for producing 1 MPa tensile strength by 23.2% and 54.5%, respectively. Similarly, these changes were increased by 38.5% and 57.7% for flexural strength and 40.9% and 56.6% for flexural modulus.

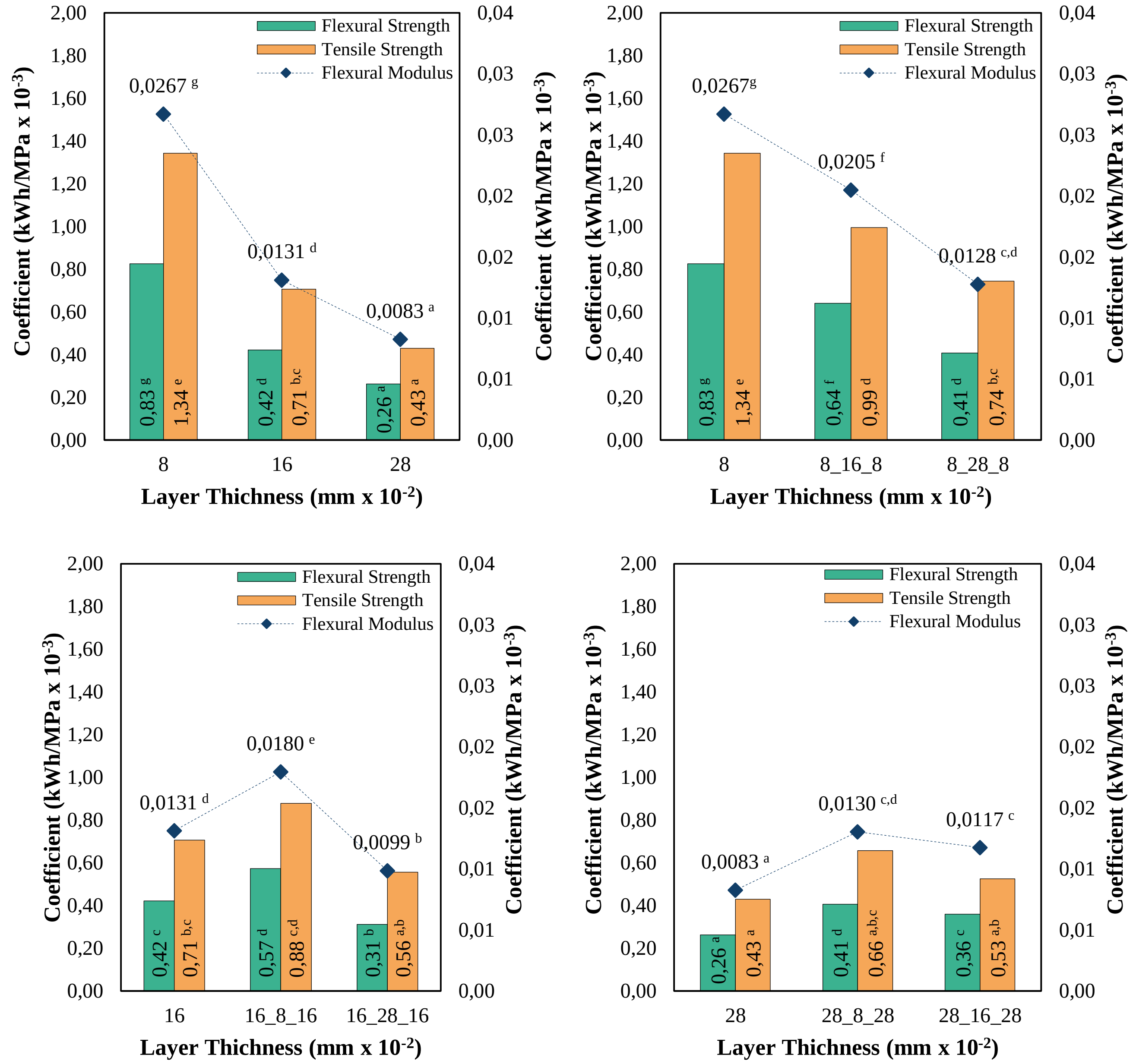

Figure 10: Coefficients for energy consumption in 3D printing to produce 1 MPa strength (Same letters were not statistically different from each other according to Tukey analysis in each test (α = 0.05).

Table 5: ANOVA results for the coefficients of energy consumption to produce 1 MPa strength in the 3Dprinting process.

Source	Tests	Sum of Squares	df	Mean Square	F-value	p-value
Between Groups	Tensile strength	1.887	8	0.236	34.13	≤ 0.001
	Flexural strength	0.771	8	0.096	2402.42	≤ 0.001

In Table 5, ANOVA results are given. According to the results, layer thickness was significant for tensile strength, flexural strength, and flexural modulus. In addition, Figure 10 also represents Tukey mean comparisons for the coefficients of energy consumption to produce 1 MPa strength, considering the aforementioned mechanical properties of 3D-printed specimens and changes in layer thickness. These coefficients were statistically different from each other in terms of tensile strength, flexural strength, and flexural modulus, separately. The same phenomenon was observed in the comparison of changes in core layers from 0.08 to 0.16 and 0.28 mm. In the case of changing core layers from 0.16 to 0.08 and 0.28 mm, the coefficient of energy consumption for the tensile strength of specimens with layer thicknesses of 0.16 mm and 0.16_0.28_0.16 mm was statistically different. On the other hand, those of flexural strength and modulus were statistically different from each other, separately. In the case of 0.28 mm, these coefficients for flexural strength were statistically different, but not for tensile strength, when changing layer thickness. Besides, those of flexural modulus with layer thicknesses of 0.28_0.08_0.28 and 0.28_0.16_0.28 mm were not statistically different.

The energy consumption during 3D printing primarily depends on the printing time. The higher printing time reduces energy consumption, but higher printing speeds lead to reduced layer width at a given thickness, which can adversely affect interlayer adhesion and the mechanical strength of the printed parts [16]. When printing speed is increased, the deposition rate rises, potentially leading to inadequate time for the material to adhere properly between layers. To optimize mechanical properties and energy consumption by reducing printing time, it is necessary to adjust the layer thickness. Energy consumption during the 3D printing process is primarily influenced by printing time, as longer print durations tend to increase energy usage. Lower printing speeds typically result in higher energy consumption due to extended operational times for the printer [23]. However, a paradox exists: although increased printing speed can minimize printing time and, consequently, energy consumption, it also leads to reduced material bonding if the speed surpasses the optimal deposition rate, which can adversely affect the mechanical strength of the printed components [24]. Specifically, when the printing speed is increased, there is a risk of insufficient bonding time between layers, leading to defects in the final product [25].

The higher layer thickness used in the 3D-printed parts reduced the printing time and, accordingly, the energy consumption. In the hybrid layer thickness, energy consumption decreased by enhancing the mechanical properties of 3D printing parts. The adjacent increase in layer thickness provided better mechanical properties. Thicker layers generally reduce the total number of layers required for a given print, thus decreasing overall printing time and energy consumption [26]. Optimizing layer thickness can improve energy efficiency through fewer passes required to complete a part while enhancing mechanical properties, provided the process parameters are well-controlled [27]. Employing a combination of different layer thicknesses can yield better mechanical properties while reducing energy consumption, as indicated in studies involving various configurations [28]. Besides, the combination of 0.08 mm and 0.16 mm layer heights provided better solutions in mechanical properties; however, the sample group with a layer thickness of 0.28 mm exhibited lower energy consumption. The 3D printing parameters highly influenced both the mechanical properties and energy consumption of the parts. The larger layer thicknesses often reduce the number of layers required, resulting in lower energy consumption throughout the printing process. Increasing the layer thickness could consequently lead to more efficient prints in terms of energy, as fewer passes are required to complete a part compared to using thinner layers. However, nozzle temperature may be highly significant in distorting materials in thinner layer thicknesses.

From an energy efficiency standpoint, configurations with thicker core layers—especially 0.28 mm—significantly reduced the energy consumed per unit strength, highlighting their potential for sustainable and cost-effective printing. However, this benefit comes at the expense of mechanical performance. Thus, the selection of layer thickness configuration must balance functional load-bearing needs with resource efficiency, especially in applications where mechanical integrity is critical.

4. Conclusion

This study comprehensively examined the effects of hybrid layer thickness configurations on the mechanical properties and energy consumption of PLA specimens fabricated via FDM. The findings revealed that both mechanical performance and energy efficiency are significantly influenced by the strategic arrangement of layer thickness within printed parts.

• Among the configurations tested, the hybrid structure with 0.16 mm outer layers and a 0.08 mm core layer demonstrated superior mechanical performance, achieving the highest tensile strength, flexural strength, and flexural modulus values. The 0.16 mm layer thickness, whether used uniformly or as outer layers, consistently enhanced mechanical behavior, suggesting its critical role in interlayer adhesion and structural integrity. Conversely, increasing the layer thickness to 0.28 mm effectively reduced printing time and energy consumption, albeit with a compromise in mechanical strength due to elevated porosity and reduced bonding quality.

• The results further indicate that hybrid layering strategies offer a promising solution to the strength-efficiency trade-off inherent in additive manufacturing. By combining the mechanical advantages of thinner layers with the processing efficiency of thicker layers, hybrid configurations can be optimized to meet specific functional and sustainability requirements.

• Additionally, scanning electron microscopy confirmed the influence of layer thickness on porosity and interfacial bonding, reinforcing the link between microstructural characteristics and mechanical performance.

Future research should expand on these findings by incorporating additional parameters such as raster orientation, infill density, and thermal gradient control to develop a holistic framework for process optimization in FDM. Moreover, the integration of real-time energy monitoring and advanced modeling tools could facilitate the predictive control of mechanical properties and resource consumption in complex part geometries.

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