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RESEARCH ARTICLE

Investigation of Layer Thickness Effects on Mechanical Properties of PLA Using FDM Additive Manufacturing

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ABSTRACT

This study explores the influence of layer thickness on the mechanical properties of Polylactic Acid (PLA) fabricated using Fused Deposition Modeling (FDM) additive manufacturing. By systematically varying the layer thickness (ranging from 0.1 mm to 0.3 mm), the aim is to understand how these changes affect tensile strength, elasticity, and overall structural integrity of the printed components. The research employs a series of controlled experiments, utilizing standardized testing procedures to measure and analyze the mechanical performance of PLA specimens. The tensile strength of the specimens ranged from 35 MPa to 45 MPa, depending on the layer thickness, while elongation at break varied between 5% and 8%. Results indicate significant variations in mechanical properties correlating with different layer thicknesses, providing valuable insights for optimizing print parameters in FDM processes. These findings contribute to the broader knowledge base, guiding the design and manufacturing of more robust and reliable 3D-printed objects.

Keywords: Layer thickness, Mechanical properties, PLA, FDM, Additive manufacturing

1. Introduction

The expeditious production of tangible models, particularly derived from three-dimensional (3D) computer-aided design (CAD) data, is facilitated through the utilization of additive manufacturing (AM) technology. Moreover, AM eliminates the necessity for conventional tooling or specialized programming. Unlike the conventional subtractive manufacturing methods, additive manufacturing involves the fusion of materials to fabricate physical entities based on 3D digital models [1]. Recently, several inexpensive and open-source Fused Deposition Modeling (FDM) machines have emerged in the market, capable of generating a variety of thermoplastic prototypes. FDM stands out as a widely adopted technology in Additive Manufacturing (AM) for its ability to rapidly fabricate intricate 3D solid objects [2]. The advantages of Fused Deposition Modeling (FDM) encompass uncomplicated material alteration, the capability for unsupervised operation, cost-effectiveness, reduced dimensions, and a low operational temperature [3]. Despite the primary utilization of FDM for prototyping, advancements in both process and material aspects have led to the potential expansion of its application for direct use in producing actual components. The production of such parts necessitates specific mechanical characteristics. Nevertheless, the enhancement of mechanical properties often results in trade-offs with printing speed, cost-effectiveness, and overall quality. Within the FDM technique, the mechanical attributes, surface texture, and geometric precision attained are influenced by various process parameters including layer thickness, raster angle, build orientation, and air gap.

Hence, meticulous selection of process parameters is essential to produce a high-quality product that

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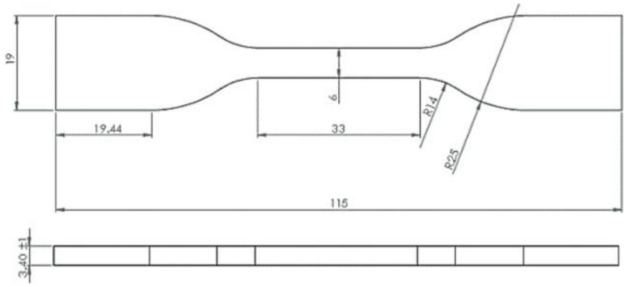

Fig. 1. Dimension of dog-bone specimen according to ASTM D638 Type IV [6].

meets customer demands. The present study will investigate the impact of layer thickness and raster angle. These process variables, found in the FDM system, can alter the mechanical characteristics of the final product, such as tensile and flexural properties. Additionally, factors like cost, part quality, and production time may also be influenced. A wide array of process parameters is at the disposal of the AM system. Virtually all these parameters can impact performance metrics including mechanical properties, geometric precision, surface finish, and fabrication time. Throughout the FDM procedure, numerous parameters necessitate attention. It is crucial to comprehend the definition of each parameter as they play a role in determining the mechanical properties and overall quality of the component. The key process parameters are delineated as follows [4].

2. Methodology

The tensile samples were printed in accordance with the American Society for Testing and Materials (ASTM) standards. The materials used in the FDM system are capable of producing durable parts and prototypes. The most commonly used materials for FDM machines are polylactic acid (PLA). The tensile specimens were prepared in a dog bone shape with dimensions specified by ASTM D638 - Standard Test Methods for Tensile Properties of Plastics [5].

This standard is widely utilized for testing purposes. Given that the test specimen is a rigid plastic, a type IV test specimen was selected. The dimensions of the test specimens for the tensile end are shown in Fig. 1.

Five samples of each combination of parameter were created to explore the impact of parameter and mechanical properties, varying in layer thickness using PLA material. The remaining process parameters were maintained at fixed levels, as detailed in Table 1. This study utilizes Design of Experiment (DOE) to systematically outline all combinations of process parameters, layer thickness, and raster angle, as illustrated in Fig. 2. Geometric models of the test specimens were developed in Solid Work and then exported in STL format for utilization in the FDM software. The test specimens were printed using the FolgerTech 3D printer. Samples with five different layer thicknesses (0.1 mm, 0.15 mm, 0.2 mm, 0.25 mm, 0.3 mm) underwent testing for tensile and flexural strength using the Ultimate Testing Machine (UTM) [7].

Table 1. Process parameter.

First layer speed			
First layer	50 mm/s	First layer infill	105 mm/s
Other layer speed			
Outer wall	22 mm/s	Inner wall	300 mm/s
Gap infill	250 mm/s	Sparse infill	270 mm/s
Internal solid infill	250 mm/s	Top surface	200 mm/s

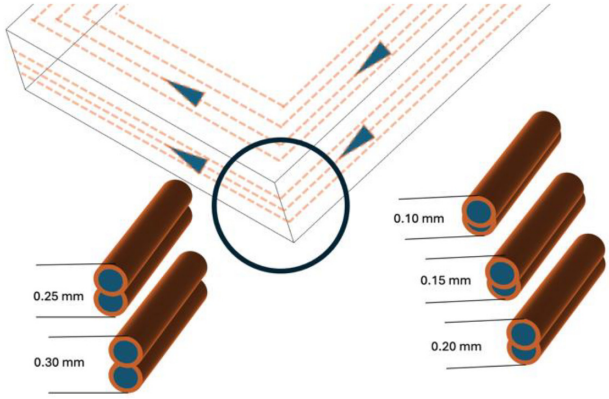

Fig. 2. Layer thickness and perimeter raster.

2.1. Materials

2.1.1. Materials and modelling

PLA filament from eryone Standard PLA made in China is employed for crafting the 3D samples. The initial step involves designing the sample in modelling software, adhering to ASTM D638 standards dimensions, and saving it in STL (Stereo Lithographic) format. Subsequently, the STL file is input into the 3D printing machine manufactured by Bambu lab P1S.

Polylactic acid (PLA) is a bio-based and biodegradable thermoplastic widely used across various industries due to its superior mechanical strength. Despite its high strength and stiffness, PLA is limited by its brittle behavior and low heat distortion temperature, as noted by Sennan et al. [8]. These characteristics make PLA a popular model material for Fused Deposition Modeling (FDM) printing. PLA filaments used in FDM can produce parts with mechanical properties

comparable to those made from bulk PLA, as reported by Farah et al. [9] Yao et al. [10], and Zhao et al. [11].

For this study, test specimens were fabricated using a Bambu P1S printer, suitable for printing with 1.75 ± 0.03 mm diameter filaments. Bambu Studio software was employed to set the printing parameters, including raster angle, head speed, and temperature. To ensure the quality of the printed parts, the nozzle and build platform temperatures were maintained at approximately 220°C and 60°C, respectively. An infill density of 100% was defined, with raster angles of 45 degrees for the infill. Various layer thicknesses were used to print the layers.

Table 1 outlines the specific printing speeds used for different stages and components within a 3D printing process.

First Layer Settings:

- First layer speed: This refers to the speed at which the printer deposits the initial layer of the print. A slower speed (50 mm/s in this case) is common for the first layer to ensure adhesion to the print bed and establish a good foundation for subsequent layers.
- First layer infill speed: This dictates the speed for printing the internal structure (infill) of the first layer. The higher speed (105 mm/s) compared to the first layer speed suggests a focus on speed without compromising the base layer's integrity.

Other Layer Settings:

- Outer wall speed: This determines the printing speed for the outermost perimeter of each layer. A moderate speed (22 mm/s) is used here, likely balancing print time with the quality of the visible surface.
- Inner wall speed: This sets the speed for printing any perimeters inside the outer wall. The significantly higher speed (300 mm/s) implies that inner walls are not as crucial for visual quality and can be printed faster.
- Gap infill speed: This refers to the speed used for printing infill patterns that bridge gaps or holes in the model. The high speed (250 mm/s) suggests a focus on efficiency for these less structurally critical areas.
- Sparse infill speed: This dictates the speed for printing infill patterns with lower density. The high speed (270 mm/s) is consistent with the focus on speed for infill areas.
- Internal solid infill speed: This sets the speed for printing completely filled internal areas. The speed (250 mm/s) is similar to gap infill, indicating a balance between speed and strength.



Fig. 3. PLA printed dog-bone samples.

- Top surface speed: This determines the printing speed for the uppermost layer of the print. A moderate speed (200 mm/s) is used, likely to ensure a smooth and visually appealing finish.

Table 1 reveals a strategy that prioritizes speed for internal structures and less visible components while maintaining moderate speeds for external surfaces and the crucial first layer. This approach aims to optimize printing time without sacrificing the overall quality and strength of the printed object (Fig. 3).

The study on the effects of layer thickness on the mechanical properties of PLA printed using FDM, weighing the test specimens is a crucial step. Precise mass measurements help in calculating the weight of the specimens and ensuring uniformity among different samples, which is important for comparing their mechanical properties accurately. Fig. 4 shows the analytical balance from Phoenx instrument ASN-224 that can measure up to 0.1mg used to measure the weight of the 3D-printed PLA specimen.

3. Results and discussion

Tensile test specimens constructed with varying layer thicknesses are examined to determine the impact of these parameters on the mechanical characteristics of the tensile material.

Fig. 5 shows the relationship between layer height and both the time it takes to print and the amount of material used, represented by layer weight.

- Layer Height: the primary variable being adjusted, ranging from 0.1 mm (very fine) to 0.3 mm (coarser).
- Printing Time (seconds): As layer height increases, printing time consistently decreases. This is because thicker layers allow the printer to lay down

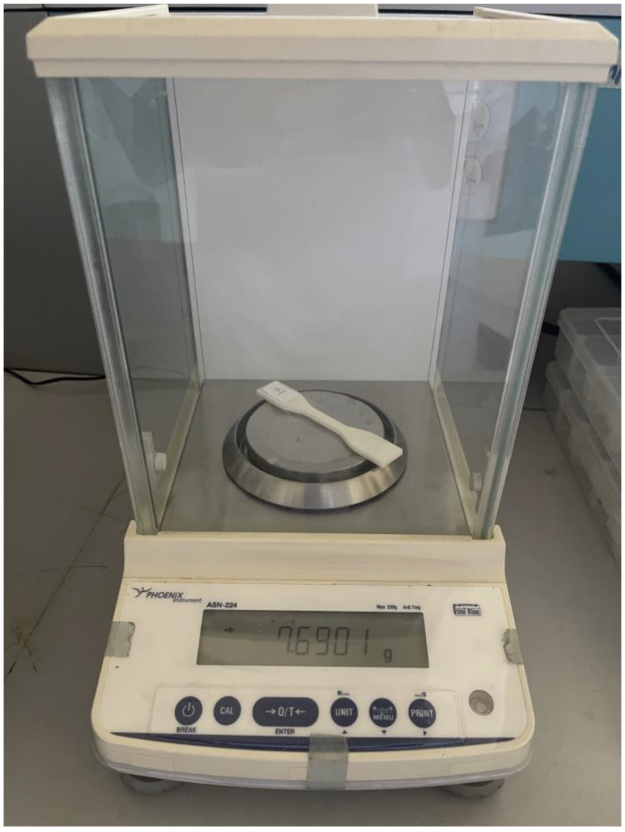

Fig. 4. Weight process set up.

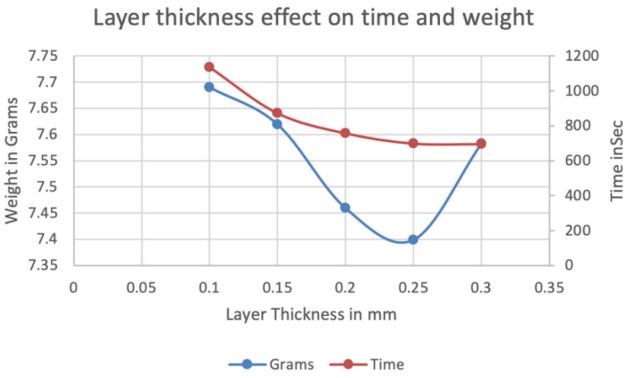

Fig. 5. Effect of layer thickness on weight and time.

material faster, resulting in quicker completion. For instance, a 0.1 mm layer height takes 1137 seconds to print, while a 0.3 mm layer height only takes 696 seconds.

- Layer Weight (grams): The relationship here is less direct. While, in general, thicker layers correspond to a heavier layer weight (more material used), there are some inconsistencies. This suggests that other factors, beyond just layer height, are influencing material consumption. These factors could include infill density, printing temperature, or even slight variations in filament diameter.



Fig. 6. Universal testing machine set up.

Tensile tests were carried out using Gunt Hamburg WP310 universal testing machine in accordance with ASTM D638 standards shown in Fig. 6. Tests were conducted at a constant crosshead speed of 2 mm/min until failure, with data on stress and strain recorded throughout the process.

Fig. 7 ilustrates the tensile test results of specimens printed with different layer thicknesses. The x-axis represents the displacement in millimeters (mm), and the y-axis represents the applied force in kilonewtons (kN). The various colored curves correspond to different layer thicknesses; Orange:

0.10 mm, Green: 0.15 mm, Purple: 0.20 mm, Red: 0.25 mm, Black: 0.30 mm.

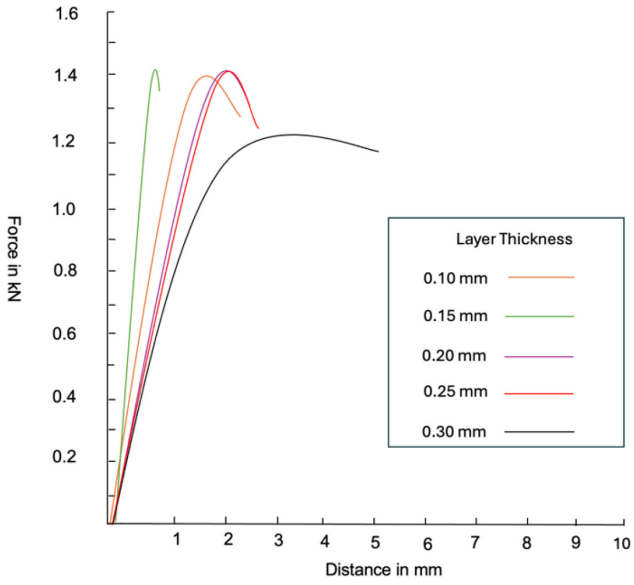

Fig. 7. load and elongation curve for all layer thickness.

- **Force:** The maximum force that the specimens can withstand varies with the layer thickness. Thinner layers (0.10 mm, 0.15 mm, and 0.25 mm) generally show higher peak forces compared to thicker layers (0.30 mm).
- **Displacement:** The displacement at which the maximum force occurs also differs. Thinner layers reach their maximum force at smaller displacements, indicating a stiffer and potentially more brittle behavior. In contrast, thicker layers (0.30 mm) exhibit higher displacements, indicating more ductility.
- **Curve Shapes:** The shapes of the curves suggest the mechanical behavior of the specimens (0.10 mm), (0.15 mm), and (0.25 mm) curves exhibit a sharp rise to their maximum force followed by a rapid drop, indicating brittle failure. The (0.30 mm) curve rises more gradually and plateaus before a more gradual decline, indicating more ductile behavior.

4. Conclusion

In summary, the mechanical properties of PLA printed with different layer thicknesses reveal that thinner layers provide higher tensile strength but are more brittle, while thicker layers are more ductile but with lower tensile strength. The choice of layer thickness in FDM printing thus significantly impacts the mechanical performance of the printed parts.

- Thicker Layers = Faster Prints: The data clearly demonstrates that increasing layer height significantly reduces printing time.
- Material Usage is Complex: While thicker layers generally use more material, other factors are clearly at play. This highlights the importance of optimizing print settings beyond just layer height to achieve the desired balance of speed and material efficiency.
- Speed vs. Quality: While thicker layers print faster, they may compromise the surface finish and detail resolution of the final print.
- Material Efficiency: Finding the optimal layer height for a specific print can help minimize material waste without significantly impacting printing time.
  - Thinner Layers (0.10 mm and 0.15 mm): These show higher tensile strength but fail more abruptly, suggesting higher stiffness but increased brittleness.
  - Moderate Thickness (0.20 mm and 0.25 mm): These provide a balance between strength and ductility, with the 0.25 mm layer showing the highest peak force.
  - Thicker Layer (0.30 mm): This demonstrates lower tensile strength but higher ductility, allowing for greater deformation before failure.

Conflict of interest

The authors declare no conflict of interest.

Author contribution

Abdullah Alhuzaim was responsible for writing the manuscript, visualization, software analysis, revision and finalization of the manuscript.

Data availability

The authors confirm that the data supporting the findings of this study are available within the article [and/or] its supplementary materials.

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