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INVESTIGATING THE EFFECT OF NOZZLE DIAMETER ON TENSILE STRENGTH IN 3D-PRINTED POLYLACTIC ACID PARTS

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Abstract: Three-dimensional (3D) printing is a rapidly evolving manufacturing technology that enables the production of intricate, customizable parts with a wide range of applications. The quality and mechanical properties of printed parts are heavily influenced by the process parameters, such as nozzle size. This study presents a comprehensive investigation of the effect of nozzle diameter on the tensile strength of 3D-printed polylactic acid (PLA) parts, focusing on six nozzle sizes: 0.3, 0.4, 0.5, 0.6, 0.7, and 0.8 mm. PLA, a commonly used thermoplastic in 3D printing, was employed as the material of choice. Using an open-source Fused Filament Fabrication (FFF) 3D printer, dog bone-shaped specimens were printed according to the ASTM D638-Type IV standard for tensile testing. The results reveal a strong correlation between nozzle size and tensile strength, with smaller nozzles producing parts with higher tensile strength due to finer layers and improved interlayer adhesion. However, the trade-off between tensile strength and printing time associated with smaller nozzle sizes must be considered when optimizing the 3D printing process for specific applications. This study provides essential insights into the influence of nozzle diameter on tensile strength, offering valuable guidance for achieving desired mechanical properties in 3D-printed parts.

Keywords: 3D printing, Fused filament fabrication, Nozzle diameter, Tensile strength, Polylactic acid, Additive manufacturing

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1. Introduction

Three-dimensional (3D) printing, also known as additive manufacturing, has revolutionized the field of manufacturing by enabling the production of complex, customized parts with reduced lead times and material waste (Farashi and Vafaee, 2022; Shaukat et al., 2022; Nazir et al., 2023). This innovative technology has found applications across various industries, including aerospace, automotive, healthcare, and consumer goods, owing to its ability to create intricate geometries and facilitate rapid prototyping (Triyono et al., 2020; Shaukat et al., 2022; Das et al., 2023). Among the numerous 3D printing techniques, Fused Filament Fabrication (FFF) is one of the most widely adopted methods due to its affordability, ease of use, and versatility in terms of material selection (Triyono et al., 2020; Hikmat et al., 2021; Mazen et al., 2022; Embia et al., 2023).

In FFF 3D printing, process parameters play a critical role in determining printed parts' quality and mechanical properties (Akhoundi and Behravesh, 2019; Tezel and Kovan, 2022). Some of the key parameters include print speed, temperature, layer height, infill pattern, infill density, and nozzle size. Among these, the nozzle size significantly influences the printed parts' resolution, surface finish, and mechanical properties, such as tensile strength (Wang et al., 2020; Hsueh et al., 2021; Mulcahy et al., 2023). Tensile strength, a vital property that dictates how a part behaves under tensile loads, is of particular interest as it often determines the suitability of printed components for specific applications (Anand Kumar and Shivraj Narayan, 2019; Wang et al., 2020;).

Despite the growing importance of 3D printing in modern manufacturing, limited research has been conducted to systematically investigate the effect of nozzle diameter on the tensile strength of printed parts (Shaukat et al., 2022). Understanding the relationship between nozzle size and tensile strength is critical for optimizing the 3D printing process to achieve desired mechanical properties and part quality (Akhoundi and Behravesh, 2019; Wang et al., 2020; Hsueh et al., 2021; Farashi and Vafaee, 2022; Shaukat et al., 2022; Tezel and Kovan, 2022; Hamat et al., 2023).

This study aims to bridge this knowledge gap by conducting a comprehensive investigation of the effect of nozzle diameter on the tensile strength of 3D-printed parts. The study focuses on six nozzle sizes, including 0.3, 0.4, 0.5, 0.6, 0.7, and 0.8 mm, to provide a detailed understanding of the influence of nozzle size on tensile strength. Polylactic acid (PLA), a common thermoplastic used in FFF 3D printing, was chosen as the material for this study due to its widespread use and ease of processing. The findings of this study will offer valuable insights for engineers, researchers, and practitioners seeking to optimize 3D printing processes for specific applications, taking into account the trade-offs between mechanical properties and other factors, such as printing time and material usage.

2. Materials and Methods

2.1. Materials and 3D Printer

Polylactic acid, also known as poly(lactic acid) or polylactide (PLA), is a thermoplastic polyester with backbone formula (C3H4O2)n or [–C(CH3)HC(=O)O–]n, formally obtained by condensation of lactic acid C(CH3)(OH)HCOOH with loss of water. It can also be prepared by ring-opening polymerization of lactide [–C(CH3)HC(=O)O–]2, the cyclic dimer of the basic repeating unit (Figure 1) (Sheikh et al., 2015). PLA is a biodegradable thermoplastic that has gained popularity in the 3D printing industry due to its origin from renewable resources such as corn starch and sugarcane. PLA has good thermal stability, is insoluble in water, and has good solvent resistance. It can be processed in a variety of ways, such as extrusion, injection molding and additive manufacturing. Products made from PLA have good biocompatibility, gloss, transparency and heat resistance, in addition to being biodegradable. PLA mechanical and thermal properties are given in Table 1. PLA is an environmentally friendly material that has a lower carbon footprint compared to petroleum-based plastics. PLA demonstrates several advantages that make it an attractive choice for 3D printing applications, including ease of processing, good printability, and a wide range of available colors. PLA material was commercially available in 1.75 mm diameter filament form by the manufacturer, Esun, which provides consistent quality and material properties. In this study, Ender 3 S1 open source 3D printer was used. Its features are listed in Table 2.

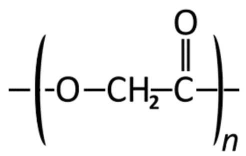

Figure 1. Polylactic acid sceletal formula (Sheikh et al., 2015).

2.2. 3D Printing Process

An open-source FFF 3D printer was utilized for this study. The printer was equipped with an interchangeable nozzle system, allowing for the easy replacement of nozzles with six different diameters. The printing parameters (Table 3), such as print speed, temperature, and layer height, were maintained constant for all specimens, except for the nozzle size, to ensure that the observed differences in tensile strength could be solely attributed to the nozzle diameter. The slicing was done in Cura software with open access code, by choosing the parameters of the print wall thickness of 0.8 mm and the fill pattern linear 45°. The produced G-codes were introduced as input to the printer.

Table 1. PLA product details

Features	Units	Value
Flexural modulus	MPa	100-150
Tensile strength	MPa	40-60
Elongation at break	%	4-10
Elastic modulus	MPa	3000-4000
Melting point	°C	176
Intensity	g/cm^3	1,25 -1,28
Processing temperature	°C	170-230

Table 2. Properties of the Ender 3 S1 3D printer

Property	Description
Printing volume	255 x 255 x 300 mm
Build surface	Adjustable heated bed
Filament	1.75mm PLA, ABS, PETG, TPU, etc.
Extruder	Single nozzle, Bowden-style
Layer resolution	0.1 - 0.4 mm
Max. print speed	180 mm/s
Nozzle diameter	0.4 mm
Connectivity	USB, SD card
Display	4.3-inch color touchscreen
Firmware	Open-source Marlin firmware
Power supply	Input: 100-120V AC/4.0A 200-240V AC/2.0A, Output: 24V
File format	STL, OBJ, G-code, AMF, etc.
Supported OS	Windows, Mac, Linux
Weight	8.9 kg

Table 3. Printing parameters for the study

Parameter	Value
Material	Polylactic Acid (PLA)
Layer height	0.2 mm
Infill density	100% (Solid)
Infill pattern	Rectilinear
Print speed	50 mm/s
Extrusion temperature	210°C
Bed temperature	60°C
Fan speed	100% (except for the first layer, 0%)
Shell thickness	1.2 mm
Top/Bottom thickness	1.2 mm
Print orientation	Flat, along the XY plane (ASTM D638 Type IV)
Test specimens per nozzle size	5

2.3. Specimen Preparation

To evaluate the tensile strength of 3D-printed parts, dog bone-shaped specimens were printed according to the ASTM D638-Type IV standard (Anand Kumar and Shivraj Narayan, 2019) for tensile testing of plastics. ASTM D638 Type IV specimens are designed to test thinner or more flexible materials, so these specimens are generally compatible with the typical dimensions and durability of 3D printed parts as referred to in the literature (Maurya et al., 2019; Chandrasekhar et al, 2019). So this type of sample is a good option for measuring the tensile properties of materials in 3D printing. This standard specifies the geometry, dimensions, and testing conditions for tensile tests, ensuring the reliability and comparability of the results. For each nozzle size, ten specimens were produced to ensure statistical significance and account for potential variability in the printing process. All specimens were printed in the same orientation with the long axis parallel to the printer bed, ensuring consistent layer orientation and minimizing the influence of anisotropy on tensile strength. Nozzles of different diameters used in printing (Figure 2.a), Ender 3 S1 open source 3D printer (Figure 2.b) was used and produced with the tensile strength of 3D-printed parts shown in Figure 2.c.

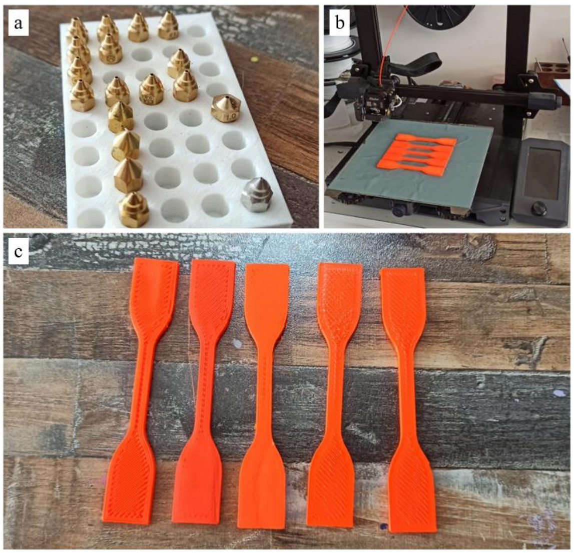

Figure 2. (a) Nozzles of different diameters used in printing, (b) Ender 3 S1 3D printer and (c) Produced the tensile sample of 3D-printed parts according to ASTM-Type IV.

2.4. Tensile Testing

Tensile tests (Figure 3) were performed using a universal testing machine equipped with a load cell appropriate for the expected tensile strength range of the printed specimens. The tests were conducted at a constant crosshead speed of 5 mm/min in accordance with the ASTM D638-Type IV standard. The load-displacement data were collected and analyzed to determine the tensile strength, defined as the maximum stress experienced by the specimen before failure. For each nozzle size, the average tensile strength and standard deviation were calculated from the ten tested specimens to provide a comprehensive understanding of the effect of nozzle diameter on tensile strength.

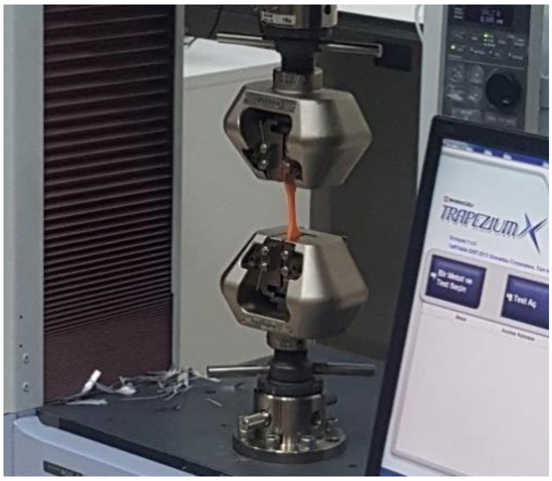

Figure 3. Experimental tensile test set-up.

2.5. Scanning Electron Microscopy

To further investigate the influence of nozzle size on the tensile strength of printed parts, Scanning Electron Microscopy (SEM) (Figure 4) was employed to analyze the fracture surfaces of the specimens after tensile testing. This analysis allowed for the visualization of the interlayer bonding, voids, and defects at different nozzle sizes, providing insights into the observed trends in tensile strength.

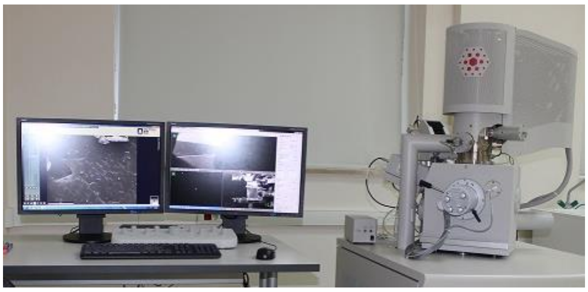

Figure 4. Taking SEM images of samples.

3. Results

The tensile test results for each nozzle size are presented in Table 4, which includes the average tensile strength and standard deviation values. The results in Table 4 reveal a consistent trend between nozzle size and tensile strength: as the nozzle size increases, the tensile strength of the printed parts decreases. This trend can be attributed to several factors related to the 3D printing process, as discussed below in Figure 5.

3.1. Layer Thickness and Interlayer Adhesion

The decrease in tensile strength with increasing nozzle size can be primarily attributed to the increase in layer thickness. Smaller nozzle diameters produce thinner layers, which result in better interlayer adhesion and, consequently, higher tensile strength. Improved interlayer adhesion can be attributed to the increased contact area between layers and the enhanced diffusion of polymer chains across the layer interfaces, promoting stronger bonding.

Table 4. Tensile strength results for different nozzle sizes

Nozzle Size (mm)	Tensile Strength (MPa)					
	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Average
0.3	60.24	60.23	60.22	60.3	60.19	60.23
0.4	54.42	54.48	54.50	54.51	54.52	54.52
0.5	51.25	51.26	51.32	51.33	51.34	51.34
0.6	47.55	47.61	47.63	47.64	47.65	47.65
0.7	43.85	43.91	43.93	43.94	43.95	43.95
0.8	40.27	40.33	40.35	40.36	40.37	40.37

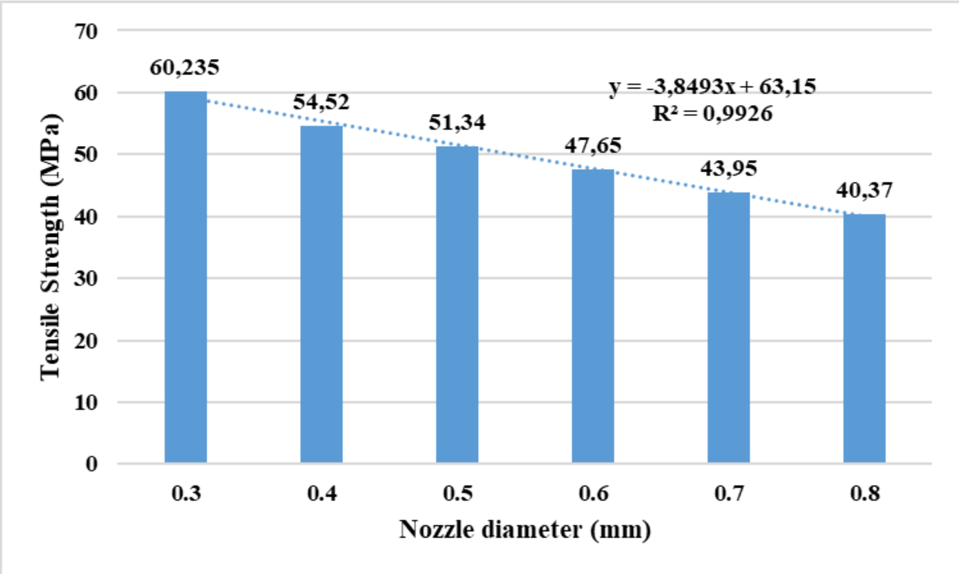

Figure 5. Effect of six different nozzle sizes on tensile strength.

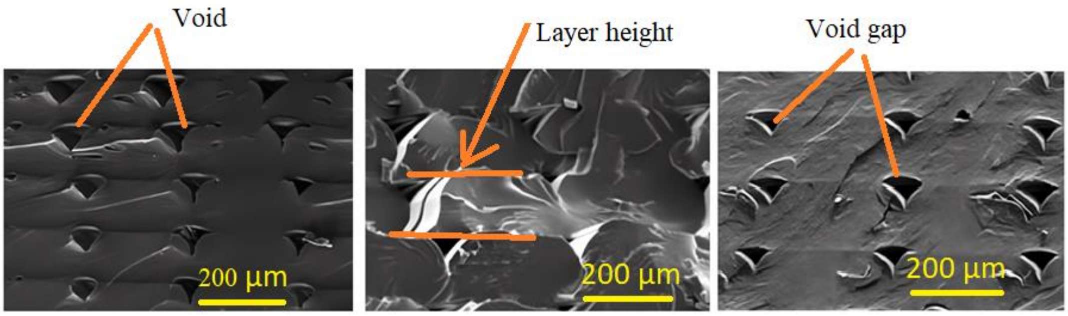

Figure 6. SEM analysis revealed that parts printed with larger nozzle sizes (0.8 mm) had more visible layer lines and larger voids.

3.2. Precision and Material Deposition

Another factor contributing to the observed trend is the improved precision and control of material deposition achievable with smaller nozzle sizes. The precise deposition of material helps reduce voids and defects in the printed parts. The absence of voids contributes to improved mechanical properties, as voids can act as stress concentrators and initiate crack propagation under tensile loads.

3.3. Scanning Electron Microscopy Analysis

SEM analysis is a powerful technique to study the surface morphology and microstructure of materials. In the case of 3D printed parts, it can provide insights into the quality of the printed object, layer adhesion, and the presence of voids or defects. The SEM analysis of the fracture surfaces supported the findings from the tensile tests. Specimens printed with smaller nozzles exhibited fewer voids and better interlayer bonding, providing further evidence for the observed relationship between nozzle size and tensile strength. Moreover, the SEM analysis revealed that parts printed with larger nozzle sizes (0.8 mm) had more visible layer lines and larger voids (Figure 6), which negatively impacted the mechanical performance under tensile loading. A larger nozzle size typically corresponds to a larger layer height, leading to a coarser surface finish and more visible layer lines. Additionally, the increased layer height reduces the resolution of the printed part, making it harder to reproduce fine details accurately.

3.4. Trade-off between Tensile Strength and Printing Time

While the results indicate that smaller nozzle sizes yield higher tensile strength, it is important to consider the trade-off between tensile strength and printing time. Smaller nozzle sizes require more time to print parts due to the finer layers and increased number of deposited layers. Consequently, the choice of nozzle size should be carefully evaluated based on the desired mechanical properties and other factors, such as printing time, material usage, and surface finish.

4. Discussion

The results demonstrate a clear trend between nozzle size and tensile strength. As the nozzle size increased, the tensile strength of the printed parts decreased. This observation can be attributed to the smaller nozzle diameters producing finer layers, which leads to better interlayer adhesion and, consequently, higher tensile strength. Moreover, smaller nozzle sizes allow for more precise control of material deposition, which helps reduce voids and defects in the printed parts. These factors collectively contribute to the improved tensile strength of parts produced with a smaller nozzle. According to Tezel and Kovan (2022), it is recommended to use a larger nozzle diameter and lower layer thickness to produce parts with superior properties. The study concluded that an increase in nozzle diameter leads to increased part strength, while layer thickness significantly affects surface quality. Increased nozzle diameter and part density contribute to reduced production time. It is recommended to use a larger nozzle diameter and lower layer thickness for parts with superior properties. Triyono et al. (2020) investigated the impact of nozzle hole diameter on the porosity and tensile strength of 3D printed parts using PLA material. The authors conducted experiments using fused deposition modeling (FDM) 3D printing, with varying nozzle hole diameters of 0.3, 0.4, 0.5, and 0.6 mm. They maintained consistent bed temperature (60°C), extruder temperature (200°C), and printing speed (80 mm/s) across all experiments. The layer thickness was set at a ratio of 20% to the nozzle hole diameter, and a 100% line-type infill pattern was used.

On the other hand, apart from the effect of the nozzle diameter specified in this study, there are also studies in the literature in which alternative aspects of improving the mechanical properties of 3D printed samples are mentioned. These are studies that mention that slicing parameters such as wall thickness, layer height, infill pattern and raster direction also play an important role in defining structural integrity and strength performances. Among them, for example, Dudescu and Racz (2017) stated that in their study on different printing directions, infill ratios and infill patterns, voids may occur even in samples printed at 100% infill ratio. On the other hand, they found that the mechanical properties of the samples were significantly affected not only by the filling ratios, but also by the printed pattern and orientation of the different layers. They pointed out that prints with higher mechanical properties can be achieved by optimizing the printing direction, fill ratio and fill patterns (Dudescu and Racz, 2017). Pandzic et al (2019) examined the effects of different filler types and filler ratios on the tensile properties of products manufactured with the FDM method and PLA material, by testing 9 samples with a total of 13 different filler types and different filler ratios from 10% to 90%. They reveal findings that 3D printing time and amount of material used can be saved by preserving the tensile properties. They pointed out that if the filling ratio of 100% is reduced to 90%, the final tensile strength and yield strength of the product obtained from PLA material will decrease by 40%. They also stated that the "concentric" fill pattern gives the highest ultimate tensile strength and yield strength. In addition, it is stated that by choosing larger layer heights, printing time can be shortened significantly at the expense of more visible layers. At the same time, it is mentioned that the reverse is also possible. It is stated that the first few of the fill lines formed in a way to form a bridge over the fill patterns of the pieces are drooping. It has been mentioned that the lower the infill, the longer the bridging distance and, consequently, the greater the sagging. It has been pointed out that this situation can be prevented by increasing the number of layers (at least 3 upper layers). It has been pointed out that this situation will directly affect the strength performance of the manufactured part (help.prusa3d.com). As a result, it is possible to produce parts with much better strength by optimizing the slicing parameters.

The results of the study demonstrated that larger nozzle hole diameters led to increased density and tensile strength of the 3D printed parts, although the relationship was not linear.

5. Conclusion

This study provided a comprehensive investigation into the effect of nozzle diameter on the tensile strength of 3D-printed PLA parts, examining six nozzle sizes ranging from 0.3 to 0.8 mm in increments of 0.1 mm.

- The results revealed a clear correlation between nozzle size and tensile strength, with smaller nozzle sizes producing parts with higher tensile strength.
- This trend can be attributed to the thinner layers and improved interlayer adhesion achievable with smaller nozzles, as well as the enhanced precision and control of material deposition, which helps reduce voids and defects in printed parts.
- The findings of this study offer valuable insights for engineers, researchers, and practitioners aiming to optimize 3D printing processes for specific applications.
- When selecting a nozzle size, the trade-off between tensile strength and printing time should be considered, as smaller nozzle sizes require more time to print parts.

- The choice of nozzle size should be carefully evaluated based on the desired mechanical properties, application requirements, and other factors, such as material usage and surface finish.

5.1. Future Work

The findings of this study lay the groundwork for further research in the field of 3D printing and mechanical properties. Potential avenues for future investigation include:

The effect of layer height on tensile strength for different nozzle sizes, as well as the interaction between layer height, nozzle size, and print speed.

The influence of nozzle size on the tensile strength of other materials commonly used in FFF 3D printing, such as ABS, PETG, and nylon. This research could help determine the generalizability of the findings across different materials and assess the impact of material-specific properties on the relationship between nozzle size and tensile strength.

The interaction between nozzle size, infill pattern, and infill density, as well as the optimization of these parameters to achieve desired mechanical properties, material usage, and print time.

Author Contributions

The percentage of the author(s) contributions is present below. All authors reviewed and approved final version of the manuscript.

	F.K.	A.K.
C	70	30
D	100	
S		100
DCP	60	40
DAI		100
L	20	80
W	80	20
CR	50	50
SR	100	
PM	60	40
FA	100	

C=Concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The author declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because of there was no study on animals or humans.

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