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Response of PLA material to 3D printing speeds: A comprehensive examination on mechanical properties and production quality

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Abstract: This study investigates the impact of printing speed on the mechanical properties of parts produced through the fused deposition modeling (FDM) method using a three-dimensional (3D) printer. Tensile test specimens, fabricated with Polylactic Acid (PLA) material on an Ender 3 S1 3D printer, were subjected to varying printing speeds from 15 mm/s to 105 mm/s in 15 mm/s increments, maintaining a 100% infill rate. Detailed measurements of sample masses, hardness values, and surface roughness were conducted to assess the potential effects of printing speed on PLA's mechanical properties. Porosity values were also calculated to evaluate internal structure homogeneity and void ratios. The results indicate that an increase in printing speed leads to a substantial reduction in production time. For instance, at a speed of 15 mm/s, the printing time was 119 minutes, decreasing to 15 minutes at 105 mm/s. As speed increased, there was a tendency for a decrease in sample masses, with a notable 12% reduction from 8.21 grams at 15 mm/s to 7.21 grams at 105 mm/s. While lower speeds (15 and 30 mm/s) exhibited higher Shore D hardness values, an overall decrease in hardness was observed with increasing speed. Surface roughness showed a proportional increase with printing speed; for example, at 0° angle, the roughness value increased from 0.8 at 15 mm/s to 1.9 at 105 mm/s. Moreover, tensile strength values decreased with higher printing speeds. For samples printed at 15 mm/s, the tensile strength was 60 MPa, decreasing to 44 MPa at 105 mm/s, representing a 27% reduction. These numerical findings underscore the significant influence of 3D printing speed on both production efficiency and the mechanical properties of the printed material.

Keywords: Additive manufacturing, three dimensional printing, polylactic acid, printing speed, mechanical properties, surface roughness.

1. Introduction

3D printing technology is a rapidly advancing method of production focused on prototypes, widely utilized in various industrial and academic fields. Among the fundamental advantages of this technology are the ease of producing complex geometries, rapid prototyping, and flexibility in production processes. The variety of materials used in 3D printing processes and the characteristics of these materials have a significant impact on the functionality and durability of printed objects. Among these materials, poly-lactic acid (PLA) is preferred due to its biocompatibility, ease of processing, and eco-friendliness. Printing speed is a factor that directly influences production time and efficiency, but it can also have important effects on the fundamental mechanical properties of the material, such as strength, hardness, surface roughness, and porosity [1-3].

PLA stands out as a widely utilized material in the

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realm of 3D printing. Its popularity is attributed to its biodegradability, ease of use, and versatility. As a dominant player in the 3D printing materials landscape, PLA's mechanical properties are of paramount importance for ensuring the reliability and functionality of printed objects.

A review of the literature reveals that some researchers have examined the effects of 3D printing process parameters on the mechanical properties and mass of PLA parts [3,4], the impact of different printing angles and speeds [5], lattice structures [6], printing speed, and extrusion temperature on mechanical properties [7], as well as their effects on strength and fatigue behavior [8]. Others have investigated the effects of process parameters and processing time on mechanical behaviors [9], hardness values [10], energy consumption [11], surface quality, and wear resistance [12]. Recent studies have delved into the intricate relationship between printing speed and the mechanical properties of PLA-printed objects. The printing speed is a critical parameter that can significantly influence the final product's strength, durability, and overall performance. Various studies have shed light on the subtle effects of varying printing speeds on the mechanical properties of PLA [13-20].

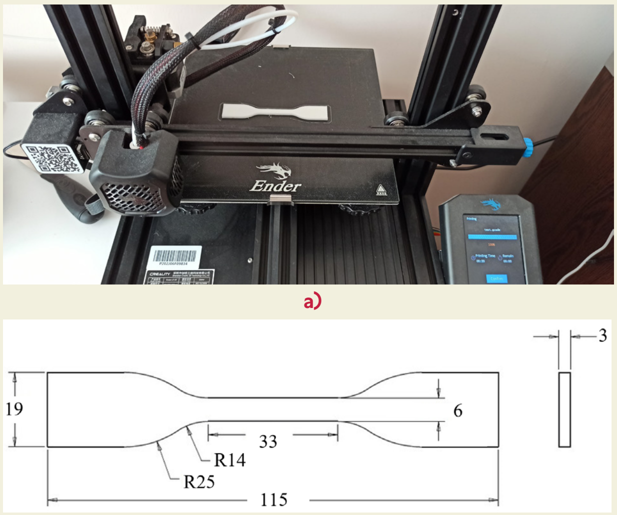
However, considering the parameters in the 3D printing process, the effects of factors such as printing speed on the mechanical properties of materials like PLA have not yet been fully understood.

Understanding how printing speed impacts layer adhesion, porosity, and overall structural integrity is imperative for optimizing 3D printing processes. These recent studies emphasize the need to consider printing speed as a crucial variable in the quest for enhancing the mechanical properties of PLA-printed objects. By incorporating these findings into the broader discourse on PLA, we can further refine our approach to 3D printing with PLA, ensuring that the mechanical performance aligns with the diverse applications and expectations within the ever-evolving field of additive manufacturing.

This study aims to examine how PLA material responds at different speeds (15, 30, 45, 60, 75, 90, and 105 mm/s) during the 3D printing process and determine the effects of these speeds on the material's mechanical properties. The research was conducted on tensile test specimens prepared using an Ender 3 S1 3D printer, and the samples' masses, hardness values, surface roughness, and porosity rates were measured. These results provide valuable information about the material's production quality and mechanical properties. It is believed that this information can contribute to the wider application of 3D printing technology. This study aims to shed light on the development of 3D printing technology and better material selection and parameter adjustment choices.

Table 1. Physical and mechanical properties of Microzey PLA Pro filament.

Properties	Units	Values
Diameter	mm	1.75
Color		White
Density	g/cm^3	1.25
Bed Temperature	°C	60-80
Printing Temperature	°C	190-210
Elasticity Modules	MPa	1500
Tensile Strength	MPa	50 ~ 60
Elongation at Break	%	7



a)

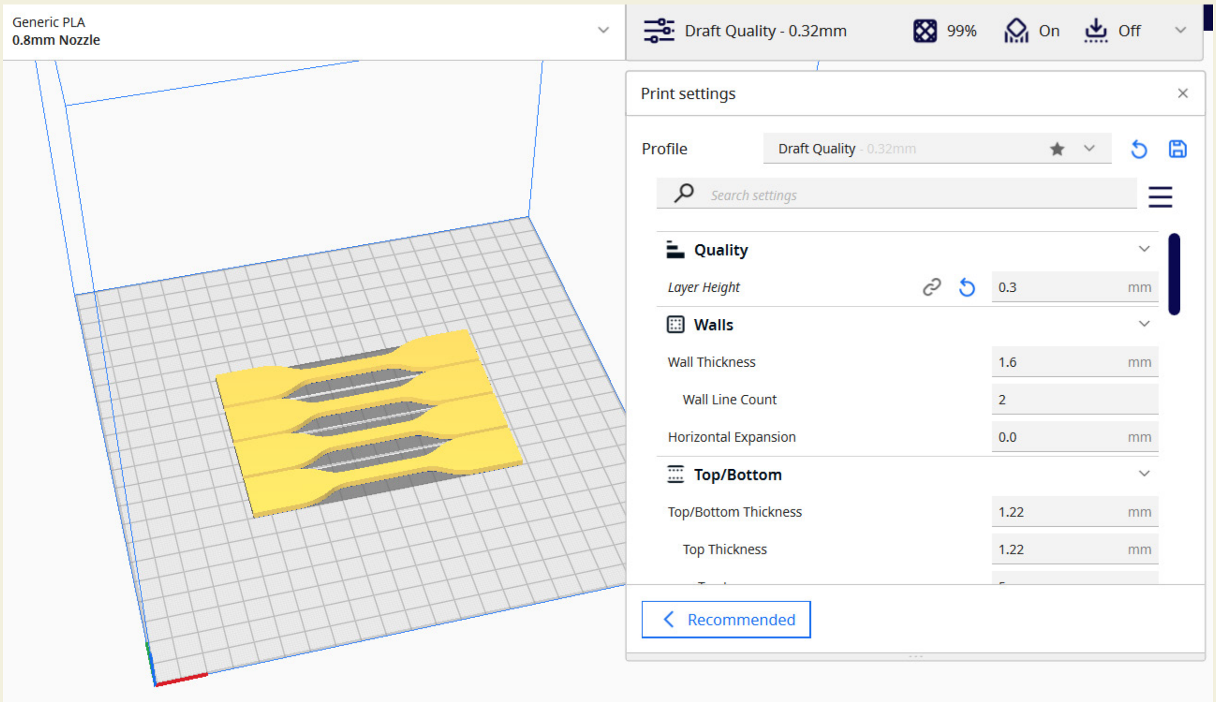
b)

Figure 1. (a) Production of test specimens using the Creality Ender 3 S1 3D printer. (b) Dimensions of samples according to ASTM D638-14/Type IV standard.

2. Material and Method

2.1. Study Process and Used Equipment

In this research, the "Creality Ender 3 S1" 3D printer, known for its precision printing potential and high-resolution production capability as shown in **▶Figure 1**.a, was used. In this study, PLA Pro filaments obtained from Microzey Limited were used. **▶Table 1** below shows some physical and mechanical properties of PLA filaments according to the supplier's information. Tensile test specimens were produced according to the dimensions specified in ASTM D638-14/Type IV standard, which is commonly preferred in the literature and depicted in **▶Figure 1**.b. The printing parameters during this production process are listed in **▶Table 2**. SolidWorks CAD software, known for its precision and



Profile: Draft Quality - 0.32mm

Layer Height: 0.3 mm

Wall Thickness: 1.6 mm

Wall Line Count: 2

Horizontal Expansion: 0.0 mm

Top/Bottom Thickness: 1.22 mm

Top Thickness: 1.22 mm

Figure 2. Model placement and printing parameter selection in the Cura slicing software.

detailed design capabilities in industry standards, was used during the 3D design process of the specimens.

2.2. G-Code Generation

To convert the created designs into formats compatible with the 3D printer, Ultimaker's Cura software, as shown in **▶Figure 2**, was used. Cura is popular for its ability to slice 3D objects and convert them into G-code. The model was transferred to the Cura slicing program, and the printing parameters given in **▶Table 2** were selected before sending it to the 3D printer for printing.

2.3. Printing Process

In this study, samples were produced at varying printing speeds within the range of 15-105 mm/s. Six different samples were prepared for each speed increment, resulting in a total of 42 samples. The primary material used in the production of the samples was "Mikrozey PLA Pro," commercially sourced. The melting and printing temperatures of the filaments were adjusted as shown in **▶Table 2**, according to the manufacturer's recommendations. Additionally, a magnetic feature Table named polyetherimide was used during 3D printing to ensure the initial layer of the samples adhered fully and smoothly to the printing surface.

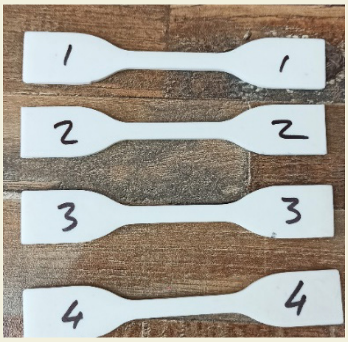


Figure 3. Tensile test specimens.

Table 2. 3D printing settings and parameters.

Parameters	Units	Value
Nozzle Temperature	°C	220
Bed Temperature	°C	60
Nozzle Diameter	mm	0.8
Layer Thickness	mm	0.3
Wall Thickness	mm	1.6
Top/Bottom Thickness	mm	1.22
Infill Density	%	100
Infill Pattern		Lines

2.4. Tests and Analyses

Some of the printed samples can be seen in ▶**Figure 3**. Mass measurements of the prepared samples were conducted using an A&D Ej-303 precision balance, hardness tests were performed using a Pepisky portable 0-100 HD Shore D device, and surface roughness measurements were taken using a Mitutoyo Surfest SJ-310 device. Furthermore, after the tensile tests, the fractured surfaces of the samples were thoroughly examined using a scanning electron microscope (SEM) to better understand how the printing process at different speeds affected the material's internal structure. SEM utilized in this study was the FEI Quanta FEG 250 model. Additionally, the Universal mechanical testing machine employed for mechanical testing was the Shimadzu Autograph AGS-X model. The Shore D hardness test was employed to assess the hardness of three different hard thermoplastic materials, following the guidelines outlined in ISO 7619-1:2010. The dimensions of the test specimens and the testing procedure adhered to the standards specified in ASTM D 2240-05.

3. Results and Discussions

This study produced tensile test samples using the Ender 3 S1 3D printer with PLA material having a 1.25 g/mm^3 density at 7 different printing speeds (15, 30, 45, 60, 75, 90, and 105 mm/s). The results obtained are presented in ▶**Table 3**. As the printing speed increased, there was a tendency for a decrease in mass and lattice volume, an increase in void volume, and porosity rates. As seen in ▶**Figure 4**.a, for example, the printing time at a speed of 15 mm/s was 119 minutes, but when the printing speed was increased by 6 times (105 mm/s), it decreased to 15 minutes, which is an 8-fold decrease. On the other hand, as shown in ▶**Figure 4**.b, when the printing speed was increased from 15 mm/s to 105 mm/s, the sample masses decreased from 8.21 grams to 7.21 grams, resulting in a 12% mass reduction. This is also confirmed by the porosity calculations shown in ▶**Table 3**.

The porosity percentage in the printed samples, depending on the printing speed, was calculated as follows [9]:

ϕ: Porosity percentage
V_{void}: Volume of voids inside the 3D printed product
V_{total}: Designed total volume of the 3D model
V_{solid}: Volume of solid material in the 3D printed product
$m_{product}$: Mass of the 3D printed product
$\rho_{filament}$: Density of the filament material

The porosity percentage has been calculated using Equation 1.

$$\phi = \frac{V_{void}}{V_{total}} \cdot 100 \tag{1}$$

The void volume has been calculated using Equation 2.

$$V_{void} = V_{total} - V_{solid} \tag{2}$$

The solid volume has been calculated from the mass using Equation 3.

$$V_{solid} = \frac{m_{product}}{\rho_{filament}} \tag{3}$$

As the printing speed increases, challenges in filament feeding accuracy and stability are expected to arise, potentially leading to insufficient filament feeding and a reduction in product mass [21,22]. ▶**Table 3** illustrates a notable increase in porosity rate from 7.02% at 15 mm/s to 15.96% at 105 mm/s, suggesting that higher speeds may result in irregular extrusion and deficiencies or voids in printed samples. High printing speeds could also contribute to issues such as inadequate filament heating, poor adhesion, and irregular layer bonding [23]. Therefore, a comprehensive evaluation of printer settings and filament characteristics is crucial to determine the optimal printing speed for achieving the best results [24].

In summary, the study conducted with the Ender 3 S1 3D printer highlights the significant impact of printing speed on both product quality and duration. This information can serve as a valuable guide for optimizing 3D printing processes to enhance efficiency and results [24-26].

However, it is essential to acknowledge that while this study provides valuable insights, further research and experimentation are necessary to fully comprehend the intricate relationship between printing speed and the mechanical properties of 3D printed objects. Delving deeper into these complexities will contribute to a more nuanced understanding, facilitating the optimization of 3D printing processes for superior and efficient results.

▶**Figure 4**.a illustrates the relationship between print speed (mm/s) and mass (g). According to the graph, as the print speed increases, the mass decreases. This implies a negative correlation between print speed and mass. The data on the graph represent masses ranging from 7.0 g to 8.4 g for print speeds varying between 15 mm/s and 105 mm/s. The graph comprises seven data points, denoted by blue dots. The blue line connecting these data points depicts the trend between print speed and mass. ▶**Figure 4**.b depicts the relationship between print speed (mm/s) and print duration (minutes). According to the graph, as print speed increases, the print duration decreases. This implies that higher speeds result in faster printing times. The graph consists of seven data points, marked with red dots. The red line connecting these data points illustrates that as print speed increases, the print duration rapidly decreases, but the rate of decrease slows down after approximately 60 mm/s.

▶**Figure 5** illustrates the relationship between print

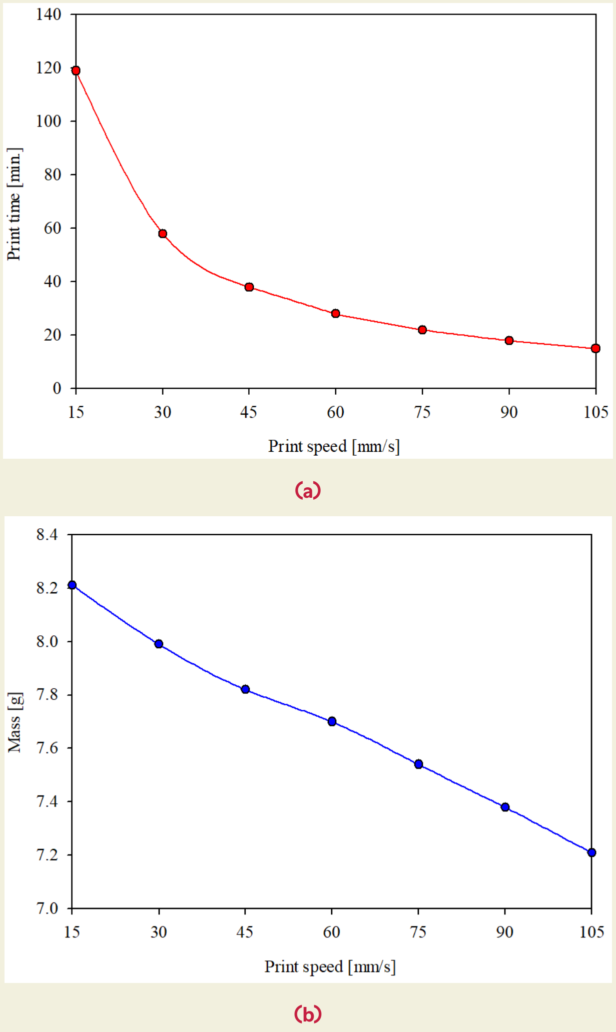


Figure 4. PLA tensile test samples produced at different printing speeds (a) Printing times and (b) Average mass values.

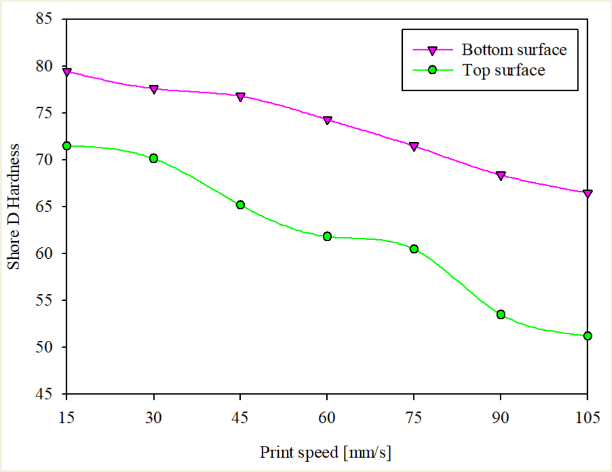


Figure 5. Shore D hardness values of test samples.

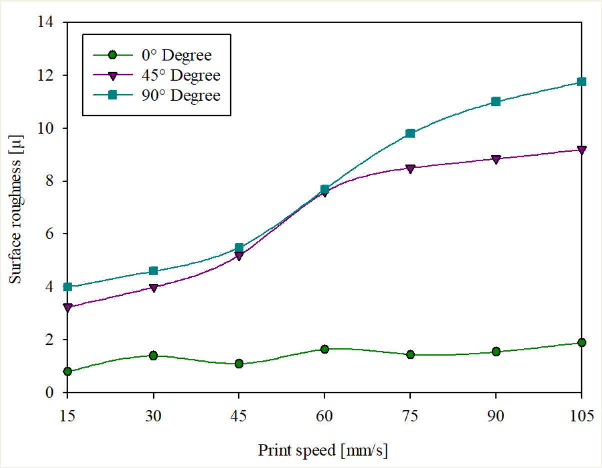


Figure 6. The variation in surface roughness values with respect to printing speed.

speed (mm/s) and Shore D Hardness. According to the graph, as the print speed increases, Shore D Hardness decreases for both the upper and bottom surfaces, with a more pronounced effect on the top surface. The graph comprises seven data points, divided into two groups: "Top Surface" (marked with green circles) and "Bottom Surface" (marked with purple triangles). Both groups indicate a decrease in Shore D Hardness as print speed increases.

▶**Figure 6** depicts the relationship between print speed (mm/s) and surface roughness (μ). According to the graph, as the print speed increases, surface roughness also increases for three different orientation angles (0°, 45°, and 90°). The 0° orientation shows the highest increase in surface roughness with increasing print speed. The graph consists of seven data points, divided into three groups: "0° Angle" (green), "45° Angle" (purple), and "90° Angle" (blue). All three groups indicate an increase in surface roughness as print speed increases.

During the printing process of the samples, a denser infill pattern is used to enhance adhesion to the printing bed. As a result, ▶**Figure 5** illustrates that the bottom surfaces of the samples exhibit higher Shore D hardness values than the top surfaces. On the other hand, an increase in printing speed leads to a decrease in hardness values for both the top and bottom surfaces. It can be inferred that the printing speed can be selected based on the desired hardness value.

It can be observed, as depicted in ▶**Figure 6**, that an increase in printing speed tends to elevate surface roughness. In this context, roughness values were measured at 0°, 45°, and 90° angles. Relatively lower roughness values were obtained in the 0° measurements, while higher values were observed at 45° and 90° measurements.

▶**Figure 7** illustrates the relationship between print speed (mm/s) and tensile strength (MPa). According to the graph, as the print speed increases, tensile strength decreases. This implies that higher speeds result in

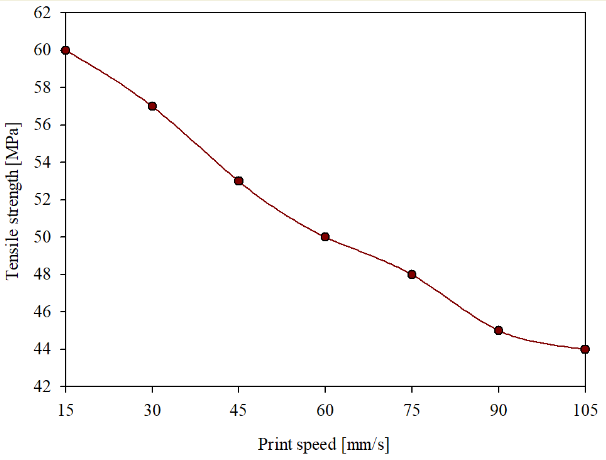


Figure 7. Variation in tensile strength values with printing speed.

materials with lower tensile strength. The graph comprises seven data points, marked with red dots. The red line connecting these data points indicates that as print speed increases, tensile strength decreases. According to the Figure, the samples printed at a speed of 15 mm/s achieved a tensile strength of 60 MPa, whereas those printed at 105 mm/s exhibited a tensile strength of 44 MPa. Thus, it has been determined that there is a 27% reduction in tensile strength.

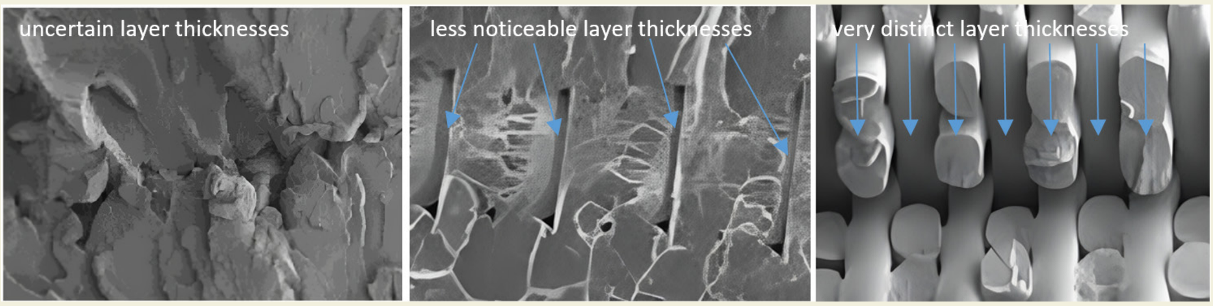
Within the domain of Fused Deposition Modeling printing, the significance of layer adhesion cannot be overstated. Inadequate adhesion between layers may lead to delamination, posing a threat to the mechanical strength of the printed object. SEM images become invaluable in this context, offering a detailed visual inspection of layer adhesion. Through the analysis of SEM images, one can glean insights into optimizing critical printing parameters, including temperature and speed, to achieve the pinnacle of layer adhesion and overall mechanical integrity.

This meticulous examination of porosity and layer adhesion through SEM analysis stands as a transformative approach in advancing the quality and performance of 3D-printed objects. The works of researchers such as Abeykoon et al. (2020), Dudek (2013), Gordeev et al. (2018), Popescu et al. (2018), Sandhu et al. (2019), Shen et al. (2018), Sood et al. (2012), and Wickramasinghe et al. (2020) underscore the importance of leveraging SEM insights to enhance the understanding and optimization of porosity and layer adhesion in the 3D printing landscape [13-20]. Printing speed is a critical factor that directly influences the quality of a 3D-printed object. Higher printing speeds can lead to increased porosity due to reduced precision in layer deposition and inadequate layer bonding. ▶**Figure 8**.a shows SEM images of samples printed at 15 mm/s, ▶**Figure 8**.b at 30 mm/s, and ▶**Figure 8**.c at 105 mm/s. It can be observed that as printing speed increases, layer thicknesses become more pronounced. Filament strands are distinguishable at a printing speed of 105 mm/s, and the gaps between them are visibly apparent. This condition can weaken strength performance on one hand and lead to worsened surface roughness on the other.

In conclusion, SEM images demonstrate that layers printed at higher speeds exhibit more irregularities and voids than those printed at lower speeds. Conversely, while consuming more time, slower printing speeds contribute to better layer adhesion and lower porosity, resulting in a stronger and more reliable final product.

4. Conclusions

This study examines the impact of printing speed on the mechanical properties of materials, particularly using PLA material, in the rapidly evolving field of 3D printing technology. Using an Ender 3 S1 3D printer, tensile test samples were prepared at different speeds (15, 30, 45, 60, 75, 90, and 105 mm/s), and their tensile strengths, masses, hardness values, surface roughness, and porosity values were measured. As a result, this study has revealed that 3D printing parameters, especially printing speed, can play a decisive role in the material's mechanical properties. The acceleration of



a) (b) (c)

Figure 8. SEM images of fracture surfaces (200x) at different printing speeds: (a) 15 mm/s, (b) 30 mm/s, and (c) 105 mm/s.

printing speeds, while potentially enhancing efficiency, introduces challenges such as reduced material mass, heightened porosity, and compromised structural integrity. This phenomenon may be attributed to insufficient filament feeding during extrusion, resulting in adverse consequences, particularly for applications prioritizing durability and structural robustness. Elevated printing speeds correlate with diminished hardness and tensile strength, potentially stemming from irregular layer assembly and increased porosity. Weak inter-layer adhesion contributes to decreased material strength and the potential formation of a more brittle structure, a concern for load-bearing applications. The escalation of surface roughness at higher speeds not only impacts aesthetic quality but also raises concerns for precision-critical applications. SEM analysis offers microscopic insights into factors like layer adhesion and porosity, emphasizing the negative implications of increased porosity on the structural integrity of objects printed at higher speeds. This finding underscores the importance of considering these factors, particularly in applications requiring mechanical strength and precision. The study results can be summarized as follows:

- As printing speed increases, printing time significantly decreases. For example, at a speed of 15 mm/s, the printing time is reduced from 119 minutes to 15 minutes at a speed of 105 mm/s. During this process, the average mass decreases from 8.21 grams at 15 mm/s to 7.21 grams at 105 mm/s, representing an approximate 12% decrease (Figure 4).

- Changes in Shore D hardness values of the samples were observed as printing speed increased. Higher hardness values were measured at low speeds (15 and 30 mm/s), while an overall decrease in hardness values was observed as speed increased. This indicates that rapid printing conditions can negatively affect material hardness (Figure 5).

- Surface roughness increased directly with printing speed. For example, the roughness value at 0° angle at a speed of 15 mm/s was 0.8, while this value increased to 1.9 at 105 mm/s. This trend indicates a decrease in surface quality at high speeds (Figure 6).

- Tensile strength values decreased as printing speed increased, indicating a rapid decrease in the structural integrity and strength of the material. The tensile strength, which was 60 MPa at a speed of 15 mm/s, decreased to 44 MPa at 105 mm/s, representing an approximate 27% decrease (Figure 7).

- The increase in printing speed adversely affects the ergonomics and mechanical properties of the part. On the other hand, reducing the printing speed significantly increases the printing time. The optimal choice can be made here according to the conflicting goals based on the expected qualities of the final product.

These numerical results demonstrate that the impact of 3D printing on mechanical properties is complex and multifaceted. It is understood that high speeds negatively affect the material's mechanical properties and surface quality, while lower speeds improve these outputs. This information shows that 3D printing parameters, especially speed settings, can significantly influence the outcome of the printing process.

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Research Ethics

Ethical approval not required.

Author Contributions

The author(s) accept full responsibility for the content of this article and have approved its submission.

Competing Interests

There is no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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Data Availability

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