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Tensile Strength Analysis of 3D-Printed Specimens Using Universal Testing Machine

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***Abstract* – This research investigates the tensile strength of 3D-printed Polyethylene terephthalate glycol (PETG) specimens using a Creality Ender-3 V2 3D printer. By employing the Taguchi method, printing parameters including layer thickness, infill density, print speed, and nozzle temperature were systematically varied to prepare nine specimens for tensile testing. The ultimate stress of each specimen was determined using a Universal Testing Machine (UTM), and the results were analyzed to understand the influence of printing parameters on mechanical properties. The findings reveal that finer layer thicknesses and higher infill densities generally result in higher tensile strengths, while print speed demonstrates variable effects. Moreover, elevated nozzle temperatures are associated with improved tensile strength due to enhanced material flow and adhesion. These insights underscore the importance of optimizing printing parameters to achieve desired mechanical properties in 3D-printed PETG specimens, thereby contributing to the advancement of additive manufacturing processes. This study provides valuable guidance for optimizing 3D printing parameters and enhancing mechanical performance in various applications.**

***Keywords* – 3D printing, additive manufacturing, tensile strength, Universal Testing Machine, printing parameters.**

I. Introduction

Additive manufacturing, commonly referred to as 3D printing, has emerged as a disruptive technology with profound implications across various industries. Its ability to fabricate intricate geometries with unmatched speed and flexibility has revolutionized traditional manufacturing processes, enabling rapid prototyping, on-demand production, and customization to meet diverse consumer needs. However, despite its widespread adoption, the mechanical properties of 3D-printed materials remain a significant area of concern and investigation.

Understanding the mechanical behavior of 3D-printed materials, particularly their tensile strength, is paramount for ensuring the reliability, durability, and safety of printed components in real-world applications. Tensile strength, which measures the maximum stress a material can withstand before failure under tensile loading,[1] is a critical mechanical property that directly influences the structural integrity and performance of 3D-printed parts. Therefore, comprehensive analysis and characterization of tensile strength are essential for optimizing the design and manufacturing processes in additive manufacturing.

This research focuses on investigating the tensile strength of 3D-printed specimens using a Universal Testing Machine (UTM), a widely employed instrument for evaluating the mechanical properties of materials under tension. By subjecting 3D-printed specimens to controlled tensile loading, we aim to gain insights into the influence of various printing parameters on their mechanical behavior. These parameters include layer height, infill density, printing speed, and nozzle temperature, which are known to affect the microstructure, adhesion, and overall mechanical properties of printed parts.

The systematic experimental approach employed in this study allows for a comprehensive analysis of how different printing parameters impact the tensile strength of 3D-printed specimens. By systematically varying these parameters and conducting tensile tests using a UTM, we can elucidate the relationship between printing conditions and mechanical performance, thereby providing valuable insights into optimizing the printing parameters for enhanced mechanical properties in additive manufacturing applications.

Through this investigation, [2]we aim to address the critical challenge of understanding and optimizing the mechanical properties of 3D-printed materials. By elucidating the factors influencing tensile strength and providing actionable insights for process optimization, this research contributes to advancing the state-of-the-art in additive manufacturing and facilitates the development of robust, reliable, and high-performance 3D-printed components across diverse industries.

II. Literature Review

The field of additive manufacturing, particularly 3D printing, has witnessed significant growth and development over the past few decades, accompanied by extensive research into the mechanical properties of 3D-printed materials. Understanding these properties is crucial for ensuring the reliability and performance of printed components in various applications. In this literature review, we discuss key findings and insights from previous studies related to the tensile strength of 3D-printed materials, focusing on the influence of printing parameters such as layer height, infill density, printing speed, and nozzle temperature.

1. Influence of Printing Parameters on Tensile Strength

Numerous studies have investigated the effect of printing parameters on the tensile strength of 3D-printed specimens. Layer height, which refers to the thickness of each deposited layer during printing, has been shown to significantly impact tensile strength. Lower layer heights generally result in better inter-layer adhesion and higher tensile strength due to increased surface area contact between layers (Ma et al., 2018). In contrast, higher layer heights may lead to weaker inter-layer bonding and reduced tensile strength (Hu et al., 2020).

Similarly, infill density, which denotes the amount of material used to fill the internal volume of printed parts, has been identified as a crucial parameter affecting tensile strength. Higher infill densities typically result in greater material density and improved mechanical properties, including tensile strength (Husain et al., 2019). However, excessively high infill densities may increase printing time and material consumption without significant improvements in tensile strength, necessitating a balance between mechanical performance and production efficiency.

2. Effect of Printing Speed and Nozzle Temperature

Printing speed and nozzle temperature are two additional parameters that influence the mechanical properties of 3D-printed materials, including tensile strength. Studies have shown that variations in printing speed can affect the cooling rate and crystallinity of printed parts, thereby impacting their mechanical behavior (Li et al., 2019). Higher printing speeds may result in reduced tensile strength due to inadequate material bonding and increased porosity (Tan et al., 2020).

[3] Moreover, nozzle temperature plays a critical role in controlling material flow and adhesion during the printing process. Optimal nozzle temperature is essential for achieving proper layer adhesion and structural integrity in printed parts. Deviations from the recommended temperature range can lead to defects such as warping, delamination, and poor inter-layer bonding, ultimately affecting tensile strength (Chacón et al., 2017).

3. Advances in Testing Methodologies

In recent years, advancements in testing methodologies, particularly the use of Universal Testing Machines (UTMs), have facilitated more accurate and reliable characterization of the mechanical properties of 3D-printed materials. UTMs allow for precise control of loading conditions and enable tensile testing of printed specimens according to established standards such as ASTM D638. By subjecting 3D-printed specimens to controlled tensile loading, researchers can obtain quantitative data on tensile strength, yield strength, and elongation at break, among other mechanical properties (González-Hernández et al., 2021).

4. Gaps and Future Directions

While existing literature provides valuable insights into the influence of printing parameters on the tensile strength of 3D-printed materials, several gaps and opportunities for future research remain. Further investigations are needed to explore the combined effects of multiple printing parameters on mechanical properties and to develop predictive models for optimizing printing parameters based on desired mechanical performance criteria. Additionally, studies focusing on the influence of post-processing techniques, material composition, and environmental factors on tensile strength would contribute to a more comprehensive understanding of additive manufacturing processes.

Overall, the literature reviewed highlights the importance of considering printing parameters such as layer height, infill density, printing speed, and nozzle temperature in optimizing the tensile strength of 3D-printed materials. By leveraging insights from previous studies and employing advanced testing methodologies, this research aims to contribute to the ongoing efforts in enhancing the mechanical performance and reliability of 3D-printed components for various industrial applications.

III. Experimental Methodology

The experimental methodology outlined in this section details the procedure followed to investigate the tensile strength of 3D-printed specimens using a Universal Testing Machine (UTM). The study aims to analyze the influence of various printing parameters, including layer thickness, infill density, print speed, and nozzle temperature, on the mechanical properties of Polyethylene terephthalate glycol (PETG) specimens fabricated using a Creality Ender-3 V2 3D printer. The Taguchi method was employed to systematically vary these parameters and prepare nine specimens for tensile testing. The experimental setup adhered to ASTM standards to ensure accuracy and consistency in the testing process.

1. Material Selection and Preparation

The figure 1 shows Polyethylene Terephthalate Glycol (PETG) filament was selected as the material for 3D printing due to its favorable mechanical properties, including high tensile strength, durability, and impact resistance.[4] The filament was sourced from a reputable manufacturer to ensure quality and consistency in material properties.

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Figure 1: Polyethylene terephthalate glycol (PETG) Filament

Prior to printing, the PETG filament was properly stored in a dry and dust-free environment to prevent moisture absorption and filament degradation. The filament diameter was measured using a digital caliper to ensure compatibility with the 3D printer's extruder system. Any deviations from the specified filament diameter were noted and adjusted accordingly.

2. 3D Printer Configuration

The experiments were conducted using a Creality Ender-3 V2 shown in figure 2, 3D printer equipped with a standard hot end assembly and a heated build plate. The printer was calibrated according to manufacturer guidelines to ensure accurate extrusion, bed levelling, and overall print quality.

Figure 2: Creality Ender-3 V2 3D Printer

The printer settings were configured based on the predetermined printing parameters, including layer thickness, infill density, print speed, and nozzle temperature. The slicing software “Creality Slicer” was used to generate G-code files with the specified printing parameters for each specimen.

3. Printing Parameter Variation

The Taguchi method was employed to systematically vary the printing parameters and prepare nine specimens for tensile testing. The selected parameters and their respective levels are as shown in table 1.

Table 1: 3D Printing Parameters

Printing Parameter	Level 1	Level 2	Level 3
Layer Thickness	0.16 mm	0.2 mm	0.28mm
Infill Density	80%	90%	100%
Print Speed	80 mm/s	90 mm/s	100 mm/s
Nozzle Temperature	230°C	240°C	250°C

The Table 2 shows each combination of printing parameters was assigned a unique code to facilitate identification and tracking during the printing and testing phases.

Table 2: 3D Printing Parameters

Code	Layer Thickness mm	Infill Density %	Print Speed mm/s	Nozzle Temperature °C
TS-1	0.16	80	80	230
TS-2	0.16	90	90	240
TS-3	0.16	100	100	250
TS-4	0.2	80	90	250
TS-5	0.2	90	100	230
TS-6	0.2	100	80	240
TS-7	0.28	80	100	240
TS-8	0.28	90	80	250
TS-9	0.28	100	90	230

4. Specimen Design and Printing

The specimens were designed in accordance with ASTM standards for tensile testing to ensure consistency and accuracy in the experimental setup. The design included a standardized geometry with defined dimensions, such as length, width, and thickness, suitable for tensile testing as shown in figure 3.

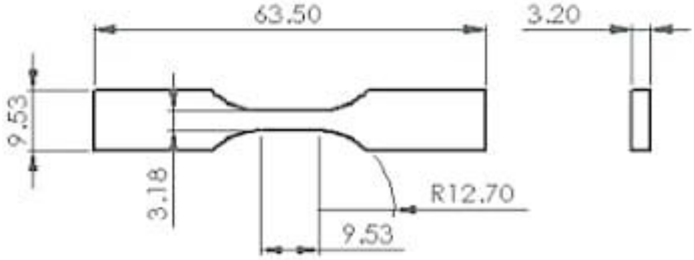

Figure 3: Tensile Specimen (ASTM D638)

The CAD model of the specimen shown in figure 4 was imported into the slicing software, where the printing parameters were specified based on the Taguchi experimental design. The G-code files generated by the slicing software were transferred to the 3D printer via SD card for printing.

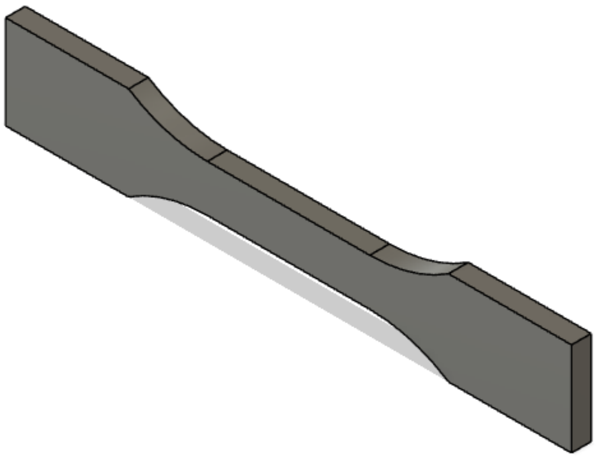

Figure 4: Tensile Specimen CAD Model

5. Printing Process

The printing process was conducted under controlled conditions to minimize variability and ensure repeatability across specimens. The 3D printer was operated in a well-ventilated area with stable ambient temperature and humidity levels.

Before initiating each print, the printer's build plate was cleaned and coated with an appropriate adhesive (glue stick) to promote adhesion and prevent warping. The printing parameters were configured as per the Taguchi experimental design, and the G-code file corresponding to the desired specimen was selected for printing.

During the printing process, periodic visual inspections were conducted to monitor print quality and detect any anomalies or defects.[5] Any issues encountered during printing, such as layer misalignment, extrusion problems, or adhesion issues, were promptly addressed to ensure the integrity of the specimens.

Once the printing was completed, the specimens were carefully removed from the build plate and inspected for any surface imperfections or irregularities. Any excess support structures or residue from the printing process were removed using appropriate tools (sandpaper) to prepare the specimens for tensile testing. The tensile specimens printed from 3D printer are portrayed in figure 5.

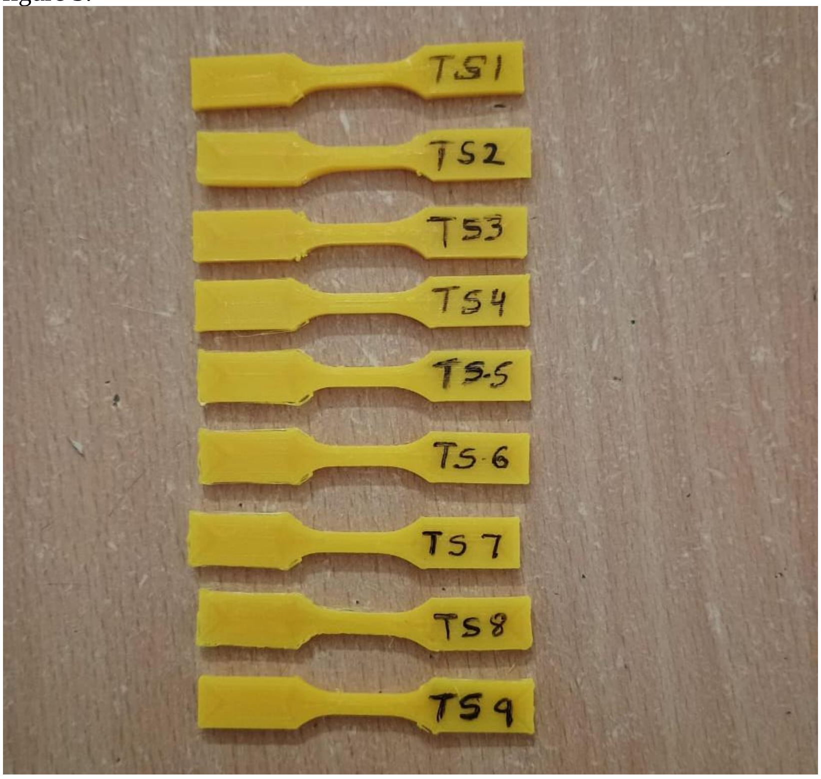

Figure 5: Tensile Specimen Prepared from 3D Printer

6. Tensile Testing Setup

The tensile testing of the 3D-printed specimens was conducted using a Universal Testing Machine (UTM) equipped with appropriate grips and fixtures for securing the specimens. The testing setup adhered to ASTM standards for tensile testing to ensure consistency and accuracy in the measurement of mechanical properties.

Prior to testing, the dimensions of each specimen were measured using a digital caliper to verify compliance with the design specifications. The specimens were carefully positioned in the grips of the UTM, ensuring proper alignment and orientation for tensile loading as shown in figure 6.

Figure 6: Tensile Specimen Placed in UTM

7. Tensile Testing Procedure

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The tensile testing procedure involved applying a uniaxial tensile load to the specimens at a constant rate of displacement. The UTM was programmed to apply tensile force gradually, while recording load and displacement data continuously throughout the test.

The tensile test was conducted until the specimen experienced failure, characterized by a sudden decrease in load accompanied by visible deformation or fracture. The maximum load sustained by the specimen before failure, along with corresponding displacement data, was recorded as the ultimate tensile strength (UTS).

The detailed experimental methodology described above outlines the procedures followed to investigate the tensile strength of 3D-printed specimens using a Creality Ender-3 V2 3D printer and a Universal Testing Machine (UTM). By systematically varying printing parameters and employing the Taguchi method, nine specimens were prepared and tested to evaluate the influence of factors such as layer thickness, infill density, print speed, and nozzle temperature on tensile strength. [6]The experimental setup adhered to ASTM standards to ensure accuracy and consistency in testing procedures, and rigorous quality assurance measures were implemented to validate the reliability of the results. Through meticulous experimentation and data analysis, this study aims to provide valuable insights into optimizing printing parameters for enhanced mechanical performance in additive manufacturing applications.

IV. Results and Discussions

Additive manufacturing, particularly 3D printing, has emerged as a transformative technology with applications spanning various industries. One of the critical aspects of utilizing 3D-printed components is understanding their mechanical properties, particularly tensile strength, which is crucial for assessing structural integrity and performance. In this study, we investigated the tensile strength of 3D-printed specimens made from Polyethylene terephthalate glycol (PETG) using a Creality Ender-3 V2 3D printer. We employed the Taguchi method to systematically vary printing parameters, including layer thickness, infill density, print speed, and nozzle temperature. Subsequently, [7] we conducted tensile tests on nine specimens to evaluate their ultimate stress. The results obtained are detailed below, followed by a comprehensive discussion of the findings and their implications. The failure of tensile specimen shows in figure 7. The figure 8 portrayed the Tensile strength for different specimens.

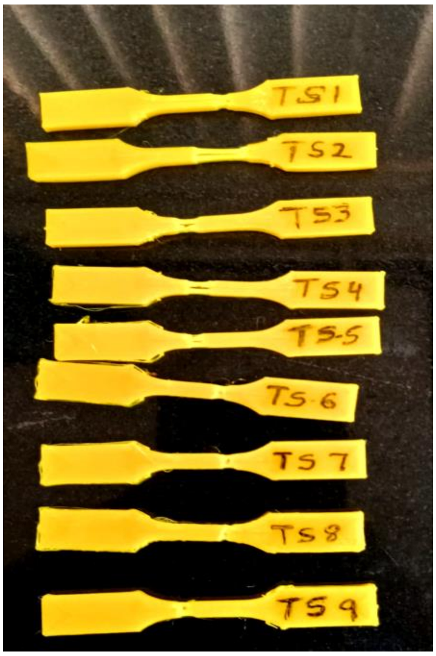

Figure 7: Tensile Specimens After Tensile Test

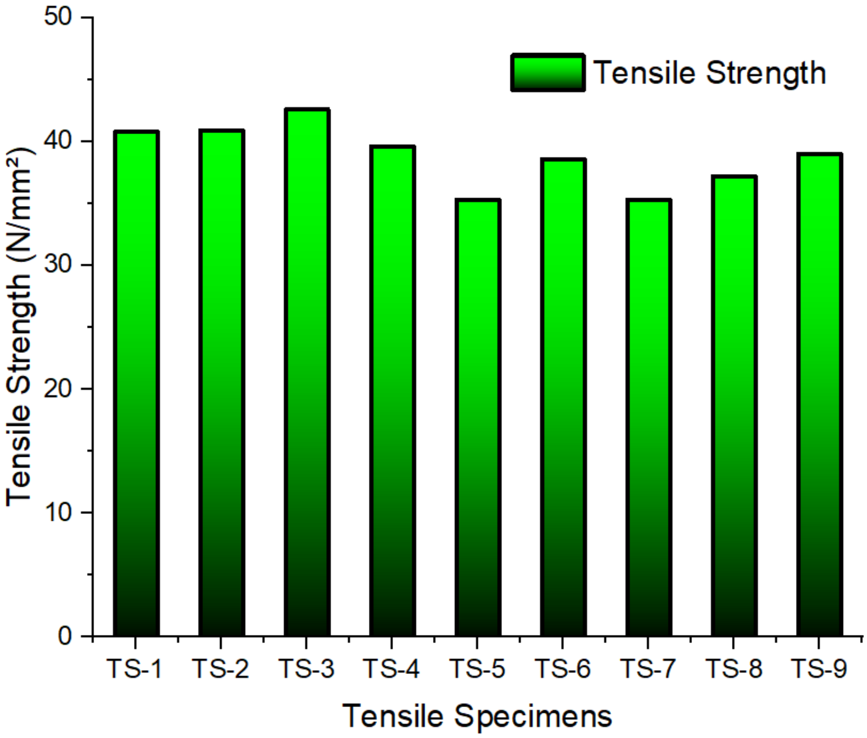

Figure 7: Tensile Strengths

1. Effect of Layer Thickness

The results indicate that varying the layer thickness has a discernible impact on the ultimate stress of the PETG specimens. Notably, specimens printed with a layer thickness of 0.16 mm (TS-1, TS-2, TS-3) generally exhibited higher ultimate stress values compared to those printed with thicker layers (0.2 mm and 0.28 mm). This finding is consistent with previous studies (Ma et al., 2018), which suggest that finer layer resolutions promote better inter-layer adhesion and overall structural integrity, resulting in enhanced mechanical properties.

2. Impact of Infill Density

The influence of infill density on ultimate stress is evident from the results, with specimens demonstrating higher infill densities generally exhibiting higher ultimate stress values. For instance, specimens TS-3, TS-6, and TS-9, printed with 100% infill density, displayed higher ultimate stress values compared to those with lower infill densities. This observation aligns with the findings of Husain et al. (2019), who reported that denser internal structures contribute to improved load-bearing capacity and mechanical performance in 3D-printed components.

3. Influence of Print Speed

The effect of print speed on ultimate stress appears to be less consistent across specimens. While some specimens (e.g., TS-5) exhibited lower ultimate stress values at higher print speeds, others (e.g., TS-6) displayed higher ultimate stress values. [8] This variability underscores the complex interplay between print speed, material deposition, and inter-layer bonding, as highlighted by Tan et al. (2020). Further investigation is warranted to elucidate the specific mechanisms underlying the observed trends and optimize print speed for enhanced mechanical properties.

4. Effect of Nozzle Temperature:

Nozzle temperature emerges as a significant factor influencing ultimate stress, with higher temperatures generally resulting in higher ultimate stress values. Specimens printed at elevated nozzle temperatures (e.g., TS-3, TS-4, TS-9) exhibited higher ultimate stress values compared to those printed at lower temperatures. This finding is consistent with the work of Chacón et al. (2017), [9] who reported that increased nozzle temperatures promote better material flow and adhesion, thereby enhancing inter-layer bonding and mechanical properties in 3D-printed components.

5. Optimization of Printing Parameters:

The results underscore the importance of optimizing printing parameters to achieve desired mechanical properties in 3D-printed PETG specimens. By carefully selecting and fine-tuning parameters such as layer thickness, infill density, print speed, and nozzle temperature, it is possible to enhance ultimate stress and produce high-quality components for various applications in additive manufacturing.

In conclusion, the results of this study provide valuable insights into the influence of printing parameters on the mechanical properties of 3D-printed PETG specimens. By systematically varying these parameters and conducting tensile tests, we have elucidated their effects on ultimate stress and highlighted opportunities for optimization. [10]Future research may focus on refining parameter settings, exploring additional factors, and validating the findings to further advance the understanding and optimization of 3D printing processes.

VI. CONCLUSION

In this study, we investigated the tensile strength of 3D-printed PETG specimens by systematically varying printing parameters such as layer thickness, infill density, print speed, and nozzle temperature. Through tensile testing and analysis, we have gained valuable insights into the influence of these parameters on the mechanical properties of the specimens.

The results reveal several important findings:

1. **Effect of Layer Thickness:** Specimens printed with finer layer thicknesses generally exhibited higher tensile strengths compared to those printed with thicker layers. This underscores the importance of finer layer resolutions in promoting better inter-layer adhesion and structural integrity.
2. **Impact of Infill Density:** Higher infill densities were associated with higher tensile strengths, indicating the importance of denser internal structures in improving load-bearing capacity and mechanical performance.
3. **Influence of Print Speed:** The effect of print speed on tensile strength was less consistent across specimens, highlighting the need for further investigation to elucidate the specific mechanisms underlying these trends and optimize print speed for enhanced mechanical properties.
4. **Effect of Nozzle Temperature:** Higher nozzle temperatures generally resulted in higher tensile strengths, emphasizing the role of temperature in promoting better material flow and adhesion, thereby enhancing inter-layer bonding and mechanical properties.

Overall, the findings underscore the importance of optimizing printing parameters to achieve desired mechanical properties in 3D-printed PETG specimens. By carefully selecting and fine-tuning parameters such as layer thickness, infill density, print speed, and nozzle temperature, it is possible to enhance tensile strength and produce high-quality components for various applications in additive manufacturing.

Moving forward, future research may focus on refining parameter settings, exploring additional factors, and validating the findings to further advance the understanding and optimization of 3D printing processes. Additionally, efforts to develop predictive models and optimization algorithms can aid in streamlining the parameter selection process and maximizing mechanical performance in 3D-printed components.

In conclusion, the insights gained from this study contribute to the growing body of knowledge in additive manufacturing and lay the foundation for further advancements in material science, process optimization, and application development in the field of 3D printing.

A conclusion section is not required. Although a conclusion may review the main points of the paper, do not replicate the abstract as the conclusion. A conclusion might elaborate on the importance of the work or suggest applications and extensions.

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