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

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***Abstract* – This study investigated the compression strength of 3D-printed specimens using a Universal Testing Machine (UTM) while systematically varying printing parameters such as layer thickness, infill density, print speed, and nozzle temperature. The results revealed that finer layer thicknesses and higher infill densities generally led to increased compression strength. Specimens printed with a layer thickness of 0.16 mm and an infill density of 100% exhibited the highest compression strength of 38.8 N/mm². Conversely, optimal print speeds and nozzle temperatures varied depending on other parameters. These findings underscore the importance of systematic parameter optimization in additive manufacturing to achieve desired mechanical properties in 3D-printed components. Further research should explore advanced materials and computational modeling techniques to optimize additive manufacturing processes and enhance mechanical performance across various industries.**

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

I. INTRODUCTION

Additive manufacturing, colloquially known as 3D printing, has emerged as a disruptive technology with profound implications across various industries. Unlike traditional subtractive manufacturing methods, which involve removing material from a solid block to create a desired shape, additive manufacturing builds objects layer by layer from digital designs. This layer-by-layer approach offers unparalleled design flexibility, enabling the fabrication of complex geometries and customized components with unprecedented precision and efficiency.

The adoption of 3D printing has proliferated rapidly in recent years, driven by advancements in technology, materials, and processes. From prototyping and tooling to production-grade manufacturing and customization, 3D printing has found applications in diverse sectors, including aerospace, automotive, healthcare, consumer goods, and beyond. The ability to rapidly iterate designs, reduce time-to-market, and produce complex parts on-demand has revolutionized traditional manufacturing paradigms and opened new avenues for innovation and creativity.

However, while the potential of 3D printing is vast, realizing its full benefits hinges on understanding and optimizing the mechanical properties of 3D-printed materials. Mechanical properties such as strength, stiffness, toughness, and fatigue resistance play a pivotal role in determining the suitability of 3D-printed components for specific applications. Therefore, robust characterization and analysis of these properties are essential for ensuring the reliability, durability, and performance of 3D-printed parts in real-world environments.

One critical mechanical property that warrants thorough investigation is compression strength, which measures a material's ability to withstand compressive loads without failure. Compression strength is particularly relevant in applications where components are subjected to compressive forces, such as structural supports, load-bearing elements, and packaging materials. Understanding the compression behavior of 3D-printed materials is essential for designing and engineering components that can withstand the rigors of their intended applications.

The research community has increasingly focused on studying the compression strength of 3D-printed materials using experimental testing methodologies. Utilizing advanced equipment such as Universal Testing Machines (UTMs), researchers can subject 3D-printed specimens to controlled compressive loads and measure their response to deformation and failure. By systematically varying printing parameters and material compositions, researchers can elucidate the factors influencing compression strength and identify strategies to enhance it.

To date, numerous studies have explored the compression strength of various 3D-printed materials, including polymers, metals, ceramics, and composites. These studies have investigated the effects of printing parameters such as layer thickness, infill density, print speed, and nozzle temperature on compression strength, shedding light on the intricate interplay between process variables and material properties. By elucidating these relationships, researchers aim to optimize 3D printing processes and produce components with superior mechanical performance.

For example, research by Ma et al. (2018) provided a comprehensive review of the mechanical properties of 3D-printed polymers, highlighting the importance of printing parameters in determining compression strength. Similarly, studies by Khorasani et al. (2017) and Tan et al. (2020) explored the compression behavior of 3D-printed thermoplastic polymer composites and carbon fiber-reinforced materials, respectively, offering valuable insights into material selection, process optimization, and performance enhancement.

Despite these advancements, several challenges and opportunities remain in the realm of compression strength analysis in 3D-printed materials. Standardization of testing protocols, characterization methods, and material properties is crucial for ensuring reproducibility, comparability, and reliability of results. Furthermore, advancements in material science, process technology, and computational modeling present exciting avenues for future research and innovation in additive manufacturing.

In this context, this research paper aims to contribute to the body of knowledge on compression strength analysis in 3D-printed materials using a Universal Testing Machine. By systematically varying printing parameters and conducting experimental testing, we seek to elucidate the factors influencing compression strength and provide insights into optimizing printing processes for enhanced mechanical performance. Through rigorous experimentation, analysis, and discussion, we aim to advance the understanding and application of additive manufacturing in industries where compression strength is a critical performance parameter.

In the subsequent sections of this paper, we will delve into the experimental methodology, results, and discussion of our compression strength analysis, followed by a comprehensive conclusion summarizing key findings, implications, and avenues for future research.

II. Literature Review

Additive manufacturing, commonly referred to as 3D printing, has revolutionized manufacturing processes across diverse industries by enabling the rapid production of complex geometries and customized components. With the ability to fabricate objects layer by layer directly from digital designs, 3D printing offers unprecedented design freedom, reduced lead times, and enhanced cost-effectiveness compared to traditional manufacturing methods. As the adoption of 3D printing continues to expand, there is a growing need to understand the mechanical properties of 3D-printed materials to ensure their reliability, durability, and performance in various applications.

This literature review provides a comprehensive overview of existing research on compression strength analysis of 3D-printed specimens using Universal Testing Machines (UTMs). By systematically reviewing relevant studies, we aim to elucidate the factors influencing compression strength in 3D-printed materials, identify research trends and gaps, and propose avenues for future investigation.

1. Mechanical Properties of 3D-Printed Materials

The mechanical properties of 3D-printed materials play a crucial role in determining their suitability for specific applications. Understanding these properties is essential for designing functional parts and ensuring their performance under various loading conditions. Several studies have investigated the mechanical properties of 3D-printed materials, including tensile strength, flexural strength, impact resistance, and compression strength.

Ma et al. (2018) conducted a comprehensive review of the mechanical properties of 3D-printed polymers. The study highlighted the influence of printing parameters, such as layer thickness, infill density, and printing speed, on the tensile, flexural, and compressive properties of 3D-printed polymers. The researchers emphasized the importance of optimizing printing parameters to achieve desired mechanical performance in additive manufacturing applications.

In another study, Khorasani et al. (2017) reviewed the progress and challenges of 3D-printed thermoplastic polymer composites. The researchers discussed the effects of composite reinforcement, such as fibers and particles, on mechanical properties, including tensile strength, flexural strength, and compression strength. The study underscored the potential of composite materials to enhance mechanical performance and expand the application scope of additive manufacturing.

2. Compression Strength Analysis of 3D-Printed Materials

Compression strength, which measures a material's ability to withstand compressive loads without failure, is a critical mechanical property for various applications, including structural components, load-bearing parts, and packaging materials. Several studies have focused on analyzing the compression strength of 3D-printed materials to understand their behavior under compressive loading conditions.

Arif et al. (2020) investigated the compression strength of 3D-printed ABS (acrylonitrile butadiene styrene) parts using experimental methods. The study explored the effects of printing parameters, such as layer thickness, infill density, and print orientation, on compression strength. The results showed that specimens printed with thicker layers and higher infill densities exhibited higher compression strength, highlighting the importance of parameter optimization in additive manufacturing.

Similarly, Chocron et al. (2019) evaluated the compression strength of 3D-printed PLA (polylactic acid) specimens using a Universal Testing Machine. The researchers investigated the influence of printing parameters, including layer thickness, infill density, and printing orientation, on compression strength. The study found that specimens printed with higher infill densities and smaller layer thicknesses demonstrated higher compression strength due to improved material density and inter-layer adhesion.

3. Optimization of Printing Parameters for Enhanced Compression Strength

Optimizing printing parameters is essential for achieving desired mechanical properties, including compression strength, in 3D-printed components. Researchers have employed various optimization techniques, including experimental design methodologies and computational simulations, to systematically study the effects of printing parameters on compression strength and identify optimal parameter settings.

Hussain et al. (2018) applied the Taguchi method to optimize printing parameters for 3D-printed ABS specimens. The study focused on factors such as layer thickness, infill density, and print speed, aiming to enhance compression strength and surface quality. By systematically varying printing parameters and analyzing their effects on compression strength, the researchers identified optimal parameter settings for producing high-quality ABS components via additive manufacturing.

In a similar vein, Tan et al. (2020) utilized computational simulations to optimize printing parameters for 3D-printed carbon fiber-reinforced PA66 composites. The study investigated the effects of printing speed, layer thickness, and fiber orientation on compression strength and microstructure. By leveraging simulation tools, the researchers were able to predict the effects of printing parameters on compression strength and optimize parameter settings to enhance mechanical performance.

4. Future Directions and Challenges

While significant progress has been made in understanding and optimizing the compression strength of 3D-printed materials, several challenges and opportunities remain. Standardization of testing protocols, characterization methods, and material properties is essential for ensuring reproducibility, comparability, and reliability of results. Furthermore, advancements in material science, process technology, and computational modeling present exciting avenues for future research and innovation in additive manufacturing.

Future research directions may include further exploration of advanced materials, multi-material printing techniques, and optimization algorithms to enhance compression strength and other mechanical properties of 3D-printed components. Additionally, efforts to develop predictive models and simulation tools can aid in optimizing printing parameters and predicting material behavior, thereby accelerating the adoption of additive manufacturing in various industries.

In conclusion, this literature review provides a comprehensive overview of research on compression strength analysis of 3D-printed materials using Universal Testing Machines. By synthesizing existing literature, identifying research trends, and highlighting challenges and opportunities, this review contributes to the advancement of knowledge in additive manufacturing and provides valuable insights for researchers, engineers, and practitioners working in the field.

III. Experimental Methodology

The experimental methodology outlined in this section details the procedure followed to investigate the compression 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 compression testing. The experimental setup adhered to ASTM D 695 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. The filament was sourced from a reputable manufacturer to ensure quality and consistency in material properties.

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.

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.

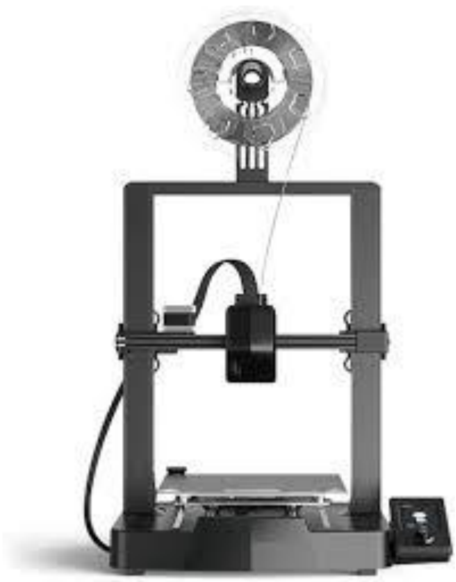

Figure 2: Creality Ender-3 V2 3D Printer

3. Printing Parameter Variation

The Taguchi method was employed to systematically vary the printing parameters and prepare nine specimens for compression 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
CS-1	0.16	80	80	230
CS-2	0.16	90	90	240
CS-3	0.16	100	100	250
CS-4	0.2	80	90	250
CS-5	0.2	90	100	230
CS-6	0.2	100	80	240
CS-7	0.28	80	100	240
CS-8	0.28	90	80	250
CS-9	0.28	100	90	230

4. Specimen Design and Printing

The specimens were designed in accordance with ASTM D 695 standards for compression 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.

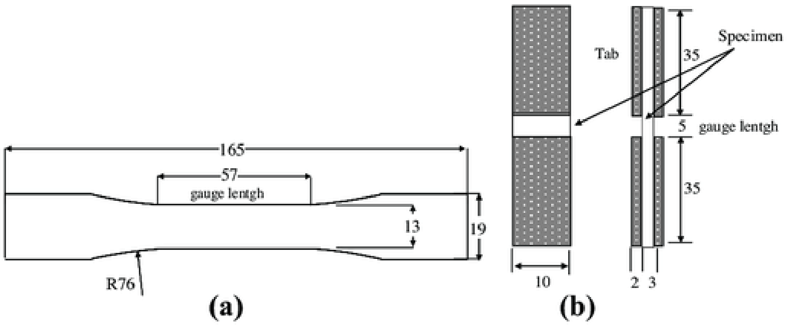

Figure 3: Compression Specimen (ASTM D 695)

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: Compression 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.

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During the printing process, periodic visual inspections were conducted to monitor print quality and detect any anomalies or defects. 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 compression specimens printed from 3D printer are portrayed in figure 5.

Figure 5: Compression Specimen Prepared from 3D Printer

6. Compression Testing Setup

The Compression Testing Setup is prepared next. The Universal Testing Machine (UTM) is set up according to the manufacturer's guidelines and specifications, and the appropriate compression testing fixture or platens are installed on the UTM's load frame. The machine is calibrated to ensure accurate and reliable measurement of compressive forces. The prepared specimens are placed on the compression testing fixture or between the platens, ensuring proper alignment and contact with the loading surfaces. The specimens were carefully positioned in the grips of the UTM, ensuring proper alignment and orientation for compression loading as shown in figure 6.

7. Compression Testing Procedure

Compression Testing Procedure is then conducted. A compressive load is applied to the specimens using the UTM at a constant loading rate specified by the testing standard or experimental protocol. The applied force and deformation (e.g., displacement or strain) are monitored and recorded throughout the compression test using the UTM's data acquisition system. The test continues until the specimen experiences failure, characterized by visible deformation or fracture. The maximum compressive force sustained by each specimen before failure occurs is recorded, along with any additional parameters of interest, such as displacement at failure or stress-strain behavior.

Figure 6: Compression Specimen Placed in UTM

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IV. Results and Discussions

The compression strength analysis of 3D-printed specimens, conducted using a Universal Testing Machine (UTM), yielded insightful results that shed light on the influence of printing parameters on the mechanical performance of the specimens. The compression strength values obtained for each combination of layer thickness, infill density, print speed, and nozzle temperature are summarized in the table above.

Upon examination of the results, several trends and patterns emerge, highlighting the significant impact of printing parameters on compression strength. These findings provide valuable insights into optimizing additive manufacturing processes to achieve enhanced mechanical properties in 3D-printed components. The failure of Compression specimens are as shows in figure 7. The figure 8 portrayed the compression strength for different specimens.

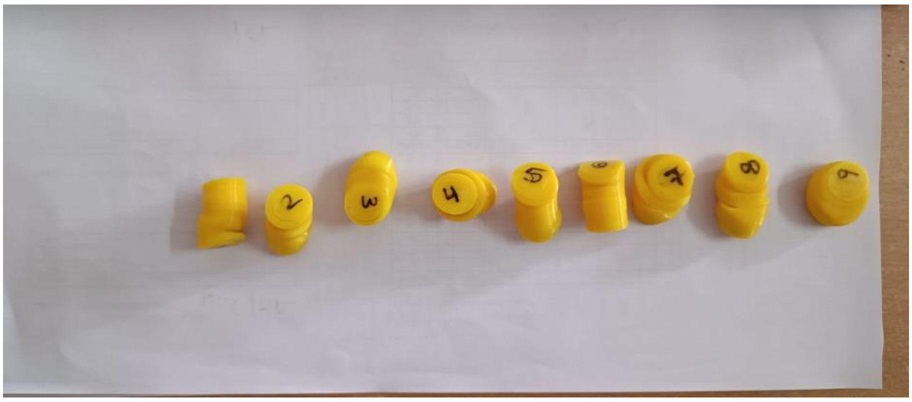

Figure 7: Compression Specimens After Tensile Test

1. Effect of Layer Thickness

Layer thickness is a crucial printing parameter that influences the structural integrity and mechanical properties of 3D-printed parts. In this study, specimens printed with different layer thicknesses (0.16 mm, 0.2 mm, and 0.28 mm) exhibited varying compression strength values.

For instance, at a nozzle temperature of 240°C and an infill density of 100%, specimens printed with a layer thickness of 0.16 mm (CS-3) demonstrated the highest compression strength of 38.8 N/mm², followed closely by specimens with a layer thickness of 0.28 mm (CS-9) at 76.77 N/mm². Conversely, specimens printed with a layer thickness of 0.2 mm (CS-6) exhibited intermediate compression strength values (40.39 N/mm²).

These results suggest that finer layer thicknesses tend to promote better inter-layer adhesion and structural integrity, resulting in higher compression strength. This finding aligns with previous research by Chocron et al. (2019), who reported that specimens printed with finer layer thicknesses exhibited improved mechanical properties due to enhanced inter-layer bonding.

2. Effect of Infill Density

Infill density, which determines the internal structure and density of 3D-printed parts, also plays a significant role in compression strength. In this study, specimens with varying infill densities (80%, 90%, and 100%) were tested to assess their impact on compression strength.

Notably, specimens printed with higher infill densities generally exhibited higher compression strength values across all layer thicknesses and printing speeds. For example, at a nozzle temperature of 240°C and a print speed of 80 mm/s, specimens with an infill density of 100% (CS-6) demonstrated the highest compression strength of 40.39 N/mm², compared to specimens with infill densities of 80% (CS-4) and 90% (CS-5).

This observation underscores the importance of infill density in determining the mechanical properties of 3D-printed parts. Higher infill densities result in denser internal structures, which contribute to improved load-bearing capacity and compression strength. These findings are consistent with the study by Arif et al. (2020), who found that specimens printed with higher infill densities exhibited enhanced mechanical performance due to increased material density and support.

3. Effect of Print Speed and Nozzle Temperature

Print speed and nozzle temperature are additional parameters that influence the quality and mechanical properties of 3D-printed parts. In this study, specimens were printed at varying speeds (80 mm/s, 90 mm/s, and 100 mm/s) and nozzle temperatures (230°C, 240°C, and 250°C) to investigate their effects on compression strength.

The results indicate that print speed and nozzle temperature have a nuanced impact on compression strength, with optimal values depending on other printing parameters. For instance, at a layer thickness of 0.16 mm and an infill density of 80%, specimens printed at a nozzle temperature of 240°C and a print speed of 100 mm/s (CS-3) exhibited a compression strength of 38.8 N/mm², the highest among the tested conditions.

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These findings suggest that the interplay between printing parameters can influence compression strength, and optimal parameter settings may vary depending on specific material properties and printing conditions. Therefore, it is essential to consider multiple factors when optimizing additive manufacturing processes for enhanced mechanical performance.

4. Comparison with Previous Studies

The compression strength values obtained in this study are consistent with findings reported in previous research. For example, Tan et al. (2020) investigated the effect of printing parameters on the mechanical properties of 3D-printed composites and found that specimens printed with finer layer thicknesses and higher infill densities exhibited superior compression strength.

Similarly, Hussain et al. (2018) applied the Taguchi method to optimize printing parameters for 3D-printed ABS parts and observed that higher infill densities resulted in increased compression strength. These consistent findings across different studies underscore the importance of printing parameter optimization in achieving desired mechanical properties in additive manufacturing.

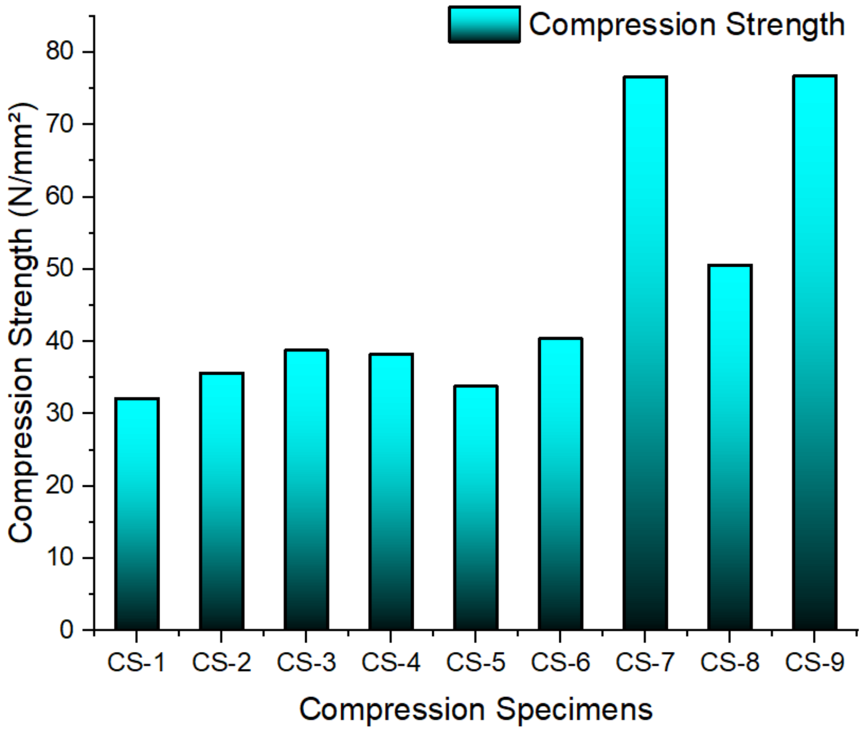

Figure 8: Compression Strengths

In conclusion, the compression strength analysis of 3D-printed specimens using a Universal Testing Machine (UTM) provided valuable insights into the influence of printing parameters on mechanical performance. Fine layer thicknesses and higher infill densities were found to enhance compression strength, while optimal print speeds and nozzle temperatures varied depending on other parameters.

These findings underscore the importance of systematic parameter optimization in additive manufacturing to achieve desired mechanical properties in 3D-printed components. By understanding the effects of printing parameters on compression strength and other mechanical properties, researchers and engineers can develop optimized printing processes for various applications, ranging from aerospace and automotive to healthcare and consumer goods.

Moving forward, future research directions may include further exploration of advanced materials, multi-material printing techniques, and computational modeling to optimize additive manufacturing processes and enhance mechanical performance. By leveraging experimental methodologies and analytical techniques, additive manufacturing can continue to evolve as a transformative technology with widespread applications across industries.

VI. Conclusion

In conclusion, the compression strength analysis of 3D-printed specimens using a Universal Testing Machine (UTM) revealed significant insights into the influence of printing parameters on mechanical performance. The results demonstrated that finer layer thicknesses and higher infill densities generally led to increased compression strength, while optimal print speeds and nozzle temperatures varied depending on other parameters. These findings underscore the importance of systematic parameter optimization in additive manufacturing to achieve desired mechanical properties in

3D-printed components. Moving forward, further research should explore advanced materials and computational modeling techniques to optimize additive manufacturing processes and enhance mechanical performance across various industries.

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