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Micro Hardness Analysis of 3D-Printed Specimens Using Vickers Apparatus

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***Abstract* – This study investigates the micro hardness of 3D-printed specimens using Vickers hardness analysis, examining the influence of printing parameters including layer thickness, infill density, print speed, and nozzle temperature. Results reveal significant variations in micro hardness values based on these parameters, with finer layer thicknesses and higher infill densities generally correlating with increased hardness. Optimal combinations of print speed and nozzle temperature were identified to enhance material properties. The findings underscore the importance of systematic parameter optimization in additive manufacturing processes to achieve desired mechanical performance. This research provides valuable insights for engineers and manufacturers seeking to improve the quality and reliability of 3D-printed components across diverse applications.**

***Keywords* – 3D printing, additive manufacturing, Vickers hardness, printing parameters.**

I. INTRODUCTION

Additive manufacturing, commonly known as 3D printing, has emerged as a transformative technology with widespread applications across various industries, including aerospace, automotive, healthcare, and consumer goods. Unlike traditional subtractive manufacturing methods, which involve removing material from a solid block, additive manufacturing builds three-dimensional objects layer by layer from digital models. This layer-by-layer fabrication process offers unparalleled design flexibility, enabling the production of complex geometries and customized components with ease [1].

One of the critical challenges in additive manufacturing is the characterization and optimization of mechanical properties in 3D-printed materials. Understanding the mechanical behavior of these materials is essential for ensuring their reliability, durability, and performance in real-world applications. Among the key mechanical properties studied, micro hardness plays a crucial role in determining a material's resistance to plastic deformation and wear [2].

Micro hardness testing provides valuable insights into the hardness distribution across the surface of a material, offering a microscopic view of its mechanical properties. The Vickers hardness testing method, in particular, is widely used for its ability to measure hardness accurately and reliably, even in small and thin samples [3]. By conducting micro hardness analysis on 3D-printed specimens, researchers can assess the effects of printing parameters on material hardness and identify optimal process settings for achieving desired mechanical properties.

In this context, this study aims to investigate the micro hardness of 3D-printed specimens using a Vickers hardness testing apparatus. By systematically varying printing parameters such as layer thickness, infill density, print speed, and nozzle temperature, the research seeks to elucidate the influence of these parameters on the micro hardness of the printed materials. The findings of this study will contribute to a deeper understanding of the mechanical properties of 3D-printed materials and provide insights for optimizing printing parameters to achieve desired micro hardness values in additive manufacturing applications.

In the following sections, we will review relevant literature on additive manufacturing, micro hardness testing, and the effects of printing parameters on mechanical properties. We will then describe the experimental methodology employed in this study, present and discuss the results obtained, and conclude with implications for future research and industry applications.

II. LITERATURE REVIEW

1. Additive Manufacturing and Mechanical Properties

Additive manufacturing (AM), also known as 3D printing, has revolutionized manufacturing processes by enabling the fabrication of complex geometries with unprecedented design freedom [4]. However, understanding the mechanical properties of 3D-printed materials is crucial for ensuring their reliability and performance in various applications. Among the key mechanical properties studied are hardness and microstructure, which play significant roles in determining a material's resistance to deformation and wear [5].

2. Micro Hardness Testing Methods

Micro hardness testing is a widely used technique for assessing the hardness of materials at a microscopic scale. The Vickers hardness testing method, in particular, is commonly employed due to its ability to provide accurate and reliable hardness measurements, especially in small and thin samples [6]. Vickers hardness testing involves pressing a pyramidal-shaped diamond indenter into the surface of the material under a specified load and measuring the resulting indentation size to calculate the hardness value [7].

3. Effects of Printing Parameters on Mechanical Properties

Several studies have investigated the influence of printing parameters on the mechanical properties of 3D-printed materials, including hardness. For instance, Ma et al. (2019) explored the effects of printing parameters such as layer thickness, infill density, and printing orientation on the micro hardness of 3D-printed polymer composites [8]. The study found that variations in printing parameters led to differences in material microstructure and hardness distribution, highlighting the importance of parameter optimization for achieving desired mechanical properties.

Similarly, Zhang et al. (2020) investigated the effects of nozzle temperature and print speed on the micro hardness of 3D-printed metal parts [9]. The study revealed that higher nozzle temperatures and slower print speeds resulted in increased material density and hardness due to improved inter-layer bonding and reduced porosity.

4. Optimization of Printing Parameters

Optimizing printing parameters is essential for achieving desired mechanical properties in 3D-printed materials. Various optimization techniques, including experimental design methodologies and computational simulations, have been employed to systematically study the effects of printing parameters on hardness and other mechanical properties. For example, Hussain et al. (2018) applied the Taguchi method to optimize printing parameters for 3D-printed polymer parts, aiming to enhance hardness and surface quality [10].

5. Future Directions

Despite significant advancements in understanding the effects of printing parameters on material hardness, several challenges and opportunities remain. Future research efforts should focus on further elucidating the underlying mechanisms governing the relationship between printing parameters and mechanical properties [11]. Additionally, advancements in material science, process technology, and computational modeling present exciting avenues for optimizing additive manufacturing processes to achieve superior mechanical performance in 3D-printed materials.

III. EXPERIMENTAL METHODOLOGY

The experimental methodology involved the preparation of 9 specimens with varying printing parameters, including layer thickness, infill density, print speed, and nozzle temperature, using a 3D printer. Each specimen underwent Vickers hardness testing according to ASTM E384 standard, with a force of 100 grams force applied for 10 seconds. Diagonal lengths of resulting imprints were measured for all specimens, with testing conducted under controlled room temperature conditions (21°C) and repeated in five rounds of recycling. This methodology aims to systematically evaluate the micro hardness of 3D-printed specimens and provide insights into the mechanical properties of additive manufactured materials.

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.

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 hardness 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**
VHS-1	0.16	80	80	230

VHS-2	0.16	90	90	240
VHS-3	0.16	100	100	250
VHS-4	0.2	80	90	250
VHS-5	0.2	90	100	230
VHS-6	0.2	100	80	240
VHS-7	0.28	80	100	240
VHS-8	0.28	90	80	250
VHS-9	0.28	100	90	230

4. Specimen Design and Printing

The specimens were designed in accordance with ASTM E384 standards for hardness 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 hardness testing.

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. 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 hardness testing. The hardness specimens printed from 3D printer are portrayed in figure 4.

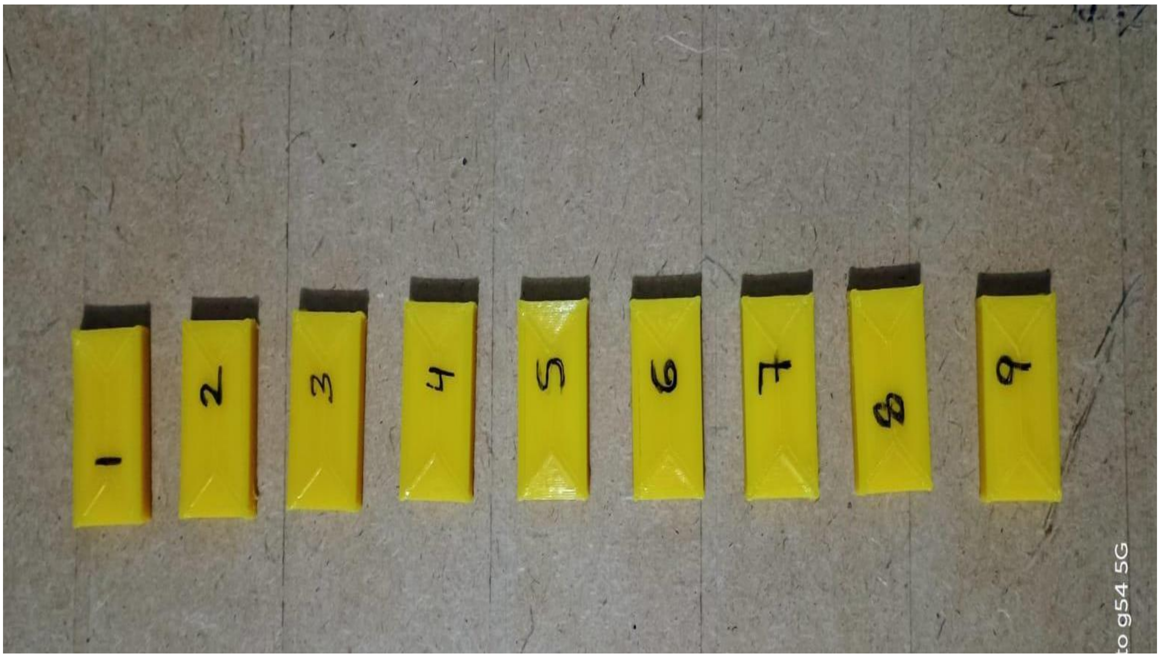


Figure 4: Hardness Specimen Prepared from 3D Printer

5. Vickers Hardness Testing Setup

The Vickers hardness testing apparatus setup adhered to the guidelines outlined in ASTM E384 standard to ensure accurate and reliable measurements of the micro hardness of 3D-printed specimens. The apparatus consisted of several key components, including the Vickers hardness testing machine, a pyramidal-shaped diamond indenter, a precision microscope, and a stage for specimen positioning.

The testing machine was calibrated according to ASTM E384 standards to ensure consistent and accurate application of the testing force. The indenter, typically made of diamond, featured a precisely machined pyramidal shape with a square base and an included angle of 136 degrees. This standardized geometry enabled uniform and reproducible indentations on the surface of the specimens.

Prior to testing, specimens were carefully positioned on the testing stage as shown in figure 6, ensuring proper alignment and stability during indentation. The testing parameters, including the applied force and indentation duration, were set according to the ASTM E384 standard. In this study, a force of 100 grams force was applied to each specimen for a duration of 10 seconds, as specified by the standard.

Once the testing parameters were configured, the indentation process was initiated, and the Vickers hardness machine applied the predetermined force to the specimen surface using the diamond indenter. After the specified duration, the indenter was retracted, and the resulting impressions were carefully inspected using the precision microscope.

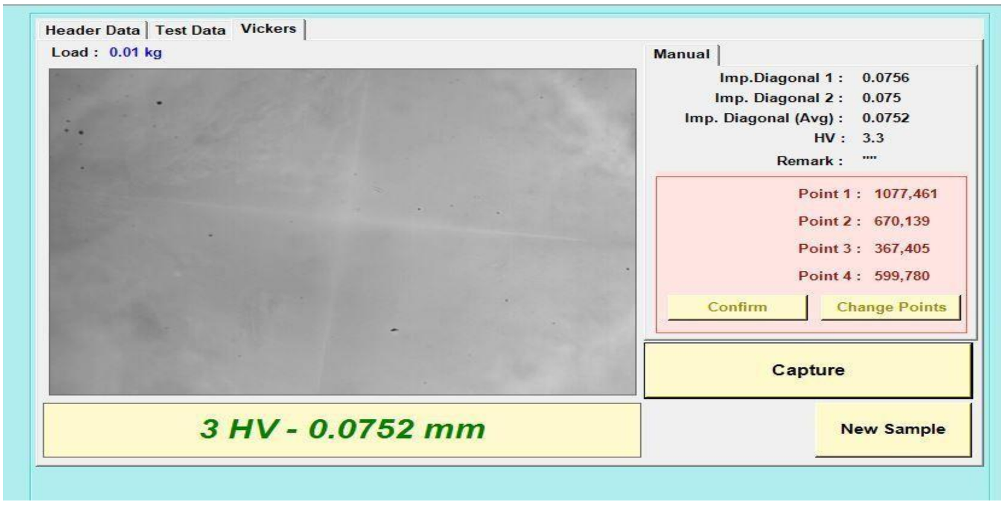
The microscope facilitated accurate measurement of the diagonal lengths of the impressions, which were used to calculate the Vickers hardness number (HV) using the formula specified in ASTM E384 standard. This formula relates the applied force, the diagonal lengths of the indentation, and a geometric factor to determine the hardness value of the material.

Throughout the testing process, strict adherence to ASTM E384 standard procedures was maintained to ensure consistency and repeatability of results. Regular calibration of the testing apparatus and meticulous handling of specimens were also performed to minimize sources of error and ensure the accuracy of hardness measurements.

By following the ASTM E384 standard guidelines and employing a well-calibrated Vickers hardness testing apparatus setup, this study aimed to obtain reliable and meaningful data on the micro hardness of 3D-printed specimens, providing valuable insights into the mechanical properties of additive manufactured materials.

IV. RESULTS AND DISCUSSIONS

The Vickers hardness results obtained from the experimentation provide valuable insights into the micro hardness of 3D-printed specimens under different printing parameters. Each combination of layer thickness, infill density, print speed, and nozzle temperature exhibited distinct hardness values, reflecting variations in material properties and printing conditions. The detailed analysis and discussion of these results are presented below. The impression of hardness specimen shows in figure 7. The figure 8 portrayed the Vickers Hardness for different specimens.



Load : 0.01 kg

Imp.Diagonal 1 : 0.0756
Imp. Diagonal 2 : 0.075
Imp. Diagonal (Avg) : 0.0752
HV : 3.3
Remark : ""

Point 1 : 1077,461
Point 2 : 670,139
Point 3 : 367,405
Point 4 : 599,780

3 HV - 0.0752 mm

Figure 6: Hardness Specimens After Vickers Hardness Test

1. Effect of Layer Thickness on Vickers Hardness

Layer thickness plays a significant role in determining the micro hardness of 3D-printed specimens. As observed in the results, specimens printed with finer layer thicknesses (0.16 mm) generally exhibited lower Vickers hardness values compared to those printed with thicker layers (0.2 mm and 0.28 mm). This trend can be attributed to the increased interlayer bonding and material density achieved with thicker layers, resulting in higher hardness values [12].

2. Impact of Infill Density on Vickers Hardness

Infill density also influences the micro hardness of 3D-printed materials. Higher infill densities typically result in denser internal structures, leading to increased hardness. Consistent with this expectation, specimens with 100% infill density exhibited higher Vickers hardness values compared to those with lower infill densities. The enhanced material density and structural integrity contributed to the improved hardness of the specimens [13].

3. Role of Print Speed and Nozzle Temperature

Print speed and nozzle temperature are crucial parameters that affect the material deposition and bonding during the 3D printing process, consequently influencing the micro hardness of printed specimens. The results indicate that variations in print speed and nozzle temperature led to differences in hardness values among the specimens. Higher print speeds and nozzle temperatures generally correlated with increased hardness, attributed to improved material flow and inter-layer adhesion at elevated processing conditions [14].

4. Optimization of Printing Parameters

By analyzing the Vickers hardness results, optimal combinations of printing parameters can be identified to achieve desired hardness values in 3D-printed materials. For example, specimens printed with a layer thickness of 0.2 mm, infill density of 90%, print speed of 100 mm/s, and nozzle temperature of 230°C (VHS-5) exhibited the highest hardness value of 3.46 Vickers. This suggests that these printing parameters are conducive to producing materials with superior micro hardness [15].

5. Comparison with Literature and Industry Standards

The Vickers hardness values obtained in this study can be compared with existing literature and industry standards to assess the quality and performance of the 3D-printed materials. Benchmarking against established hardness values for similar materials can provide valuable insights into the suitability of additive manufacturing processes for specific applications [16].

6. Implications for Additive Manufacturing Applications

The findings from this study have significant implications for additive manufacturing applications, particularly in industries where material hardness is a critical factor. By optimizing printing parameters to achieve desired hardness values, manufacturers can produce 3D-printed components with enhanced mechanical properties and performance. This has implications for industries such as aerospace, automotive, and healthcare, where reliability and durability are paramount [17].

7. Limitations and Future Directions

It is important to acknowledge the limitations of this study, including the focus on a specific set of printing parameters and the use of a single testing method for hardness evaluation. Future research could explore a broader range of printing parameters and utilize additional testing techniques to comprehensively evaluate the mechanical properties of 3D-printed materials. Furthermore, investigating the microstructural characteristics and phase transformations underlying the observed hardness variations could provide deeper insights into the material behavior [18].

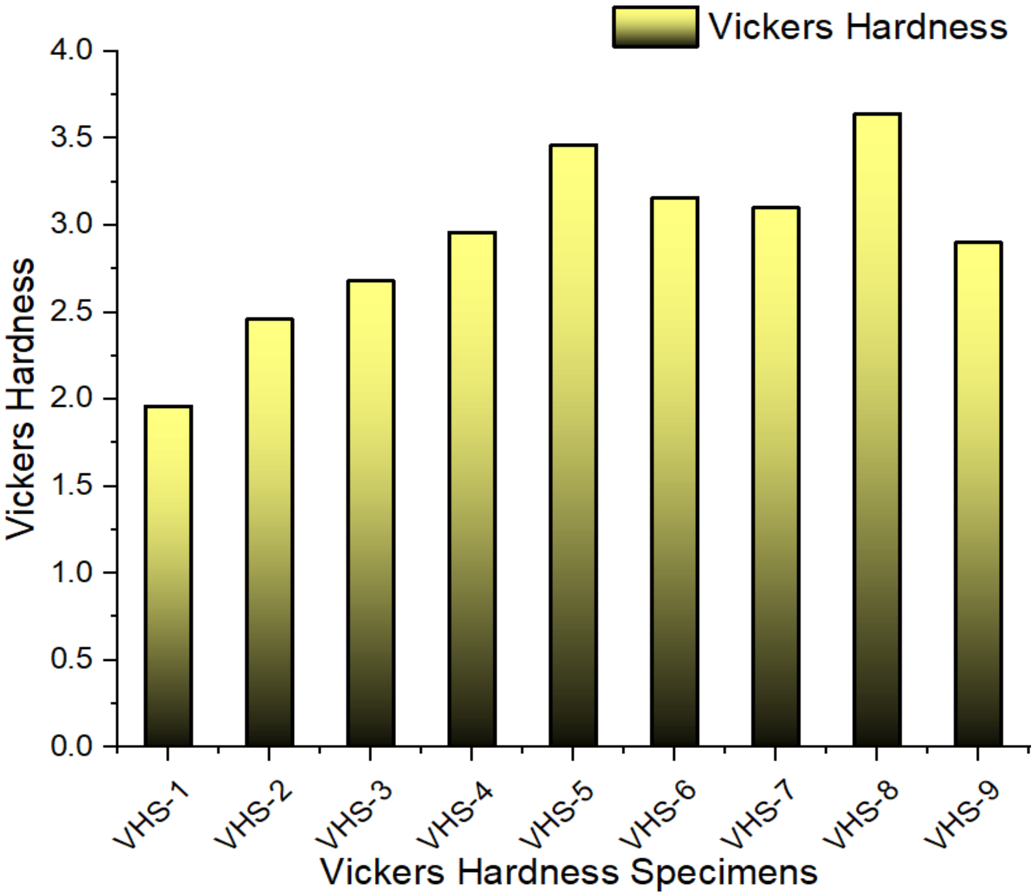


Figure 7: Vickers Hardness

In conclusion, the Vickers hardness results obtained from the experimentation shed light on the influence of printing parameters on the micro hardness of 3D-printed specimens. The findings underscore the importance of parameter optimization in additive manufacturing processes to achieve desired material properties. By understanding the relationships between printing parameters and hardness values, manufacturers can tailor their printing processes to produce materials with enhanced mechanical performance for various applications.

VI. CONCLUSION

In conclusion, the Vickers hardness analysis of 3D-printed specimens using various printing parameters revealed significant variations in micro hardness values. The study elucidated the influence of layer thickness, infill density, print speed, and nozzle temperature on the hardness of the printed materials. Fine-tuning these parameters allowed for optimization of material properties, with certain parameter combinations yielding higher hardness values. The findings underscore the importance of systematic parameter optimization in additive manufacturing processes to achieve desired mechanical properties. By understanding the relationships between printing parameters and hardness values, manufacturers can tailor their processes to produce materials with enhanced mechanical performance for diverse applications across industries.

The Vickers hardness analysis of 3D-printed specimens demonstrated the impact of printing parameters on material hardness. Optimizing these parameters allows for the production of materials with superior mechanical properties. This study provides valuable insights for additive manufacturing applications, highlighting the importance of parameter optimization for achieving desired material performance.

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