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A STUDY ON THE INFLUENCE OF PRINTING ORIENTATION IN METAL PRINTING USING MATERIAL EXTRUSION TECHNOLOGY ON THE MECHANICAL PROPERTIES OF 17-4 STAINLESS STEEL PRODUCTS

This study investigated the influence of print orientation on the mechanical properties of 17-4 PH stainless steel parts fabricated using material extrusion technology. Tensile test specimens were 3D printed in different orientations (flat, on-edge, and upright), and their mechanical properties were evaluated. The results showed that the print orientation significantly affected the ultimate tensile strength, yield strength, and elongation at failure of the specimens. The flat and on-edge orientations exhibited similar mechanical properties, while the upright orientation resulted in lower strength and higher fracture susceptibility. Hardness measurements also indicated variations in hardness distribution among the orientations. The findings emphasize the importance of optimizing the print orientation parameter to achieve desired mechanical characteristics in 17-4 PH stainless steel parts.

1. INTRODUCTION

Additive manufacturing has revolutionized the manufacturing industry, allowing for the production of complex-shaped products that were previously difficult or impossible to manufacture using traditional methods. According to ASTM/ISO standards, metal 3D printing technology is classified into seven groups, and one of the popular metal 3D printing technologies is Material Extrusion (ME), which involves the layer-by-layer deposition of material [1]. The material extrusion printing process is illustrated in Fig. 1. The composition of the printing filament can vary, depending on the type of metal powder combined with ABS or PLA plastic materials, and the ratio of metal powder to plastic can be adjusted accordingly [1]. The resulting product is a mixture of metal powder particles dispersed within the binding plastic material [2]. In ME, the printing filament is composed of a binder material, typically plastic, and fine metal powder. This filament is heated and extruded through a printer nozzle, as shown in Fig. 2. The nozzle heats the printing filament to its melting temperature, and it is then extruded layer by layer to form the 3D product. After printing, the product undergoes a two-step post-processing: washing and sintering, to create high-density metal parts.

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The circular shape of the printer nozzle and the spacing between printed layers result in a relatively low surface quality of the printed object. The washing process is performed to remove the polymer component from the "green" parts, which have a high porosity. These washed parts are then placed in a sintering furnace to further remove any remaining polymer and solidify the material by heating it beyond the melting temperature of the metal powder. The objective is to achieve a theoretical density of 96-99.8% for the metal component. Density plays a crucial role in determining shrinkage and is calculated during the data transmission stage [3].

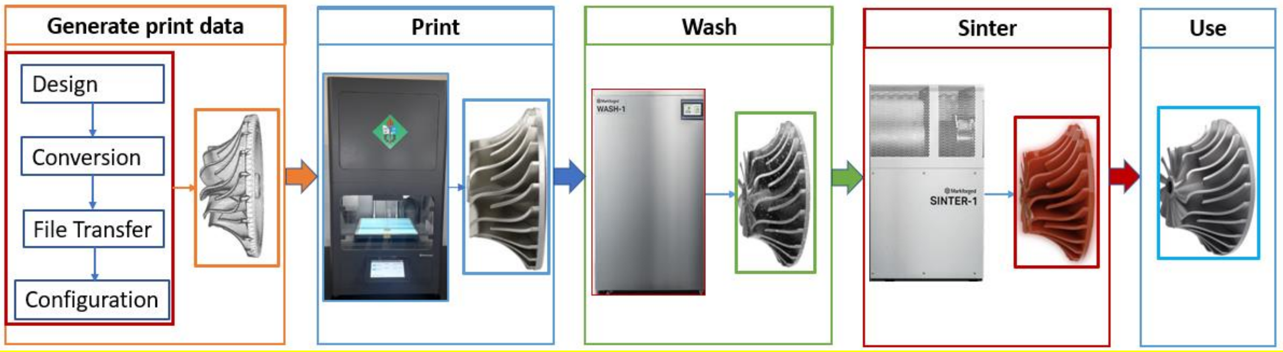

Fig. 1. Schematic diagram of the material extrusion printing process

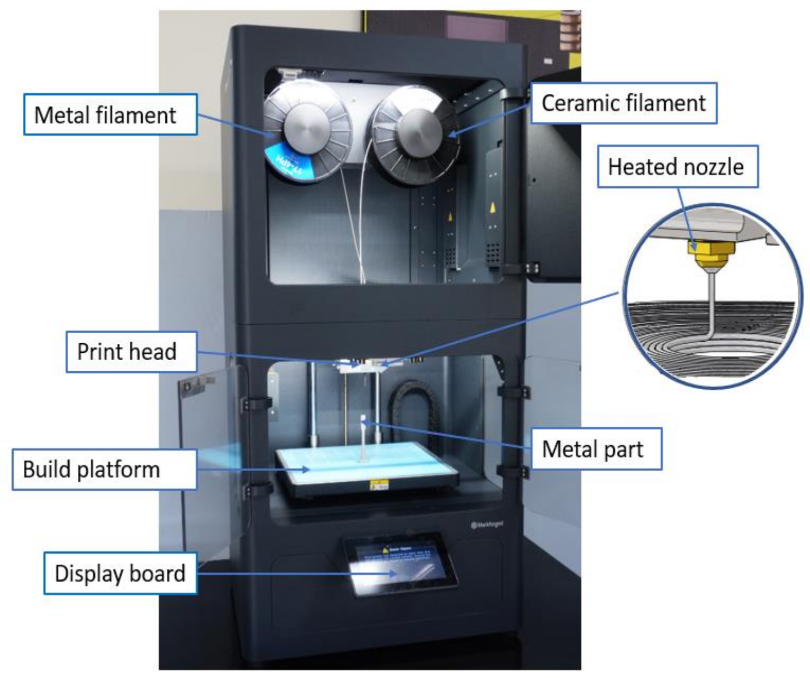

Fig. 2. Schematic of a ME machine

Stainless steel is highly favoured in 3D printing due to its exceptional strength and corrosion resistance. 17–4 PH stainless steel is known for its high strength and good corrosion resistance. The Ultimate Tensile Strength (UTS) of 17–4 PH stainless steel typically ranges from 1000 to 1250 MPa. The Elongation at Break (EB) of this material is usually around 15–20%, indicating its ability to undergo deformation before breaking. Regarding hardness, 17–4 PH stainless steel typically exhibits a hardness of approximately 30-35 HRC (Rockwell Hardness Scale). According to the Markforged supplier, the chemical composition of 17–4 PH stainless steel is as indicated in Table 1. 17–4 PH stainless steel finds extensive applications across industries such as aerospace, medical, and defence for 3D printing purposes. However, employing the Material Extrusion (ME) technology for printing 17–4 PH stainless steel presents challenges, notably the influence of print orientation on the properties and characteristics of the printed products. Therefore, it is crucial to study the effects of print orientation on the mechanical properties of 17–4 PH stainless steel parts fabricated via material extrusion. This research endeavour aims to optimize the manufacturing process and enhance the quality of the printed products.

Table 1. The composition of 17–4 PH stainless steel

Composition	Amount
Chromium	15-17.5%
Nickel	3-5%
Copper	3-5%
Silicon	1% max
Manganese	1% max
Niobium	0.15-0.45%
Carbon	0.07% max
Phosphorous	0.04% max
Sulfur	0.03% max
Iron	bal

Print orientation profoundly impacts the mechanical properties of 3D printed objects. It pertains to the placement of the printed part on the printer bed and can assume horizontal, vertical, or angled orientations. Print orientation affects the grain structure, thermal stresses, and cooling rate of the material, thereby influencing its mechanical properties. Numerous studies have explored the influence of print orientation on aluminum parts printed using ME technology, revealing significant effects on the microstructure, mechanical properties, and surface quality of the printed components [4–8].

Although limited research has been conducted to characterize modern ME processes, it is insightful to refer to previous reports that investigate mature extrusion-based techniques. Anisotropy represents one common defect observed in such processes, attributed to the linear formation of intra-filament pores at the interface between solidified layers, resulting from the spherical profile of the extrusion nozzle [9–11]. These pores generate localized stress concentrations that compromise bond strength and contribute to structures susceptible to premature failure in the plane parallel to the applied load. Notably, the manifestation of these defects is significantly influenced by the build orientation and layer thickness (LT) [12]. For instance, studies have demonstrated that fused filament fabrication (FFF) tensile samples printed perpendicular to the loading direction (flat and on-edge) exhibit the highest strength, while samples printed parallel to the loading direction (vertical) display the lowest strength [13]. Furthermore, flat and on-edge samples consistently outperform vertically printed samples, exhibiting higher relative density [14–17]. Minimizing the layer thickness (LT) has also been found to improve tensile strength by reducing pore size and enhancing overall density [13]. However, conflicting results have been reported in other studies [18]. Increasing the layer thickness (LT) has shown potential for improving the tensile strength of certain parts, possibly by reducing the number of filament strands and interfaces between bonds, leading to fewer intra-filament pores. Nevertheless, contradictory findings were observed in a separate study where altering the LT had a negligible effect on the density of printed parts [19].

Advancements in modern ME technologies have shown promising results, particularly with parts produced by bound metal deposition (BMD), exhibiting comparable mechanical properties to those achieved through metal injection moulding (MIM) when oriented flat with rafts [19]. For example, sintered samples achieved a tensile strength of 776 MPa, falling within the MIM range of 775–950 MPa. However, such parts may experience a reduction in stiffness by up to 7%. It is believed that this reduction can be mitigated by improving surface finishes through machining, although this hypothesis has not yet been verified [1].

There have been studies on the influence of print orientation on the mechanical properties of 17–4 PH stainless steel parts fabricated using material extrusion. In the study by AJ Hensley et al. [20], the authors investigated the impact of print orientation on the tensile strength and ductility of 17–4 PH stainless steel parts manufactured using fused filament fabrication. The results showed that the print orientation strongly affected the tensile strength and ductility, with parts printed in the *Z*-axis direction exhibiting the highest values. Similarly, in the study by S. Bhowmik et al. [21], the authors evaluated the influence of process parameters, including print orientation, on the mechanical properties of 17–4 PH stainless steel parts fabricated using FFF. The results indicated that print orientation significantly affected the ultimate tensile strength, yield strength, and elongation at fracture of the parts, with parts printed in the Z-axis direction demonstrating the highest mechanical properties. In contrast, the study by RS Mishra et al. [22] investigated the influence of print orientation on the mechanical properties of 17–4 PH stainless steel parts fabricated using selective laser melting (SLM). The results showed that print orientation had a negligible effect on the mechanical properties of the parts, with parts printed in both the horizontal and vertical orientations exhibiting similar mechanical properties. Zhang et al. [23] studied the influence of print orientation on the strength of 17–4 PH stainless steel parts fabricated using material extrusion. The study showed that print orientation significantly affected the ultimate tensile strength, yield strength, and elongation at fracture of the parts. Samples printed in the horizontal direction exhibited the highest ultimate tensile strength, while samples printed in the vertical direction showed the highest yield strength. Diagonal-printed samples exhibited the highest elongation at fracture. Overall, this study emphasized the importance of print orientation in determining the mechanical properties of material-extruded parts. Gao et al. [24] investigated the influence of print orientation and heat treatment on the microstructure and mechanical properties of 17–4 PH stainless steel parts fabricated using laser powder bed fusion. The study demonstrated that print orientation significantly affected the microstructure and mechanical properties of the parts, with vertically printed specimens exhibiting a fine equiaxed grain structure and the highest hardness, while horizontally printed specimens showed the highest tensile strength. This research provided valuable insights into the influence of print orientation on the microstructure and mechanical properties of 17–4 PH stainless steel parts fabricated using a different method than material extrusion. Hu et al. [25] examined the influence of print orientation on the mechanical properties of 17–4 PH stainless steel parts fabricated using material extrusion. The study revealed that print orientation significantly affected the ultimate tensile strength, yield strength, and elongation at fracture of the parts. Samples printed in the horizontal direction exhibited the highest ultimate tensile strength, while samples printed in the vertical direction showed the highest yield strength. Diagonal-printed samples exhibited the highest elongation at fracture.

The aforementioned studies demonstrate that print orientation during the material extrusion of 17–4 PH stainless steel significantly influences its mechanical properties. The findings indicate that the optimal print orientation may depend on the specific product and desired characteristics of the components. Therefore, further research is needed to gain a better understanding of the underlying mechanisms behind the observed phenomena and characteristics associated with print orientation, aiming to optimize the printing process for 17–4 PH stainless steel products.

2. MATERIALS AND METHODS

To evaluate the influence of print orientation parameters, experimental samples were printed in various directions. The printing material consisted of a composite of 17–4 PH stainless steel and a polymer, which served as the feedstock for the material extrusion 3D printer. Tensile specimens were printed in three different orientations: flat, on-edge, and upright (Fig. 3). The infill pattern for each orientation was displayed as shown in Fig. 4, with a triangular fill pattern selected as the fill pattern parameter. The post-sintered layer height was set to 0.127 mm.

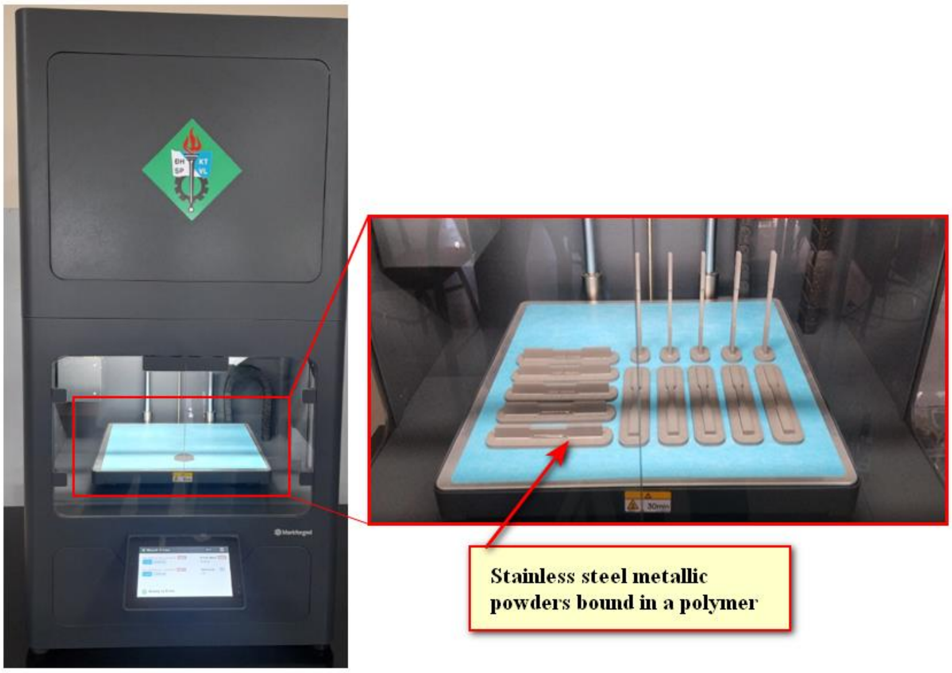

Fig. 3. Experiments on the ME machine

When printing in the On-Edge orientation, the empty space underneath is filled with support material (Fig. 4). The test samples were manufactured using the Markforged Metal X commercial 3D printer located in the additive manufacturing laboratory at Vinh Long University of Technology Education, Vinh Long City, Vietnam, as illustrated in Fig. 5.

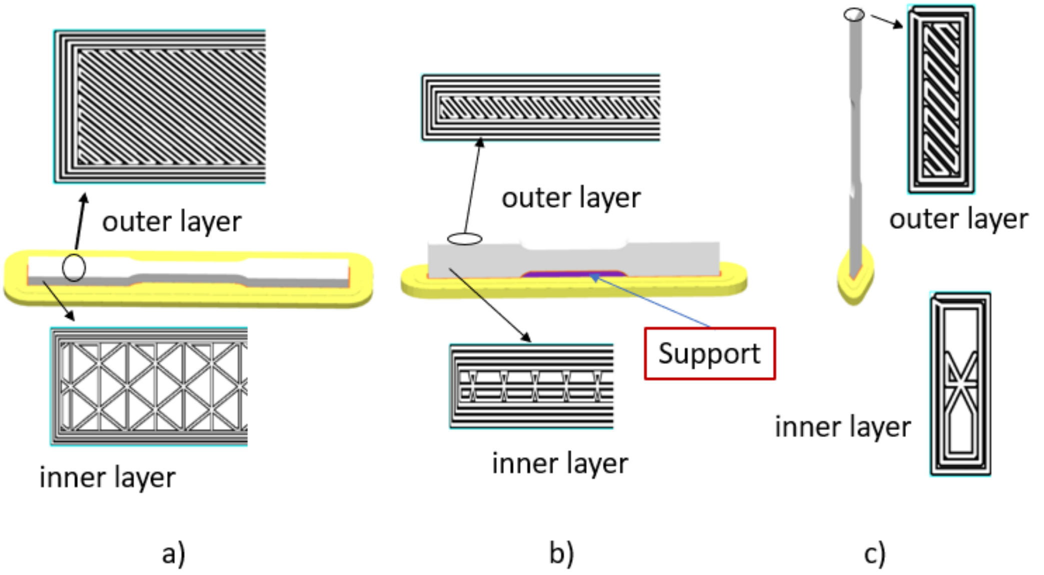

Fig. 4. The structure of the infill pattern depends on the print orientation: a) Flat, b) On-Edge, c) Upright

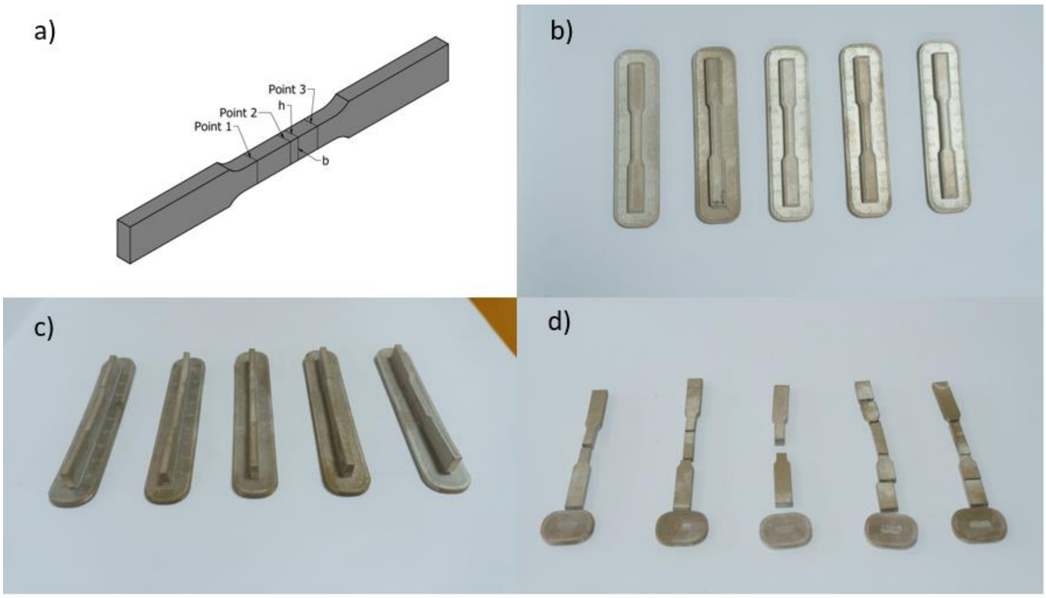

Fig. 5. The sample components after the printing process: a) Size measuring position, b) Flat (horizontally), c) On-Edge, d) Upright (vertically)

The accuracy of a 3D printed product refers to how closely its dimensions align with the design dimensions. The design dimensions are based on the CAD model, while the dimensions of the printed product are measured at a specific location using measuring equipment. In this study, the width and height dimensions in the middle region of the test specimen were utilized to assess accuracy. The CMM COORD3 BENCHMARK 5.4.4 measuring machine was used to measure the dimensions of the samples. The cross-section dimensions at three points (both ends and the middle) of the middle part of the sample were measured, as depicted in Fig. 5a, and compared to the CAD design dimensions to evaluate the accuracy. For each printing orientation, five samples were printed under the same conditions. These five samples were then measured using the same settings, and the average dimensions were calculated. The measuring equipment and procedure are illustrated in Fig. 6.

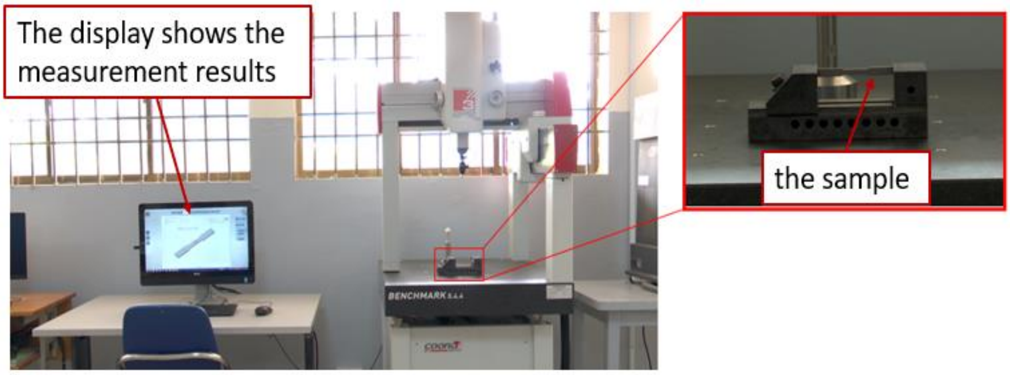

Fig. 6. Measure the size and geometry of the sample

The tensile strength testing is conducted using the 300DX Static Hydraulic Universal Testing Machine in accordance with the ASTM standard 8-08. Five samples from each printing orientation are tested for tensile strength, and the average values are obtained. Before testing, the samples are conditioned in a room with a humidity of 60–65% and a temperature of 27 degrees Celsius (ambient temperature in Vietnam) for 48 hours. The specimens for tensile testing are prepared as depicted in Fig 5.

3. RESULTS AND DISCUSSION

Figure 5 displays the outcomes of the product samples following the printing, washing, and sintering stages. Notably, the samples printed in the Upright position and then subjected to sintering tend to fracture into multiple pieces. This is attributed to the layering arrangement and the effect of gravity during the solidification process, which increases the risk of deformation and eventual breakage of the part.

3.1. ASSESSING THE ACCURACY OF THE PRODUCT AFTER THE PRINTING PROCESS

The average dimensional accuracy of the five test samples is shown in Fig. 7. The measured average values are presented in Table 2. These measured results are compared with the design dimensions (width “b” = 5 mm and thickness “h” = 3.2 mm) to assess the accuracy.

Table 2. The average measurement results of the samples

Print orientation	Flat		On - Edge		Upright	
Dimension	b	h	b	h	b	h
	4.833	3.275	5.153	3.181	5.007	3.186

From the measurement results, it can be observed that there is not much variation in size among the test samples, although the number of layers and infill pattern had a slight impact on size variation in certain cases. The outermost layer structure of each print orientation significantly influenced the dimensions. Thinner outermost layers reduced warping and improved accuracy, while thicker outermost layers resulted in significant temperature variations and increased warping. The variation in the internal layer structure also affected the shrinkage rate and influenced the dimensions and warping of the product. The measurement results of the test samples showed significant similarity between the Flat and On-edge orientations, while the Upright orientation exhibited the highest level of dimensional accuracy.

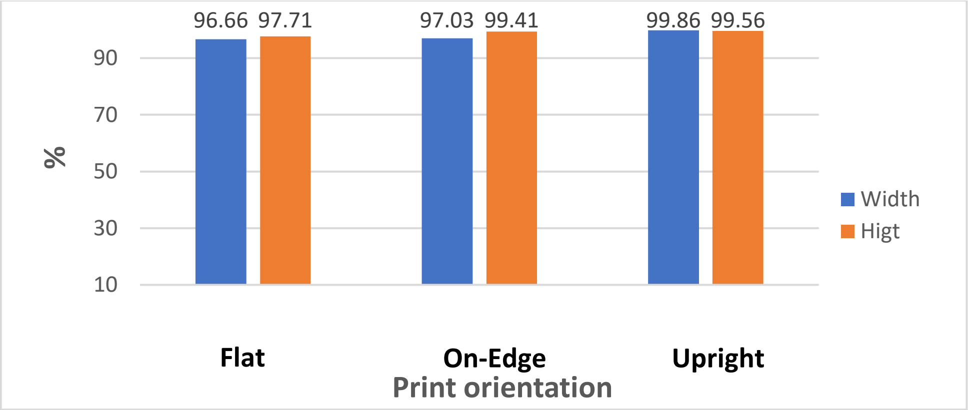

Fig. 7. The average accuracy of tensile test specimens printed in various orientations

The Upright orientation exhibits the highest level of accuracy due to its smaller contour compared to the Flat and On-Edge cases. The average accuracy for height and width across all orientations is 98.89% and 97.85% respectively, relative to the nominal dimensions.

3.2. ANALYSIS OF TENSILE STRENGTH TESTING RESULTS

The results of the tensile strength testing are presented in Fig. 8, clearly illustrating the stress-strain curves of the Flat and On-Edge specimens are nearly identical. Among the tested specimens, the Flat specimens exhibit the highest flexibility, while the On-Edge specimens show the highest fracture strength. Interestingly, the Upright specimens fracture into multiple pieces during the sintering stage. To explain these results, we can refer to the structure of the printed lines in the test samples as shown in Fig. 4. The internal structure is composed of the outer shell lines and inner infill lines. In the case of Flat specimens, the outer shell lines are parallel to the applied force of the tensile testing machine, while the inner infill lines are oriented at a 45-degree angle with respect to the direction of the applied force, making them prone to deformation. On the other hand, the On-Edge specimens have a more complex structure with relatively smaller outer shell lines and a thicker outer shell layer, along with shorter infill lines. This arrangement enhances their strength during the tensile testing process. Overall, these results highlight the significant influence of the printing orientation on the mechanical properties of the specimens, which aligns with previous studies.

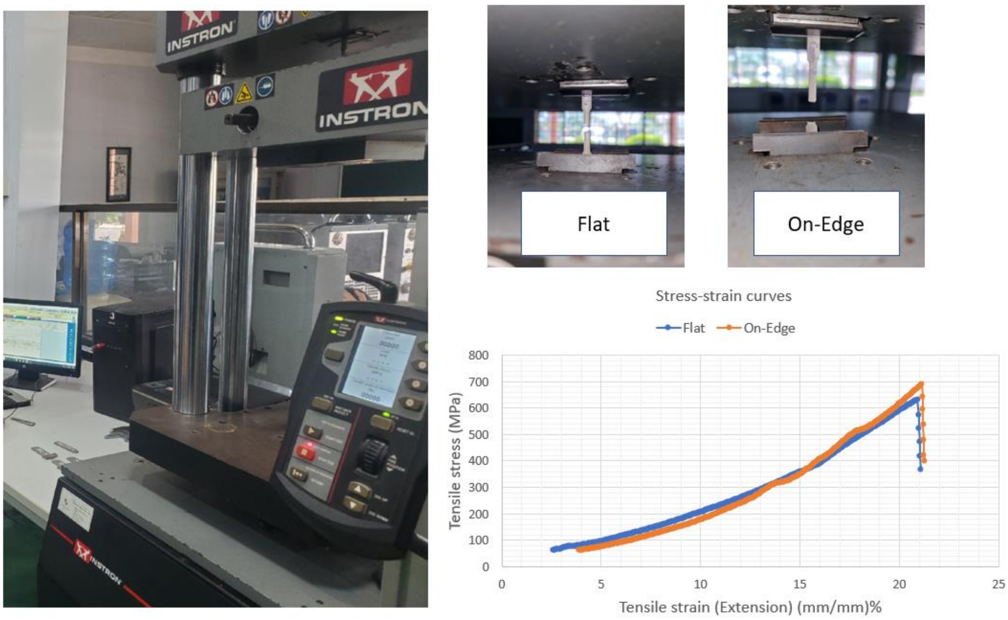

Fig. 8. The tensile deformation curves and fracture surface shapes of the test specimens

The Flat specimens have a tensile strength of 630 MPa, while the On-Edge specimens exhibit the highest UTS of 691 MPa, indicating a 9% increase in tensile strength for the On-Edge specimens compared to the Flat ones. The On-Edge specimens also show the highest elongation at break of 21.24%, slightly higher than the 21.05% for the Flat specimens.

The deformation and fracture surface morphology vary among the different printing orientations. The Flat and On-Edge specimens both exhibit ductile deformation during the tensile testing, which can be attributed to the orientations of the printed lines. The fracture surface of the Flat specimen occurs at an angle that corresponds to its printed line structure. In contrast, the On-Edge specimens demonstrate higher tensile strength due to the resilient structure of the internal printed layers and the duplicated outer layers, which aligns with their characteristic tensile properties.

3.3. DETERMINATION OF HARDNESS

The Rockwell hardness testing method was employed to determine the hardness of the test specimens. Hardness measurements were taken at three points on each specimen (at the top, transition, and middle positions). The results revealed hardness distributions for the Flat, On-Edge, and Upright orientations to range from (57–60), (59–62.5), and (46–60) HRA, respectively, as depicted in Fig. 9. The highest hardness values were observed in the On-Edge and Upright specimens. The heterogeneous distribution of hardness values along the specimen length can be attributed to factors such as non-uniform cooling during the material extrusion process, the development of residual stresses, variations in microstructure, inhomogeneous material flow, and the influence of heat treatment processes. These factors can result in variations in the hardness of different regions within the specimen.

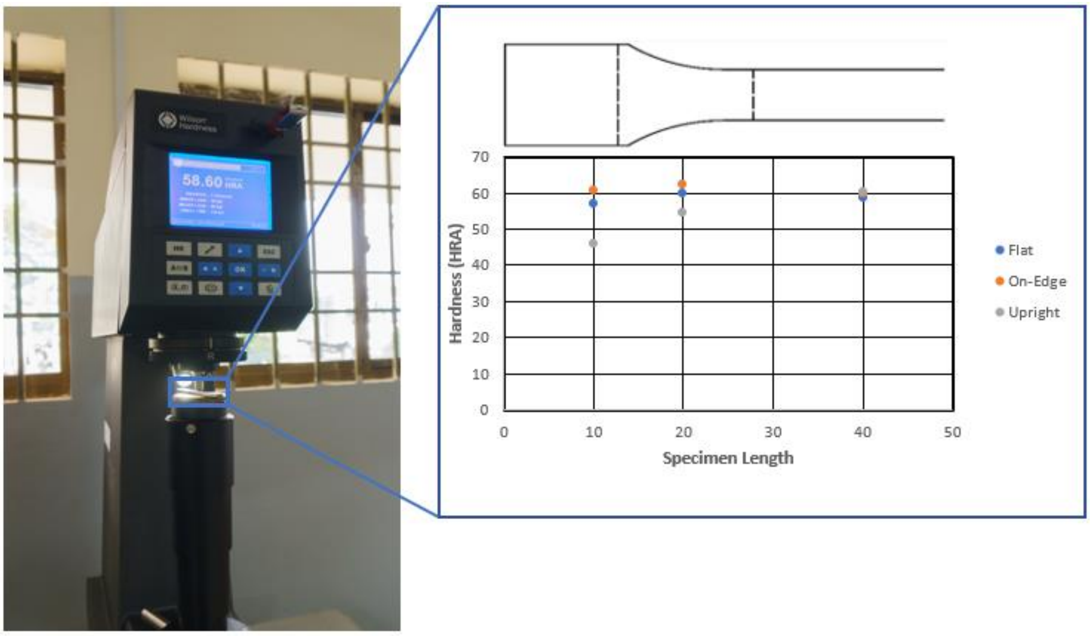

Fig. 9. Results of the hardness test

4. CONCLUSION

The findings of this study highlight the significant impact of the print orientation parameter on the mechanical properties of 17–4 PH stainless steel parts produced through material extrusion. The results clearly demonstrate that the choice of print orientation parameter directly influences the tensile strength, elongation at break, and hardness of the printed parts. The observed variations in mechanical properties can be attributed to several underlying factors. First, the print orientation parameter affects the distribution of residual stresses within the printed parts, leading to variations in mechanical behavior. Second, the print orientation parameter influences the microstructural features, such as grain orientation and size, which directly impact the mechanical properties. Additionally, the print orientation parameter affects the cooling rate and solidification behavior during the printing process, further contributing to the observed variations in mechanical properties. These findings underscore the importance of carefully selecting the print orientation parameter to achieve desired mechanical characteristics in 17–4 PH stainless steel parts. Researchers and practitioners should consider the specific application requirements and desired mechanical properties when determining the optimal print orientation parameter. To further advance our understanding, future research should focus on investigating the specific mechanisms that govern the relationship between the print orientation parameter and mechanical properties. This can involve more detailed microstructural analysis, finite element simulations, and additional experimental studies. By gaining deeper insights into these underlying mechanisms, we can develop improved strategies for optimizing the print orientation parameter and enhancing the mechanical performance of 17–4 PH stainless steel parts.

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