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Mechanical and Microstructure Characterization of Binder Jetting Additive Manufacturing of 17-4PH Stainless Steel

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The present work provides insights into the Binder Jet Additive Manufacturing (BJAM) process parameters that influence the material properties such as porosity, and mechanical properties of the 17-4PH stainless steel parts. The number of specimens was 27, in which a layer thickness, drying time, and saturation of a binder were selected as process variables. Porosity of the BJAM specimens is in the range of 1.96%-3.95%, Low porosity was achieved with thinner layers, longer drying times, and higher binder saturations. The observed maximum microhardness of heat-treated specimens was 48 HRC at the given parameters, but 51 HRC was found for the material whose morphology was wrought. From the results related to tensile properties, it is concluded that thinner layers and higher binder saturation lead to better Ultimate Tensile Strength (UTS) and Yield Strength (YS). Elongation, which characterizes the ductility of materials, was dependent on the density and process efficiency enhancement that were carried out. Parts produced by the BJAM process yielded fracture patterns that can be described as ductile-brittle mixed mode fractures.
Keywords: Binder Jetting, Additive Manufacturing, 17-4PH Stainless Steel, Mechanical Properties, Microstructure.

1. Introduction

Additive manufacturing (AM) has allowed for the realization of complicated and precise parts at a production scale, previously unattainable in terms of design freedom and material utilization [1]. Among the various AM techniques, binder jetting additive manufacturing (BJAM) has been noted because it can produce complex shapes economically without the need for high-temperature processes in the course of printing [5]. It is particularly useful in the

aerospace, medical and industrial fields where great detail is required [2]. One alloy that is in increasing amounts used through BJAM is 17-4PH stainless steel, which is a precipitation-hardened martensitic alloy with high strength, hardness and durability [3]. Typical methods for manufacturing 17-4PH are either casting or machining which are both expensive and wasteful of material. BJAM on the other hand is able to produce parts that are near net shapes, with minimal wastage of material and low cost of production [10]. Although using the BJAM process to produce 17-4PH stainless steel parts is quite promising, the mechanical properties and microstructure of such steel alloys however, remain an area of ongoing studies. This study seeks to assess how the mechanical characteristics and microstructure of 17-4PH stainless steel are influenced through varying binder jetting process parameters, and seeks to provide relationships between the parameters, and the microstructure features such as porosity and grain structure, and material properties such as hardness, tensile strength, and impact resistance [6].Through the use of binder jetting technology, the construction of a 3D object is done by sequentially coating a powder bed with a liquid binder. The so-called 'green part' then has to be post-processed, including but not limited to debindering and sintering, for it to reach the final density and the required mechanical qualities [4]. As the final consolidation of the materials occurs independently of the building process, this two-step technique allows combining several materials, including ceramics, polymers, and metals. In regard to metals, sintering is firmly established and essential for the densification of the materials in order to obtain the required mechanical strength [11]. BJAM has demonstrated some successes in producing metallic components in a dense state having complexity in geometry although attaining complete densification, microstructure control and porosity are yet performed optimally to improve the mechanical performance [9].

Several investigators state that porosity, which is commonly attributed to inadequate sintering or poor binder-powder interactions, can adversely affect mechanical performance such as tensile strength and impact resistance [12]. This research seeks to achieve an understanding of how these problems can be addressed by varying BJAM process parameters on 17-4PH stainless steel [7]. Present literature review suggests that very few studies have been carried out looking at the effect of the process parameters of BJAM on the mechanical properties of 17-4 PH stainless steel components produced via BJAM.This paper is focussed on studying the effect of three key BJAM parameters namely layer thickness , binder saturation and drying time on the microhardness, ultimate strength, yield strength, porosity and stress-strain of 17-4 PH specimens made by BJAM. In this paper, A comparison of of BJAM built 17-4 PH specimen with wrought 17-4 PH specimen is also presented.

2. MATERIALS AND METHODS

17-4PH stainless steel is a precipitation-hardened alloy consisting of iron, chromium, nickel, and copper, with trace elements that impart unique properties [2]. This alloy exhibits high strength, hardness, and corrosion resistance, making it ideal for demanding environments, including aerospace and medical applications [3]. Given its desirable properties, 17-4PH stainless steel produced via BJAM has the potential to meet stringent requirements for various applications, provided that BJAM can consistently deliver the necessary mechanical and microstructural characteristics [1].This SEM image showed in below figure 1 is 17-4

precipitation-hardened (PH) stainless steel powder at a magnification of 500x. The powder consists of spherical particles with varying diameters, characteristic of gas-atomized metal powders used in additive manufacturing and powder metallurgy. The spherical morphology improves flowability and packing density, which are critical for applications such as 3D printing.

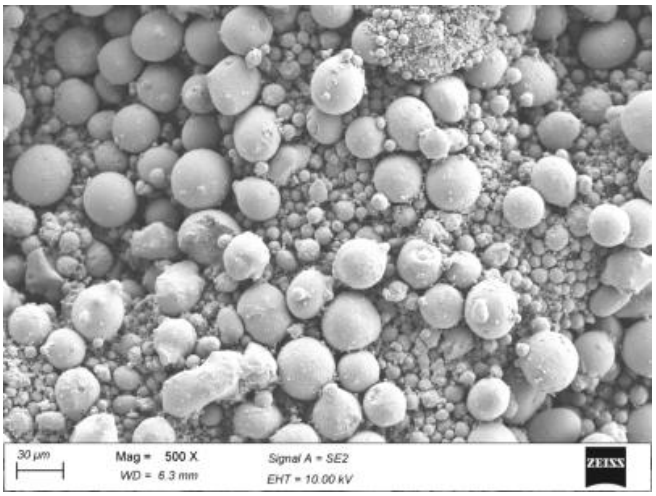


Figure 1: Scanning Electron Microscope (SEM) Image Of 17-4 PH Stainless Steel Powder

This study explores how process parameters can be optimized to reduce porosity and enhance mechanical strength [6]. This study investigates the mechanical and microstructural properties of BJAM-fabricated 17-4PH stainless steel, focusing on the influence of binder jetting parameters on the final product. Create a 3D CAD model of the specimen using computer aided design software, export the 3D model as STL. File format as shown in figure 2(a). Now the specimen is imported into the interface software for necessary process parameters setting and incorporate necessary support structures based on component complexity. Prepare the additive manufacturing binder jetting machine by filling the powder in the mechanism and setting the process parameters using the liveBuild software as shown in figure 2(b). During the building process, the feeder moves up and the base plate moves down along the Z-axis by the height of the layer thickness.

The roller spreads a fine layer of powder on the base plate in the X-Y directions. For each layer, the printer spreads metal powder across the build bed and precisely jets an aqueous based binding agent to bond the loose powder and define the part geometry. This process repeats until the entire build volume is filled with bound parts and surrounding loose powder. Printing time depends on part density and typically ranges from 2 hr 13 min. To convert green parts into brown parts, place the 3D printed build cake in a pre-baking oven for about 24 hours. This step removes moisture from the binder, resulting in less porous and denser components. After the build is complete, remove the build box and place it in a powder station for bulk and fine depowdering using a hand-held air pick. All loose powders are removed and recovered via a built-in powder recycling system with sieving. Depowdering time depends on build preparation, complexity, and quantity, usually ranging from 45 min. Place the brown parts in a sintering station with an argon gas. Depowdered parts are arranged on trays in a high-

throughput furnace for batch sintering. With temperatures reaching up to 1350°C for 2 hours and an external gas hookup, the furnace processes high-strength binders and provides reliable sintering cycles. Detach the built part from the base plate. The Dog bone tensile test specimens with size 100*10*3 mm were fabricated for the physical and mechanical characterizations as shown in figure 2(c). The specimen is subjected to heat treatment H1100 to reduce the porosity and enhance the mechanical properties. H1100 (593OC for 4 hours) [20] increase the strength and toughness, in this paper the porosity, Tensile strength, yield strength, Elongation and hardness of Binder jetting additively manufactured 17-4PH stainless steel before and after heat treatment is compared. The BX53 microscope from Olympus is used to take microstructural images of cross sectional specimens to calculate the porosity. Emery paper with grits varying from 180 to 4000 was used to grind the sintered specimens. The polished specimen was etched with a mixture of 15 mL glycerin, 10 mL HCl, and 5 mL nitric acid, as per ASTM standard E407–07. For image processing, the programs Olympus were employed. By thresholding, the voids or pores were extracted in Olympus. The InstronUTM is used to measure the tensile strength, yield strength, elongation, and Young's modulus of a material. These properties are critical for understanding how a material will behave under various types of mechanical stress.The hardness measurments are carried out with Micro Vickers VH-1MDX is a Digital automatic Turrent Micro Vickers Hardness Tester with testing load of 100kgf and hardness mesuring range of 8-2900HV. The Testing force application method used is Automatic loading and unloading. The specimens' hardness was measured at various points, and the average of the measurements is calculated.

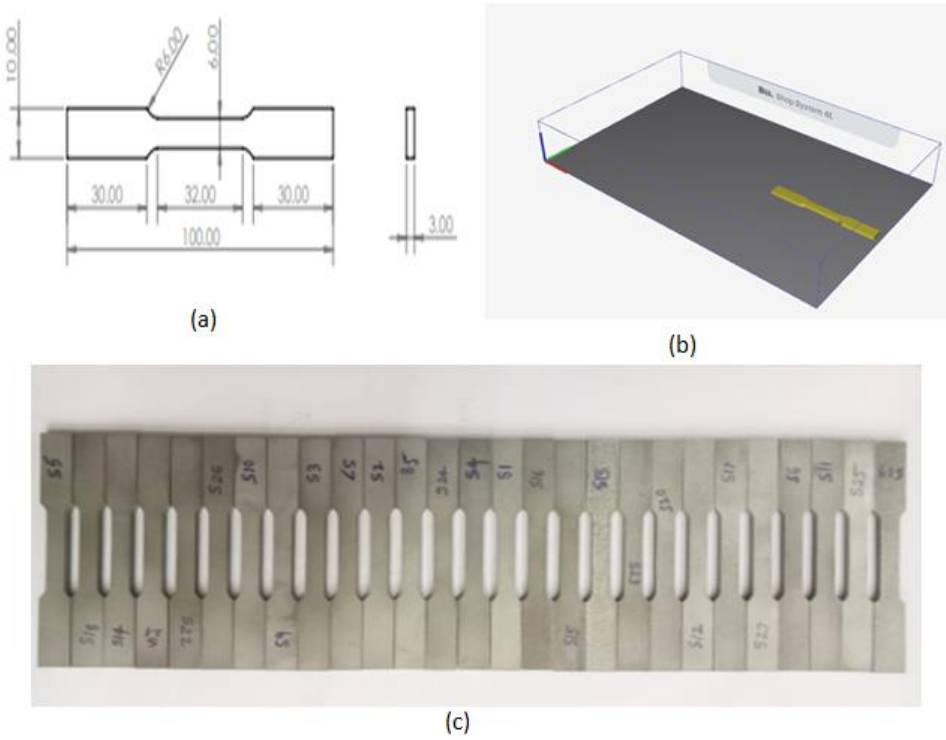
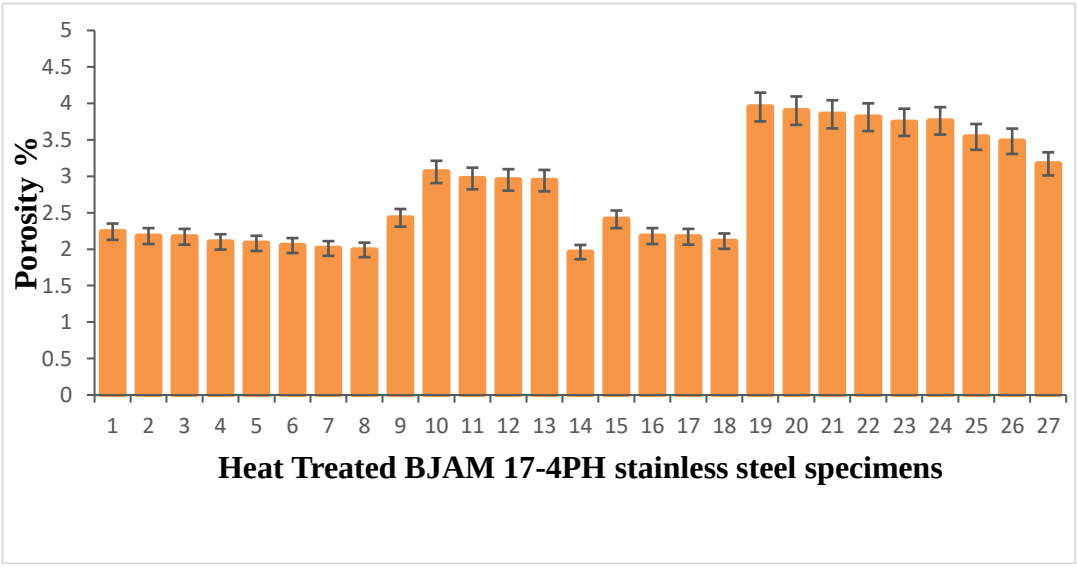


Figure 2: (A) CAD of the Specimen (B) Specimen Ready For BJAM (C) BJAM Specimens Of Dog Bone Tensile Specimens

3. RESULTS AND DISCUSSION

Porosity

The results of the porosity test conducted on the 27 specimens as described in the table 3 and porosity of H1100 heat treated and wrought material represented in graph 1 with bars representing the deviation from each specimen. The variation of porosity across the different sets confirms the influence of BJAM process parameters on the porosity of the BJAM-produced specimens. Also, it is noted that specimens with number 14 produced parts with very low porosity of 1.96% which layer thickness 75 mm, a drying time of 25 sec, and binder saturation of 80% while specimen 19 produced parts of high porosity of 3.95% with corresponding layer thickness of 100 mm, a drying time of 20 sec and binder saturation of 70%. The values of porosity for the wrought material obtained are less than 0.02% which is comparatively better than the values of porosity for the heat treated specimens made using the BJAM technology. The porosity in the binder jet additive manufacturing technology is greatly affected by the following parameters drying time, layer thickness, and binding percentage. Basing on the analysis of 27 specimens, it can be stated that these parameters have a significant impact on the internal structure porosity levels of components made with the help of the BJAM technology.



Graph 1: Percentage of Porosity of Heat Treated BJAM 17-4PH Stainless Steel Specimens

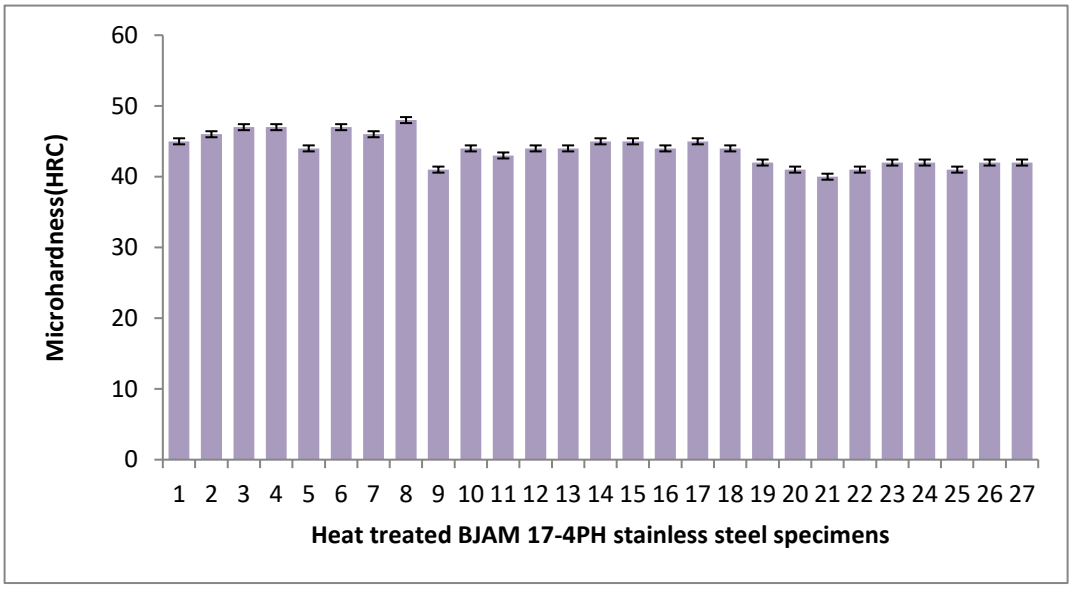
Specimen 14 showed low porosity. Thinner layers enhance powder packing, reduce gaps, and improve bonding during sintering. Longer drying time allows sufficient solvent evaporation, avoiding pore formation, while higher binder saturation strengthens particle bonding, reducing voids. Specimen 19 had resulting in higher porosity. Thicker layers may weaken interlayer bonding, while shorter drying times leave residual solvents that create gas pockets during sintering. Lower binder saturation further weakens particle bonding, increasing porosity. Compared to BJAM parts, wrought materials exhibit very low porosity (~0.02%) due to mechanical compression that yields a denser microstructure. Although BJAM parts, even after

heat treatments like H1100, retain some porosity, optimizing parameters can improve density, bringing BJAM closer to the uniformity of wrought materials

MECHANICAL PROPERTIES

Microhardness

Results of the Microhardness, for the 27 specimens along with microhardness of heat treated (H1100 condition) and wrought material are presented in graph 2 below with bars showing the deviation for each specimen. Variation of microhardness across the different sets confirms the influence of different BJAM process parameters on the microhardness of the BJAM-produced specimens. We also notice that specimen8 Heat treated BJAM produced part have higher microhardness of 48HRC with corresponding process parameters layer thickness 50 mm, Drying time 30 seconds, binder saturation 80% and the specimen 21 produced part exhibits lowermicrohardness with corresponding parameters layer thickness 100 mm, Drying time 20mm, binder saturation 90%.

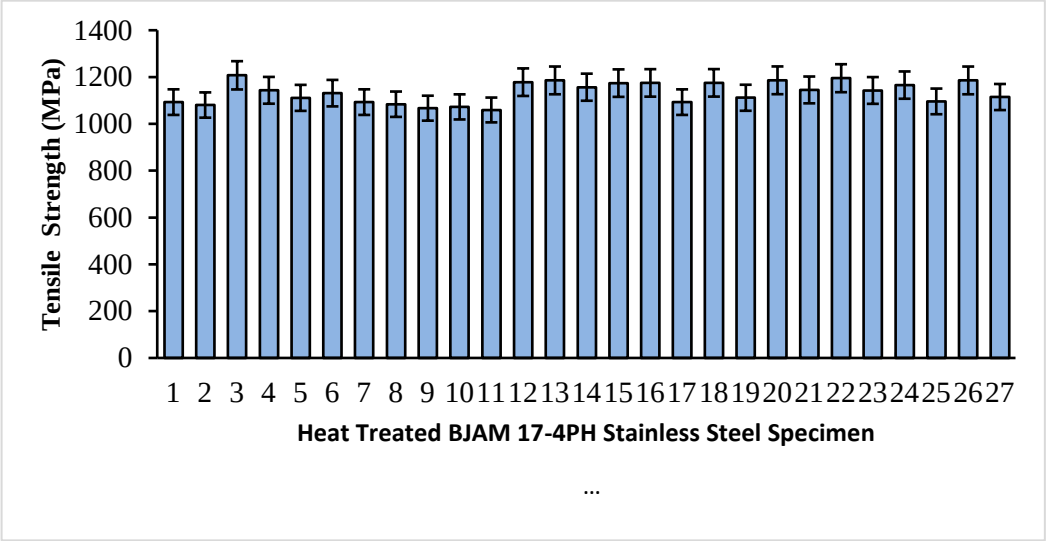


Graph 2: Microhardness of Heat Treated BJAM 17-4PH Stainless Steel Specimens

The microhardness of the wrought material obtained is 51HRC which is much higher than heat treated BJAM produced specimen. We observe Thinner layers (50 mm) promote better densification, while thicker layers (100 mm) may lead to increased porosity. Longer drying times (30 seconds) allow for more complete binder removal, while shorter times (20 seconds) result in residual binder , also Influences binder removal and pore formation. Binder Saturation Impacts particle bonding and density. Higher binder saturation (90%) enhances particle bonding, while lower saturation (80%) may lead to reduced density. Heat Treatment Improves microhardness by reducing porosity and promoting grain growth. Wrought material's higher microhardness (51 HRC) indicates better densification and microstructural uniformity. BJAM process limitations, such as porosity and incomplete densification, contribute to lower microhardness.

TENSILE PROPERTIES

In binder jet additive manufacturing (BJAM) of 17-4PH stainless steel, tensile test results can vary based on the processing parameters, post-processing treatments, and powder characteristics. Here's an overview of key tensile properties like ultimate tensile strength (UTS), yield strength, and elongation, along with cited studies that provide experimental data.



Graph 3: Ultimate Tensile Strength of Heat Treated BJAM 17-4PH Stainless Steel Specimens

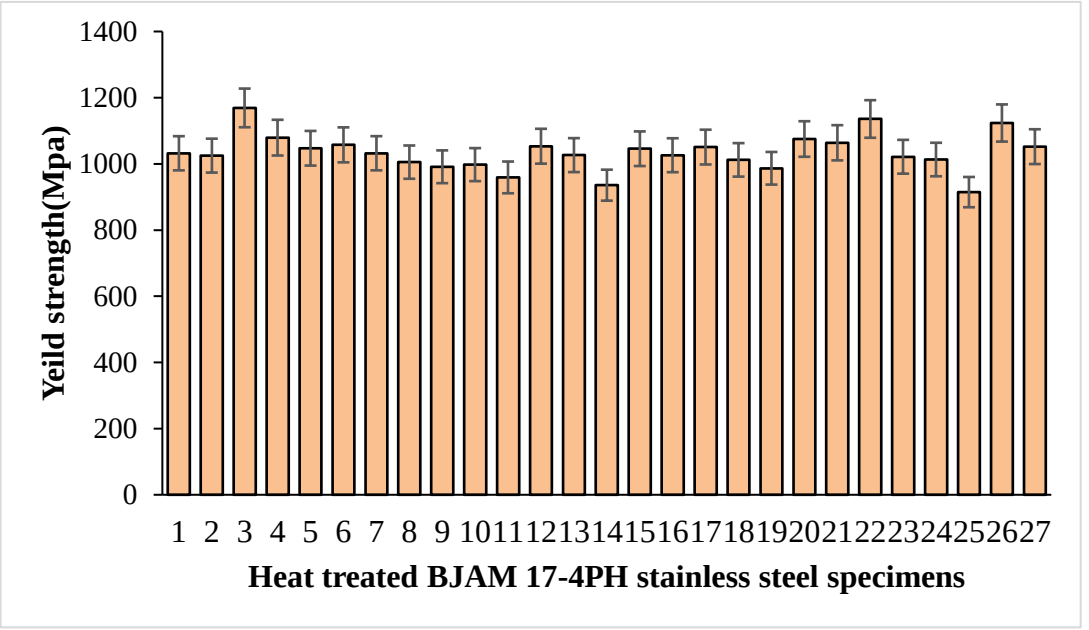
Ultimate Tensile Strength (UTS): Observations indicate that the Ultimate Tensile Strength (UTS) in BJAM-produced 17-4PH steel parts can significantly vary depending on specific manufacturing parameters as shown in graph 3. In comparing specimens, specimen 11, with a layer thickness of 75 µm, drying time of 20 seconds, and 80% binder saturation, displayed a lower UTS of 1059.45 Mpa than specimen 3, which used a thinner layer thickness of 50 µm and a higher binder saturation of 90% of 1207.45 Mpa. These differences suggest that thinner layers and higher binder saturation enhance particle bonding and reduce porosity, resulting in higher tensile strength.

This conclusion aligns with findings by Pumphrey et al. (2019), where BJAM-produced 17-4PH steel parts subjected to solution treatment and H900 aging achieved UTS values around 950 MPa. This high strength is attributed to enhanced density and refined microstructure from optimized thermal treatments, which further support the role of tightly controlled process parameters in achieving maximum material performance.

Overall, results suggest that parameters promoting denser particle packing—such as thinner layers and higher binder saturation—contribute to greater UTS. The drying time, kept constant in both specimens at 20 seconds, appears to have minimized variability in binder hardening, allowing layer thickness and binder saturation to be the main influences on UTS in this comparison.

Yield Strength (YS):Bai et al. (2021) demonstrated that higher sintering temperatures in

BJAM processing can improve the density of 17-4PH steel parts, which translates to increased yield strengths, reaching approximately 700 MPa. This improvement in density and strength underscores the importance of optimizing BJAM process parameters to achieve strong, dense parts.



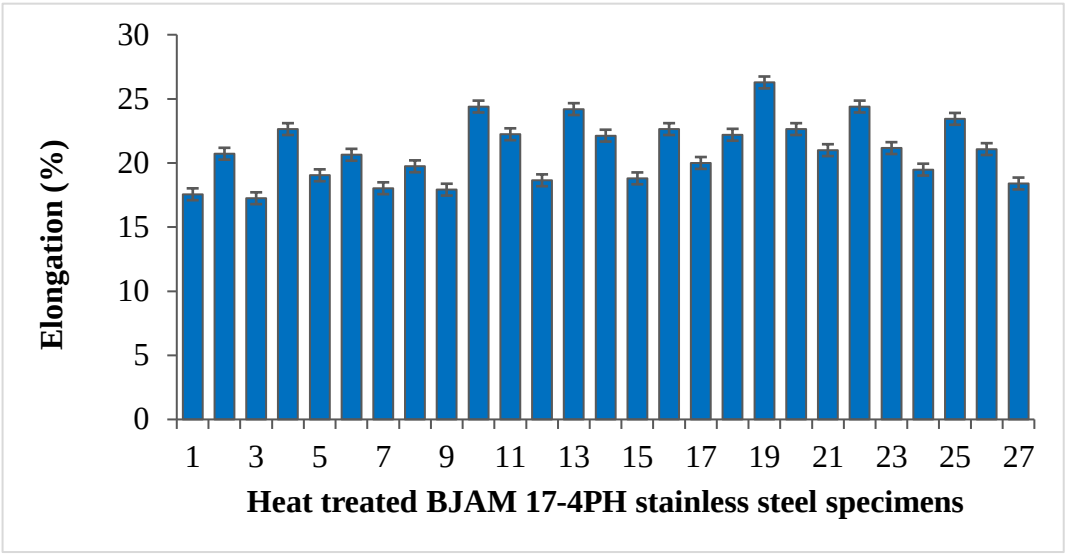
Graph 4: Yield Strength of Heat Treated BJAM 17-4PH Stainless Steel Specimens

In observations as ploted in graph 4, specimen 25, which has a larger layer thickness (100 µm), longer drying time (30 seconds), and lower binder saturation (70%), exhibited a lower yield strength 914.69 Mpacompared to specimen 3. Specimen 3, processed with a thinner layer thickness (50 µm), shorter drying time (20 seconds), and higher binder saturation (90%), displayed higher yield strength of 1169.1Mpa. These findings align well with Bai et al., conclusions, as specimen 3's parameters likely promoted better particle packing, higher density, and improved interlayer bonding, contributing to greater yield strength.

In contrast, the thicker layers, extended drying time, and reduced binder saturation in specimen 25 may have hindered effective bonding and reduced part density, thereby decreasing yield strength. These variations highlight the critical role of layer thickness, drying time, and binder saturation in influencing the mechanical properties of BJAM-manufactured 17-4PH steel.

Elongation at Break: Elongation, a measure of a material's ductility, indicates how much a material can stretch before breaking, expressed as a percentage of its original length. In BJAM 17-4PH steel, elongation values between 2% and 10% reflect differences in density and ductility, with higher elongation suggesting improved material uniformity and bonding. Research by Wilkes et al. (2022) found that optimized sintering and surface finishing could enhance elongation, reaching values around 6-7%. In our findings, specimen 19, with a layer thickness of 75 µm, drying time of 20 seconds, and binder saturation of 70%, exhibited a higher elongation percentage 26.28% compared to specimen 3, which had a thinner layer

thickness (50 µm) and higher binder saturation (90%) under the same drying conditions exhibited lower elongation percentage of 17.25%. The thinner layers and higher binder saturation in specimen 3 likely led to a denser and more ductile material, improving its elongation. In contrast, the parameters used for specimen 10 might have resulted in a more porous structure, decreasing its ability to stretch and reducing its elongation percentage.



Graph 5: Percentage of elongation of Heat Treated BJAM 17-4PH Stainless Steel Specimens

Factorography

These scanning electron microscopy (SEM) images depict fracture surfaces, which reveal insights into material behavior. Below figure 3 is an analysis of each image focusing on ductile and brittle fracture characteristics, porosity, unmelted powder particles, and possible inclusions or contaminations.

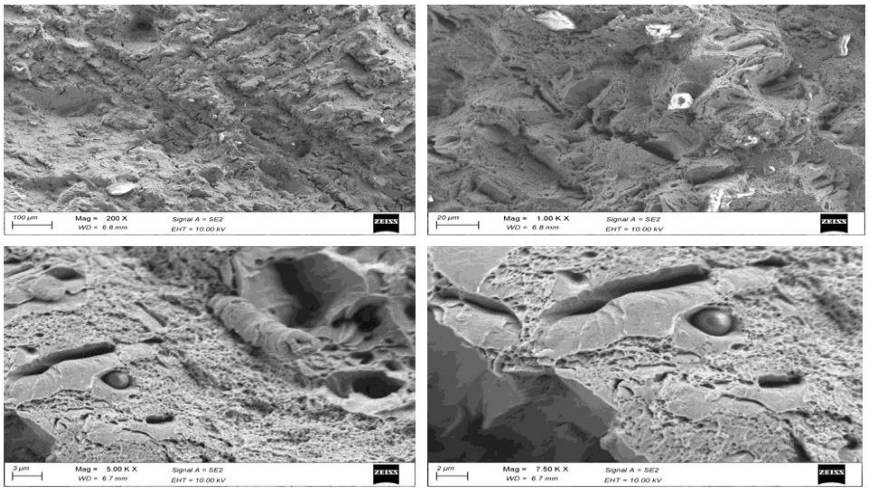


Figure 3: SEM Images Of Heat Treated BJAM 17-4PH Stainless Steel Specimen

The fracture surface examined reveals characteristics of mixed ductile-brittle type of fracture. Roughness and irregularity as well as some elongated structures and ductile tearing indicate ductile behavior taking place. Cleaved facets and sharp edges are indicative of brittle failure mechanisms. There is also evidence of microvoid coalescence, which is a sure hallmark of ductile fracture. It presents a mixture of ductile dimple regions with brittle facet regions, exhibiting mixed-mode fracture. Some clear voids or pores are visible that might have formed during manufacture or processing and can act as stress raisers. The porosity is finer and more localized, which indicates incomplete densification or trapped gas during processing. No clear sign of separately solid powder particles is perceived, although some particles may be held in the matrix or partially fused. Spherical particles may be unreacted, or partially reacted powders—typical of both additive manufacturing and general processing. Surface contaminants are not visible at first glance, but probable contaminants might be sealed within its surfaces. The possible contaminations develop as impulsive characteristics, though their chemical composition demands further scrutiny. The outlook of the surface points towards a complex mode of fracture with participation from both ductile and brittle failure modes.

4. CONCLUSIONS

The study investigated the impact of BJAM process parameters on porosity, microhardness, tensile strength, and elongation at break. The results showed that process parameters, such as layer thickness, drying time, and binder saturation, can significantly effect the mechanical properties of BJAM parts. Porosity was found to be significantly affected by BJAM process parameters resulting in a porosity of 1.96% and a higher porosity of 3.95%. Wrought materials exhibited superior density and porosity levels (~0.02%) due to mechanical compression during manufacturing. Microhardness varied from 40 HRC to 48 HRC in BJAM specimens, with optimal parameters resulting in the highest value (48 HRC). Wrought materials consistently demonstrated higher microhardness (51 HRC), attributed to better densification and uniformity. Tensile strength was improved with thinner layers and higher binder saturation, enhancing particle bonding and reducing porosity. Elongation at break was influenced by porosity and density, with higher elongation observed in specimens with higher porosity. Mixed fracture characteristics, including ductile and brittle modes, were observed, withmicrovoids and pores acting as stress concentrators. The mechanical properties of parts manufactured using BJAM are rather lower than wrought materials due to limitations of the process, such as incomplete densification, and presence of porosity. These shortcomings, however, can be improved through the optimization of the process, which consequently increases BJAM's suitability for advanced applications.

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