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RESEARCH ARTICLE

MICROSTRUCTURE AND SURFACE QUALITY ANALYSIS OF 17-4PH STAINLESS STEEL FILAMENT FABRICATED VIA VACUUM-ASSISTED FUSED DEPOSITION MODELING: PRE-DEBINDING & PRE-SINTERING

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Abstract. In recent years, both polymer-based materials and stainless steel have been widely used in additive manufacturing, especially in the automotive and medical sectors. Among these materials, 17-4PH stainless steel filament, a polymer-based composite, has gained attention for aerospace and marine applications due to its excellent strength, corrosion resistance, and mechanical properties. However, with the growing use of fused deposition modeling (FDM) for metal fabrication, a deeper understanding of how the filament microstructure influences the final properties of printed components is needed. While previous research has emphasized microstructural integrity for successful debinding and sintering, limited attention has been given to the pre-processing stages. This study investigates the surface roughness of 17-4PH stainless steel filament fabricated via vacuum-assisted FDM before the debinding and sintering process. Samples measuring 10 mm x 10 mm x 5 mm were produced using an Ultimaker S5 at various vacuum pressures, layer heights, and printing speeds. Surface roughness was evaluated using a surface roughness tester, and surface morphology was analyzed using scanning electron microscopy (SEM). Each analysis shows that the sample printed using a vacuum has reduced surface roughness up to nearly 8.5 %. This improvement is attributed to vacuum-assisted printing, which reduces contamination, minimizing oxidation and porosity during the printing process. Besides that, outgassing characteristics and vacuum stability can also influence the printing. The printing parameters that are optimized can improve the mechanical properties of the products. These analyses are crucial, as they directly impact densification, porosity, and sintering behaviour, which in turn affect the mechanical properties of the final product.

Keywords: 17-4PH stainless steel, vacuum-assisted fused deposition modeling, pre-debinding, pre-sintering.

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1. INTRODUCTION

Additive manufacturing (AM), also known as 3D printing, is a revolutionary manufacturing process that has gathered significant attention in recent years. Unlike traditional subtractive manufacturing methods, which involve cutting, machining, or moulding materials to create a final product, AM builds products layer by layer, directly from digital design data. AM has transformed the production of complex components, offering flexibility, reduced material waste, and the ability to create complicated geometries [1].

Among the various additive manufacturing techniques, fused deposition modeling (FDM) has gained popularity due to its simplicity and cost-effectiveness. Traditionally used for polymer-based materials, FDM is now being adapted for metal fabrication, expanding its applications across industries such as aerospace, automotive, medical, and marine [2]. This shift has significantly raised interest in metal-polymer composite filaments, especially those based on stainless steel.

Special attention has been given to materials like the 17-4PH stainless steel, a precipitation-hardened steel used in an extensive range of applications due to its very good mechanical properties, such as high strength and resistance to corrosion [3]. Its application in FDM has led to the development of highly durable and lightweight components used in industries related to aero and marine engineering. Despite these advantages, there are still challenges regarding the optimization of properties of 3D-printed components with metal composites. The fabrication process, printing, debinding, and sintering, determines the microstructure and final properties that are critical for the printed parts [4]. With this in mind, a deeper understanding of the evolution of the material microstructure through these stages is imperative for enhancing the performance of metal parts produced through FDM.

Vacuum-assisted FDM enhances the deposition process by creating a vacuum environment, which aids in the removal of trapped gases and improves material flow [5]. This technique has shown promise in producing high-density metal components with refined microstructures. Previous studies have demonstrated that vacuum-assisted FDM effectively minimizes defects such as porosity and enhances interlayer bonding, crucial for the mechanical performance of the final product [6]. Additionally, the manipulation of process parameters such as layer thickness, extrusion temperature, and build orientation has been found to significantly influence the mechanical properties and quality of FDM-printed parts. Vacuum-assisted FDM, in particular, has been shown to improve the quality of printing due to better bonding between layers [7]. With the help of vacuum technology, 3D-printed components can minimize the staircase effect, and fusion between layers improves and creates stronger bonds due to proper cooling and heating rates [8-10].

For this material, debinding and sintering play a crucial role. Although much research has gone into analyzing the microstructural integrity during the debinding and sintering process, relatively few have been done on the pre-processing stages that go before these two milestone processes [11]. In particular, the surface characteristics are of critical importance to guarantee the success of subsequent densification, control of porosity, and sintering, all these processes determining the mechanical strength, durability, and quality of the final component in general. Among many parameters, surface roughness is particularly critical because it directly governs the efficiency of sintering by influencing initial particle contact, pore closure, and densification pathways. Unlike porosity or grain structure, which evolve during sintering, surface roughness is a pre-sintering condition that dictates how well adjacent layers bond and densify. A smoother surface facilitates more uniform shrinkage and enhanced interlayer diffusion, while rougher surfaces can trap voids and create non-uniform stresses, ultimately limiting mechanical performance.

The pre-debinding and pre-sintering stages are critical for achieving the desired microstructure in metal AM. These processes involve the removal of the binder used during the FDM process and the initial densification of the material. Debinding is essential for eliminating residual binder materials that can negatively impact the mechanical properties of the final product. Various debinding techniques, including thermal and solvent debinding, have been studied extensively. Research indicates that careful control over temperature and time during debinding is necessary to avoid defects such as cracking or warping [12]. Sintering follows debinding and significantly influences the final microstructure. This process promotes particle coalescence, leading to increased density and improved mechanical properties. Studies suggest that optimizing sintering temperature and time is crucial to achieving a balance between strength and ductility in 17-4PH stainless steel [13].

Microstructure analysis is vital for understanding the relationships between processing parameters, microstructure, and mechanical properties. Techniques such as Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD) are commonly employed to characterize the microstructural features of materials produced via AM processes [14]. The microstructural features directly correlate with the mechanical properties of the material. For instance, grain size, phase distribution, and the presence of defects can significantly affect yield strength, tensile strength, and ductility. Understanding these relationships is essential for optimizing processing techniques and enhancing the performance of 17-4PH stainless steel fabricated via vacuum-assisted FDM, which is lacking in previous studies.

The objective of this study is to investigate the influence of vacuum-assisted FDM on the surface roughness and microstructure of 17-4PH stainless steel in the pre-debinding and pre-sintering stages, providing insights to optimize processing conditions for improved mechanical performance.

2. MATERIALS AND METHODS

2.1 3D Printing Setup

An Ultimaker S5 open-sourced FDM 3D printer was used for this experiment, due to its capability to heat the nozzle to 300 °C. To create an enclosed environment, a vacuum chamber was fabricated with internal dimensions of 570 mm x 860 mm x 720 mm x 20 mm. The vacuum pump was attached to one of the valves and the pipeline as an outlet. Figure 1 shows the schematic diagram for a vacuum-assisted 3D printing system. While the machine is heating up before the printing process, the vacuum takes place to suck the air into an enclosed chamber, creating a designated vacuum environment. The pressures set for this experiment are 0, 10 and 20 kPa.

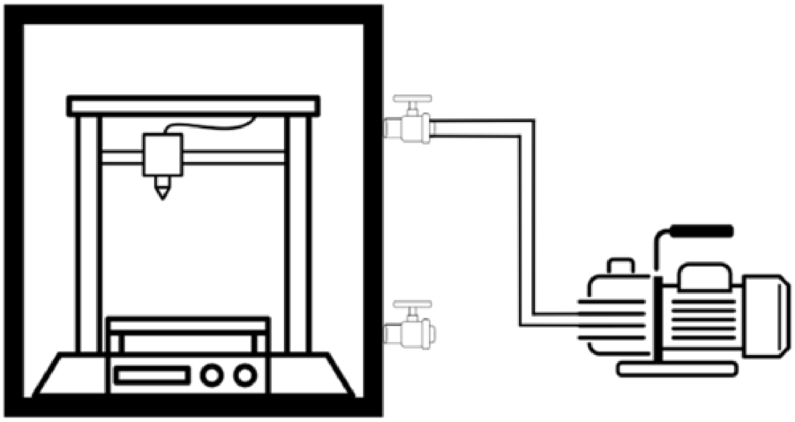

Figure 1: Schematic diagram of a vacuum-assisted 3D printing system

2.2 Sample Preparation

An SEM sample was printed using Ultrafused 17-4PH stainless steel, with dimensions 10 mm x 10 mm x 6 mm, as shown in Figure 2. The 3D design was created using SolidWorks 2022 and exported to Ultimaker Cura 5.2.1, where printing parameters were configured.

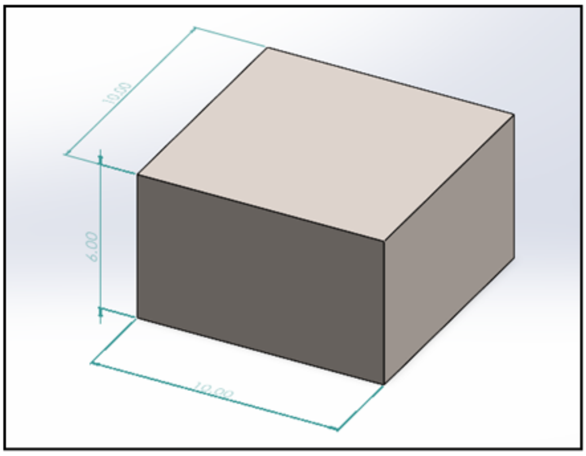

Figure 2: SEM sample dimension

Two key variable parameters, vacuum pressure and layer height, were systematically adjusted during the fabrication process, and other parameters, such as nozzle temperature and print bed temperature, were fixed. All of the details are tabulated in Table 1. Three different levels of vacuum pressure, 0, 10 and 20 kPa, were applied to evaluate the impact on the surface finish and porosity reduction. Meanwhile, the layer heights of 0.100, 0.125 and 0.150 mm were varied to understand their influence on the print resolution, interlayer adhesion, and mechanical properties.

Table 1: Printing parameters

Printing Parameters	Value
Vacuum pressure (kPa)	0, 10, 20
Layer height (mm)	0.100, 0.125, 0.150
Printing speed (mm/s)	25
Nozzle temperature (°C)	240
Print bed temperature (°C)	70
Print axis	Flat-XY axis

The vacuum pressure varied from 0.0 kPa to 0.2 kPa because of the compatibility of the vacuum chamber. Meanwhile, layer height varied from 0.100 mm to 0.150 mm because of the recommendations from BASF. The parameters used in Samples A, B, and C are tabulated in Table 2.

Table 2: Sample parameters

Samples	Vacuum Pressure (kPa)	Layer height (mm)
A	0.0	0.100
B	0.1	0.125
C	0.2	0.150

2.3 Surface Roughness Analysis

Mitutoyo Surftest SJ-301 Series was used to analyze the surface roughness of the samples. The equipment was calibrated according to ISO 1997, with a working detector distance of 2.4 mm. The surface was analyzed by retracting perpendicularly to the layered surface of the sample, as shown in Figure 3. Each layered face was measured three times and counted as the average data.

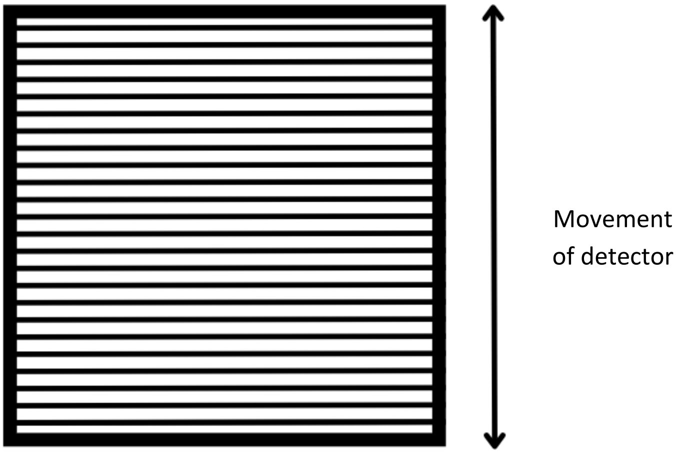

Figure 3: Movement of the detector for Surftest SJ-201 Series

2.4 Surface Morphological Analysis

Surface morphological analysis was conducted to evaluate the structural characteristics of the 3D-printed samples. A scanning electron microscope (SEM) was used to analyze the surface morphology of the printed samples. SEM images act as a visual indication that supports the results obtained by the surface roughness analysis, as they show detailed surface texture, including the layered surface of the samples.

3. RESULTS AND DISCUSSION

The result reveals critical relationships between process parameters and the resulting microstructure of 17-4PH stainless steel filaments during the fabrication process. Figure 4 shows the result of surface morphological analysis for 3D-printed samples by using 17-4PH stainless steel material for sample A.

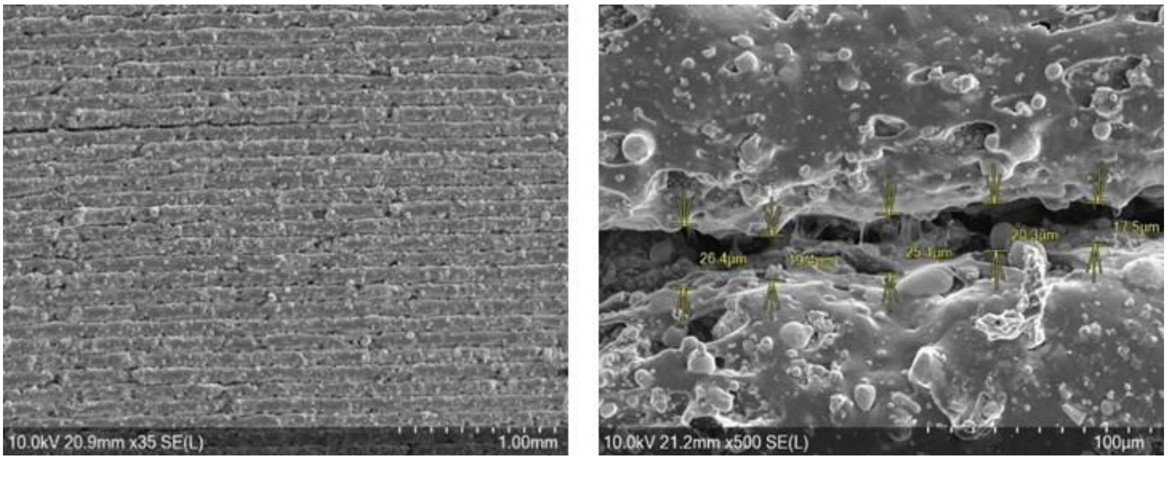

Figure 4: Surface morphology of layer and microstructure images for 3D-printed 17-4PH stainless steel parts for sample A

In the layer morphology for Sample A (0 kPa vacuum pressure, 0.100 mm layer height, 25 mm/s printing speed), the overall surface structure is characterized by a series of distinct, parallel layers. These layers exhibit a high degree of uniformity, indicating a well-controlled deposition process. The smoothness of the surface suggests effective layering techniques, which could be indicative of optimized processing parameters. However, there are observable cracks and slight surface roughness, which may arise from the inherent characteristics of the materials used or minor fluctuations during the FDM processes. Similar observations have been reported in studies focusing on the additive manufacturing of metal-based filaments, highlighting the interplay between deposition parameters and surface morphology [15]. This layered architecture is crucial for applications that require specific mechanical properties, as it can enhance material strength and stability. The microstructure image offers a closer examination of the internal features between these layers. The presence of voids was noticed, with sizes ranging from approximately 17.5 µm to 26.4 µm. These voids suggest potential issues related to binder removal or incomplete sintering during production.

Studies by [16] have similarly emphasized the role of pore size and distribution in determining mechanical integrity, as voids act as stress concentrators and reduce load-bearing capacity. The pore sizes observed in Sample A ranged from 17.5 µm to 26.4 µm, which are smaller than those typically reported in conventional FDM studies without vacuum assistance (>30 µm), but still larger than the finer pores (<15 µm) achieved in some optimized vacuum-assisted AM processes. This indicates that vacuum improved pore refinement compared to standard FDM, further optimization of debinding and sintering is necessary to match the densification levels reported in advanced vacuum-based approaches. While these pore sizes are larger compared to those seen in other samples, their distribution and variability indicate inconsistencies in processing. The presence of these gaps can significantly affect material mechanical integrity, potentially acting as stress concentrators that could lead to failure underload. The presence of well-defined layers and the identified voids introduce a dual challenge. The structural organization indicates potential for high-performance application and the voids highlight the need for further optimization of processing parameters. Addressing these issues, particularly through improved sintering and debinding methods, could enhance the overall density and mechanical properties of Sample A. Such improvements are consistent with advancements reported in recent studies focusing on vacuum-assisted fused deposition modeling and its impact on porosity and mechanical strength [17].

Sample B (10 kPa vacuum pressure, 0.125 mm layer height, 25 mm/s printing speed) as shown in Figure 5 presents a detailed view of a surface with a well-defined layered structure, indicative of the manufacturing process. The layer image reveals a series of parallel layers that are uniformly arranged, suggesting a consistent deposition technique during fabrication. This orderly arrangement contrasts with other samples' irregularities, presenting a more refined surface texture. The consistency in layering aligns with findings from [18], which highlight the influence of optimized deposition parameters on achieving uniform surface characteristics in additive manufacturing. However, despite this apparent uniformity, the surface does display some minor roughness and scattered particles, hinting at the complexities involved in achieving a perfect finish. The observed surface roughness is a common challenge in metal additive manufacturing, where particle adhesion and minor material inconsistencies are attributed to variations in layer-by-layer deposition or post-processing conditions. In the microstructure, the image reveals intriguing features within the layers.

The presence of pores, with sizes ranging from approximately 22.9 µm to 31.8 µm, is evident, indicating that while the overall structure is orderly, there are still voids present that can affect material integrity. The identified voids, measured at varying dimensions, reflect areas where binder removal may not have been entirely efficient, potentially due to insufficient processing conditions. These gaps can lead to inconsistencies in mechanical performance, as they may act as stress concentrators under load. The effect of such voids on mechanical properties, including reduced load-bearing capacity and stress concentration effects, has been extensively documented in prior research, such as the work by [19]. Addressing these voids through enhanced debinding and sintering techniques could significantly improve the structural integrity and reliability of components fabricated using this method.

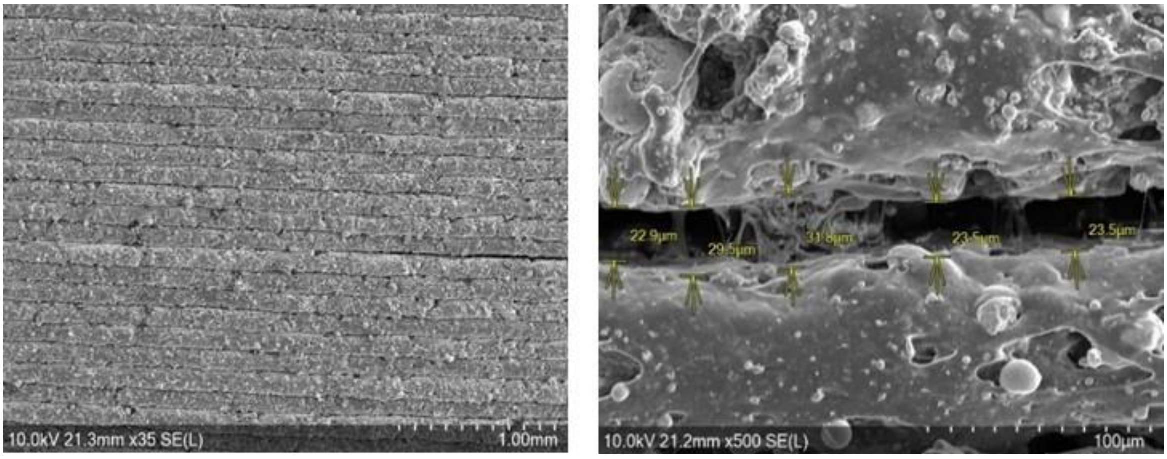

Figure 5: Surface morphology of layer and microstructure images for 3D-printed 17-4PH stainless steel parts for Sample B

Figure 6 presents surface morphology of Sample C (20 kPa vacuum pressure, 0.150 mm layer height, 25 mm/s printing speed) showing both structural uniformity and notable imperfections. On the layer image, the layered structure is prominently displayed, characterized by a series of parallel lines that indicate a consistent layering technique during its fabrication. The layers appear relatively smooth and well-defined, which suggests a controlled deposition process. However, unlike Sample B, there is a more pronounced variability in the spacing and alignment of these layers, which could imply slight inconsistencies during production. Previous studies emphasized the impact of processing conditions on layer alignment and uniformity in fused deposition modeling. This layered arrangement, while orderly, is complemented by a surface that exhibits some irregularities and minor roughness, hinting at the complexities of the manufacturing process.

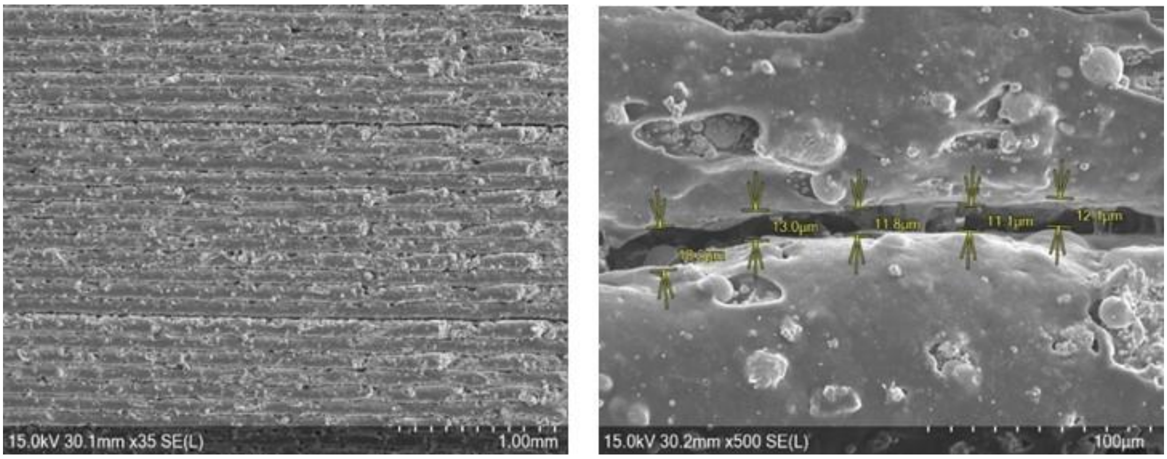

Figure 6: Surface morphology of layer and microstructure images for 3D-printed 17-4PH stainless steel parts for Sample C

Overall, Sample A shows more compact layers compared to Sample B and Sample C. All the three samples appear to have gaps along the layer bond. The challenges of achieving perfectly smooth surfaces in additive manufacturing have been similarly noted by [20], who highlighted that roughness often arises due to factors such as material properties and deposition speed. The microstructure image provides a closer inspection of the interlayer regions, revealing critical features that influence the material's overall performance. Here, the presence of voids is evident, with measured sizes ranging from approximately 11.1 µm to 18.5 µm. These voids, although smaller on average compared to those in Sample B, are indicative of incomplete binder removal or insufficient sintering conditions. Such voids can have significant implications for the mechanical integrity of the material, as they may act as initiation points for failure under stress. The variability in pore sizes and the presence of these gaps underscore the need for further refinement in processing parameters. While the layered structure of Sample C demonstrates the potential for high-quality applications, the identified voids and surface imperfections suggest that optimizing debinding and sintering techniques is crucial. Studies by [19] have emphasized the importance of refining these processes to enhance material density and mechanical properties. Addressing these issues could lead to enhanced density and mechanical properties, ultimately improving the performance of the final product.

Table 3 tabulates the surface roughness data that supports the findings from the SEM images for samples A, B, and C. Sample A has a surface roughness of 21.73 µm and is linked to SEM image A from Figure 4, which reveals a lot of irregular pores and defects. Interestingly, as the vacuum pressure increase, the surface roughness decreases, with Sample C achieving the smoothest surface at 19.15 µm. The improvement of surface roughness is affected by higher layer thickness, as slower cooling produces more uniform shrinkage. It is also due to consistent microstructure when higher vacuum pressure is applied, highlighting the important role of vacuum-assisted fabrication in enhancing the surface quality of the material.

Table 3: Sample parameters

Sample	Vacuum pressure (KPa)	Layer height (mm)	Printing speed (mm/s)	Surface roughness (µm)
A	0	0.100	25	21.73
B	10	0.125	25	20.87
C	20	0.150	25	19.15

Vacuum conditions, particularly under high vacuum, play a crucial role in the printing process by significantly reducing pressure and limiting the presence of gases and contaminants. This controlled environment minimizes the risk of oxidation, porosity, and other undesirable chemical reactions that may compromise the structural integrity of the material, which is especially important when processing metals and ceramics.

The reduction in roughness from 21.73 µm in Sample A to 19.15 µm in Sample C represents approximately an 11.87 % improvement in surface smoothness. Even small decreases in roughness can significantly enhance fatigue resistance, as surface irregularities act as stress concentrators. Compared to conventional non-vacuum FDM processes where surface roughness often exceeds 22 µm to 25 µm and pores are typically larger than 30 µm, this study demonstrate that vacuum-assisted FDM not only reduces surface roughness but also refine pore size distribution. This confirms the novelty of the approach, showing that vacuum can achieve finer microstructural features than previously reported in standard FDM, thereby enhancing the potential of 17-4PH stainless steel for high-precision applications in aerospace, automotive, and biomedical fields where durability and reliability are critical. However, the larger pores seen in SEM image A might still affect the mechanical strength, pointing to the need for further post-processing methods, such as sintering or hot isostatic pressing, to achieve the desired material properties.

4. CONCLUSIONS

This study demonstrates that vacuum assisted FDM plays a pivotal role in shaping the surface quality of 17-4PH stainless steel filaments before the critical debinding and sintering steps, which are essential for producing high performance metal components. The application of vacuum during FDM reduces surface roughness by stabilizing material deposition, resulting in more uniform and consistent printed layers. Nonetheless, layer height remains a key factor, as thinner layers enhance surface smoothness and consistency. Improving surface roughness is particularly important because it influences densification, pore distribution, and sintering behavior, factors that ultimately determine the mechanical properties and overall performance of the final product.

By optimizing pre-processing parameters such as vacuum pressure and layer height, defects can be minimized, enhance material consolidation, and achieve better microstructural characteristics. This research provides valuable insights into refining additive manufacturing techniques by examining how pre-processing conditions influence the resulting microstructure. Ultimately, it paves the way for producing 17-4PH stainless steel components more efficiently and higher quality, meeting the demands of advanced industrial sectors.

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Author Contributions

All authors contributed toward data analysis, drafting and critically revising the paper and agree to be accountable for all aspects of the work.

Disclosure of Conflict of Interest

The authors have no disclosures to declare.

Compliance with Ethical Standards

The work is compliant with ethical standards.

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