

EFFECT OF 3D PRINTING PROCESS PARAMETERS ON
THE MECHANICAL, TRIBOLOGICAL AND CORROSION
RESISTANCE PROPERTIES OF 316L STAINLESS STEEL

BY

Mohammed A. S. Yousif

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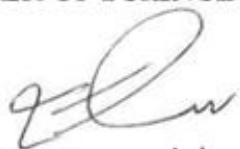
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DHAHRAN- 31261, SAUDI ARABIA

DEANSHIP OF GRADUATE STUDIES

This thesis, written by **Mohammed A. Shummo Yousif** under the direction of his thesis advisor and approved by his thesis committee, has been presented and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE IN MECHANICAL ENGINEERING.**



Dr. Sulaiman AlTuralli'
ME Summer chairman
on behalf of Dr. Antar

Dr. Mohamed Antar
Department Chairman



Dr. Suliman Al-Homidan
Dean of Graduate Studies

Date: May 2024



Dr. Khaled Al-Athel
(Advisor)



Dr. Syed Sohail Akhtar
(Member)



Dr. Usman Ali
(Member)



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2024

I dedicate this thesis to God for His guidance and protection. I also dedicate it to my parents for their love and support. To my entire family, thank you for always encouraging me and standing by me. I am truly grateful for your sacrifices and motivation, which made this achievement possible.

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LIST OF ABBREVIATIONS

AM	:	Additive manufacturing
BJ	:	Binder jetting
CAD	:	Computer Aided Design
DED	:	Directed energy deposition
EDS	:	Energy Dispersive X-ray Spectroscopy
EBM	:	Electron beam melting
FDM	:	Fused deposition modelling
OCP	:	Open Circuit Potential
EIS	:	Electrochemical Impedance Spectroscopy
CPDP	:	Cyclic Potentiodynamic Polarization
LPBF	:	Laser powder-bed fusion
HIP	:	Hot Isostatic Pressing
MAM	:	Metal Additive Manufacturing
SEM	:	Scanning electron microscope
SLA	:	Stereolithography
SLS/ SLM	:	Selective laser sintering/melting
DLP	:	Digital Light Processing
UTS	:	Ultimate Tensile Strength
YS	:	Yield Strength
XRD	:	X-ray Diffraction
LENS	:	Laser Engineered Net Shaping
UV	:	Ultraviolet

LOM	:	Laminated Object Manufacturing
ASTM	:	American Society for Testing and Materials
UAM	:	Ultrasound Additive Manufacturing
DLMS	:	Direct Metal Laser Sintering
AC	:	Alternate Current
EEC	:	Equivalent Electrical Circuit
BoD	:	Ball on Disk
COF	:	Coefficient of Friction
SWR	:	Specific Wear Rate
SCE	:	Saturated Calomel Electrode

ABSTRACT

Full Name : Mohammed A. Shummo Yousif

Thesis Title : Effect of laser powder bed fusion process parameters on the mechanical, tribological and corrosion resistance properties of 316L stainless steel parts

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This thesis focused on the effect of laser powder bed fusion process parameters on the mechanical, tribological and corrosion resistance properties of 316L stainless steel parts. The study aims to study and understand the effect of build orientation and sample size on the mechanical, wear and corrosion properties of LPBF 316L stainless steel parts, with the objective of enhancing the adaptability and capabilities of LPBF technology. The printed samples were characterized to determine the microstructural evolution, particle distribution and grain morphology using characterization techniques such as XRD, SEM, EDS, and optical microscope. The samples were also subjected to microhardness, tensile tests to determine the effect of sample size and build orientation on the mechanical properties of LPBF 316L stainless steel parts. Wear and corrosion tests were also conducted to reveal the material behavior in specific environments. The findings of this work showed that 0° samples and bigger sample size have finer grain morphology and significantly higher hardness, elastic modulus, and tensile strength of the samples. However, the ductility was adversely affected. Porosity appeared in all the printed samples which significantly influenced their properties. The 0° samples showed superior wear resistance as well as corrosion and pitting resistance. The findings also highlighted the importance of considering sample size and density in LPBF processes for optimizing mechanical, wear, and corrosion properties.

ملخص الرسالة

الاسم الكامل: محمد عبد الرحيم شمو يوسف

عنوان الرسالة: تأثير متغيرات عملية الاندماج الانتقائي بالليزر على الخصائص الميكانيكية، التآكل، ومقاومة التآكل لقطع

الفولاذ المقاوم للصدأ 316L

التخصص: الهندسة الميكانيكية

تاريخ الدرجة العلمية: مايو ٢٠٢٤

ركزت هذه الرسالة على تأثير متغيرات عملية الاندماج الانتقائي بالليزر على الخصائص الميكانيكية، التآكل، ومقاومة التآكل لقطع الفولاذ المقاوم للصدأ 316L. وتهدف الدراسة إلى فهم واستكشاف تأثير اتجاه البناء وحجم العينة على الخصائص الميكانيكية، البلى، وخصائص مقاومة التآكل للفولاذ المقاوم للصدأ المصنوع بتقنية الاندماج الانتقائي بالليزر، بهدف تعزيز قابلية وإمكانيات تقنية الاندماج الانتقائي بالليزر. تم اختبار العينات المطبوعة لتحديد تطور التركيب المجهرى، توزيع الجسيمات ومورفولوجيا الحبوب باستخدام تقنيات التوصيف مثل SEM، XRD، EDS، والمجهر الضوئي. كما خضعت العينات لإختبارات الصلادة المجهرية واختبارات الشد لتحديد تأثير حجم العينة واتجاه البناء على الخصائص الميكانيكية للفولاذ المقاوم للصدأ. بالإضافة إلى ذلك، أجريت اختبارات البلى واختبارات التآكل للكشف عن سلوك المواد في بيئات محددة. أظهرت نتائج هذا العمل أن اتجاه البناء الصغير (0 درجة) وحجم العينة الأكبر يحسنان مورفولوجيا الحبوب بشكل كبير ويحسنان بشكل ملحوظ صلادة، معامل المرونة، وقوة الشد للعينات. ومع ذلك، تأثرت الإستطالة سلباً. ظهرت المسامية في جميع العينات المطبوعة التي أثرت بشكل كبير على خصائصها. وقد أظهرت العينات ذات الزاوية 0° أيضاً مقاومة تآكل وبلى وتكوين حفر متفوقة. كما أبرزت النتائج أهمية الأخذ بعين الاعتبار حجم العينة والكثافة في عمليات الاندماج الانتقائي بالليزر لتحسين الخصائص الميكانيكية، ومقاومة البلى، وخصائص مقاومة التآكل.

CHAPTER 1

INTRODUCTION

1.1 Background

Additive manufacturing (AM) has revolutionized the field of manufacturing, enabling the production of components with complex geometries through a streamlined design-to-manufacture process. This technology has opened new avenues for creating parts that are customized and intricate with enhanced efficiency.

AM has seven different techniques used in the industry, including Direct Energy Deposition, Powder Bed Fusion, Binder Jetting, Material Jetting, Material Extrusion, Vat Polymerization, and Sheet Lamination. Each of these techniques represents a specific AM technique, tailored to different material types and specialized applications in the field of manufacturing. Laser powder bed fusion (LPBF) technique is widely used in the manufacturing industry due to its ability to fabricate complex components, reduce cost, time, and Labor. The LPBF technology utilized a wide range of metals and alloys, such as Aluminum alloys, titanium alloys, steel, magnesium alloys, nickel-based alloys, and ceramics in the form of powders. This process is used to produce components for different applications such as aerospace, automotive, medical, machinery, nuclear reactors, marine/oil and gas, shipbuilding, food and transportation, electronics, and consumer applications [1].

Studying the process parameters such as scan speed, laser power, hatch spacing, etc. and its influence on the properties of AM components such as mechanical properties, surface finish, density, wear resistance and corrosion performance is important. All these parameters are user-defined so it can easily change, so it should be optimized to reduce the defects and get the best properties.

Extensive research to select the optimal parameters provides valuable insights into critical factors affecting the printing process. However, achieving specific porosity or mechanical properties often necessitates integrating these parameters with post-processing techniques like stress-relieving, surface machining, and heat treatments. Such additions can extend the production time for LPBF components and introduce variability in part behavior [2], [3]. For instance, experiments have shown that applying different heat treatments to samples created with identical printing parameters and powder can significantly modify their mechanical properties due to microstructural alterations [4].

This research aims to investigate the effects of building orientation as well as sample size on mechanical, wear resistance, density, and corrosion performance of LPBF 316L stainless steel. This material is widely used in various applications due to its corrosion resistance and biocompatibility.

1.2 Motivation

The motivation for this study focuses on investigating the influence of build orientation and sample size on the properties of 316L stainless steel fabricated using LPBF. Recognizing the potential variability in material characteristics arising from these factors, the research aims to conduct a comprehensive analysis through various tests. This approach seeks to deepen the understanding of how these specific production parameters can affect the resulting properties of LPBF-manufactured stainless steel components.

1.3 Thesis objectives

- I. Fabricate 316L stainless steel samples with different orientations and sizes using LPBF.
- II. Perform surface characterization for the printed samples categorized by process parameters.

- III. Conduct experiments to investigate the effect of changing build orientation and sample size on: Mechanical properties, Coefficient of friction and wear resistance, Density, Corrosion performance.

1.4 Methodology

The main objective of this thesis is to experimentally study the effect of various orientations and varying the size on mechanical, tribological and corrosion resistance properties. Starting with the design and manufacturing of the samples using LPBF GE M1 machine with vertical, horizontal and 45° orientations and 2, 0.5, and 5mm sizes with specific printing configuration. Then the samples were prepared by grinding and polishing to conduct the experimental testing.

XRD analysis was conducted to ascertain the phases of 316L stainless steel. SEM and EDS were utilized for microstructural and chemical composition analysis. The Archimedes method measured the relative densities of the components, while Vickers micro-hardness tests were performed using micro-indentation equipment. Tribological testing involved a linear reciprocating tribometer with an alumina ball, and the resultant wear tracks were analysed using SEM, EDS, and a 3D profilometer to assess wear volume and depth. Corrosion resistance was evaluated through Open Circuit Potential (OCP), Electrochemical Impedance Spectroscopy (EIS), and Cyclic Potentiodynamic Polarization (CPDP), with SEM and EDS characterizing the surface and corrosion products.

CHAPTER 2

LITERATURE REVIEW

2.1 Additive Manufacturing

Additive manufacturing (AM) is the most appropriate term for 3D printing or rapid prototyping, a technology that can produce near net products from a computer aided design (CAD) model [5]. AM technology utilizes different kinds of materials such as liquids, semisolid pastes, powders, or solids [6]. Post-processing of as built AM parts involves machining and polishing, Heat treatment, hot isostatic pressing (HIP), shot peening, and others [7–9]. The versatility of AM technology enables its application in prototyping, manufacturing of consumer parts, and providing rapid and cost-effective repairs, making it an excellent tool for identifying market changes and creating a wide range of opportunities into the market [5,10]. Additive manufacturing process starts with a concept design or a new modification of an existing part using drawings. The concept model is then developed in modeling software and referred to as the "CAD model of the concept part" [11]. The CAD model undergoes thorough examination of its dimensions after printing, residual stress, tolerance, printing time, and other relevant factors before being finalized [12,13]. Figure 2.1 illustrates the steps of the process.

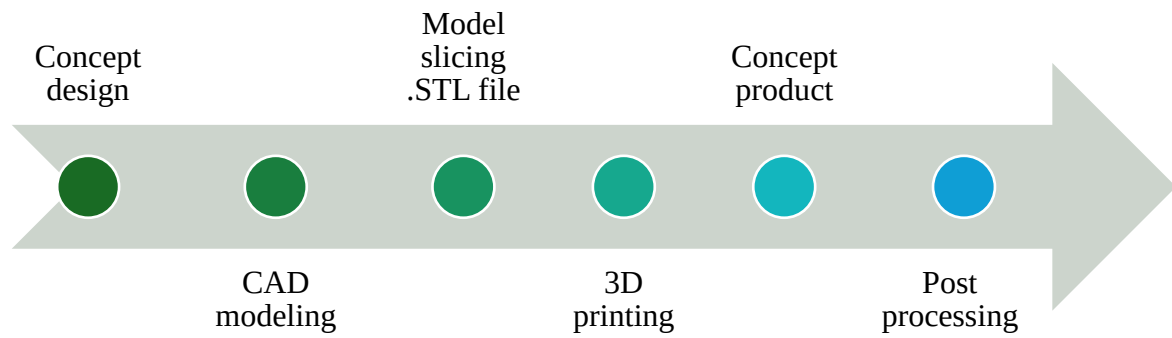


Figure 2.1 Process flow diagram of 3D printing

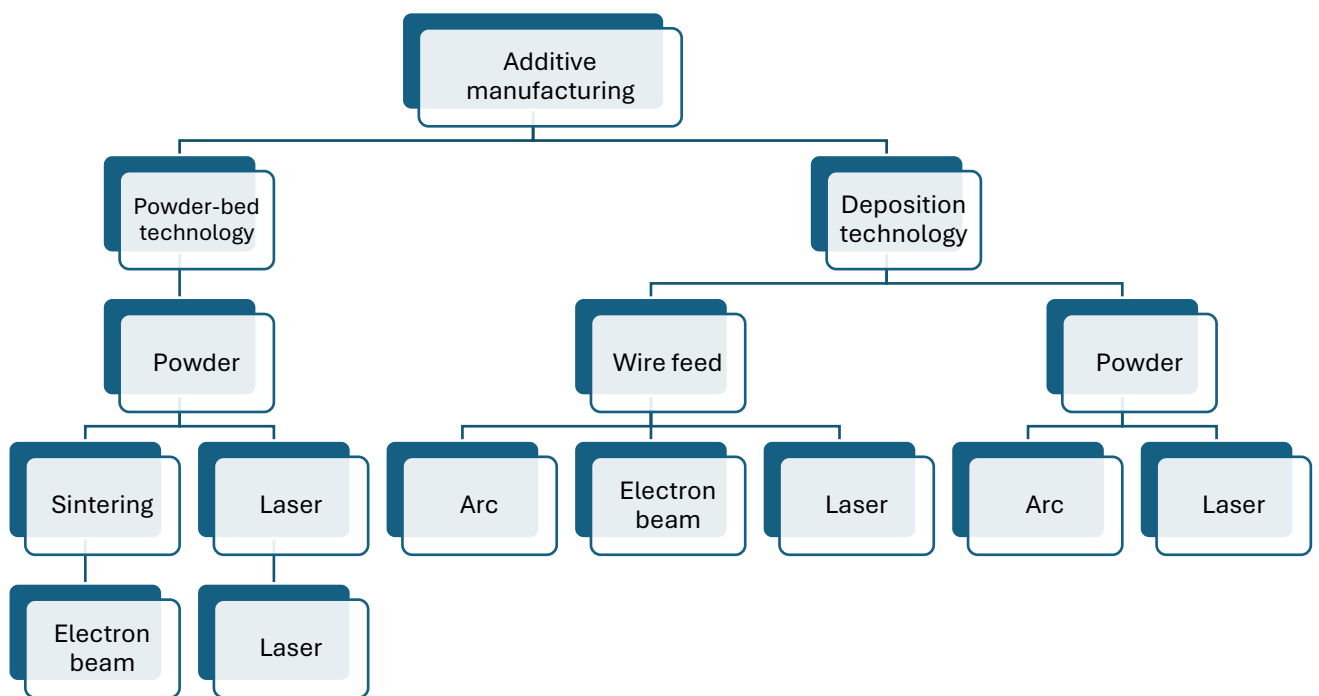


Figure 2.2 Metal Additive Manufacturing processes

Metal Additive Manufacturing (MAM) materials are categorized based on the energy or heat source used in the process as shown in Figure 2.2. Techniques such as stereolithography (SLA) and digital light processing (DLP) utilize a liquid or semi-solid paste that is projected by a digital light projector. MAM involves using a metal powder feed stock to create solid objects layer by layer and it can be classified into three main categories, depending on the material feed stock including powder feed system, powder bed system, and wire feed system [25]. There are different types of methods that can be used to fabricate metal components, such as direct metal sintering, selective laser sintering (SLS), direct energy deposition (DED), and metal binder jetting (BJ).

2.2 Classification of AM processes

Numerous AM techniques are available, each with its distinct advantages and disadvantages. According to the ASTM Standard F2792, there are seven primary AM processes: binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination, and vat photopolymerization. Each technique offers unique benefits and limitations, making them suitable for different applications in the industry [14].

2.2.1 Directed Energy Deposition

Directed Energy Deposition (DED) is a 3D printing technique frequently utilized for adding material to or repairing existing components [15,16]. This method features a nozzle that precisely controls material extrusion and grain structure, capable of moving in various directions. While DED can be applied to polymers and ceramics, it is primarily used with metals and metal-based alloys, either in wire or powder form. Laser deposition and Laser Engineered Net Shaping (LENS) are notable examples of this technology [17,18]. Laser deposition, a relatively recent innovation, supports the creation or repair of parts ranging from

millimeters to meters in size and is increasingly used in industries such as aerospace, transportation, and tooling. Figure 2.3 below illustrates the schematic of the DED system.

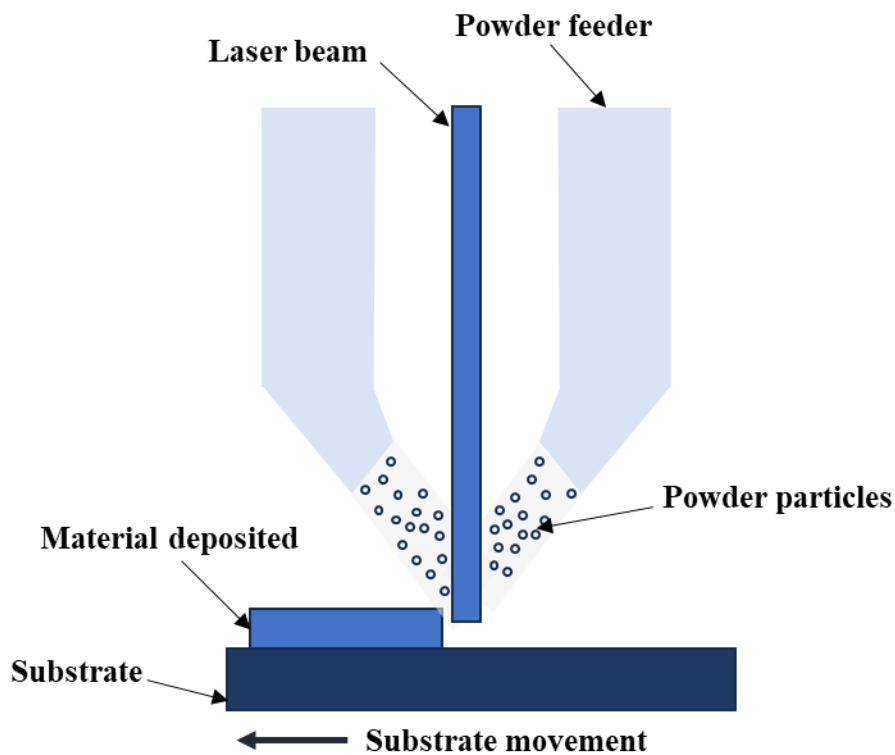


Figure 2.3 Schematic of DED system

2.2.2 Binder Jetting

Binder jetting (BJ) is an additive manufacturing technique that produces parts by using a powder material as feedstock and a binding agent to adhere the particles together, a chemical binder is sprayed onto the spread powder to create the layer. Binder jetting technology is commonly used to produce large quantities of casting patterns, unfinished sintered goods, or similar products from sand. Ceramics, metals, sand, polymers, hybrids, and other materials can be printed using binder jetting. The binder jetting procedure is straightforward, fast, and inexpensive because the powder particles are glued together, and sand is one of the materials that do not require any further processing. Additionally, binder jetting can print extremely large objects [19,20].

2.2.3 Materials extrusion

Material extrusion is a versatile 3D printing technique that enables the fabrication of objects from plastics, edible materials, and even living cells, offering a wide array of colors and material types [21]. This technique is cost-effective, widely used, and it can produce functional product components [10]. One prominent example of material extrusion is the fused deposition modeling (FDM) system, which was developed in the early 1990s and primarily uses polymers as its material [22]. FDM constructs parts by heating and extruding thermoplastic filament layer by layer, starting from the bottom and moving up. FDM operates in two stages:

- I.** The extruder heats and extrudes a semi-liquid thermoplastic material in tiny beads along the designated path [23].
- II.** Support material, which can be removed later, is deposited by the 3D printer where needed for support or buffering. For instance, FDM may utilize a hard plastic material to produce 3D models of bones [23].

2.2.4 Vat Photopolymerization

Photopolymerization stands out as the most prevalent method in 3D printing, where photo-reactive polymers are hardened using a laser, other light sources, or ultraviolet (UV) radiation [24,25]. Notable among photopolymerization-based 3D printing techniques are Digital Light Processing (DLP) and Stereolithography (SLA). In SLA, factors such as the photo initiator, irradiation exposure, UV absorbers, and specific operational conditions are crucial to the process. Conversely, DLP employs a more traditional light source like an arc lamp paired with a liquid crystal display panel, enabling it to process the entire layer of photopolymer resin in a single pass, which generally allows for faster operation than SLA. In the broader category of Vat Photopolymerization, initially utilized with liquid resins, the wavelength, power, and exposure duration are critical parameters, with materials solidifying upon exposure to

ultraviolet light. Photopolymerization is particularly suited for creating high-quality products characterized by intricate details and a smooth surface finish [26].

2.2.5 Sheet Lamination

Sheet lamination involves joining material sheets together to form a component, as per the standards set by ASTM. Laminated object manufacturing (LOM) and ultrasound additive manufacturing (UAM) are two 3D printing techniques that use this method [27]. This method is advantageous due to its ability to produce full-color prints, cost-effectiveness, ease of material handling, and the ability to recycle excess materials. LOM can produce complex geometries at a faster and more affordable rate [28]. UAM involves bonding layers of metal from plain foil stock using sound waves.

2.2.6 Materials jetting

Material jetting is an AM method that precisely ejects build material in droplets, in alignment with ASTM Standards. This technique constructs parts layer by layer, utilizing a photosensitive material that hardens upon exposure to UV light, effectively solidifying the droplets to form the final object [29]. Material jetting technology produces parts characterized by their exceptional surface quality and high precision in dimensions. It can process a diverse range of materials, including polymers, ceramics, composites, biological substances, and hybrid materials. Furthermore, this method facilitates the printing of objects with multiple materials simultaneously, enhancing its versatility in manufacturing complex components [30].

2.2.7 Powder bed fusion

The Powder Bed Fusion (PBF) process is integral to several AM techniques, including Selective Laser Sintering (SLS), Electron Beam Melting (EBM), Direct Metal Laser Sintering (DMLS), and Selective Laser Melting (SLM) [1,31,32]. This process employs either a laser or

an electron beam to melt or fuse powder materials in accordance with the geometry of the component [33]. PBF can utilize a diverse range of materials such as metals, ceramics, polymers, composites, and hybrids. For instance, SLS specifically uses a powerful laser to sinter polymer powders, constructing 3D objects layer by layer. Figure 2.4 below provides a schematic of an LPBF system where inert gases like argon or nitrogen are utilized to minimize oxidation and clear out fumes generated during the manufacturing process. The thickness of each powder layer typically ranges from 20-100 μm , while particle sizes vary between 10-45 μm [34].

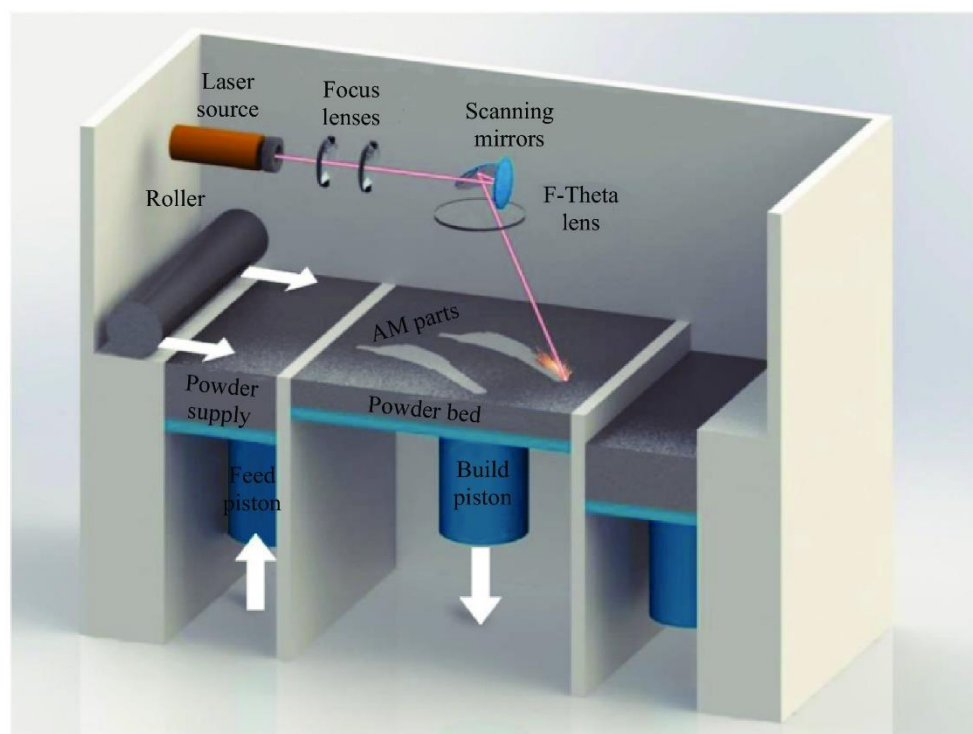


Figure 2.4 Schematic illustration of LPBF system[35]

2.3 Stainless Steel

Stainless steel is a broad category, known for their corrosion resistance and thermal robustness, fundamentally characterized by a chromium content exceeding 11wt.% [36,37]. Stainless steel is used across a diverse range of industrial sectors due to its widespread availability, welding characteristics, excellent machinability, and robust strength [5]. Its applications range from domestic tools such as cookware and household furnishings to large scale industrial applications within the automotive, medical, petrochemical, oil and gas and power generation sectors. Stainless steel is typically sorted into five principal categories: ferritic, austenitic, martensitic, duplex, and precipitation hardening. This classification reflects the extensive utility of stainless steel in various fields [38].

2.3.1 Austenitic Stainless Steel

Austenitic stainless steels represent the largest category within the stainless-steel family, including subgroups such as Cr- Mn, Cr-Ni, and Cr-Ni-Mo alloys [39]. These alloys are known for their notable corrosion resistance, excellent formability, and superior weldability. Austenitic 316L stainless steel is prevalently used in biomedical implant applications. Its widespread adoption is attributed to its favourable biocompatibility in oxygen-rich environments and its cost effectiveness relative to titanium, making it very attractive material that can be used in different applications. It is used in biomedical sector such as joint replacement implant, having the acceptable biocompatibility, and required density [40].

2.3.2 Ferritic Stainless Steel

This type of stainless steel is recognized for that they have the similar microstructure as for carbon steels, primarily characterized by a content of chromium ranging from 10.5 to 18 wt.% and low nickel content [39]. They have found widespread applications across different industries, including vehicle chassis, rail transport, power generation and mining. This broad usage shows their adaptability and resilience in diverse operational environments. The low

nickel content inherently makes ferritic grades more cost effective compared to other stainless steels. Different from austenitic stainless steels, the presence of ferrite makes them magnetic. On the other hand, for mechanical strengthening, it shows similar behavior as austenitic grades. Both can be strengthened through cold working, to a limited degree and not by heat treatment.

2.3.3 Martensitic Stainless Steel

Martensitic stainless steels are well-regarded for their excellent mechanical properties, which include robust ductility and high mechanical strength, along with notable corrosion resistance attributable to their chromium content. These steels are typically strengthened through heat treatment processes. In terms of corrosion resistance, martensitic stainless steels are often compared to ferritic grades due to the similarities in their microstructures. [39].

2.3.4 Duplex Stainless Steel

Duplex Stainless steels are characterized by having a combined microstructure of both ferritic and austenitic phases, often described as austenitic-ferritic stainless steels. This composition typically manifests in an approximately equal phase balance of 50% ferrite and 50% austenite, giving the material a distinctive set of properties. These types of stainless steels are known for their high chromium and low nickel content. Specifically contains about 20-26 wt.% chromium, 1.5-8 wt.% nickel, and 0.1-4 wt.% molybdenum [41].

Duplex stainless steels are known for their exceptional strength and resistance to stress corrosion cracking, making them suitable for applications in which it is subjected to high mechanical stress and harsh corrosive environments. Frequently used in the chemical and offshore industries, particularly for pipes as well as in shafts, valves, pins, and desalination plants components. In terms of their strengthening mechanism, all duplex stainless steels are susceptible to hardening through cold working however they cannot be strengthened by heat treatments. Additionally, the presence of ferrite gives the duplex magnetic properties [39].

2.3.5 Precipitation Hardened Stainless Steel

Precipitation-hardened stainless steels are produced through a specialized process that encourages the formation of precipitates within their microstructure [39]. This method enables these steels to achieve markedly enhanced strength via heat treatment. Key mechanical properties, including strength, ductility, and toughness, as well as corrosion characteristics like self-corrosion potential and current density, are essential for evaluating metallic structural materials. Given their robust properties, precipitation-hardened stainless steels are widely utilized in various industrial applications, including in the aerospace sector, marine environments, and nuclear reactors.

2.4 Wear Mechanisms in Additively Manufactured Steel

This research primarily examines how printing parameters affect the wear behavior of LPBF-ed 316L stainless steel. Numerous studies have explored the impact of process parameters on the mechanical properties, microstructure, and wear behavior of 316L stainless steel in both dry and lubricated conditions. Zhu et al. [42] observed that LPBF 316L stainless steel parts exhibit a higher wear rate due to the presence of pores between the molten layers. Conversely, Tascioglu et al. [43] found that, due to the fine structure and post-processing techniques, both the coefficient of friction (COF) and wear rates were significantly lower than those of parts produced through traditional manufacturing methods.

Sun et al. [44] conducted a study on the tribological and corrosion behaviors of 316L stainless steel samples, focusing on the effects of varying laser scan speeds. Their findings indicated that samples produced through SLM exhibited reduced resistance to dry sliding wear. The researchers suggested that increasing the density of these SLM-produced samples might enhance their wear resistance. Additionally, Liverani et al. [45] investigated how SLM parameters such as laser power, scanning speed, hatch spacing, and build orientation influence

the microstructure and mechanical properties of SLM-manufactured 316L stainless steel. Their research identified optimal process settings for these parameters, which led to improvements in the quality and performance of the fabricated samples.

Sander et al. [46] analysed the microstructure, mechanical properties, and wear behaviour of FeCrMoVC tool steel parts produced using SLM and conventional casting methods. Their findings indicated that parts fabricated via SLM exhibited higher hardness and a reduced wear rate compared to those produced through casting.

Li et al. [47] explored the impact of different build orientations on the dry wear performance of 316L stainless steel created using SLM technology. They found that factors such as hardness, density, and surface roughness remained relatively consistent across different building orientations, suggesting that build orientation does not significantly affect the COF and wear rate.

Khan et al. [48] conducted research on the dry wear behaviour of 316L stainless steel parts manufactured by LPBF. Utilizing a ball-on-disc tribometer under various conditions, they discovered that surface features significantly influence the wear behaviour of the samples. Notably, decreasing the sliding speed and temperature while increasing the normal load led to higher wear rates and COF values.

Bae et al. [49] investigated the wear resistance of 316L stainless steel manufactured using SLM technology in various building orientations. They performed the wear tests using ball-on-disc tribometer and assuming the deformation under a high sliding speed condition. The investigation showed that the building direction significantly impacted the wear resistance. Specifically, when the load direction was parallel with the building direction, the severity of wear was more compared to when the load was applied perpendicularly to the building direction.

Zhang et al. [50] experimentally investigated the effects of build orientation and hatch scanning angle on the mechanical properties of 316L stainless steel fabricated using SLM process. The results illustrated that the optimal scanning angle is 30°. Huang et al. [51] found that the 316L stainless steel produced by SLM samples have better wear performance than that of rolled samples. Carassus et al. [52] performed experimental research to assess how specimen thickness and build orientation affect the mechanical properties of 316L stainless steel samples fabricated using SLM. Their findings revealed that samples oriented horizontally exhibited the highest tensile stress compared to samples in other orientations.

Numerous studies have focused on improving the wear performance of 316L stainless steel parts manufactured through LPBF. Key findings indicate that post-processing techniques, such as heat treatments following the SLM process, promote microstructural changes that significantly enhance the mechanical properties of the material. These modifications typically result in improved wear resistance, highlighting the importance of post-process thermal management in optimizing the performance of LPBF-fabricated stainless-steel components [53–55]. Tascioglu et al. [55] reported the effect of different heat treatment temperatures of 316L stainless steel fabricated by SLM on the wear performance, microstructure, porosity, and microhardness. They found that the microstructure changed at 850 °C, at which it starts to homogenize. The porosity and hardness of the samples were observed to decrease with the increase of heat treatment temperatures. It stated that the wear performance is mainly affected by the sample's porosity more than by hardness so better wear resistance was recorded after heat treatment. Shin et al. [56] investigated the effect of heat treatments of SLM 316L stainless steel on the mechanical properties and wear performance, the samples manufactured with various laser powers and scan speeds. Heat treatments increase the SLM samples density, decrease in tensile strength as well as an increase in the elongation, also the wear resistance and surface hardness reduced with the heat treatments.

2.5 Electrochemical Corrosion Behaviour

Corrosion is an electrochemical phenomenon, including simultaneous oxidation and reduction reactions on metal surfaces in corrosive environments, leading to metal degradation and electrolyte reduction. This process can be divided into two main forms, general corrosion which is characterized by uniform metal dissolution across a surface, and localized or pitting corrosion, which occurs at small areas. To analyze corrosion, electrochemical techniques such as open circuit potential (OCP), electrochemical impedance spectroscopy (EIS), and cyclic potentiodynamic polarization (CPDP) are employed, offering insights into the corrosion behavior of metals.

2.5.1 Open Circuit Potential (OCP)

Open circuit potential (OCP) is defined as the equilibrium potential occurred between the working electrode and the reference electrode in the absence of external electrical potential when there is no current flow [57,58]. This method includes monitoring the potential of the sample as it immerses and interacts with the electrolyte. OCP provides insights into the electrochemical behavior of the sample in corrosive environments.

2.5.2 Electrochemical Impedance Spectroscopy (EIS)

Electrochemical Impedance Spectroscopy (EIS) stands out as an advanced, non-destructive technique in the field of steady-state electrochemistry, particularly for corrosion analysis. Its capability to offer valuable insights into reaction parameters, corrosion rates, oxide formation, surface integrity, porosity, and various other interfacial properties makes it a highly sophisticated tool for corrosion evaluation [59,60]. In EIS a small amplitude of alternate current (AC) is applied to the system in a certain frequency range. The data was collected using a potentiostat or galvanostat, and then interpreted by fitting it to an equivalent electrical circuit (EEC) model. This approach is significant to convey the EIS data into meaningful

interpretations, developing a good understanding of the electrochemical characteristics of the system [61].

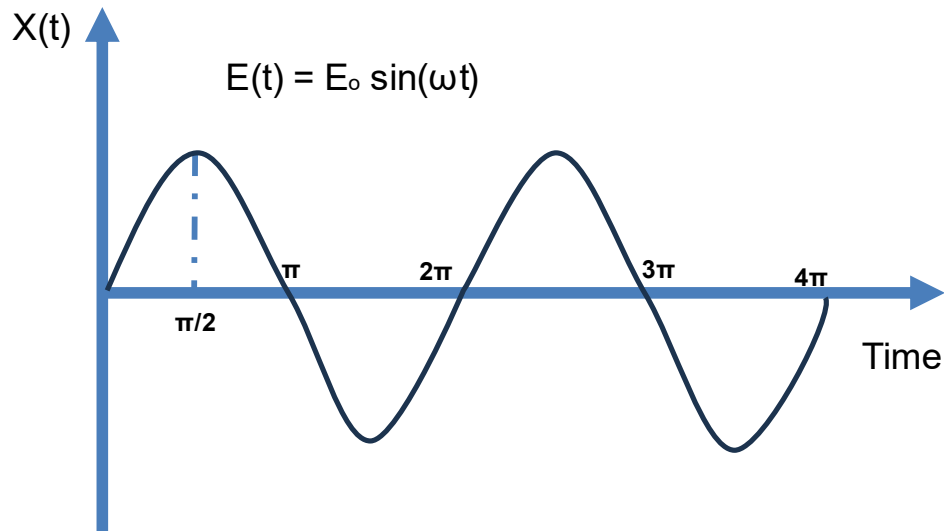


Figure 2.5 Illustration of a vector rotating with a constant angular frequency ω and the corresponding sinusoidal signal [62]

Figure 2.5 show the signal used in the EIS calculation as a function of time, and the equation as stated below:

$$E(t) = E_o \sin (\omega t) \quad (1)$$

Where $E(t)$ is the potential at time (t) , E_o is the amplitude of the signal, ω is the angular frequency (radian/ s). The relationship between ω and the frequency (f in hertz) is given by:

$$\omega = 2\pi f \quad (2)$$

Equation 3 can be used to calculate $I(t)$, which is the response current at time (t) , I_o is the response signal amplitude, ϕ is the shifted phase angle.

$$I(t) = I_o \sin (\omega t + \phi) \quad (3)$$

From Ohm's law, the impedance (Z) of the system can be calculated as follows:

$$Z = \frac{E(t)}{I(t)} = \frac{E_o \sin (\omega t)}{I_o \sin (\omega t + \phi)} \quad (4)$$

The electrochemical interactions occurring between an electrode and an electrolyte during an EIS test can be conceptualized through an Equivalent Electrical Circuit (EEC). This model employs a combination of electrical components, notably capacitors and resistors, to simulate the observed electrochemical processes. Illustrations below (Figure 2.6) include a Nyquist plot, accompanied by the corresponding EEC model, providing a visual representation of these electrochemical dynamics.

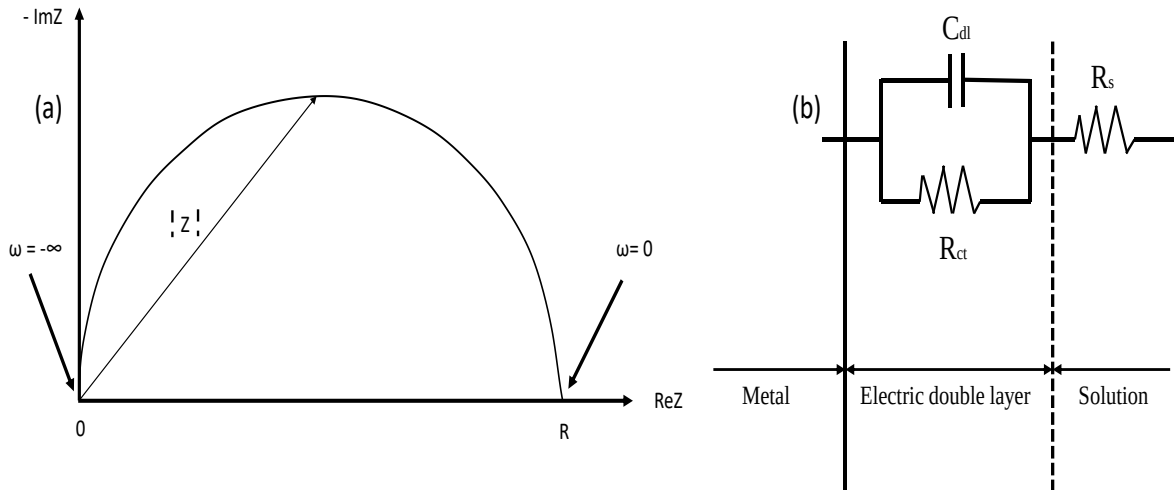


Figure 2.6 (a) Nyquist plot, (b) The equivalent electrical circuit (EEC)

2.5.3 Cyclic Potentiodynamic Polarization (CPDP)

The cyclic potentiodynamic polarization (CPDP) measurement, first introduced in the 1960s, is a widely used technique to evaluate the material resistance to localized corrosion or

degradation rate [63,64]. This method is specifically effective to predict the localized corrosion and useful to determine spontaneously passivating alloys that are prone to localized corrosion.

The CPDP test begins by measuring the Open Circuit Potential (OCP) of a metal sample immersed in an electrolyte, which involves determining the potential difference between the working electrode (the sample) and a reference electrode. The OCP measurement is considered stable when its fluctuation is less than 3 mV per minute. Once OCP stabilization is achieved, the sample undergoes anodic polarization. This starts from a potential slightly below the OCP value, advancing at a slow scan rate, typically 1 mV/s. Polarization is reversed once a predefined current value is reached, commonly set at 1 mA/cm² or two orders of magnitude higher than the passive current density, as depicted in Figure 2.7.

According to ASTM F2129 standard, CPDP tests can result in three different outcomes: completion of the hysteresis loop with continuous scanning potential indicating repassivation, as shown in Figure 2.7 (a); occurrence of oxygen evolution and transition from anodic to cathodic potential as in Figure 2.7 (b); or an incomplete hysteresis loop that returns to the corrosion potential as seen in Figure 2.7 (c). Per ASTM G61 standard, the reverse scan proceeds until the hysteresis loop is completed or the corrosion potential is revisited, adhering to the established criteria [65–67].

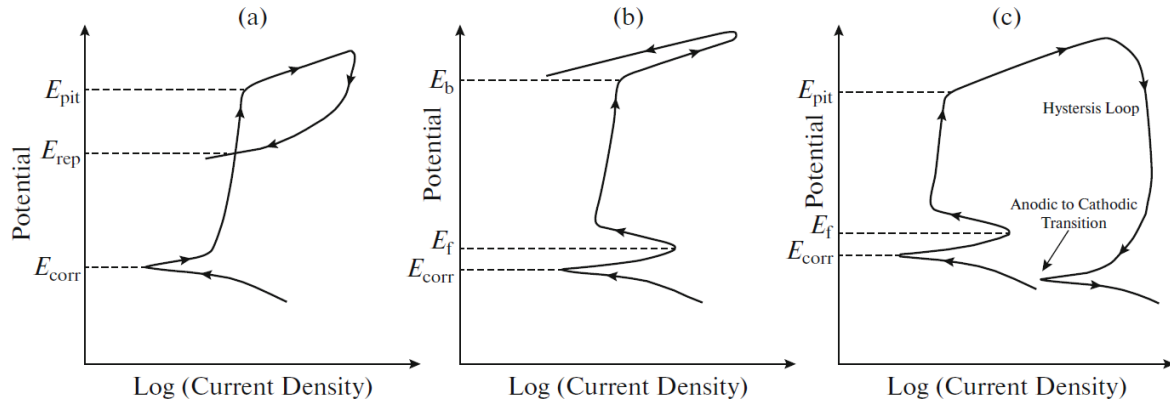


Figure 2.7 Typical CPDP curves, a) with repassivation, b) with oxygen evolution, c) with no repassivation [64].

The LPBF is widely used in the industry, therefore a lot of research has been done to investigate the corrosion behavior of LPBF components. Stainless steels are the most used materials in the industry, due to their superior corrosion performance as well as their mechanical properties. There are different factors affecting the additively manufactured material properties, such as scanning speed, laser power, building direction, post-processing [68–70]. These factors influence properties including porosity, microstructure, and corrosion resistance.

Trisnanto et al. [71] explored how crystallographic orientation affects the general and pitting corrosion of LPBF 316L stainless steel samples in a saline environment. Their findings indicated that the sample oriented at 35° exhibited the highest general corrosion resistance, followed by vertical and horizontal orientations, respectively. This behaviour is thought to be linked to the activation energy and surface density of the samples.

Andreatta et al. [72] examined the corrosion properties of 316L stainless steel produced using the SLM technique in 3.5 wt.% NaCl solutions at both neutral and 1.8 pH levels. Similarly, Nie et al. [73] analysed the relationship between microstructure, passive film formation, and pitting corrosion of AM 316L stainless steel in a 3.5 wt.% NaCl solution. They noted that LPBF 316L stainless steel offers higher general corrosion resistance than wrought materials, primarily due

to the development of a thicker passive film. Supporting these findings, research by Karimi et al. [74] demonstrated that LPBF 316L stainless steel samples possess enhanced corrosion resistance, attributed to the formation of a stable passive film and reduced defects compared to wrought samples.

Additionally, Sander et al. [75] investigated how building direction and residual stress influence the corrosion behaviour of 316L stainless steel fabricated using the SLM process. Their results suggested that the anisotropy of the microstructure, resulting from rapid cooling rates, endowed these samples with better pitting resistance compared to wrought samples. Notably, samples with a horizontal building orientation showed superior pitting resistance.

Current literature highlights the critical need to explore how different processing parameters affect properties like mechanical strength, microstructure, wear performance, and corrosion resistance in additively manufactured materials. Such studies are essential for comprehensively understanding how these materials behave under various operational conditions. This study specifically aims to thoroughly examine the impacts of build orientations and part sizes on the corrosion resistance, wear performance, and mechanical properties of components fabricated using LPBF. This research is intended to provide deeper insights into optimizing additive manufacturing processes for enhanced material performance.

CHAPTER 3

MATERIALS AND METHODS

In this chapter, an overview is provided of the materials, systems, instruments, and methodologies used in this research study. This section is essential for understanding the experimental framework and the approaches undertaken to achieve the research objectives.

3.1 Research Framework

The samples for this study were fabricated using the GE concept laser M1 type Laser Powder Bed Fusion (LPBF) equipment, located at IMMENSA Additive Manufacturing Company in Saudi Arabia, the process configuration is shown in Table 3.1. Post-manufacturing, the samples prepared by different processes such as sectioning, mounting, grinding, and polishing for conducting hardness, wear, and corrosion tests. These tests were crucial for assessing the influence of both the build orientations and the size of the samples on their different material properties. Concept Laser GmbH supplied 316L stainless steel powder with a particle size ranging from approximately 10 to 45 μm . The chemical composition of this metal powder can be found in Table 3.2. The fabrication process of the LPBF samples started by slicing the 3D CAD model (in. STL format) into layers with a thickness of 45 μm . Subsequently, the CAD file was loaded into the machine software to identify the printing parameters for the component fabrication. Additionally, Inert argon gas was used during the manufacturing process. The dimensions of the samples are 87x24 mm with different thicknesses of 0.5 mm, 2 mm, and 5 mm. Also, these samples were manufactured in different orientations of 0°, 45°, and 90°. All samples were built at the same build plate as shown in Figure 3.1, and samples specifications shown in Table 3.3.

Table 3.1 LPBF GE concept laser M1, machine configuration [76]

Material	Laser power (W)	Scan speed (mm/s)	Layer thickness (mm)	Trace width (mm)	Energy density (J/mm^2)
SS 316L	180	800	0.045	0.15	33.33

Table 3.2 Chemical composition of 316L stainless steel powder from EOS [76]

Element	Fe	Cr	Ni	Mo	Mn	Si	P	C	S
(wt%)	Bal.	16.5-18.5	10-13	2-2.5	0-2	0-1	0-0.045	0-0.03	0-0.03

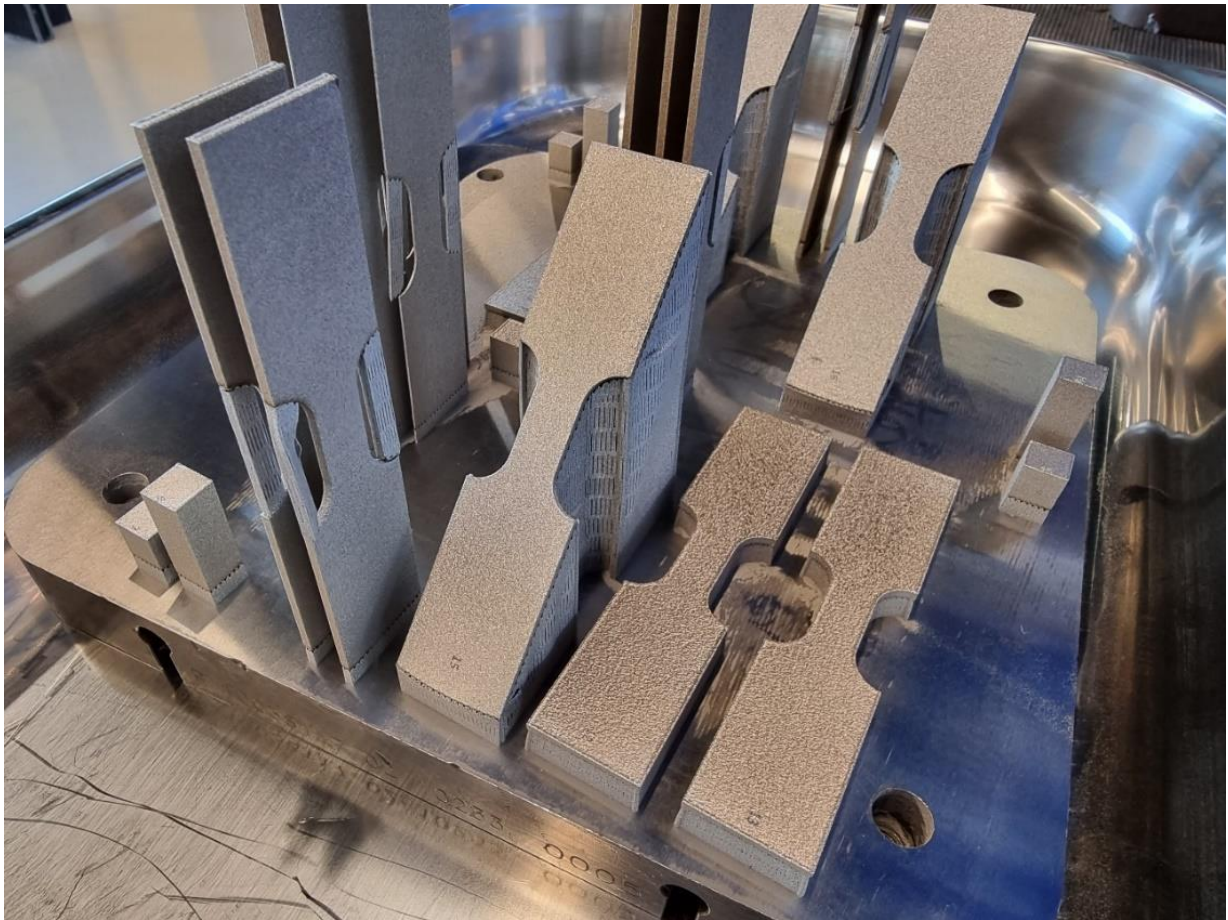


Figure 3.1 All printed samples

Table 3.3 Printed samples specifications

NO.	Powder Material	Sizes (mm)	Building orientation	Quantity
1	316L Stainless Steel	0.5	90°	3
2		5	90°	3
3		2	90°	3
4		2	45°	3
5		2	0°	3

3.2 Surface Preparation and Analysis

The as-produced samples underwent grinding and polishing to ready them for various tests including microstructure examination, corrosion, and tribological assessments. The grinding process employed a range of silicon carbide emery papers with grit sizes from 60 up to 1200. Subsequently, the samples were cleansed with acetone. Polishing was performed using fine-grade (1-3 μm) diamond paste and further refined with a silica colloidal solution to achieve a mirror-like finish. These prepared samples were then used for evaluations involving a 3D profilometer, microstructural analyses, indentation, friction, corrosion, and wear tests. An optical microscope (Contour GT-K, Bruker Nano GmbH, Germany) was utilized to assess surface characteristics as depicted in Figure 3.2. Furthermore, the surface topography, roughness, and wear volume were analyzed using a 3D profilometer (Profilom3D®, KLM, USA), illustrated in Figure 3.3. Additionally, scanning electron microscopy (SEM) (Quanta 250 FEG, FEI, Oregon, USA) examined the microstructure of the wear track surface, and its

chemical makeup was analyzed using integrated Energy-dispersive X-Ray spectroscopy (EDS, Oxford, USA), as shown in Figure 3.4.



Figure 3.2 Optical microscope



Figure 3.3 3D profilometer

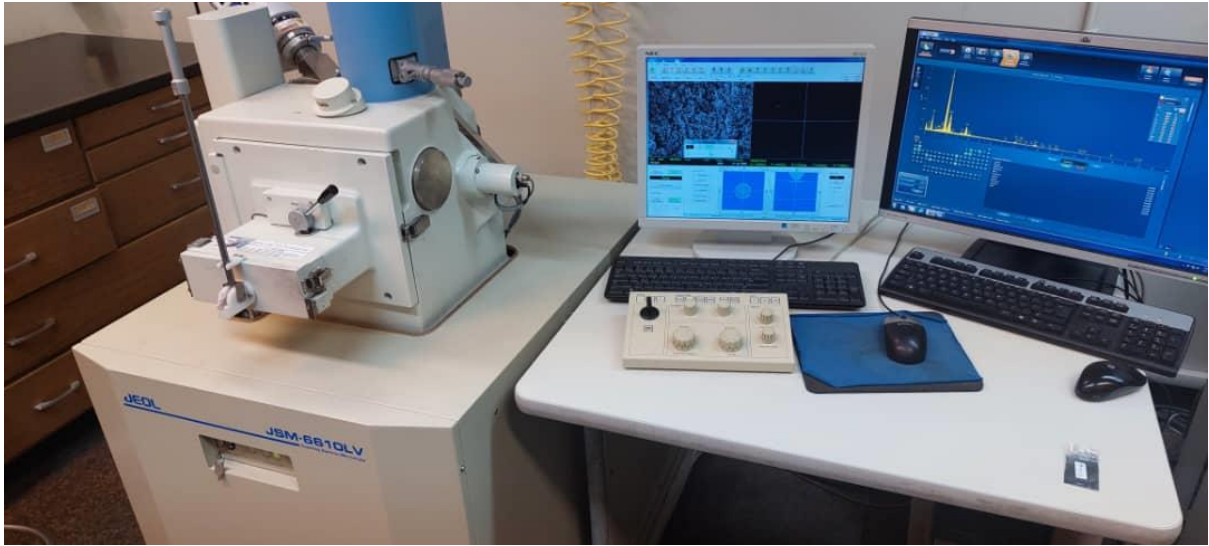


Figure 3.4 SEM/EDS equipment

3.3 Density Measurement

Density measurements of LPBF 316L stainless steel samples were conducted using a Mettler Toledo model AG285 electronic balance, accurate to ± 0.0001 g, in adherence to Archimedes principle. This procedure entailed the precise determination of sample weights in both air and distilled water, facilitating the accurate calculation of their densities. Equation (5) was then used to calculate the experimental density of the sample.

$$\rho_o = \left(\frac{A}{A-B} \right) * (\rho_l - \rho_a) + \rho_a \quad (5)$$

Where ρ_o = density of the sample, ρ_l = Density of Liquid, A = Weight in Air, B = Weight in liquid and ρ_a = Density of Air



Figure 3.5 Density device

3.4 Micro indentation test

The micro indentation test was conducted using a Vickers diamond indenter on a MicroCombi Tester from CSM Instruments, Peseux, Switzerland, shown in Figure 3.6. The test applied a maximum load of 500 N, reached a depth of approximately 2000 nm, employed a loading and unloading rate of 1000 mN/min, and included a dwell time of 10 seconds. Six indentations were performed to determine the average hardness and elastic modulus of the samples.

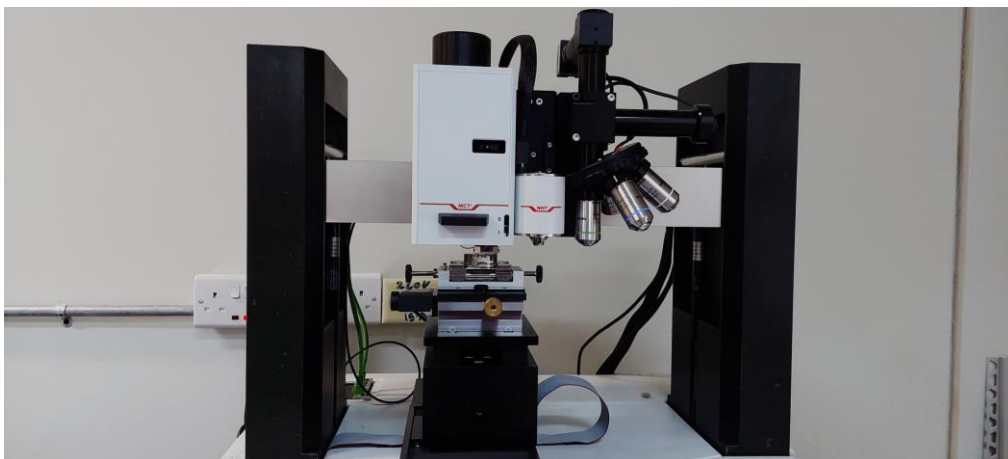


Figure 3.6 Micro and Nano indentation equipment

3.5 Tribological Characterization

Friction and wear tests were performed using a ball on disk (BoD) linear reciprocating tribometer (TR-282, Ducom Instruments, India) with counterpart material of alumina $\alpha\text{-Al}_2\text{O}_3$ ball with 6 mm diameter sliding against the sample shown in Figure 3.7. The coefficient of friction (COF) and wear rate were assessed in a dry environment at room temperature with a relative humidity of 45%. The sliding speed was consistently maintained at 0.1 m/s which simulates moderate operational conditions without excessive heating. Both the 12,500 sliding cycles which capture steady-state wear behavior, and a 10 N contact pressure which reflects typical operational loads. Post-testing, the wear track was examined using a 3D profilometer to determine the wear rate according to Archard's law [77]. The process involved aggregating the width and depth profiles of the wear track to compute the wear volume (V). This volume was then divided by the product of the contact load and the total sliding distance, providing a measure of the specific wear rate (SWR) for the LPBF sample, as outlined in Eq. (6) and Eq. (7) [77].

$$V = A \times l \quad (6)$$

$$SWR = V / S \times W \quad (7)$$

where l is the stroke length, S is the sliding distance, and W is the applied normal load.



Figure 3.7 Linear reciprocating Tribometer

The relative motion between the ball and the samples described as follows:

- Components created with an orientation of 0° will have their perpendicular axis aligned with the overlap direction of the layers.
- Components created with an orientation of 90° will have their parallel axis aligned with the overlapping direction of the layers.
- Components created with an orientation of 45° will have their axis positioned at a 45° angle in relation to the overlapping direction of the layers.

3.6 Electrochemical Analysis

Electrochemical analyses, specifically electrochemical impedance spectroscopy (EIS) and cyclic potentiodynamic polarization (CPDP), were performed on the LPBF specimens. These tests utilized a standard three-electrode system, which included a graphite counter electrode and a saturated calomel electrode (SCE) as the reference electrode. Prior to testing, the working electrode samples were polished using silicon carbide papers to a finish of 800 grits. They were then masked to leave only a 1 cm^2 area exposed to a 3.5 wt.% NaCl solution. The samples were subsequently rinsed with distilled water and acetone to ensure cleanliness before conducting the corrosion tests. During the EIS tests, an AC voltage of 10 mV was applied over a frequency range from 10^{-2} to 10^5 Hz. CPDP tests were executed

at open circuit potential (OCP), with a scan rate of 0.125 mV/s and potentials varying from -0.20 V cathodically to +0.50 V anodically. Tafel parameters were derived from the analysis of the CPDP curves.



Figure 3.8 Potentiostat setup used for corrosion testing

3.7 X-ray diffraction (XRD)

The phase analysis of all the samples was performed using X-ray diffraction, using XRD equipment (Bruker D2 PHASER, Madison, WI) (Figure 3.9) working with Cu-K α radiation ($\lambda = 1.54\text{\AA}$). The diffraction angle 2θ ranged between 20° and 80° .



Figure 3.9 XRD equipment

CHAPTER 4

RESULTS AND DISCUSSION

This chapter presents a comprehensive analysis of the mechanical, tribological, and corrosion behavior of LPBF 316L stainless steel components. It critically examines how build orientation and sample size influence the material mechanical properties, wear resistance, surface features, and corrosion resilience. The findings offer valuable insights into the potential applications and performance of LPBF 316L stainless steel in various conditions, enhancing our understanding of its suitability for different industrial uses.

4.1 Effect of Build Orientation

4.1.1 Microstructure and crystallographic phases

The surfaces of the printed samples were examined using SEM to identify specific surface features, as depicted in Figure 4.1. The analysis revealed balling on all as-built surfaces, characterized by un-melted particles sticking to the surfaces of the LPBF parts, which contributes to high surface roughness due to incomplete melting [1,78]. This phenomenon is also linked to increased porosity within the printed samples. Moreover, the morphology of the melt pools in the LPBF parts showed an overlapping pattern, indicative of effective powder fusion and the directional growth of columnar grains along the trajectory of the laser. Notably, pores were observed between layers, which reduce the density and strength of the parts. These pores are mainly influenced by process parameters, especially by the partial or incomplete melting at the layer boundaries. Wang et al. [79] investigated how the growth of columnar grains in the melt pool varies. Their findings showed a clear correlation between the preferred crystal orientation and the directional growth of these grains. This connection is crucial for understanding how the structural characteristics of grains affect the material overall properties,

emphasizing the significance of grain orientation in improving the mechanical performance of materials. During the printing process, the previously deposited layer is subject to repeated melting, which controls nucleation during solidification and instead facilitates the growth of partially remelted grains. As a result, this remelting process tends to orient the grains perpendicular to the curvature of the fusion line, thereby directly impacting grain orientation and structural formation in LPBF-manufactured components.

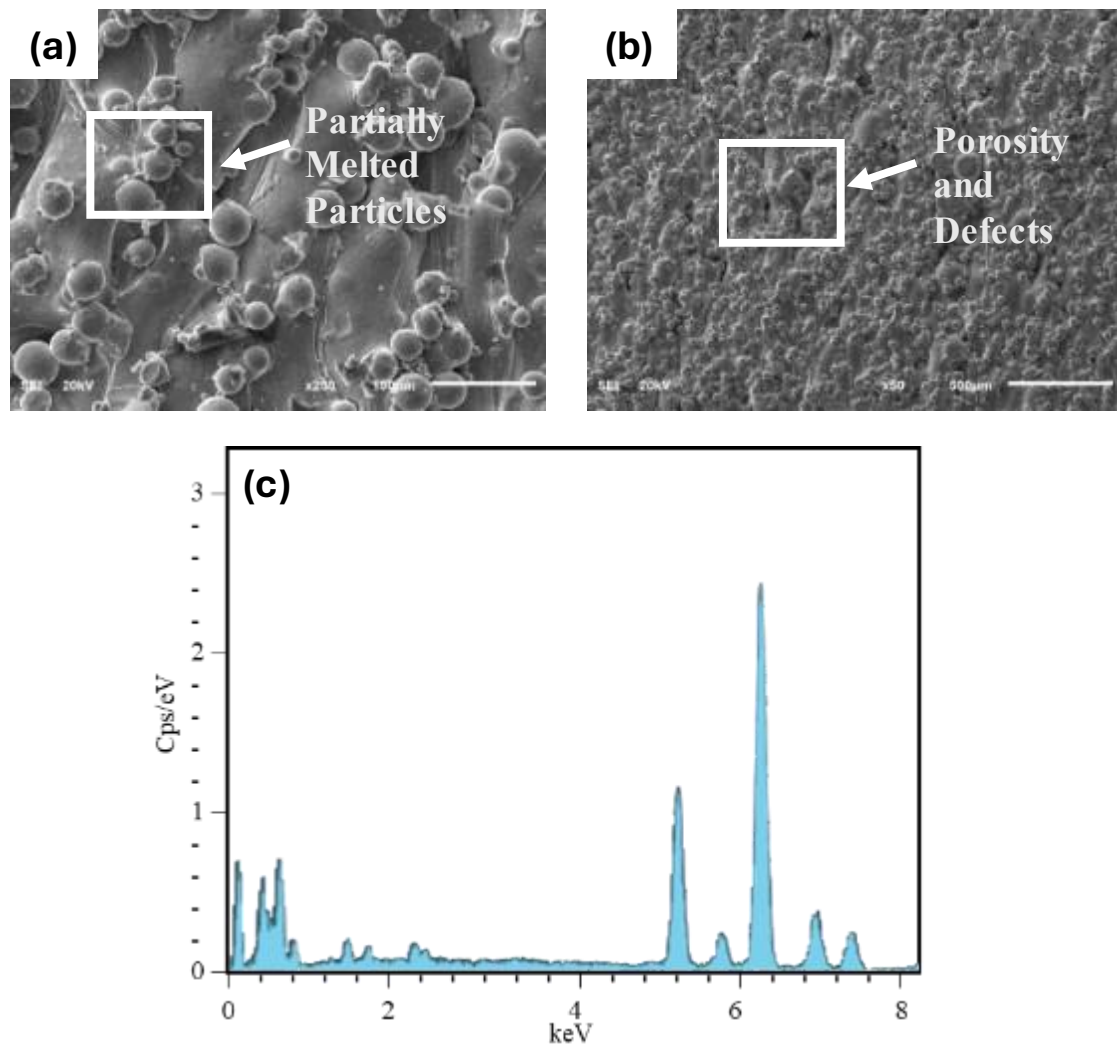


Figure 4.1 SEM micrographs and EDS result for the surface of LPBF 316L stainless steel samples

The microstructure of the printed samples was examined to investigate the characteristics of melt pools under different orientations (0° , 45° , and 90°) as shown in Figure 4.2. Analyzing the microstructure is crucial, particularly to identify any porosity that might result from surface

balling, which is evident in the microstructure of the samples [80]. The observations revealed the presence of crescent-shaped melt pools accompanied by micropores. These pores are primarily caused by the balling phenomenon, a process issue during the LPBF process, where the molten material, due to its surface tension, does not adequately fuse to the substrate, leading the material to form more spherical shapes as shown in Figure 4.2 [81].

Further analysis measured the melt pools' average depth and width at approximately 65 μm and 120 μm , respectively, across samples oriented at 0°, 45°, and 90°. Microporosity was noted in all samples, with average pore sizes measured at 110 μm , 51 μm , and 62 μm , respectively. The presence of these pores significantly reduces the density of the printed components. Moreover, the balling phenomenon not only affects porosity but also increases surface roughness, underscoring the importance of surface finishing in the post-processing stage.

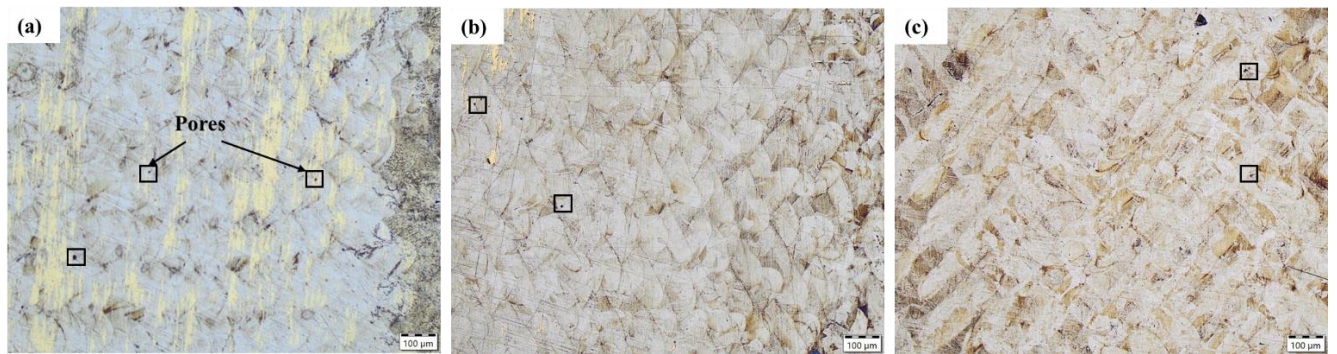


Figure 4.2: Optical microscope cross-sections of LPBF samples: a) 0° (XZ), b) 45° (YZ), and c) 90° (XY)

A macro-scale density approach was also used to analyze the sample densities using the Archimedes approach (Figure 4.3). The results show that 0° samples show the highest density (8.17 g/cm³) followed by 45° (8.04 g/cm³) and 90° (7.83 g/cm³) samples. These results are also in-line with the micrographs which show presence of bigger porosities in the 90° parts. An increase in porosity is expected to result in lower hardness and strength, which will be investigated in the following sections.

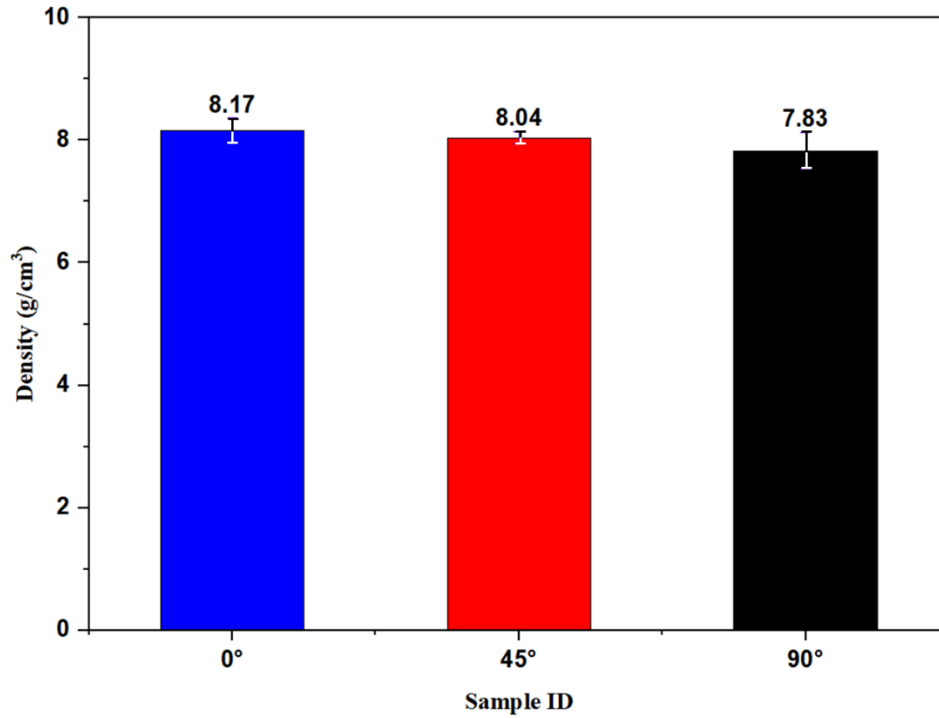


Figure 4.3: Density of LPBF samples with different orientation

Figure 4.4 shows the XRD pattern of LPBF 316L stainless steel material with different building orientations. The results show sharp peaks that correspond to the crystallographic planes of austenite (face-centered cubic structure (FCC)). The primary peaks in the XRD are located around 2θ values of approximately 43.5° , 50.7° , and 74.6° . These peaks correspond to the (111), (200), and (220) planes of the FCC austenitic phase. Calculations of crystallite size from XRD data showed a decrease with increasing build orientation: $23.1\ \mu\text{m}$ at 0° , $18.9\ \mu\text{m}$ at 45° , and $15.95\ \mu\text{m}$ at 90° . This trend indicates the significant impact of thermal gradients and cooling rates during the LPBF process, emphasizing the importance of thermal management to optimize microstructural properties. Zhang et al. [50] conducted a detailed study on the microstructural evolution of 316L stainless steel fabricated via SLM at different orientations, finding smaller grains in the 90° orientation due to higher thermal gradients and faster cooling rates.

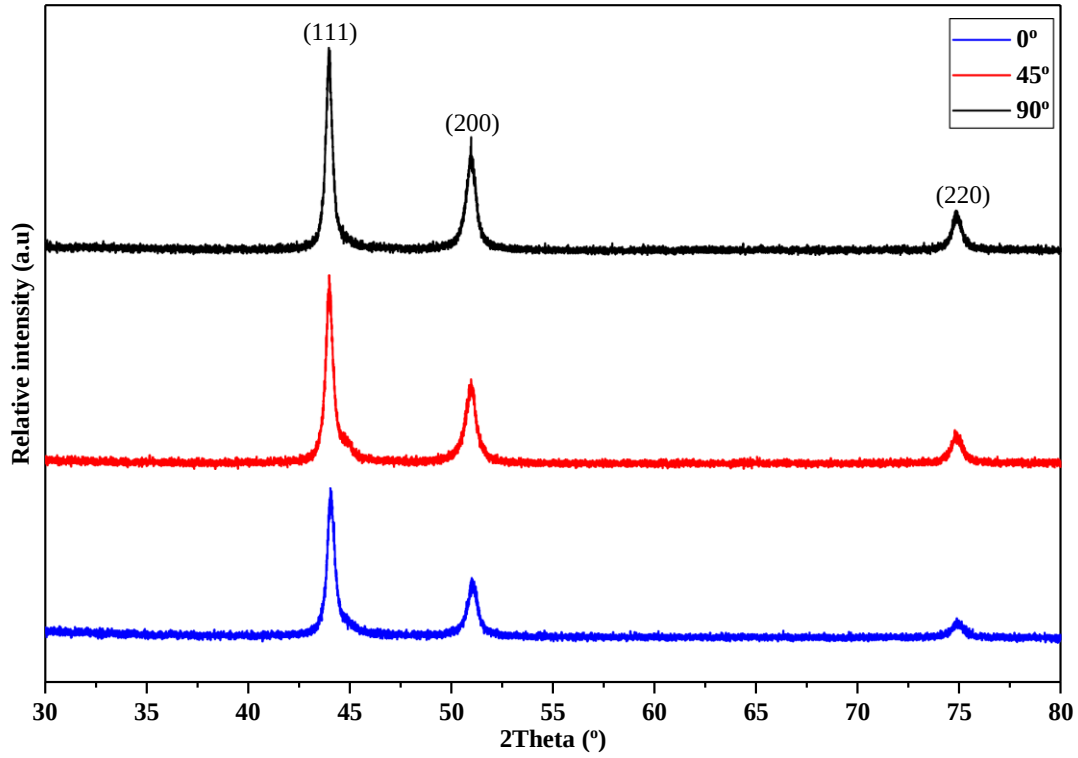


Figure 4.4: XRD pattern of LPBF 316L stainless steel samples with different orientations

The examination of SEM micrographs, EDS data, melt pools, and XRD analyses revealed that balling on the surface was prevalent across all samples. This occurrence is attributed to the specific process parameters selected during the manufacturing process. Furthermore, the analyses indicated the presence of micropores in all samples, which are likely to diminish the part density and potentially impair the mechanical, wear, and corrosion properties of the components. Additionally, the EDS and XRD analyses did not reveal any significant differences in the elemental composition or phases across the samples.

4.1.2 Mechanical properties

The microstructure results show the presence of micropores and variance in the melt pools based on the different print orientations. In addition, the XRD results show a grain size variation between the samples with 90° samples showing the smallest grain size and this could be attributed to the rapid cooling and temperature gradients as reported by Sander et al. [75]

and Dong et al. [82]. However, the influence of orientations on the hardness of the printed parts should be studied to connect the microstructure to the part strength. In addition, the elastic modulus can also be studied by analyzing the micro-indentation results. Elastic modulus provides an important measure of materials performance under applied stress [83].

The force-displacement curves for the three different orientations are presented in Figure 4.5 (c), illustrating how hardness and elastic modulus values are influenced by the contact area. These results indicate the absence of creep in the indentation curve. It is evident that the hardness and elastic modulus are dependent upon various processing parameters, highlighting the complexity of material behavior under different conditions.

Micro-indentation measurements were taken on different locations of each sample cross section to determine the microhardness and elastic modulus (Figure 4.5). The results demonstrated that different orientations have a significant effect on the microhardness of printed parts. The 0° orientation, benefiting from more uniform thermal management, shows the highest hardness, while the 90° orientation, affected by rapid cooling and higher thermal gradients, exhibits the lowest hardness.

The elastic modulus significantly decreases as the building angle increases, dropping from 241 GPa at 0° to 182 GPa at 90° . This reduction is likely due to variations in the cooling rate of the layers and the overall part density, as depicted in Figure 4.3. Additionally, a quantitative analysis of the relationship between hardness and porosity demonstrated a clear direct correlation: lower porosity levels are associated with higher hardness, highlighting the crucial role of material density in determining mechanical strength. Tucho et al. [84] explored how porosity and process parameters influence hardness, finding that increased porosity leads to decreased hardness and vice versa. Furthermore, specimens built at 0° , which have smaller build surfaces, experience more uniform cooling rates, leading to differences in microstructure

across samples as shown in Figure 4.2. These variations in microstructure consequently affect the elastic response, thereby influencing the elastic modulus. [85,86].

It is important to note that the hardness and elastic modulus are impacted by the specific parameters used during the LPBF process. Marattukalam et al. [87] investigated the effects of various laser scanning strategies on mechanical properties. Their research demonstrated that the choice of laser scanning strategies significantly alters the mechanical characteristics of materials, including hardness, Young's modulus, yield strength, and elongation at fracture. These properties are shaped by the resulting microstructure, porosity levels, and the texture within the samples. Additionally, Wang et al. [88] analyzed how laser power influences mechanical properties, finding that the Ultimate Tensile Strength (UTS) decreases as power density increases. In this study, however, all samples were fabricated using consistent parameters. Through the analysis of hardness and elastic modulus data, it is possible to compute the plasticity index (H/E) ratio. This ratio is crucial for assessing a material's ability to endure wear and resist elastic strain that could lead to failure. The plasticity index values calculated for samples at 0°, 45°, and 90° orientations are 0.012, 0.012, and 0.014, respectively. Therefore, it can be concluded that the finer grains in the 90° orientation contribute to a slightly higher hardness-to-elasticity (H/E) ratio, offering a balance between stiffness and ductility. In contrast, the larger grains and denser packing in the 0° and 45° orientations enhance material stiffness and hardness but limit plastic deformation.

The microhardness trends observed in the LPBF samples are closely linked to their microstructure. The 90° orientation, characterized by finer grains due to higher thermal gradients and faster cooling rates, exhibits a higher hardness-to-elasticity (H/E) ratio, balancing stiffness, and ductility. In contrast, the 0° and 45° orientations, which experience more uniform cooling, have larger grains and denser packing. This results in higher hardness and stiffness but limits plastic deformation. These findings underscore the crucial role of thermal

management in optimizing the microstructural properties and mechanical performance of LPBF-fabricated materials.

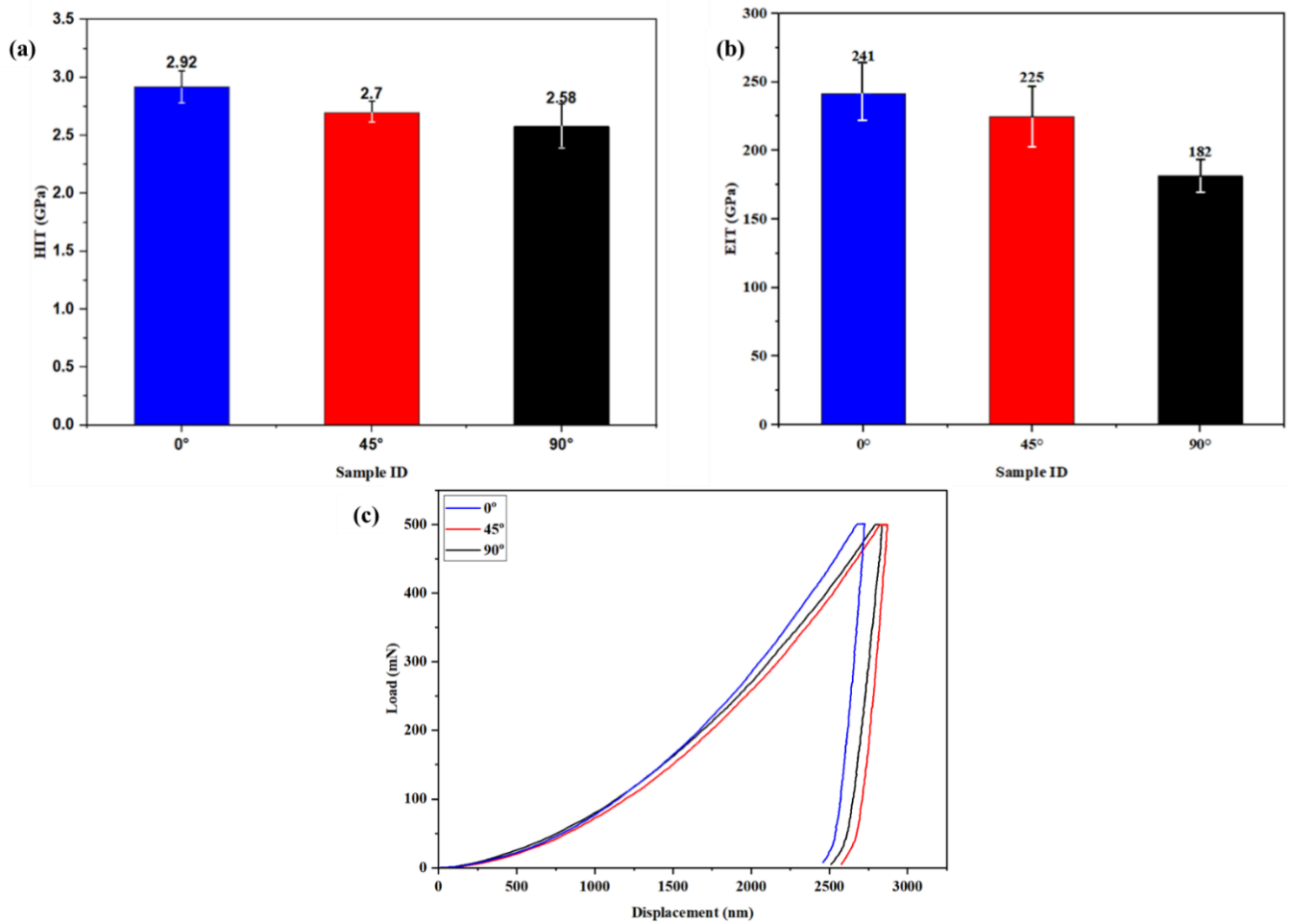


Figure 4.5: The (a) Micro-hardness, (b) Elastic modulus, (c) Load vs Depth curves for various orientations.

Figure 4.6 shows the stress-strain curves for LPBF-manufactured 316L stainless steel specimens. The tensile results of all samples with different orientations were shown in Table 4.1. The yield strength (YS) and ultimate tensile strength (UTS) of the LPBF 316L stainless steel samples were reduced with the increase in built orientation, this observation is confirmed in the previous studies on the tensile properties of LPBF 316L samples [89–91]. Higher UTS (784 MPa) and lower ductility were observed for the samples printed in 0° orientation followed

by 628 and 566 MPa UTS for 45° and 90° respectively. On the other hand, the elongation increases with the increase in built orientation angle as shown in Table 4.1. All the results showed that there is a relationship between the density and mechanical properties of LPBF samples. From these results building a part with high density could enhance the mechanical properties of printed parts.

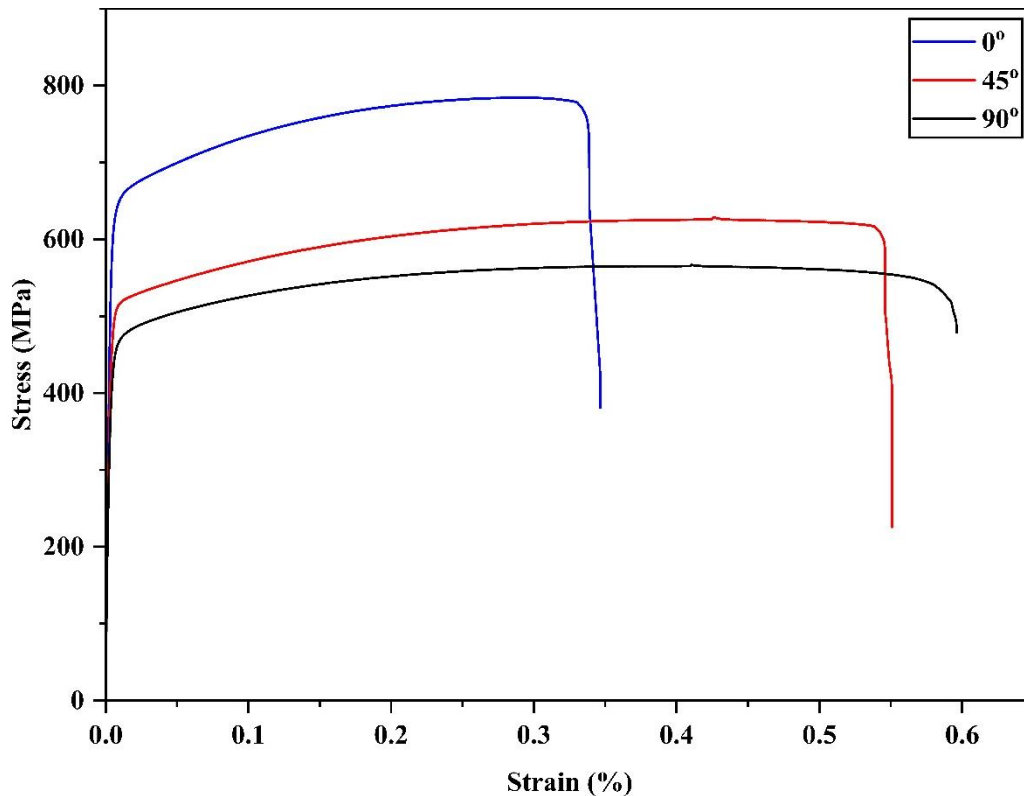


Figure 4.6 : Stress-strain curves of LPBF-manufactured 316L stainless steel for different build orientations

From Figure 4.6 the sample oriented at 45° exhibits the highest toughness, attributed to its balanced performance in terms of both strength and ductility. Conversely, the 0° orientation, although it achieves the highest peak stress, demonstrates lower toughness due to its brittle failure mode. The 90° orientation sample, while showing the lowest peak stress, exhibits moderate toughness, which can be primarily ascribed to its high ductility.

Table 4.1 The tensile results of all samples with different orientations

Orientation	YS (MPa)	UTS (MPa)	EL (%)
0°	645	784	38
45°	516	628	55
90°	471	566	57

The study highlights how build orientation significantly affects the mechanical properties of parts, primarily through variations in part density. A clear correlation was established showing that reduced porosity enhances mechanical performance. This relationship is detailed and supported by the research findings. Consequently, the highest values for density, hardness, and tensile strength were recorded in samples fabricated at 0°. These were followed in performance by samples printed at 45° and 90°.

4.1.3 Tribological analysis

The correlation between the part orientation density, hardness and tensile strength shows consistency between all observed values. The results highlight the significance of orientation in obtaining the maximum strength from 316L LPBF parts. However, a high density, strength, and hardness does not guarantee other mechanical properties of LPBF parts such as tribological properties. In this work, the tribological properties were also investigated to study the effect of orientation on the tribological properties (wear and coefficient of friction (COF)) of LPBF 316L samples. The tribological properties are mostly associated with the microstructure and sample porosity [48]. Therefore, based on literature, it is hypothesized that the increase in orientation from 0° to 90° will show an increase in wear and COF.

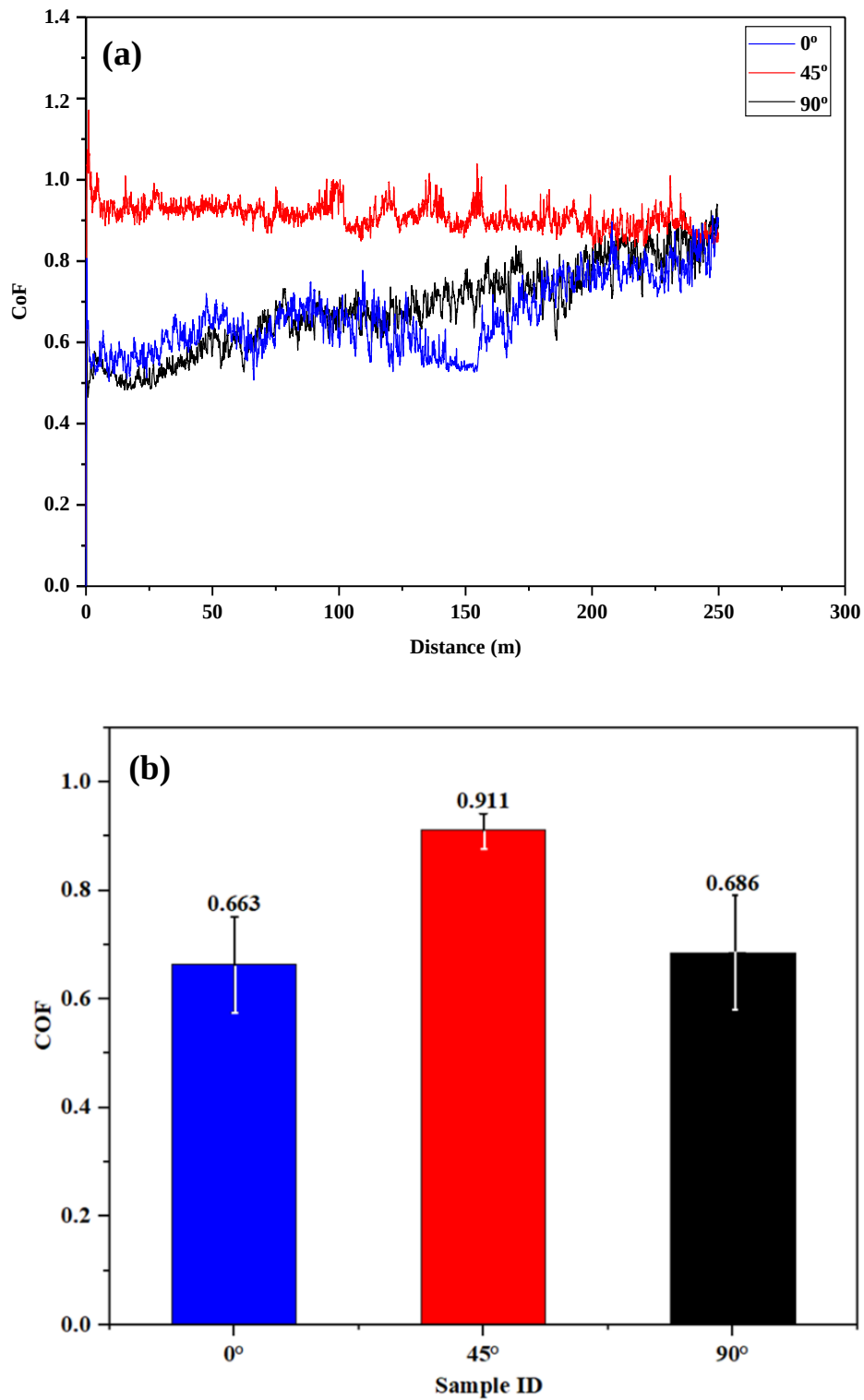


Figure 4.7 : (a) COF curves, and (b) COF values.

COF results were calculated and are shown in Figure 4.7. Results of ball on disk tribometer under dry conditions show the effect of building orientation on the wear performance of LPBF 316L stainless steel samples. At a fixed load and speed, the COF of the 0° orientation exhibited

the lowest COF. At the beginning of wear testing, the COF for the 0° and 90° samples initiated at a lower level, contrasting with the notably higher COF observed for the 45° sample, which started at around 1.18 before stabilizing.

This behavior can be attributed to surface softening. The formation of debris may influence the interaction between the part surface and the alumina ball. Towards the end of the tests, all printed samples exhibited nearly identical COF values, as shown in Figure 4.7 (a). The average COF values were calculated as 0.663 (± 0.087), 0.911(± 0.03) and 0.686 (± 0.1) for 0°, 45°, and 90°, respectively (Figure 4.7 (b)). The sample with 0° orientation reported the lowest COF during testing against the alumina ball. This can be attributed to uniform grain sizes and lower porosity, which enhanced its hardness and wear behavior.

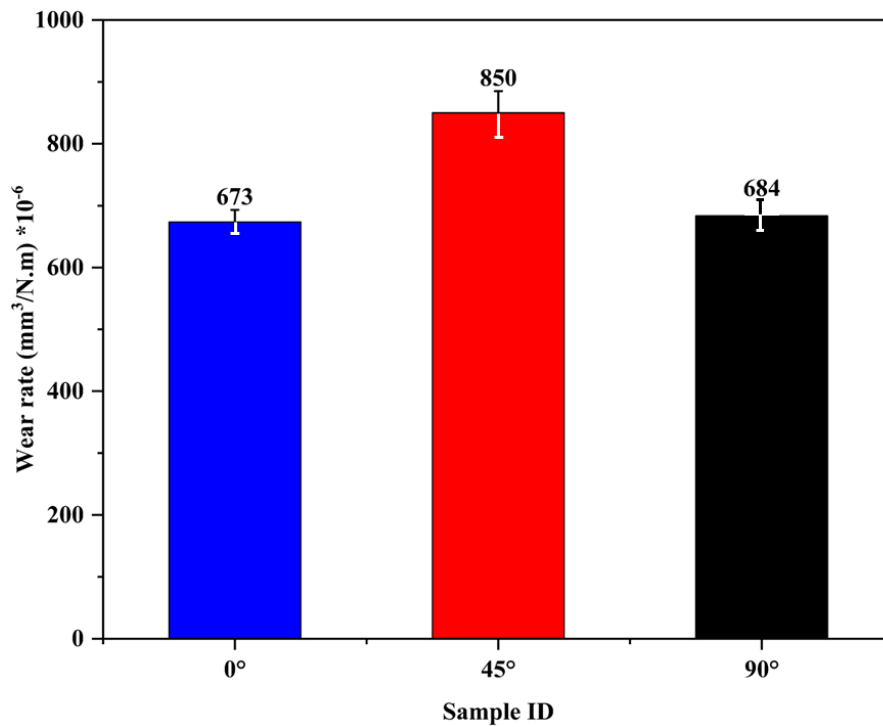


Figure 4.8 : Wear rate of LPBF samples

The wear rate results align with the trends observed in the COF results, as shown in Figure 4.8. The computed average wear rates for samples oriented at 0°, 45°, and 90° were 673.5×10^{-6} , 850.1×10^{-6} , and 683.5×10^{-6} mm³/N.m, respectively. Notably, the sample at 0° orientation

demonstrated the lowest wear rate, which may be attributed to various factors, with porosity being a significant determinant in its tribological behavior, in addition to surface roughness. However, since all samples underwent polishing, the influence of surface roughness on these results is minimal. These observations are corroborated by the elastic modulus findings. Research conducted by Choi et al. [92] established a direct link between increased porosity and higher surface contact with the alumina ball, consequently raising both the COF and wear rate. By considering these elements, a thorough understanding of the friction reduction in the 0° sample is achieved. This assessment combines insights into material properties and process parameters, aiming to elucidate the mechanisms influencing frictional behavior.

The study of changes in wear tracks topography was undertaken to elucidate the mechanisms influencing the variations in COF and wear rates, as depicted in Figure 4.9. Wear debris, acting as third-body particles, was noted in all samples, contributing to increased wear rates and COF [93]. Notably, the 45° sample exhibited a higher wear rate, as evident from the SEM images of the wear track. To support these findings, 3D profiles alongside the SEM micrographs of the wear tracks were analyzed. These profiles, highlighting the peaks and valleys, confirm the presence of an abrasive wear mechanism on the surface. The results distinctly indicate a significant deviation in the 45° samples when compared to the 0° and 90° samples. This discrepancy is likely due to porosity within the samples, which may lead to cracking and delamination under high stress concentrations [94].

The observed reduction in wear and COF in the 0° samples can primarily be ascribed to their grain structure, which results from fewer layers and reduced cooling cycles. This grain structure enhances hardness and strength, consequently lowering the wear rate as per Archard's theoretical wear equation [93]. The wear behavior is closely related to their hardness. Higher hardness enhances wear resistance by providing greater resistance to surface deformation and material loss during the contact between the surfaces.

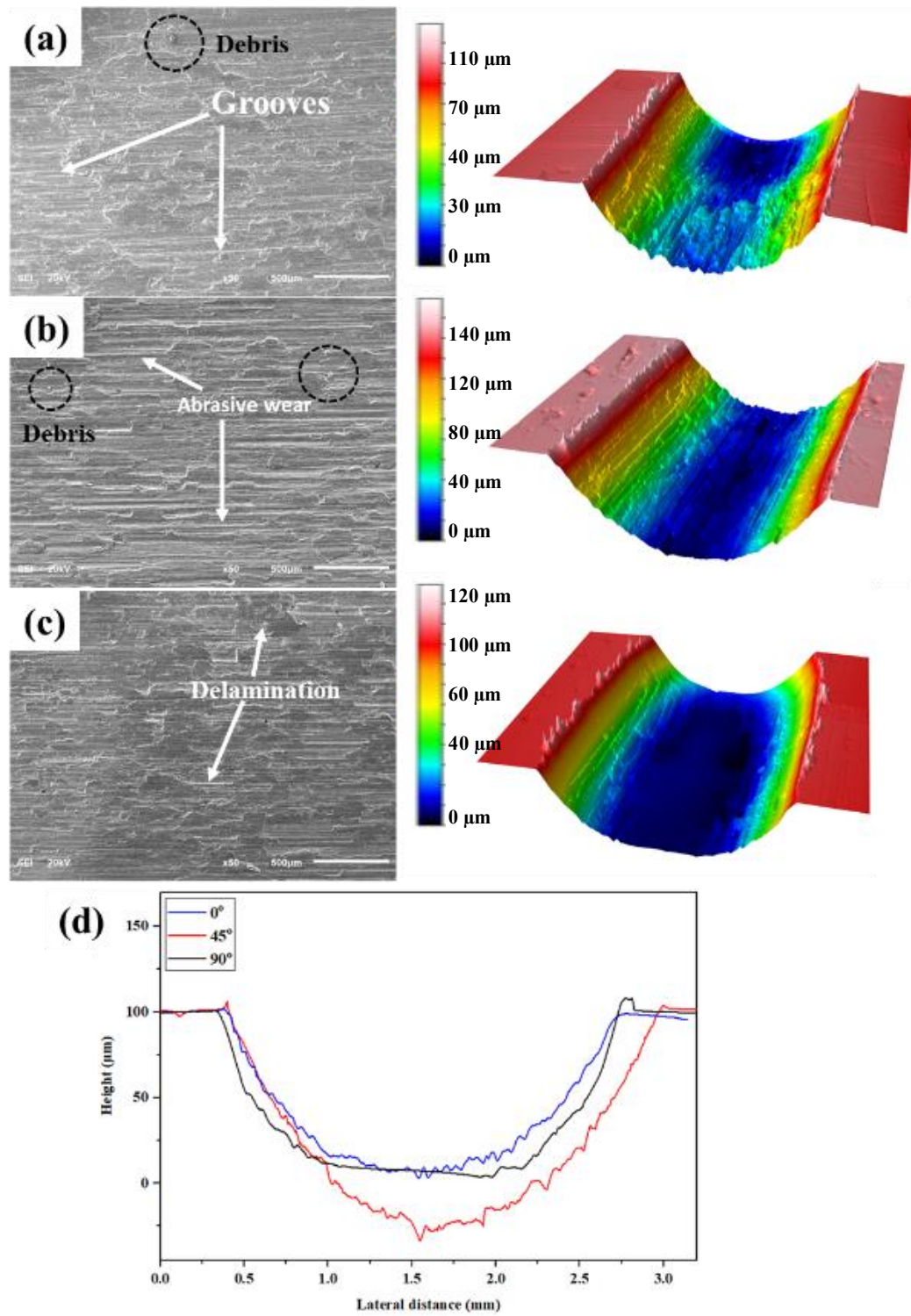


Figure 4.9 : 3D profilometry and SEM micrographs for wear track of LPBF samples. (a) 0°, (b) 45°, (c) 90°, (d) wear track depth.

Beyond microstructure, the density of the part also significantly impacts wear behavior. Porosity in the printed parts can increase wear debris formation by facilitating particle delamination from the surface. Additionally, pores serve as initiation points for cracks, which can propagate and lead to surface failures and subsequent wear debris accumulation along the wear track [47]. These observations highlight the intricate relationship between porosity, structural integrity, and tribological performance in LPBF-manufactured parts. In the 0° samples, the synergy of high hardness and density effectively reduces both wear rate and COF, a contrast to what is seen in other orientations.

Analysis of the COF and wear tracks for 0°, 45° and 90° shows that the trend for the COF does not follow the trends observed for part density, hardness, and tensile properties. Unlike the mechanical properties, tribological properties show an increased COF and wear rate for the 45° samples. This could be attributed to the different factors influencing surface interactions during wear test such as wear debris, and surface condition. While density and hardness affect the material's bulk properties and resistance to deformation. The examination of wear tracks across all samples indicated that the wear mechanisms involved both abrasive and adhesive wear, regardless of the LPBF sample orientation. Detailed analysis reveals that wear in the 0° samples predominantly occurred layer by layer (abrasive wear), whereas in the 90° samples, wear extended across multiple layers (adhesive wear). Meanwhile, the 45° samples exhibited a combination of both wear types, resulting in higher COF and wear rates.

The findings in this section demonstrate that microstructural characteristics, hardness, and tensile properties are insufficient to predict the tribological behavior of printed parts across different orientations. While the 0° and 90° samples align with previously observed results, the 45° samples deviate, showing the highest COF and wear rate. This underscores the necessity of thorough tribological and material response assessments in LPBF parts, particularly since

the choice of printing orientation can significantly influence the functionality of designed LPBF components.

4.1.4 Electrochemical corrosion behavior

The results from the mechanical and tribological results highlight the importance of build orientation in controlling the properties of 316L LPBF parts. As 316L parts are also used in corrosive environments under mechanical loads, resulting in friction and wear, a complete study is required to understand the mechanical-tribological-corrosion behavior of these parts. Open circuit potential (OCP), Electrochemical Impedance Spectroscopy (EIS) and Cyclic potentiodynamic polarization (CPDP) measurements were employed to understand the corrosion behavior of 316L LPBF parts under different build orientations.

4.1.4.1 Open circuit potential (OCP) Measurement

OCP measurements were utilized to determine the inherent corrosion potential of LPBF 316L samples without applying any external current. These measurements are critical for assessing the stability of the electrochemical environment prior to the introduction of polarization. Over time, as the samples remain immersed, they are expected to reach a stable condition marked by a consistent potential. Additionally, OCP measurements are instrumental in providing insights into the samples' thermodynamic propensity for corrosion [95,96]. The results indicated that the samples reached an equilibrium state within one hour, with potential variations ranging from 0.016 to 0.2 mV. Specifically, the 0° sample exhibited the highest reactivity with a stable potential of 16.86 mV, compared to the 90° and 45° samples, which showed stable potentials of 37.09 mV and 20.53 mV, respectively.

The trend in OCP values, especially the fluctuations within the initial 30 minutes for the 90° and 0° orientations, suggests the gradual formation of a protective passive film [97]. This film, commonly observed in 316L stainless steel, enhances corrosion resistance significantly. Higher

OCP values reflect the presence of a stable passive film on the surface, which is crucial for protecting the metal against further corrosion.

4.1.4.2 Cyclic potentiodynamic polarization (CPDP) Measurement

Cyclic potentiodynamic polarization (CPDP) is a widely utilized technique to assess corrosion behavior and to calculate corrosion rates in specific environments. The CPDP findings for the LPBF 316L stainless steel parts are depicted in Figure 4.10. These results uniformly indicate that all samples displayed comparable corrosion behaviors in a 3.5 wt.% NaCl solution, although the corrosion current density and potential were found to vary with the change in build orientation. Notably, the corrosion potential of the 45° sample was more negative compared to the 0° and 90° samples. The corrosion potential (E_{corr}), corrosion current density (I_{corr}), and corrosion rate (CR) for the LPBF 316L stainless steel samples were determined using Tafel extrapolation, as shown in Table 4.2. Corrosion parameters serve as quantitative metrics for comparing the corrosion responses of various samples. Furthermore, an analysis of corrosion potential offers critical insights into the reactive behavior of the system. Notably, the 0° and 90° samples demonstrated a minor difference in their corrosion potential (E_{corr}) values, recorded at -141 mV and -136 mV, respectively. In contrast, the 45° samples displayed the lowest E_{corr} value at -337 mV, indicating a heightened susceptibility to corrosion in such environmental conditions. The lowest corrosion current density (I_{corr}) was observed in the 0° sample at 0.65 $\mu\text{A}/\text{cm}^2$, correlating with the slowest corrosion rate among the samples. Conversely, the 45° and 90° samples exhibited higher I_{corr} values at 0.795 $\mu\text{A}/\text{cm}^2$ and 1.58 $\mu\text{A}/\text{cm}^2$, respectively, influencing their corrosion rates accordingly. This pattern may be associated with the finer microstructure and greater density of the 0° sample, followed by the 45° and 90° samples. Typically, a lower I_{corr} reflects enhanced corrosion resistance and a reduced rate of corrosion. The findings clearly indicate that as the build orientation increases, so does the corrosion rate.

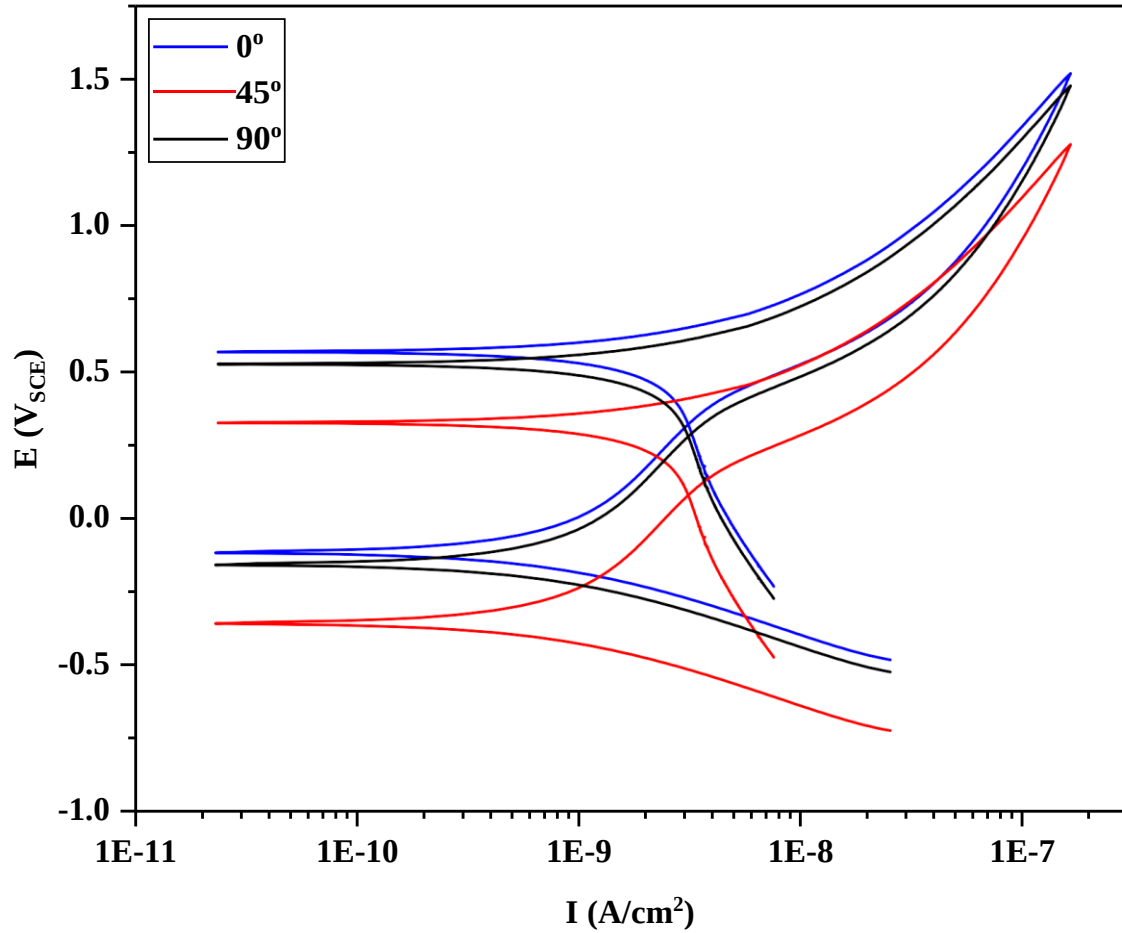


Figure 4.10 : Representative cyclic-potentiodynamic polarization curves for the LPBF 316 L stainless steel samples in 3.5 wt. % NaCl solution.

Pitting corrosion was observed in all LPBF 316L stainless steel samples. Key parameters such as pitting potential (E_{pit}), passivation current density (I_p), and repassivation or protection potential (E_p) were calculated, as they are crucial for evaluating localized pitting corrosion behavior [98,99]. The results showed that the 0° samples exhibited the highest E_{pit} at 1511 mV and the lowest I_p at $38.29 \mu\text{A}/\text{cm}^2$. Notably, a high E_{pit} coupled with a narrow hysteresis loop indicates superior resistance to pitting corrosion, a trend that was followed by the 90° and 45° samples. Variations in the repassivation results among the 0° , 45° , and 90° samples were significant, with E_p values ranging from -474.6 mV to -232.8 mV for the LPBF 316L stainless steel samples. Consequently, the 0° sample demonstrated a lower susceptibility to pitting

corrosion damage and was less prone to pit initiation, followed by the 90° and 45° samples, respectively [75]. The electrochemical behavior of LPBF 316L stainless steel, influenced by material density and grain size [100], suggests that pores within the material may hinder the formation of a protective film, potentially leading to localized corrosion. This could enhance the anodic current through oxidation within the pores. Among the samples, the 0° orientation displayed the most robust passivation behavior.

It is suggested that the E_{corr} , I_{corr} and E_{pit} values of LPBF 316L stainless steel significantly change with the sample porosities which confirmed by previous studies [101,102]. Furthermore, it is also indicated that low levels of porosity (< 0.4%) do not affect the pitting corrosion in stainless steel.

Table 4.2 : Tafel extrapolated data and pitting parameters obtained from the CPDP measurement for the 316L samples.

Sample ID	Tafel fit			CPDP		
	I_{corr} ($\mu\text{A}/\text{cm}^2$)	E_{corr} (mV)	CR (mpy)	E_{pit} (mV)	I_p ($\mu\text{A}/\text{cm}^2$)	E_p (mV)
0°	0.650	-136	297.1E-6	1511	38.29	-232.8
45°	0.795	-337	363.1E-6	1267	203.5	-474.6
90°	1.580	-141	721.0E-6	1467	487.4	-274.2

It is recognized that a finer grain size and reduced porosity contribute to improved corrosion properties [103]. Therefore, the observed variations in corrosion rate and pitting resistance among the 316L LPBF samples can largely be attributed to the effects of microstructure, porosity, and grain size. For instance, the 0° samples, which exhibited the smallest porosity

and finest grain size, demonstrated the lowest corrosion rates and the highest resistance to pitting.

While OCP and CPDP are valuable for assessing corrosion susceptibility and determining corrosion rates, EIS was employed to provide non-destructive insights into the corrosion characteristics of all the LPBF 316L stainless steel samples. This method offers a deeper understanding of the electrochemical dynamics without damaging the samples.

4.1.4.3 Electrochemical Impedance Spectroscopy (EIS) Measurement

EIS stands out as a highly sophisticated, non-destructive technique in steady-state electrochemistry, widely used for evaluating corrosion. It has the capability to provide crucial insights into various parameters including reaction dynamics, corrosion rates, formation of oxides, surface integrity, porosity, and other critical interfacial properties [59,60]. As a result, the investigation into the corrosion behavior of the LPBF 316L stainless steel samples was carried out employing the EIS technique.

The EIS results for LPBF 316L stainless steel samples, examined under different build orientations in a 3.5wt.% NaCl solution, are displayed in Figure 4.11. The Bode and Nyquist plots are shown in Figure 4.11 (a) and (b), respectively. The Bode plots illustrate the correlation between the impedance modulus, phase angle, and frequency as presented in Figure 4.11 (a). These plots can be categorized into three frequency domains: a low-frequency range (10m – 1 Hz), an intermediate frequency range (1 – 1k Hz), and a high-frequency range (1 – 100 kHz). In the low-frequency domain, the impedance signifies the polarization resistance of the sample within the electrolyte. During the intermediate frequency range, the impedance diminishes as frequency increases at a consistent slope, indicating capacitive behavior [104]. Conversely, in the high-frequency domain, the decreasing impedance modulus with rising frequency suggests resistive behavior [97].

An equivalent circuit, depicted in Figure 4.11 (c), was utilized to analyze the electrochemical response of the samples, similar to methodologies employed in prior studies [104,105]. The high-frequency time constant in this circuit, denoted by R_f and CPE_f , reflects the charge transfer resistance and electrochemical double-layer capacitance, respectively. The subsequent parallel configuration of R_{ct} and CPE_{fdl} represents the resistance and capacitance of the passive film. The overall corrosion process involves both electron transfer and charge transport, with the sum of R_f and R_{ct} comprising the total resistance (R_T) [106,107]. As illustrated in Figure 4.11 (c), the solution resistance (R_s) is connected in series with R_f and CPE_f .

The Nyquist plots, analyzed from the fitted results, suggest that samples exhibiting larger loops possess more stable oxide films, which correlate with higher corrosion resistance. As depicted in Figure 4.11 (b), the sample oriented at 0° displays the largest loop, followed by the 45° and 90° samples. This pattern aligns with the trends seen in the I_{corr} data derived from CPDP tests. The EIS results from the equivalent circuit (EC) fitting are detailed in Table 4.3. Consequently, the diameter of the semicircles in the Nyquist plots indicates increased resistance to electrochemical dissolution, reflecting a more stable passive film, particularly for the 0° orientation samples, which exhibit superior corrosion resistance.

The accuracy of the EIS model fits is quantitatively verified by the chi-square (χ^2) value, with a lower χ^2 indicating a better fit of the data to the model. The dispersion coefficient 'n' associated with the Constant Phase Element (CPE) is crucial for this analysis. The total resistance (R_T) values show a decrease with increasing build orientation: $23.7E6$ for 0° , $9.0E5$ for 45° , and $5.76E5$ for 90° . A higher R_T value is indicative of a thicker passive layer, which enhances corrosion resistance. The 0° sample, with the highest R_T value, forms a thick, defect-minimized passivation film on the surface, confirming the known correlation between R_T values and surface defects [108].

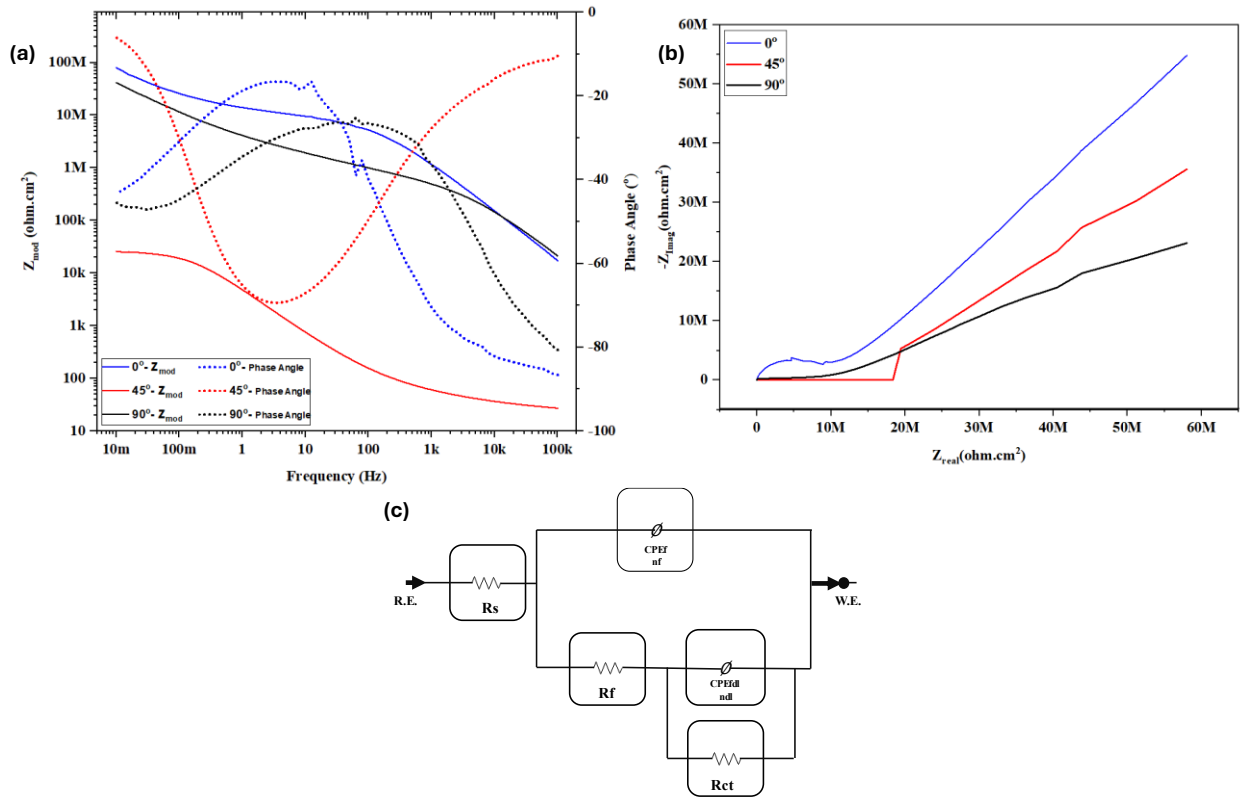


Figure 4.11 : EIS plots, (a) Bode plots, (b) Nyquist plots, (c) Equivalent circuit used in fitting the EIS data.

Table 4.3 : EIS parameters obtained from the EC fitting for the LPBF 316L SS in 3.5wt% NaCl at different orientations.

Sample ID	R_s Ohm.cm ²	R_{ct} kohm.cm ²	CPE_{dl} $\mu F/cm^2$	n_{dl}	R_f kohm.cm ²	CPE_f $\mu F/cm^2$	n_f	$R_T(R_{ct}+R_f)$ kohm.cm ²	$\chi^2 \times 10^{-4}$
0°	0.025	2.37E+7	59.1	0.48	7.68E+3	0.33	0.90	23.7E+6	0.47
45°	5.67	8.99E+5	119	0.59	3.01E+2	0.52	0.85	9.0E+5	0.58
90°	1.13	5.75E+5	135	0.48	5.39E+2	0.94	0.82	5.76E+5	0.74

The results from both EIS and CPDP indicate that the 0° oriented sample exhibits the best corrosion performance compared to the other LPBF 316L stainless steel samples at 45° and 90° orientations.

4.2 Effect of Sample Size

4.2.1 Microstructure analysis

Figure 4.12 shows the microstructure of the XY cross-sectional area for the different specimens. In depth analysis of the microstructure shows a direct correlation between sample sizes and melt pool boundaries. This correlation is important in understanding the mechanical properties, as smaller samples reveal increased porosity, a consequence of the balling effect. This observation aligns with the findings of Ronneberg et al. [109], which noted the similar correlation trend for the 316L stainless steel fabricated by LPBF. Discussing these correlations provides insight into how LPBF parameters can be optimized for different components.

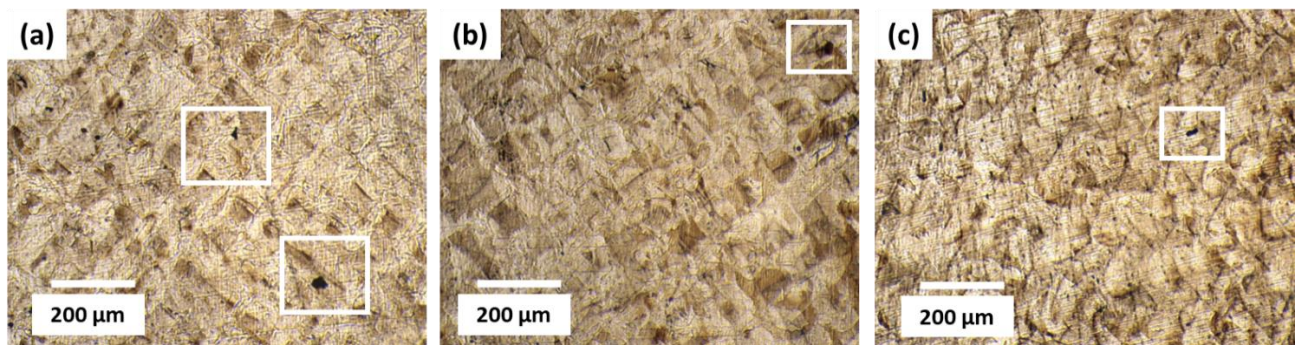


Figure 4.12 Optical microscope XY cross section micrographs of the specimens: (a) 0.5-V, (b) 2-V and (c)

5-V

As seen in Figure 4.13, balling occurs when the molten material fails to adequately bind with the underlying substrate because of the surface tension, leading the liquid to take on a more spherical form. The post-processing stage of surface finishing plays a crucial role due to its

impact on mitigating the balling effect, which typically elevates surface roughness in the production process. This step is essential for enhancing the final quality of the product.

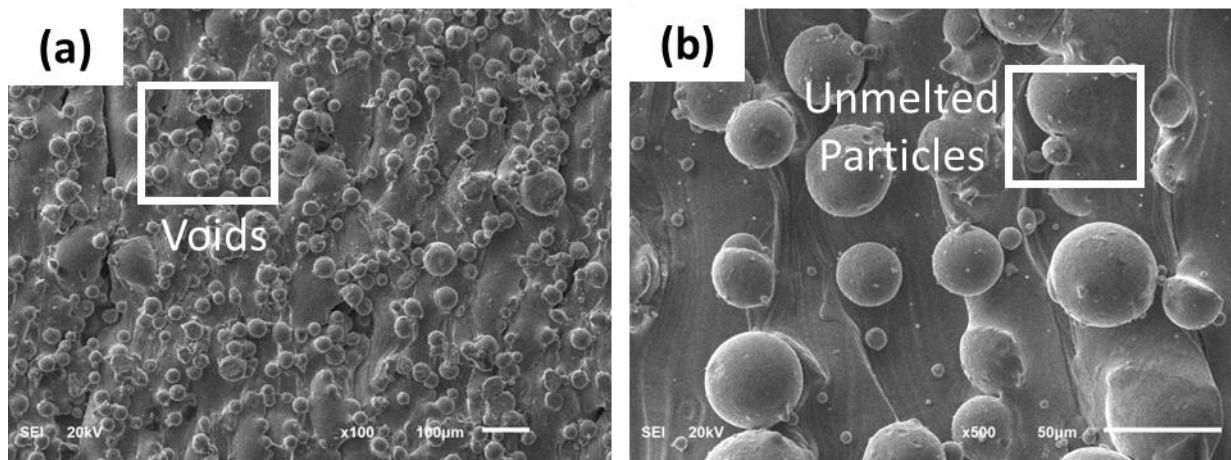


Figure 4.13 SEM surface images of the LPBF 316L stainless steel samples (a) 100 μm , and (b) 50 μm

XRD analysis on the 316L stainless steel samples fabricated using LPBF revealed a consistent austenitic phase across varying sample sizes. As demonstrated in Figure 4.14, the samples exhibited austenite peaks characterized by identical positions, intensities, and widths, indicating uniform phase composition irrespective of their size. The samples with 5 mm size show higher crystallinity and phase purity, which indicates better crystal growth and alignment along the planes also fewer defects and more stable austenitic phase. In contrast, the small sizes show increased defects and lower crystallinity due to faster cooling rates and higher thermal gradient. From the results, the grain size analysis shows 5 mm samples have larger grains “45.8 nm” due to slower cooling. 2 mm samples have grains with 30.6 nm size, while 0.5 mm have finer grains with 22.9 nm size due to rapid cooling.

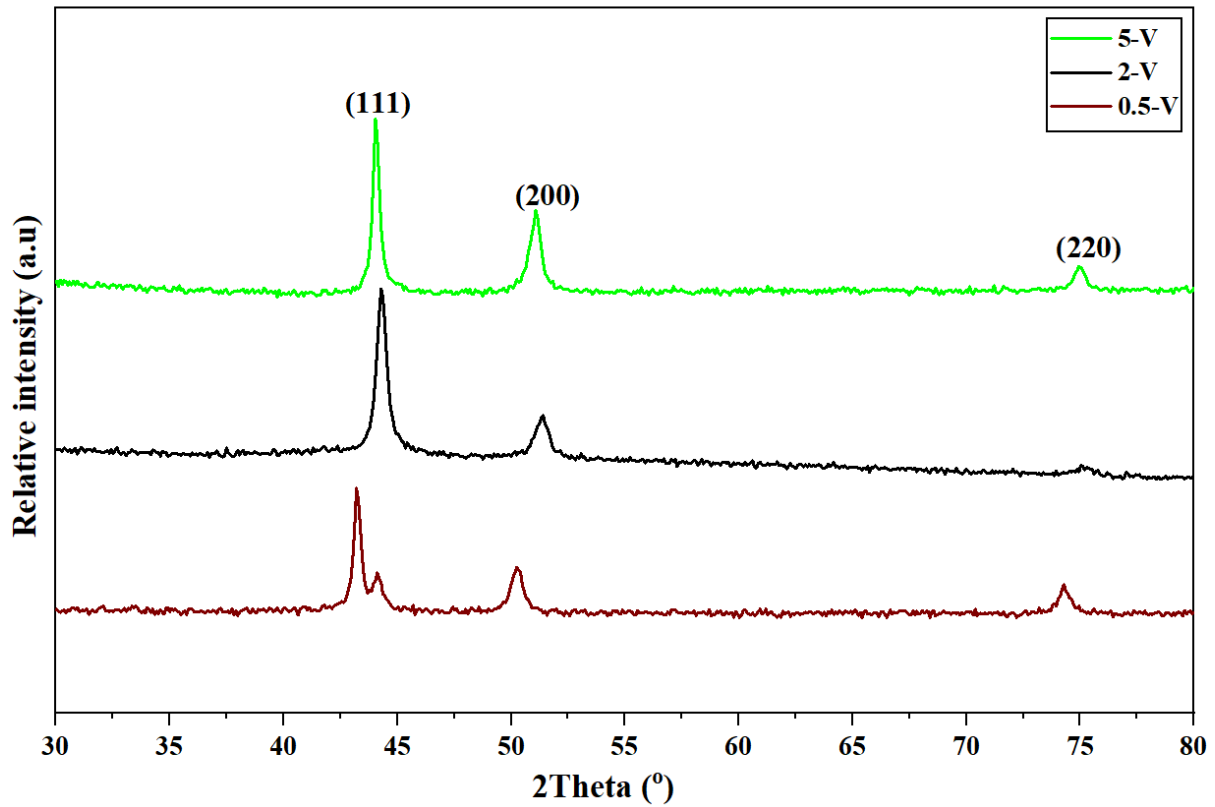


Figure 4.14 XRD pattern of LPBF 316L stainless steel samples.

4.2.2 Mechanical properties

In this study, the 316L stainless steel manufactured using LPBF displayed a consistently uniform microstructure across various specimen sizes. Consequently, the hardness, which reflects the overall impact of this inherent microstructure, shows a slight difference across all size variations as shown in Figure 4.15. Despite the consistent microstructure, a slightly noticeable pattern of reduced elastic modulus becomes evident as the hardness increased. While the microstructure governs material properties, the structural characteristics of components are shaped by a combination of the intrinsic properties of the material and the geometry of the component [110].

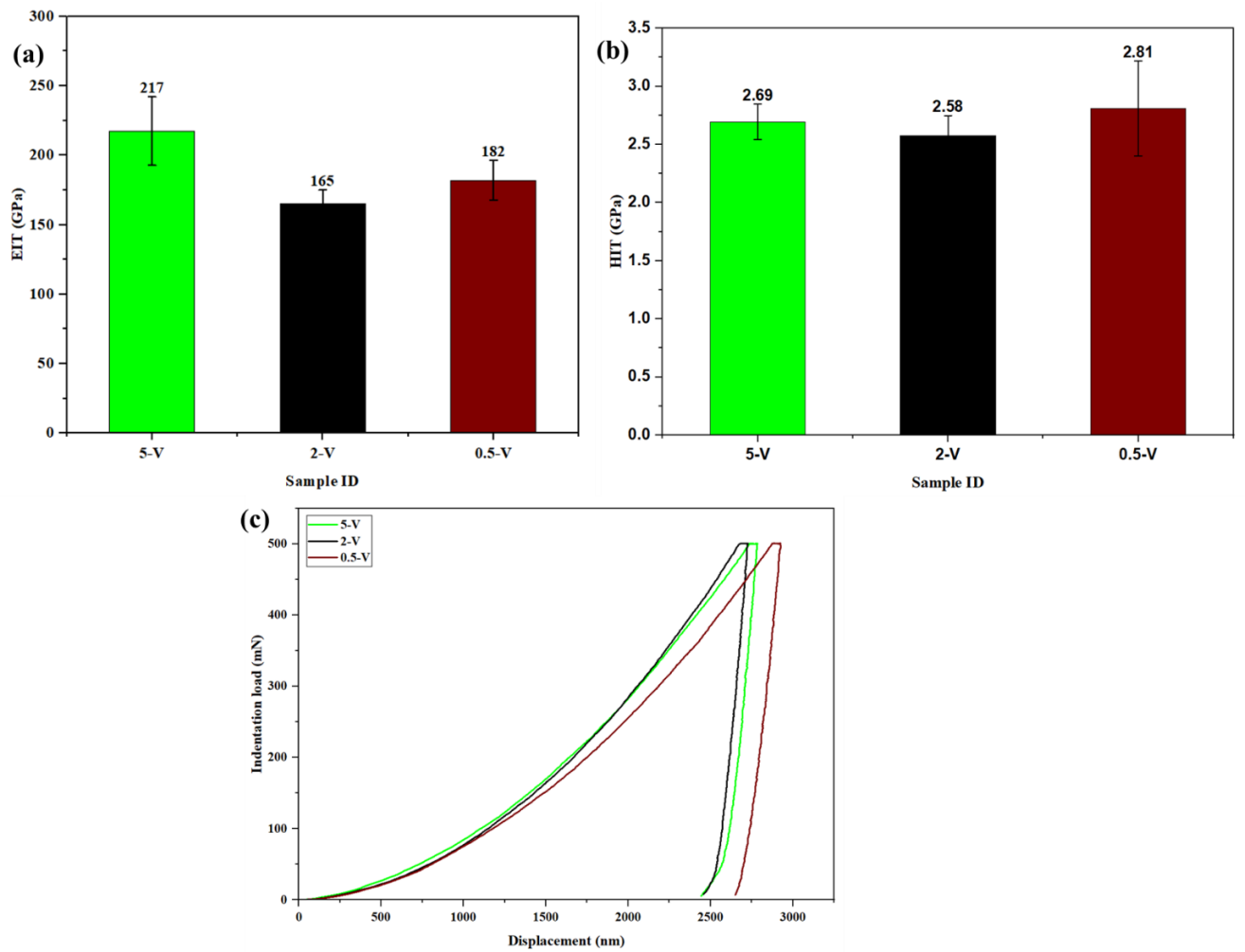


Figure 4.15 The (a) Elastic Modulus, (b) Microhardness, and (c) Load vs Depth curves form micro indentation tests for various thicknesses.

Figure 4.16 shows the tensile stress-strain curves for the samples fabricated using LPBF with varying sample sizes (5 mm, 2 mm, and 0.5 mm). The results show distinct differences in mechanical performance. The 5 mm sample shows the highest UTS and ductility, as indicated by its superior stress and strain at fracture. This suggests that the larger sample size benefits from better heat dissipation and more uniform microstructural development, resulting in enhanced mechanical properties. The 2 mm sample displays moderate UTS and ductility, falling between the 5 mm and 0.5 mm samples, indicating a balanced but slightly less optimal heat distribution and microstructure compared to the larger sample. The 0.5 mm sample exhibits the lowest UTS and strain at fracture, likely due to the increased difficulty in

maintaining consistent heat input and achieving complete melting in such a small volume, leading to higher porosity and microstructural defects. These findings highlight the significant influence of sample size on the mechanical properties of LPBF-fabricated 316L stainless steel.

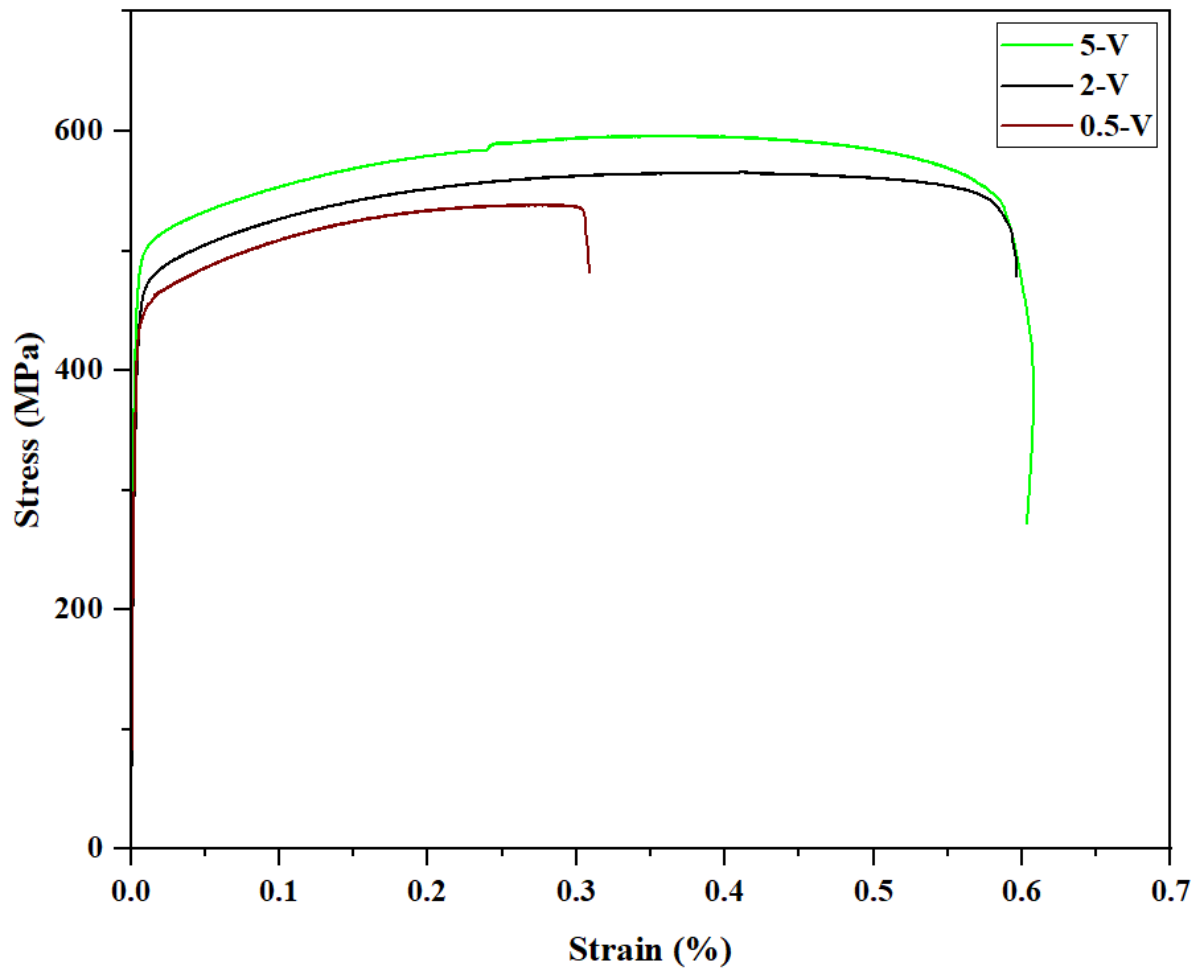


Figure 4.16 Stress-strain curves of LPBF-manufactured 316L stainless steel for different sizes

4.2.3 Surface characteristics

In depth analysis of surface roughness for the samples with various sizes is shown in Figure 4.17 and detailed in Table 4.4 as per ISO 25718-2 standard [111]. The measurements were performed on the upper surface of the samples and the results show that the sample with 0.5 mm size has the highest arithmetic mean (R_a) when compared to the samples with higher sizes (2 mm and 5 mm), which aligns with the results reported in previous study by Karlsson et al.

[112]. The heightened roughness in thinner samples is due to increased thermal gradients and resultant heat accumulation during the layering process. This phenomenon has implications for the functional application of these materials, particularly in precision-required environments. Understanding the interplay between size, thermal conditions, and surface texture is vital for optimizing LPBF processes for specific end-use requirements.

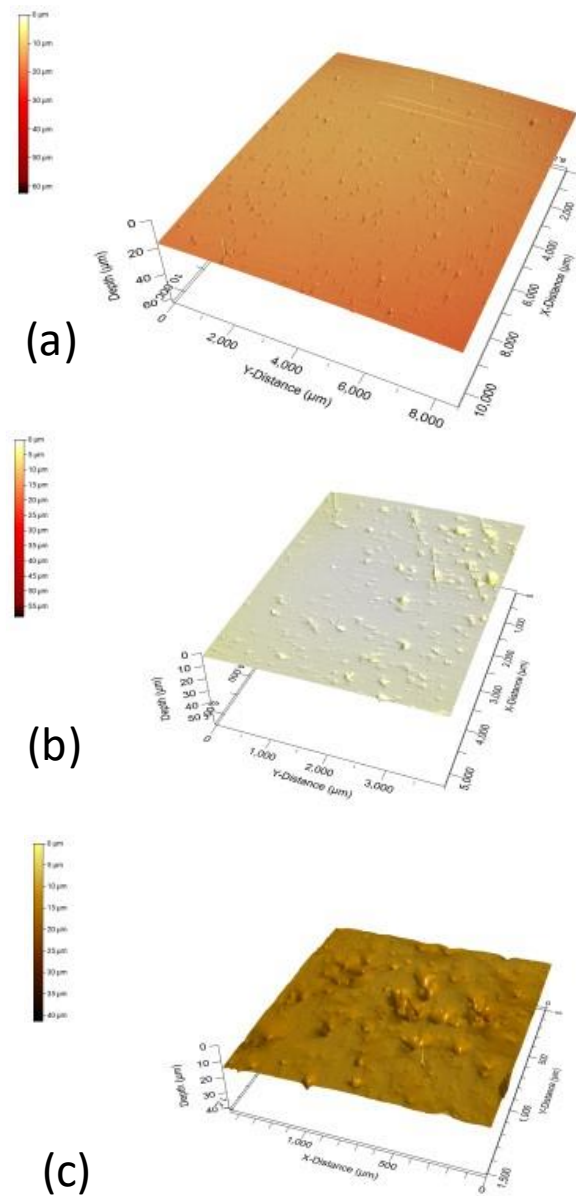


Figure 4.17 3D profilometer surface topography (a) 5-V, (b) 2-V and (c) 0.5-V.

Table 4.4 Surface roughness and Density of the different samples

Sample thickness (mm)	Surface roughness Ra (μm)	Density (g/cm^3)
0.5	1.16	7.92
2	0.24	7.83
5	0.53	7.96

4.2.4 Sliding wear behavior

Figure 4.18 shows the average coefficient of friction (COF) values of the samples with different sizes as measured using the reciprocating tribometer under dry conditions. The sample with 2 mm size shows the highest COF followed by the 0.5-V and 5-V, respectively. Unlike the hardness and elastic modulus, the 2-V and 5-V samples have a noticeable difference in the values.

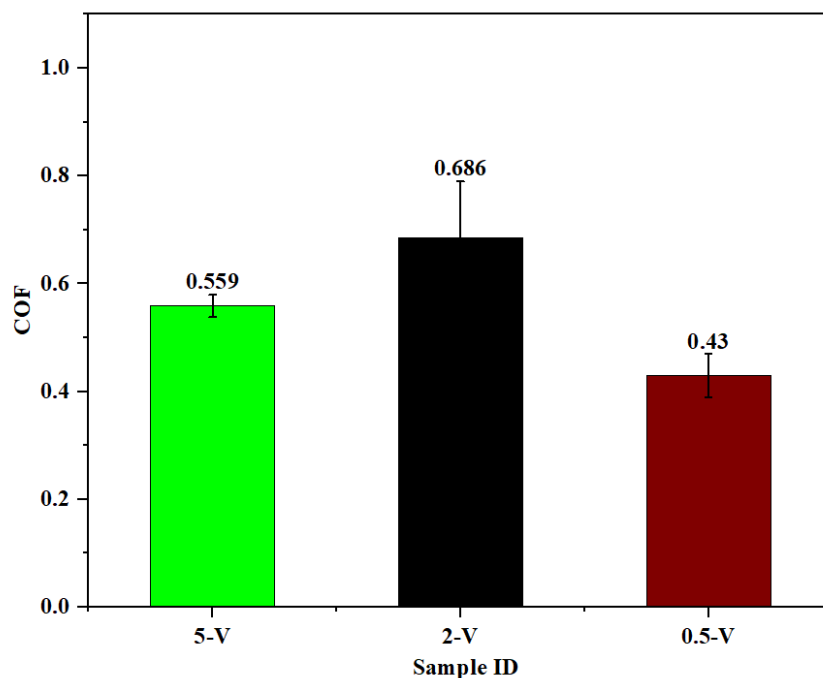


Figure 4.18 Coefficient of friction (COF) for various sizes

The wear rate values are shown in Figure 4.19. The results show that the sample with 2 mm size has the highest wear rate among the other samples, and this can be attributed to its lower hardness. The wear track profiles, measured by a 3D profilometer and shown in Figure 4.20, confirm that the wear track is more pronounced in the 2-V sample. This indicates that both COF and wear rate are influenced not only by hardness but significantly by porosity as well.

Several observations can be made from the wear data: first, all the samples suffer from severe wear by abrasive wear mechanism, and clearly the sample with (2 mm) size has a weak wear resistance among the other samples. Second, the results exhibit a correlation between the wear rate and the sample density: wear rate increases with the decreasing density as shown in Table 4.4 the results.

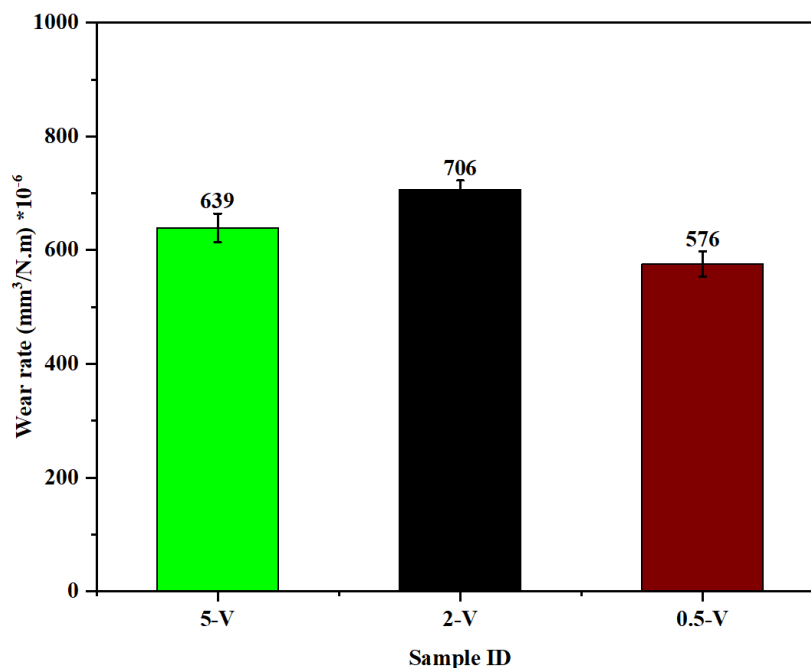


Figure 4.19 Wear rate values for various sizes

Figure 4.21 shows the SEM micrographs of the wear track. The figure shows that there is a presence of iron oxide film on the surface, which affects the COF and wear behavior. These films, smooth with shear-like features, play a crucial role in wear dynamics. A consistent COF

is observed until the oxide layer delaminates, exposing the metallic surface, leading to a sudden COF increase. In general, it has been observed that when the sample layers are perpendicular to the sliding direction, the wear resistance is higher as compared to the sample with parallel layers to the sliding direction [113]. The wear tracks exhibit large debris and surface cracks, which evolves into more extensive damage, suggesting that cracking and abrasive wear are the predominant wear mechanisms.

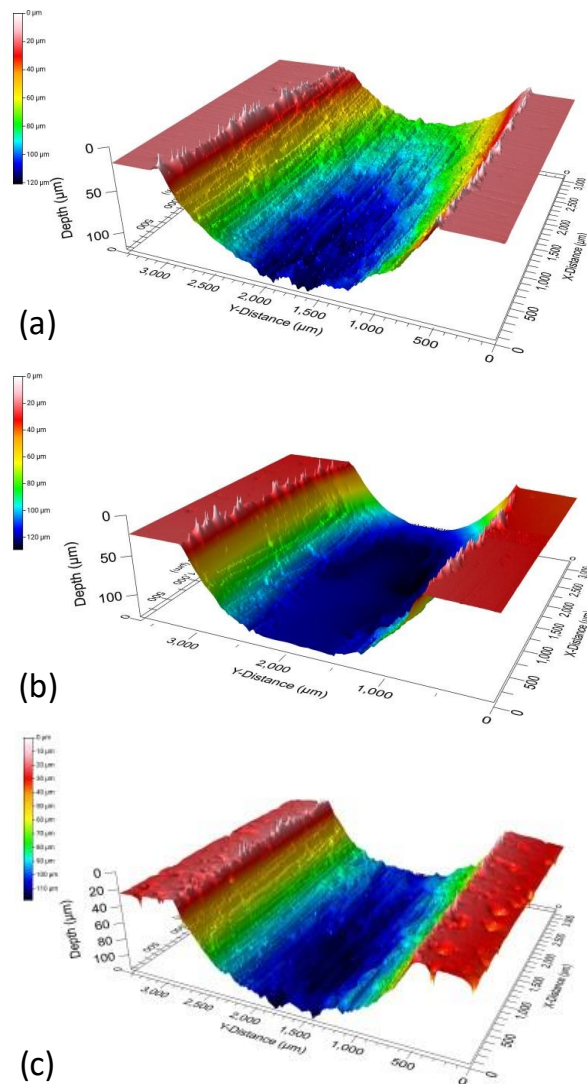


Figure 4.20 3D profilometry wear tracks of LPBF samples (a) 5-V, (b) 2-V and (c) 0.5-V.

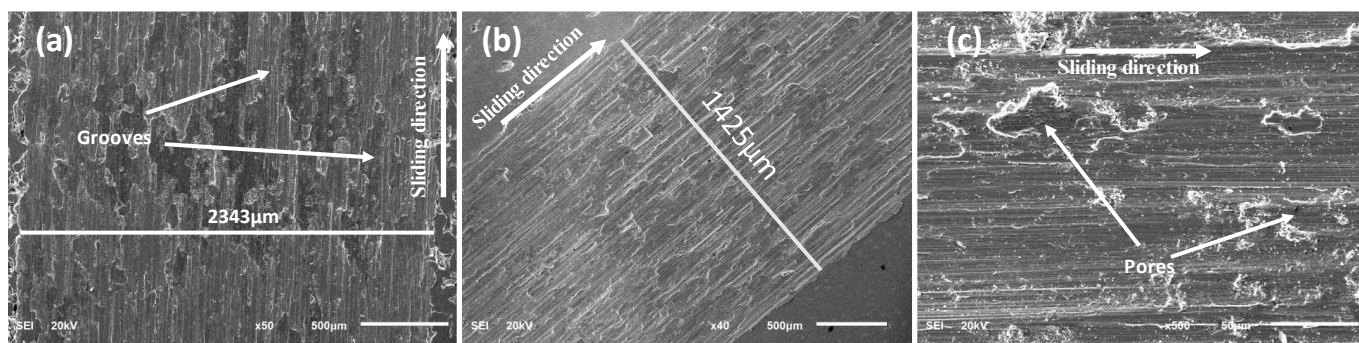


Figure 4.21 SEM micrographs for the wear track, (a) 0.5-V, (b) 2-V and (c) 5-V.

4.2.5 Corrosion behavior

The OCP and polarization curves for samples of varying sizes in 3.5 wt% NaCl solution are presented in Figure 4.22. The corrosion rate (CR), corrosion current density (I_{corr}) and corrosion potential (E_{corr}) were calculated for all samples and the data, including comparative analysis, are systematically compiled in Table 4.5.

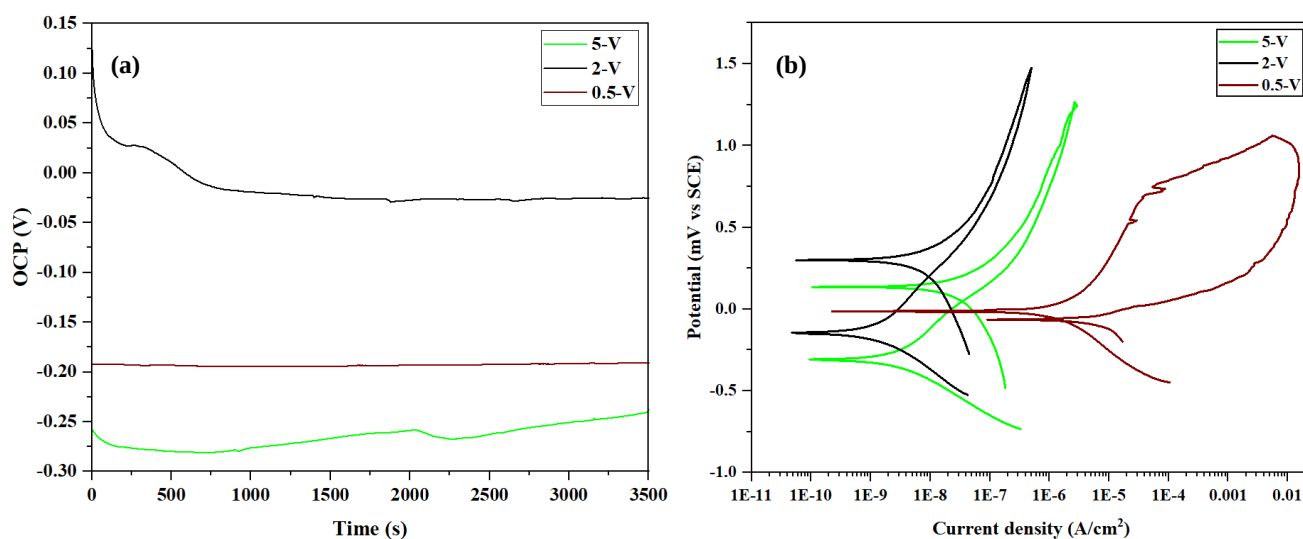


Figure 4.22 OCP and polarization curves for the samples with various sizes in 3.5 wt.% NaCl solution

From Figure 4.22 it can be observed that, the corrosion current density of the sample with 2-V thickness is considerably lower than the samples with 5-V and 0.5-V thicknesses. The sample with 2-V thickness also observed the lower corrosion rate (or highest polarization resistance)

followed by the 5-V and 0.5-V, respectively. But it is important to note the 2-V and 5-V samples are within the same magnitude, despite the difference.

Table 4.5 Tafel extrapolated data obtained from the CPDP measurement.

Sample ID	Tafel fit				
	β_a (mV/decade)	β_c (mV/decade)	I_{corr} ($\mu\text{A}/\text{cm}^2$)	E_{corr} (mV)	CR (mpy)
5-V	417	244.9	0.0037	-309	1695E-6
2-V	573.6	297.7	0.002	-146	914.3E-6
0.5-V	1280	1139	17	-218	7.749

OCP serves as a crucial indicator of the propensity of a material to develop a protective passive film, whereas the corrosion current density at OCP reflects the rate of material dissolution. A higher corrosion potential typically signifies greater passivity of the material, and an increased corrosion current density denotes a higher corrosion rate [114]. The polarization curves for the 2-V and 5-V samples follow the same pattern, which is smoother compared to 0.5-V sample curve. The presence of spikes in this sample curve indicates the instability of the passive film due to the presence of pores, which will lead to localized corrosion. A study examining the characteristics of the passive film on stainless steels has revealed that this film is double layered, comprising an inner and an outer layer [115]. The inner layer, situated close to the metal/oxide junction, is formed of anhydrous Cr oxide. In contrast, the exterior layer, located adjacent to the oxide/electrolyte boundary, is made up of iron oxide/hydroxides.

Finally, this comprehensive analysis aims to synthesize findings to understand the combined impact of build orientation and sample size on the properties of LPBF 316L stainless steel

components. Build orientation has a significant effect on the mechanical integrity and surface quality of the printed parts. Notably, samples fabricated at a 0° orientation generally show superior mechanical strength, attributed to optimal layer bonding, and minimized porosity. This orientation promotes finer grain structures, enhancing density and mechanical properties such as hardness and tensile strength, which are critical for reducing wear and improving tribological performance.

On the other hand, 45° and 90° orientations show variations in porosity and grain orientation, potentially compromising mechanical strength and wear resistance. These orientations also exhibit different corrosion behaviors, with increased susceptibility to pitting and accelerated corrosion rates due to less effective passive film formation.

The influence of sample size is similarly significant, particularly affecting microstructure and surface characteristics. Larger samples generally demonstrate better overall structural integrity but could show variable tribological properties depending on LPBF process specifics, such as energy input and cooling rates. Smaller samples benefit from rapid cooling and fine microstructures but often suffer from increased porosity due to the balling effect, which adversely affects both mechanical properties and corrosion resistance.

The interaction between build orientation and sample size shows a complex balance required to optimize material properties. While the 0° orientation optimizes material density and mechanical properties, adjusting sample size can modify these effects by influencing porosity levels and grain size. This intricate relationship underscores the necessity for a strategic approach to LPBF settings to tailor material properties to specific application requirements.

Understanding these synergistic and detrimental effects is significant for industries using LPBF technologies, such as aerospace and automotive, where precision and reliability are paramount. The insights from this study provide guidance for selecting appropriate LPBF parameters to achieve desired material characteristics, ensuring optimal performance in practical applications. Moreover, these findings facilitate the development of predictive models for material behaviour, enhancing design processes and improving material utilization efficiency in manufacturing.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

Systematic research work on the effect of build orientation and sample size on the mechanical, tribological and corrosion properties of 316L stainless steel samples manufactured using laser powder bed fusion technique has been achieved. The conclusions for this work are as follows.

- All LPBF 316L stainless steel samples exhibited porosity due to balling phenomena and insufficient fusion of metal powder.
- Optical microscopy revealed that grain structure and morphology were strongest at 0° build orientation and weakest at 90° orientation.
- Density measurements showed the highest values at 0° orientation (8.17 g/cm³), followed by 45° (8.04 g/cm³) and 90° (7.83 g/cm³).
- XRD analysis confirmed the presence of an austenitic phase across all orientations, with similar positions, intensity, and widths.
- Microhardness and elastic modulus were highest in 0° orientation samples, decreasing with an increase in build orientation.
- Tensile testing indicated a decrease in yield strength (YS) and ultimate tensile strength (UTS) with increasing build orientation, while elongation increased.
- The coefficient of friction (COF) was highest in 45° samples, indicating varied tribological properties based on orientation.
- Wear resistance was highest in 0° samples, which also showed superior corrosion and pitting resistance due to a dense passive film formation.

- Additional findings on sample size revealed that 2 mm samples under dry sliding conditions had the highest wear rate, correlating with lower hardness and surface roughness.
- A direct relationship was noted between sample density and wear resistance, where higher density led to improved wear resistivity; the wear mechanisms primarily involved fracture and abrasive wear, with pores acting as focal points for crack initiation.
- Corrosion behavior in 3.5 wt.% NaCl solution varied with sample size; 0.5 mm samples showed the least resistance, whereas 2 mm samples exhibited the most.
- Achieving full density in LPBF samples significantly enhances both wear resistance and corrosion resistance, underscoring the importance of sample size and density in optimizing mechanical and corrosion properties.

5.2 RECOMMENDATIONS

Based on the results from this study which explored the effects of build orientation and sample size on the mechanical, tribological, and corrosion properties of 316L stainless steel parts produced using the LPBF process, it is evident that further detailed investigations could enhance the application and effectiveness of this additive manufacturing technology.

Recommended future work includes:

- Conduct more advanced microstructural characterization techniques such as Electron Backscatter Diffraction (EBSD) to obtain detailed insights into grain orientation and texture, which could influence mechanical properties.
- Conduct a parametric study focusing on optimizing laser power, scan speed, and hatch spacing to reduce defects such as porosity and improve the overall quality of the printed parts.

- Evaluate the effects of various post-processing treatments such as heat treatment, surface polishing, and coating applications on the tribological and corrosion properties of the produced parts.
- Investigate the corrosion resistance of 316L stainless steel in different aggressive environments, including those simulating marine, industrial, and body fluids, to establish broader application potential and durability.
- Investigate the long-term durability and fatigue behavior of 316L stainless steel parts produced by LPBF under cyclic loading to assess their viability in critical applications.

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Vitae

Name: Mohammed Abdelrahim Shummo Yousif

Nationality: Sudanese

Date of Birth: 03/13/1997

Email: Shummo2011@live.com

Address: Dhahran, Saudi Arabia

Academic Background:

Master of Science (Mechanical Engineering), 2024:

King Fahd University of Petroleum and Minerals, Saudi Arabia

Bachelor of Science (Mechanical Engineering), 2020:

University of Khartoum, Sudan