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Analysis of Phase Transformations and Structural Properties in Stainless Steel 316L Powder

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***Abstract:** Using X-Ray Diffraction (XRD), this research characterized phase contents and structural validity of SS316L stainless steel powder. SS316L features enhanced corrosion resistance, mechanical strength, and heat tolerance making it a universal selection across challenging environments. XRD identified SS316L powder crystallographic structure and also identified any unwanted secondary phases that may negatively impact its capability to function in actual world applications.The XRD pattern of the powder included 3 distinct peaks at 2θ = 43.5°, 50.6°, and 74.6° for the (111), (200), and (220) planes of a face centered cubic (FCC) crystal structure indicating it is in the austenitic phase (γ-Fe). The three distinctive peaks likewise imply no undesirable secondary phases (ferrite, sigma phase, or chromium carbides) existed meaning high structural integrity in the powder.The structural integrity of the SS316L powder is vital, considering its value addition in the form of corrosion resistance, mechanical stability over a wide service performance, and performance dependability for use in applications such as; biomedical implants and aerospace parts. XRD results support the SS316L powder can and will work for additive manufacturing, and other high-performance fabrication performance-based processes wherein structural integrity is the priority. Thus, XRD analysis offers itself as a useful tool for verification of powder phases and quality control for high performance engineering metal powders as additive manufacturing increases in popularity.*
***Keywords:** SS316L Stainless Steel, X-Ray Diffraction (XRD), Phase Analysis, Austenitic Stainless Steel, Face-Centered Cubic (FCC), Structural Characterization, Secondary Phases*

I. INTRODUCTION

Stainless steel 316L (SS316L), a low carbon containing austenitic stainless steel, provides an impressive balance of corrosion resistance, mechanical strength, and weldability[1]. Due to these features, SS316L is a crucial material used across multiple industries including aerospace, marine, medical, chemical processing, and additive manufacturing[2]. The performance and reliability of important components made from SS316L rely heavily on SS316L's microstructural features, specifically phase composition and structural quality.The crystallographic structures associated with metallurgy can be an important consideration for how a material behaves physically and mechanically[3], [4]. Austenitic stainless steels are a class of material that is primarily made from face centered cubic (FCC), also referred as the gamma (γ) phase[5], [6]. The gamma phase gives a material with primarily FCC features exceptional ductility, toughness, and corrosion resistance to a variety of corrosion modes[7], [8], [9]. However, during the processing of the material or the preparation of the powder the formation of secondary and sometimes undesirable phases can occur[8]. Secondary phases such as ferrite, sigma phase or chromium carbides can impact corrosion resistance, create brittleness and/or impact the overall mechanical performance of the material from SS316L[10], [11].

When producing or utilizing SS316L powder in advanced manufacturing methods such as Selective Laser Melting (SLM), or any powder-bed fusion additive manufacturing, it is very important to confirm that the SS316L powder maintains its structural purity. In additive manufacturing processes, the feed-stock material must be very high quality. Structural deviations in phase composition will lead to dimensional inconsistencies, reduced mechanical properties, and premature failures in service[12], [13].

X-Ray Diffraction (XRD) analysis is one of the most common and effective methods of confirming phase composition for SS316L powder. XRD determines crystalline structures by analyzing the diffracted X-ray beams from X-ray interaction with the materials atomic lattice[14]. By analyzing the position and intensity of the diffracted peaks, we can derive detailed insight into phase constituents, crystal structure and lattice parameters. SS316L powder should have a pure austenitic structure that produces sharp peaks at certain known 2θ values, as a result of the (111), (200) and (220) planes.

The aim of this study was to evaluate SS316L powder using XRD to confirm solely the presence of the austenitic phase and confirm there are not any secondary phases. The powder was then scanned over a range of 2θ angles using a Cu Kα radiation source (λ = 1.5406 Å), the output then compared to standard reference diffraction patterns.

Stainless Steel 316L (SS316L), which is a low-carbon metal alloy that undergoes an austenitic process for use, is widely used in biomedical, aerospace, marine, and chemical industries because of its excellent corrosion resistance, mechanical strength, and thermal stability[15], [16]. All of these functional properties are linked to its phase composition and microstructure, which must be controlled at all times and especially when using advanced manufacturing methods such as Selective Laser Melting (SLM) and other powder-bed fusion processes[17]. The austenitic phase in SS316L is a face-centered cubic crystal with outstanding ductility, toughness, and localized corrosion resistance[7], [10]. Improper thermal treatment, defects from powder production, overheating, and any poorly processed phase changes during powder production can lead to transitions to unwanted secondary phase constituents in SS316L such as ferrite, sigma phase, or chromium rich carbides[7], [12]. Separately, the sigma phase and pristine carbides can lead to a dramatic decrease in mechanical performance and corrosion resistance[16].

Phase characterization utilizing the X-ray diffraction (XRD) technique is important in phase analysis of metallic systems[18]. XRD allows the phase structure of the material to be determined by studying the material's diffraction positions[19]. The XRD approach of this study will allow direct identification of the crystallographic structure, as well the identify any phase impurities before the SLM process whether by blocking the Ultraviolet light treatment process[20]. All three unique XRD diffraction peaks are identical and sharp, at 2θ values of 43.5°, 50.6°, and 74.6° respectively and from their (111) (200) and (220) planes proven to be single phased FCC structure of SS316L. XRD will use the results from the current study on the SS316L.

II. METHODOLOGY

X-ray diffraction (or XRD) analysis was used to characterize the crystallographic structure and phase composition of the SS316L stainless steel powder. For the elemental crystallography activity, a standard laboratory diffractometer was utilized with a Cu Kα source (λ= 1.5406 Å). The Cu Kα x-ray diffraction wavelength and performance is common in the characterization of metallic materials, particularly, due to the performance of the material in the diffraction processes while also possessing an adequate depth of penetration. For XRD analysis, the Bragg-Brentano geometry (θ–2θ configuration) was used to collect distinct levels of interplanar spacing and crystallography representation of the powder. Given the important need to quantify the key presence of distinct phases, scanning for the austenitic phase of the sample, while capturing the potential secondary/unwanted secondary phases (ferrite, sigma phase, or chromium carbide) scans were completed over a 2θ range of 20° to 100°. A step size of 0.02° and a scan pace of 1–2° per minute were used to capture high resolution scans using low contrasting backdrop in post-processing analysis.

Taken together, the x-ray diffraction allowed for evidence of the primary phase (austenitic) (i.e. γ-Fe) along with the potential of the powder to have measurable secondary or conducted phases. In addition, the XRD analysis illustrated sharp diffraction peaks for standard crystallography planes, yielding a structural purity of powder data. The methodology suggested complete representation of phase composition allowing down-range inference of the crystal structure of the powder which is confidence and reliability can be utilized to determine the structural reliability of the spheres for engineering significance step.

III. RESULTS AND DISCUSSION

A. Phase Composition via X-Ray Diffraction (XRD)

The XRD analysis performed on the SS316L powder was used to assess the crystallographic phases of the powder and identify any structural impurities. The powder exhibited three peak diffractions at almost identical 2θ values of 43.5°, 50.6°, and 74.6° which corresponded to the (111), (200) and (220) planes (where θ is the diffraction angle). The XRD spectra of the SS316L powder are shown in Fig. 1

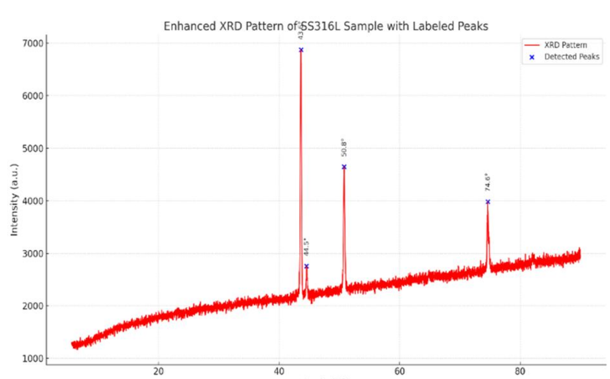

Figure 1. Spectra of SS316L.

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The peak positions of the powder showed a face-centered cubic (FCC) crystal structure that is representative of austenitic stainless steel (γ-Fe) so no indication of a phase was formed in the powder. The diffraction peaks and their corresponding phases are listed in Table I.

Table I: XRD Analysis Summary of SS316L Powder

2θ (°)	(hkl)	Phase	Structure	Observation
43.5	(111)	γ-Fe	FCC	Strong peak; confirms austenitic phase
50.6	(200)	γ-Fe	FCC	Clear peak; indicates single-phase FCC
74.6	(220)	γ-Fe	FCC	High-angle peak; matches SS316L profile

Thus, there were no secondary phases (ferrite, sigma phase, or chromium carbides, for example) indicated during the analyses providing that the structural purity of the powder was free of unwanted transformations. The absence of detrimental phases in the powder is important to the powder's corrosion resistance, ductility, and long-term mechanical stability in its intended final-use applications.
The XRD data of the SS316L powder exhibited a clear face-centered cubic (FCC) crystal structure, which was anticipated for austenitic stainless steels. The three strongest diffraction peaks of 2θ = 43.5°, 50.6°, and 74.6° corresponding to the planes (111), (200) and (220), respectively, demonstrates the presence of a strong γ-Fe (austenite) phase. This has been confirmed with the JCPDS data for SS316L, which allows one to anticipate the crystal structure.
The absence of peaks from any secondary phases such as ferrite, sigma phase, or chromium carbides is advantageous concerning phase purity, because the presence of such substandard phases can impact the corrosion resistance, mechanical stability and ductility of the SS316L. The corresponding single-phase FCC structure should provide consistent mechanical performance and thermal stability for SS316L powder to be used in applications such as additive manufacturing, metallic medical implants, and applications with elevated service temperatures.
In addition, the distinctive and well-defined nature of the powder diffraction peaks suggests a good crystallinity in the powder particles therefore it is safe to say that the powder had minimal distortion or residual stress imparted to it in processing. All of which affords better performance and reliability of parts manufactured from this powder.
In summary, the XRD results confirm that the SS316L powder used in this study has the correct austenitic structure, has no detectable contamination, and has no undesirable phase transformations. These results confirm that this powder was fit-for-purpose for use in high-end engineering applications that are intended to maintain phase stability and corrosion resistance.
The current results align with recent studies [2], [4], [7], [14], where SS316L had a stable FCC austenitic phase without any secondary phases. Sharma et al. [2] also recorded sharp peaks in additive manufactured SS316L while Özgeneci [3] confirmed structural purity for aerospace applications, amongst others. Thus, it would possible to make the comparisons that would support the current XRD analysis and further support the use of SS316L for advanced manufacturing.

IV. CONCLUSION

X-Ray Diffraction (XRD) analysis was utilized in this study to characterize the phase composition and crystallographic structure of SS316L powders, a commercially available material that is used in high-end industries (biomedical, aerospace, and additive manufacturing). All three obtained XRD representative diffraction peaks of the SS316L powder occurred at 2θ values of 43.5° 50.6°, and 74.6°, which respectively are related to the (111), (200), and (220) planes of a FCC structure, indicating that the material is in a stable austenite (γ-Fe) form. More importantly, there were no other secondary phases (ferrite, sigma phase, or chromium carbides) observed, indicating structural purity and overall quality of the SS316L powder. The absence of these detrimental phases supported the materials known advantages; including corrosion resistance, mechanical integrity, and soundness at elevated temperatures, meaning the material is suitable for high performance and precision reliant applications.

The present work emphasizes the applicability of using XRD as a reliable and non-destructive metrics of phase verifications and quality assurance for form and functionality in metal powders for advanced manufacturing. The SS316L powder material was solidly deemed structurally acceptable for additive manufacturing and other related engineering applications with potential risk.

V. ACKNOWLEDGMENT

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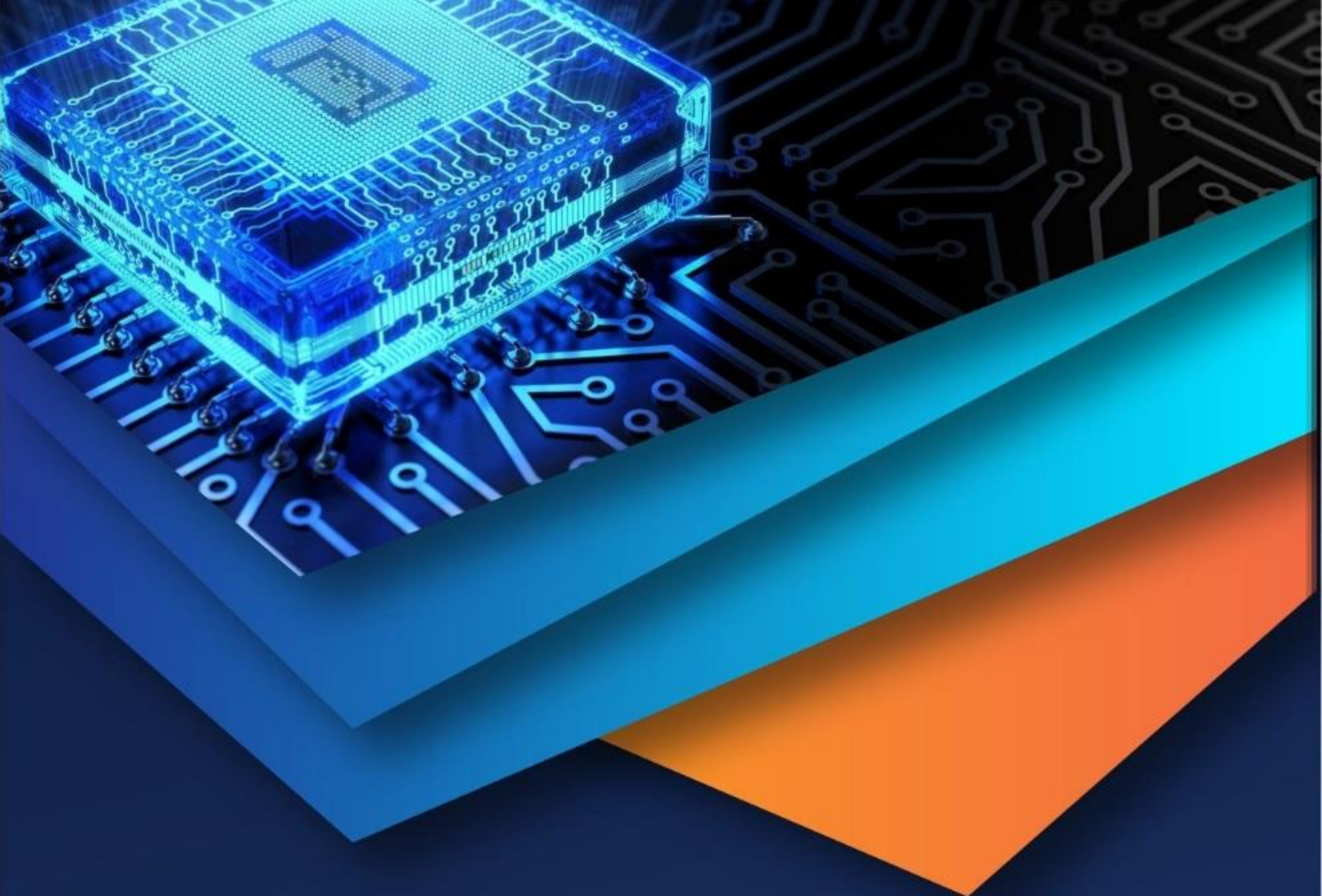

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