The 2025 World Congress on
Advances in Structural Engineering and Mechanics (ASEM25)
BEXCO, Busan, Korea, August 11-14, 2025

3D printed super duplex stainless steel for structural applications

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ABSTRACT

The objective of this study is to evaluate the viability of utilizing 3D-printed super duplex stainless steel (SDSS) with a modified chemical composition for structural node connectors, particularly curtain wall spider fittings and other load-bearing architectural joints. The primary idea is to assess the mechanical behavior, microstructural characteristics, and corrosion performance of the printed material in order to ascertain its suitability for high-strength structural connections in modern facade systems. This study investigates the effect of nickel addition and heat treatment on the microstructure, mechanical properties, and corrosion resistance of super duplex stainless steel (SDSS) processed by Laser Powder Bed Fusion (LPBF). Two powder compositions were analysed: standard SDSS and SDSS with 3 wt.% Ni. The as-printed microstructure was primarily ferritic due to rapid cooling, while solution annealing produced a balanced duplex structure. Mechanical testing showed improved ductility after annealing and higher tensile strength in as-printed SDSS+3%Ni. Both compositions reached ~30% elongation after heat treatment. Electrochemical tests confirmed improved corrosion resistance with heat treatment and further enhancement with nickel addition. SDSS+3%Ni exhibited more noble open circuit potentials and higher polarization resistance. These results demonstrate that nickel enrichment effectively improves phase balance, mechanical behaviour, and corrosion resistance in LPBF-processed SDSS.

1. INTRODUCTION

The utilisation of 3D-printed stainless steels in structural and architectural components is a subject that is receiving increasing attention due to the high strength, corrosion resistance and design flexibility that these materials offer. Among the various applications of these materials, steel node connectors, curtain wall spider glass fittings, and optimized lattice structures require exceptional mechanical performance,

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microstructural stability, and resistance to environmental degradation. The limitations imposed on design complexity and material efficiency by traditional manufacturing methods, such as casting and machining, are well-documented. Conversely, the additive manufacturing process, particularly the Laser Powder Bed Fusion (LPBF), Directed Energy Deposition (DED), and Wire Arc Additive Manufacturing (WAAM) techniques, facilitates the fabrication of lightweight, topology-optimised components. These techniques allow for the customisation of properties, thus tailoring the material to specific needs (Abdelwahab 2001, Chern 1992).

Duplex stainless steels are a special type of stainless steel, created due to the existing demand for a combination of mechanical strength possessed by ferritic steels with corrosion resistance, which in turn is characterized by austenitic steels. A particularly important subclass within this family is the super duplex stainless steels (SDSS), which have attracted significant attention due to their exceptional combination of mechanical and corrosion-resistant properties. These alloys are characterized by an approximately equal volume fraction of ferrite (α) and austenite (γ) phases, a balance that confers superior strength, high impact resistance, and excellent resistance to localized corrosion mechanisms such as pitting and crevice corrosion. The enhanced performance of SDSS stems from their refined chemical composition, which includes higher contents of chromium (typically 24–26 wt.%), molybdenum (3–5 wt.%), and nitrogen (up to 0.3 wt.%) compared to conventional DSS. These elements act synergistically: chromium and molybdenum improve resistance to chloride-induced pitting, while nitrogen stabilizes the γ-phase and enhances mechanical strength (Nilsson 1992).

The superior mechanical and corrosion-resistant properties of Super Duplex Stainless Steels (SDSS) make them ideal candidates for applications in highly aggressive environments. With the advancement of additive manufacturing technologies, particularly laser-based powder bed fusion and directed energy deposition, the potential to fabricate complex, load-bearing SDSS components is expanding. In this context, a key area of interest is the development of high-performance structural connections for modern façade systems, where both mechanical strength and long-term durability in corrosive urban or coastal environments are critical. However, achieving and maintaining the required phase balance is challenging due to the material's sensitivity to thermal history and compositional fluctuations. One of the main difficulties lies in the tendency of SDSS to form harmful intermetallic phases, such as sigma (σ) and chi (χ) phases, during prolonged exposure to intermediate temperatures, which can severely impair both ductility and corrosion resistance (Xie 2023).

In response to these processing challenges, AM technologies, especially LPBF, have been investigated as novel routes for fabricating SDSS components with complex geometries and tailored microstructures. LPBF involves the selective melting of fine metal powders layer-by-layer using a focused laser beam, providing high geometric resolution and control over local thermal gradients. However, the rapid solidification rates inherent to LPBF (~10^6 K/s) hinder the diffusion of γ-stabilizing elements like nickel and nitrogen, often resulting in as-built structures dominated by ferrite and depleted in austenite. Such unbalanced microstructures are associated with high hardness, low ductility, and diminished resistance to pitting corrosion due to chromium nitride precipitation (Cui 2022, Xiang 2023, Zhao 2024, Karavias 2024).

To overcome these microstructural limitations, two primary optimization strategies are employed: post-process solution heat treatment and modification of the chemical composition of the powder feedstock. Solution annealing typically at 1050–1150 °C promotes the reformation of austenite, dissolution of secondary phases, and reduction of residual stresses, thereby improving mechanical and corrosion performance (Chuqi 2023). Alternatively, adjusting the alloy composition by increasing the nickel content is increasingly favoured. Nickel is a potent γ-phase stabilizer and has been shown to significantly enhance austenite formation during cooling, even under the rapid solidification conditions of LPBF. The presence of nickel also improves elongation, impact resistance, and corrosion behaviour, particularly in chloride-laden environments.

Recent studies demonstrate that in-situ alloying through powder blending, particularly by combining super duplex stainless steel powders like SAF 2507 with austenitic stainless steels such as AISI 316L, offers a practical method to tailor the chemical composition during the LPBF process. This technique allows controlled adjustment of the chromium equivalent to nickel equivalent ratio (Cr_{eq}/Ni_{eq}), a key parameter influencing phase stability in DSS. By fine-tuning this ratio, researchers have achieved near-equilibrium phase distributions, with nearly equal proportions of ferrite and austenite directly in the as-built microstructure (Cui 2022).

This compositional adjustment mitigates the ferrite excess typically observed in LPBF-processed DSS due to rapid cooling, which otherwise hinders γ-phase formation. Notably, the incorporation of AISI 316L, rich in nickel and molybdenum, not only promotes austenite formation but also enhances pitting resistance and mechanical ductility. The resulting microstructure demonstrates significant improvements in hardness uniformity, tensile strength, elongation, and electrochemical stability when exposed to chloride environments. In-situ alloying thus reduces the dependency on post-process heat treatments and provides a cost-effective route to microstructural and performance optimization, making it a viable strategy for industrial applications demanding high mechanical and corrosion performance.

Therefore, the current study aims to systematically evaluate the effect of nickel enrichment (3 wt.%) and subsequent solution annealing on SDSS processed via LPBF. The focus lies in assessing changes in phase distribution, grain morphology, hardness, tensile behaviour, and corrosion resistance in chloride-containing environments. The results aim to fill existing knowledge gaps and contribute practical guidelines for the reliable deployment of SDSS in advanced manufacturing applications using LPBF.

1. EXPERIMENT PROCEDURE

Super duplex stainless steel (SDSS) Ospray 2507 powder grade (EN 1.4410), with a particle size range of 15–45 µm, was mixed with pure nickel powder (particle size: 22–45 µm) in proportions of 3 wt.%. The powders were blended for 20 minutes using a Turbula mixer. The resulting final compositions are presented in Table 1. The initial SDSS powder contains approximately 6 wt.% nickel, which increases to 9 wt.% in the composition designated as SDSS+3%Ni.

Horizontal samples for tensile testing (dog-bone shape) and Charpy impact testing were fabricated using an AM125 RENISHAW, Wotton-under-Edge, UK, printer with the following process parameters: laser power of 180 W, hatch distance of 120 µm, layer thickness of 30 µm, and scan speed of 300 mm/s. These settings correspond to a volumetric energy density of approximately 166 J/mm³. A meander scanning strategy with a rotation of 67° between successive layers was applied. After fabrication, the samples underwent post-processing heat treatment by solution annealing at 1100 °C for 15 minutes, followed by rapid water quenching.

Table 1. Chemical composition of studied SDSS

Designation	Alloying elements, wt.%.									
	Cr	Ni	Mo	Mn	Si	Cu	S	P	C	N
SDSS	25.2	6.3	3.8	0.4	0.30	0.15	0.001	0.024	0.016	0.35
SDSS+3%Ni	24.44	9.1	3.69	0.39	0.29	0.14	0.001	0.024	0.016	0.35

Microstructural characterization was carried out using scanning electron microscopy (SEM) and X-ray diffraction for phase identification. Mechanical property evaluation included hardness measurements (HRA), tensile testing and Charpy impact testing on unnotched samples. Corrosion resistance was assessed using potentiodynamic polarization measurements conducted via the Tafel extrapolation method. The tests were performed in a 3.5% NaCl aqueous solution at ambient room temperature to simulate chloride-rich environments commonly encountered in service conditions. The key corrosion parameters were determined, including corrosion potential (E_{corr}), corrosion current density (I_{corr}), and polarization resistance (R_{pol}). The Open Circuit Potential (OCP) was monitored for a duration of 60 minutes prior to polarization testing to ensure the electrochemical stabilization of the sample surface in the test environment.

1. RESULTS AND DISCUSSION

The as-printed super duplex stainless steel (SDSS) reveals an almost fully ferritic microstructure due to the rapid cooling rate of the laser powder bed fusion (LPBF) process. The X-ray diffraction pattern (Fig. 1) shows only a weak peak corresponding to the austenite – Fe-γ (111). After the solution annealing at 1100 °C for 15 min, the phase content becomes balanced, and strong peaks from both austenite and ferrite are visible in the XRD pattern. Quantitative analysis indicates that the austenite content is approximately 5% in the as-printed SDSS, increasing slightly to 7% in the SDSS+3%Ni composition. Solution annealing results in the formation of a well-balanced microstructure, with ferrite and austenite phases present in nearly equal proportions: 52% austenite in SDSS, increasing to almost 60% in SDSS+3%Ni.

The microstructure of LPBF-processed SDSS in the as-printed condition is predominantly ferritic for both compositions, as shown in Figs. 2a and 2b. The ferritic grains exhibit elongated, columnar morphology oriented along the build direction, with smaller, rounded grains also observed. Additionally, grain boundary austenite (GBA) is likely present, contributing to the duplex character of the alloy. In the solution-annealed condition (Fig. 2c, 2d), a balanced and refined ferritic-austenitic microstructure was formed in both cases. However, for the SDSS+3%Ni composition, the austenite content is more pronounced. Austenitic grains form distinct islands, and a high number of fine acicular grains are homogeneously distributed throughout the microstructure.

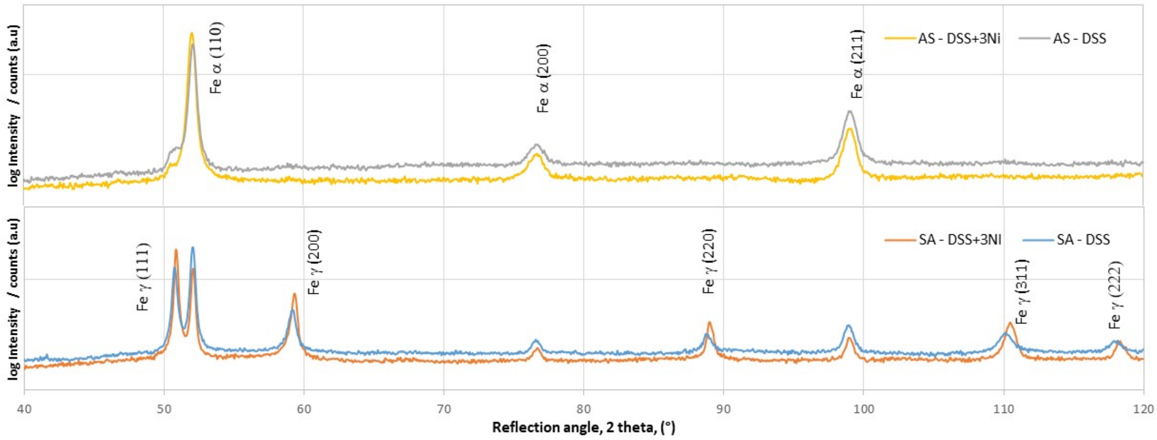

Fig. 1. XRD patterns of as-printed (AS) and solution annealed (SA) super duplex stainless steel compositions: SDSS and SDSS+3%Ni

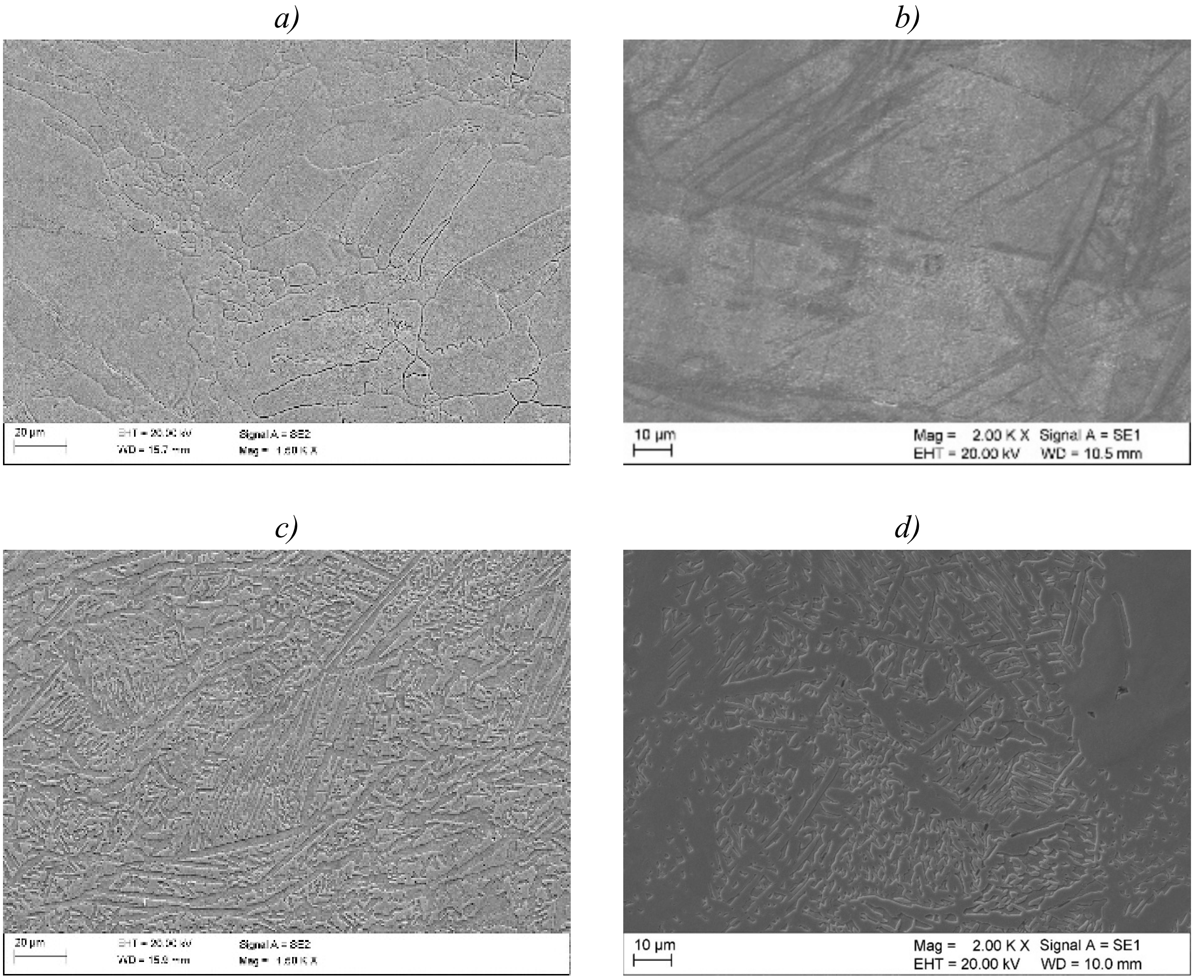

Fig. 2. The microstructure of a) as-printed SDSS, b) as-printed SDSS+3Ni, c) solution-annealed SDSS and d) solution-annealed SDSS+3Ni

When comparing the mechanical properties of the studied conditions (Table 2), it is evident that the SDSS+3%Ni composition exhibits higher ductility in the as-printed condition, due to its increased austenite content. The elongation after fracture for SDSS+3%Ni is approximately 7%, compared to 4.8% for standard SDSS (Fig. 3). The yield strength (Rp0.2) of SDSS+3%Ni is lower than that of standard SDSS, indicating an improved capacity for plastic deformation prior to fracture. In contrast, standard SDSS shows very similar values for yield strength and ultimate tensile strength (Rm), suggesting limited plastic deformation before failure. After solution annealing, the SDSS+3%Ni composition exhibits increased tensile strength compared to SDSS. The tensile strength increases from 860 MPa for SDSS to 890 MPa for SDSS+3%Ni. In terms of maximum elongation to fracture, both compositions exhibit similar values of approximately 30%.

Table 2. Mechanical properties of the LPFB-manufactured super duplex stainless steels Mechanical

Mechanical properties	SDSS as-printed	SDSS solution annealed	SDSS+3Ni as-printed	SDSS+3Ni solution annealed
HRA, core	69.92 ± 1.53	60.48 ± 2.49	72.20 ± 2.20	62.50±1.50
$R_{p0.2}$, MPa	1310 ± 20	575 ± 8	1094±17	559 ±7.9
Rm, MPa	1390 ± 5	861 ± 3	1324±25	890 ± 1.9
A, %	4.8 ± 0.6	33.7 ± 0.5	6.8±1.9	29.6±0.8
Impact energy, J	103 ± 26.67	≥ 450	120± 14	≥ 450

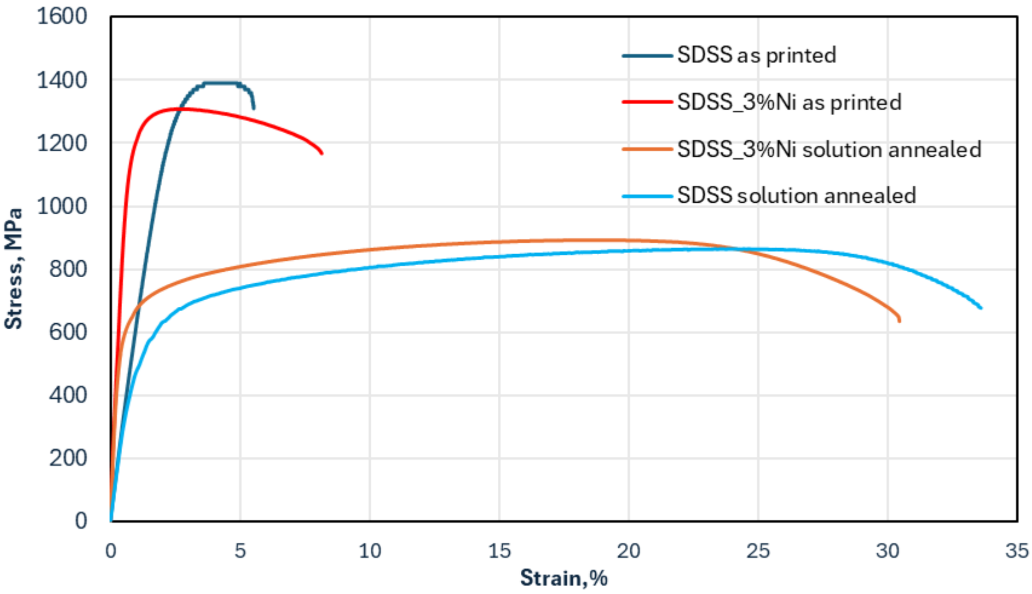

Fig. 3. Stress–strain curves of LPBF-manufactured SDSS super duplex stainless steels

The hardness of the as-printed samples is higher in both compositions (Table 2) due to strong internal stress concentrations resulting from the LPBF process. In contrast, solution annealing softens the material by promoting a balanced phase distribution and relieving residual stresses through uniform microstructural reformation. This heat treatment also has a significant effect on impact toughness, which is low in the as-printed condition but increases dramatically after solution annealing, reaching values ≥450 J (unnotched samples), indicating a substantial improvement in energy absorption and resistance to brittle fracture.

The corrosion resistance of LPBF-manufactured SDSS is influenced by chemical composition, phase content, and applied heat treatment. Results of the Tafel analysis and electrochemical parameters are summarized in Table 3. For the SDSS composition, solution annealing enhances corrosion resistance. The polarization resistance (R_{pol}) increases from 126 kΩ·cm² to 149 kΩ·cm² compared to the as-printed condition. Additionally, the open circuit potential (E_{OCP}) shifts towards more positive values, from –966 mV to –835 mV. A positive shift of E_{OCP} indicates a lower thermodynamic tendency for corrosion, reflecting a more stable and protective passive film on the material surface.

Table 3. The electrochemical parameters of LPBF manufactured SDSS

Parameter	SDSS as-printed	SDSS solution annealed	SDSS+3Ni as-printed	SDSS+3Ni solution annealed
E_{OCP}, mV	- 966	-835	-350	-212
J_{corr}, μA/cm^2	140.63	131.89	237.18	114.19
E_{corr}, mV	-147.17	-136.35	-378.62	-250.63
R_{pol}, kΩ*cm^2	126.82	149.35	148.86	165.44

In comparison, the SDSS+3%Ni composition exhibits a significantly more positive E_{OCP}, ranging from –350 mV in the as-printed state to –212 mV after solution annealing. This improvement is attributed to the higher austenite content, which enhances passivity and electrochemical stability. The R_{pol} value also increases after heat treatment, from 149 kΩ·cm² to 165 kΩ·cm², indicating further improvement in corrosion resistance.

Comparison of polarization resistance confirms that SDSS+3%Ni exhibits higher R_{pol} values in both conditions compared to standard SDSS. For both compositions, solution annealing improves corrosion resistance, as reflected by increased R_{pol} and more noble EOCP values.

All studied compositions demonstrated repassivation upon reversal of the polarization current. Among them, the solution-annealed SDSS exhibited faster repassivation compared to the as-printed condition, further supporting the beneficial effect of heat treatment on corrosion performance.

The results of this study demonstrate that both solution annealing and nickel addition significantly influence the microstructure, mechanical properties, and corrosion resistance of LPBF-processed super duplex stainless steels. The as-printed samples exhibited a predominantly ferritic microstructure, high hardness, low ductility, and limited impact toughness due to rapid solidification and residual stress accumulation. Solution annealing effectively transformed the microstructure into a balanced ferritic-austenitic phase composition, reducing hardness while substantially increasing ductility and impact toughness.

Nickel addition proved especially beneficial in the as-printed condition by promoting the formation of austenite, leading to improved ductility and lower yield strength, indicating enhanced plastic deformability. Furthermore, the SDSS+3%Ni composition exhibited superior corrosion resistance in both conditions, with more noble open circuit potentials and higher polarization resistance. These findings confirm that controlled nickel enrichment improves phase stability, mechanical performance, and electrochemical behaviour even without post-processing, making it a promising strategy for tailoring SDSS properties in additive manufacturing applications.

Super duplex stainless steels, such as UNS S32750 (EN 1.4410) and UNS S32760 (EN 1.4501), offer excellent mechanical performance in the form of flat products, including plates and sheets. According to EN 10088-2, these steels typically have tensile strengths (R_m) of over 795 MPa and yield strengths ($R_{p0.2}$) of at least 550 MPa. These properties exceed the typical requirements for structural elements in façade systems, where a high strength-to-weight ratio, rigidity and long-term durability are essential, particularly for brackets, connection plates and cladding supports.

Additive manufacturing using LPBF has demonstrated the capacity to reproduce, and in some cases even exceed, these strength levels, a feat attributable to the rapid solidification and refined grain structures characteristic of this process. However, LPBF-fabricated SDSS may exhibit reduced ductility compared to wrought products, primarily due to residual stresses, microsegregation, and the formation of brittle secondary phases. As delineated in the EN 10088 series, wrought SDSS (Stainless and Duplex Steel) typically exhibits an elongation above 25% and a Charpy V-notch impact toughness exceeding 60 J at −46°C. This ensures energy absorption under dynamic or impact loading. In order to achieve equivalent performance, LPBF components necessitate suitable post-processing, such as solution annealing, to restore phase balance and enhance ductility and fracture resistance. When administered correctly, LPBF SDSS is deemed appropriate for structural applications, including seismic-resistant façade anchors and flexible joints.

A significant benefit of SDSS is its enhanced corrosion resistance in hostile environments, attributable to its balanced austenite-ferrite microstructure and substantial alloy content. This resistance is critical for exposed façade connectors in coastal, marine, or industrial atmospheres. However, the LPBF process has been observed to disrupt this equilibrium, thereby promoting the formation of intermetallic phases such as sigma (σ) or chi (χ), which have been shown to compromise corrosion performance. These effects can be mitigated by post-build heat treatment at 1050–1100°C, thereby restoring the desired dual-phase structure. In order to ensure that the performance of the product is equivalent to that of wrought products described in EN 10088-2 and EN 10088-3, it is essential to conduct corrosion testing such as ASTM G48 (pitting resistance) and ASTM G150 (critical pitting temperature). When appropriately processed, LPBF SDSS has the potential to satisfy the long-term durability and low-maintenance expectations for façade applications.

Notwithstanding the aforementioned advantages, several challenges must be addressed if the widespread adoption of LPBF-manufactured SDSS in structural façade connections is to be realised. The EN 10088 standards apply exclusively to wrought materials and do not yet encompass additive manufacturing, necessitating component-specific qualification and testing. Furthermore, the consistent control of microstructure, surface integrity, and corrosion resistance remains a technical challenge due to the sensitivity of duplex grades to thermal gradients during printing. Surface finishing is of paramount importance in ensuring compliance with both corrosion protection and aesthetic standards, necessitating the introduction of additional steps in the manufacturing process. In conclusion, it is imperative to undertake a comprehensive evaluation of the economic competitiveness of LPBF, in comparison with conventional forming and joining methods, for each distinct application. In order to facilitate the adoption of LPBF SDSS in architectural and structural contexts, there is a necessity for the establishment of AM-specific standards, the implementation of robust process control strategies, and the creation of formal certification protocols.

3. CONCLUSIONS

The microstructure of as-printed SDSS fabricated by LPBF is nearly fully ferritic, with minor amounts of grain boundary austenite. Solution annealing at 1100 °C for 15 min results in a balanced duplex microstructure, significantly increasing the austenite content to 52% in SDSS and up to 60% in SDSS+3%Ni. The addition of 3 wt.% Ni to the SDSS composition promotes austenite formation, both in the as-printed and heat-treated conditions, as confirmed by XRD and microscopy analysis. Mechanical properties of SDSS+3%Ni show improved ductility in the as-printed state and increased tensile strength after solution annealing compared to standard SDSS. After solution annealing, both compositions reach elongation values near 30%, indicating excellent plasticity. Corrosion resistance is significantly enhanced by solution annealing, as shown by increased polarization resistance and more noble open circuit potentials. SDSS+3%Ni consistently exhibits better electrochemical stability, associated with its higher austenite content and improved passivity. The deliberate increase of nickel content by adding Ni powder to SDSS feedstock is an effective alloying strategy, enhancing phase balance, improving corrosion resistance, and optimizing mechanical performance in both as-printed and heat-treated conditions.

The utilisation of LPBF-manufactured SDSS in structural applications within modern façade systems is a subject of considerable interest, given their demonstrated capacity for enhanced strength and corrosion resistance. In order to ensure that the performance of the resultant material is equivalent to that of wrought products, it is essential to exercise meticulous control over the microstructure and to employ appropriate post-processing techniques. Nevertheless, the absence of AM-specific standards and qualification protocols continues to act as a hindrance. With ongoing advancements in process control and standardisation, LPBF SDSS has the potential to emerge as a viable solution for demanding architectural applications.

ACKNOLEDGMSENT

This work has been supported by the Horizon Europe MSCA Staff Exchange Programme, the SynAM project, Grant Agreement No. 101129996, and co-funded by the Minister of Science and Higher Education's programme entitled "PMW" for the years 2024-2027, Contract No. 5783/HE/2024/2.

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