Biointerface Research in Applied Chemistry
Platinum Open Access Journal (ISSN: 2069-5837)

Review
Volume 12, Issue 1, 2022, 1110 - 1119
https://doi.org/10.33263/BRIAC121.11101119

Technology and Challenges in Additive Manufacturing of Duplex Stainless Steels

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Received: 1.03.2021; Revised: 5.04.2021; Accepted: 8.04.2021; Published: 26.04.2021

Abstract: Duplex stainless steels (DSS) comprise equivalent proportions of ferrite (α) and austenite (γ) and exhibit excellent integration of mechanical and corrosion properties. The ferrite matrix provides better strength and stress corrosion resistance, whereas the austenite matrix accounts for good pitting corrosion resistance and toughness. Duplex stainless steels are widely utilized in the chemical industry, oil refineries, and machine industries. Direct energy deposition (DED) and powder bed fusion (PBF) are the two additive manufacturing techniques widely used for metals. This article covers the technologies like processing DSS by selective laser melting (SLM), variation in mechanical and microstructural properties of duplex stainless steels manufactured by additive manufacturing technique, and challenges of additive manufacturing processes.

Keywords: duplex stainless steels (DSS); metal additive manufacturing; selective laser sintering (SLS); selective laser melting (SLM); fused deposition modeling (FDM).

1. Introduction

The American Society for Testing and Materials (ASTM) F2792 describes additive manufacturing (AM) as "a process of joining materials to make objects from three-dimensional (3D) model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies." It is possible to divide metal additive manufacturing technologies into two parts: (1) The direct way in which the metal powder fully melts to form the final part. (2) An indirect way to attach metal powder particles with a binder. Post-processing is important for both direct and indirect methods to achieve the desired density [1]. The classification of metal additive production processes is shown in Figure 1.

Table 1. Nomenclature.

DSS	Duplex Stainless Steels
DED	Direct Energy Deposition
PBF	Powder Bed Fusion
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
AM	Additive Manufacturing

EBSD	Electron Back Scattered Diffraction
SAF	Sandvik austenitic-ferritic
Epit	Pitting Potential
V_{SCE}	Voltage at Saturated Calomel Reference Cell
DDPM	Dual Drive Planetary Mill

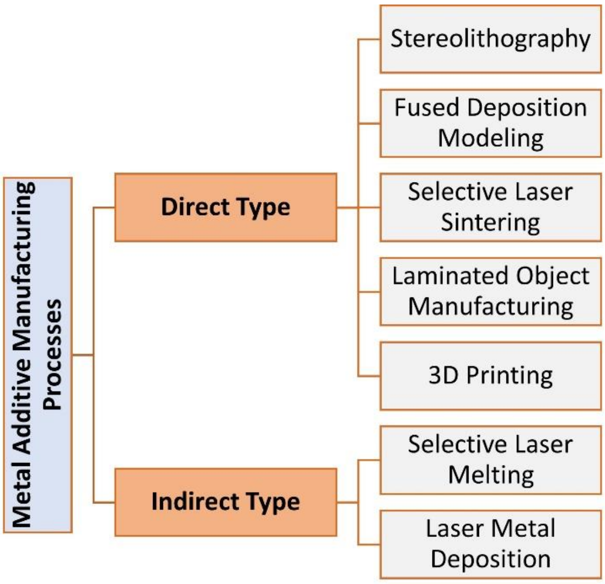


Figure 1. Classification of metal additive manufacturing processes [1].

2. Selective Laser Melting

In this process, the laser beam that passes through a lens system is reflected on the scanner mirror's platform surface. The mirrors regulate the laser beam's spot movements in the direction of X and Y. The platform moves a step down when the first powder layer is selectively melted. The recoating device pushes a fresh layer of powder from the powder dispenser to the top of the previously built layer surface. The laser melting process continues [2]. The Argon (inert) gas fills the SLM system chamber. In certain machines, argon gas is used to prevent the oxidation of metals during melting and solidification. Advantages and disadvantages of SLM were reported by Bartolo *et al*. elsewhere [3].

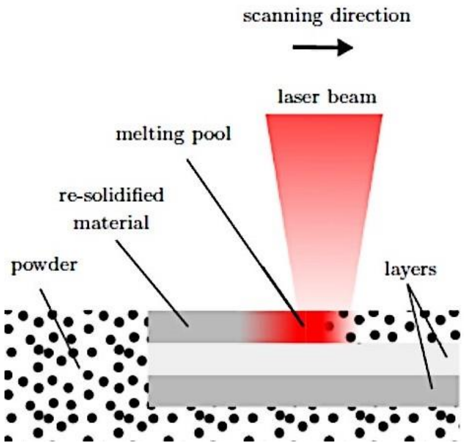


Figure 2. Selective laser melting technique [2].

3. Mechanical and Microstructural Properties of SLS Processed Duplex Stainless Steels

Hengsbach *et al*. used DSS powder UNS S31803 that has a mean particle size of 22.7µm [4]. The DSS grade chemical composition was 0.02 C, 1.54 Mn, 0.38 Si, 5.46 Ni, 2.76

Mo, 22.78 Cr, 0.16 N, 0.02 P with Fe equilibrium [4]. Using an SLM 280^{HL} fitted with a 400 Watt yttrium fiber laser, the specimens were prepared. To stop the consequences of notches, the SLM specimens were grounded to 15µm for mechanical testing. The samples were heat-treated for 5 minutes in evacuated quartz glass tubes with temperatures varying from 900 °C to 1200°C in steps of 50°C and then quenched in cold water. The authors found that the relative density of the specimens processed by SLM was approximately 99.6%.

The electron backscattered diffraction (EBSD) maps are well described by Hengsbach *et al.* in their previous publication, along with the EBSD image [4]. These elongated grains indicate that the isotropic microstructure results in epitaxial grain growth. In the as-built state, they reflect a completely ferritic microstructure. Authors have found that the formation of austenite and other precipitations is completely suppressed in the as-built state [4]. The recrystallized microstructure in the solution annealed samples shows the formation of ferrite and austenite. The austenite content reaches 34% at 1000°C and reaches its lowest volume at 1200°C, resulting in converting austenite into ferrite.

Suvi Papula *et al.* used DSS powder SAF 2205 and performed SLM. Table 2 refers to the chemical composition of the powder. The AM method's efficiency depends solely on the quality of the powder, as per the author's perspective.

Table 2. Chemical composition of SAF2205 powder [5].

Element	**Ni**	**Cr**	**Mo**	**Mn**	**Si**	**N**	**C**	**P**	**S**	**Fe**
wt%	5-6	22-23	2.8-3.6	2.0	1.0	0.15-0.21	0.03	0.03	0.015	bal.

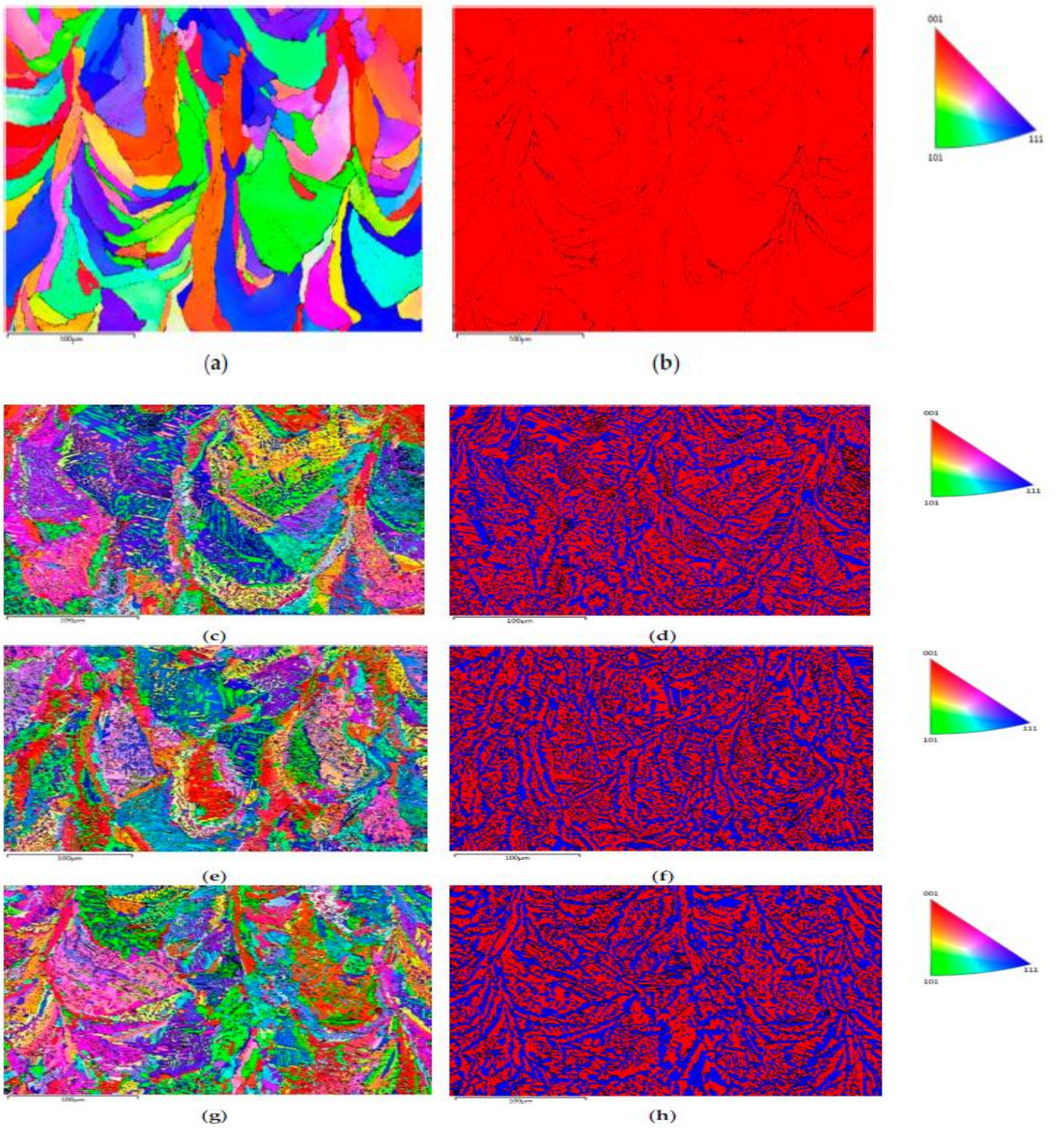
2205 DSS powder with a particle size between 15 and 45µm [5] was used by Suvi Papula *et al*. The particles of the powder are circular in shape. Based on the parameters specified in table 3, SLM was performed.

Table 3. Optimal SLM Parameters [5]

Laser Power (W)	**Scan Speed (mm/sec)**	**Layer Thickness (µm)**	**Hatch Spacing (µm)**	**Track Energy (J/mm)**	**Laser Energy Density (J/mm^3)**
250	850	50	100	0.29	59

The 250 W laser power was used to process SAF 2205 DSS, which in turn decreases porosity. The density obtained between the successive layers was 99.97 percent by 66 ° rotation and 99.01 percent with the non-rotated scanning strategy in the scanning direction. By using a scanning technique with rotation in the scanning, minimal porosity is achieved between the layers.

The columnar grain morphology of as-built materials aligned in the direction of construction [5] is represented in Figures 3 (a) & (b). Due to columnar grains' spread into consecutive layers, epitaxial growth is observed in the AM processed materials. The authors noted that the as-built material displays a completely ferritic solidification microstructure because of higher cooling speeds. Significant fractions of the austenite content were observed after successive heat treatment of the as-built samples. The high dislocation density of as-built DSS specimens is the main driving force behind the nucleation and recrystallization of austenite during the subsequent heat treatment.



(a) (b)

(c) (d)

(e) (f)

(g) (h)

Figure 3. Specimen heat treated at 1000 °C/5 min (c,d), specimen heat treated at 1050 °C/5 min (e,f), and specimen heat treated at 1000 °C/60 min (g,h). EBSD inverse pole figures (a,c,e,g) and phase maps (b,d,f,h) of the as-built specimen with 66 ° scanning rotation (a,b) [5].

Suvi Papula *et al*. discussed the austenite volume fractions for heat-treated specimens. The content of austenite for the annealing temperature ranging from 950°C to 1150°C is over 40 percent. For a longer annealing time of 60 minutes, the austenite content rises by up to 46.4 percent. In the temperature range of 1000°C to 1050°C, Suvi Papula *et al.* concluded that the maximum austenite content was observed [5].

Suvi Papula *et al*., in their publication, concluded that due to high dislocation density and nitride precipitates formation, the as-built specimen shows high yield and tensile strength but less ductility [5]. The tensile and yield strength values are considerably higher for heat-treated DSS specimens because of the microstructure's small phase size.

For the SLM processed as-built material, the pitting breakdown potential (Epit) observed is 0.4 V_{SCE} for the potential range between 300 Mv below OCP up to 1.0 V_{SCE}. When the polarization direction was reversed, the marked hysteresis was observed, and the return polarization curve followed an active path. Due to the material porosity, the re-passivation potential reduced in as-built SLM processed material (Figure 4). The pitting corrosion resistance of SLM samples significantly increased due to consecutive heat treatment. The as-built DSS specimen was almost 99 percent ferritic, and on successive heat treatment, the austenite content increased up to 46 percent. DSS's corrosion resistance is greater than the single-phase ferritic and austenitic steels in chloride-rich surroundings.

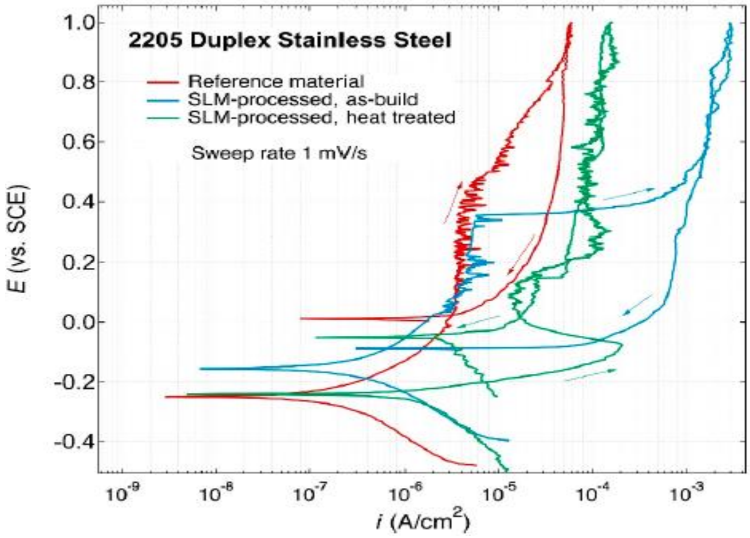


Figure 4. Cyclic potentiodynamic polarization curves for as received 2205 DSS, SLM processed as-built 2205 DSS, and SLM processed heat treated 2205 DSS [5].

Bajaj *et al.* reported the mechanical properties of various chrome steel grades [6]. They concluded that the range of ultimate enduringness varies with variation within the elongation for conventionally processed duplex stainless steels. Except for the AM processed duplex chrome steel, the range of ultimate enduringness is sort of constant with variation within the elongation.

4. Challenges of Additive Manufacturing

4.1. Void formation.

This issue emerges as a result of decreased holding between progressive surfaces and prompts substandard mechanical execution. The measure of porosity incited additionally relies on the development of voids during the AM cycle.

4.2. Stair stepping.

Step Stepping is identified with the layering defects in the created parts. This kind of blunder is deficient for inside manufactured layers and causes an extraordinary effect on item quality [7].

4.3. Anisotropic mechanical properties and microstructure.

A large portion of the AM advances parts are delivered layer by layer and this will bring about the development of warm angle [7]. AM handled parts have various properties and microstructure along the build direction and other directions.

4.4. *Small build volume.*

Additive manufacturing technologies are possibly implied for building more modest volumes, and if we need to assemble an immense segment, we need to downsize the segment or cut into subparts. But in most cases scaling down the model is not feasible and effective.

5. Mechanical Alloying approach to prepare metal powders

Ball milling is a high-energy technique that falls under the mechanical alloying group [8]. The milling balls' effect deforms the powder particles and then plastically deforms the powder particles, forming new surfaces and allowing the particles to weld together.

Stainless steels are divided into four main families based on their microstructure: ferritic, austenitic, martensitic, and duplex stainless steel. Duplex stainless steels have a balanced proportion of ferrite and austenite phases [9]. They have strong corrosion resistance and are resistant to pitting corrosion and stress corrosion cracking in several environments [9].

As materials are reduced to the nanoscale, their properties improve dramatically, according to Shashanka *et al.* [10]. As a result, they used a high-energy planetary milling method to prepare and synthesize DSS powders. According to Shashanka *et al.*, planetary milling [10,13,14] is one of the most basic and commonly used plastic deformation methods for achieving extreme refinement in material structure. After 10 hours of subsequent milling in a Dual Drive Planetary Mill, Shashanka *et al.* developed nanostructured DSS powders (DDPM) [15-22].

According to the authors, the importance of nano Y_2O_3 additions to DSS powders was stated by Shashanka *et al*. The addition of Y_2O_3 increases the density and hardness significantly, according to the authors [11]. The experiment also demonstrates that yttria's addition increases phase change from $\alpha - Fe$ to $\gamma - Fe$. The dry and wet ball milling results were also examined by Shashanka *et al.* They concluded that dry milling produces spherical stainless-steel powders, while wet milling produces irregularly formed particles. When stainless-steel samples are milled in an argon atmosphere, they have smaller particles, smaller crystallites, and higher lattice strain than when milled in a toluene atmosphere [12]. The authors concluded that the milling atmosphere is critical in grinding powder size, morphology, and phase change.

6. Conclusions

Additive manufacturing techniques allow for high levels of personalization and customization while reducing manufacturing complexity and expense. Selective laser melting (SLM) can be used for applications that require high-level component power. A wide variety of metals, metallic alloys, ceramics, and polymers can be used to produce a wide range of biocompatible materials. The arrangement of austenite-ferrite for the SLM processed DSS is balanced upon subsequent heat-treatment. With excellent mechanical properties, the porosity of the SLM processed SAF 2205 DSS was 0.03 percent. SAF 2205 DSS pitting corrosion resistance was increased following successive thermal treatment. In chloride-rich conditions, the SAF 2205 DSS grade has greater corrosion resistance. Stainless steel produced by additive manufacturing has superior corrosion properties to stainless steel produced traditionally. The hardness and tensile strength of steel produced by AM equal to or exceeds that of steel produced conventionally. Design versatility, product customization, and the ability to create complex structures are only a few of AM technology's advantages. Some drawbacks require improvement and careful examination, such as small part size, anisotropic mechanical properties, high costs, gaps in the top layers, and over-extrusion.

Table 5. Studies related to various AM Processes.

Author	Year	Objective	Method	Work Material
Karl Davidson *et al.* [23]	2015	To prepare fully dense solid parts without significant losses in mechanical properties	Selective Laser Melting	SAF 2507
Karl Davidson *et al.* [24]	2016	To achieve strong, soft magnetic characteristics	Selective Laser Melting	SAF 2507
K Saeidi *et al.* [25]	2016	To obtain superior mechanical properties	Selective Laser Melting	SAF 2507
Wu, Wenjin *et al.* [26]	2016	To achieve better mechanical and corrosion properties	Selective Laser Melting	SS316L, SS304L, SS-420 and SAF 2507
Karl Davidson *et al.* [27]	2017	To obtain strong columnar microstructure and fine cellular internal grain structure	Selective Laser Melting	SAF 2507
Gerhard Posch *et al.* [28]	2017	To achieve better surface roughness and enhancement in strength and toughness	Wire Arc Additive Manufacturing	G 2293 N L
Cem Ornek [29]	2018	To obtain controlled microstructure to get reproducible properties	Selective Laser Melting	SAF 2507
Adebola Adeyemi *et al.* [30]	2018	To enhance wear resistance, strength property and improvements in product performance	Selective Laser Melting and Selective Laser Sintering	SS316L
Magnus Eriksson *et al.* [31]	2018	To decrease weld defects and to enhance mechanical properties	Wire Arc Additive Manufacturing	SAF 2507
Vahid A *Hosseini et al.* [32]	2019	To develop the continuous running system to minimize the production time and to achieve the highest deposition rate	Wire Arc Additive Manufacturing	2209 DSS
Majid Laleh *et al.* [33]	2019	To enhance hardness and pitting corrosion resistance	Selective Laser Melting	SS316L
Fen Shang *et al.* [34]	2019	To enhance compressive mechanical properties and pitting resistance	Selective Laser Melting	UNS S32707 HDSS
Greg N. Nigon *et al.* [35]	2020	To obtain finer grain orientation	Selective Laser Melting	2205 DSS
Majid Laleh *et al.* [36]	2020	To obtain higher pitting corrosion resistance and unique microstructural features	Selective Laser Melting	SS316L, 2205 DSS
R Keshavamurthy *et al.* [37]	2020	To enhance the friction and wear properties of ABS	Fused Deposition Modelling	Acrylonitrile Butadiene Styrene(ABS) +2.5 wt% Cu, ABS+5wt% Cu
Wanwan Jin *et al.* [38]	2020	To reduce residual stress and distortion	Wire Arc Additive Manufacturing	SS316L, 2209DSS
Malin Lervag *et al.* [39]	2020	To reduce weld defects and the formation of intermetallic phases	Wire Arc Additive Manufacturing	2507 DSS

Author	Year	Objective	Method	Work Material
Pratik Murkute *et al.* [40]	2020	To produce corrosion-resistant SDSS clads with higher pitting and stress corrosion cracking resistance	Laser Powder Bed Fusion	SAF 2507
Jia-Hao Wen *et al.* [41]	2020	To increase microhardness and tensile strength of Intensive Dual-phase steel alloy (IDP) powders	Laser Additive Manufacturing	SAF 2205

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Acknowledgments

The authors declare no acknowledgments.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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