

Investigation of Corrosion in WAAM Manufactured Materials

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ABSTRACT

To develop the commercial applicability of Wire-Arc Additive Manufacturing (WAAM), there is a crucial need to understand the corrosion behaviour of the fabricated materials for industry acceptance. It is well-known that WAAM process has a complex thermal process, resulting in unique microstructures and material surfaces. The current studies on corrosion resistance in the WAAM process are focused on Stainless Steels, Steels and Nickel-based alloys due to the potential industrial applications. Hence, a comprehensive review of the resulting microstructural evolution and corrosion resistance of the WAAM manufactured Stainless Steels, Steels and Nickel-based alloys has been presented.

It was found that the understanding of the corrosion resistance and corrosion testing needs further development for the mechanisms that the alloys are susceptible to. Development of various standardized corrosion testing for the metal alloys is necessary to optimize WAAM applications based on industrial requirements.

Key words: Wire-Arc Additive Manufacturing, Corrosion Mechanisms, Metals, Material Performance

INTRODUCTION

Among the many additive manufacturing processes, Wire Arc Additive Manufacturing (WAAM) has recently been drawing interest due to its great and attractive prospect for fabrication of large parts, the possibility to process a vast range of materials in form of welding wires, and the addition of further details to semi-finished components [1]. However, most of the research have currently focused on optimization of the WAAM process parameters and analysis of the resulting thermal and residual stresses [2]. Unlike conventional manufacturing processes, WAAM process and post-processing treatments result in unique microstructures and material surfaces that alter the corrosion performance of the materials but are not fully studied or understood yet.

For instance, additively manufactured steels are subjected to very different time-temperature profiles and process parameters [3], consequently leading to strong differences in the microstructures. Overview of the microstructure of steels after conventional and additive manufacturing is depicted in Figure 1. Subsequently, the resulting microstructure also leads to variation in the corrosion resistance in the alloys.

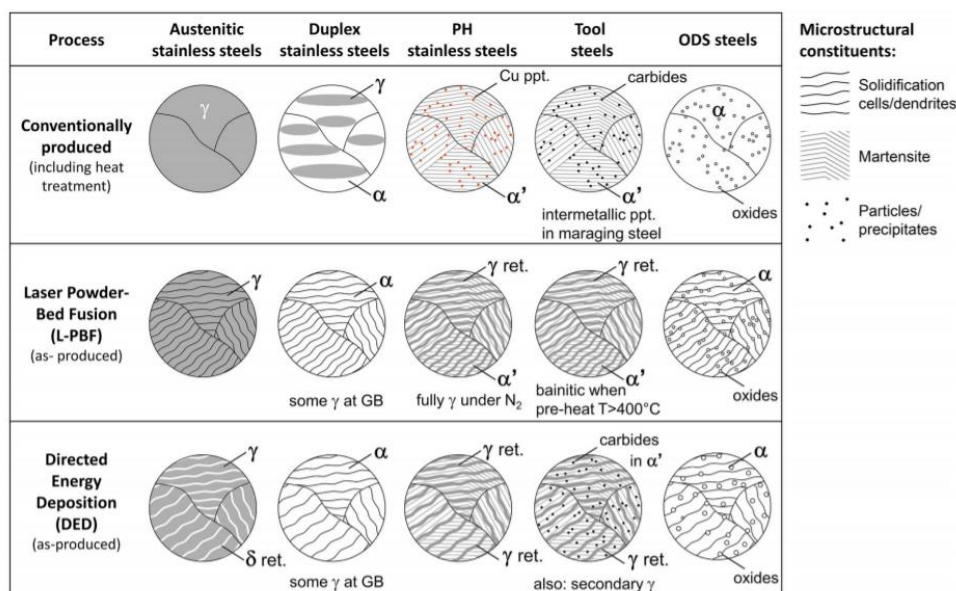


Figure 1: Overview of typical microstructures of conventionally produced and additively manufactured steels [4]

In order to mature the WAAM process for mass production in the industry, it is necessary to understand the microstructure and the resulting corrosion behaviour. Corrosion resistance is one of the most crucial criteria in industrial applications and there is a pressing need to address the concerns regarding the corrosion susceptibility of commonly used materials, for industrial acceptance and adoption. There has been an increase in papers related to corrosion in WAAM recently (Figure 2) but they usually focus on specific materials or corrosion issues.

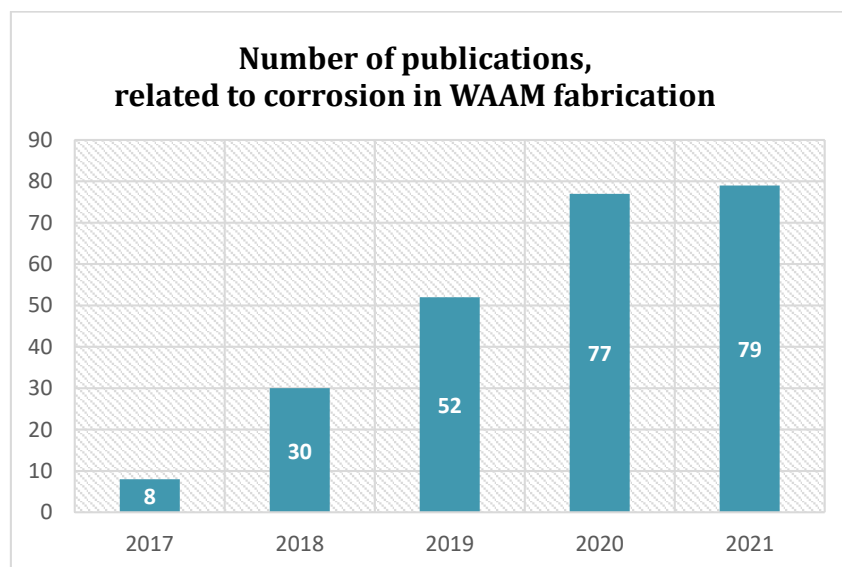


**Figure 2: Number of research publications concerning WAAM and corrosion
(Data taken from Sciencedirect as of March 2021 [5])**

In order to have effective corrosion control, there is a need to have a thorough knowledge of the various forms of corrosion in industrial applications. It is apparent that industry professionals will be wary about pitting corrosion, intergranular corrosion, and particularly stress corrosion cracking as they are critical and common in weldments. Due to the similarities in the technologies of welding and WAAM, it would be beneficial to draw experience from corrosion in weldments and be cautious of the same predominant corrosion mechanisms in WAAM as well as the corrosion mechanisms that the materials are usually susceptible to. Hence this review analyses the recent academic advancements in corrosion behaviour of commonly manufactured WAAM stainless steels, steels and nickel based alloys, in comparison to their conventionally manufactured counterparts, with a special focus on microstructure.

Stainless Steels

Ron et al evaluated the stress corrosion behaviour of WAAM austenitic stainless steel 316L alloy with its counterpart wrought AISI 316L [7]. Unlike the AISI 316L with a single austenitic phase, the WAAM-316L alloy's microstructure consisted of an austenitic matrix and a secondary ferritic phase at the grain boundaries. However, despite the differences in mechanical properties and microstructure, both the alloys' stress corrosion susceptibility and electrochemical performance did not differ drastically in 3.5 % NaCl solution, with the corrosion rate of the WAAM alloy being 0.005 mmpy in comparison to the value of 0.001 mmpy of the counterpart alloy [7].

In the Potentiodynamic Polarization (PDP) analysis, the polarization curve of the WAAM alloy reflected lower corrosion resistance but an improved passivation process was reflected by its considerably higher break potential than the AISI 316L [7].

However, despite the display of localised corrosion attack in both alloys, the corrosion mechanisms differed in both alloys. In the WAAM alloy, the localized corrosion attack (Figure 3 a,b) was mainly attributed to the micro-galvanic corrosion at the boundaries as a result of the lower corrosion resistance of the secondary ferritic phases in contrast to the austenitic phase [7]. In the counterpart AISI 316L, the localised corrosion attack mainly presented in the form of typical pitting morphology [7, 8].

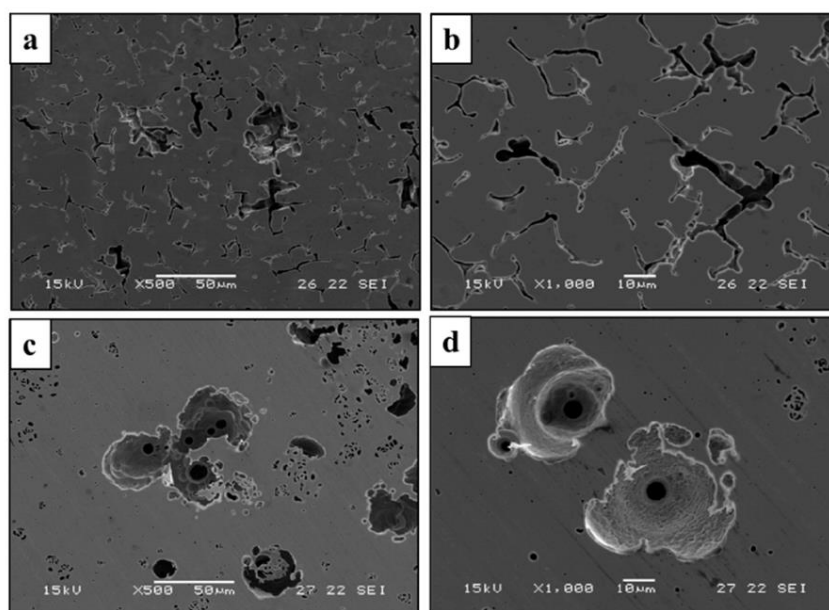


Figure 3: SEM image of the surface of (a,b) WAAM SS 316L alloy (c,d) counterpart AISI 316L alloy [7]

The similarity in the resistance of the two alloys to stress corrosion was demonstrated by nearly equal time to failure at a slow strain rate of $2.5 \times 10^{-7} \text{ s}^{-1}$, where the environmental effect was most dominant [7]. As expected in 316L stainless steel alloy [9], this similarity was also demonstrated by the characteristics of ductile failure in the post-SSRT fractography analysis (Figure 4) [7].

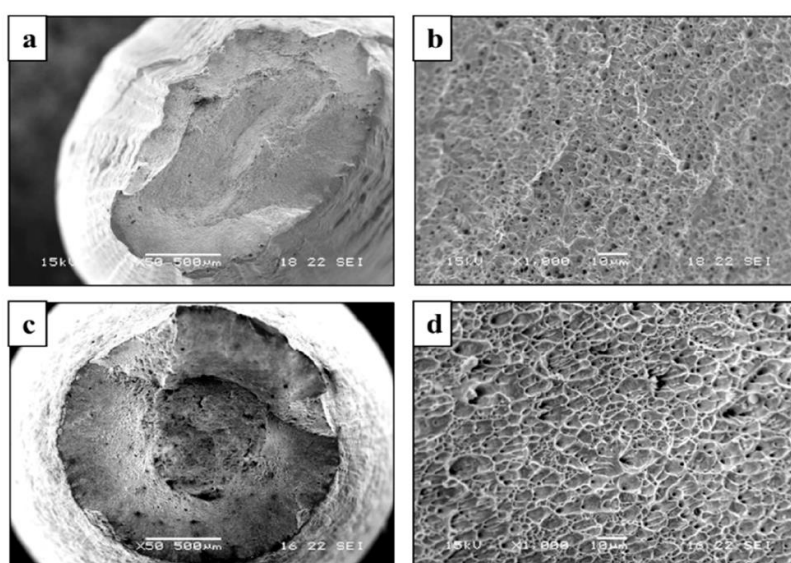


Figure 4: Fracture surface of (a,b) WAAM SS316L alloy, (c,d) counterpart wrought AISI 316L after SSRT at a strain rate of $2.5 \times 10^{-7} (1/S)$ in 3.5% NaCl solution [7]

In a different approach, Chakkravarthy and Jerome defined the influence of torch angle on texture, orientation and topology [10] by fabricating multiwalled stainless steel 316L samples with cold metal transfer. The study revealed that heat input increased considerably when the torch inclination angle was increased from 5° to 15° , giving rise to slow cooling rates that favoured the austenite growth towards $\langle 111 \rangle$ direction. Since surface energy has a great influence on the corrosion resistance and $(1\ 1\ 1)$ plane has the least surface energy in the face centered cubic stainless steel 316L, the directional austenite growth consequently led to improved corrosion resistance [10].

Wen et al studied the dependence of the microstructure and corrosion resistance of WAAM austenitic stainless steel (similar composition to stainless steel 316LN) on the linear heat input (LHI) [11]. In the study, it was apparent that pitting corrosion resistance was poor in the WAAM steel, subjected to high LHI. Figure 5 presents the morphology of the pitting corrosion and the corresponding polarization results. With the increase in LHI, the number and depth of etch pits significantly increased while the coalesce of etch pits formed several corrosion cracks. This was further supported by the polarization study, which showed an increase in corrosion current density and decrease in the passivation voltage range with the increase of LHI [11].

During the WAAM manufacturing process, the large molten pool is sustained by the energy from the high LHI. The fine temperature gradient and low cooling rate thus offers a long diffusion period for Cr, Mo and Ni atoms. With the increase of LHI, the content of Ni decreases while the contents of Cr and Mo increases in the residual δ -ferrite [11], leading to poor corrosion resistance in the WAAM fabricated steel [11].

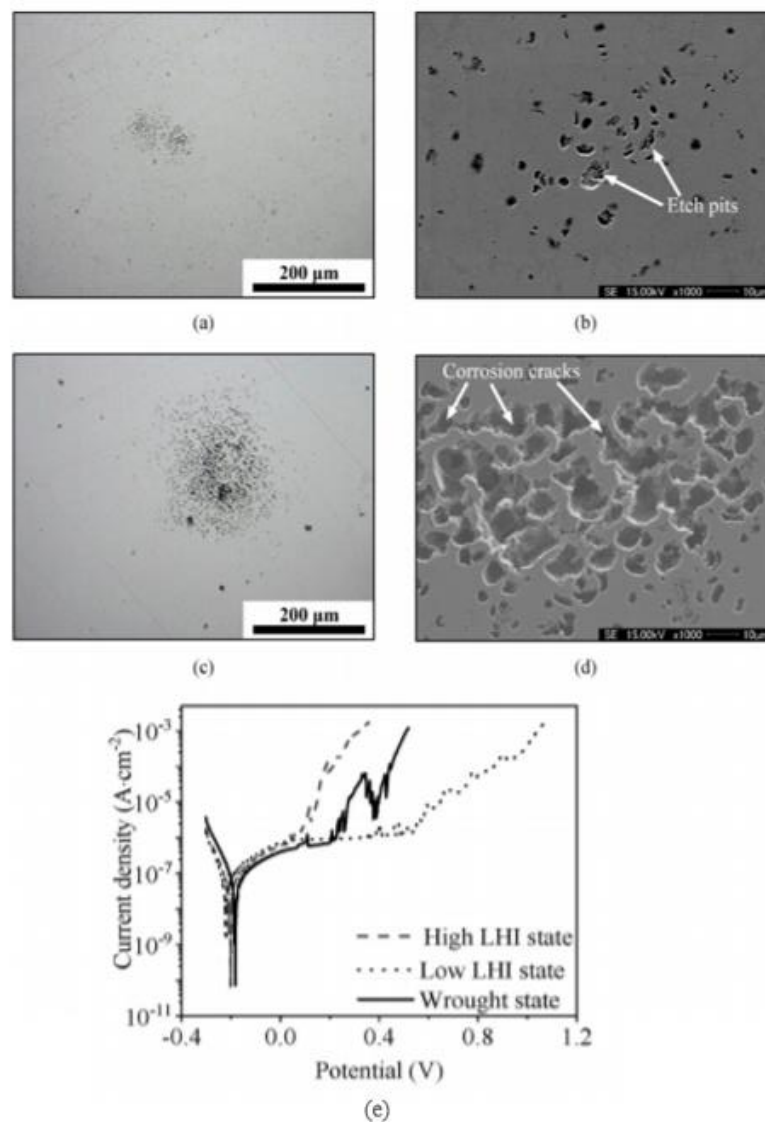


Figure 5: Pitting Morphology of WAAM austenitic stainless steel under (a–b) low LHI; (c–d) high LHI; and (e) the corresponding polarization curve [11]