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Corrosion, Heat Treatment, and Microstructural Studies of GTA Welded 316 Austenitic Stainless-Steel Joint

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Abstract:
The formation of a protective chromium carbide passive film makes austenitic stainless steel (ASS) alloys suitable for corrosive and high-temperature environments. This paper examined the transformation of the microstructure, corrosion, and mechanical properties of gas tungsten arc welded 316 austenitic stainless steel. The scientific principles governing metallurgical transformation and corrosion dynamics were discussed. The review shows that passive film on 316L ASS gradually erodes as the concentration of chloride ion rises. Metallurgical properties of FZ are completely changed, and solid-state transformation occurs at HAZ during the GTA welding process. These transformations affect the microstructure, corrosion, and mechanical properties of GTA welded ASS alloys.

Keywords: *Austenitic stainless steel, gas tungsten arch welding, corrosion, heat treatment*

1. Introduction

Austenitic stainless steels, ASS, are iron-chromium (Fe-Cr) alloys with a face-centered cubic structure containing chromium content between 16 and 25 wt. % (ASM International, 2008). These alloys are widely utilized in several engineering applications, particularly in the pressure vessels, chemical, food, transportation, and medical industries, due to a combination of corrosion resistance, minimal maintenance, low cost, and excellent mechanical properties (Prasad et al., 2014; Warikh Abd Rashid et al., 2012).

A major limitation to the reliability of this grade of stainless steel, especially in the food processing and petrochemical industries, is its susceptibility to stress-corrosion cracking and intergranular corrosion in service conditions (Samantaray et al., 2012; Warikh Abd Rashid et al., 2012). This is often the case when stainless steel alloys are exposed during fabrication to temperatures within a critical range of 500 - 800°C. The degradation in service of the alloy has been attributed to sensitization that occurs during the fabrication of the stainless-steel material, which is due to the precipitation of chromium-rich carbide. This makes the materials susceptible to sensitization and induces stress corrosion cracking in the components (Warikh Abd Rashid et al., 2012).

Fusion welding is the conventional approach commonly used in joining metallic alloys during fabrication in most engineering industries (Deyev & Deyev, 2005; Vasilev et al., 2021). However, due to the heat input during welding, base metal metallurgical characteristics are often transformed into the fusion zone, FZ, or the heat-affected zone, HAZ. These metallurgical changes may be attributed to the causes of failure of the components of ASS during service or/and testing (Dadfar et al., 2007; Garcia et al., 2008). Gas tungsten arc GTA is a welding process of choices for stainless steel and aluminum alloys due to moderate heat input and low damage on the based materials (Jayakrishnan & Chakravarthy, 2017; Radmehr et al., 2021). An inert gas, typically argon or helium, shields the tungsten electrode and the molten metal. Unlike gas metal arc welding (GMAW), the GTAW process generates an arc on the base metal using a non-consumable tungsten electrode (Moslemi et al., 2015).

2. The Corrosion of 316 ASS in Acidic Solutions

For aggressively corrosive conditions, such as those found in the pharma, petrochemical, and nearshore oil drilling industries, 300 family ASS alloys are suitable alloys (Warikh Abd Rashid et al., 2012). Their high chromium content, which facilitates the creation of passive protective layers on their surface, is what gives them their high corrosion resistance. Therefore, the underlying film made of chromium oxide and the passive film generated at the metal/solution interface resulted in a region that prevents further deterioration of the alloy (Pardo et al., 2008). Under some circumstances, notably those involving chloride ions, these protective passive film layers could frequently degrade, leading to the rapid deterioration of stainless steel machinery, which is frequently brought on by pitting corrosion (Kelly, 2003; Refaey et al., 2006).

Examining the electrochemical behavior of AISI 316 ASS in acidic solutions has been attempted numerous times. Warikh Abd Rashid et al., (2012) used the open-circuit potential, cyclic voltammetric, and chronoamperometric techniques to study the corrosion dynamics of AISI 316 ASS in deaerated HCl and sulphuric solutions. They concluded that:

- Samples with increased HCl concentrations showed enhanced corrosion of stainless-steel samples and that HCl depletes the passive film more dramatically than sulphuric acid, and
- Environmental acidity and chloride ion concentration have a significant impact on the electrochemical behavior of 316 ASS.

Chloride ions increase metal corrosion through the passive layer and lower the passivity breakdown potential when they are present. Likewise, the electrochemical corrosion behaviour of 316 ASS in fluoride ion containing dilute HCl acid and acetic acid solutions that were aerated with oxygen was also examined by Li and his colleagues (Li et al., 2001). They discovered that 316 ASS might passivate in weak acidic solutions under room-temperature conditions, as seen by the polarization curves and electrochemical impedance spectroscopy spectra. Furthermore, as the concentration of fluoride ions rises, the passive impedance marginally declines. Results from both investigations unambiguously show that 316 ASS will lose passive film when exposed to an acidic solution with a high chloride ion concentration.

3. Fusion Welding of Austenitic Stainless Steel

'Stainless steel' refers to steels that contain at least 12% chromium. When exposed to the atmosphere, the chromium content is responsible for their corrosion resistance by forming tenacious surface films (ASM International, 2008). Therefore, when joining metallic alloys subjected to harsh environments, it is critical to ensure that the joint meet up with the desirable properties to perform successfully in service. This is especially true for highly alloyed stainless steels, where the entire material design has been formulated to provide optimal properties. When a fusion welding process is used, the original microstructure of the fused is transformed, and a new structure is formed, much like a casting. The resulting room temperature is determined by the phases formed during solidification and the extent of solid-state transformation (Ferro &Nilsson, 2021; Molak et al., 2009).

The alloy content and the thermal cycle determine the degree to which solid-state transformations occur in the heat-affected zone (HAZ) adjacent to the fusion zone (FZ). Depending on the location of the FZ boundary, various thermal cycles are experienced in the HAZ. For example, in multiphase welds, some materials are subjected to several cycles with varying peak temperatures. Likewise, a range of thermal cycles is experienced in the HAZ, depending on the distance from the fusion boundary. In multipass welds, some material is subjected to several cycles with varying peak temperatures.

In the manufacturing industries, GTA welding is the primary method for joining thin stainless-steel parts. For non-ferrous metals like aluminum and stainless steel, this welding technique produces welds of excellent quality (Moslemi et al., 2015). Numerous studies have been conducted to study how the welding parameters affect base metals' metallurgical and mechanical properties since the development of GTA welding. The effect of hydrogen in argon (Durgutlu, 2004), welding current (Moslemi et al., 2015), oxide fluxes (Tseng, 2013; Tseng & Hsu, 2011), single-pass and multi-pass (Sakthivel et al., 2011) and other factors have all been extensively examined with regard to the metallurgical and mechanical properties of 316 ASS.

Moslemi's research team investigated how welding current affected the microstructure and mechanical properties of 316 ASS welded joints. Their findings show that increasing the welding current causes a large amount of thermal energy input in the welding pool, an increase in the width and depth of the welding pool, a cumulative sigma phase in the matrix, and a decrease in the chromium carbide percentage in 316 ASS (Moslemi et al., 2015). Therefore, they recommended an arc welding current of 100A because it produces the fewest defects and has the highest strength and hardness value for 316 ASS alloy.

4. The Corrosion of GTA Weld 316 ASS in Acidic Solutions

It is anticipated that stainless steel will be fused together to manufacture reliable and long-lasting industrial products (Dadfar et al., 2007; Reclaru et al., 2001). ASS's weld zones are highly vulnerable to corrosion and residual stress. The primary cause of their degeneration is the formation of detrimental phases such as second-phase particles because of the high temperature and prolonged heat input (Reclaru et al., 2001).

The need to fabricate GTA ASS for critical industrial applications has resulted in extensive research into the roles of GTA ASS corrosion during testing and service. Dadfar's research team investigated the effects of GTA welding without filler on the corrosion dynamics of 316L ASS by measuring the corrosion rate in FZ and HAZ in a physiological solution. Their findings show that the HAZ is more susceptible to corrosion than the FZ. They claimed that the increased corrosion degradation in HAZ was caused by the formation of secondary phases, which resulted in the dissolution of essential alloying elements (Dadfar et al., 2007). Through synchrotron X-ray radiography studies, numerous pit propagation characteristics, including pit depth, pit width, and pit stability, were identified for the analyses of pitting corrosion of 304 L and 316 l ASS in chloride media by Ghahari and others. Their findings indicate that dissolution kinetics inside the pit caused the pit's depth to rise over time.

In contrast, solution conductivity and the perforated metal covers on the pit had an impact on lateral pit growth and stability (Ghahari et al., 2015). Dikshant and Shani conducted a comparative study on 316 ASS weld joints made with AISI 316 L and Nb-based stabilised AISI 347 steel filler. These fillers' effects on the metallurgical, fatigue, and pitting corrosion of weld joints were investigated. They concluded that a higher oxygen, chromium, and nickel concentration in the AISI 314 weld's passive film was responsible for its improved pitting corrosion resistance (Malhotra & Shahi, 2020).

5. Microstructural Changes and Heat Treatment in GTA Weld Stainless Steel

The high percentage of Cr and Ni in Type 316L austenitic stainless steel distinguishes it from other steels. The Ni content helps to stabilise the austenite phase at low temperatures and increases corrosion resistance (Mokhtari et al., 2021). Despite their excellent resistance to general corrosion, ASSs are susceptible to stress corrosion cracking (SCC). However, welding, which is distinguished by rapid heating and cooling, exacerbates SCC in ASS due to microstructural evolution and metallurgical changes (Prasad et al., 2014).

Weldments have distinct microstructural characteristics that must be studied to predict the corrosion characteristics of welded structures. The FZ, the unmixed region, the partially melted region, the HAZ, and the unaffected base metal are the five distinct regions that are normally identified micro-structurally. Figure 1 depicts this microstructural transition. The unmixed region belongs to the FZ, while the partially melted region belongs to the HAZ. All five zones, however, may not be present in any given weldment. The HAZ is the area of the weld joint that has been exposed to temperatures high enough to cause solid-state microstructural changes. During welding, each position in the HAZ relative to the fusion line experiences a distinct thermal cycle in terms of maximum temperature and cooling rate. As a result, each position has its own distinct microstructural characteristics and corrosion susceptibility. Microstructural gradients are commonly observed within the HAZ because of the different time-temperature cycles experienced by each material element. Gradients on a similar scale exist within solidified multi-pass weld metal due to bead-to-bead thermal experience variations (Wahid et al., 1993).

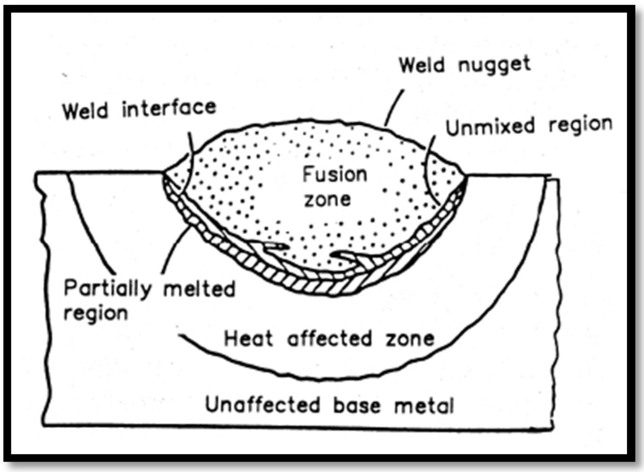

Figure 1: Different Zones of a Heterogeneous Weld (ASM International, 2008)

Welded microstructures are composed of an FZ with a dendritic structure. The ferritic-austenite solidification mode is responsible for the lack of cracks in this region (El-Batahgy, 1997). Significant grain growth in the HAZ and coarse cast structure in the weld zone are two significant phenomena that can jeopardise the mechanical properties of the welded material relative to the base material in the case of fusion welding of steels (Weng, 2009). The cast structure of austenitic stainless steel welded metal contains 2-10% -ferrite in the austenite matrix. A small amount of -ferrite is required to avoid hot cracking during weld solidification (Patchett & Bringas, 2003). Some studies (Fang et al., 1994; Prasad et al., 2014; Shaikh et al., 1993) confirmed the occurrence of selective dissolution in δ-ferrite, which resulted in corrosion-related failure of welded austenitic stainless steels. The HAZ is attacked by microstructural changes caused by heating and cooling cycles. However, sensitization caused by chromium carbide precipitation in the HAZ is a significant challenge in corrosion engineering (Khatak et al., 2018). Zhu et al. (2017) investigated the microstructure and corrosion characteristics of the 316L austenitic stainless steel weld joint's base metal (BM), heat-affected zone (HAZ), and weld zone (WZ). WZ, including ferrite and austenite phases, was primarily composed of columnar dendrites, whereas BM and HAZ exhibited a full-austenite structure with low coincidence site lattice boundaries, particularly twin boundaries (Zhu et al., 2017).

After establishing that detrimental transformation, particularly at the HAZ and occasionally in the FZ, it is believed that post-heat treatment techniques could be used to help alleviate the depleted alloying chromium and nickel in ASS. Heat treatment techniques such as solution annealing, dimensional stabilisation, and stress relief transformed delta ferrite in weld metal (WM) to secondary phases such as M23C6 carbide, chi (χ), and sigma (σ). WM was solidified either in the primary ferritic solidification mode or in the primary austenitic solidification mode with a duplex structure. It was previously assumed to have stress corrosion cracking (SCC) resistance comparable to the base metal (Baeslack et al., 1979). It has been established that the welding process introduces features such as slag and other inclusions, dendritic microstructure, residual stresses, secondary phases, defects, phase transformations, etc., which typically reduce the corrosion resistance of the WM in comparison to the parent metal (Toppo et al., 2018).

Stress corrosion cracking in Austenitic stainless steel is caused by a combination of:

- Corrosive media,
- Tensile stress (applied or residual), and
- A vulnerable microstructure

Welding typically introduces heterogeneous microstructural features into austenitic stainless steel, making it an excellent candidate for stress corrosion cracking (Wahid et al., 1993). The mechanical properties of the welded structure are thus a function of this microstructural evolution. Therefore, characterization is required to comprehend these constitutive behaviours.

6. Conclusions

The following conclusions are deducted from this study are:

- Due to the formation of a protective chromium carbide passive film, ASS alloys are suitable for corrosive and high-temperature environments.
- The passive film on 316L ASS gradually erodes as the chloride ion concentration rises.
- During the GTA welding process, the metallurgical properties of FZ are completely altered, and solid-state transformation occurs at HAZ.
- These transformations affect the microstructure, corrosion, and mechanical properties of GTA welded ASS alloys.

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9. Conflict of Interest

The authors declare that there is no conflict of interest.

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