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Microstructure evolution and mechanical properties of briefly heat-treated SAF 2507 super duplex stainless steel welds

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HIGHLIGHTS

- Brief PWHT on SAF 2507 SDSS welds was executed.
- The microstructure of the weld zones deviated far from the equilibrium state.
- The as-welded HAZ was high in hardness and low in toughness.
- The evolution of mechanical properties versus temperature was discussed.
- The optimum brief PWHT temperature was determined.

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ABSTRACT

The effects of brief post-weld heat treatment at different temperatures on the microstructure evolution and mechanical properties of SAF 2507 super duplex stainless steel welds were investigated. The results showed that the weld zones were high in hardness and low in toughness due to their far deviation from the equilibrium state. After brief post-weld heat treatment, the austenite volume fraction in the weld zones was elevated significantly. The highest impact toughness of SAF 2507 super duplex stainless steel welds was achieved when the specimens were briefly heat-treated at 1080 °C.

1. Introduction

Duplex stainless steels (DSS), as a kind of structural materials, are widely used in chemical, petrochemical, marine, nuclear and paper industries due to their excellent combination of mechanical properties and corrosion resistance in various types of environments [1–6]. To ensure a good corrosion resistance and high strength, it is essential for these alloys to maintain a roughly equal amount of ferrite and austenite phases, as well as no secondary phases [7–9]. However, this phase balance is disturbed during welding [10,11].

It is well-known that welding is an inevitable fabrication process in large industrial applications. The rapid heating and cooling cycles cause the heat affected zone (HAZ) and weld metal (WM) of DSS welds an excessive ferritization [12,13]. Furthermore, some unwanted phases such as carbide, sigma phase, chi phase and chromium nitride are prone to form during welding [14,15]. The undesirable excessive ferritization and the unwanted precipitations will worsen the mechanical properties of DSS welds [15,16]. In order to improve the mechanical properties of DSS components, the effects of metallurgical factors, welding parameters and welding processes on the microstructure evolution of DSS welds have been broadly investigated [17–21]. Ramkumar [17] investigated the effect of filler metals on the weldability of super duplex stainless steel (SDDS) plates and found that the tensile and impact strength are improved by using appropriate filler wire contained a higher content of the austenite stabilizers. Hosseini et al. [18] found that a nitrogen loss during welding causes the DDS welds a more excessive ferritization as well as the larger grain size. After investigating the effect of the different welding processes on microstructure, impact toughness, and pitting corrosion resistance of DSS welding

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joints, Zhang et al. [19] reported that the excessive ferritization in the HAZ and WM was alleviated by using the N_2-supplemented shielding gas, which significantly improved the impact toughness and the pitting resistance of the GTAW DSS welding joints. Furthermore, the ferrite/austenite ratio also depends on the energy input in welding [20,21]. For DSSs, although an approximate phase balance in the WM may be obtained by adjusting heat input between 0.3 and 1.5 kJ/mm [22], the austenite phase of the HAZ is stile overwhelmed by the ferrite phase [23]. In order to get an optimal phase balance, several studies have focused on post-weld heat treatment (PWHT) on DSS weld joints [24,25]. Although this process was an effective operation in eliminating the excessive ferritization for DSS welds, it is unpractical to perform PWHT for the large weldments, especially for the pipe joints. Therefore, a special solution treatment technique called on-line solution treatment was recommended in workshop to meet the practical application. With specified temperature and quench conditions, this kind of solution treatment technique calls for the heat treatment time as short as possible.

Recently, SDSSs were wildly used in heat exchangers, pressure vessels and boilers, fire-fighting systems, desalination plants, high pressure RO-plant and power industry systems given its improved tensile and fatigue strength, good toughness, adequate formability and weldability, excellent pitting corrosion resistance, high resistance to stress corrosion cracking (SCC) in chloride and sulfide environments [26,27]. The pitting resistance equivalent (PRE) numbers of these alloys were greater than 40% [28]. However, the excessive ferritization in SDSS welds is heavier due to their alloying with higher levels of chromium and molybdenum. Furthermore, tungsten inert gas (TIG) welding is prevalent in industry due to its comparatively easier applicability and better economy. Therefore, investigating the effect of brief PWHT on the microstructure evolution and mechanical properties of SAF 2507 SDSS welds will provide guidance on reducing security risks of SAF 2507 SDSS components, as well as on designing a new alloy with excellent weldability. However, no reports shed light on this issue to date.

Here, the effect of brief PWHT on the microstructure evolution and mechanical properties of SAF 2507 SDSS welds was investigated. TIG welding process was carried out with appropriate welding parameters to which a less excessive ferritization and no secondary phases in the welds were expected to be obtained. The relationships among the microstructure evolution, heat treatment temperature and mechanical properties of SAF 2507 welds were discussed in detail. An optimum brief heat treatment temperature was determined.

2. Experimental

2.1. Materials and heat treatment

The investigated material in this work is a commercial SAF 2507 SDSS produced by Outokumpu Stainless. The alloy was cold rolled into sheets 5 mm in thickness and annealed at 1100 °C for 30 min in argon flow. The nominal composition of this alloy is shown in Table 1. The base metal plates were polished with 400 grit silicon carbide paper to remove surface contamination, and then cleaned with acetone. Single TIG welding procedure was applied to fabricate the joints without filler metal by using a subsection welding method. A non-consumable tungsten electrode, shielded by inert gas, was used to strike an electric arc with the base metal. A thermal-arc AC welding machine (HeroTIG 250P) was used to help the electric arc trigger heat to melt and joint the base metal. The traveling speed of the electrode was controlled by a servo mechanism. The welding parameters are listed in Table 2. The heat treatment was carried out at 1020, 1050, 1080 and 1100 °C, respectively, in a tube furnace in argon flow. In order to simulate the on-line solution treatment conditions, the muffle furnace was heated to the setting temperature, and then the weld joints were put into it and held for 3 min at the setting temperature. After that, the joints were taken out and quenched in water to avoid the formation of the secondary phases. These heat treatments were performed in the "precipitation-free" temperature range. In order to have the WM, HAZ and base metal (BM) included in the coupons, the specimens were cut into plates with a dimension of $5 \times 10 \times 55$ mm^3 for microscopy and mechanical properties tests.

2.2. Microstructure characterization

To observe the optical microstructures of the BM, HAZ, and WM in the welded alloy, the specimens were ground successively to 2000 grit, and then polished with diamond paste to 0.25 μm. After that, the polished specimens were electrochemically etched in a 30 wt% KOH electrolyte, which made the austenite phase light and the ferrite phase dark. The volume fractions of the ferrite and austenite phases were evaluated carefully using a CARL ZEISS optical microscope equipped with a KS400 quantitative metallographic analysis system. The final value was the average of at least 12 measurements. Electrolytic etching was also done at 2.5 V for 10 s in a 10% oxalic acid solution before metallographic investigations for further identification of nitrides. Nitrides are visible as mottled dark areas after this etching process [29,31]. The chemical compositions of the austenite and ferrite phases, and the fractographs were measured using energy dispersive X-ray spectroscopy (EDS) linked to a scanning electron microscopy (SEM, FEI Quarter 400) with a Robinson backscattered electron detector. To reduce the effect of concentration fluctuations, more than 10 measurements were carried out for a single sample and the average value of the element distribution was adopted.

2.3. Mechanical measurements

Charpy V-notch impact studies were carried out on the coupons fabricated as per ASTM E23-02a standards [32]. Notches were made such that fracture occurred only within the weld zone (Fig. 1) and the test was performed at the ambient temperature on sub-sized samples. The hardness tests were performed using a Vickers hardness tester HV-50Z under a test load of 5 kg and a dwell time of 10 s in accordance with the ASTM standard E3 84-99. All the data obtained were an average of at least five determinations.

3. Results and discussion

3.1. Microstructure of as-welded metal

Fig. 2 shows the microstructure of different zones of the as-welded metal. The optical microstructure of the base metal

Table 1
Chemical composition of SAF 2507 super duplex stainless steel.

Element	C	Si	Mn	P	S	Cr	Ni	Mo	N	Fe
Wt%	0.016	0.40	0.75	0.021	0.001	24.88	6.88	3.79	0.269	Bal