Surface & Coatings Technology 244 (2014) 45–51

Contents lists available at ScienceDirect

Surface & Coatings Technology

journal homepage: www.elsevier.com/locate/surfcoat

Effect of current type on microstructure and corrosion resistance of super duplex stainless steel claddings produced by the gas tungsten arc welding process

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ARTICLE INFO

Article history:
Received 11 September 2013
Accepted in revised form 24 January 2014
Available online 2 February 2014

Keywords:
Super duplex stainless steel
Cladding
Pitting corrosion
Electrochemical impedance spectroscopy
Reformed austenite
Thermally activated secondary austenite

ABSTRACT

In this research, super duplex stainless steel filler metals were clad on high strength low alloy steel substrates by the tungsten arc welding process using pulsed and constant currents. To characterize the pulsed current effect, the phase composition and microstructure of the claddings were compared, and the corrosion behavior of the claddings was evaluated using cyclic polarization, electrochemical impedance spectroscopy and critical pitting temperature measurements. The results showed that the slower cooling rate of the constant current cladding led to a higher total reformed austenite content and better corrosion resistance. It was also found that the formation of thermally-activated secondary austenite did not influence the corrosion behavior significantly. The electrochemical impedance spectroscopy indicated that the passive film formed on the pulsed current cladding was more defective. The constant current cladding also showed ten degree higher critical pitting temperature than the one which was produced by pulsed current.

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1. Introduction

Although super duplex stainless steels (SDSSs) were first developed in 1930s for use in pulp and paper industries, soon they found many applications particularly where high performance and good corrosion resistance at low temperatures, especially in the presence of chloride ions, were required [1,2]. The properties of these steels are strictly related to the chemical composition and microstructural balance, i.e. ferrite/austenite fraction ratio. It has been also demonstrated that the formation of secondary phases such as chromium nitride (Cr_2N) [3], secondary austenite (γ_2) [2,4] and intermetallic phases such as sigma (σ) [5] and chi (χ) [6] has a great influence on the properties and performance of these steels. It is well known that the chemical composition and heating cycles are the dominant factors which affect the precipitation of these detrimental phases in SDSSs [2]. However, if they are produced properly and employed in the correct temperature range, SDSSs exhibit an excellent mixture of toughness and workability of austenitic stainless steel grades with higher strength and higher stress corrosion resistance of ferritic stainless steel grades with additional excellences over them: they exhibit excellent pitting and stress corrosion cracking resistance at much lower nickel content than (super) austenitic stainless steels, and thus, have lower price; also they show better weldability than ferritic stainless steel grades. Hence, due to their excellent performance, SDSSs are reasonable choices to being used as clad on plain carbon steels for application in the intermediate temperatures. Generally, the quality and properties of such claddings depend upon the chemical composition of selected cladding alloy and deposition process. Although the desirable characteristics of such claddings are their reasonable corrosion/wear resistance and higher strength, achievement of sufficient metallurgical bond between the clad and substrate is required and shall be acquired [7]. Generally, such corrosion resistant alloy claddings may be applied by any conventional arc welding processes such as flux-cored arc welding (FCAW), gas-tungsten arc welding (GTAW), submerged arc welding (SAW), etc. The main differences between these processes are welding efficiency, dilution [8], and deposition rate. Although the GTAW process permits a low deposition rate, it offers a great control over dilution and heat input which are necessary in welding of SDSSs; it also offers a great portability which is required in field operations and repair welding. GTAW, like almost any other arc welding processes, can be performed by applying pulsed currents. As mentioned in [9], the pulsed current welding technique may show several advantages, including refined grain size [7], reduced residual stress, lower thermal distortion [10], and more stable arc [11]. In this technique, the welding current is alternated between the background current (which is not enough to melt the base metal, but is sufficient to maintain a stable arc) and the peak current (which can melt a small region of the base metal). The self-quenching process induced by surrounding the narrow melted region with solidified metal, causes a more rapid cooling rate in this process [7], which may be considered advantageous in many applications [12,13]. However, the main advantage of pulsed current welding is the retardation of dendrites' growth which produces favorable nucleation sites and leads to a finer grain structure [7]. But there's a dispute about propriety of pulsed current in welding of SDSSs; because although

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http://dx.doi.org/10.1016/j.surfcoat.2014.01.047

the refined structure can improve the mechanical properties of SDSS claddings, according to some authors [14,15] it may increase ferrite/austenite grain boundaries and promote the precipitation of deleterious phases in claddings.

In recent years, many authors [16–19] have investigated optimization of pulsed current parameters in SDSS claddings. However, these works mainly deal with the numerical modeling, and thus, deep examination of microstructure and/or corrosion behavior of claddings has not been provided. On the other hand, few published researches on the effect of pulsed current in welding of SDSSs [20,21] do not provide enough detail about the microstructure and/or corrosion resistance differences between pulsed and constant currents. Thus, the aim of this paper is to evaluate the effect of pulsed current on microstructure and the subsequent corrosion behavior of SDSS cladding on a high strength low alloy (HSLA) steel substrate.

2. Experimental procedure

2.1. Materials

In this study, two successive layers of ER2594N SDSS were clad on HSLA steel substrates with dimensions of 6 × 4.5 × 1.4 cm. The filler metal used has been widely utilized in fusion welding of SDSSs. The chemical composition of this filler metal is equivalent to balk UNS S32750 with additional nickel content for enhancing austenite formation from solid δ-ferrite. The chemical compositions of the filler metal and substrate can be reviewed in Table 1.

2.2. Welding process

Before the cladding process, the substrate surfaces were ground and then washed with acetone to remove any oxide scales and contaminants, respectively. The direction of cladding was chosen parallel to the substrate rolling direction. The cladding process was carried out in the flat position with two different currents at the fixed theoretical heat input of 0.94 $kJ \cdot mm^{-1}$. The first cladding was performed at the constant current of 110 A and the second at the average pulsed current of 110 A (pulsed current: 150 A, base current: 70 A, duty cycle: 50%, and frequency: 5 Hz). These parameters were selected based on a previous work [16]. Other parameters were kept constant for both cladding processes (see Table 2). According to the literature [22,23], the cooling rate in the temperature range of 1200 to 800 °C ($\Delta T_{12/8}$) plays the main role in austenite formation in SDSSs; thus, to determine the cooling rate and its effect on the claddings, the temperatures between 800 and 500 °C ($\Delta T_{8/5}$) were measured. $\Delta T_{8/5}$ was used because it is relatively easier to be measured accurately than $\Delta T_{12/8}$ [22]. The temperature versus time was logged using K-type thermocouples embedded in 3 mm away from the fusion line in half depth of the substrate plate.

2.3. Examination of microstructures

After the cladding process and proper post cleaning of the surface, the ferrite content of the claddings was measured using a FMP30 Ferrite-scope® calibrated with the secondary standards in accordance with the procedures specified in AWS A4.2 [24]. Ferrite number (FN) measurement was repeated ten times on the top surface of the weld beads. Volume percent of the ferrite phase was also obtained for 20 images using the point counting method in accordance with ASTM E562 [25] at 200× magnification. The average grain size was also measured on the top surface of claddings in accordance with ASTM E112 [26] at 100× magnification.

Generally, the preparation of dissimilar metal welding samples for microstructural observations is very difficult, because different etchants and/or etching methods should be applied in sequence to etch different regions without affecting each other. Therefore, a special procedure is required for preparation and etching of metallographic samples. In this study, the top surface and cross-section metallographic specimens were ground, polished using 0.3 μm alumina powders, and then electro-polished in a solution consisted of 25 g CrO_3, 133 mL acetic acid, and 7 mL distilled water. Then, the samples were etched using two different techniques: (1) electro-etching in 40% NaOH at 3-5 V DC to create a contrast between the primary phases (ferrite and austenite) and also to detect the presence of secondary phase precipitates [27], and (2) etching with Beraha's reagent (80 mL H_2O, 20 mL HCl and 0.8 g $K_2S_2O_5$) to create a higher contrast between the ferrite and austenite. Austenite Stainless steel (304L) was used as cathode in both electro-polishing and electro-etching. The microstructures were observed using an optical microscope and Philips XL 30 scanning electron microscope (SEM). Philips X'pert X-ray diffractometer was used for phase detection and analysis on the top side of the claddings. A step size of 0.05° was used to scan 2θ from 40 to 100° using Cu kα radiation.

2.4. Cyclic polarization readings

All corrosion samples were prepared in accordance with ASTM G1 standard [28]. Accordingly, small rectangular samples were cut from the original SDSS claddings, ground mechanically up to 1200 grit with SiC emery paper, rinsed with distilled water, and then dried quickly in hot air for use in the corrosion evaluations. The corrosion resistance of the samples was evaluated using electrochemical techniques in 1 M NaCl solution under a natural aerated condition. For this purpose, a cylindrical cell was constructed on the surface of the mentioned specimens to expose 1 cm^2 of their surface to aggressive solution. A silver/silver chloride electrode (SSE) and a platinum electrode were used as the reference and auxiliary electrodes, respectively. After one hour immersion at open circuit potential (OCP), cyclic polarization tests were run according to ASTM G61 standard [29], using AMETEK potentiostat/galvanostat (PARSTAT 2273) at a scan rate of 1 $mV \cdot s^{-1}$commencing at −250 mV below OCP toward the anodic direction. The scanning direction was then reversed when the current density reached 5 $mA \cdot cm^{-2}$. In each case, the readings were repeated three times to ensure repeatability of the results.

Table 2
Constant parameters of cladding process.

Parameter	Value
Shielding gas	Pure (99.99%) argon
Shielding gas flow rate	10 $L \cdot min^{-1}$
Filler rod diameter	2.4 mm
Welding electrode	AWS EWTH-2 (98% W + 2% Th)
Electrode diameter	2.4 mm
Polarity	Electrode negative (EN)
Arc voltage (V)	15 V
Welding speed (S)	105 $mm \cdot min^{-1}$
Maximum inter-pass temperature	150 °C
Heat input	0.94 $kJ \cdot mm^{-1}$

Table 1
The chemical compositions of substrate and clad metal (wt.%).

Material	C	Cr	Ni	Mo	N	Mn	Si	Cu	Al	Ti	V	Nb	B	Cr_{eq}	Ni_{eq}
Substrate	0.26	0.02	–	0.05	–	1.36	0.41	0.05	0.107	0.02	0.01	0.01	0.003	0.08	9.11
Clad metal	0.03	25.9	9.2	4.2	0.22	0.75	0.94	0.54	–	–	–	–	–	30.1	14.64

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