Corrosion Science 70 (2013) 170–179

Contents lists available at SciVerse ScienceDirect

Corrosion Science

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

The influence of microstructure on the protective properties of the corrosion product layer generated on the welded API X70 steel in chloride solution

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ARTICLE INFO

Article history:
Received 30 September 2012
Accepted 20 January 2013
Available online 30 January 2013

Keywords:
A. Low alloy steel
B. EIS
B. SEM
C. Alkaline corrosion
C. Passive films

ABSTRACT

In the present work, a novel heat treatment process was used to investigate the influence of microstructure alteration on the corrosion behavior of base metal (BM), heat affected zone (HAZ) and weld metal (WM) in welded pipe steel of grade API X70. The electrochemical impedance spectroscopy (EIS) measurements were carried out to study the protective properties of the corrosion product layer after 90 days immersion in a high-pH solution. The EIS results showed that, the corrosion resistance of HAZ and WM increased after heat treatment due to formation of fine and compact corrosion product layer with fewer defects.

1. Introduction

High-strength low-alloy (HSLA) pipeline steels have been used more and more widely all over the world due to their favorable properties. Coincided with the development of the HSLA steels applications, the various aspects of these steels corrosion have been investigated. To date, several studies were conducted to investigate corrosion of pipeline steel in various media such as acidic soil environments [1–3] and carbonate/bicarbonate solution [4–9]. Among the various aspects of corrosion, stress corrosion cracking (SCC) has been much interest of researchers. In this relation, there are several studies on the SCC of API X65 [6,10,11] and API X70 [1–3,12–14] steels in near-neutral pH and/or high pH environments. Some investigators have focused their studies on corrosion of pipeline steels under disbanded coating [7,10,11,15–17]. Moreover, hydrogen damage of API X70 [18–21] and corrosion of API X100 [8,9,22] have been considered. Although there are a lot of investigates on the corrosion of HSLA pipeline steels, but there are few studies in the case of welded or heat treated steels [23–25].

API X70 steel pipes are considerable candidate due to good combination of strength and toughness, good weldability, low crack sensitivity coefficient and low ductile to brittle transition temperature [26,27]. These advantages are enhanced due to controlled rolling and controlled cooling techniques used in original coil manufacturing [28,29].

Welding is the most commonly method which is used for pipes connections. Due to welding process, the microstructure and the mechanical properties of welded zone differs significantly with other zones. In general, the welded joints reveal three distinguishable zones of base metal (BM), unchanged part of the welded joint, heat affected zone (HAZ), the area of the base metal which its microstructure and properties have altered due to heat generating by welding process and subsequent re-cooling, and weld metal (WM), the area with a close chemical composition to the base metal which has experienced melting and resolidification during welding thermal cycle. As a result of welding, the protective properties of generated corrosion product layer on the various welded joint sub-zones changes due to different microstructures [30]. It has been reported that, the corrosion product layer can protect the steel surface from corrosive species through a physical blocking effect [30]. In this relation, the structure of the corrosion product layer plays an essential role on the corrosion resistance of steel in the corrosive media such as chloride containing carbonate/bicarbonate solution. Chloride ions have a significant effect on the corrosion behavior of many metals and alloys over a wide range of pH. In the presence of chloride ions, the protective film generated on the metal surface breaks down frequently [31]. Progressive local breakdown of the permanent corrosion product layer makes a good opportunity to rapid active dissolution of the substrate metal [32]. It has been demonstrated that the chloride ions are more and more adsorbed to the surface [33–35] and then penetrate through the corrosion product layer especially at its point defects and flaws and reach the base metal surface [32]. Consequently, some soluble metal–chloride complexes would be form due to penetration of chloride ions through the layer and reacting with metal cations

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0010-938X/$ - see front matter
http://dx.doi.org/10.1016/j.corsci.2013.01.026

in the metal/layer interface [36]. Replacement of the soluble metal–chloride complexes with the stable oxides within the corrosion product layer creates appropriate sites for localized corrosion ultimately.

The main goal of the present study is to improve the corrosion behavior of heat affected zone and weld metal in the chloride-containing carbonate/bicarbonate solution by restricting access of chloride ions to the metal surface. In fact, the objective of this work is modification of physical protective properties of the HAZ and the WM corrosion product layer using an appropriate heat treatment cycle to get a suitable microstructure. To do this, the protective properties of the corrosion product layer generated on the sub-zones of welded API X70 steel before and after heat treatment are investigate separately.

2. Experimental procedure

2.1. Test material

The material under investigation was an API grade X70 gas pipeline with 1422 mm outside diameter and 19.8 mm wall thickness welded with double V-shape of the weld pool by submerged arc-welding technique. The original steel used for pipe manufacture, produced by thermo-mechanical control-rolled process (TMCR). The measured chemical composition of the BM, WM and the welding wire (EA2 standard wire) are given in Table 1.

Microstructural observations were carried out using the high-resolution scanning electron microscope (SEM) MIRA//TESCAN (mixed SE/BSE mode) after etching the samples in 2% Nital (2 mL nitric acid (HNO_3), 98 mL ethanol) and 4% Picral (4 g picric acid ($(NO_2)_3C_6H_2OH$), 100 mL ethanol) solutions as suggested by ASM Metals Handbook [37].

2.2. Heat treatment procedure

A 100 × 20 × 19.8 mm specimen was obtained from the welded pipe so that the weld metal was placed in the middle of the specimen. Before heat treatment, this sample is called as-received welded joint and after heat treatment this sample is called heat treated welded joint. A one-step austenitizing with two-step quenching and tempering treatment was performed on the as-received specimen as shown schematically in Fig. 1.

2.3. Mechanical properties

The Vickers hardness test and standard tensile experiments were performed on test material to measure its mechanical properties for both as-received and heat treated weld joints. Every hardness data was an average of three measurements with 100 N indentation load (HV10) in the mid-thickness of the both as-received and heat treated welded joint. The tensile samples (with 50 mm gauge length and 10 mm gauge diameter) were machined in the loop direction before and after heat treatment from the original pipe as suggested by API 5L standard [38]. To conduct the tensile experiments, an INSTRON 5586 testing machine under low displacement rate of 0.05 mm/s at room temperature was used.

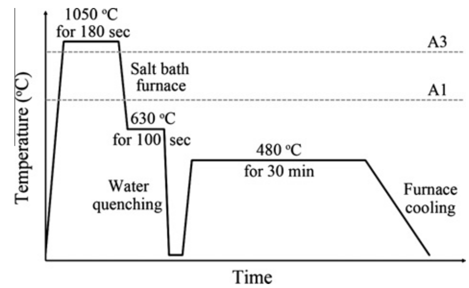

Fig. 1. The schematic illustration of the heat treatment cycle designed for API X70 welded joint.

2.4. EIS measurements of corrosion product

The test samples (of 7 × 7 × 3 mm dimensions) were cut from BM, HAZ and WM of both as-received and heat treated welded joints. The samples were soldered to copper wires and then mounted in cold-cured epoxy resins. They were sequentially wet-grounded with 120, 320, 500 and 1000 grit silicon carbide emery papers and then degreased ultrasonically with ethyl alcohol for 10 min. Afterwards, they were rinsed with distilled water and finally dried with cool air. The behavior of corrosion product layer formation was studied in a mixture of naturally aerated 0.5 M sodium carbonate (Na_2CO_3), 1 M sodium bicarbonate ($NaHCO_3$) and 0.1 M sodium chloride (NaCl) solution with pH of 9.7 after 90 days immersion. The carbonate/bicarbonate solution used in this study was simulated the collected electrolyte at the interface of buried pipeline and disbanded coating in alkaline environment which have been reported in several studies [7,15,23]. Before starting the test, the samples were removed from the container and were immersed in fresh solution. All of the tests were performed after 30 min to ensure that a steady state was reached. Electrochemical impedance spectroscopy (EIS) measurements were conducted using a typical three-electrode electrochemical cell system with the steel specimen as the working electrode, a saturated calomel electrode as the reference electrode and a coiled platinum wire as the counter electrode. EIS measurement frequency was selected to be in the range of 100 kHz to 10 MHz with an applied AC perturbation of 10 mV (RMS). The ZSimpWin V3.21 impedance analysis software was used to fit the achieved data.

3. Results and discussion

3.1. Microstructural observation

Fig. 2a reveals three main distinguishable sub-zones of the API X70 welded joint (BM, HAZ and WM) and Fig. 2b specifies the metallographic cut direction (cross-cut) of the under investigation samples. Figs. 3 and 4 show the SEM images of as-received BM and HAZ at two magnifications respectively. As it can be seen form Fig. 3, the as-received BM exhibits a microstructure including very fine grains of bainite (B) and acicular ferrite (AF). The fine microstructure of the as-received BM is caused by TMCR process. The HAZ microstructure contained a mixture of acicular ferrite and bainitic ferrite (BF) as shown in Fig. 4. Fig. 5a and b represent the

Table 1
The measured chemical composition of the BM, WM and welding wire of the API X70 welded joint.

Element (wt%)	Cu	V	Cr	Ni	Ti	Mo	Nb	Al	S	P	Si	Mn	C	Fe
Base metal	0.010	0.04	0.010	0.187	0.018	0.24	0.05	0.03	0.015	0.008	0.20	1.50	0.05	Balance
Weld metal	0.036	0.03	0.015	0.130	0.009	0.31	0.03	0.02	0.003	0.008	0.25	1.40	0.06	Balance
EA2 standard wire	0.350	–	–	–	–	0.45–0.65	–	–	0.025	0.025	0.20	0.95–1.35	0.05–0.17	Balance