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Comparative study of the SCC behavior of E690 steel and simulated HAZ microstructures in a SO_2-polluted marine atmosphere

Hongchi Ma [a], Zhiyong Liu [a], Cuiwei Du [a,*], Xiaogang Li [a,b], Zhongyu Cui [a,c]

[a] Corrosion and Protection Center, University of Science and Technology Beijing, Beijing 100083, China
[b] Ningbo Institute of Material Technology & Engineering, Chinese Academy of Sciences, Ningbo 315201, Zhejiang, China
[c] Ocean University of China, Qingdao 266100, China

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ABSTRACT

Simulated microstructures of the typical CGHAZ, FGHAZ, and ICHAZ of an E690 welded joint were prepared with heat treatment at peak temperatures of 1300, 850, and 750 °C, respectively. Slow strain rate tensile (SSRT) tests were implemented to investigate the stress corrosion cracking (SCC) behavior of E690 steel and the simulated HAZ microstructures in a SO_2-polluted marine atmosphere. Results revealed that E690 steel and its simulated HAZ microstructures all had a high SCC susceptibility in the simulated SO_2-polluted marine atmosphere with a combined mechanism of AD and HE. The SCC susceptibility gradually increased in the following order: BM, CGHAZ, FGHAZ, and ICHAZ. The cracking mode of BM and CGHAZ was transgranular, whereas that of FGHAZ and ICHAZ was intergranular. The lower SCC susceptibility of BM and CGHAZ was probably due to the impeding effect of lath bainitic grain boundaries on SCC propagation, whereas the higher SCC susceptibility of FGHAZ and ICHAZ was attributed to the facilitating effect of M-A islands on crack initiation and propagation.

1. Introduction

With the extensive exploitation of ocean resources, the steel used in ocean platforms has been developed towards the direction of high strength–toughness and thick plates, which consequently causes welding problem and high risk of stress corrosion cracking (SCC) [1].

The heat-affected zone (HAZ) undergoes phase transformation; its mechanical properties deteriorate because of the welding thermal cycle. The HAZ with different distances from the fusion line would be transformed into various microstructures at different peak temperatures (PT) and cooling rates [2,3]. The HAZ of high-strength low-alloy (HSLA) steel is generally categorized into four distinct regions according to different PT: (1) the subcritical HAZ (SCHAZ), where no detectable transformation to austenite occurs because the PT is below the start temperature of austenitization (Ac1), (2) the intercritical HAZ (ICHAZ), where partial transformation to austenite occurs because PT is between Ac1 and the temperature of complete austenitization (Ac3), (3) the fine-grained HAZ (FGHAZ), where transformation to austenite occurs completely at a PT slightly above the Ac3, and (4) the coarse-grained HAZ (CGHAZ), where austenite grains become significantly coarse at a PT much higher than the Ac3. The toughness of CGHAZ is usually much lower than that of the parent metal because of grain coarsening and high hardness, whereas the strength–toughness of ICHAZ is also deteriorated by the hard and brittle phase M-A islands [4–6]. Moreover, the variation of microstructure and the deterioration of mechanical properties in HAZ easy induce the occurrence of localized corrosion and SCC because of the micro-galvanic effect, which has been demonstrated in previous research [7–10]. Therefore, the mechanical properties and SCC resistance of HAZ are crucial factors that affect the service safety of the whole platform.

The HAZ is a narrow zone that includes various microstructures; thus, the individual performance of these microstructures is inconvenient to study. To date, the application of thermo-mechanical simulators in welding thermal cycle simulation can obtain a uniform microstructure that is similar to real HAZ; the microstructure and mechanical properties of these simulated materials can be subsequently characterized [11–13]. However, the “amplification” of the uniform microstructure is merely by several millimeters; the investigation of SCC behavior of specific microstructures is impractical. To overcome this obstacle, some researchers have prepared uniform microstructures of larger sizes that are similar to HAZ; the corrosion behaviors of various uniform microstructures have also been studied [14,15].

In this work, various microstructures in HAZ, including CGHAZ, FGHAZ, and ICHAZ, were simulated by heat treatment according to

* Corresponding author. Fax: +86 10 62334005.
E-mail address: dcw@ustb.edu.cn (C. Du).

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real HAZ microstructures of the HSLA steel, E690. The SSRT method was subsequently used to investigate the SCC behavior and mechanism of various microstructures, which can give essential insight into the effects of microstructure on SCC behavior and provide references for the optimization of welding procedures.

2. Experimental

2.1. Material

The material used in this study is HSLA E690 steel, with the following chemical composition (wt%): 0.15% C, 0.20% Si, 1.00% Mn, 0.0058% P, 0.0014% S, 0.99% Cr, 1.45% Ni, 0.0091% Cu, 0.37% Mo, 0.030% V, 0.036% Al, and Fe balance. The microstructure of the steel is mainly fine-grained lath bainite (Fig. 1), with yield strength of approximately 690 MPa.

2.2. Preparation of simulated HAZ microstructures

Simulated HAZ microstructures were prepared by theoretical calculation and repeated attempts according to the real HAZ microstructures and the thermal cycle process they underwent. According to the following empirical equation proposed by Andrews [16], the austenite formation temperatures AC1 and AC3 of E690 steel can be predicted:

$$\begin{aligned} Ac1\ (^{\circ}C) &= 723 - 10.7\omega\ (Mn) - 3.9\omega\ (Ni) + 29\omega\ (Si) + 16.7\omega\ (Cr) + 290\omega\ (As) + 6.38\omega\ (W) \\ &= 723 - 10.7 \times 1.00\% - 3.9 \times 1.45\% = 740\ ^{\circ}C \end{aligned}$$

$$\begin{aligned} Ac3\ (^{\circ}C) &= 910 - 230\omega\ (C)^{0.5} - 15.2\omega\ (Ni) + 44.7\omega\ (Si) + 104\omega\ (V) + 31.5\omega\ (Mo) + 13.1\omega\ (W) \\ &= 911\ ^{\circ}C \end{aligned}$$

where ω is the mass fraction of each element.

After repeated attempts based on the predicted temperature, the heat treatment process of simulating HAZ microstructures was determined. Rectangular samples of 145 mm × 20 mm × 12 mm were maintained in a furnace at 1300 °C, 850 °C, and 750 °C for 10 min and then cooled in air to obtain the simulated microstructures of CGHAZ, FGHAZ, and ICHAZ, respectively.

2.3. Slow strain rate tensile (SSRT) test

To investigate the SCC behavior and mechanism of the E690 base metal and the simulated HAZ microstructures in a SO_2-polluted marine atmosphere, the SSRT method was conducted in a self-designed device that simulated this environment (Fig. 3). Rectangular samples of 145 mm × 20 mm × 12 mm were used to produce simulated HAZ microstructures according to Section 2.2, which were machined into smooth tensile specimens as shown in Fig. 2. The tests were conducted according to ASTM G129. Prior to each SCC test, the specimens were sequentially ground with 1500# grit emery paper in a grinding direction parallel to the loading direction. The specimens were rinsed with deionized water, degreased in dehydrated ethanol and acetone by ultrasonic sound, and sealed with silicone rubber, thereby retaining a working section of approximately 30 mm.

SSRT tests were performed on the WDML-30 KN Materials Test System with a strain rate of $0.5 \times 10^{-6}\ s^{-1}$. The schematic diagram of the experimental device is shown in Fig. 3. An atomizer was used to generate moisture to form a thin electrolyte film on the specimen surface to simulate a marine atmosphere that contains SO_2. The solution in the atomizer was 3.5% NaCl+0.01 mol/L $NaHSO_3$, with a pH of approximately 3.8. Tests were conducted at the ambient temperature (approximately 25 °C). Prior to each test, the specimen was maintained in an atmosphere with 100% RH for 24 h to ensure electrolyte film formation on the surface. Moisture was continuously pumped during the whole experiment. After failure, the corrosion products were removed before the percentage of elongation and area reduction of each specimen were calculated. Each microstructure was reproduced thrice to ensure the reliability of experimental data. In addition, fracture morphologies were observed by SEM. The cross-sectional morphologies of the fracture were observed after polishing and etching to investigate the micro cracking morphology and cracking mode. To further evaluate the SCC susceptibility of various microstructures, the loss percentage of elongation (I_δ) and area reduction (I_Ψ) were calculated with the following formulas:

$$I_\delta = \left(1 - \frac{\delta_s}{\delta_0}\right) \times 100\%$$

$$I_\psi = \left(1 - \frac{\psi_s}{\psi_0}\right) \times 100\%$$

where δ_s and δ_0 are the elongation, whereas Ψ_s and Ψ_0 are the area reduction, measured in moisture and in air, respectively.

3. Results and discussion

3.1. Characterization of simulated HAZ microstructures

The SEM morphologies of simulated HAZ microstructures are shown [Fig. 4(a′)–(c′)] with the real HAZ microstructures for comparison. The real HAZ microstructures [Fig. 4(a)–(c)] originated from a real welded joint of E690 steel as shown in Fig. 5. The

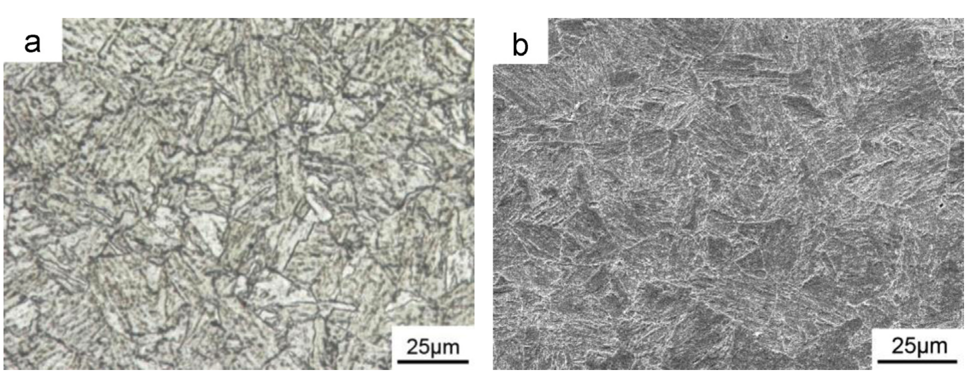

Fig. 1. Microstructure morphology of E690 steel in (a) OM, and (b) SEM.