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Effect of SO_2 content on SCC behavior of E690 high-strength steel in SO_2-polluted marine atmosphere

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ABSTRACT

Slow strain rate tensile (SSRT) test in a simulated device was employed to investigate the effect of SO_2 on stress corrosion cracking (SCC) behavior of E690 steel in SO_2-polluted marine atmosphere. Results revealed that SO_2 can greatly enhance the SCC susceptibility of E690 steel in marine atmosphere and the SCC mechanism in this environment is a combination of anodic dissolution (AD) and hydrogen embrittlement (HE). The increase of SCC susceptibility was attributed to the formation of a compact rust layer on steel surface that SCC microcracks can initiate from the bottom of cracks in the rust layer consequently. Moreover, hydrogen evolution was greatly enhanced with the increase of SO_2 content, and SCC susceptibility increased rapidly as a result.

1. Introduction

Due to its long-term service in the harsh marine environment such as seawater splashing, alternating dry/wet corrosion, polluted marine atmosphere et al. and high stress level from internal and external load, high-strength steel is vulnerable to SCC under the synergistic action of stress and corrosion (Han et al., 2014).

As for steel structures exposed in marine atmosphere, a thin electrolyte layer would be formed on the steel surface due to high humidity and temperature fluctuation. In that case, the cathodic reaction can be greatly promoted due to the easier diffusion of oxygen through the thin electrolyte layer; meanwhile, anodic dissolution and hydrolysis reaction of iron ions would be significantly enhanced leading to the acidification of electrolyte layer and crack tip (Nishikata et al., 1997; KONG et al., 2013). Besides, corrosive ions in crack tip would be concentrated with the thinning of electrolyte layer and ion migration due to occluded cell effect (Guocheng et al., 2008). Therefore, anodic dissolution and hydrogen evolution reaction of crack tip would be greatly enhanced, and the hydrogen evolved can be enriched in the high-strained region near the crack tip through stress-induced diffusion (Qiao et al., 1998; Dmytrakh et al., 2013; Adrover et al., 2003), promoting the SCC process through anodic dissolution (AD) and hydrogen embrittlement (HE) effect (Gu et al., 1999; Li and Cheng, 2007). Worse still, marine atmosphere in many cities along the coastal lines such as Qingdao in China has been polluted with SO_2 with the development of industry, and has been changed to coastal-industrial atmosphere with the co-existence of SO_2 and Cl^-. In such environment, due to acidification effect of SO_2 on thin electrolyte layer and reproduction of H^+ through $FeSO_4$ (Chen et al., 2014a, 2014b; Wang et al., 2008), the corrosion rate is greatly accelerated with a more significant hydrogen evolution, which may furtherly promote the SCC process of high-strength steel (Wang et al., 1997; Nishimura et al., 2004).

E690 steel, as a type of newly-developed high-strength bainitic steel, is very promising to be widely used in offshore platform in the near future for its excellent performance (Xiaoqiang et al., 2013). However, the resistance to corrosion and SCC of this steel in marine environment still needs to be investigated. At present, preliminary researches have been conducted on its corrosion and SCC behavior in marine environment (Zhang et al., 2012; Ma et al., 2015), but few works have investigated its SCC behavior in marine atmosphere, especially in SO_2-polluted atmosphere. Therefore, it's of great significance to investigate the SCC behavior and mechanism of E690 steel in this environment.

In this work, slow strain rate tensile (SSRT) test was employed in a self-designed simulated device to investigate the SCC behavior of E690 steel in SO_2-polluted marine atmosphere, focusing on the effect of SO_2 on its SCC behavior and susceptibility.

2. Experimental

2.1. Material

The material used in this study is high-strength steel E690 with the following chemical composition (wt%): 0.15%C, 0.20%Si, 1.00%Mn,

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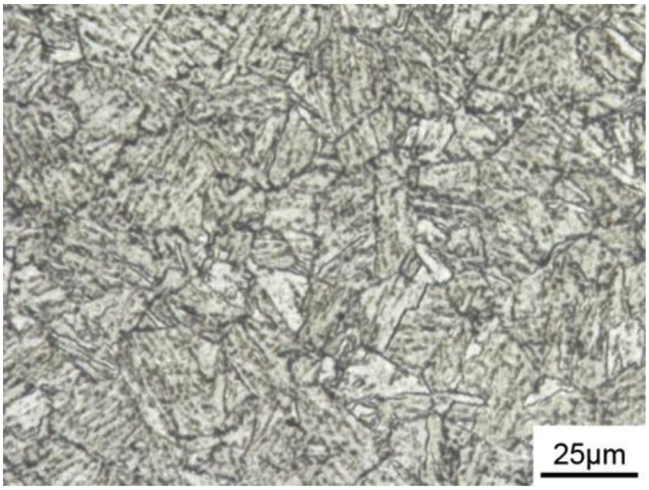

Fig. 1. Microstructure of E690 steel.

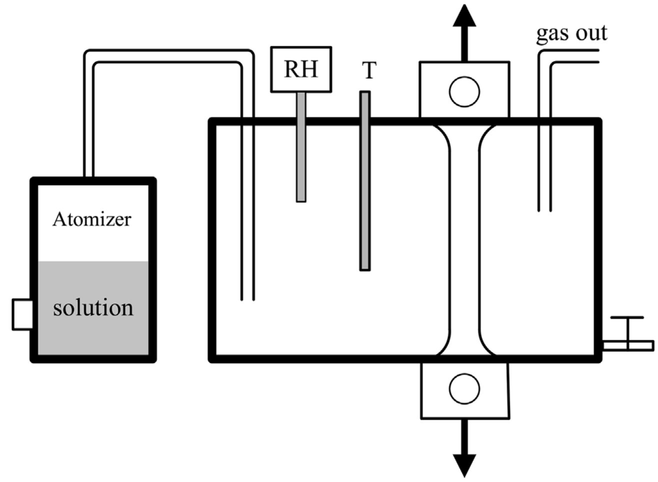

Fig. 3. Schematic diagram of experiment device for SSRT test.

0.0058%P, 0.0014%S, 0.99%Cr, 1.45%Ni, 0.0091%Cu, 0.37%Mo, 0.030%V, 0.036%Als, and Fe balance. The microstructure of the steel is mainly lath bainite (Fig. 1) with a yield strength of approximately 690 MPa.

2.2. Electrochemical measurements

Electrode used for electrochemical measurement was prepared by sealing the specimen with epoxy resin with an exposed area of 1 cm^2 and was polished by successive silicon carbide paper up to 1000 #. The working electrode was then rinsed with deionized water, degreased in acetone and dehydrated ethanol by ultrasonic sound, and dried in air. An electrochemical working station (Reference 3000, Gamry) was employed to carry out electrochemical measurements by using a traditional three-electrode cell, with the steel as a working electrode, a large area of Pt plate as a counter electrode, and KCl saturated calomel electrode (SCE) as a reference electrode. The test solution is 3.5% NaCl with 0, 0.005, 0.01, 0.03 mol/L $NaHSO_3$, respectively, and the pH values in different solutions were measured to be 8.0, 4.1, 3.8, 3.7, respectively. Potentiodynamic polarization curves were measured with potential sweep rate of 0.5 mV/s in a potential range from −1200 mV to −560 mV (vs. SCE).

2.3. Slow strain rate tensile tests

SSRT method was employed to investigate the effect of SO_2 on SCC behavior of E690 steel in simulated SO_2-polluted marine atmosphere. The tests were conducted according to ASTM G129 (ASTM G129-1995, 1995), and the tensile specimens were machined into smooth flat-plate specimens shown as Fig. 2. Prior to each SCC test, the specimens were polished in longitudinal direction by successive emery paper up to 1500#, then rinsed with deionized water, degreased in dehydrated ethanol and acetone by ultrasonic sound, dried in air, and then sealed with silicone rubber, retaining an exposed length of approximately 30 mm.

SSRT tests were performed on WDML-30KN Materials Test System with a strain rate of 0.5×10^{-6} per second. Fig. 3 shows the schematic diagram of experiment device. An atomizer was used to generate moisture to form a thin electrolyte layer on specimen surface to simulate marine atmosphere containing SO_2. The solution in the atomizer was in accordance with that used for electrochemical measurement (section 2.2). Tests were conducted at 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 layer formation on the surface. Moisture was pumped continuously during the whole experiment. After failure, the percentage of elongation and reduction in cross-sectional area of each specimen were measured after removing corrosion products, and fracture morphologies were observed using SEM. The loss percentage of elongation (I_δ) and reduction in cross-sectional area (I_Ψ) were calculated to evaluate the SCC susceptibility for each condition:

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

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

where δ_s, δ_0 and Ψ_s, Ψ_0 are elongation and area reduction measured in

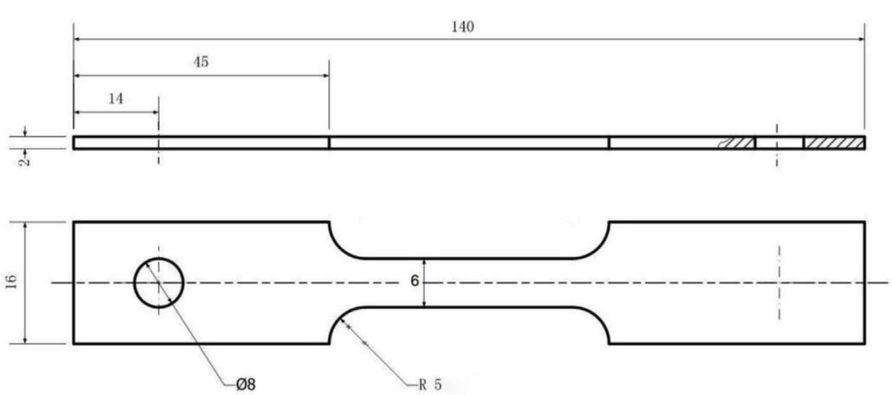

Fig. 2. Schematic diagram of the flat-plate tensile specimen used in this work.