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Role of water chemistry and microstructure in stress corrosion cracking in the fusion boundary region of an Alloy 182-A533B low alloy steel dissimilar weld joint in high temperature water

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ABSTRACT

Stress corrosion cracking (SCC) in the fusion boundary (FB) region of an Alloy 182-low alloy steel (LAS) dissimilar weld joint in 288 °C water was investigated by experiments and finite element simulation. Creviced bent beam and crack growth rate (CGR) experiments showed that, while the FB was a barrier to SCC growth, further crack growth into LAS was activated by a combined effect of sulfate and dissolved oxygen in water. Finite element simulation suggested that a positive gradient of hardness as the crack approached to the FB in dilution zone caused decreased CGR. Role of microstructure and water chemistry in SCC was discussed.

1. Introduction

Stress corrosion cracking (SCC) of Alloy 182 weld metal in high temperature water has caused concerns in recent years on the SCC behavior of the fusion boundary (FB) region of an Alloy 182-low alloy steel (LAS) dissimilar weld joint in light water reactors [1,2]. The FB region has a complex microstructure due to the jump of the composition across the FB and the heat input from the welding process, including the change in the crystallographic structure from FCC (the weld metal) to BCC (the base metal), the dilution of the weld metal, the heated affected microstructure in the base metal, and the high residual strain adjacent to the FB, etc. [3–5]. Further, Nelson et al. [6–8] found that a random-misorientation relationship existed at the FB between the base and weld metal grains in a dissimilar weld joint of 409 stainless steel-AISI 1080 alloy. They also concluded that the type-II boundary, which parallels the FB in the weld metal within 100 μm, was a potential path for cracking. A more recent work on a characterization of the microstructure of the FB region in an Alloy 182-LAS dissimilar weld joint revealed that the narrow zone between the type-II boundary and FB had the highest residual strain and hardness in the weld joint [9].

The complex microstructure of the FB region led to changes in the mechanical property and corrosion resistance [3,9–11]. Research revealed that the narrow zone adjacent to the FB in an austenitic stainless steel-LAS dissimilar weld joint had much higher susceptibility to SCC than the base and weld metals in the primary water doped by 60–150 ppb sulfate [10]. It was also concluded that a SCC propagated perpendicular to the FB in the weld metal could cease propagation after it reached the FB in an Alloy 182-A508 dissimilar weld joint in 288 °C, oxygenated water with high purity or with a sulfate concentration of 30 ppb [3,11]. In addition, the SCC growth behavior of the dilution zone (DZ) of the weld metal in 288 °C, oxygenated water was found to be similar to that of the bulk weld metal [3,11]. These investigations revealed the importance of the microstructure of the FB region and the sulfate in water in the SCC behavior of a dissimilar weld joint.

While knowledge about the microstructure and SCC behavior of the FB region has been obtained, to the authors' knowledge the effects of water chemistry and material microstructure on SCC in the FB region require further investigations. The SCC growth behavior of the FB region in high temperature oxygenated water doped with sulfate at a concentration of >30 ppb remains incompletely understood. Since the dissolved oxygen (DO) in water has a strong effect on the anion concentration at the crack tip [12,13], a combined effect of DO and sulfate on SCC growth can be expected. Further, the critical sulfate concentration in water that may cause the reactivation of SCC

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growth at the FB, and the mechanism for the cessation and reactivation of SCC growth in the FB region need to be clarified.

The objectives of this work are to investigate the combined effect of DO and sulfate in water on SCC growth in the FB region, and to develop an improved understanding of the mechanism for the cessation and reactivation of SCC growth in the FB region in sulfate doped, high temperature water. The SCC behavior was investigated by a crack growth rate (CGR) test of a contoured double cantilever beam (CDCB) specimen, and by an exposure test of creviced bent beam (CBB) specimens. Simulation of the plastic strain distribution at the tip of a crack propagating toward the FB in the DZ was conducted by finite element method (FEM) to reveal the effect of material mechanical property on the crack growth. The following sections report the results of the experimental and simulation works, and discussions on the role of microstructure and water chemistry in crack growth in the FB region from DZ of the weld metal to heat affected zone (HAZ) of the base metal across the FB.

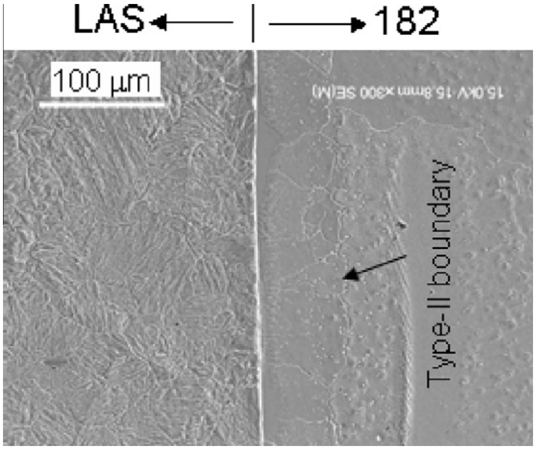

Fig. 1. SEM observation of the FB region in the Alloy 182-A533B dissimilar weld joint.

2. Experimental

2.1. Materials and specimen

The dissimilar weld joint of Alloy 182-A533B LAS was prepared by multi-pass shielded metal arc welding followed by post-welding heat treatment at 615 °C for 25 h with air cooling to relieve the residual stress. The chemical composition of the weld and base metals are listed in Table 1. The yield strengths of the base and bulk weld metals measured at 288 °C are 414 and 404 MPa, respectively [9]. Microstructure of the FB region in the dissimilar weld joint was observed by scanning electron microscopy (SEM) (Fig. 1). A type-II boundary parallels the FB within a distance of about 100 μm was observed in the DZ in Alloy 182 side. The evolution of type-II boundary was proposed to be a result of allotropic transformation in the base metal that occur on cooling and change the nature of the fusion boundary [6–8].

A 25-mm thick, CDCB specimen was used for the CGR test. Orientation, geometry, and size of the CDCB specimen are shown in Fig. 2. A constant stress intensity factor (K) can be obtained in a CDCB specimen under constant load [14,15]. The CDCB specimen was machined in an orientation so that the crack propagation from the notch tip in the DZ is vertical to the FB of the dissimilar weld joint. A precrack from the notch tip in the specimen was introduced by fatigue in air before the CGR test. Length of the precrack was controlled so that the distance from the tip of the precrack to the FB was approximately 1 mm. Following the precracking, the CDCB specimen was 5% side grooved on each side.

A total of three notched CBB specimens in which the FB plane parallels the upper and lower surfaces of the specimen were tested as well. Notches were machined in the DZ of Alloy 182 side in the specimen to allow crack initiation in the DZ and propagation toward the FB (Fig. 3).

2.2. Test in high temperature water

The CGR and CBB tests were performed in refreshed water at 288 °C in a stainless steel autoclave attached with a dynamic loop. Water purity was controlled by processing water through a water purification system to ensure ultra-high purity (~0.055 μS/cm) at inlet. DO in the inlet water was controlled by bubbling either pure nitrogen gas or a mixture of nitrogen and oxygen in the water tank until equilibration occurred. A low pressure pump drew water from the water tank to supply the high pressure pump, and recirculate excess water back into the tank for measurements of DO and conductivity of inlet water. Sulfate solution from a tank was injected to the low temperature, high pressure section of the loop by a metering pump. The concentration of the solution injected and injection rate were calculated according to the target sulfate concentration and refresh rate of water in the loop. Water exiting the autoclave was cooled down and depressurized, measured for DO and conductivity, then purified by an ion-exchanger before flowing back into the water tank. sulfate concentration in the loop was analyzed by ion-chromatography at the start of each step of the test with sulfate doping and occasionally during the test to verify the target sulfate concentration.

The CDCB specimen was loaded by clevis pins and electrically isolated from the pins and clevises using surface oxidized zirconium sleeves inserted into the specimen, and surface oxidized zirconium washers inserted into the space between the side faces of the specimen and the clevises. A series of steps with various environmental conditions were employed for the CGR test to investigate the combined effect of DO and sulfate on CGR. In the first two steps, an in situ precracking in pure water at 288 °C and 0.25 ppm DO was conducted under triangular and trapezoidal wave loadings with a maximum K ($K_{\max}$) of 23–25 MPa$\sqrt{}$m. Then the SCC growth rate was tested under a constant K of 30 MPa$\sqrt{}$m. Sulfate doping in water was started in the following step with 20 ppb (defined by weight, the same hereafter) and then with 50 ppb to observe the change in CGR. In the next two steps DO was ramped to 2 ppm with sulfate concentrations of 50 and 20 ppb to investigate the combined effect of DO and sulfate on CGR. Then one step was employed to investigate the effect of hydrogen water chemistry (HWC) on CGR at DH = 0.3 ppm and DO < 5 ppb. To pursue the critical sulfate concentration that could reactivate the SCC growth in the FB region, a few steps were employed in the following by increasing sulfate concentrations

Table 1
Chemical composition (wt.%) of the base and weld metals of the Alloy 182-A533B dissimilar weld joint.

	C	Si	Mn	P	S	Cu	Ni	Cr	Mo	V	Nb + Ta	Ti	Fe
A533B	0.20	0.24	1.41	0.009	0.004	0.12	0.65	0.13	0.54	0.001		0.001	Bal.
Alloy 182	0.053	0.44	6.50	0.004	0.002		68.90	14.7			1.55	0.52	7.23