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Hydrogen Effects on Mechanical Behaviors of SA508 Cl.3 Pressure Vessel Steel at High Temperature

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Abstract

In order to investigate hydrogen effects on environmentally assisted cracking (EAC) of SA508 Cl.3 pressure vessel steel, tensile tests and fatigue crack growth rate (FCGR) tests were carried out at 288 °C with hydrogen-charged specimens. From results of the tensile tests, it was found that the charged hydrogen gave rise to some softening and ductility loss. Fracture surface observations of the hydrogen-charged specimens indicated some flat regions. These results can be explained that such softening may be induced due to the shielding effect, strain localization by dynamic strain aging (DSA), and internal pressurization. In the FCGR tests, crack growth rate of the hydrogen-charged specimen was increased by 2~3 times of that of as-received specimen at the same loading condition. Further, the fracture morphology of the hydrogen-charged specimen revealed a striationless cleavage-like feature with few secondary cracks. Through the test results described above, it may be considered that the hydrogen in materials can be involved in the occurrence of the EAC.

1. Introduction

The reactor pressure vessel, which performs a barrier to prevent fission product release, is one of the most critical components in a nuclear power plant. The safety and integrity of nuclear power plant are affected by degradation process. The important degradation mechanisms of the reactor pressure vessel are fatigue, corrosion, and irradiation embrittlement. EAC is also important degradation mechanism because pressurized water reactor (PWR) environment is corrosive. It has been reported that the EAC can be accelerated by a combination of some degradation mechanisms, such as slip oxidation/dissolution, DSA, and hydrogen-induced cracking [1]. Therefore, the hydrogen effects on the mechanical properties of reactor pressure vessel steel must be clarified for the integrity of a nuclear power plant.

During the last several decades, the hydrogen effects on the mechanical properties of structural materials used in a nuclear power plant have been studied. In previous studies, the hydrogen effects at relatively low temperature were focused, while those at high temperature still have many arguments because of the fast diffusion and degassing rate of hydrogen [2]. However, it has been reported that the hydrogen effects occur at high temperature and are also related with the EAC process [1,3,4].

The objective of this work is to investigate the hydrogen effects on the mechanical behaviors , such as tensile properties and fatigue crack growth behaviors, of SA508 Cl.3 pressure vessel steel at high temperature.

2. Experimental

2.1. Test material

In this study, the test material used was ASME SA508 Cl.3 forged vessel steel of 250 mm thickness, produced by Dusan Heavy Industries & Construction Co. In as-received condition, this material had been austenized at 880 °C for 7 hours and water quenched, then tempered at 655 °C for 9 hours followed by air cooling. The chemical composition of the test material is given in Table 1. The microstructure is tempered bainite with well-developed laths as shown in Fig. 1. Tensile specimens with a gauge section of 4 mm in diameter and 24 mm in length and 1T CT specimens were used in this work.

2.2. Tensile tests

In order to remove effects of surface roughness on test results, the specimens were polished with SiC paper up to 2400 grit along loading direction, and then cleaned using a ultra-sonic cleaner. After polishing, hydrogen was electrochemically charged into the specimens in a solution of 1N H_2SO_4 + 250 mg/L As_2O_3 for 10 minutes with 5 mA/cm^2 and 20 mA/cm^2, respectively. The specimens were polished again with SiC paper and rinsed with distilled water. Copper was then electrochemically plated on the surfaces of the specimens to suppress degassing of hydrogen during testing [5,6]. Tensile tests were performed with as-received and hydrogen-charged specimens in the strain rate range of 3.472×10^{-5} to 0.972×10^{-2} s^{-1} at 288 °C. After each test, fracture surfaces were observed by a scanning electron microscope (SEM).

2.3. FCGR tests

Fatigue test with hydrogen-charged specimen was performed in 288 °C argon gas environment. The argon gas environment was obtained by purging a high purity argon gas at pressure of 400 kPa. The specimens were charged with hydrogen by an electrochemical method for 10 hours with 5 mA/cm^2, and copper coated by an electrochemical method to reduce degassing of charged hydrogen. After each test, fracture surfaces were observed by a scanning electron microscope (SEM).

3. Results and Discussion

3.1. Tensile test results

The hydrogen effects on the tensile properties of SA508 Cl.3 RPV steel at 288 °C are shown in Fig. 2 (a), (b), (c), and (d). Yield stress for the hydrogen-charged specimens were smaller than that for the as-received specimens at all strain rates. The charged hydrogen also induced a decrease of ultimate tensile stress, whereas ductility was not affected significantly. The decrease of yield stress and ultimate tensile stress, that is, softening was enhanced with increasing hydrogen charging current density. The tensile properties at the slower strain rate were higher than those at the relatively faster strain rate because of the DSA. Fig. 3 (a) and (b) show a typical ductile fracture surface of a specimen tested at 288 °C. Some flat regions were observed on the fracture surfaces of hydrogen-charged specimens.

At high temperatures, the hydrogen in material suppresses interactions between a given dislocation and other dislocations, solute atoms, and precipitates, thus inducing softening [2,7]. Another reason to be associated with softening is related to interactions between hydrogen and DSA [8]. Lüders bands are produced by DSA, the high dislocation density in these bands can easily trap hydrogen. Thereby, hydrogen concentration increases in the Lüders bands, and this high concentration of hydrogen induces multiplication and enhancement of dislocation mobility, which gives rise to greater strain localization in the bands. Such strain localization induces an increase of local stress concentration at inclusions/matrix or precipitates/matrix interfaces, and lath boundaries. Therefore, initiation and growth of microvoids occur within these regions even though the average strain of the test specimen is small. Moreover, it is indicated that a localized strain structure is a favourable trap for hydrogen, which leads to the initiation and growth of microvoids at lower strain [9]. The internal stress and the number of pile-ups of dislocations can be decreased by these microvoids formed in earlier stage, thus contributing to the softening [10]. Further, hydrogen is easily trapped in the microvoids because the microvoids become preferred traps for hydrogen [11]. Thus, hydrogen trapped in the microvoids causes an internal pressure that aids the void growth. Such an internal pressurization can induce softening during deformation [12]. Furthermore, the microvoid growth assisted by internal pressurization results in some flat areas as shown in Fig. 3 (b).

3.2. FCGR test results

Fatigue crack growth rates of SA508 Cl.3 vessel steel in argon gas and air environment are shown in Fig. 4. In air environment, the crack growth rate increased by two or three times at 288 °C than that at room temperature, while in argon gas environment, the crack growth rate at 288 °C and 0.1 Hz was similar to that in room temperature air. For the test at 5 Hz and 288 °C in argon gas environment the growth rate was much lower than that in room temperature air. This trend of crack growth behaviors may result from reduced oxidation rates, which depend on temperature and oxygen pressure. The loading frequency effect appeared in argon environment would be attributed to a low oxygen pressure within argon gas.

The test of hydrogen-charged specimen showed an enhance growth by 2~3 times of as-received at the same environment and loading condition. In argon gas environment, the fracture surface of as-received specimen showed a typical ductile fatigue cracking morphology with secondary cracks and well-developed striations as represented in Fig. 5(a). In a similar manner, the fracture surface of hydrogen-charged specimen tested in argon gas environment reveals striationless cleavage-like fracture with few secondary cracks and striations as shown in Fig. 5(b). The cleavage-like fracture path is equivalent to bainitic lath boundaries as shown the microstructural feature in Fig. 1 (b). Even though at high temperature, a kind of the EAC appeared in cracking morphology of the hydrogen-charged specimen, the morphology is different from that of as-received specimen. The enhancement of crack growth rate can be attributed to the cracking path shown the EAC features [13]. The cracking process would depend on loading and environment condition, and hydrogen content in the steel; bainitic lath boundaries seem to be the fracture route in the test in argon gas with the hydrogen-charged specimen. Besides the cracking morphologies of the test with hydrogen-charged specimen is not exactly coincident with those in high temperature water, but the occurrence of EAC pattern supports that hydrogen can be involved in the enhancement of the crack growth rate at high temperature.

4. Summary

The investigation results are summarized as follows;

(1) The charged hydrogen induced softening at 288 °C. These results may be associated with the shielding effect, strain localization due to interactions between hydrogen and DSA, and internal pressurization by hydrogen trapped in microvoids. The internal pressurization by the charged hydrogen induces some flat areas on the fracture surfaces of hydrogen-charged specimens.

(2) The fatigue crack growth of the hydrogen-charged specimen showed an enhanced rate by 2~3 times of the as-received specimen at the same environment and loading condition. The enhancement of crack growth rate was related to the cracking morphology showing EAC features.

Acknowledgement

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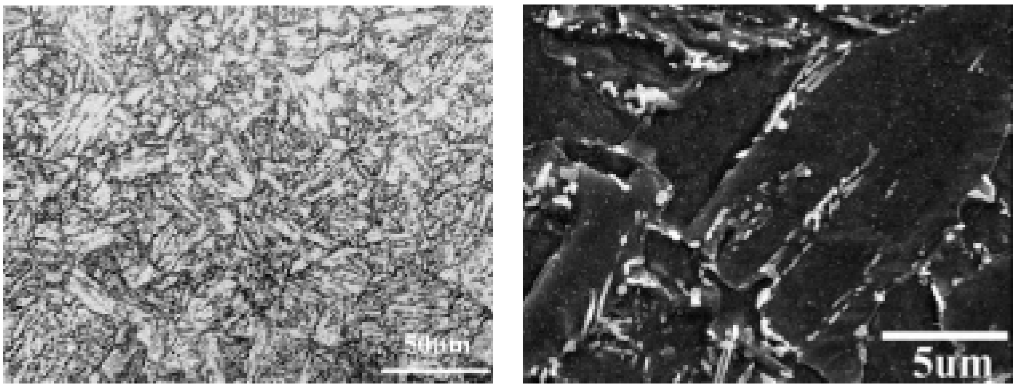
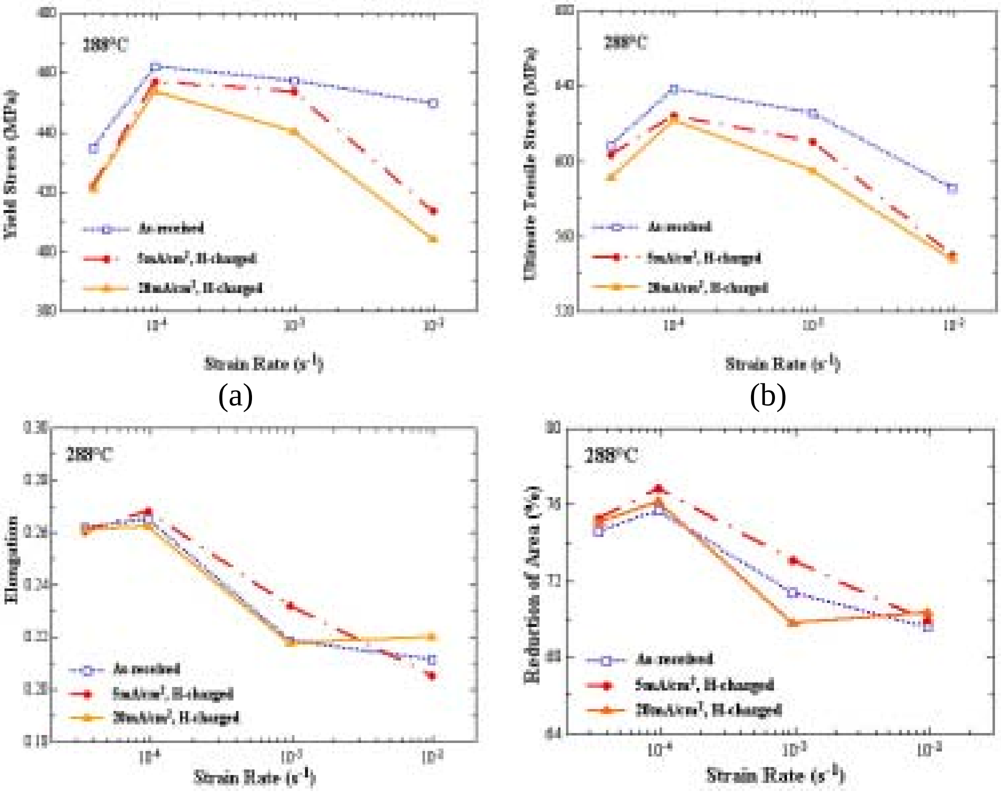
Table 1 Chemical composition of SA508 Cl.3 RPV steel

	C	Si	Mn	S	P	Ni	Cr	Mo	Al	Cu	V
wt%	0.21	0.25	1.24	0.002	0.007	0.88	0.21	0.47	0.008	0.03	0.004



(a) (b)

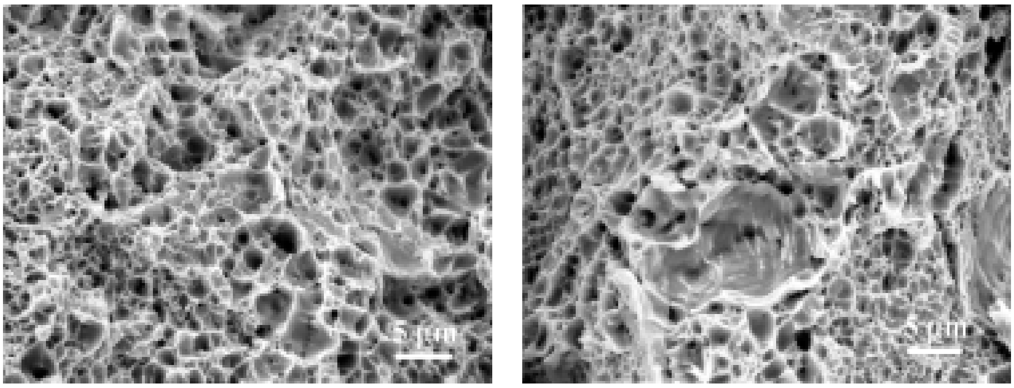
Fig. 1. Microstructure of SA508 Cl.3 RPV steel; (a) Optical microscope (b) SEM



(a) (b)

(c) (d)

Fig. 2. The change of tensile properties at 288 °C; (a) Yield stress (b) Ultimate tensile stress (c) Elongation (d) Reduction of area



(a) (b)

Fig. 3. Fracture morphologies of tensile specimens tested at 288 °C; (a) as-received (b) hydrogen-charged

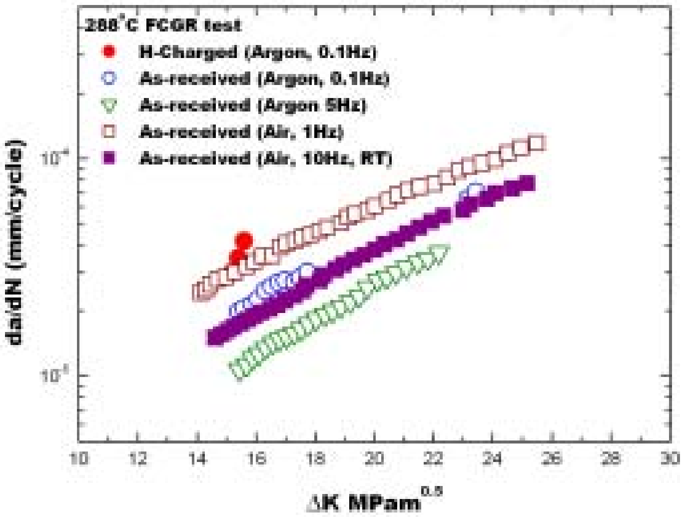
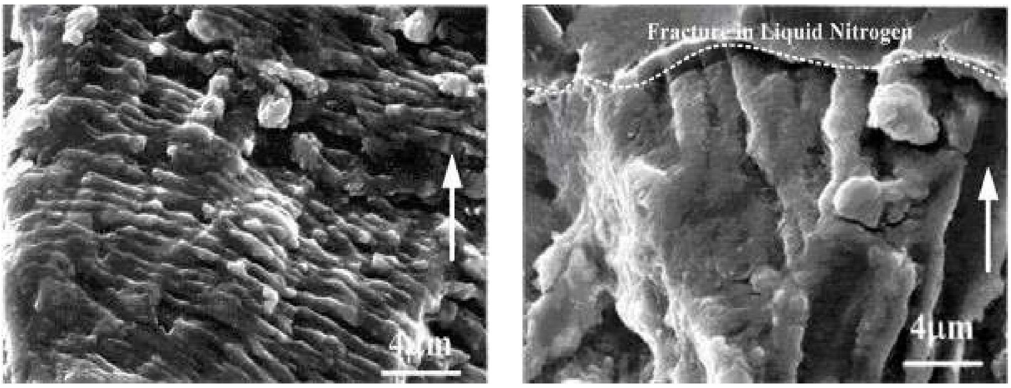


Fig. 4. Fatigue crack growth behaviors of as-received and hydrogen-charged specimens



(a) (b)

Fig. 5. Fracture morphologies of fatigue test specimens in 288 °C argon; (a) as-received (b) hydrogen-charged