Fatigue crack growth of SA508 Cl.3 pressure vessel steel in high-temperature argon and water environments

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Abstract

Effects of environment on the fatigue crack growth rate were studied. The hydrogen-charged SA508 Cl.3 was tested at 288°C to determine the effect of hydrogen on environmentally assisted cracking (EAC) in high-temperature water. The growth rate with the H-charged specimen was enhanced by 2–3 times that of the as-received specimen under the same environment and loading conditions. Then the fracture surface revealed a striationless cleavage-like fracture showing few secondary cracks and striations. The fracture path of the enhanced crack growth was related to bainitic lath boundaries. The data reflected that hydrogen in steel can actually be involved in the occurrence of the environmentally assisted cracking.

1 Introduction

In a high-temperature water environment, the fatigue crack growth behavior of low alloy steels is very different from that in air at ambient temperature [1-3]. The characteristics of the crack growth in a water environment are not easily explained by air data trends, and a fast crack growth may be enhanced by cyclic loads in combination with environments. The environmentally assisted crack (EAC) is manifested by the fracture modes of intergranular, cleavage, or brittle striated types [1-11].

Many researchers have performed studies on the characteristics of EAC in nuclear pressure boundary materials. The behaviors of the EAC are characterized by water chemistries, loading conditions, and material properties. However, the proposed mechanisms for EAC [4,5] are still contradictory, since
it is difficult to differentiate experimentally whether anodic (metal dissolution) and cathodic (hydrogen evolution) is critical.
In this paper, the fatigue crack growth rate of SA508 Cl.3 steel is reported, and the hydrogen effect on EAC is compared to H-charged specimens in high temperature water.

2 Test procedure

2.1 Material

The SA508 Cl.3 used in this study was a forged vessel steel of 10 inch thickness. In as-received condition, the vessel steel had been austenized at 880 °C for 7 hr and water quenched, then tempered at 655 °C for 9 hr followed by air cooling. The chemical composition of the steel is given in Tables 1. As shown in Figure 1, the microstructure is an upper bainite with well developed laths.

2.2 Fatigue crack growth rate test

Fatigue Crack Growth Rate (FCGR) test of SA 508 Cl.3 was performed in various environments: room temperature (RT) and 288 °C in air, inert gas and water environment. In addition, fatigue test with hydrogen charged specimens was performed in argon gas to determine hydrogen effects on cracking at high temperature. The argon environment was obtained by purging a high purity argon gas at the pressure of 400 kPa. The specimens were charged with hydrogen by an electrochemical method for 10 hr with 5 mA/cm², and copper coated by an electrochemical method to reduce desorption of charged hydrogen.

2.3 Observations of fracture surface

After each test, the specimen was broken in liquid nitrogen, and then a fractographic study was performed through scanning electron microscope (SEM). The crack length was corrected after the test by comparing with the in-situ measurement of Direct Current Potential Drop (DCPD) method.

3. Results of FCGR tests in argon and air environments

3.1 Fatigue crack growth rates

The fatigue crack growth rate of SA 508 Cl.3 in argon and air environments is shown in Figure 2. In air environment the crack growth rate increased by two or three times at 288 °C than at RT, while in argon gas environment the crack growth rate at 288 °C and 0.1 Hz was similar to that at room temperature in air environment. For the test at 5 Hz and 288 °C in argon gas environment the
growth rate was much lower than at RT. This trend reflected the crack growth rate depended on oxidation rates at the crack tip in argon and air environments. The test of H-charged specimen showed an enhanced growth rate by 2–3 times that of the as-received specimen at the same environment and loading condition.

3.2 Fracture surface morphologies

The fractographic examinations of specimen tested in high temperature water would reveal three principal fracture morphologies [7]: (1) transgranular, ductile striations; (2) transgranular, brittle striations; and (3) striationless cleavages-like fracture. According to the definitions [7], in air and argon environments the fractured surfaces of as-received specimen showed a typical ductile fatigue cracking morphology with secondary cracks and well-developed striations as represented in Figure 3. In a similar manner, the fracture surface of the H-charged specimen tested in the argon gas reveals striationless cleavage-like fracture with few secondary cracks and striations as shown in Figure 4. The cleavage-like fracture path is equivalent to bainitic lath boundaries as shown the microstructural feature in Figure 1(b).

4. Discussion

4.1 The trends of crack growth rate in various environments

In argon and air environment, the fatigue crack growth rate of SA508 alloy follows Paris' law as shown in Figure 2. In the applied load range, the crack growth rate increased by two or three times at 288 °C than that at room temperature in air environment, while crack growth rate at 288 °C in argon environment decreased to a lower level than that in room temperature air. This trend of crack growth rate may result from reduced oxidation rates, which depend on temperature and oxygen pressure. The loading frequency effect appeared in the argon environment would be attributed to a low oxygen pressure within argon gas. Crack growth rate in water environments depended on the dissolved oxygen (DO) content and the loading frequency as shown in Figure 5 [10]. Crack growth rate was enhanced at high DO content, while there was little effect at low DO. The crack growth rate increased with decreasing frequency up to a critical frequency in the range of 0.01 Hz and 0.05 Hz, and then the crack growth rate returned to that in air environment at 1Hz.

4.2 The effects of MnS, DO content and loading frequency in high-temperature water

Major parameters affecting the crack growth rate would be MnS, DO and loading frequency [9,10]. These parameters can determine the electrochemical
and mechanical condition inside of the crack. According to the fractography results [7,8,10], dissolved MnS inclusion is a source of sulfur ion at a crack tip with forming the oxide scale band in oxygenated water. At the high-oxygenated water, an activity of sulfur ion at a crack tip is higher than at oxygen free water due to a potential drop between crack mouth and tip [4,5]. The activity of sulfur at the crack tip is crucial to determine the crack growth rate, because it controls the rate of metal dissolution and hydrogen evolution. This could cause the crack growth rate to increase with the dissolved oxygen content. However, the crack growth rate at 1 Hz in the aerated water was not enhanced and the band around dissolved-inclusion-sites was not formed [10], although the potential drop may exist. This implies that loading frequencies can affect sulfur activities at the crack tip and an environmental effect was nearly diminished at the 1 Hz test. In addition, crack growth was less enhanced at 0.01 Hz condition than at 0.05 Hz. It seemed there is a critical frequency between 0.01 Hz and 0.05 Hz where the crack growth rate is maximized. Effect of loading frequency can be accounted for that loading frequency affects the fracture rate of oxide film at the crack tip, a pumping velocity at crack surfaces, and a diffusion time of sulfur ion [4,5]. Oxide film may act as a rate-determining parameter of metal dissolution and hydrogen absorption [6,7], which makes it difficult to differentiate experimentally the above mechanisms.

4.3 Fatigue cracking process in high-temperature water environment

Even though in the high temperature, a kind of EAC appeared in the cracking morphology of H-charged specimen, the morphology is different from that of as-received. The enhancement of crack growth rate can be attributed to the cracking path showing EAC features. The cracking process would depend on the 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 H-charged specimen. The sectioned area of samples was observed to follow the cracking process [11]. For the test in argon the crack tip yielding zone is clean as shown in Figure 6. It seems that crack grew continuously. While there are several microcracks in crack tip yielding zone for the 0.05 Hz test in water as shown in Figure 7(a). Some microcracks around inclusion or precipitate are linked to the main crack with brittle manners. Further, there are microcracks, formed by strain localization on slip bands, in the crack tip yielding zone as shown in Figure 7(b).

Above features of cracking may imply to a certain extent the characteristics of hydrogen assisted cracking that brittle micro-cracks ahead of the main crack were enhanced due to hydrogen atom at crack tip plastic zone. Moreover the cracking was equivalent to the hydrogen induced cracking mechanism assumed by Hanninen et al.[8] from the fractographic evidence. Besides the cracking morphologies of the test with H-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 fatigue crack growth of H-charged specimen showed an enhanced rate by 2 ~ 3 times of as-received at the same environment and loading condition. The enhancement of the crack growth rate was related to the cracking morphology showing EAC features.
(2) The cracking process depended on the loading and environment conditions, and hydrogen content in the steel; bainitic lath boundaries seem to be a fracture path in the test in argon gas with the H-charged specimen.
(3) Even though in the high temperature, EAC was produced by the fatigue test in argon gas with H-charged specimen. This supports that the cracking micro-mechanism in high temperature water can be assumed to be hydrogen embrittlement.

Acknowledgments

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References

Table 1: Composition of SA508 Cl. 3

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Figure 1: Microstructure of SA508 Cl. 3; (a) Optical, (b) SEM

Figure 2: Fatigue crack growth rate of as-received and H-charged specimens
Figure 3: Fracture surface of as-received specimen tested in 288°C argon gas environment with 0.1Hz; (a) low magnification, (b) high magnification

Figure 4: Fracture surface of H-charged specimen tested in 288°C argon environment with 0.1Hz; (a) low magnification, (b) high magnification

Figure 5: Fatigue Crack Growth Rate in high temperature water environments
Figure 6: Observation of secondary cracking morphology in sectioned specimen tested in argon environment at 288°C [11].

Figure 7: Observation of secondary cracking morphology [11] in sectioned specimen tested in 8ppm DO water at 288°C; (a) low magnification, (b) high magnification of (a).