Fatigue-crack growth behavior of Type 347 stainless steels under simulated PWR water conditions

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1. Introduction

The pressurizer surge line, which connects the hot leg pipe to the pressurizer, is used under the highest temperature and pressure condition of pressurized-water reactors (PWRs), at 316 °C and 150 atm. Surge line suffers from a fatigue damage arising from repeated thermal and mechanical stress, as well as environmental damage. Although stainless steels(S) are used in pressurizer surge line owing to high corrosion resistance and toughness, acceleration of fatigue crack growth may occur owing to corrosion fatigue under PWR water conditions [1]. Fatigue crack growth rate (FCGR) curve of stainless steel exists in ASME code section XI, but it is still not considering the environmental effects. The longer time nuclear power plant is operated, the more the environmental degradation issues of materials pop up. There are some researches on fatigue crack growth rate of S304 and S316, but researches of FCGR of S347 used in Korea nuclear power plant are insufficient.

In this study, the FCGR of S347 stainless steel was evaluated in the PWR high temperature water conditions. The FCGRs of S347 stainless steel under pressurized-water conditions were measured by using compact-tension (CT) specimens at different levels of dissolved oxygen (DO) and frequency.

2. Methods and Results

2.1 Fatigue-crack growth-rate tests under PWR water conditions

In this study, commercial S347 was used. Before the experiment, S347 was homogenized by annealing (1050°C-1hrs). The FCGR tests were performed using pre-cracked CT specimens (width: 25.4 mm, thickness: 5 mm, and orientation: T-L). The initial crack size was approximately 0.24 of the specimen width. FCGRs under PWR water conditions were evaluated using a fatigue-testing machine (8502, Instron, USA) comprised of a water chemistry control loop and a high pressure-temperature autoclave as shown in Fig. 1. Various PWR water conditions (DO level, dissolved-hydrogen (DH) level, pH, and conductivity) were controlled using the loop system. PWR water conditions under normal operation were simulated using ultra-pure water with resistivity of 15–17 MΩ cm, 5 ppb (μg/kg) of DO, 30 cm3 kg-1 of DH, and pH of 7. The test temperatures were set as nuclear-reactor operation temperature of 316°C. In order to examine the effects of DO on the FCGR, tests were carried out under the 5 ppb (μg/kg) and 100 ppb (μg/kg) of DO levels. The detailed experimental conditions are shown in Table 1. In accordance with ASTM E647 [2], the range of the stress intensity factor, ΔK, was increased under a constant load with an R-ratio (R = Pmin/Pmax, ratio between the minimum and maximum loads; P = load) of 0.1 and a loading frequency of 0.1–10 Hz. The direct-current potential-drop (DCPD) method was used to measure the fatigue-crack growth inside the autoclave, and the test procedures followed the ASTM E647 standard method [2]. The DCPD-measured crack lengths agreed well with the fatigue-crack lengths observed on the fractured specimen surfaces.

Table 1. Water chemistry environment and test conditions.

Pressure	2250 psi
Temperature	316°C
Dissolved Hydrogen (DH)	30 cc/kg
Dissolved Oxygen (DO)	5, 100 ppb
Conductivity	0.05 μs/cm
pH	7
R-ratio (R = Pmin/Pmax)	0.1
Frequency	0.01, 0.1, 1, 10 Hz

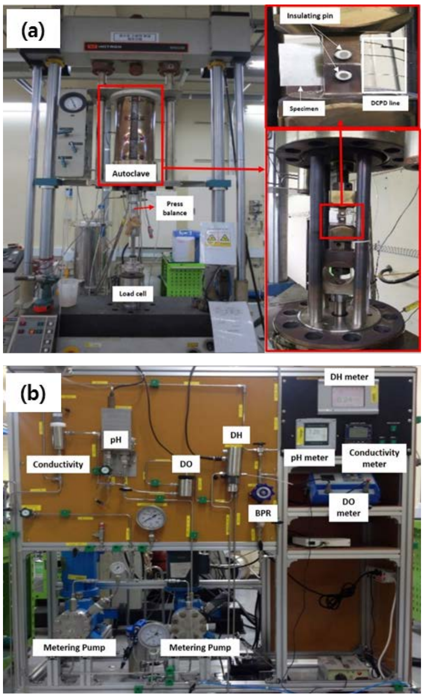

Fig. 1. (a) Instron with autoclave for environmental fatigue test. Enlagred image shows specimen with DCPD lines (b) Loop system for PWR water chemistry control.

2.2 Fatigue-crack growth-rate at high frequency (1Hz, 10Hz) under PWR water conditions (100ppb and 5ppb of DO levels)

FCGRs at high frequency (1Hz, 10Hz) under PWR water conditions are shown in figure 2, and it is compared with ASME code section XI FCGR curve of stainless steels under air condition. ASME XI [3] curve equation are shown in equation (1).

$$da/dN = CS\Delta K^{3.3} \text{ [mm/cycle]} \quad (1)$$
$$C=10\text{^}[-8.714+1.34*10^{-3}T-3.34*10^{-6}T^2+5.95*10^{-9}T^3]$$
$$S = 1.0 \ (S \leq 0)$$
$$= 1.0 + 1.8R \ (0 < R \leq 0.79)$$
$$= -43.35 + 57.97R \ (0.79 < R < 1.0)$$

FCGRs at high frequency are similar regardless of test conditions, and they are slightly slower than curve ASME XI. Especially, the FCGR at 100ppb-10Hz is slower than those of other conditions.

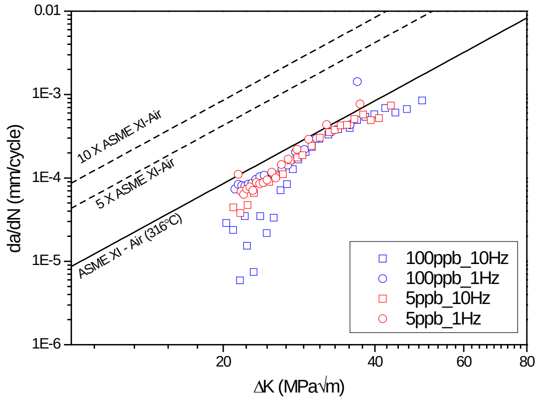

Fig.2. Fatigue-crack growth-rate of SS347 at low frequency (1Hz, 10Hz) under PWR water conditions (100ppb and 5ppb of DO levels)

2.3 Fatigue-crack growth-rate at low frequency (0.1Hz, 0.01Hz) under PWR water conditions

FCGRs at low frequency (0.1Hz, 0.01Hz) under PWR water conditions are shown in figure 3, and it is compared with ASME code section XI FCGR curve of stainless steels under air condition. FCGRs at low frequency are faster than curve ASME XI. When testing frequency is lower, FCGRs are faster. Five times fast curve than ASME XI curves could be used as an upper bound FCGR curve of SS347 in a range of 0.01Hz ~ 10Hz under the given PWR conditions.

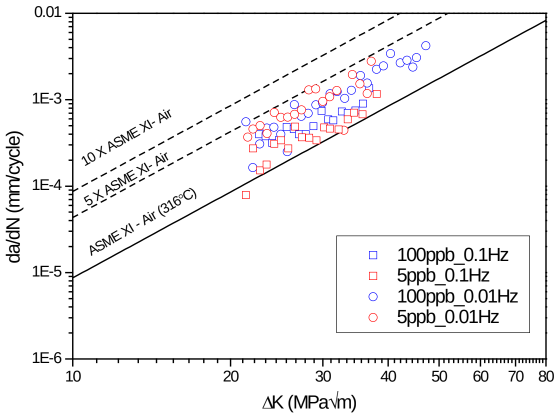

Fig.3. Fatigue-crack growth-rate of SS347 at low frequency (0.1Hz, 0.01Hz) under PWR water conditions (100ppb and 5ppb of DO levels)

3. Discussion

3.1 Effects of frequency and DO condition on Fatigue crack growth rate

FCGR under environmental fatigue can be expressed as follows in equation (2) [4].

$$a_{env} = a_{SCC} + a_{CF} + a_{Air} \quad (2)$$

Each term is representing the contribution of stress corrosion cracking (SCC), corrosion fatigue (CF), and mechanical fatigue (non-environmental condition) to

FCGR. In previous research, SCC is very unlikely in PWR water with low DO content. Thus effect of SCC can be neglected because of its small value.

At high frequency conditions, FCGRs of SS347 are similar with each other and ASME XI curve. It means that environmental effects did not occur at high frequency conditions. Unlike the other conditions, the FCGR remarkably decreased at 100ppb-10Hz condition. It was observed that the size of oxide particles and the oxide-layer thickness were huge at a DO level of 100 ppb as shown in figure 4. It is known that oxide particles formed at crack tips can induce the crack-closure phenomenon at low ΔK levels [5]. The crack closure affected beneficial effects to FCGR unexpectedly.

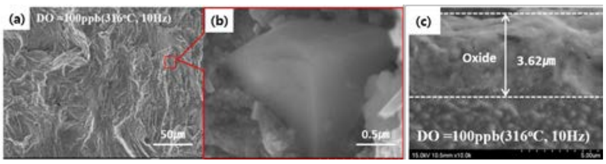

Fig.4. (a) Fatigue fracture surface, (b) its magnifited image, and (c) its cross section image.

However, at low frequency, FCGR of SS347 are faster than ASME XI curve, and FCGR are the fastest at 0.01Hz frequency condition (the slowest frequency). It means that fatigue crack growth was accelerated by environmental degradation and the effects were more severe when the frequency was slower. It is because that the crack tip opening time (CTOT) increased at low frequency, exposing the crack tip to the PWR water conditions for a longer period of time and it increased the FCGR [6]. Similar results have been reported, in which the fatigue life decreased with a decrease in the strain rate in low-cycle fatigue-life assessments in PWR water environments [7].

4. Conclusions

1. FCGRs of SS347 were slower than that in ASME XI and environmental effect did not occur when frequency was higher than 1Hz.
2. Fatigue crack growth is accelerated by corrosion fatigue and it is more severe when frequency is slower than 0.1Hz.
3. Increase of crack tip opening time increased corrosion fatigue and it deteriorated environmental fatigue properties.

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