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Comparison of fatigue crack growth rate of Type 347 stainless steel with ASME and JSME models

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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 fatigue damage arising from repeated thermo-mechanical stress, as well as environmental damage. Although stainless steels (SSs) 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. Fatigue crack growth rate (FCGR) curve of stainless steel exists in ASME code section XI (ASME XI), but it is still not considering environmental effects [1]. There are some researches on fatigue crack growth rate of 304SS and 316SS, but FCGR researches of 347SS used in Korea nuclear power plant are insufficient.

ASME has been making FCGR model considering environmental effects in ASME draft code case N809, and it is under the revision [2]. Japanese researchers also made the environmental FCGR model based on their environmental FCGR data [3-5]. Usually those models are derived from FCGR data based on 304 and 316 SSs which are mostly used in pipe lines of NPPs.

In this study, the FCGR of 347SS was evaluated in modified PWR high temperature water conditions. The FCGRs of 347SS under modified pressurized-water conditions were measured by using compact-tension (CT) specimens at different levels of dissolved oxygen (DO), and it were compared with other models proposed by ASME and Japanese groups.

2. Methods and Results

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

In this study, commercial 347SS was used. Before the experiment, 347SS 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 modified 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. Modified 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 pressurizer surge line 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, the range of the stress intensity factor, ΔK, was increased under a constant load with an R-ratio ($R = P_{min}/P_{max}$, ratio between the minimum and maximum loads; P = load) of 0.1 and a loading frequency of 0.1 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. The DCPD-measured crack lengths agreed well with the fatigue-crack lengths observed on the fractured specimen surfaces.

Table 1. Modified PWR water chemistry environment and test conditions.

Pressure	150 atm
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	0.1

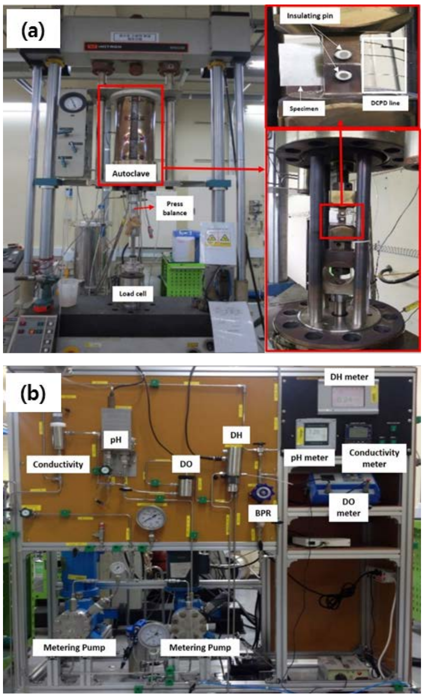

Fig. 1. (a) Instron with autoclave for environmental fatigue test. Enlagred image shows specimen with DCPD lines (b) Loop system for PWR water chemistry control.

2.2 Fatigue-crack growth-rate models in ASME and Japanese groups works.

Reference model of FCGR for stainless steel in ASME code section XI did not consider the environmental effects. Nowadays, ASME has developing the reference model of FCGR for stainless steel considering environmental effects. Japanese also made their environmental FCGR model for stainless steel under PWR and BWR condition. Each reference model is indicated as below;

1) FCGR model of SS in ASME code section XI under air condition. : ASME XI

$$da/dN = CS\Delta K^{3.3} \quad \text{[mm/cycle]}$$

$C=10$^$[-8.714+1.34*10^{-3}T-3.34*10^{-6}T^2+5.95*10^{-9}T^3]$
$S = 1.0$ ($S \leq 0$)
$= 1.0 + 1.8R$ ($0 < R \leq 0.79$)
$= -43.35 + 57.97R$ ($0.79 < R < 1.0$)

2) FCGR model for 304 and 316 SS in ASME draft code case N 809. Revision 7A. It considers environmental effects. : ASME Draft

$$\frac{da}{dN} = 9.10 \times 10^{-6} e^{-2516/T_K} \left(1 + e^{8.02(R-0.748)}\right) t_R^{0.3} \Delta K^{2.25}$$

3) FCGR model for SS derived from Japanese data base under PWR environment: J-PWR

$$\frac{da}{dN} = 1.61 \times 10^{-10} T^{0.63} t_R^{0.33} \Delta K^{3.0}/(1-R)^{1.56}$$

4) FCGR model for SS in JSME under BWR environment (T=288°C): J-BWR

$$\frac{da}{dN} = 8.17 \times 10^{-9} \times t_R^{0.5} \times \Delta K^{3.0}/(1-R)^{2.12}$$

Above 3 equations use same value of t_R=1s for t_R <1s condition. The symbols used in these equations are defined; TK: temperature (°K), t_R: rising time.

2.3 Fatigue-crack growth-rate of 347SS under PWR water conditions

FCGRs at 0.1Hz under PWR 5ppb and 100 ppb water conditions are shown in figure 2, and it is compared with FCGR models. Under 5ppb water condition, FCGRs of 347SS are faster than curve ASME XI and J-PWR, and it is similar with Draft code case N809, J-PWR, but it is slower than J-BWR. Under 100ppb water condition, FCGRs of 347SS are faster than curve ASME XI, Draft code case N809, and J-PWR, but it is slower than J-BWR. FCGRs of 347SS are faster under high DO water conditions.

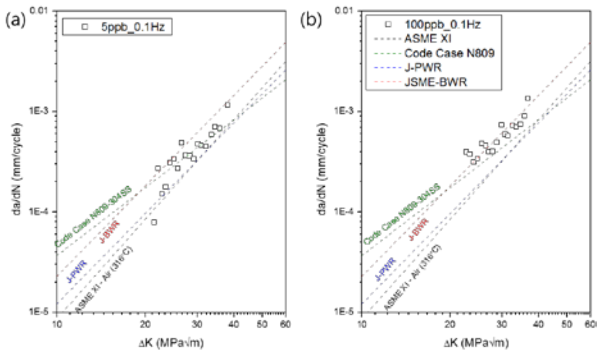

Fig.2. Fatigue-crack growth-rate of SS347 under PWR water condition; (a) 5ppb of DO and (b) 100 ppb of DO

3. Discussion

Environmental FCGR models and FCGR of 347SS are faster than FCGR model in ASME XI. This means that environmental effects accelerate FCGR. FCGR under environmental fatigue can be expressed as follows: [6].

$$a_{env} = a_{SCC} + a_{CF} + a_{Air}$$

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, and effect of SCC can be neglected because of its small value. Therefore the difference of FCGRs of 347 stainless under different fatigue conditions is caused by corrosion effects. FCGR are faster under high DO water condition. Figure 3 shows corrosion particles and thickness of corrosion layer. Size and layer thickness of corrosion particle are larger when DO level increased. It means that fatigue crack growth was accelerated by environmental degradation, and the effects were larger when the corrosion severely occurred.

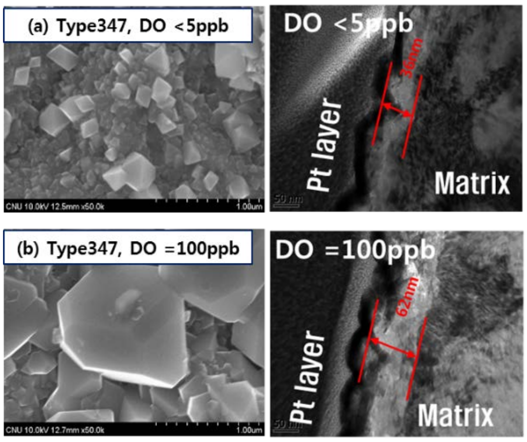

Fig.3. Fatigue-crack growth-rate of SS347 under PWR water conditions ((a) 5ppb and (b) 100ppb DO levels)

4. Conclusions

1. Corrosion fatigue is main factor of environmental fatigue effect. Increase of DO level in water induced more corrosion damage, and it accelerated FCGR in PWR.

2. FCGR of 347SS in PWR water condition was faster than reference curves in J-PWR and ASME draft code case derived by 304 and 316 stainless steel, but it was slower than J-BWR reference curve. Using J-BWR model for estimating the FCGR of 347SS under PWR might be conservative.

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