Cyclic Stress Response and Fatigue Life of Type 316LN Stainless Steel in 310 °C Low Oxygen-containing Water

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1. Introduction

It has been known that environmental effects play a dominant role in fatigue behavior of structural materials used in light water reactor (LWR) [1,2]. Up to now, it has been carried out so many studies on low cycle fatigue (LCF) behavior of structural materials, such as low alloy steel, carbon steel, and stainless steel (SS) in various environments [1,2]. Some hardening mechanisms is not yet clearly known in spite of the various suggestions made during the last few years. Also, design fatigue curves specified in ASME Boiler and Pressure Vessel Code Section III do not address the effects of environments on fatigue lives of structural materials explicitly [3]. Therefore, study on LCF behavior of type 316LN SS in high temperature water is needed for reliable performance during the service time of LWR. In order to contribute to the understanding of the cyclic hardening mechanism and fatigue life of type 316LN SS in high temperature water, we report here the results of studies on LCF behavior of this material in 310 °C low oxygen-containing water.

2. Experimental details

2.1 Test Material and LCF Specimen

Chemical composition of type 316LN SS is (wt.%): C, 0.018; Mn, 1.84; S, 0.016; Si, 0.46; Cr, 16.37; Ni, 11.30; Mo, 2.11; N, 0.096; B, 0.0015; Co, 0.10; Cu, 0.28. Round bar type LCF specimens with gauge diameter of 9.63mm and gauge length of 19.05 mm were used in this study.

2.2 Test Conditions

Test system for LCF tests in high temperature water is composed a servo-electric fatigue test machine, an autoclave, and a water circulation loop. LCF tests were performed in a symmetric uniaxial push-pull mode in 310 °C low oxygen-containing water. Strain rates were 0.4, 0.04, and 0.008 %/s, and strain amplitudes varied from 0.4 to 1.0 %. The DO content of the test water was kept less than 1 ppb and the conductivity was maintained below 0.1 μS/cm. And fatigue life was defined as a number of cycles, N_{25}, achieved before the load to dropped 25 % from its peak value. After each test was finished, we observed dislocation structure and fatigue surface using JEOL-2010 transmission electron microscope (TEM) and Philips 500 scanning electron microscope (SEM).

3. Results and Discussion

3.1 Cyclic Hardening Behavior

Cyclic stress response of type 316LN SS in 310 °C low oxygen-containing water is shown in Figure 1. The test material experienced a primary cyclic hardening, followed by a moderate softening. At strain amplitude of 0.4 %, secondary hardening occurred at the specimens tested in the strain rates of 0.4 and 0.04 %/s, as shown in Figure 1 (d). However, at 0.008 %/s, the saturation stage was observed before load drop.

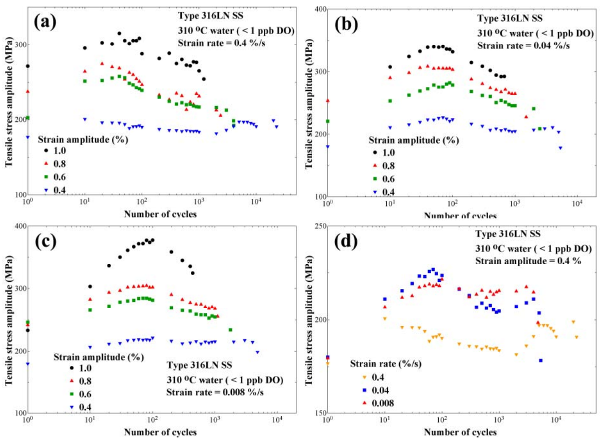

Figure 1. Cyclic stress response of type 316LN SS in 310 °C low containing water at strain rates of (a) 0.4 (b) 0.04 (c) 0.008 %/s, and (d) three strain rates at 0.4 %.

In dynamic strain aging (DSA) range, diffused solute interacts with mobile dislocation and pin it, then such an interaction induces more stress. Therefore, it can be considered that the hardening behavior is induced due to DSA.

For the specimen tested at strain rate of 0.4 %/s, tangled dislocation structure was observed as shown in Figure 2 (a). Dislocations get tangled, and then, the tangled dislocations can prevent movements of other dislocation. So, tangled structure can attribute to some cyclic hardening behavior. Secondary hardening occurred explicitly for strain rate of 0.4 %/s, thus, tangled dislocation structure can lead to the secondary hardening. As shown in Figure 2 (b), cell structure composed of tangled dislocations was observed for the specimen tested at strain rate of 0.04 %/s. Dislocation structure can be stabilized by formation of cell structure, and then saturation of stress may be started [4]. Hence, it can be considered that the extent of secondary hardening at strain rate of 0.04 %/s decreases due to formation of cell structure composed of tangled dislocations. On the other hand, wall structure observed for the specimen tested at strain rate of 0.008 %/s may be related to saturation stage in cyclic stress response.

3.2 Strain-Fatigue Life (ε-N) Curve

The ε-N curves of type 316LN SS with various strain rates in 310 °C low oxygen-containing water are shown in Figure 3, and the ASME design fatigue curve and the statistical models for type 316NG SS established in Argonne National Laboratory (ANL) are also presented for comparison [1,3].

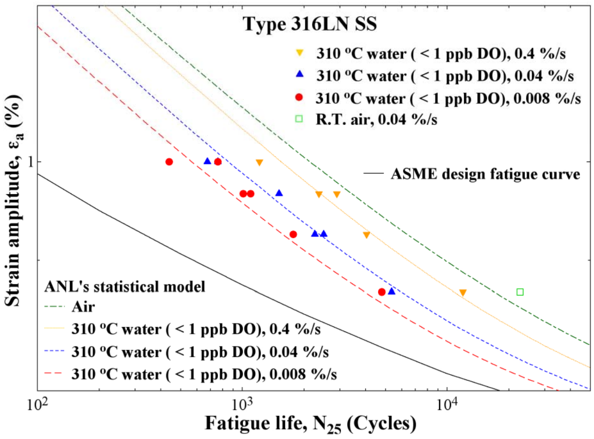

Figure 3. ε-N curves of type 316LN SS in 310 °C low oxygen-containing water.

As shown in Figure 3, the fatigue life of type 316LN SS in 310 °C low oxygen-containing water was shorter than that of the statistical model in air. Moreover, the fatigue life was reduced with decreasing strain rate from 0.4 to 0.008 %/s. DSA is reason for the decrease of fatigue life in 310 °C low oxygen-containing water . DSA lead to form fatigue cracks in an earlier stage of LCF deformation, and to induce a large stress concentration at the crack tip and then an increase of crack propagation [5]. Under DSA condition, cohesion of fatigue cracks is greater at lower strain rates. Hence, it can be considered that the enhancement of reduced fatigue life with decreasing strain rate from 0.4 to 0.008 %/s is related to DSA.

In SEM observation of fatigue surface, well-developed striations were observed, as shown in Figure 4. The striation spacing shows very good agreement with decreasing fatigue life. The presence of well-developed striations suggests that mechanical factors are more important than slip dissolution/oxidation process. So, environmentally assisted reduction in the fatigue life of type 316LN SS can be caused by hydrogen-enhanced crack growth.

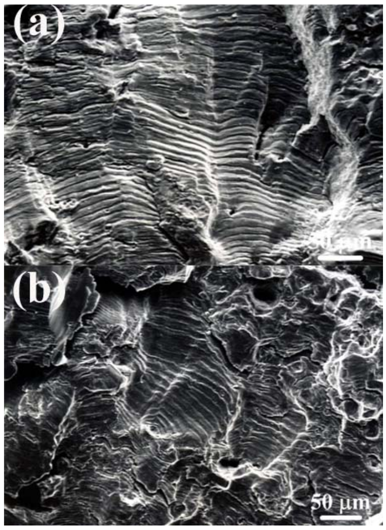

Figure 4. Fatigue surface morphology of type 316LN SS in 310 °C low oxygen-containing water at strain rate of (a) 0.04 and (b) 0.008 %/s.

3. Summary

(1) Type 316LN SS in 310 °C low oxygen-containing water experienced a primary hardening, followed by a moderate softening. The interaction between mobile dislocation and solute atoms, which occurs under DSA range, induces the hardening.

(2) At strain amplitude of 0.4 %, the secondary hardening was observed in the strain rate range from 0.04 to 0.4 %/s. From TEM study, the secondary hardening can be related to tangled dislocation structure.

(3) Fatigue life of type 316LN SS decreased in 310 °C low oxygen-containing water. The reduction in fatigue life in 310 °C low oxygen-containing water may be associated with DSA and hydrogen-enhanced crack growth.

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