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Environmental Fatigue Behaviors of Type 316LN Stainless Steels in Simulated PWR Water with Different Dissolved Hydrogen Contents – Preliminary Results

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1. Introduction

Fatigue behaviors of structural materials in nuclear power plant (NPP) environment are affected by many environmental factors. So, much effort has been being paid to understand the effect of environmental factors on the fatigue behaviors in NPP environment. Currently, to reduce the susceptibility to primary water stress corrosion cracking (PWSCC) of nickel-base alloy, the optimization of dissolved hydrogen (DH) level is under discussion. In this circumstance, the effect DH level on other environmental degradation mechanisms should be considered as well. In this regard, the effects of DH and water conductivity on low cycle fatigue (LCF) behaviors of type 316LN stainless steel (SS) are being investigated through LCF tests and proper analysis.

2. Experimental

2.1 Test Materials

The material used in this study was a type 316LN SS which was solution-annealed at 1050°C for 30 minute then water quenched. Tensile properties and chemical compositions were measured and summarized in Table 1 and 2.

Table 1: chemical compositions of type 316LN SS

C	Mn	P	S	Si	Cr	Ni	Mo	N
.03	1.93	.010	.010	.63	18.90	13.91	2.78	.16

Table 2: Tensile property of LASs

	Y.S. (MPa)	U.T.S. (MPa)	Elong. (%)
RT	357	634.1	68.6
310°C	216.1	487.6	48.4

2.2 Test Conditions

Table 3 shows test conditions. The test environment were a 310°C deoxygenated water, 310°C simulated PWR water, and 310°C high DH PWR water. To investigate the effect of DH and water conductivity, the DH level was increased from 0 cc/kg to 80 cc/kg and water conductivity was changed from 0.1 to ≈ 25 ㎲/㎝.

Table 3: LCF test conditions

Test environment		In deoxygenated water	In simulated PWR water	In high DH PWR water
Waveform		Fully reversed triangular		
Strain rate		0.04 %/s		
Strain amplitude		0.4, 0.6, 0.8, 1.0 %	0.4, 0.6, 1.0 %	
Test temperature		310°C		
Water Chemistry	DO	< 1 ppb		
	DH	Non - detectable	25 cc/kg	80 cc/kg
	Cond.	< 0.1 μS/cm	≈ 22 μS/cm (1200 ppm H_3BO_3 + 2.2 ppm LiOH)	

3. Results and Discussion

3.1 Fatigue Life

Figure 1 shows the fatigue life of type 316LN SS in a 310°C deoxygenated water. The difference of fatigue life of type 316LN SS with increase in water conductivity from below 0.1 to about 22 ㎲/㎝ was not clearly observed. The fatigue life of type 316LN SS was slightly increased with increase in DH level in specific range from 0.6 to 1 % strain amplitude. On the other hand, the trend is not so clear at lower strain amplitude. More tests are needed to clearly understand the behaviors.

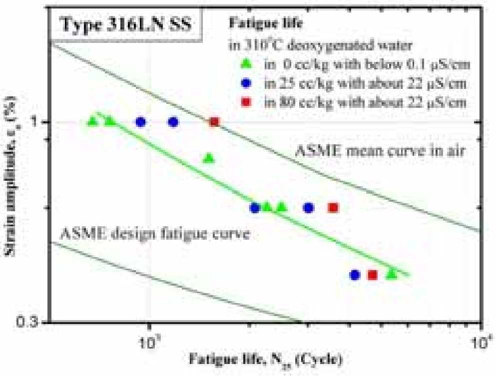
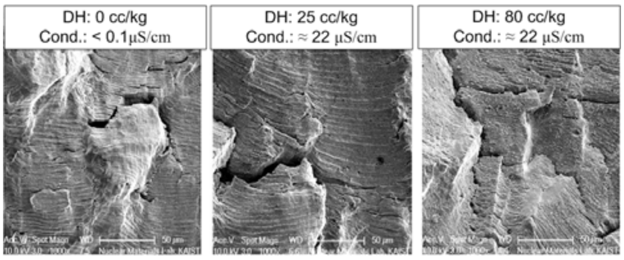


Figure 1. Fatigue life of LASs in 310°C deoxygenated water.

3.2 Fractography Observation

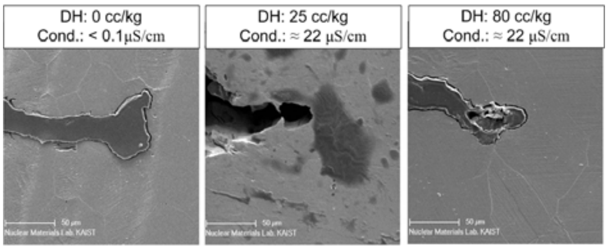
Figure 2 shows fatigue surfaces of type 316LN SS. Relatively clear striations were observed on fatigue surfaces in propagation stage although they were covered with oxide particles. It has been known that the dominant EAC mechanism of type 316LN SS in 310oC deoxygenated water is slip-oxidation/rupture. As shown in Fig. 2, the amount of the spinel type oxide particles in fatigue surfaces in 80 cc/kg of DH water are much larger than those in other environment. These phenomena are observed and reported in other study results [1]. However, these spinel oxide particles consisted of Fe_3O_4 could not explain the difference of fatigue life.



(a) (b) (c)

Figure 2. Fatigue surfaces of type 316LN SS: (a) in 310°C deoxygenated water, (b) in 310°C simulated PWR water, (c) in 310°C high DH PWR water.

Figure 3 shows main fatigue crack of test materials. All of fatigue crack tips were shown blunt crack tips which are typical crack tip characteristics tested in high temperature water. The morphologies of fatigue cracks have no distinct difference with change of DH and water conductivity.



(a) (b) (c)

Figure 3. Fatigue crack tip morphologies of type 316LN SS: (a) in 310°C deoxygenated water, (b) in 310°C simulated PWR water, (c) in 310°C high DH PWR water.

3.3 Effect of DH level on Fatigue Behaviors

From LCF test results, the fatigue life of type 316LN SS seems to depend on DH level in specific range. In general, as the increase in DH level could decrease electrochemical corrosion potential (ECP) on test material, the fatigue life could be enhanced by reduction of corrosion rate of test material. However, in our test results, the ECP variation by increase in DH level from 25 cc/kg to 80 cc/kg was only about 50 mV because the ECP change is only controlled by H_2/H_2O reaction. Andresen reported that Fe/Fe_3O_4 line in phase diagram in simulated PWR environment, whose equilibrium potential is ≈ 200 mV below H_2/H_2O line [2]. Therefore, the small change of ECP by increasing DH may not be a significant factor to environmental fatigue behaviors of type 316LN SS.

The hydrogen permeation rate is primarily controlled by hydrogen fugacity [2]. The absorbed hydrogen at the crack tip could enhance hydrogen induced cracking (HIC) mechanism, thereby reducing fatigue life. However, when the protective oxide film is ruptured by applied strain, the hydrogen concentration at the crack tip would be very high due to corrosion generated hydrogen. Thus, the bulk DH level could not have significant effect on fatigue crack growth by HIC. Unfortunately, the experimental observation, or longer fatigue life at high DH could not be explained by electrochemical potential or hydrogen fugacity. Further tests and analysis are underway.

3.4 Effect of Water Conductivity on Fatigue Behaviors

It is recognized that the water conductivity could give detrimental effect on fatigue crack growth due to local acidification by selective diffusion at the crack tip. However, our experimental fatigue life data of type 316LN SS did not depend on water conductivity by boric acid (H_3BO_3) and lithium hydroxide (LiOH). In deoxygenated water, little consumption of oxygen at the crack tip could induce little potential gradient between surface and crack tip. So, the anion diffusion into crack tip could be negligible. Therefore, there is no local acidification. Moreover, very little ionization of boric acid can make relatively small water conductivity even in high temperature [3]. Therefore, the water conductivity by containing 1200 ppm H_3BO_3 and 2.2 ppm LiOH could not be a significant factor to fatigue crack growth in simulated PWR water.

4. Conclusions

1. The fatigue life of type 316LN SS were slightly improved with increasing DH level. From fractography analysis, the definite difference of EAC in fatigue crack growth could not be observed. To investigate the effect of DH level on LCF behaviors, LCF tests and proper analysis will be continued.
2. The fatigue life of type 316LN SS in simulated PWR primary water were not affected by water conductivity because in deoxygenated water, small potential gradient and little ionization of boric acid could not induce significant local acidification by anions diffusion at the crack tip.

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