Fatigue Test for 316 Stainless Steel in a High Dissolved Hydrogen Environment

Taesoon Kim [a*], Hyeonbae Lee [b]
[a]*KHNP, Central Research Institute, 70, 1312 Yuseong-daero, Yuseong-gu, Deajeon 34101, KOREA*
[b]*KAIST, Nuclear & Quantum Eng. Dept., 291 Daehak-ro, Yuseong-gu, Deajeon 34141, KOREA*
[*]*Corresponding author: taesoon.kim@khnp.co.kr*

1. Introduction

As the design life of nuclear power plants is expanded over 60 years, many environmentally assisted fatigue (EAF) tests were carried out results including Argonne National Laboratory's consistently indicated the substantial reduction of fatigue life in the light water reactor environments [1, 2]. It is necessary to clarify the effects of light water environments on fatigue life while considering more plant-relevant transient conditions such as hold-time. For this reason, we have focused on comparing the fatigue life of stainless steels incorporating the hold-time during the low cycle fatigue (LCF) test in simulated pressurized water reactor (PWR) environments [3]. In the previous test results, it was reported that the fatigue life was increased to a significant level when zinc was injected in the typical dissolved hydrogen (DH) environment and peak strain holding was applied. In addition, even in high DH environment, the fatigue life slightly increased. Based on these results, it is expected that the fatigue life of stainless steels used in NPPs could be further increased by injecting zinc in the high DH environment. Therefore, the EAF behavior of type 316 stainless steel is evaluated in zinc with high DH environment, and the influence of waveform was also considered by applying various strain holding conditions.

2. Test Material and Method

2.1 Test Material

In this study, the 316 stainless steel of round bar type were used for fatigue life test. The mill test certificate and chemical composition are shown in the Table I. The analyzed chemical compositions are in good agreement with the relevant American Society for Testing Materials (ASTM) specifications. Tensile properties of the test material were measured using sub-size round bar specimens, as shown in Table II. Three tests were performed at room temperature and 325 ℃ using a displacement rate of 0.72 mm/min. The results are summarized in Table II and the room temperature tensile properties meet the requirements of ASTM.

Table I: Chemical composition of 316 stainless steels

Material Type	C	Ni	Cr	Fe	Mo	Mn	Si	P	S
Round Bar	0.058	10.14	17.07	Bal.	2.07	1.31	0.29	0.029	0.029

Table II: Tensile properties of 316 stainless steels

Material Type	Spec.	Temp.	Yield Strength (MPa)	Ultimate Strength (MPa)	Elongation (%)
Round Bar	ASTM A276	RT	310	620	30
	Measured Property	RT	332	648	66.4
		325 ℃	222	497	43.0

2.2 Test Conditions and Specimens

Low cycle fatigue (LCF) tests were performed in fully-reversed loading (R = -1) under strain-controlled mode. The test conditions in dissolved hydrogen (DH) are summarized in Table III, and LCF tests were performed in room temperature air, 325 ℃ air, and a typical PWR primary environment. Some parameters were added to the PWR environment such as zinc and DH, and peak strain holding was applied during some of the tests. Since the DH is typically maintained in the range of 25~50 cc/kg to reduce the dissolved oxygen (DO) concentration in the primary water system of NPPs, LCF tests were performed in high DH concentrations (50 cc/kg).

A strain amplitude of 0.4 % and a strain rate of 0.004 %/s were used, and for some tests, the strain was held at the maximum strain value for 400 seconds to partly simulate the real loading condition of NPPs where there is typically a long duration between transients, as shown in Fig. 1. The DO level and electrical conductivity were kept below 5 ppb and 22~25 μ S/cm during the test period, respectively. Also, the pH value in room temperature was maintained at 6.3. The specimens used in LCF tests were of a round bar type, with a 9.63 mm gauge diameter and 19.05 mm gauge length.

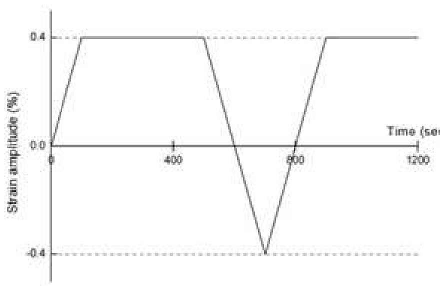

Fig. 1. Strain amplitude curve with peak holding.

Table III: Low cycle fatigue test conditions

Test materials		Austenitic SSs (Type 316)		
Environment		Air	PWR	
Temperature (℃)		RT/325	325	
Control		Strain control		
Strain rate (%/s)		0.004		
Strain amplitude (%)		0.4		
Hold-time (sec.)		0	0	400
Water chemistry	Zinc (ppb)	-	0	30
	DO (ppb)	-	< 5	
	DH (cc/kg)	50		
	Conductivity	-	20~25 μS/cm	
	pH	-	6.3	

3. Test Results

In high DH environment, the change in fatigue life depending on zinc addition and peak strain holding condition was observed and the results of fatigue life are shown in Fig. 2 and 3. As shown in the ε – N curve of Fig. 2, the effect of application of zinc addition and peak strain holding on fatigue life is opposite in high DH environment to that in typical DH environment. In the typical DH environment, the fatigue life is greatly improved when the zinc addition and peak strain holding are applied simultaneously ($PWR_{Zn/PH}$) as reported in previous section. However, the decrease in fatigue life is observed when zinc is added in the high DH environment regardless of whether triangle or peak strain holding is applied ($PWR_{HH/Zn}$ and $PWR_{HH/Zn/PH}$).

In order to confirm the environmental effect, F_{en} was calculated using LCF life in air environment. In zinc-free high DH environment, F_{en} values for 4 cases are in the range of 4.0~3.1, and in zinc-added high DH environment are in the range of 7.9~4.2. The cyclic hardening response for each test condition is shown in Fig. 4, which indicates the secondary hardening behavior occurred in $PWR_{HH/PH}$ and $PWR_{HH/Zn/PH}$. The secondary hardening occurs when the dissolved hydrogen penetrates into the crack tip and locates at stress concentrated region such as defects, resulting in relaxation of stress and increasing contribution of DSA.

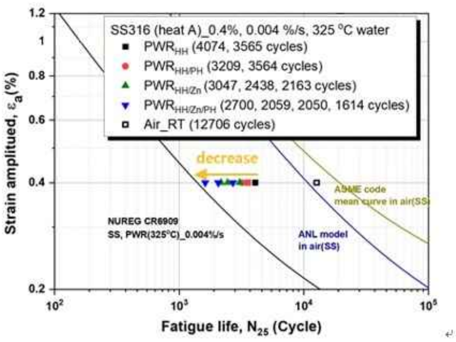

Fig. 2. EAF test results of 316 stainless steel according to loading conditions in a high DH environment.

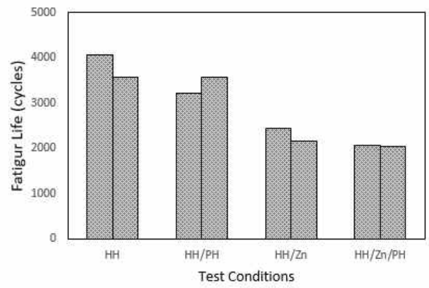

Fig. 3. Fatigue life comparison of 316 stainless steel according to loading conditions in a high DH environment.

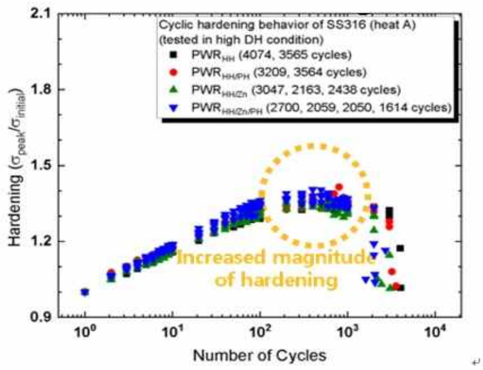

Fig. 4. Cyclic hardening of 316 stainless steel in a high DH environment.

4. Conclusions

The effect of peak strain holding on fatigue life of 316 stainless steel in a high DH environment was evaluated. In addition, the effect of zinc addition were also considered. Contrary to the test results in zinc-added typical DH environment or in zinc-free high DH environment, the fatigue life decreases when zinc is added in high DH environment. As a result of analysis of the crack tip oxide film formed in zinc-added high DH environment, it was observed to have an amorphous structure. Therefore, though zinc is detected in some part of oxide film at crack tips, it was found to be insufficient to prevent corrosion in the zinc added high DH environment.

REFERENCES

[1] M. Higuchi, K. Sakaguchi and Y. Nomura, Effects of Strain Holding and Continuously Changing Strain Rate on Fatigue Life Reduction of Structural Materials in Simulated LWR Water, ASME PVP-2007, 26101, 2007.

[2] O. K. Chopra and G. L. Stevens, Effect of LWR Water Environments on the Fatigue Life of Reactor Materials, U.S. Nuclear Regulatory Commission, NUREG/CR-6909, Rev. 1, Final report, Washington, DC, May 2018.

[3] C. Jang, H. Jang, J.-D. Hong, H. Cho, T. S. Kim and J. G. Lee, Environmental Fatigue of Metallic Materials in Nuclear Power Plants – A Review of Korean Test Programs, Nuclear Engineering and Technology, Vol. 45, No. 7, pp. 929-940, December 2013.