The hold-time effects on the low cycle fatigue behaviors of 316 SS in PWR primary environment

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1. Introduction

Many studies have been conducted to evaluate the effect of light water reactor (LWR) coolant environments on fatigue life of materials. The effects of the environments on fatigue life of the structural materials used in nuclear power plants (NPPs) were known to be significant according to the extensive test results. Accordingly, the fatigue analysis procedures and the design fatigue curves were proposed in the ASME Code [1]. However, the implication that the existing ASME design fatigue curves did not sufficiently reflect the effect of the operation conditions of nuclear power plants emerged as an issue to be resolved. However, there is a discrepancy between laboratory test data and plant operating experience regarding the effects of environment on fatigue. One of possible reasons to explain the discrepancy is that the laboratory test conditions do not represent the actual plant transients. Therefore, 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, this study will focus on the fatigue life of type 316 stainless steel (SS) in the pressurized water reactor (PWR) environments while incorporating the hold-time during the low cycle fatigue (LCF) test in simulated PWR environments.

2. Experimental

2.1 Test material

In this study, a commercial grade type 316 SS which is used as structural material in domestic nuclear power plant was used for fatigue life test. The chemical compositions and mechanical properties are shown in Table I and Table II. The chemical compositions and mechanical properties are within the specification of ASTM A-240 [2].

Table I: Chemical composition of 316 SS

C	Mn	P	S	Si	Cr
0.052	0.56	0.028	0.001	0.54	16.74
Ni	Mo	N	Cu	Fe	
10.24	2.13	0.029	0.22	Bal.	

Table II: Mechanical properties of 316 SS [2]

	YS (MPa)	UTS (MPa)	Elongation (%)
Measured	316.58	598.08	77.86
ASTM A240	Min. 215	Min. 515	Min. 40

2.2 Test conditions

To simulate the condition when the transients were completed, the sub-peak holding was applied after the peak stress (or strain) was applied (that is, down-hill holding). The strain level for the sub-peak holding was determined from the hysteresis loop of the low cycle fatigue test of type 316 SS in simulated PWR environments as shown in Fig. 1. The sub-peak holding was applied at the strain corresponding to the quasi-yield stress of the 1st cycle as shown in the Fig. 1. The sub-peak holding condition is somewhat related to the heat-up and cool-down transient. As the test material, type 316 SS would experience hardening and/or softening during the LCF test, and the stress level at the holding would be changed at different cycle.

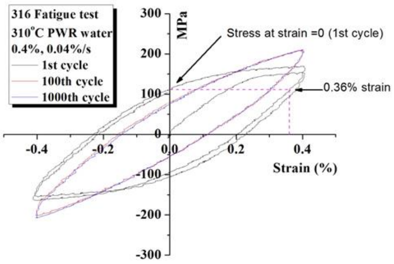

Fig. 1. Stress-strain curves of type 316 SS during low cycle fatigue test in PWR water

The LCF tests were performed under fully reversed triangle waveform with strain rates of 0.004 - 0.4 %/s. The test environment were RT air, 310 °C air and simulated 310 °C PWR water with addition of chemicals (1200 ppm of boric acid and 2.2 ppm of lithium hydroxide) and dissolved hydrogen (DH). Details of loading and environmental condition are described in Table III. Smooth cylindrical specimens with a gauge length of 19.05 mm and a diameter of 9.63 mm were used for the fatigue tests. Details about the test facility have been described in elsewhere [3]. Moreover, the LCF life, N_{25}, is defined as the number of cycles for the tensile stress to drop 25 % from the peak value.

Table III: Test environments

Environment		Air, simulated PWR
Hold time case		60 and 300 sec. (Sub-peak)
Waveform		Fully reversed triangular (R = -1)
Control		Strain control
Strain rate		0.004 - 0.4 %/s
Strain amplitude		0.4 %
Water chemistry	DO	< 5 ppb
	DH	~ 25 cc/kg
	Conductivity	~ 20~25 μS/cm (1200 ppm H_3BO_3 + 2.2 ppm LiOH)
	pH	6~7

3. Results and Discussion

3.1 LCF life

As shown in Fig. 2, The LCF lives of 316 SS obtained from LCF tests in 310°C air, PWR environment. For comparison, the predicted life per NUREG/CR-6909 Draft Rev.1 is also shown in Figs. 2 [4]. As shown in the Fig. 2, our test results are somewhat higher than the estimated fatigue life in 310℃ air and PWR environments. Nonetheless, the results confirm the general tendency of lower LCF life (or, greater environmental effect) for the tests with slower strain rate. Also, LCF tests with sub-peak hold 60 seconds in PWR environment are on-going to clarify the effect of hold time on LCF life in PWR environment.

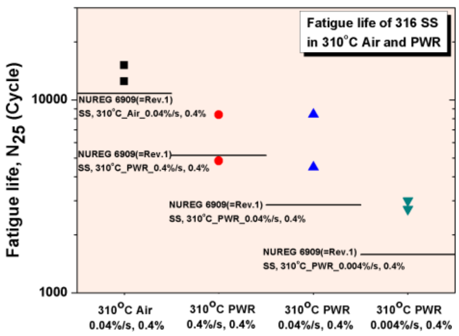

Fig. 2. Fatigue life of 316 SS in 310°C air and PWR environment

3.2 Cyclic stress response

Cyclic stress behaviors of type 316 SS in 310°C air, PWR and hold time conditions are shown in Fig. 3. As shown in the figure, after the primary hardening and softening, the secondary hardening was observed before the end of the test, which is similar to the behaviors of type 316 LN SS in the low amplitude [5]. Similar secondary hardening behavior was observed for type 316 SS in 310°C PWR environments at high strain rate of 0.4 %/s. Also, cyclic response with sub-peak holding will be studied after hold time condition test.

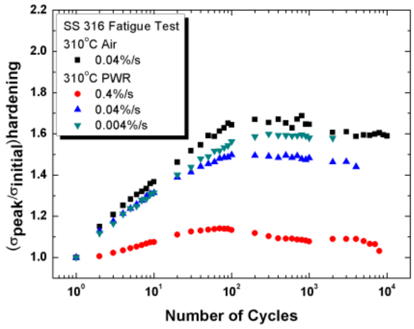

Fig. 3. Cyclic stress behavior of 316 SS in air and PWR environments at 310°C

4. Conclusions

The objective of this study is to characterize the effects of hold-time on the fatigue life of austenitic stainless steels in PWR environments in comparison with the existing fixed strain rate results. Low cycle fatigue life tests were conducted for the type 316 SS in 310°C air and simulated PWR environments. To simulate the heat-up and cool-down transient, sub-peak strain holding during the down-hill of strain amplitude was chosen. Currently, LCF tests with 60 seconds holding are in progress. The 0.4, 0.04%/s strain rate condition test results are presented in this study, which shows somewhat longer fatigue life. However, further tests are needed to draw any meaningful conclusions on the effects of hold-time on LCF life of type 316 SS in PWR environments.

Acknowledgements

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REFERENCES

[1] EPRI, "Environmentally Assisted Fatigue Gap Analysis and Roadmap for Future Research: Roadmap", 2012.
[2] ASTM, "Standard Specification for Chromium and Chromium-Nickel Stainless Steel Plate, Sheet, and Strip for Pressure Vessels and for General Applications", ASTM A-240.
[3] C. Jang, H. Jang, J.-D. Hong, H. Cho, T.S. Kim, and J.-G. Lee, "Environmental Fatigue Tests of Structural Materials – Review of Korean Test Programs," Nuclear Engineering Technology, 45, 7, 929-940, 2013.
[4] O. K. Chopra and G. L. Stevens, "Effect of LWR Coolant Environments on the Fatigue Life of Reactor Materials", NUREG/CR-6909, 2014.
[5] Y. J. Oh, et al., "A Comparison of Low-cycle Fatigue Properties in Stainless Steel Types 347N and 316N", Materials Transactions, Vol. 46, pp. 317-322, 2005.