Fatigue Life of Stainless Steel in PWR Environments with Strain Holding

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1. Introduction

Many components and structures of nuclear power plants are exposed to the water chemistry conditions during the operation. Recently, as design life of nuclear power plant is expanded over 60 years, the environmentally assisted fatigue (EAF) due to these water chemistry conditions has been considered as one of the important damage mechanisms of the safety class 1 components. Therefore, many studies to evaluate the effect of light water reactor (LWR) coolant environments on fatigue life of materials have been conducted. Many EAF test results including Argonne National Laboratory's consistently indicated the substantial reduction of fatigue life in the light water reactor environments [1].

However, there is a discrepancy between laboratory test data and plant operating experience regarding the effects of environment on fatigue: while laboratory test data suggest huge accumulation of fatigue damage, very limited experience of cracking caused by the low cycle fatigue in light water reactor. 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 in the pressurized water reactor (PWR) environments while incorporating the hold-time during the low cycle fatigue (LCF) test in simulated PWR environments.

2. Test Material and Method

2.1 Test Material

In this study, a commercial grade type 316 stainless steel was used for fatigue life test. The mill test certificate and chemical composition are shown in the Table I. The chemical composition meets the requirements specified in ASTM A-240. The tensile properties such as yield strength, ultimate tensile strength, and elongation are measured as shown in the Table II. According to the tensile test results, the yield strength and ultimate tensile strength of the test material are 316.58 MPa and 598.08 MPa, and the elongation is 77.86%. Therefore the tensile properties of the test material satisfied the requirements of ASTM.

Table I: Chemical composition of type 316 stainless steel

	C	Mn	P	S	Si	Cr	Ni	Mo	N	Cu	Fe
CMTR	0.052	0.56	0.028	0.001	0.54	16.74	10.24	2.13	0.029	0.22	Bal.
ASTM A240	Max 0.08	Max 2.00	Max 0.045	Max 0.03	Max 0.75	16-18	10-14	2-3	Max 0.10	-	-

Table II: Tensile properties of type 316 at room temperature

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

2.2 Test Conditions

The water chemistry conditions to simulate the typical PWR primary coolant environment are listed in Table III. To simulate the condition when the transients were completed, the sub-peak holding was applied after the peak stress. By selecting the down-hill holding, comparison of our results with those of published by other previous researchers would be possible [2].

The strain level for the sub-peak holding was determined from the hysteresis loop of the low cycle fatigue test of type 316 stainless steel in simulated PWR environments. As the LCF tests are performed in strain-controlled mode, holding at yield stress is not practical as the stress-strain response is continuously changing during the LCF test. Alternatively, we decided to apply the sub-peak holding at the strain corresponding to the quasi-yield stress of the 1st cycle as shown in the Fig. 1. In our case, the sub-peak holding condition is somewhat related to the heat-up and cool-down transient. As the test material would experience hardening and/or softening during the LCF test, the stress level at the holding would be changed at different cycle.

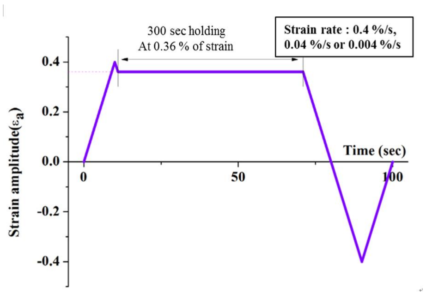

Fig. 1. Strain amplitude curve with sub-peak holding.

Table III: Low cycle fatigue test conditions

Test material		Austenitic SS (Type 316)	
		Air/PWR(ref.)	Hold-time (300 sec.)
Specimen		3 X 2 = 6	3 X 2 =6
Temperature		310℃	
Control		Strain control	
Strain rate (%/s)		0.4 / 0.04 /0.004	
Strain amplitude (%)		0.4	
Water chemistry	DO	< 5 ppb	
	DH	25 cc/kg	
	Conduc.	~ 20~25 μS/cm	
	pH	6 ~ 7	

3. Test Results

The results of the fatigue life test on the type 316 stainless steel performed in 310°C air and PWR environments are shown in Fig. 2. For comparison, the mean fatigue life data taken from the NUREG/CR-6909 Draft Rev.1 are also shown [3]. As shown in the figure, our test results are somewhat higher than the estimated fatigue life in NUREG/CR-6909 Draft Rev.1 in 310°C air and PWR environments. It seems that the scatter in fatigue life is rather large, though such is the typical of LCF tests in high temperature water environments. For those with large scatter, additional test may be needed to reduce the scatter. Otherwise, the results confirm the general tendency of lower LCF life for the tests with slower strain rate.

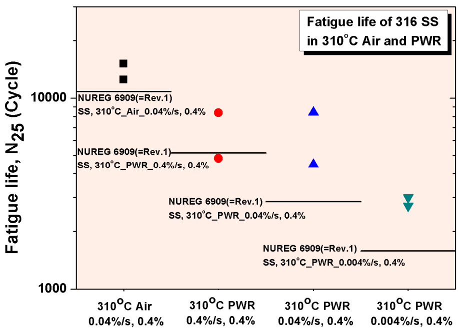

Fig. 2. Fatigue life in 310°C air and PWR environments.

The LCF tests to evaluate the effects of hold-time were performed at 310°C PWR environments. As mentioned previously, tests were performed twice at each low cycle test condition and total 6 cases were carried out. The results of the fatigue life test performed in 310°C PWR environments with strain holding 300 seconds are shown in the Fig. 3. For comparison purpose, the fatigue life model of NUREG/CR-6909 Rev. 1, which is proposed by O. K. Chopra and G. L. Stevens of ANL in 2014, in air and PWR at 310°C are also described in the figure. As shown in test results, the fatigue life is increased for 0.4 and 0.004 %/sec. strain rate, but reduced for 0.04 %/sec. Therefore, additional tests are required to evaluate more precisely the effects of sub-peak holding on the LCF life in PWR environments.

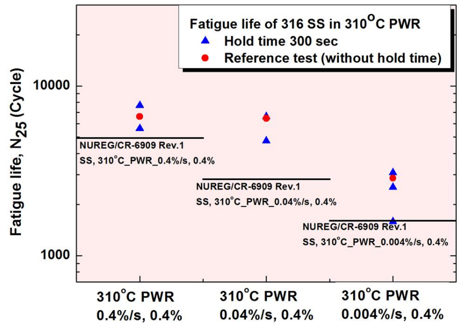

Fig. 3. Fatigue life when the sub-peak holding is applied during 300 seconds.

4. Conclusions

These hold-time effect tests are preformed to characterize the effects of strain holding 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 stainless steel in 310℃ air and PWR environments with triangular strain. In agreement with the previous reports, the LCF life was reduced in PWR environments. Also for the slower strain rate, the reduction of LCF life was greater than the faster strain rate.

The LCF test conditions for the hold-time effects were determined by the references and consideration of actual plant transient. To simulate the heat-up and cool-down transient, sub-peak strain holding during the down-hill of strain amplitude was chosen instead of peak strain holding which used in the previous researches. For 0.4% strain amplitude, a sub-peak holding at 0.36% of strain was decided from the 1st hysteresis loop of fatigue cycles. Total 7 LCF tests with 300 seconds holding are carried out and compared with the reference test results. Our test results indicated that hold-time effect was varied depending on strain rate and did not have a certain trend. Therefore, further tests including peak-holding tests are needed to draw any meaningful conclusions on the effects of hold-time on LCF life of type 316 stainless steel in PWR environments.

REFERENCES

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[3] O. K. Chopra and G. L. Stevens, Effects of LWR Coolant Environments on the Fatigue Life of Reactor Materials, NUREG/CR-6909, Rev.1, 2014.