Fatigue Life Comparison of Stainless Steels with Strain Holding in PWR Environments

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1. Introduction

Recently, as design life of nuclear power plant (NPP) 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. And these class 1 components and pipes are exposed to the water chemistry conditions during the operating period. Many EAF test results including Argonne National Laboratory's consistently indicated the substantial reduction of fatigue life in the light water reactor environments [1~4]. 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 the pressurized water reactor (PWR). 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 comparing the fatigue life of 2 types of stainless steels with different heat numbers 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, 2 types of commercial grade 316 stainless steels were used for fatigue life test. The one is ASTM A276 stainless steel of round bar type and the other is ASTM A240 of plate type. The mill test certificate and chemical composition are shown in the Table I. The analyzed chemical compositions are in good agreement with the relevant ASTM specifications.

Tensile properties of both test materials 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. The room temperature tensile properties of Heats A and B meet the requirements of ASTM A276 and ASTM A240, respectively.

Table I: Chemical composition of 316 stainless steels

Material Type	C	Ni	Cr	Fe	Mo	Mn	Si	P	S
Round Bar (Heat A)	0.058	10.14	17.07	Bal.	2.07	1.31	0.29	0.029	0.029
Plate (Heat B)	0.05	10.73	17.3	Bal.	2.15	0.64	0.6	0.020	0.001

Table II: Tensile properties of 316 stainless steels

Material Type	Spec.	Temp.	Yield Strength (MPa)	Ultimate Strength (MPa)	Elongation (%)
Round Bar (Heat A)	ASTM A276	RT	310	620	30
	Measured Property	RT	332	648	66.4
		325 ℃	222	497	43.0
Plate (Heat B)	ASTM A240	RT	205	515	40
	Measured Property	RT	316	598	77.8
		325 ℃	211	458	50.3

2.2 Test Conditions

Low cycle fatigue (LCF) tests were performed in fully-reversed loading (R = -1) under strain-controlled mode. The test conditions 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 dissolved hydrogen (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 normal DH concentrations (25 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 μS/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.

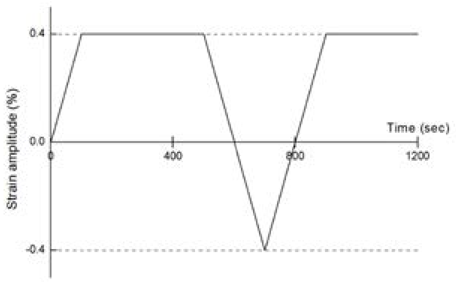


Fig. 1. Strain amplitude curve with peak holding.

Table III: Low cycle fatigue test conditions

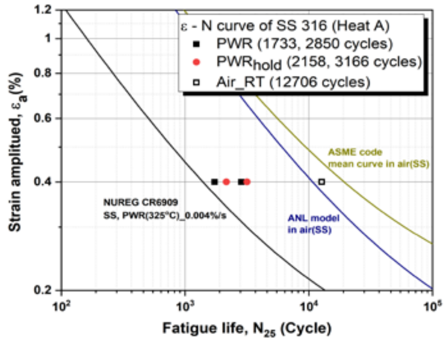
Test materials		Austenitic SSs (Type 316)	
Environment		Air	PWR
Temperature		RT/325℃	325℃
Control		Strain control	
Strain rate (%/s)		0.004	
Strain amplitude (%)		0.4	
Hold-time (sec.)		0	0/400
Water chemistry	DO	-	< 5 ppb
	DH	-	25 cc/kg
	Conduc.	-	20~25 μS/cm
	pH	-	6.3

3. Test Results

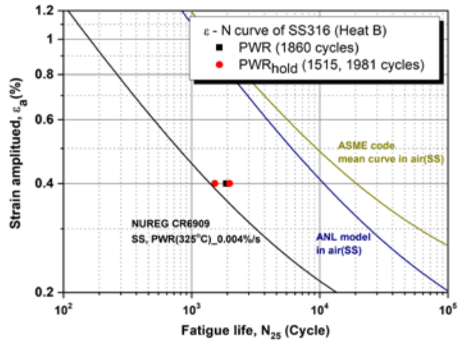
Based on the results of the preliminary tests, additional LCF tests were carried out at a strain rate of 0.004 %/s in order to provide additional time for the zinc to be absorbed into the oxide film at the crack tip. Both heat A and heat B were used in a normal DH environment test and the resulting fatigue life results are shown in Fig. 2. As shown in Fig. 2, there are small differences between two heat numbers in the fatigue life depending on the use of a peak strain hold period.

The cyclic hardening behavior for heat A and heat B from the tests is shown in Fig. 3. The results in this figure indicate that there is no significant difference regardless of the material heats when peak strain holding are applied. All the test conditions except for the tests performed in room temperature air indicate that there is primary hardening behavior up to 100 cycles, followed by softening behavior.

Under PWR_{hold} conditions, the longer softening behavior was observed compared to other test conditions. This suggests that the fatigue growth rate was lowered. Therefore, it is postulated that the effect of peak strain holding decreased the contribution of hydrogen induced crack (HIC) by reducing the hydrogen generation and absorption at the fatigue crack tip.

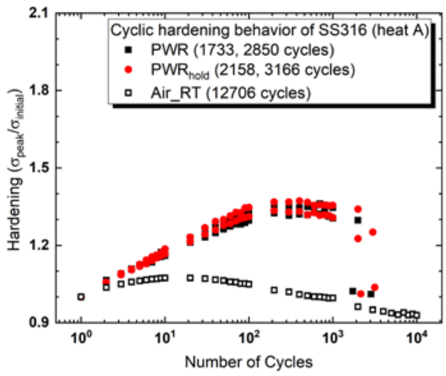


(a) Heat A

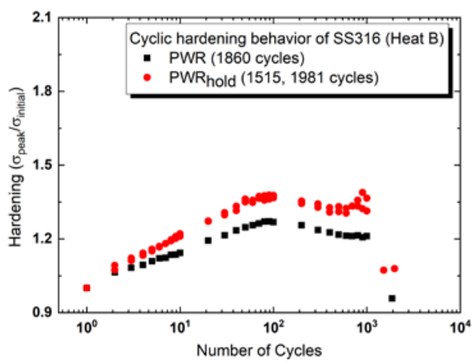


(b) Heat B

Fig. 2. Fatigue life for 316 SSs in PWR environments



(a) Heat A



(b) Heat B

Fig. 3. Cyclic hardening behavior of 316 SSs

4. Conclusions

The effect of zinc addition and peak strain holding in a normal DH PWR environment was evaluated. The results showed that fatigue life for the strain holding condition is very slightly increased and the environmentally assisted fatigue impact of NPP primary system water was decreased for two heats of 316 stainless steel. These results have a significant implication because the peak strain holding condition is related to the actual loading conditions in NPPs where there are large hold times between transients that cause LCF. Because the maximum strain in NPPs produced during one transient cycle tends to decrease after the maximum strain is reached, the peak strain holding condition is described for these tests is likely more conservative compared to actual NPP loading conditions. Because the fatigue crack tip is exposed to the corrosive environment for longer periods during peak strain holding, the amount of hydrogen generation and absorption at the crack tip is increased.

Nevertheless, it is not yet apparent whether strain holding improves the EAF life of stainless steels by reducing the generation and absorption of hydrogen, thereby increasing the resistance to crack propagation at the crack tip. Further testing with strain holding below the peak strain level including additional conditions such as zinc injection are needed to clarify the beneficial effects observed in this testing.

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