Fatigue Life of Austenitic Stainless Steel in Zinc Injection Environments

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1. Introduction

Since Regulatory Guide 1.207 for the application of environmental fatigue design issued by USNRC in 2007, there has been industry-wide activity led by Electric Power Research Institute (EPRI) to develop proper fatigue design methodology incorporating the Guide and its technical basis document NUREG/CR-6909. One of that efforts was to assess the effect of water chemistry in light water reactor (LWR) environments.

Over the years, we have tested and analyzed various structural materials in simulated PWR water environments. It was suggested by Jang et al. that hydrogen-induced cracking (HIC) could be the dominant mechanism of crack acceleration during EAF test for austenitic stainless steels [1, 2]. They also suggested that the difference in corrosion resistance could explain the different sensitivity to EAF between austenitic stainless steels and nickel-base alloys. Meanwhile, it has been well known that zinc addition would significantly improve the stress corrosion cracking resistance of nickel-base alloys in PWR environments by modifying the oxide layer [3].

Based on these understanding, it was proposed that, if oxide layer of austenitic stainless steels could be modified by zinc addition, the hydrogen generation by corrosion would be reduced, resulting in less contribution HIC during EAF test. Therefore, we have performed the EAF test program in the zinc-added environment and analyzed test results.

2. Test materials and conditions

Commercial-grade type 316 stainless steel rods were procured and used for the test and is equivalent to round bar 316 SS of ASTM A276. For verification, chemical composition was re-tested and the results. The chemical compositions in the material test report and verification analysis are compared in Table 1. Overall, the compositions are in good agreement.

Low cycle fatigue (LCF) tests were performed in fully-reversed loading (R = -1) in strain-controlled mode using triangular waveform. Same strain rates will be used at rising and falling parts of the strain cycle. In addition to LCF tests in zinc-added simulated PWR environment, LCF tests were performed in room temperature air, 325 °C air, and a typical PWR environment for comparison purpose. For all tests, 2 strain amplitude of 0.4 % and 1.0 % and 2 strain rate of 0.04 %/s and 0.004 %/s will be used. As the anticipated beneficial effect of added zinc during LCF in PWR environment is the modification of oxide layer, addition of 30 ppb zinc was chosen for this test program. The detailed test conditions are summarized in Table 2.

Room temperature pH was maintained in 6 ~ 7 by adding 1200 ppm boric acid and 2 ppm lithium hydroxide. The dissolved oxygen (DO) is maintained below 5 ppb and dissolved hydrogen (DH) concentration is 25 and 50 cc/kg-H_2O. Zinc was added to the distilled water in zinc acetate after the 10 ml of stock solution was mixed with 100 liter of water with boric acid and lithium hydroxide to make test solution of 30 ppb Zn.

Table 1 Tensile Properties of type 316 austenitic stainless steel

	YS (MPa)	UTS (MPa)	Elongation (%)
ASTM 276(RT)	310	620	Min. 30
Measured at RT	332.29	648.06	66.44
Measured at 325℃	221.90	496.95	42.96

Table 2 Fatigue test conditions in Zn-added PWR environments

Test material		Aus. Stainless Steel (316)		
Environment		Air	PWR	
Temperature		RT/325 °C	325 °C	
Strain amplitude (%)		0.4 / 1.0		
Strain rate (%/s)		0.04 / 0.004		
Water Chemistry	DO (ppb)	-	< 5	
	DH (cc/kg)	-	25	25
	Zinc (ppb)	-	0	30
	pH (RT)	-	6 ~ 7	

3. Low cycle fatigue tests

The LCF test results of SS316 in 325 °C PWR environment are shown in Fig. 3-1 and Table 5. In Fig. 1, the calculated fatigue life curve using NUREG/CR-6909 method is also shown for comparison. The average fatigue life was 3,027 cycle at 0.4 % strain amplitude with 0.04 %/s strain rate, which is somewhat greater than the estimated fatigue life of 2,540 cycles per NUREG/CR-6909 [4].

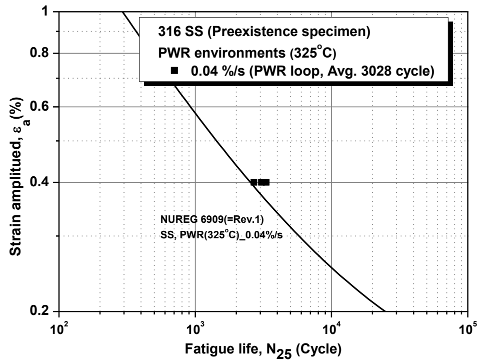

Fig.1 Fatigue life of SS316 in 325 °C PWR environment at 0.04 %/s

The LCF test results of SS316 in 30 ppb Zn-added 325 °C PWR environment are shown in Fig. 2. In Fig. 2, the LCF test results in PWR environment without Zn are also shown. The average LCF life in Zn-added environment is 3,655 cycles at 0.4 % strain amplitude with 0.04 %/s strain rate, which is slightly greater than that in Zn-free environment of 3,027 cycles. Such difference is within the scatter band of LCF test results, and the effect of Zn-addition on LCF life in PWR environment is not clear.

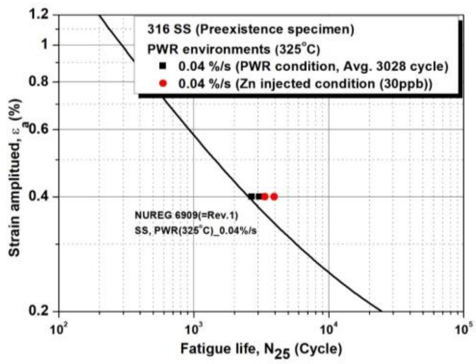

Fig.2 Fatigue life of SS316 in 325 °C Zn-added PWR environment at 0.04 %/s

The LCF test results of SS316 in 30 ppb Zn-added 325 °C PWR environment at strain rate of 0.004 %/s are shown in Fig. 3. In Fig. 3, the LCF test results in PWR environment without Zn are also shown. The average LCF life in Zn-added environment is 2,339 cycles at 0.4 % strain amplitude with 0.004 %/s strain rate, which is less than that with 0.04 %/s strain rate, as expected. The average fatigue life is about 1.68 times of the estimated fatigue life calculated by NUREG/CR-6909 methodology (1,393 cycles). As it is still within the scatter band, it is not clear whether there is the effect of Zn-addition on LCF life in PWR environment.

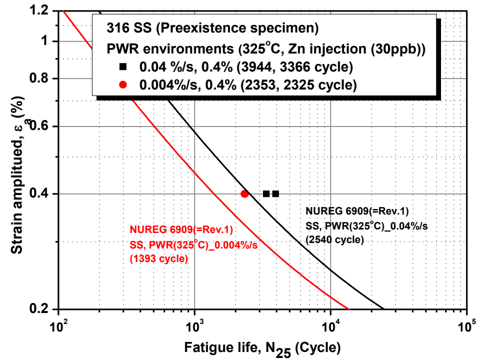

Fig.3 Fatigue life of SS316 in 325 °C Zn-added PWR environment at 0.004 %/s

4. Summary

To see the effect of Zn addition on the low cycle fatigue (LCF) behavior of austenitic stainless steels in PWR environment, a systematic test matrix was devised and some low cycle fatigue tests are performed. Referring literature on zinc addition to PWR primary system, it was decided that proper Zn concentration would be 30 ppb Zn. Test were performed in strain controlled mode with fully-reversed (R=-1) triangular loading at 0.4 % strain amplitude with 2 strain rate of 0.04 %/s and 0.004 %/s. Our tests in PWR environments with and without Zn addition were performed. According to the test results so far, the fatigue life of SS316 in Zn-added PWR environment was slightly longer than that in Zn-free PWR environment. In order to get more clear results on Zinc injection, the additional tests with longer hold-time and 0.004 %/s strain rate are in progress.

References

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