Evaluation of Environmentally-assisted Fatigue Behavior of Type 316L Stainless Steel in Simulated Small Modular Reactor Environments

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1. Introduction

As the issue of carbon neutrality has emerged around the world, the European-Union (EU) recently announced green taxonomy, and which includes nuclear power. However, in order for nuclear power to be used continuously, it must meet the requirements of green taxonomy. Therefore, new and innovative nuclear power plant (NPP) technologies should be developed, and the small modular reactor (SMR) has recently been in the spotlight as the next generation of NPP. Many countries have been developing their own design for SMR, representative of which are NuScale of the United States and CAREM of Argentina [1,2]. Moreover, Rep. of Korea is continuously conducting research to develop SMR such as SMART and i-SMR designed by Korea Atomic Energy Research Institute (KAERI) and ATOM designed by Korea Advanced Institute of Science and Technology (KAIST).

In pressurized water reactors (PWRs), the soluble boron diluted in primary coolant water for homogeneous reactivity control. However, it is known that the use of boric acid has unfavorable safety features such as slow response of reactivity control, shifting of the moderator temperature coefficient positively at the beginning of the reactor cycle, and occurrence of CRUD induced power shift (CIPS) due to boron accumulation at the nuclear fuel as known as axial offset anomaly (AOA) [3,4]. Therefore, the soluble boron free (SBF) environment is adopted as a water chemistry condition for NuScale and CAREM.

Meanwhile, environmental multiplier (F_{en}) is to be reflected in the fatigue design of new NPPs. However, since the F_{en} derived in NUREG/CR-6909 [5] is a proposed value based on environmentally-assisted fatigue (EAF) database in the light water reactor (LWR) environment. Therefore, it cannot be applied to SMR environment of SBF condition. Consequently, new F_{en} should be proposed for SMRs by conducting the EAF test.

In this study, the low cycle fatigue (LCF) test of type 316L stainless steel (SS) in both air and simulated SMR environment is performed to propose the F_{en}. Moreover, the EAF behavior is investigated through analysis from the aspect of the cracking mechanism and corrosion.

2. Experimental

2.1. Test Material

Test material used in this study is plate type of 316L SS. The Chemical composition measurement and evaluation of mechanical properties were performed prior to EAF test. The chemical compositions were analyzed by the inductively coupled plasma atomic emission spectroscopy (ICP-AES) as shown in Table 1. The dog-bone shaped LCF test specimen was used in this study, which has a gauge diameter and length diameter of 9.63 mm and 19.05 mm, respectively. The surface roughness (R_a) of LCF test specimen is 0.093 ± 0.009 μm.

2.2. Water chemistry condition for simulating SMR environments

To simulate the SMR environment of SBF condition, two different pH control agents of KOH and ammonia (NH_3) were used. The criterion for determining the concentration of the pH agents is the pH value at the test temperature (pH_T). The pH_T value is based on 7.1, which was selected as the water chemistry requirements for VVER that has a tight pH range of water chemistry and using KOH and ammonia as well.

2.3. EAF test equipment set-ups and test conditions

The EAF test equipment is consist of water loop system and two autoclaves equipped with servo actuator. The water chemistry is controlled at water loop system first, then is flow into autoclaves. An actual cyclic load is applied inside the autoclaves with 0.4 % of strain amplitude and 0.004 %/s of strain rate. According to NUREG/CR-6909, the effect of strain rate on EAF was observed in the range of 0.0004 to 7 %/s [5]. Therefore, the strain rate of 0.004 %/s was used in this study with consideration of test period and comparison with extensive test results. The detailed test conditions can be found in Table 2.

Table 1. Chemical compositions of SS 316L.

	Fe	Cr	Ni	C	Mn	Mo	Si	P	S	N
ASTM	Bal.	16.0-18.0	10.0-14.0	0.030	2.00	2.00-3.00	0.75	0.045	0.030	0.10
CMTR	Bal.	16.69	10.08	0.02	1.24	2.06	0.51	0.030	0.003	0.072
Measured	Bal.	16.82	10.01	0.027	1.28	2.04	0.53	0.032	0.001	0.067

Table 2. Test conditions.

Simulated SMR environment		KOH	NH_3
Temperature		325 °C	
Pressure		15 MPa	
Water chemistry	Dissolved Hydrogen	25 cc/kg-H_2O	
	Dissolved Oxygen	< 5 ppb	
	pH agent content (PPM)	2.75	0.85
Loading condition	Strain amplitude (%)	0.4	
	Strain rate (%/s)	0.004	

3. Results

3.1. EAF test results

The LCF tests were performed in the air environment and simulated SMR environment of 316L SS, and the results are shown in Fig. 1. In addition, the reference lines, which is calculated based on LCF test database in the air and PWR environment as following NUREG/CR-6909, are shown in the graph simultaneously.

The EAF tests were conducted under KOH and ammonia contained SMR environment, respectively. As shown in the Fig. 1, the fatigue lives are plotted in ε-N curve. Furthermore, in accordance with NUREG/CR-6909, reference lines calculated based on the LCF test database in the air and PWR environments is simultaneously displayed on the graph. The fatigue life in KOH-SBF environment is 1991 cycles, and which shows negligible difference compared to reference line of fatigue life in PWR environment. It is thought that the effect of pH agent is not significant because the pH_T is almost same compared with when boric acid and lithium hydroxide are added as pH agent. However, it is hasty to jump to conclusion whether different pH agent has effect on EAF behavior or not due to the lack of test result. Therefore, additional EAF test in both KOH-SBF and NH_3-SBF SMR environments are currently being performed. The effect of pH agent on EAF behavior will be evaluated by comparing the fatigue life results and cyclic response behavior.

3.2. Fracture surface and cross-sectional observation

During the fatigue test, the striation is formed on fracture surface, and which can indirectly indicate the fatigue crack growth rate by measuring striation spacing. The results of striation spacing measurement by scanning electron microscopy (SEM) will be added.

The fatigue crack propagation facet can be observed by cross-sectional analysis. In general, the crack propagation facet of fatigue is transgranular. However, the shape of crack tip, whether sharpening or blunting, can be different depending on test environment. Therefore, the cross-sectional analysis by SEM will be added

3.3. Weight changes and oxide film observation

The coupon specimens, which have 12 mm of diameter and 1 mm of thickness, for weight change measurement and oxide film observation are prepared. The surface of coupon specimens is polished using 1200 grit of SiC paper for weight change measurement and down to 1 μm for oxide film observation.

The coupon specimens are immersed in each test environment during EAF test. After the EAF test, the weight change and the oxide film observation will be performed and its results will be added.

4. Conclusion

The EAF tests of 316L SS are performed in simulated SMR environment, which are KOH- and NH_3-SBF environment. Currently, the EAF test in KOH-SBF environment is undergoing. After that, the EAF test in NH_3-SBF environment will be performed. Therefore, the conclusion would be made after EAF tests and several analysis such as fractography and cross-sectional analyses. Moreover, the corrosion behavior will be evaluated by weight change measurement and oxide film observation.

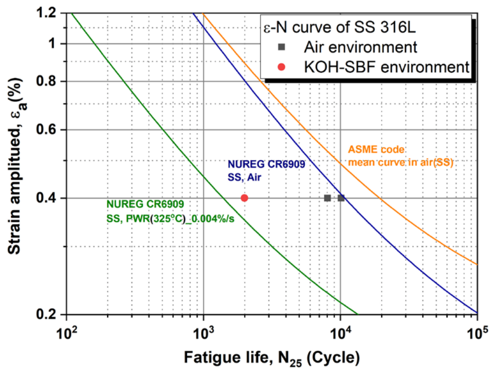

Figure 1. The EAF test results of 316L SS.

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