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Effects of mixed strain rates on low cycle fatigue behaviors of austenitic stainless steels in a simulated PWR environment

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ABSTRACT

Though strain rates are hardly fixed during the actual transients in nuclear power plants (NPP), most of the existing environmental fatigue ε–N data were obtained under simple loading histories with constant strain rates. In an effort to incorporate the actual loading conditions, strain rate was changed during the low cycle fatigue (LCF) test. The LCF tests were performed in a strain control mode in both simulated pressurized water reactor (PWR) environment and 310 °C air to evaluate the effects of mixed strain rates on fatigue life. The test results indicated that the modified strain rate approach and average strain rate method could be applied to the fatigue evaluation considering environmental effects. The cyclic stress response showed that the trend of hardening with mixed strain rate was consistent with a negative strain rate sensitivity, which was observed in the constant strain rate test. In addition, the increase in striation spacing on the fracture surface is in good agreement with the increase of bulk dislocation density and reduction of fatigue life.

1. Introduction

A significant reduction in low cycle fatigue (LCF) life of metallic materials in nuclear power plant (NPP) environments has been reported by the Argonne National Laboratory (ANL) [1–3] and Japanese researchers [4–7]. Such a phenomenon was named as an "Environmental Fatigue" and has been a significant safety concern for the NPPs. Based on the extensive test results and analysis, U.S. NRC (United States Nuclear Regulatory Commission) issued a Reg. Guide 1.207 which requires designers to incorporate the environmental correction factor (F_{en}) in fatigue design of new reactors [8]. The technical basis is well described in a NUREG/CR-6909, which provides the detailed statistical models to predict the fatigue life for carbon and low-alloy steels (LASs), stainless steels (SSs), and Ni–Cr–Fe alloys in primary water condition of NPP [1].

If the statistical models in the report were applied, the fatigue usage factors, determined by the ratio of the actual number of fatigue cycle to the allowable number of fatigue cycle, would increase significantly and exceed unity in some components of the operating NPPs. Nonetheless, cracking of failure by low cycle fatigue is rare in operating NPPs. One of possible explanations for the discrepancy between lab test results and field experience is the fact that nearly all of the environmental fatigue ε–N data were obtained under simple loading histories with constant strain rate which is far from the actual loading conditions in NPPs [1–5]. Previously, limited amount of tests with varying strain rate and strain holding were conducted to incorporate the actual plant operation transient condition in boiling water reactor (BWR) condition [6,7]. But the effects of complex loading such as a varying strain rate and holding at tensile strain are still unknown due to the lack of relevant test data and study.

In an effort to assess the effects of complex loading, the strain rate was changed (mixed strain rate) during the low cycle fatigue (LCF) test of 316LN SS in a simulated pressurized water reactor (PWR) environment and air environment, and the results were compared with the estimated values by analytical methods such as modified rate approach (MRA) and average strain rate approach. As a reference, the fully reversible triangular loading test (hereinafter denoted as "constant strain rate test") was also performed. Also, the cyclic stress response, dislocation structure, and cracking morphologies were analyzed to help understanding the effect of the mixed strain rate on the LCF behaviors.

2. Experimental

2.1. Test material

The test material used in this study was a forged 316LN SS, which has been used in the primary piping system of

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Table 1
Chemical compositions of 316LN SS (wt.%).

C	Mn	P	S	Si	Cr	Ni	Mo	N	Co	Cu
0.018	1.84	0.022	0.016	0.46	16.37	11.30	2.11	0.096	0.10	0.28

Table 2
Tensile properties of 316LN SS.

	Y.S. (MPa)	U.T.S. (MPa)	Elong. (%)
RT	294.7	577.1	67.7
310 °C	174.2	478.2	44.3

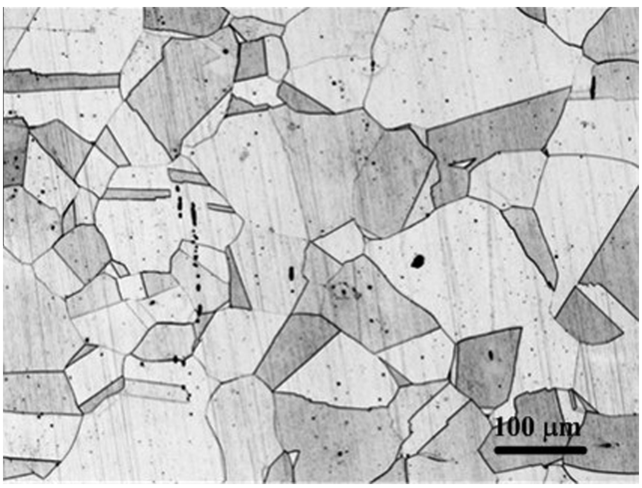

Fig. 1. Microstructure of 316LN SS used in this study.

some PWRs. A round-bar shape 316LN was obtained as solution-annealed at 1065 °C for 1 h followed by quenching in water. The chemical compositions of the test material were analyzed by inductively coupled plasma (ICP) method and shown in Table 1. Before the LCF test, tensile properties were measured at room temperature (RT) and 310 °C, and the results are summarized in Table 2. As shown in the tables, the composition and tensile properties are within the specifications of ASME SA-312 [9]. As shown in Fig. 1, the material has fully austenitic structure and the average grain size is about 100 μm.

2.2. Test conditions and methods

LCF tests were performed in accordance with ASTM E 606 [10] using round bar type specimens with gauge length 19.05 mm and gauge diameter 9.63 mm. During the LCF test, the strain in the gauge section was indirectly measured using a linear variable differential transformer (LVDT) attached at the shoulders of the specimen. The strains in the gauge section were calculated from the values between the shoulders using the correlation between the two values which was established before the test as described before [11]. The schematics of strain measurement are shown in Fig. 2. For given strain amplitudes in the gauge section, corresponding LVDT values between the shoulders are measured, which were used in the LCF tests.

The test system for LCF in a PWR primary water environment consists of servo-electric fatigue testing machine, an autoclave, and the water circulation loop. The details are described in the previous studies [11,12]. The test environment was simulated PWR water at 310 °C and 15 MPa (hereinafter denoted as "PWR water") containing representative concentrations of dissolved boric acid and lithium hydroxide. The levels of dissolved oxygen (DO), dissolved hydrogen (DH), conductivity and pH were monitored and controlled at RT throughout the test. After the DO was in the test water reduced below 5 ppb by Ar gas bubbling, the concentration of OH was controlled at 2.2 ppm (correspond to 25 cc H_2/kg-H_2O) to simulate the PWR water condition.

The LCF tests were performed in strain control mode with a fully reversed ($R = -1$) mixed waveform (varying strain rate) and triangular waveform (constant strain rate). The two different strain amplitudes were used (0.28%, 0.83% in PWR water and 0.28%, 0.65% in air). The constant strain rate tests were performed at the rates of 0.24, 0.024, and 0.005%/s while mixed strain rate tests were conducted at 0.24–0.024%/s and 0.24–0.005%/s. The mixed waveform consists of two different strain rates such that the strain rate from 0% to 75% of strain amplitude is 0.24%/s and that from 75% to peak is 0.024 or 0.005%/s, as shown in Fig. 3. The details of test conditions are summarized in Table 3. The fatigue life, N_{25}, is defined as the number of cycles for the tensile stress to drop 25% from

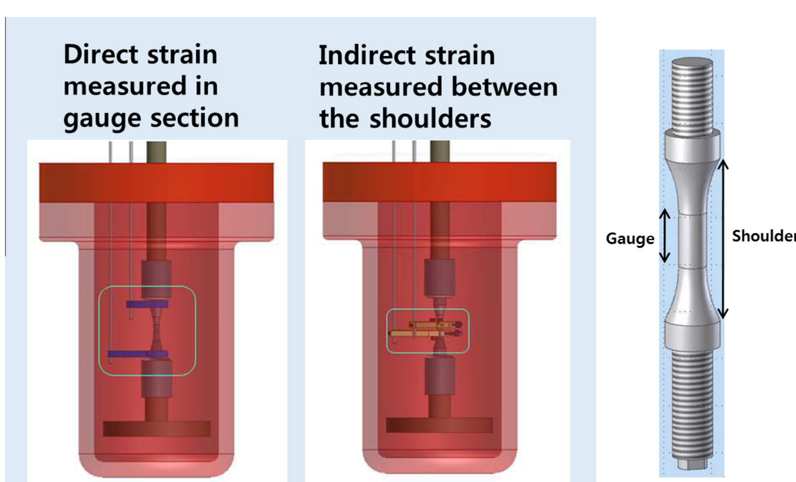

Fig. 2. Schematics of direct and indirect strain measurement for correlation.