Cyclic Deformation Behavior of SA508 Gr.1a Low Alloy Steel under Low Cycle Fatigue Loading in 310 ^{o}C Low Oxygen-Contained Water

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1. Introduction

It has been known that fatigue failure is one of the most significant degradation mechanisms occurred in nuclear power plants. Because operating condition of nuclear power plants is high temperature water, the fatigue failure induced by environmental parameters, such as temperature, dissolved oxygen (DO) content, etc, is very important as well as fatigue failure induced by loading parameters [1]. Furthermore, fatigue damage may be even accelerated by a combination of loading parameters and environmental parameters. Low alloy steels are widely used for structural components in nuclear power plants. Thus, study on low cycle fatigue (LCF) deformation of SA508 Gr.1a low alloy steel (LAS) in high temperature water is required for safety and integrity of nuclear power plants. This work was aimed to investigate cyclic deformation behavior of SA508 Gr.1a LAS under LCF loading in 310 ^{o}C low DO water.

2. Experimental procedures

2.1 Test Material and LCF Specimen

Test material used presently was ASME SA508 Gr.1a LAS piping material. The as-received test material had been normalized at 920 ^{o}C for 10 min and water quenched, and then tempered 650 ^{o}C for 130 min in air. The chemical composition of this steel is (wt.%): C, 0.300; Si, 0.400; Mn, 1.35; P, 0.025; S, 0.0100; Al, 0.040; Cu, 0.200; Cr, 0.250; Ni, 0.400; Mo, 0.100; and Fe rem. Test material has a ferrite-pearlite microstructure, and grain size of this steel is 9-10. Round bar type LCF specimens with gauge diameter of 9.63mm and gauge length of 19.05 mm were machined from this steel pipe.

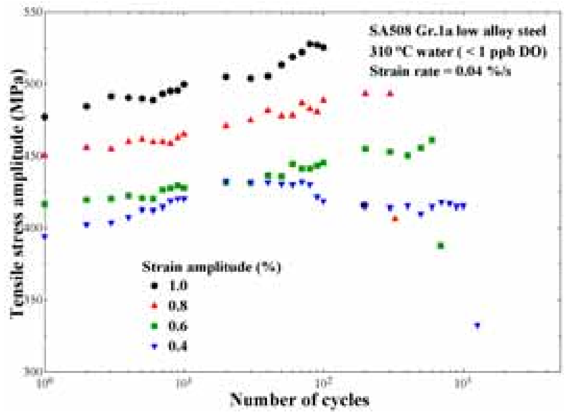
2.2 Test System and Conditions

The system for LCF tests in high temperature water is composed a servo-electric fatigue test machine of ± 60 kN in dynamic load, an autoclave, and a water circulation loop. In this work, two water columns were used to control DO content of the purified water conveniently and quickly. Applied strain was measured by the recorded difference of dual extensometers, mounted with the LCF specimen. Fatigue life was defined as a number of cycles, N_{25}, achieved before the load to dropped 25 % from its peak value. LCF tests were conducted in strain control mode with fully reversed triangular waveform (R=-1) in 310 ^{o}C low DO water. Strain rates were 0.04 and 0.008 %/s, and strain amplitudes varied from 0.4 to 1.0 % in this work. The DO content in the test water was controlled under 1 ppb on the feed water and the return water line. The conductivity was maintained below 0.1 μS/cm.

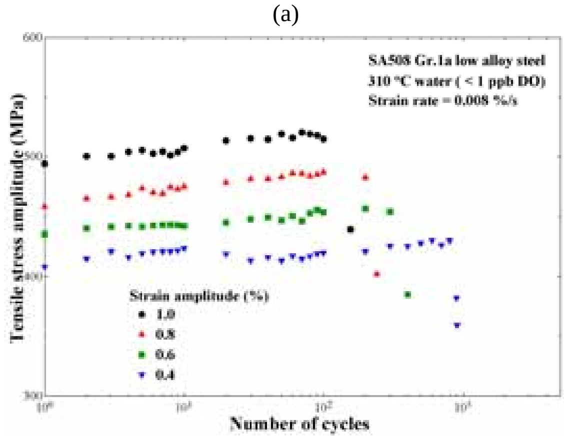
3. Results and Discussion

3.1 Cyclic Hardening Behavior

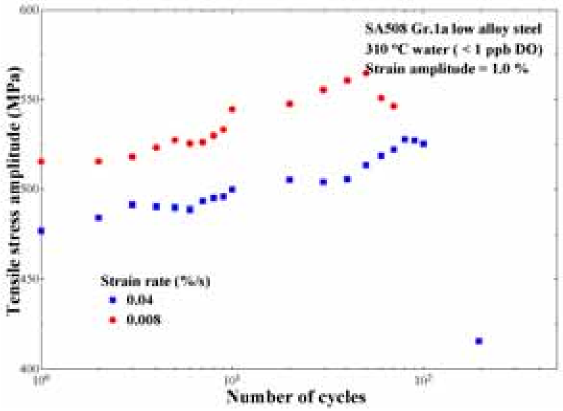
Cyclic stress responses of SA508 Gr.1a LAS with strain rate in 310 ^{o}C low DO water are shown in Figure 1. The test material exhibited a moderate cyclic hardening at all testing conditions. A saturation stage or a slightly secondary hardening occurred with decreasing strain amplitude.



(a)



(b)



(c)

Figure 1. Cyclic stress response of SA508 Gr.1a LAS in 310 °C low DO water; (a) 0.04 %/s , (b) 0.008 %/s, (c) comparison with strain rate

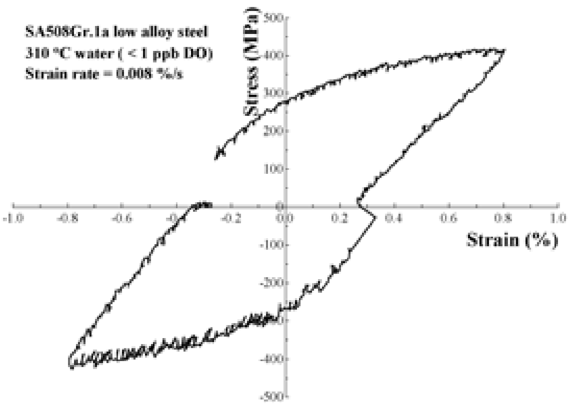


Figure 2. Serrated flow in the stress-strain hysteresis loop

It may be considered that dynamic strain aging (DSA) induce the hardening behavior [2]. Negative strain rate sensitivity, i.e. an increase of stress amplitude with decreasing strain rate and serrated flow in the stress-strain hysteresis loop are observed. The negative strain rate sensitivity and serration are typical manifestations of the DSA [3]. The serrated flow was induced by interaction between diffused solute atoms and moving dislocations in the regime of DSA. The negative strain rate sensitivity occurred due to an increase of total dislocation density with decreasing strain rate. It is necessary to increase applied stress to make the pinned dislocation break away and continuously move forward. Also the increase of total dislocation density induces an increase of flow stress for applying same strain during LCF deformation. Therefore, it may be considered that DSA is related to the cyclic hardening behavior observed in this work.

3.2 Strain-Fatigue Life (ε-N) Curve

The ε-N curves of SA508 Gr.1a LAS in 310 °C low DO water are shown in Figure 3, where the ASME design fatigue curves are also presented for comparison [4].

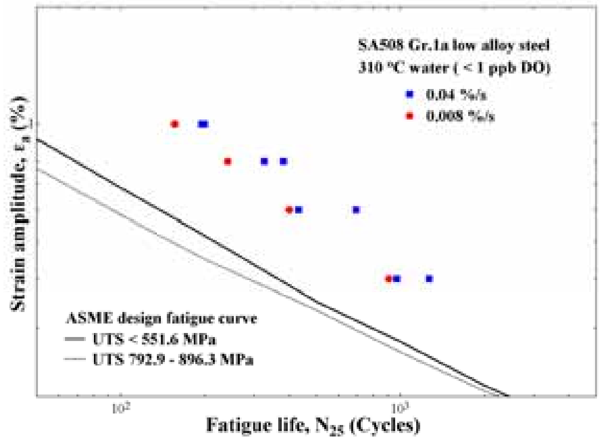


Figure 3. ε-N curves of SA508 Gr.1a LAS in 310 °C low DO water

As shown in Figure 3, fatigue life decreases a little with decreasing strain rate. DSA is potential reason for the reduction of fatigue life with decreasing strain rate in 310 °C low DO water [2]. DSA leads to initiation of fatigue cracks in an earlier stage of fatigue deformation, and an increase of crack propagation [3]. It had been reported that the effect of strain rate on fatigue life is dependent on DO level [5]. So, the reducing rate of fatigue life with a decrease of strain rate is not large due to low DO concentration. More tests and analysis are required to conclusively prove the effect of DSA and environment on the fatigue life of SA508 Gr.1a LAS in high temperature water.

3. Summary

(1) SA508 Gr.1a LAS exhibited a moderate cyclic hardening in 310 °C low DO water. A saturation stage or a slightly secondary hardening was occurred with decreasing strain amplitude.
(2) Fatigue life of SA508 Gr.1a LAS decreases a little with decreasing strain rate in 310 °C low DO water.

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