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The effect of dissolved oxygen on fatigue behavior of Alloy 690 steam generator tubes in borated and lithiated high temperature water

Jibo Tan[a], Xinqiang Wu[a,*], En-Hou Han[a], Xiaoqiang Liu[b], Xuelian Xu[b], Haitao Sun[c]

[a] *Key Laboratory of Nuclear Materials and Safety Assessment, Liaoning Key Laboratory for Safety and Assessment Technique of Nuclear Materials, Institute of Metal Research, Chinese Academy of Sciences, Shenyang 110016, PR China*
[b] *Shanghai Nuclear Engineering Research and Design Institute, Shanghai 200233, PR China*
[c] *Nuclear and Radiation Safety Center, SEPA, Beijing 100082, PR China*

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ABSTRACT

Corrosion fatigue behavior of Alloy 690 tubes used for actual steam generator (SG) was investigated in borated and lithiated high temperature water containing <5 ppb (by weight) and 5500 ppb dissolved oxygen (DO) using boat-shaped specimens. It was found that the fatigue life at 5500 ppb DO was longer than at <5 ppb DO. The surface cracks and fracture characteristics of the specimens after fatigue tests were carefully examined. The effects of DO concentration on fatigue crack initiation and propagation of Alloy 690 tubes in high temperature water are discussed.

1. Introduction

Because of its good corrosion resistance and mechanical property, Alloy 690 has been widely used as steam generator (SG) tubes in pressurized water reactors (PWRs). During the process of heat exchange, Alloy 690 tubes might suffer from corrosion fatigue (CF) damage due to thermal loading and flow induced vibration [1–6]. The current American Society of Mechanical Engineers (ASME) code design curve [7] for austenitic alloys did not fully consider the effects of light water reactor (LWR) environment. Therefore, it could not evaluate the CF damage of Alloy 690 tubes accurately. In 2007, the US Nuclear Regulation Commission (NRC) promulgated RG 1.207 [8], which required a new nuclear power plant to fully address the environmental factors into fatigue damage evaluation. Many researchers [2–6,9–15] have studied the effects of LWR environments on CF behavior of nuclear-grade structural materials. Their results suggested that dissolved oxygen (DO) was one of the key factors influencing fatigue crack initiation and propagation. The concentration of DO affected the structure of oxide film of nuclear-grade structural materials, such as low alloy steels, austenitic stainless steels and nickel-based alloys, in high temperature pressurized water [16–24]. It is believed that the compactness of oxide film and the adhesion strength between the oxide film and the substrate affects the CF crack initiation. In addition, the concentration of DO in high temperature water affected the crack tip water chemistry, which was related to fatigue crack growth rate (da/dN) [25–28]. Chopra and Shack [3] reported the fatigue life of carbon steel and low alloy steel reduced with increasing DO, especially under low strain rate condition. Katada et al. [29] suggested the da/dN of A533B steel increased with increasing DO concentration in high temperature pressurized water. Seifert et al. [9] reported the da/dN of austenitic stainless steel under LWR condition increased with increasing DO concentration. Ruther et al. [30] reported the da/dN of Alloy 600 and Alloy 690 in high temperature water showed independence on DO concentration at a load ratio of 0.6, but slightly increased with increasing DO concentration at a load ratio of 0.9. However, Chopra and Shack [3] reported the fatigue life of austenitic alloys in LWR environments increased with increasing DO concentration. The JNSE-SS-1005 [4] also showed the influence of strain rate was more prominent in PWR environment than in boiling water reactor (BWR) environment. Therefore, the effect of DO on CF crack initiation was different from that on CF propagation for austenitic alloys under LWR condition. It is interesting and important to investigate and clarify the role of DO concentration on fatigue crack initiation for austenitic alloys under LWR condition.

In the present work, low cycle fatigue (LCF) tests of Alloy 690 tubes used for actual SG were performed in borated and lithiated

* Corresponding author. Fax: +86 24 2389 4149.
E-mail address: xqwu@imr.ac.cn (X. Wu).

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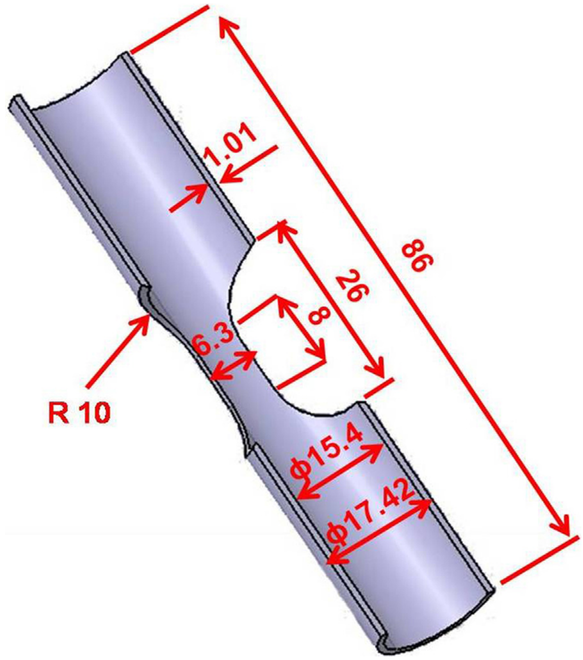

Fig. 1. Illustration of boat-shaped specimen used in the present work.

high temperature water with different DO concentrations to investigate the DO dependent fatigue crack initiation and propagation mechanisms.

2. Experimental details

2.1. Materials

Three types of as-received Alloy 690 SG tubes were used in the present study. One was made in Japan, which was labeled as tube J. The other two were made in China, which were labeled as tube C1 and C2, respectively. Tables 1 and 2 show the compositions and mechanical properties of the tubes used.

Table 1
Composition of Alloy 690 SG tubes investigated (wt.%).

	Ni	Cr	Fe	Mn	C	Al	Ti	Cu	Si	N
Tube J	59.3	29.89	9.2	0.26	0.018	0.13	0.26	0.029	0.31	0.0067
Tube C1	60.2	29.47	9.8	0.018	0.020	0.11	0.13	0.010	0.04	0.01
Tube C2	59.4	29.47	9.9	0.079	0.019	0.12	0.27	0.016	0.20	0.028

Table 2
Mechanical property of the investigated Alloy 690 SG tubes at room temperature.

	$R_{p0.2}$ (MPa)	R_m (MPa)	Elongation (%)
Tube J	321	732	67.8
Tube C1	355	779	62.1
Tube C2	337	774	63.7

2.2. Microstructural analysis

Alloy 690 tube samples for microstructure observation were prepared by sequential grinding through 240, 800, 2000 grit silicon carbide papers followed by 2.5 μm diamond polishing, and its surface was parallel to the axis and normal to radial direction. The polished specimens were electrolytic etched in a 10–15% H_2CrO_4 solution for about 10 s at 4 V to reveal their microstructural characteristics.

2.3. Fatigue specimen and experimental procedure

The diameter and thickness of the as-received SG tubes are 17.4 mm and 1.01 mm, respectively. A kind of boat-shaped LCF test specimen with 8 mm gauge length, 6.3 mm gauge width and 1.01 mm thickness was designed and machined along the axial direction of the SG tubes (Fig. 1). The specimen was machined by wire-electrode cutting. The specimen kept the original inner and outer surfaces and its lateral surfaces (machined surfaces) were ground successively with silicon carbide paper up to 2000 grit, which made sure its surface roughness (R_a, which is the arithmetical mean deviation of the profile) was better than 0.4 μm. The surface roughness is identical for tubes J, C1 and C2. Then, the specimen was cleaned ultrasonically with alcohol, dried and preserved in a desiccator. The equipment for LCF tests in high temperature water consisted of a electro-servo hydraulic fatigue testing machine of ±50 kN in dynamic load, an austenitic stainless steel autoclave of

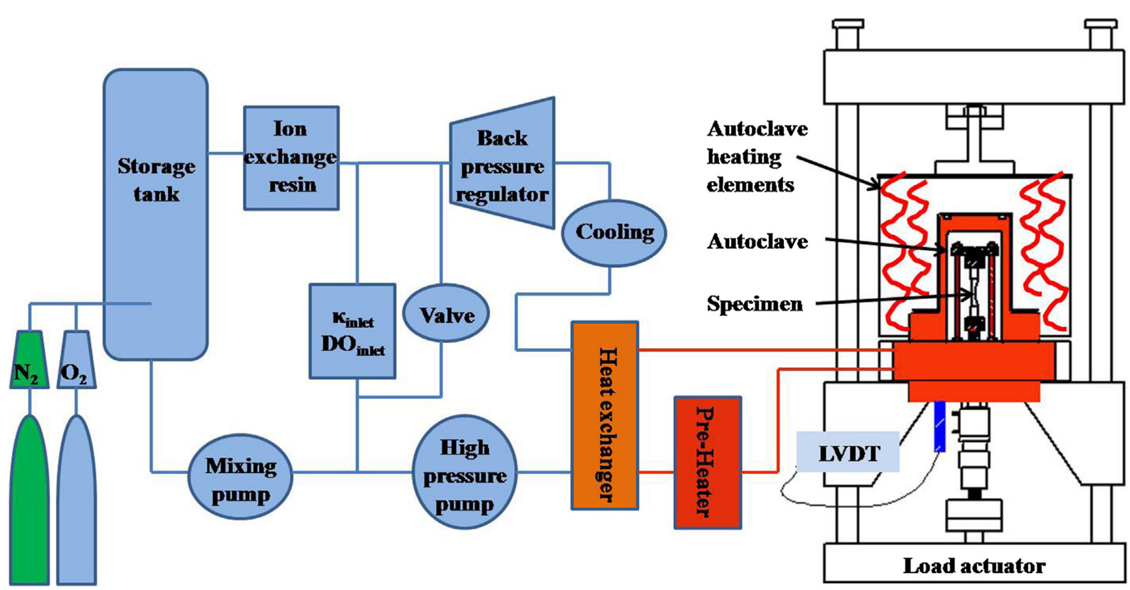

Fig. 2. Schematic of high-temperature water corrosion fatigue test machine.