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Crack growth of throughwall flaw in Alloy 600 tube during leak testing

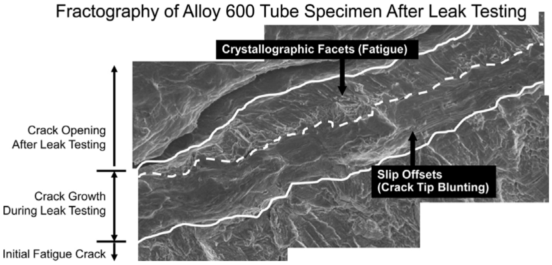
Chi Bum Bahn[a,*], Saurin Majumdar[b]

[a] Pusan National University, 2 Busandaehak-ro 63beon-gil, Geumjeong-gu, Busan 609-735, Republic of Korea
[b] Argonne National Laboratory, Lemont, IL 60439, USA

HIGHLIGHTS

- A series of leak testing was conducted at a constant pressure and room temperature.
- The time-dependent increase in the leak rate was observed.
- The fractography revealed slip offsets and crystallographic facets.
- Time-dependent plasticity at the crack tip caused the slip offsets.
- Fatigue by jet/structure interaction caused the crystallographic facets.

GRAPHICAL ABSTRACT



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ABSTRACT

We examined the issue of whether crack growth in a full thickness material can occur in a leaking crack. A series of leak tests was conducted at a room temperature and constant pressure (17.3 MPa) with Alloy 600 tube specimens containing a tight rectangular throughwall axial fatigue crack. To exclude a potential pulsation effect by a high pressure pump, the test water was pressurized by using high pressure nitrogen gas. Fractography showed that crack growth in the full thickness material can occur in the leaking crack by two mechanisms: time-dependent plasticity at the crack tip and fatigue induced by jet/structure interaction. The threshold leak rate at which the jet/structure interaction was triggered was between 1.3 and 3.3 L/min for the specific heat of the Alloy 600 tube tested.

1. Introduction

Argonne National Laboratory (ANL) performed several series of leak rate tests on steam generator (SG) tube specimens containing laboratory-grown stress corrosion cracks (SCCs). In some cases, dramatic increases in leak rates have been observed over relatively short times under nominally constant pressure conditions (Begley, 2008). A series of tests conducted on specimens with a trapezoidal or rectangular electric discharge machining (EDM) notch also showed such behavior (Begley, 2008; Bahn and Majumdar, 2010). These time-dependent leak rate increases suggest that time-dependent crack growth can occur at room temperature in Alloy 600 tube specimens tested with relatively non-corrosive water (tap water). Hwang et al. (2005, 2007) also reported the time-dependent leak rate increases. The possible mechanisms for this time-dependent crack growth at constant pressure and room temperature are limited. Fractographic observations can be used to determine whether fatigue or ductile tearing by creep was responsible for the observed time-dependent crack growth. Electric Power Research Institute (EPRI) has implemented a program to determine the significance of the ANL leak rate test data relative to the leakage integrity of operating SGs and the current methodologies of determining, evaluating and projecting the leak integrity of service-degraded SG tubing (Begley, 2008). ANL leak rate test specimens that showed time-dependent leak behavior have been fully characterized (Begley, 2008). SEM fractographs revealed both ductile

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* Corresponding author. Tel.: +82 51 510 1033; fax: +82 51 514 7460.
E-mail address: bahn@pusan.ac.kr (C.B. Bahn).

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Table 1
Leak test specimens with crack lengths, leak rate results, and fractography results (Begley, 2011).

Specimen ID	Crack length before test @ OD, mm (in)	Crack length after test, mm (in)		Avg. wall thickness, mm (in)	Leak rate, L/m (gpm)		Total test time (h)	Fractography
		at OD	at ID		Initial	Final		
EPRI-01	Not measured	9.73 (0.383)	9.55 (0.376)	1.14 (0.0449)	1.3 (0.35)	1.2 (0.33)	7.3	Ductile
EPRI-03	12.0 (0.471)	12.0 (0.471)	11.6 (0.457)	1.19 (0.0469)	3.3 (0.88)	3.6 (0.96)	6.7	Ductile + crystallographic facets
EPRI-04	13.3 (0.525)	13.3 (0.525)	13.0 (0.512)	1.15 (0.0453)	7.2 (1.9)	7.9 (2.1)	4.4	Ductile + crystallographic facets
EPRI-05 at 16.3 MPa	17.2 (0.678)	17.2 (0.679)	17.1 (0.675)	1.13 (0.0445)	27 (7.1)	30 (8.0)	2.0	Ductile + crystallographic facets
EPRI-05 at 17.3 MPa					~42 (~11)	47 (12.3)	2.1	

tearing of the remaining ligaments and fatigue crack growth at low ΔK levels indicated by crystallographic facets. In some cases, the fatigue crack grew not only in the tapered ligaments but also in the full thickness material. Therefore, two mechanisms could be attributed to the time-dependent leak behavior: a time-dependent plasticity at the crack tip and fatigue that might be induced by water jet/structure interaction. However, all the specimens that showed fatigue crack growth were tested in a facility equipped with a high-pressure pump that could induce pressure pulsation. However, further examination (Bahn and Majumdar, 2010; Bahn et al., 2011) proved that a thin tapered ligament could be fractured by fatigue in a test facility without pump pulsation.

The fracturing of a tapered ligament creates a throughwall rectangular crack. The leak rate from such a rectangular crack can be significantly increased under constant pressure if the full-thickness ligament ahead of the crack tip can be continually fractured, resulting in a progressively longer crack. Time-dependent ligament fracture can occur by the time-dependent plasticity mechanism and by fatigue caused by pressure oscillations due to jet/structure interaction. Of these two mechanisms, fatigue is a more serious concern because the time-dependent plasticity is generally self-limiting, whereas the fatigue crack growth rate generally increases with the number of cycles or time. Therefore, it is important to determine whether a leaking, tight rectangular throughwall crack can grow through the full thickness of the material by fatigue under constant pressure conditions.

The main objective of this work is to conduct leak testing at constant pressure conditions (17.3 MPa (2500 psig)) with Alloy 600 SG tube specimens containing a tight rectangular throughwall axial fatigue crack. The axial crack length of the test specimen was increased after completing each leak test until the time-dependent leak behavior becomes significant. To exclude the pulsation effect by a high-pressure pump, the Blowdown Test Facility at ANL was used. Following leak testing, fractographic analyses of the tube specimens were conducted to determine the fundamental mechanisms of the time-dependent increases in leak rates, if any.

2. Experimental methods

2.1. Leak test facility

A detailed configuration of the Blowdown Test Facility is described in earlier literatures (Bahn et al., 2011; Begley, 2011; Kasza et al., 2002). A brief description of the test facility is provided as follows. A tube specimen containing a throughwall fatigue crack was installed in a test chamber. The tube's interior was pressurized with water at 17.3 MPa (2500 psig), while the tube's outside pressure was atmospheric pressure. The water leak rates through the crack were measured during the leak testing. To sustain leak testing over long durations, the 850 L (225 gal) water storage vessel of the Blowdown Test Facility was used for this purpose. To maintain the water pressure at 17.3 MPa during leak testing, a nitrogen cover gas was supplied to the top plenum of the water vessel. The measurement error of the pressure was less than ±0.03 MPa (4.5 psi).

Two independent methods were used to measure the leak rates through a crack. First, a turbine flow meter was installed downstream from the water vessel and upstream from the test specimen. The flow meters were calibrated and the measurement error was less than ±0.25% of the full scale (9.5 or 30 L/min (2.5 or 8 gpm)). Second, the leak rates were measured indirectly by monitoring the weight change of the water vessel. Load cells were calibrated in-house as a system; instead of removing the load cells from the system. Standard lead and steel blocks of known weight were stacked on the water vessel supporting frames. The blocks were removed one-by-one, and the load cell meter signals were calibrated against the actual total block weights. The measurement error of the leak rate by the weight change method was less than ±1.5 L/min.

In the test chamber, the Alloy 600 tube specimen was surrounded by six neighboring 19.05 mm (3/4 in.) outside diameter (OD) stainless steel tubes. To simulate actual SG conditions, drilled hole-type tube support plates were used. Six neighboring stainless steel tubes passed through the holes in the tube support plates. They were placed horizontally and supported by two tube support plates, forming a hexagon shape. The Alloy 600 tube specimen was positioned in the center of the neighboring tubes. A fatigue crack in the Alloy 600 tube specimen faced upward in the test chamber.

2.2. Fatigue crack specimen fabrication

Alloy 600 tubing (Heat # 96834) with a 19.1 mm (3/4 in.) OD and a nominal wall thickness of 1.07 mm (0.043 in.) was used for the leak test specimens. It is noted that the measured wall thickness of this tubing was slightly larger than the nominal value. The actual wall thickness of each specimen is described in Table 1. The yield and ultimate tensile strengths of this tubing at room temperature are 389 and 737 MPa (56.4 and 106.9 ksi), respectively. Final mill annealing was conducted at 927 °C (1700 °F) for 3–5 min. To make an axial throughwall fatigue crack in the Alloy 600 tube specimen, an EDM starter notch with a depth of 40% throughwall (TW) and an axial length of 6.3 mm (0.25 in.) was machined on the OD surface. To initiate and grow a fatigue crack from the starter notch, the tube interior pressure was cycled. Once a throughwall crack was formed, a plastic bladder was inserted into the tube specimen to prevent leakage through the crack. Then, the tube interior pressure was cycled again until the total axial fatigue crack length reached a target value. Fig. 1 shows a schematic of the hydraulic system used to fabricate the fatigue crack specimens. A hydraulic cylinder was connected to a servo-hydraulic test machine and the outlet pressure line of the hydraulic cylinder was connected to the Alloy 600 tube specimen. The hydraulic cylinder, the outlet pressure line, and the tube specimen were filled with hydraulic oil.

Fig. 2 shows the maximum tube interior pressures needed to keep the maximum stress intensity factor less than 33 MPa $\sqrt{\text{m}}$ (30 ksi $\sqrt{\text{in}}$) during the fatigue loading as a function of the axial throughwall crack length. Usually the tube interior pressure was