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LIGAMENT RUPTURE AND BURST PRESSURE OF MECHANICAL DEFECTS OF STEAM GENERATOR TUBINGS

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ABSTRACT

Some events of a steam generator tube rupture have been reported in some nuclear power plants around the world. Main causes of the leakage are from various types of corrosion in the steam generator (SG) tubing. Primary water stress corrosion cracking (PWSCC) of steam generator tubing has occurred in many tubes in Korean plants, and they were repaired using sleeves or plugs. In order to develop proper repair criteria, it is necessary to ascertain the leak behavior of the tubings. Various types of Electro-Discharged-Machined (EDM) notches with different lengths in the axial and circumferential direction were machined on the OD of test tubes to study the ligament rupture or burst behavior. Ligament rupture pressures as well as the burst pressures were measured for the tubes at room temperature. For the axial flaw which ranged from 25 mm up to 62 mm, the burst pressure of the part through-wall tubes depended rather on the defect depth than on the defect length. Circumferential defects showed a two times higher burst pressure than that of the axial defect of which the length was the same. Pressurization rate effect on the burst pressure of the circumferential defects was not so big. A back up foil increased the burst pressure of the circumferential defect.

Keywords: PWR, Steam generator tube, Leak/Burst test, Failure pressure, Burst pressure.

1. INTRODUCTION

For many years, steam generators of a Pressurized Water Reactor (PWR) have suffered from many types of corrosion, such as pitting, wastage and stress corrosion cracking (SCC) in the primary and secondary sides (Kim 2003, MacDonald, 1996). In order to prevent the primary coolant from leaking into the secondary side, the tubes are repaired by sleeving or plugging(Benson, 1999). It is important to establish the repair criteria to maintain the plugging ratio to within a plugging limit which allows for a successful plant operation.

In the international steam generator tube integrity program (ISG TIP) supported by the US NRC (Nuclear Regulatory Commission), tasks such as in-service inspection technology development, and studies on steam generator tube degradation modes have been undertaken. As a part of the cooperation work, leak and burst tests were carried out, and the burst behavior of axial mechanical flaws was studied.

This article aims at evaluating the rupture/burst and leak behavior of EDM defects for alloy 600 SG tubes in various pressurization modes.

2. EXPERIMENTS

Various types of axial (longitudinal along the tube) EDM notches were machined on Alloy 600 SG tubes of

195 mm length. The tubes were 19.05 mm in outside diameter, and 1.07 mm in thickness as shown in Table 1. They were fabricated from high temperature mill annealed alloy 600, of which the yield strength and ultimate tensile strength were 241 MPa and 655 MPa respectively. The leak rate and ligament rupture pressure for the part through-wall defects were measured for the tubes at room temperature. The lengths of the part through-wall defects ranged from 5 mm to 62 mm.

Tests with 100 % axial through-wall defects were carried out to measure tube burst pressure at room temperature. The lengths of the 100% through-wall defects ranged from 12 mm to 30 mm. A flexible plastic tube is usually used for the through-wall defect to ensure a leak tightness during the pressurization (Cochet, 1991). In this test, however, it was attempted to obtain a crack opening displacement (COD) variation during a slow pressurization. Flexible Tygon™ tubes (bladder) of 175 mm in length were used for the 100% through-wall tubes in both the slow pressurization and the fast pressurization. Ten tubes with a 100 % TW circumferential defect were subjected to the pressure test by using the same procedure as the axial defected tubes.

Table 1. Information on the tested tubes (Alloy 600 HTMA)

Flaw type	Number of test tubes	Tube Dimension, mm	Flaw length, mm	Flaw depth % TW*	Bladder
EDM notch Axial	33	19.05 OD x 1.07 t	5~62	50, 60, 75, 80, 100	With or Without
EDM notch Circumferential	10	19.05 OD x 1.07t	14-25	100	With or Without

% TW*: % tube wall penetration depth

To determine the effect of the pressurization rate on the rupture/burst pressure, different pressurization rates were applied for the same types of tube defects. Water leak rates just after the ligament rupture or burst were measured by a balance; water coming out of the failed tube was collected in a plastic container for a designated time, and the leak rate was calculated by dividing the amount of water by the time. The water flow rate through the tubes and the pressures versus the time were recorded on a computer. Evolutions of the crack opening during the pressurization were recorded using a conventional digital camera.

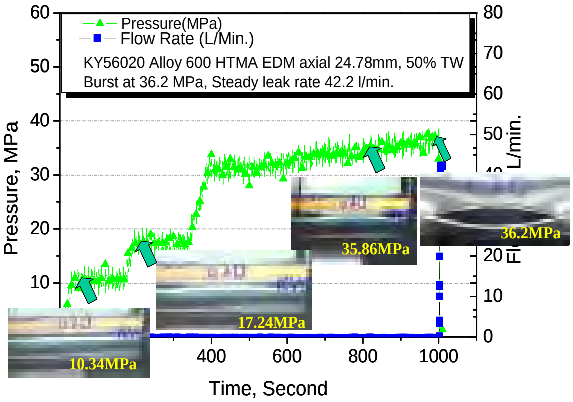


Fig. 1 COD changes of a part through wall axial defect

3. RESULTS AND DISCUSSION

3.1 Crack opening displacement

COD as a function of the applied pressure is important in the modeling of a ligament rupture or the burst pressure in SG tubes. The COD increased a little as the pressure increased during the slow pressurization as shown in Fig. 1. When the pressure reached 10 MPa, the flaw began to show a COD increase. The COD corresponding to an applied pressure of 36 MPa was larger than that corresponding to 10 MPa. Whereas the tube integrity was sustained before a ligament rupture, a small pressure increase of 1 MPa caused the tube ligament rupture followed by a burst. Finally, the tube showed a fish-mouth like opening as shown in Fig. 1.

Through-wall defect tubes showed a larger COD than that of the part-through-wall defect tubes at the same pressure as shown in Fig. 2. The 175 mm long bladder inserted inside the 31 mm long

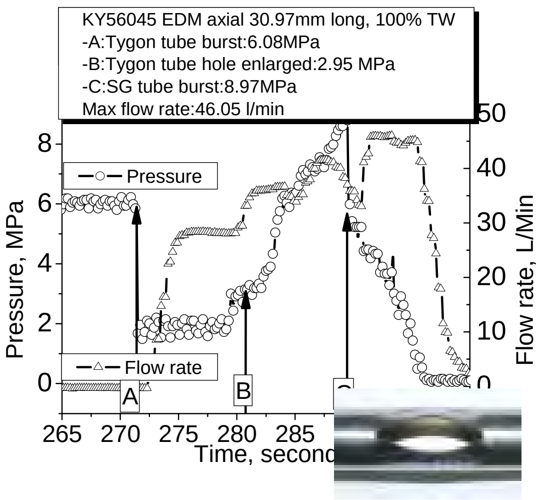


Fig. 2 Crack opening behavior of a 100% TW axial defect.

100% TW defect tube (KY56045) was perforated at 6.08 MPa, a water jet came out of the bladder. After the perforation, the water pressure dropped to around 2 MPa. The bladder extruded out of the defect when the pressure reached 2.97 MPa. A hole in the bladder was enlarged at a constant pressure, and then the COD of the tube increased for 2 to 3 seconds. There was an extrusion of the bladder throughout the tube opening followed by a tube rupture at 8.97 MPa.

A circumferential defect of 20 mm in length, 100 % TW which had a Cu back up foil showed a severe bladder extrusion at 30 MPa, it was not perforated. The tube burst at 31.3 MPa , was shown as in Fig. 3.

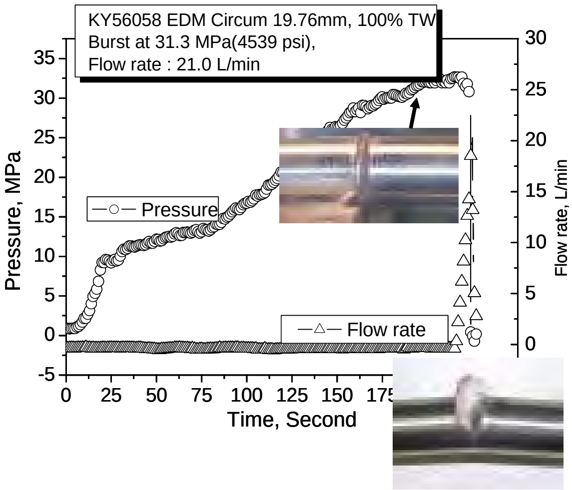


Fig. 3 Crack opening behavior of 100 % TW circumferential defect.

3.2 Effect of the defect depth and length on the rupture/ burst pressure

Burst pressures of axial defects as a function of the defect depth are plotted in Fig. 4. Closed symbols and open symbols are obtained in the present study and acquired from another research group (Cochet, 1991), respectively. Rupture pressures have a linear dependency on the defect depth. These results suggest that the rupture pressure of the part through-wall tubes depends rather on the defect depth than on the defect length.

In the case of the 100% through-wall defects, they showed a strong length dependency from about 12 MPa for a 50 mm long defect to 45 MPa for a 7 mm long defect. Fig. 4 shows the rupture pressures as a function of the defect length. Closed symbols were obtained in the present study. Rupture pressures of a 50 % TW defect and a 75 % TW are around 35 MPa and 20 MPa, respectively regardless of their length from 25 mm up to 62 mm. Short defects below 25 mm, however, showed a dependency on the defect length.

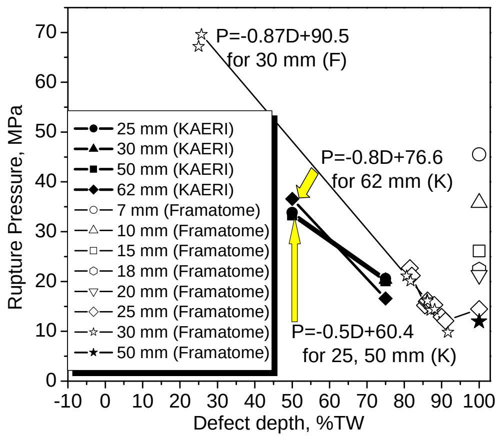
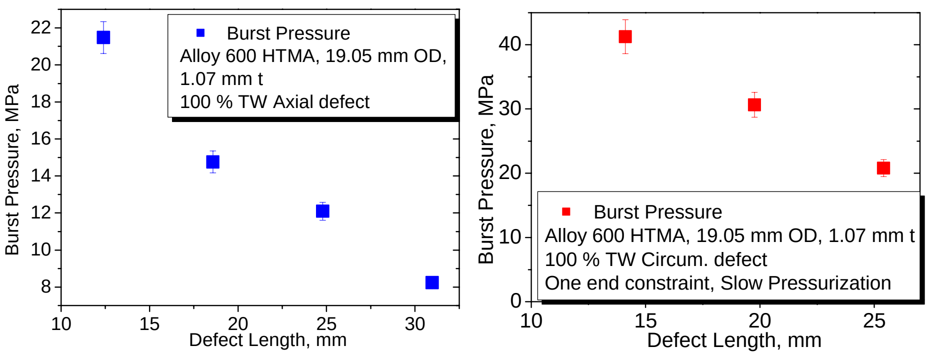


Fig. 4 Effect of the defect depth on the burst pressure.

3.3 Comparison of the burst pressure between the axial and circumferential defects

Fig. 5 shows the burst pressures of the axial and circumferential defects of which lengths are different. The pressure of the circumferential defect is two times higher than that of the axial defect: 21 MPa of a 13 mm long axial defect, 40 MPa of a 14 mm long circumferential defect.



(a) Axial defect (b) Circumferential defect

Fig. 5 Comparison of burst pressure of axial and circumferential defect

The higher burst pressure of the circmferential defect is considered to be caused by a constraint of one end of the tube. The burst pressure of an unflawed tube of 19.05 mm OD, 1.07mm thick is known to be 61 MPa(Alzheimer J.M., 1979). The lower burst pressures seem be a result of a partially constrained condition. According to Majumdar, a circumferential through wall crack at the top of a tube sheet, for any crack of 180^{o} or less shows the burst pressure of unflawed tubes (Majumdar, 2000).

3.4 Effect of the pressurization rate on the burst pressure

The pressurization rate effect on the burst pressure has been evaluated for an axial defect (Hwang, 2004). Burst pressure of a fast pressurization rate was about 7.5 MPa, which was smaller than the 9 MPa of a slow pressurization.

In the test on the circumferential defect, a fast pressurization rate of 13.89 MPa/sec(2000 psi/sec) led to a little higher burst pressure as shown in Fig. 6. It has been reported that there was no burst pressure difference between fast and slow tests without a foil (Keating, 2001). It has also been reported that if a foil reinforcement was used in the fast tests, an average burst pressure increase would be about 25 %. In case of the part through-wall defects, the ligament rupture pressure was reported to increase when the pressurization rate increased (Kasza, 2002). It can be generally said that the pressurization rate effect on the burst pressure is not so critical.

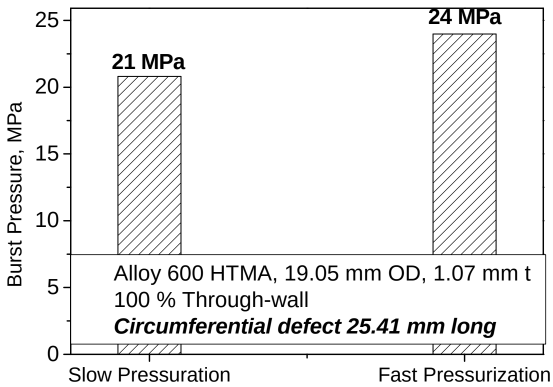
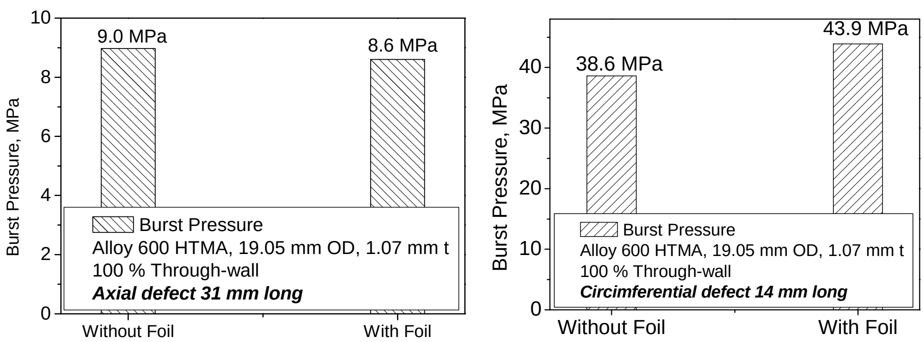


Fig. 6 Effect of the pressurization rate on the burst pressure of circumferential defects

3.5 Effect of the back up foil on the burst pressure

Thin metallic back up foils(0.1 mm thick Cu foil) were used, when measuring the burst pressure of a 100 % through wall defect. It does not seem to have a reinforcement effect on the burst pressure of an axial defect as shown in Fig 7-(a). Circumferential defects, however, revealed a little higher burst pressure when the through-wall defect was backed up by the foil.



(a) Axial defect (b) Circumferential defect

Fig. 7 Effect of back up foil on the burst pressure of axial and circumferential defects

4. CONCLUSIONS

(1) While the tube integrity was sustained before a burst, a small pressure increase of 1 MPa caused a tube ligament rupture followed by a burst.
(2) For the axial defects which ranged from 25 mm up to 62 mm, the burst pressure of the part through-wall tubes depended rather on the defect depth than on the defect length.
(3) Circumferential defects showed a two times higher burst pressure than that of the axial defect of which the length was the same.
(4) Pressurization rate effect on the burst pressure of the circumferential defects was not so great.
(5) A back up foil increased the burst pressure of the circumferential defect.

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