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Rupture pressure of wear degraded alloy 600 steam generator tubings

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Abstract

Fretting/wear degradation at the tube support in the U-bend region of a steam generator (SG) of a pressurized water reactor (PWR) has been reported. Simulated fretted flaws were machined on SG tubes of 195 mm in length. A pressure test was carried out with the tubes at room temperature by using a high pressure test facility which consisted of a water pressurizing pump, a test specimen section and a control unit. Water leak rates just after a ligament rupture or a burst were measured. Tubes degraded by up to 70% of the tube wall thickness (TW) showed a high safety margin in terms of the burst pressure during normal operating conditions. Tubes degraded by up to 50% of the TW did not show burst. Burst pressure depended on the defect depths rather than on the wrap angles. The tube with a wrap angle of 0° showed a fish mouth fracture, whereas the tube with a 45° wrap angle showed a three way fracture.

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1. Introduction

SG tubes of a PWR have suffered from various types of corrosion, such as pitting, wastage and stress corrosion cracking (SCC) on both the primary and secondary side of the SG tubes [1,2]. Ligament rupture pressure of axial notch defect machined by an electrodischarge machining (EDM) has been evaluated [3–5]. Wastage was another concern with new steam generator, and it was usually found in the region of a low coolant flow and a high heat flux until the late 1970s [6]. After change of the secondary side water chemistry from a phosphate to an all volatile water treatment (AVT) in the early 1980s, the wastage substantially decreased. Then denting caused by corrosion of carbon steel support and SCC became the main degradation problems of a SG in PWRs. Recently, fretting/wear degradation at the tube support region has been reported in some Korean nuclear power plants as shown in Fig. 1. It is important to establish the repair criteria to assure reactor's integrity and yet maintain the plugging ratio within the limits needed for an efficient operation.

The objective of the burst test in the present work is to obtain a relationship between the burst/leak rate and the shape of the fretted flaws fabricated with the EDM.

2. Experimental

Simulated fretted flaws were machined on SG tubes of 195 mm in length. The outer diameter and wall thickness of the tubes were 19.05 mm and 1.09 mm, respectively. The tubes were high temperature mill annealed alloy 600, of which the yield strength and tensile strength were 241 MPa and 655 MPa, respectively. Tables 1 and 2 show a dimension of wastage and wear scar defects, respectively. The schematic features of the test specimens are shown in Fig. 2. The room temperature pressure test facility consisted of a water pressurizing pump, a test specimen section and a control unit as shown in Fig. 3. The main features of it including a maximum pressurizing capacity of about 52 MPa (7500 psi) are similar to the high pressure burst test system at the Argonne National Laboratory (ANL) [7].

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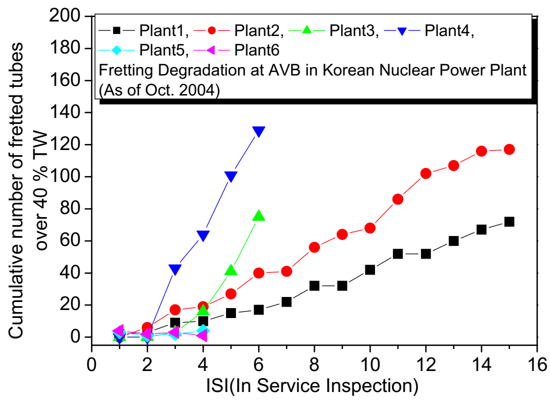

Fig. 1. Degradation trend of a fretting/wear at the AVB in Korean Plants.

Water pressure inside the tube was increased slowly in a step-like manner with a holding of about 10 s. While holding the pressure, the features of the degraded area were recorded by using a conventional digital camera. Water leak rates just after a ligament rupture or a burst were measured; 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.

3. Results and discussion

3.1. Ligament rupture pressure and leak rate of wastage tubes

Fig. 4 shows the behavior of the pressure and the leak rate during water pressurization for a fretted tube specimen. In the case of a large remaining thickness and low water pressure, the tube did not display a significant bulging. When the water pressure reached a yielding value, the tube showed an abrupt rupture, then the flow rate out of the ruptured tube was recorded. The tube of which the defect depth was 70% of the TW showed a ligament rupture at 37 MPa. This pressure is much lower than that of the unflawed tube; 66.9 MPa [6]. Ligament rupture pressures of the tubes with different defect depths and different wrap angles are shown in Fig. 5. Pressures of 30–40 MPa were obtained for the tubes with 70% TW defects. For the tubes with 90% TW defects, ligament rupture pressures of 15–20 MPa were recorded, which are higher than that of a pressure difference for the normal operating pressure difference between the primary and the secondary side of the SG tubes. The ligament rupture pressures showed a wrap angle dependency as indicated in Fig. 6; as the angle increased from 0° to 90°, the pressure decreased and showed the minimum value at 90°. As the wrap angle was greater than 90°, the pressure increased and it showed a similar value at 135° to that at 45°.

Flow rates from the burst tubes are illustrated as a function of the wrap angle in Fig. 7. The flow rate increased with the wrap angle. It implies that a thin wall of the larger wrap angled specimens was torn easier, and it showed a larger defect opening than that of the small wrap angled specimens. The pressures were similar from the aspect of the wrap angle, but they decreased a lot when the defect depth changed from 70% to 90% TW. So the main controlling factor for the rupture pressure seems to be the defect depth.

Features of the burst tubes are shown in Fig. 8, which show a larger flaw opening for the 135° wrap angled specimens than that for the 0° wrap angled ones with the same

Table 1
Dimension and test results of the wastage specimens

Tube ID	Length (mm)	Depth (% TW)	Wrap angle (°)	Rupture pressure (MPa)	Folw rate (L/min)
KY56-Frt-015, 016	25	50	135	No burst at 46	None
KY56-Frt-017, 018	25	70	0	40.6	None
KY56-Frt-019, 020	25	70	45	36.1	None
KY56-Frt-021, 022, 051, 052	25	70	90	35.7	46.3
KY56-Frt-023, 024, 053, 054	25	70	135	30.8	46.5
KY56-Frt-025, 026	25	90	0	19.5	15
KY56-Frt-027, 028	25	90	45	15.4	46.7
KY56-Frt-029, 030, 055, 056	25	90	90	15.3	35.1
KY56-Frt-031, 032, 057, 058	25	90	135	19.9	37.6

Table 2
Dimension and test results of the wear scar specimens

Tube ID	Angle (°)	Length (mm)	Max depth (% TW)	Rupture pressure (MPa)	Leak rate (L/min)
KY56-Frt-035, 036	1	30	48	No burst at 45.8	0
KY56-Frt-037, 038	1	35	56	41.8	37.75
KY56-Frt-039, 040	1	40	64	41.4	38.1
KY56-Frt-041, 042	1	50	80	28.7	38.85
KY56-Frt-043, 044	1.5	25	60	No burst at 44.3	0
KY56-Frt-045, 046	1.5	30	72	37.6	39.6
KY56-Frt-047, 048	1.5	35	84	26.15	39.85
KY56-Frt-049, 050	2	25	80	36	39.75

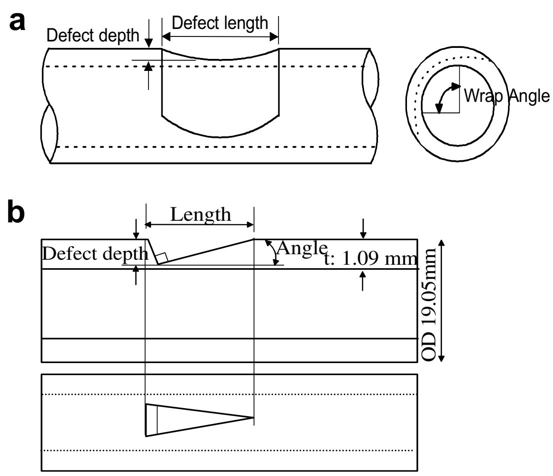

Fig. 2. Schematic illustrations of (a) elliptical wastage (fretted) specimen [after NUREG CR/0178, 1979] and (b) the wear scar specimens.

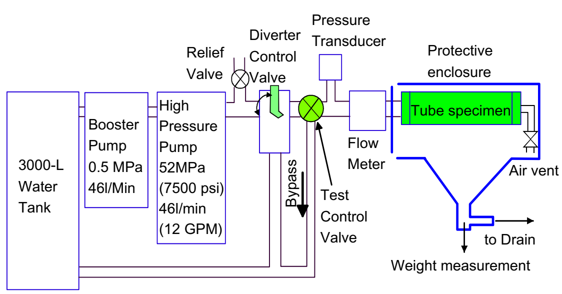

Fig. 3. Schematic illustration of high pressure burst test facility.

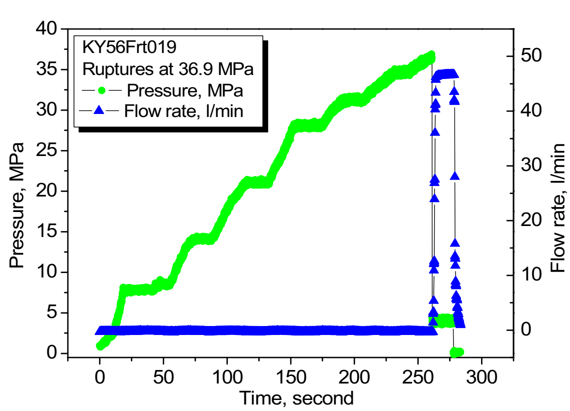

Fig. 4. Burst pressure and leak rate of a wastage tube (KY56frt019).

tube wall degradation of 70%. The tube with a wrap angle of 0° showed a fish mouth fracture, whereas the tube with a 45° wrap angle showed a three way fracture.

3.2. Ligament rupture pressure and leak rate of wear scar tubes

A total of 16 wear scar tubes were tested in accordance with the same test protocol as that for the wastage tubes.

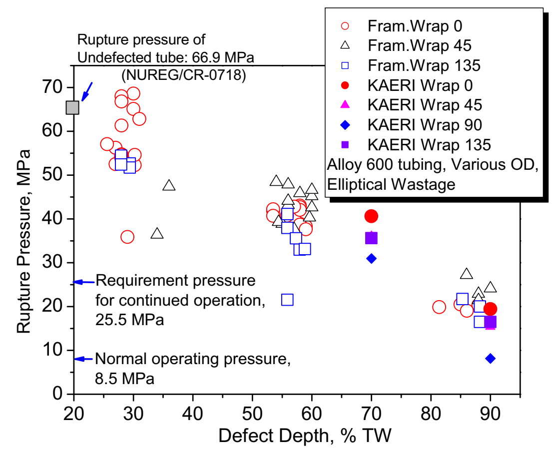

Fig. 5. Effect of the defect depth on the burst pressures of elliptical wastage specimens.

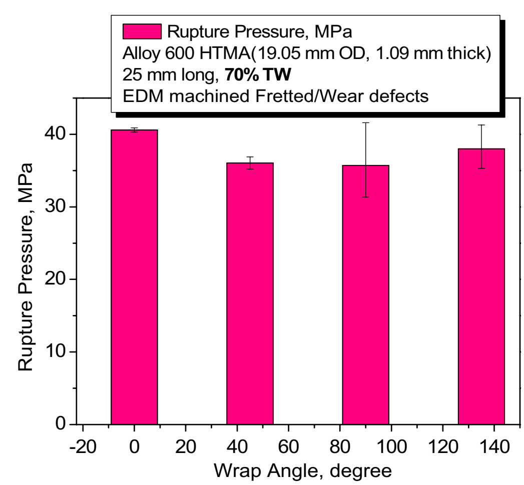

Fig. 6. Effect of the wrap angle on the burst pressure of the wastage specimens.

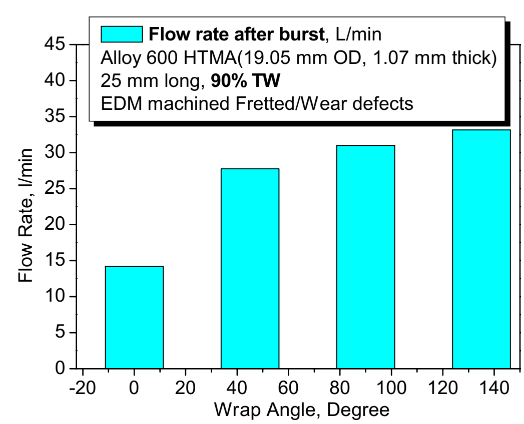

Fig. 7. Effect of the wrap angle on the flow rate of the wastage specimens.

The defect depth of this type of specimen was controlled by the angle and the length; the depth is automatically defined by the angle and length.

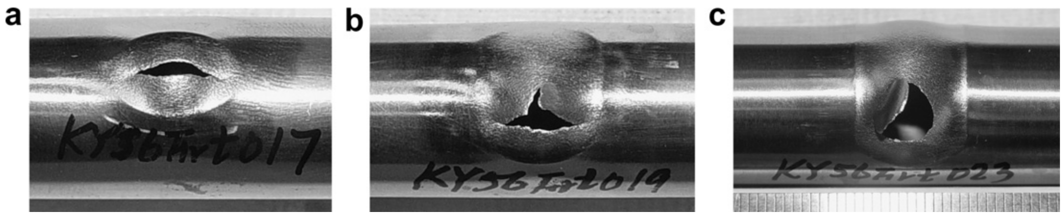

Fig. 8. Opening of the fractured tubes of 70% TW (a) wrap angle of 0°, (b) wrap angle of 45°, (c) wrap angle of 135°.

In a general trend, as the defect depth increases, the rupture pressure decreases as shown in Fig. 9. The tubes of 40% and 47% TW with an angle of 1° did not undergo a ligament rupture at the maximum system pressure limit of 46 MPa. Those of a 60% TW with an angle of 1.5° also did not show a ligament rupture at the pressure limit of the testing system.

Fig. 10 shows the relationship between the rupture pressure and the defect length. The slope for a 1.5° specimen is much larger than the case of 1°; the slope is 1.8 for 1.5° specimen, and 0.72 for 1° specimen, respectively. And the constants of the linear relationship were calculated. Since the defect depth is proportional to the length, it can be also said that the rupture pressure depends on the defect depth and length. Tubes of over 80% TW did not satisfy the three times normal operation pressure difference criterion required for a continued operation, which is similar to the elliptical wastage specimens.

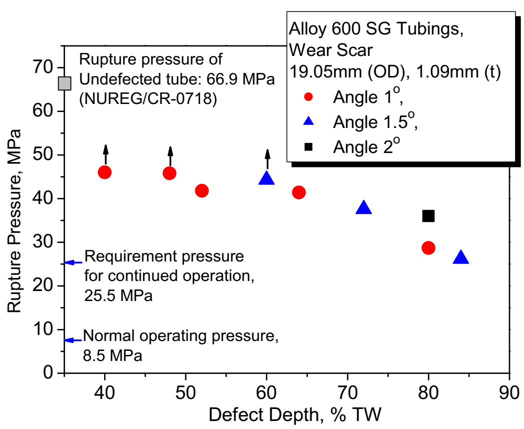

Fig. 9. Effect of the defect depth on the ligament rupture pressure of the wear scar tubes (alloy 600 HTMA).

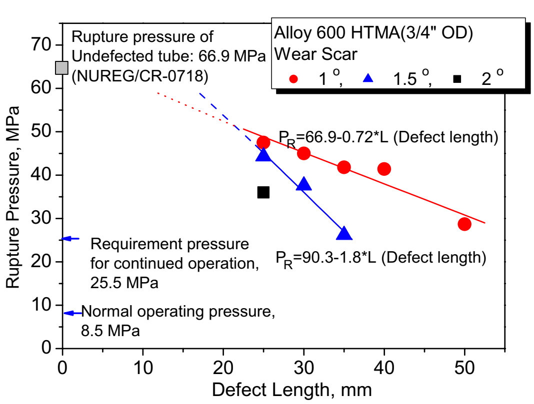

Fig. 10. Effect of the defect length on the ligament rupture pressure of the wear scar tubes (alloy 600 HTMA).

4. Conclusions

(1) There is a high safety margin in terms of the burst pressure during normal operating conditions even for the 70% wastage tubes.
(2) Wastage tubes with a 50% TW did not undergo a ligament rupture at 46 MPa.
(3) Ligament rupture pressure depended on the defect depths rather than on the wrap angle.
(4) The tube with a wrap angle of 0° showed a fish mouth fracture, whereas the tube with a 45° wrap angle showed a three way fracture.
(5) Tubes of over a 80% TW did not satisfy the safety limit for a continued operation.
(6) The two types of specimens (wastage and wear) showed similar behaviors in terms of the rupture pressure.

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