PWSCC growth characteristic of a high temperature mill annealed Alloy 600 tube for a Korean standard nuclear power plant (KSNP)

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1. Introduction

It is known that the sensitivity of Alloy 600 to a primary water stress corrosion cracking (PWSCC) is influenced significantly by its microstructure [1]. The microstructure is mainly controlled by a heat treatment. There are several heat treatment methods for Alloy 600; a) a thermal treatment (TT) precipitating a discontinuous carbide in the grain boundary, b) a high temperature mill anneaingl (HTMA) treatment at high temperature to dissolve the carbides completely, c) a low temperature mill annealing (LTMA) treatment at a relatively low temperature at which the carbide does not dissolve completely, d) a sensitization treatment at 600°C to cause both a carbide precipitate and a Cr depletion at the grain boundary.

The resistance to a PWSCC is known to be order in TT, HTMA. When the Korean standard nuclear power plant (KSNP) was designed, TMA Alloy 600 was chosen for a steam generator tubing materials. It was thought that the decision was reasonable at that time.

Although the general characteristics of Alloy 600 to a PWSCC are well reported, the PWSCC growth rate for HTMA Alloy 600 tubing materials is rarely or never reported at present. Therefore, WSCC growth rate tests are carried out and those values are reported in this paper.

2. Experimental

The testing material is an archive steam generator tubing material for KSNP, HTMA Alloy 600. The nominal outer diameter is 19.05 mm and the wall thickness is 1.05 mm. The chemical composition is shown in Table 1.

Table 1. Chemical composition of the Alloy 600 tube.

Fe	Cr	Ni	C	P	S	Si	Cu	Ti	Al	N	B
8.62	15.63	74.76	0.025	0.007	0.001	0.14	0.03	0.34	0.21	0.01	0.004

The testing equipment was constructed by using a primary water circulating system and a constant elongation rate tester (CERT). The primary water used in this study contained a 1200 ppm B and 2.2 ppm Li. The dissolved oxygen (DO) was controlled to be below 10 ppb. The dissolved hydrogen (DH) in the primary water loop was maintained to be 30cc/kg during PWSCC tests. These conditions were monitored on-line and off-line during the PWSCC tests. The PWSCC test condition was 330°C-16 bars.

The PWSCC test periods varied from a few weeks to a few months. The actual test conditions during the PWSCC tests were as follows: DO 2ppb, pH 7~8, conductivity 17µS/cm, hydrogen pressure 10 psi, flow rate 90 cc/min.

The double tube compact tension specimen (DTCT) is shown in Fig. 1. The relationship between the crack length and the applied K_I is as follow [1]:

$$K_I = 8.1121 x P \sqrt{(-1.122x10^{-4} + 1.247 \times 10^{-2} a)} \quad (1)$$

Were, K_I is MPa√m unit, P is a force in Newton, a is crack length in meter. The stress intensity factor, K_I, can be defined, only when the crack length is longer than 9 mm.

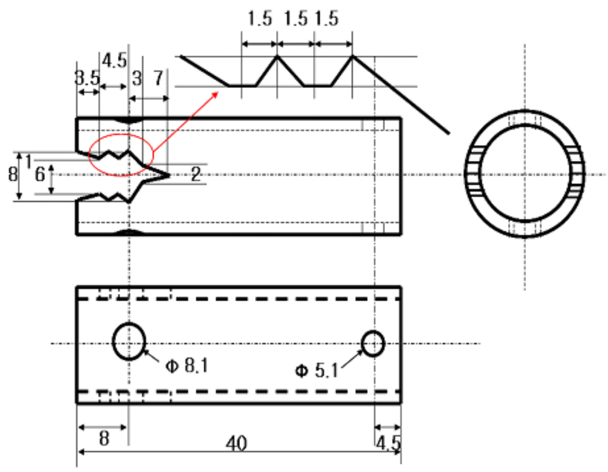

Fig. 1. Drawing of a double tube compact tension (DTCT) specimen for the HTMA Alloy 600 tube.

The PWSCC crack length was measured by SEM, because the PWSCC fracture surface is very rough. The crack growth rate was calculated by a normalization, for the crack length to the testing time.

3. Results and Discussions

The HTMA Alloy 600 tube consists of 50µm grains. Fracture surface examination showed that a PWSCC crack grew along the normal plane in the loading direction whereas a pre-fatigue crack did not. Furthermore, the PWSCC crack grew early in the center region (half thickness region), as shown in Fig. 2.

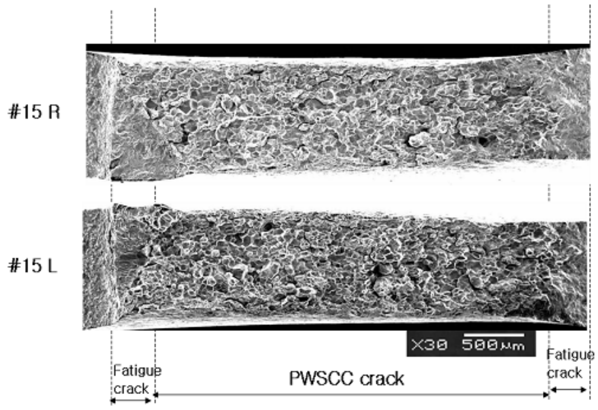

Fig. 2. Photographs of the fracture surfaces for the HTMA Alloy 600 tube.

The PWSCC crack growth rate measured at 330°C is plotted according to K_I in Fig. 3. Because the in-situ K_I is varied, as the PWSCC crack grows, the averaged K_I is used in Fig. 3. The curve plotted together is calculated by Scott's relationship. The two curves in Fig. 3 are a fitted curve for the minimum and the maximum values. The ratio of the maximum to the minimum value is 2.1 time. This seems to be very consistent.

The PWSCC growth rate at K_I = 15 MPa√m in the axial direction in HTMA Alloy 600 is 3~6 x 10^{-11} m/s , and that at K_I = 45 MPa√m is 2~4 x 10^{-10} m/s.

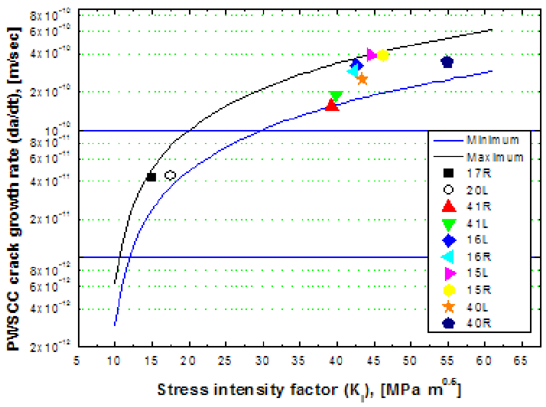

Fig. 3. PWSCC crack growth rate vs K_I in the HTMA Alloy 600 tube at 330℃-160 bar.

A well known empirical PWSCC relation is Scott's relationship. This relationship tells us that the minimum K_I value to cause a PWSCC is K_I = 9 MPa√m. This can be expressed as follows [2];

$$da/dt = C (K_{I\ applied} - 9)^{1.16} \quad (2)$$

Where da/dt is the PWSCC growth rate, and C is a constant varied with the materials, $K_{I\ applied}$ is an applied stress intensity factor for a crack.

The required time to form a through wall crack in HTMA Alloy 600 tube can be calculated. Let's assume that a tube with a 40% depth flaw was detected. The remaining ligament of this tube would be 0.63 mm. If the stress intensity factor for the existing crack is defined as K_I = 15 MPa√m and it is assumed that the PWSCC growth rate in the axial and the radial direction is the same, the required time to grow or form a through wall crack is calculate as 2900 ~5800 hours (4~8 months).

The PWSCC growth rate is determined by an archive tube material for KSNP. However, the plane strain condition can not be satisfied due to the thin wall thickness of the tubes. Therefore, it is expected that the measured value would not be conservative, enough.

4. Conclusions

Primary water stress corrosion cracking (PWSCC) tests for an Alloy 600 tube were carried out in a primary water environment at 330℃ and 160 bar. PWSCC crack growth rate in the HTMA Alloy 600 tube was measured by using a double tube compact tension (DTDT) specimen. PWSCC growth rate appeared as 3~6 x 10^{-11} m/s and 2~4 x 10^{-10} m/s under $K_{I\ applied}$ = 15 MPa√m and 45 MPa√m, respectively. This seems to be slightly underestimated, because the plane strain condition cannot be satisfied due to a limitation of the tube thickness in the DTCT specimens. The effect of the hydrogen concentration on the PWSCC crack growth rate in a primary water environment is discussed.

Acknowledgements

This work has been carried out in the Nuclear Materials Technology Development project as a part of the Nuclear R&D program funded by the Ministry of Science and Technology in Korea.

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