

Development of PWSCC Initiation Evaluation Method of High Corrosion Resistant Structural Materials Using Rupture Disk Type Corrosion Test

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1. Introduction

Nickel alloys and stainless steels, which are used as structural materials in nuclear power plants, have showed various corrosion behaviors with long-term operation, such as intergranular corrosion, corrosion fatigue, pitting and stress corrosion cracking. PWSCC(primary stress corrosion cracking) is one of the major corrosion behaviors of pressure boundary components made of Alloy 600 pipes and tubes, because the primary water and radioactive species may leak out of pressure boundary when the crack grows through wall of the components. Therefore, there have been extensive studies on PWSCC growth behavior of nickel alloys and stainless steels. Recently, there is increasing research activities on PWSCC initiation, because the components spend most of their life in the initiation regime. In this study, a novel technique for PWSCC initiation evaluation was developed using a rupture disk type corrosion test.

2. Experimental Methods

2.1 Material

The test material in this study was Alloy 600 and its chemical compositions are shown in Table. 1. Table. 2 shows the mechanical properties obtained at room temperature and 350 °C in air. From the optical image of the microstructure given in Fig. 1, the average grain size was about 77 μm according to ASTM standard E112-13 [1].

Table. 1: Chemical compositions of Alloy 600(wt %)

Cr	Fe	Si	Mn	C	Cu	P	S	Ni
16.11	8.83	0.34	0.26	0.062	0.02	0.005	0.001	Bal

Table. 2: Mechanical properties of Alloy 600

Specimen	Test Temp. (°C)	YS (MPa)	UTS (MPa)	EL (%)
Alloy 600	25	254	671	50.9
	350	222	613	44.6



Fig. 1. Microstructure of Alloy 600

2.2 Rupture disk type corrosion test

A rupture disk is a pressure relief safety device that, in most uses, prevent overpressure of a pressure vessel or loop system. In this work, the rupture disk type specimen is used for development of new test method for PWSCC initiation study. The schematic diagram of the specimen was shown in Fig. 2. The diameter of the specimen is 12 mm and the average thickness varied within approximately 0.1 ~ 0.2 mm. The main concept of the rupture disk type (RDT) corrosion test was described in Fig. 3. The initiation of PWSCC on the rupture disk surface exposed to a primary water solution at high temperature and pressure can be easily detected by burst of the disk. In addition, the test utilizes very simple and small-size test chamber, which allowing multiple tests in one primary water loop system at the same time.

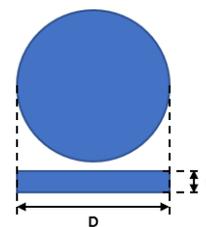


Fig. 2. Schematic drawing of the rupture disk type specimen

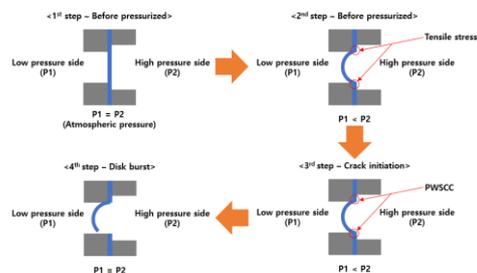


Fig. 3. Brief concept of PWSCC initiation and disk burst in RDT test

2.3 Primary water loop system

Fig. 4 provides the loop system used in this work to simulate typical primary water chemistry of the pressurized water reactor, which were 1200 ppm of B, 2.2 ppm of Li, 6.4 pH, 23 μ S/cm of conductivity, under 5 ppb of dissolved oxygen and 22 cc/kg of dissolved hydrogen. For acceleration test, temperature and pressure was maintained at 360 °C and 3000 psi, respectively.



Fig. 4. The loop system(left) and heater(light)

3. Results and Discussion

3.1 Burst pressure of rupture disk type specimen

To utilize the rupture disk as the specimen for PWSCC initiation test in this work, the disk thickness should be controlled above the minimum thickness that withstands the test pressure but leads to burst when surface crack initiates on the specimen. For this purpose, the burst pressure was calculated as a function of thickness and then measured for verification. The calculation formula [2] of the burst pressure is shown in Fig. 5.

$$p = \frac{8\Delta\sigma_{us}}{D} \sqrt{\frac{V \left(1 + \frac{\delta}{100} \right) - 1}{1 + \frac{\delta}{100}}}$$

Fig. 5. The calculation formula of the burst pressure.

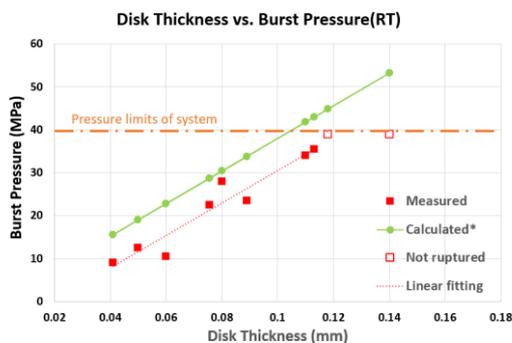


Fig. 6. Burst pressure vs. disk thickness calculated and measured at room temperature.

Fig. 6 shows the burst pressure calculated and measured at room temperature as a function of disk

thickness. The burst pressure calculation and test results at high temperature are demonstrated in Fig. 7. From the comparison, it is obvious that the burst pressure increased as disk thickness increased linearly with a similar slope. However, there was slight difference between calculated and measured values, that was attributable to the surface roughness of the specimen, the thickness deviation, or material property variation used in the calculation and measurement. From the results, the desirable thickness of the disk specimen for the PWSCC test was determined to 0.14 mm in this work, in consideration of about 50% decrease of burst pressure when a crack with depth of 50% through-wall existed on the disk surface

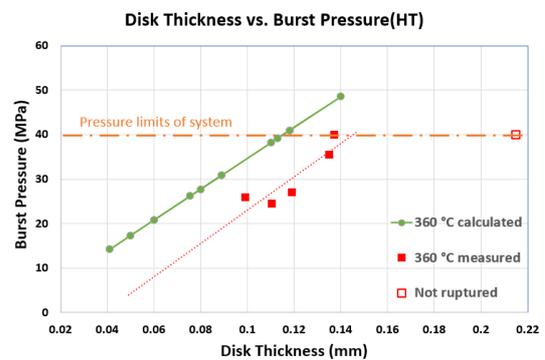


Fig. 7. Burst pressure for disk thickness in high temperature condition.

3.2 Finite element analysis of stress and deformation of the disk specimen

The finite element analysis(FEA) was performed to predict the effective stress and deformation at the site for PWSCC initiation and rupture as a function of thickness. Fig. 8 shows one of the FEA results for the stress distribution in air and in the primary water, and the deformation of the disk specimen at the test condition. Fig. 9 gives the cross-sectional image of the disk specimen that was not ruptured after the rupture test. Compared with the FEA results, it is confirmed that the thickness change of the test specimen shows the maximum at the site where the maximum stress is expected.

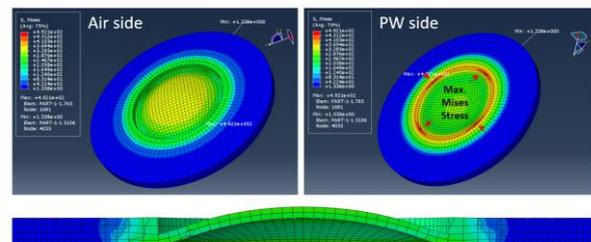


Fig. 8. FEA results of the rupture disk (Φ : 10 mm, D : 5mm, t : 0.2 mm)

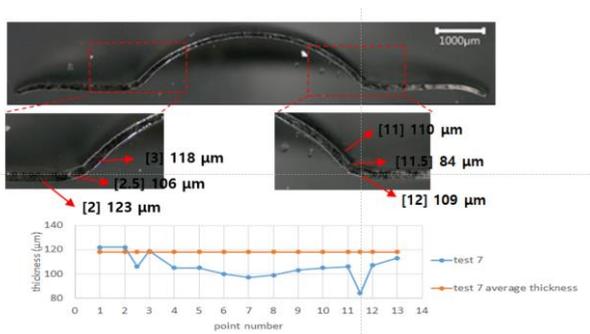


Fig. 9. The thickness change measurement (test 7 - not ruptured specimen)

3.3 Prediction of PWSCC initiation time

PWSCC initiation time can be predicted based on the FEA results in this work and test results previously reported [2]. Fig. 10 presents the maximum stress applied on the disk specimen at the site where PWSCC initiation could occur as a function of disk thickness. From the FEA results, two disk specimens were selected to have thickness of $0.146\text{mm}(\pm 0.05)$ and $0.129\text{mm}(\pm 0.05)$, corresponding to the applied stress of 575MPa and 600MPa, respectively. PWSCC initiation time of the specimens was predicted to be about 3 to 4 months from comparison with the test results previous reported [3]. The PWSCC initiation tests are now in progress.

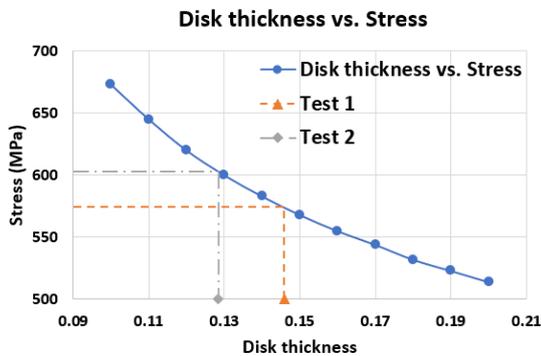


Fig. 10. The applied stress vs. specimen thickness expected from the FEA results

3. Conclusions

The following conclusions were obtained from the FEA and test results.

1. The results of burst pressure test showed that the rupture pressure increased with increase of disk thickness. Also, the desirable thickness of specimen for the PWSCC test was set to 0.14 mm.
2. From FEA and test results, it was confirmed that the thickness change of the test specimen showed the maximum at the site where the maximum stress was expected.

3. The PWSCC initiation time was predicted based on the FEA results. The corrosion test using the primary water loop system is currently ongoing.

4. References

- [1] Annual Book of ASTM standards, Standard Test Method for Determining Average Grain Size, Designation: ASTM E 112, 2013
- [2] V. I. Vodyanik, Design of Safety Rupture Discs, Khimicheskoe I Neftyanoe Mashinostroenie, No. 6, p. 43-44, 1972
- [3] Z. Zhai, M. B. Toloczko, M. J. Olszta and S. Bruemmer, Stress corrosion crack initiation of alloy 600 in PWR primary water, corrosion science, No. 123, p. 76-87, 2017