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Effect of Residual Strain on PWSCC Initiation of Alloy 690 in Primary Water of PWR

Eun-Hee Lee, Sung-Woo Kim*, Ki-Hyeon Eom, and Seong-Sik Hwang
Nuclear Materials Safety Research Division, Korea Atomic Energy Research Institute,
Daedeok-daero 989 beon-gil 111, Yuseong-gu, Daejeon 34057, Republic of Korea
**Corresponding author: kimsw@kaeri.re.kr*

1. Introduction

Nickel-base Alloy 690 has been widely used as a structural material for steam generator tubes in recent pressurized water reactors (PWRs) [1]. It has a higher corrosion resistance than that of Alloy 600 and corrosion failures for this material have rarely been reported in operating PWRs [1]. However, recent laboratory tests revealed that Alloy 690 is not immune to primary water stress corrosion cracking (PWSCC) [2-5]. However, it is difficult to study the SCC initiation of Alloy 690 in operating condition of PWRs because of long initiation times [4]. Therefore, it needs to test in an accelerated condition to find out key factors that could affect cracking of Alloy 690 [3]. Recently, high levels of cold work have been shown to accelerate intergranular SCC (IGSCC) of Alloy 690 in simulated PWR primary water [5,6].

The object of this study is to attempt to correlate the susceptibility to crack initiation of Alloy 690 with the levels of cold work in simulated primary water. Experiments were conducted in high-temperature water to accelerate the cracking behavior and to determine the severity of crack initiation as a function of level of cold work for Alloy 690. Cracking susceptibility was determined by measuring the crack length per unit area and crack density.

2. Experimental

The test material was Alloy 690 bar (Heat No. 135264) with a highly carbide banded structure. Alloy 690 was cold-worked (20, 30, and 40%) by one-dimensional rolling to an axial direction of the bar. Specimens with a tapered gage section were fabricated from the cold-rolled material, which is shown in Fig. 1. Before testing, the specimens were mechanically polished with progressively finer grades of diamond paste. The test solution was prepared by adding 2 ppm of lithium (as LiOH) and 1,200 ppm of boron (as H_3BO_3) to purified water, to simulate the representative PWR primary water chemistry. Slow extension rate tensile (SSRT) testing was conducted in the simulated primary water at a constant strain rate of $1x10^{-7}$ s^{-1} and at 360℃ for 624 h. The dissolved hydrogen content was controlled at the feed vessel to be at the Ni/NiO equilibrium state by varying the hydrogen overpressure.

After testing, the specimens were examined by scanning electron microscopy (SEM) to characterize the cracking on the surface of gage section. The crack length was measured by tracing cracks using a digitizer software.

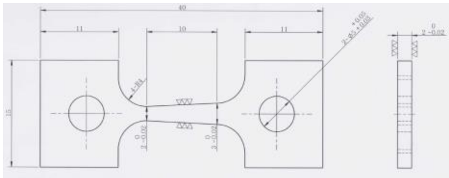

Fig. 1. Tapered specimen used for PWSCC test (unit: mm).

3. Results and Discussion

Fig. 2 shows the micrographs of the surfaces of the gage section of 20%, 30%, and 40% cold-rolled Alloy 690. For all tested specimens, many cracks and oxide particles were observed on the gage surfaces. The 20% cold-rolled Alloy 690 exhibited mostly IG cracks, while the 30% and 40% cold-rolled Alloy 690 revealed significant amounts of IG and transgranular (TG) cracks. Recently, Moss et al. observed mainly IGSCC on specimens of Alloy 600 and Alloy 690 pre-strained to 20%, followed by a constant strain rate test as a function of temperature [3,4]. From the results, it was proposed that the difference in cracking mode was mainly due to the increase of residual strain induced by cold-rolled process prior to SSRT tests.

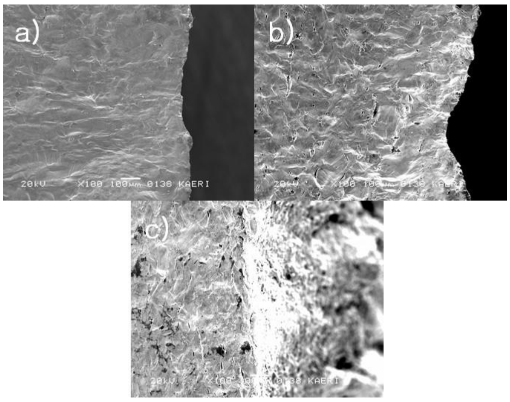

Fig. 2. Micrographs of the gauge surfaces of Alloy 690 at 360℃ with varying levels of cold work (a) 20%, (b) 30%, and (c) 40%.

For all specimens, most cracks on the gage surfaces occurred perpendicular to the tensile direction. However, some cracks were observed in the diagonal direction. As the level of cold work increased, the number of cracks which is perpendicular to the tensile axis increased. On the 40% cold-rolled specimen, almost all cracks were perpendicular to the tensile direction. This can be explained by the nature of IG and TG cracks; IG cracks are known to occur along the random high angle grain boundaries (HAGBs) which are most susceptible path to SCC, while TG cracks usually occur along the maximum principal stress direction perpendicular to the tensile axis.

In order to correlate the SCC initiation susceptibility with the level of cold work, two different parameters were introduced in this work; one is the total crack length per unit area, as total sum of crack length measured in a given area, and the other is the crack density given by the number of cracks per unit area. Fig. 3 gives the micrograph of the surface of the gage section of 20% cold-rolled Alloy 690 after the SSRT test. It revealed that most cracks were found in the smallest cross-section area of the tapered gage section where severe necking occurred due to the maximum stress applied during the SSRT test.

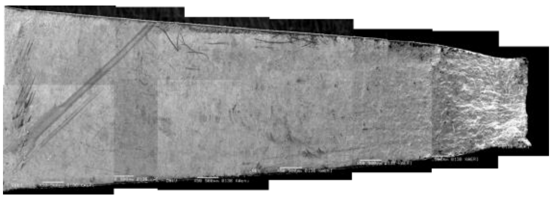

Fig. 3. Micrograph of the gauge surface of 20% cold-rolled Alloy 690 after the SSRT test at 360℃.

As a preliminary analysis of the SCC initiation susceptibility, the crack length per unit area and density were measured, as shown in Table 1. As the distance from the failed surface increased along the gage length, the crack length per unit area increased first and then decreased gradually. Considering the severe necking at the smallest cross-section area in the tapered specimen, the higher SCC initiation susceptibility was found at the area where the higher stress was applied during the SSRT test. The crack density exhibited the similar behavior to that of the crack length per unit area.

Table 1. Results of SSRT tests of 20% cold-rolled specimen

Gage Length from Failed Surface (μm)	Crack Length/Unit Area (μm/mm^2)	Crack Density (#/mm^2)
200-400	1823	141.3
400-600	2671	224.8
600-800	3403	215.1
800-1000	2664	134.8
1000-1200	1953	76.1

4. Conclusions

SCC initiation susceptibility of Alloy 690 increased with increase of the residual strain induced by the prior cold-rolling process. The 20% cold-rolled specimen exhibited mostly IG cracks, while the 30% and 40% cold-rolled specimens revealed significant amounts of IG and TG cracks. This means that the main factor of SCC may change from cracking along HAGBs to cracking along the maximum principal stress direction.

Most cracks were observed near the smallest cross-section area of the tapered specimen, where the maximum stress was applied, indicating that the SCC initiation susceptibility was strongly dependent on the applied stress. In order to find the correlation between SCC initiation susceptibility and residual strain induced by cold work, more analyses need to be performed in terms of the crack length per unit area and the crack density, as a strong indicative for SCC initiation susceptibility.

REFERENCES

[1] W. Kuang, X. Wu, E. H. Han, and J. Rao, The Mechanism of Oxide Film Formation on Alloy 690 in Oxygenated High Temperature Water, Corrosion Science, Vol. 53, p. 3853, 2011.

[2] P. L. Andresen, M. M. Morra, A. Ahluwalia, and J. Wilson, Effect of Deformation and Orientation on SCC of Alloy 690, Proc. 14th Int. Symp. on Environmental Degradation of Materials in Nuclear Power Systems-Water Reactors, Aug. 23-27, 2009, Virginia Beach, Virginia, USA.

[3] T. Moss and G. S. Was, Accelerated Stress Corrosion Crack Initiation of Alloy 690 and Alloy 600 in High Temperature Hydrogenated Water, Proc. 16th Int. Symp. on Environmental Degradation of Materials in Nuclear Power Systems-Water Reactors, Aug. 11-15, 2013, Asheville, North Carolina, USA.

[4] T. Moss and G. S. Was, Factor of Improvement in Resistance of Stress Corrosion Crack Initiation of Alloy 690 over Alloy 600, Proc. 17th Int. Symp. on Environmental Degradation of Materials in Nuclear Power Systems-Water Reactors, Aug. 9-13, 2015, Ottawa, Ontario, Canada.

[5] S. M. Bruemmer, M. J. Olszta, M. B. Toloczko, and L. E. Thomas, High-Resolution Characterizations of Grain Boundary Damage and Stress Corrosion Cracks in cold-Rolled Alloy 690, Proc. 15th Int. Symp. on Environmental Degradation of Materials in Nuclear Power Systems-Water Reactors, Aug. 7-11, 2011, Colorado Springs, Colorado, USA.

[6] S. M. Bruemmer, M. J. Olszta, N. R. Overman, and M. B. Toloczko, Microstructural Effects on Stress Corrosion Crack Growth in Cold-Worked Alloy 690 Tubing and Plastic Materials, Proc. 16th Int. Symp. on Environmental Degradation of Materials in Nuclear Power Systems-Water Reactors, Aug. 11-15, 2013, Asheville, North Carolina, USA.