Effects of Thermal Aging and Cold Work on PWSCC Initiation Time of Alloy 182 Weld

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1. Introduction

Over the past few decades, initiation of primary water stress corrosion cracking (PWSCC) for Ni-base alloys has emerged as one of the most critical safety issues, which threats to the structural integrity of commercial nuclear power plants (NPPs) [1, 2]. Although many pieces of research have been performed to predict the initiation time of PWSCC for Ni-base alloys, most of them were focused on the base metal, such as Alloy 600, and rarely studied on the weld metal, such as Alloy 182. Furthermore, with the aging of the existing NPPs, it is getting important to consider the effect of time-dependent degradation of material (i.e., material aging) directly affecting the PWSCC initiation time. Note that the thermal aging and cold work effects were investigated for Alloy 600 base metal [3, 4], but there has been no related research for Alloy 182 weld. With this background, we experimentally investigated the effects of long term thermal aging and cold work on the PWSCC initiation of Alloy 182.

2. Experimental Methods

2.1 Specimen Preparation

First, the Alloy 182 bulk specimen was fabricated by the weld deposit method on the 316 L stainless steel plate (see Fig. 1). After the fabrication, we confirmed that there is no defect (e.g., pre-existing crack, macroscopic void) in the bulk specimen by performing the ultrasonic test. Table I shows the chemical composition of the Alloy 182 used for the specimen.

Table I: Chemical composition of Alloy 182 weld

C	Si	Mn	P	S	Fe
0.048	0.08	8.38	0.011	0.007	3.10

Cu	Ni	Ti	Cr	Cb+Ta
0.01	REM.	0.02	13.97	1.29

The Alloy 182 bulk specimen was divided to simulate the following four conditions: 1) as-welded (AW), 2) thermally aged for 15 years (15Y), 3) thermal aged for 30 years (30Y), and 4) cold-rolled (CR).

From the precedent studies on the thermal aging of Alloy 600, Cr precipitate was reported to be an important factor in determining the mechanical properties and PWSCC resistance of Ni-based alloys [3, 5]. Therefore, we assumed Cr diffusion as a key factor and perform the accelerated thermal aging.

In order to simulate the thermal aging conditions, which are corresponding to 15 and 30 years of operation in typical NPPs at 320 °C, heat treatment was performed for 1713 and 3427 hours in the 400 ° C Ar furnace, respectively. The heat treatment time was calculated using the following Arrhenius equation:

$$\frac{t_{\text{aging}}}{t_{\text{ref}}} = \exp\left[-\frac{Q\left(\frac{1}{T_{\text{ref}}}-\frac{1}{T_{\text{aging}}}\right)}{R}\right] \qquad (1)$$

where, t_{aging} is the heat treatment time, t_{ref} is the corresponding operation time of NPPs, T_{ref} the is operation temperature, T_{aging} is the temperature of the heat treatment, R is the universal gas constant, and Q is the activation energy of Cr diffusion along grain boundary. In this work, Q is assumed to 180 kJ/mol according to the precedent literature [3, 6].

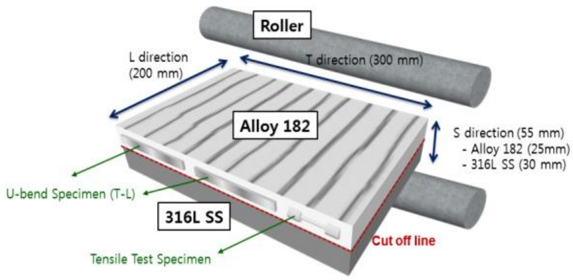
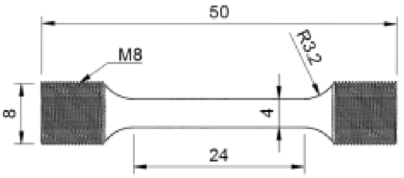


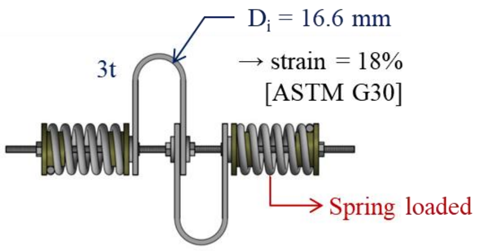
Fig. 1. Geometry of Alloy 182 bulk specimen, direction of cold rolling, U-bend and tensile test specimens.

As shown in Fig. 1, the part of the bulk specimen was subjected to cold rolling with a reduction of 20% in thickness to simulate the cold worked condition.

Tensile test specimens and U-bend specimens were taken along the T-L direction from the each divided bulk specimen having different condition (e.g., AW, CR), because the T-L direction was reported to have the weakest PWSCC resistance [7].



(a)



(b)

Fig. 2. Geometry of the Alloy 182 (a) tensile test specimen, and (b) U-bend specimen.

Figure 2 shows the geometry of the tensile and U-bend test specimens. Before the U-bending process, the surface of the specimen was polished with SiC paper up to 800 grit. The U-bend specimens were loaded by spring to reduce stress relaxation at high temperature. Geometrically, the calculated strain of the U-bend specimens is 18% in accordance with the ASTM G30 standard. To prevent the galvanic corrosion and simulate the electrochemical potential in typical NPPs, the bolts and nuts that contact with the Alloy 182 specimen were made of Alloy 600 material.

2.2 Tensile and PWSCC Initiation Tests

Tensile tests were carried out according to the standard procedure ASTM E8M both in room temperature and high temperature of 325 ℃. For each testing conditions, at least three tensile testing were performed to investigate the uncertainties of measured mechanical properties.

For PWSCC initiation test, we set up a loop type testing facility to simulate the primary water conditions of pressurized water reactors. Figure 3 shows the schematic illustration of the PWSCC testing facility and Table II shows the simulated primary water conditions. In Table II, DO implies the dissolved oxygen, DH is the dissolved hydrogen, Li is the lithium concentration, B is the boron concentration in the water.

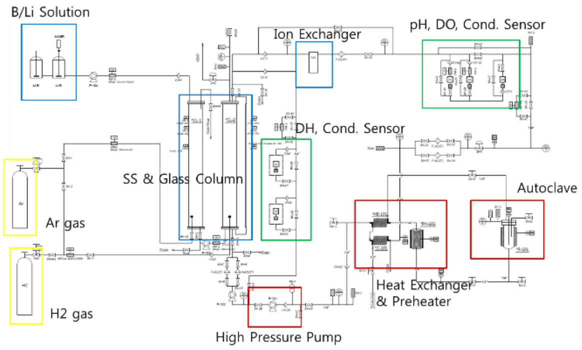


Fig. 3. Schematic illustration of loop type PWSCC testing facility.

Table II: Simulated of primary water condition in PWSCC testing loop.

Temp. [℃]	DO [ppb]	DH [cc/kg]	Li / B [ppm]
340	< 5	30	1200 / 2.0

For each testing condition (i.e., AW, 15Y, 30Y, CR), ten U-bend specimens were fabricated. Thus, a total of forty U-bend specimens were immerged into the PWSCC testing autoclave.

To check the initiation time of PWSCC of specimens, we took out all specimens periodically from the autoclave. In this work, the criterion of crack initiation is whether any crack is visible by naked eyes or not.

3. Results and Discussion

3.1 Tensile Test

Figure 4 shows the results of tensile tests for all testing conditions. The elongations of the thermally aged specimens were increased. We think is caused by the relation of the weld residual stress. There is no significant change in strength of thermally aged specimens. For cold worked specimens, yield and tensile strength increased significantly, but elongation decreased. This is due to the increase in residual stress by the work hardening (i.e., increase of dislocation density).

3.2 PWSCC Initiation Test

Figure 5 shows the result of the PWSCC initiation test. As shown in Fig. 5, thermally aged specimens showed relatively long PWSCC initiation time and cold-rolled specimens showed short PWSCC time compared to the reference as-welded specimen group. That is, the thermal aging decrease the susceptibility, and the cold work increases the susceptibility of PWSCC.

We think the weld residual stress plays a key role in this behavior. When thermally aged, the existing weld residual stress decreases because of the thermal diffusion. Since there is no significant susceptibility difference between 15Y and 30Y conditions, it seems that the stress relaxation ends up before the 15 years of plant operation. For the case of cold-worked material, we think the reason for increasing susceptibility is cause by the work hardening and accumulation of residual stress.

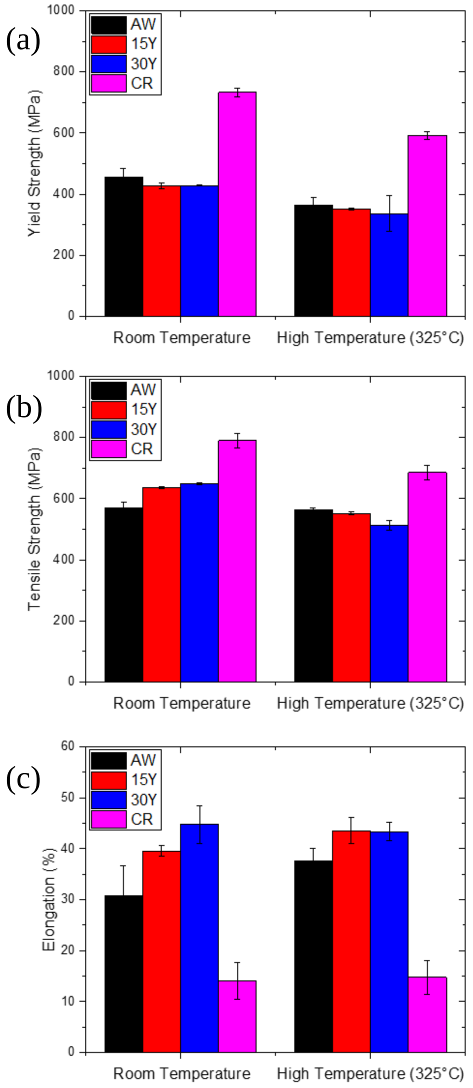


Fig. 4. Mechanical properties of Alloy 182 weld, (a) yield strength, (b) tensile strength, (c) elongation.

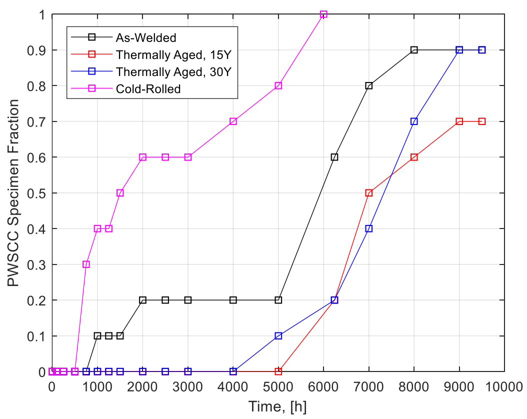


Fig. 5. Result of Alloy 182 PWSCC initiation test.

4. Conclusions

In this paper, we experimentally investigated the effects of long term thermal aging and cold work on the PWSCC initiation of Alloy 182. The testing results showed that the effect of thermal aging decrease the susceptibility of PWSCC initiation, and the cold work increases the susceptibility. We think the weld residual stress plays a key role in this behavior.

ACKNOWLEDGEMENT

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