Effect of Thermal Aging and Cold Work on PWSCC Susceptibility of Alloy 182 Weld

Jae Phil Park [a], Seung Chang Yoo [b], Ji Hyun Kim [b], Chi Bum Bahn [a*],
[a]*School of Mechanical Engineering, Pusan National University, Busan, Republic of Korea*
[b]*School of Mechanical, Aerospace and Nuclear Engineering, Ulsan National Institute of Science and Technology, Ulsan, Republic of Korea*
[*]Corresponding author: bahn@pusan.ac.kr

1. Introduction

To ensure the structural integrity of nuclear power plants, it is essential to evaluate the lifetime of Alloy 182 weld, which was usually used for welding materials of pressure boundary components in nuclear reactors [1]. The lifetime of Alloy 182 weld is directly related to the Primary Water Stress Corrosion Cracking (PWSCC) initiation time [2].

The pressure boundary components of the reactors were exposed to a relatively high temperature (300℃ or more) for a long time. In such a high temperature environment, the physical and chemical properties of the material can be changed by thermal aging, and furthermore, the susceptibility of PWSCC also can be changed [3]. However, the effect of thermal aging on the PWSCC susceptibility of Alloy 182 weld was not studied so far. In addition, it is known that the changes in mechanical properties and residual stress due to the cold work can also affect crack initiation time.

Therefore, in this study, we investigated the effect of thermal aging and cold working on the PWSCC susceptibility of Alloy 182 weld through the experiments.

2. Methods and Results

2.1 Specimen Preparation

We produced the Alloy 182 parent specimen by weld depositing on a 316L stainless steel plate. Table 1 shows the chemical composition of the Alloy 182 used for the sample production.

Table 1. 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 parent specimen was cut into four parts to simulate the following conditions: 1) as-welded, 2) 15 years of thermal aging, 3) 30 years of thermal aging, and 4) cold worked.

We presumed the Cr as a main element of thermal aging since many precedent studies concluded that Cr precipitate is one of the most important elements determining the mechanical properties and PWSCC susceptibility of Ni-base alloys [3, 4]. For the accelerated simulation, heat treatment was carried out at 400 °C in an Ar environment for 1713 and 3427 hours, respectively, in order to simulate 15 and 30 years of plant operation at 320 °C according to the Arrhenius equation as given by:

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

where, t_{aging} is the heat treatment time, t_{ref} is the target plant operation time, T_{ref} is the target plant operation temperature, T_{aging} is the heat treatment temperature, R is the universal gas constant, and Q is the activation energy of the Cr diffusion. In this case, we input $Q = 180\ kJ/mol$ from the precedent study on Alloy 600 [3, 5].

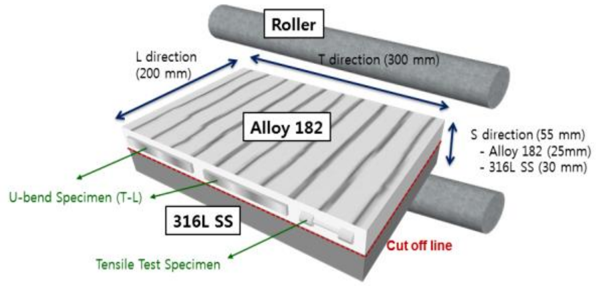
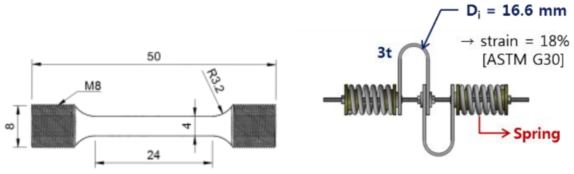


Fig. 1. Geometry of Alloy 182 parent specimen, direction of cold rolling, U-bend and tensile test specimens.

To simulate the cold worked condition, we performed cold rolling to reduce the 20% thickness of the Alloy 182 parent specimen (see Fig. 1). From the parent specimen, U-bend specimens and tensile test specimens were machined in accordance with the T-L direction known as to have the weakest PWSCC resistance [6] (see Fig. 1).

Figure 2 is the geometry of the tensile test specimen and U-bend specimen. Before the U-bending process, we polished Alloy 182 specimens up to 800 grit with silicon carbide paper. The bolts and nuts which contacted Alloy 182 U-bend were fabricated with Alloy 600 in order to prevent galvanic corrosion,



(a) (b)

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

2.2 Tensile Test

We performed tensile test according to ASTM E8M. Table 2 shows the test results performed at both the room temperature and high temperature (325℃) environment.

Table 2. Mechanical properties of the Alloy 182 welds (RT: room temperature; AW: as-welded; 15Y: 15-year of thermal aging; 30Y: 30-year of thermal aging; CR: cold-rolled)

Specimen		Yield Strength [MPa]	Tensile Strength [MPa]	Elongation [%]
AW	RT	457.5 ± 26.8	568.3 ± 19.6	30.8 ± 5.9
	325℃	363.9 ± 25.0	562.9 ± 7.2	37.6 ± 2.5
15Y	RT	428.5 ± 9.0	637.6 ± 3.4	39.6 ± 1.1
	325℃	350.3 ± 2.9	552.2 ± 3.8	43.6 ± 2.5
30Y	RT	429.1 ± 1.5	648.6 ± 3.1	44.8 ± 3.7
	325℃	336.9 ± 59.2	512.7 ± 16.1	43.4 ± 1.8
CR	RT	733.3 ± 14.0	790.24 ± 23.8	14.1 ± 3.6
	325℃	592.8 ± 12.1	686.5 ± 23.2	14.8 ± 3.3

From the result, we observed the following phenomena:

- At room temperature testing, the tensile strength and elongation of the thermally aged specimens increased. It appears to be caused by the precipitate hardening and relief of the residual stress.
- For cold-rolled specimen, yield and tensile strength became very large but elongation became small. We think that it is due to the work hardening and addition of the residual stress.

2.3 PWSCC Initiation Test

We set up the loop circulation system to simulate the primary water environment as shown in Table 3. In this case, testing was performed at 340 ℃ for acceleration.

Table 3. Internal condition of PWSCC initiation test loop.

Temp. [℃]	DO [ppb]	DH [cc/kg]	Li / B [ppm]
340	~ 0	30	1200 / 2.0

We fabricated six U-bend specimens for each condition (e.g., AW, 15Y). However, since there was a pre-existing crack on CR #6 specimen, we excluded that specimen and fabricated more two CR specimens. Therefore, the number of U-bend specimens for CR condition is seven.

We censored all specimens every 250 h of testing time to check the initiation time of PWSCC. An optical microscopy was used for the censoring. If the product of measured length and width was larger than 5,000 μm^2 for the censored crack, we regarded it as a crack initiation (see Fig 3).

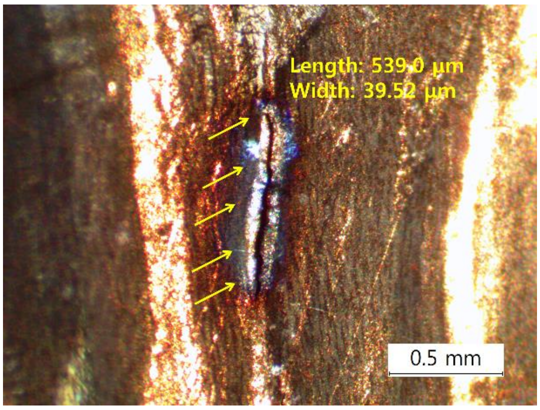


Fig. 3. Example of crack initiation (CR #3, 750 h).

Table 4 shows PWSCC test result as a cracking fraction of each specimen group at every censoring time. However, as shown in Table 4, the testing is not terminated and will be scheduled to continue. Thus, we note that the result of this paper is just in an intermediate stage.

Table 4. PWSCC test result: Cracking fraction of each specimen group at every censoring time.

Condition	Censoring time			
	0h	**250h**	**500h**	**750h**
AW	0/6	0/6	1/6	2/6
15Y	0/6	0/6	1/6	1/6
30Y	0/6	0/6	2/6	2/6
CR	0/7	1/7	2/7	5/7

2.4 PWSCC Susceptibility Modeling

It is known that the Weibull distribution is an appropriate statistical model of PWSCC initiation time [7] given by:

$$F(t;\beta,\eta) = 1 - \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right], \qquad (2)$$

where F is the cumulative probability function of crack initiation, t is the plant operation time, β is the Weibull shape parameter and η is the Weibull scale parameter.

From the PWSCC test result (i.e., Table 4), we estimated the Weibull parameters of each specimen group by maximum likelihood estimation method [7]. Table 5 shows the estimated Weibull scale parameter $\hat{\eta}$ and its relative ratio to $\hat{\eta}_{AW}$.

Table 5. Estimated Weibull scale parameter $\hat{\eta}$ and its relative ratio to $\hat{\eta}_{AW}$.

Condition	AW	15Y	30Y	CR
$\hat{\eta}$ [h]	1044.3 ($\equiv \hat{\eta}_{AW}$)	3256.5	1303.4	699.2
Relative ratio to $\hat{\eta}_{AW}$	$\hat{\eta}_{AW}$	3.12 $\hat{\eta}_{AW}$	1.25$\hat{\eta}_{AW}$	0.67$\hat{\eta}_{AW}$

We simply assumed that the relative ratio to $\hat{\eta}_{AW}$ is the effect of thermal aging and cold working on the PWSCC susceptibility. To model the effect of thermal aging, we adopted the following model by the 2nd order polynomial fitting (see Fig. 4):

$$\begin{aligned} &\hat{\eta}(t) \propto d(t)\hat{\eta}_{AW}, \\ &d(t) = 1 + (3.130 \times 10^{-5})t \\ &\qquad\qquad - (1.155 \times 10^{-10})t^2 \end{aligned} \tag{3}$$

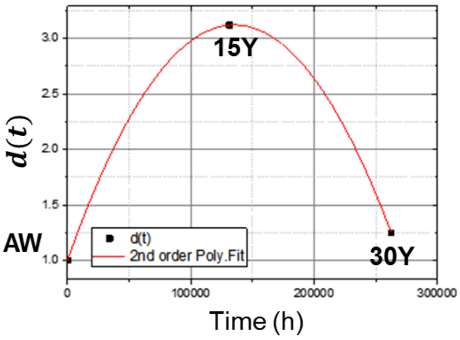


Fig. 4. Derived effect of thermal aging model from data in Table 5.

where, $d(t)$ is the effect of thermal aging at the time t and t is the thermal aging time or plant operation time. The result indicated that the PWSCC resistance is improved until 15 years due to the thermal aging, and then deteriorated thereafter. We speculate that the relief of residual stress is dominant until 15 years while microstructural degradation of materials (e.g., Cr depletion in grain boundaries) slowly proceeded.

Meanwhile, we adopted the following equation from the precedent study of Garud [8] to model the cold work effect:

$$\begin{aligned} &\hat{\eta} \propto \frac{1}{m^q}\hat{\eta}_{AW}, \\ &m = 30.0\epsilon_{pre} + 1 \end{aligned} \tag{4}$$

where, m is the measure of cold work, q is the empirical constant, and ϵ_{pre} is the applied pre-strain or thickness reduction [8]. From the data in Table 5, we can calculate that the value of q is 0.2062 for Alloy 182. This value is relatively smaller than that for Alloy 600 (= 0.375 [8]). However, the tendency of cold work effect (e.g., heavy cold working increases PWSCC susceptibility) was not changed as compared to the case of Alloy 600.

3. Conclusions

The effects of thermal aging and cold working on the PWSCC susceptibility of Alloy 182 weld were investigated. Tensile test and PWSCC initiation test were carried out. From the result of PWSCC initiation test, the effect model of thermal aging and cold working for Alloy 182 PWSCC susceptibility was estimated based on the precedent researches.

Acknowledgement

This work was supported by the Nuclear Safety Research Program through the Korea Foundation of Nuclear Safety (KOFONS), granted financial resource from the Nuclear Safety and Security Commission (NSSC), Republic of Korea (No. 1403006) and was supported by "Human Resources Program in Energy Technology" of the Korea Institute of Energy Technology Evaluation and Planning (KETEP), granted financial resource from the Ministry of Trade, Industry & Energy, Republic of Korea. (No. 20164010201000).

REFERENCES

[1] W. Lunceford, T. DeWees, and P. Scott, *EPRI Materials Degradation Matrix, Rev. 3*, EPRI, Palo Alto, CA, USA 3002000628, 2013.

[2] P. Scott and M.-C. Meunier, *Materials Reliability Program: Review of Stress Corrosion Cracking of Alloys 182 and 82 in PWR Primary Water Service (MRP-220)*, EPRI, Palo Alto, CA, USA, 2007.

[3] S. C. Yoo, et al. "Microstructural evolution and stress-corrosion-cracking behavior of thermally aged Ni-Cr-Fe alloy." *Corrosion Science* 111: 39-51, 2016.

[4] J. A. Gorman et al., "Guidelines for prediction of PWSCC in steam generator tubes," *ISCMIR, Fontevraud III*, Vol.1, 311-318, 1994.

[5] D.D. Pruthi et al., "Diffusion of Chromium in Inconel-600," *J. Nucl. Mater*. 64, 1997.

[6] *Materials Reliability Program: Experimental Program on the Effects of Surface Condition on Primary Water Stress Corrosion Cracking of Alloy 182 Welds (MRP-215)*, EPRI, Palo Alto, CA:2007, 1015016.

[7] Park, J. P., Park, C., Cho, J., and Bahn, C. B. "Effects of Cracking Test Conditions on Estimation Uncertainty for Weibull Parameters Considering Time-Dependent Censoring Interval." *Materials*, 10(1), 3, 2017.

[8] EPRI. *Stress Corrosion Cracking Initiation Model for Stainless Steel and Nickel Alloys: Effects of Cold Work*, 1019032, 2009.