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Effect of Microstructural and Environmental Factors on IASCC of PWR Core Internals by Statistical Analysis

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1. Introduction

For a proactive management of an irradiation-assisted SCC (IASCC) of reactor core internals such as baffle, former, bolts and flux thimble tubes, a lot of works have been performed in boiling water reactors (BWR) [1, 2]. From the works, among various microstructural factors, the radiation-induced segregation (RIS) is believed to play a role in IASCC of BWR core internals. Due to the irradiation of neutron, Cr, Fe and Mo are generally depleted, and Si, P and Ni are enriched in the materials. In particular, the depletion of Cr at the grain boundary (GB) is known as the most important RIS to induce the IASCC of stainless steels from the comparative studies of the susceptibility of SCC as a function of degree of Cr depletion at GB by irradiation of neutron and thermal sensitization [3].

Neutron fluence and stress are also crucial as the environmental factors of IASCC. From a lot of works on effect of neutron fluence on the SCC susceptibility in BWR, the threshold value was reported to be about 5×10^{20} n/cm^2 (E > 1 MeV) or 0.7 DPA(displacement per atom). On the other hand, the yield strength and ultimate tensile strength are increased, and ductility and fracture toughness are reduced due to the formation of point defects and dislocation loop in the materials by the neutron irradiation. Therefore, the effect of the applied stress to the materials on the SCC susceptibility is also changed.

Under the circumstances, many works have been performed to figure out the mechanisms of IASCC for the proactive management of core internals in pressurized water reactors (PWR). However the mechanism of IASCC in PWR is not fully understood yet as compared with that in BWR due to a lack of reliable data from laboratories and plants. This work is concerned with a statistical analysis of the microstructural and environmental factors affecting IASCC of austenitic stainless steels, especially for PWR core internals. A lot works on IASCC of stainless steels in PWR as well as BWR were reviewed and various factors reported to affect IASCC were critically evaluated by statistical analysis.

2. Statistical analysis

Statistical evaluation of the experimental data was performed using MINITAB[TB](release 13.20, MINITAB Inc.) software. The relationship between the SCC susceptibility (%IGSCC) and the Cr depletion at GB of the austenitic stainless steels was evaluated using the correlation analysis tool. The effect of neutron fluence on the SCC susceptibility was investigated by the probit analysis of the SCC susceptibility as a function of DPA. From the analysis, the threshold fluence of IASCC was statistically estimated at various temperatures. In addition, the effect of the applied stress on the time-to-failure of IASCC was studied based on the accelerated life testing (ALT) model, and then the life of a baffle-former bolt, one of the significant core internals in PWR, under the complex environments of irradiation and stress was statistically calculated.

3. Results and discussion

Fig.1 presents the susceptibility of SCC as a function of the degree of Cr depletion at GB due to irradiation collected from the previous works[4]. All data were measured from the slow strain rate test (SSRT) in the same experimental conditions, that is, in the normal water chemistry of BWR with the content of dissolved oxygen (DO) is about 32 ppm at 288 ^{o}C, and at the similar strain rate of 1×10^{-7}/s. %IGSCC is increased with decrease of the Cr content at GB.

From the experimental data in Fig. 1, the Pearson correlation coefficient and P-value were calculated by the correlation analysis. In the case of the thermally sensitized stainless steels, the P-value is lower than the significance level, α of 0.05, indicating that the SCC susceptibility is strongly correlated with the Cr depletion at GB. For irradiated stainless steels, however, P-value is higher than α of 0.05. This means that the SCC susceptibility and the Cr depletion at GB are not correlated with each other, that is, the Cr depletion at GB is not the main factor of the irradiated stainless steels. Recently, several works on the microstructural factors have pointed out the RIS of minor elements such as Si, P and S as the other factors affecting IASCC in BWR [1, 2] and the Ni enrichment in PWR [1].

Fig. 2 gives the SCC susceptibility of the stainless steels irradiated to various neutron fluences, measured from the SSRT in the same conditions of the primary water chemistry of PWR (DH ~ 30 cc/kg) at various temperatures. %IGSCC is remarkably increased with increasing fluence. The relation between %IGSCC and the neutron fluence follows the Weibull distribution as shown in Fig. 3. From the probit analysis, the threshold fluence for IASCC of stainless steels was estimated as the percentile at 2% of failure probability. It should be noted that the threshold value decreases remarkably from 5.799 to 5.253 and 1.914 DPA with increasing temperature from 325 to 325 and 340 ^{o}C.

Fig. 4 presents the time-to-failure of the irradiated stainless steels at various neutron fluences in PWR, measured from the constant elongation test at the same conditions of the primary water chemistry of PWR (DH ~ 30 cc/kg and 340 ^{o}C). From the distribution analysis of the experimental data in Fig. 4, the Weibull shape parameters were about 1 for low DPA and about 2 for high DPA regardless of the applied stress, confirming that the ALT model is applicable. According to the inverse power equation based on the ALT model, the characteristic life of a baffle former bolt exposed to neutron fluence of 20 and 75 DPA in PWR was calculated to be at least 131 and 2.8 years, respectively, whereas the B2 life was at least 2.5 and 0.4 year, respectively, within 95% confidence interval.

4. Conclusion

The Cr depletion at grain boundary was determined to have no significant correlation with the IASCC susceptibility. The threshold irradiation fluence of IASCC in PWR was statistically calculated to decrease from 5.799 to 1.914 DPA with increasing temperature from 320 to 340 ^{o}C. From the analysis of the relationship between applied stress and time-to-failure of stainless steel components based on the ALT model, it was found that B2 life of a baffle former bolt exposed to neutron fluence of 20 and 75 DPA was at least 2.5 and 0.4 year, respectively, within 95% confidence interval.

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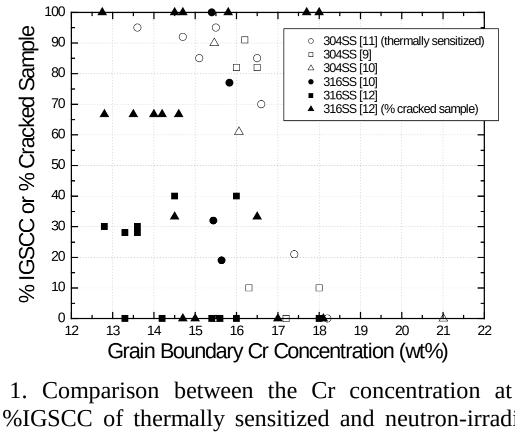

Fig. 1. Comparison between the Cr concentration at GB and %IGSCC of thermally sensitized and neutron-irradiated stainless steels in BWR normal water chemistry (Ref. in [4]).

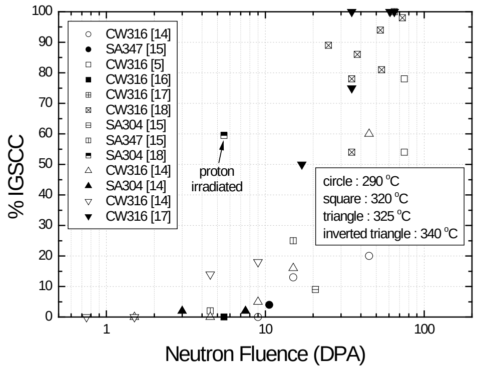

Fig. 2. %IGSCC of various stainless steels at various neutron fluence in PWR primary water chemistry (Ref. in [4]).

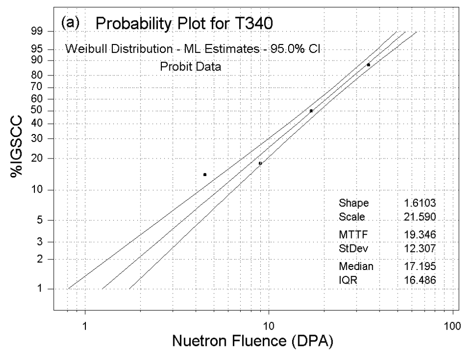

Fig. 3. The relation between %IGSCC and the neutron fluence in PWR primary water chemistrr (Ref. in [4]).

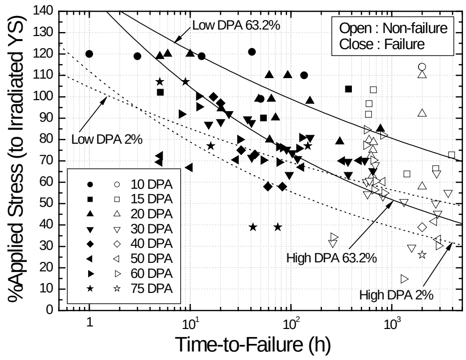

Fig. 4. The relation between %IGSCC and the neutron fluence in PWR primary water chemistry (Ref. in [4]).