Microstructure Evolution and Performance of Neutron Absorber in Spent Nuclear Fuel Pool

Yunsong Jung [a], Woong Ha [a], Kiyoung Kim [b], Sangjoon Ahn [a*]
[a]*Department of Nuclear Engineering, Ulsan National Institute of Science and technology*
50 UNIST-gil, Ulju, Ulsan, 44919, Republic of Korea
[b]*Central Research Institute, Korea Hydro & Nuclear Power Co., Ltd.,*
70, Yuseong-daero 1312 beon-gil, Yuseong-gu, Daejeon 34101, Republic of Korea
[*]*Corresponding author: sjahn99@unist.ac.kr*

1. Introduction

Neutron absorbers are widely used in spent fuel pool (SFP) and dry cask to ensure the subcriticality with more densely stored fuel assemblies. The performance and safety of the absorbers in SFP was experimentally demonstrated considering only neutron and gamma irradiation at a relatively low temperature (20 to 49 °C). However, radiation damage induced by the $^{10}B(n, \alpha)^{7}Li$ reaction could be concentrated at or near boron-bearing particles, which could lead to premature failure of the absorbers.

Recently, unexpectedly faster degradation, white spots, from the surface of surveillance coupons was discovered with reduced boron-10 areal density [1]. In this study, we characterized several-year irradiated neutron absorbers, Al-B_4C metal matrix composites (MMC), and observed highly radiation damaged structure with the reduction of boron-10 concentration.

2. Experimental

2.1 Materials

The Al-B_4C MMC consists of a high purity aluminum 6061 alloy matrix with Type 1 ASTM C-750 isotopically graded (^{10}B: 19.90 ± 0.3 at%) boron carbide [2]. The surveillance coupons (100 mm × 200 mm × 2.7 mm) of Al-32.4 wt% B_4C MMC for three different storage periods in the SFP (2y9m: 2 years 9 months, 4y4m: 4 years 4 months, and 8y3m: 8 years 3 months) were characterized.

2.2 Characterization

As-received coupons were sectioned into cuboids (5 mm × 5 mm × 2.7 mm) using waterjet to avoid adverse effects on microstructure [3]. The surface morphology was observed using a field-emission scanning electron microscopy (FE-SEM, FEI Quanta 200 FEG System) and micro-chemical analysis was carried out using an energy dispersive X-ray spectroscopy (EDS, Genesis 2000, EDAX). TEM specimens (7 µm × 5 µm × 100 nm) were prepared using focused ion beam (FIB, Helios 450HP, FEI) with the lift-out technique from the surface and characterized using a transmission electron microscope (TEM, JEM-2100F, JEOL).

2.3 Thermal neutron attenuation test

The thermal neutron field consists of ^{241}Am-Be neutron source, graphite moderator, He-3 detector, and cadmium cover as a thermal neutron filter. The thermal neutron transmission rate was calculated using the equation (1).

$$P = \frac{S_t - S_e}{R_t - R_e} \times 100 \qquad (1)$$

P : Thermal neutron transmission rate (%)
S_t: Count rate from the source with a coupon (cps)
S_e: Count rate from the source with a coupon and Cd cover (cps)
R_t: Count rate from the source (cps)
R_e: Count rate from the source with Cd cover (cps)

3. Results and discussion

3.1 Microcracks and pits in boron carbide

Surface degradation of boron carbide particles was universal for all three periods as shown in Fig. 1. Microcracks were formed in boron carbide, which can channel the release of helium gas from the $^{10}B(n, \alpha)^{7}Li$ reaction [4]. The small pits in boron carbide were observed, that can lead to the potential risks of boron-10 loss or redistribution.

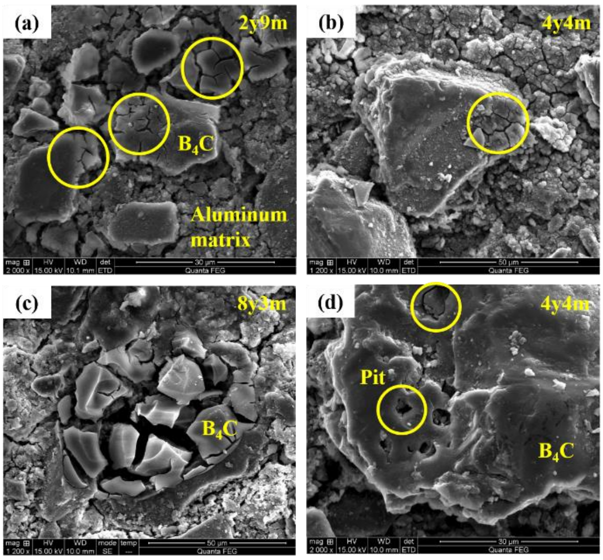

Fig. 1. The microcracks in 2y9m (a), 4y4m (b), and 8y3m (c) and pits in 4y4m (d)

3.2 Helium bubble formation in the aluminum matrix

Figure 2 shows numerous helium bubble formation induced by the $^{10}B(n, \alpha)^{7}Li$ reaction in the aluminum matrix of 8y3m. Based on the premature corrosion failure of surveillance coupons and this highly damaged aluminum matrix, energetic α-particles (~1.5 MeV) and lithium ions (~0.8 MeV) emitted from the $^{10}B(n, \alpha)^{7}Li$ reaction could have expedited the corrosion of neutron absorbers owing to ballistic and radiation-enhanced diffusivity, radiation-damaged porous microstructure, and locally elevated system temperature.

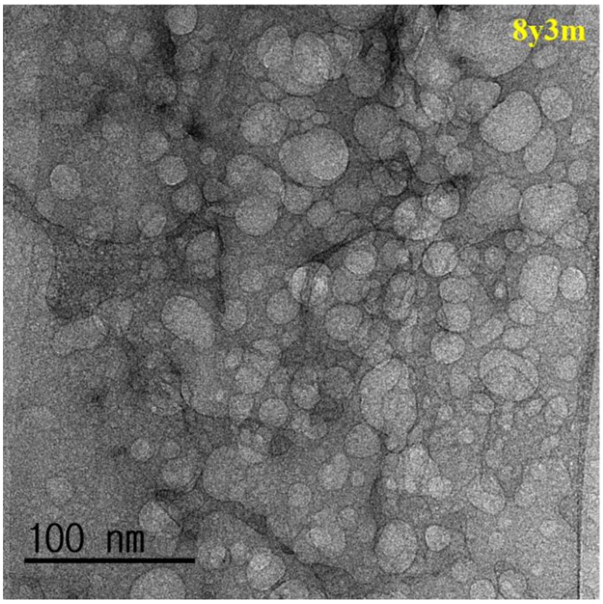

Fig. 2. Helium bubble formation in the aluminum matrix of 8y3m

3.3 Reduction of boron-10 concentration

Since the severe microstructural evolution suggested potentially large boron depletion, thermal neutron attenuation tests of 16 coupons (2y9m: 4, 4y4m: 6, and 8y3m: 6) were performed. The boron-10 areal density of pre-irradiated coupons was 0.0335 ± 0.0005 g/cm^2. In Fig. 3, thermal neutron transmission rate exponentially increased in the order of storage period in the SFP, which means the boron-10 depletion rate increases continuously. Therefore, the performance of neutron absorbers should be monitored periodically to ensure the subcriticality in the SFP.

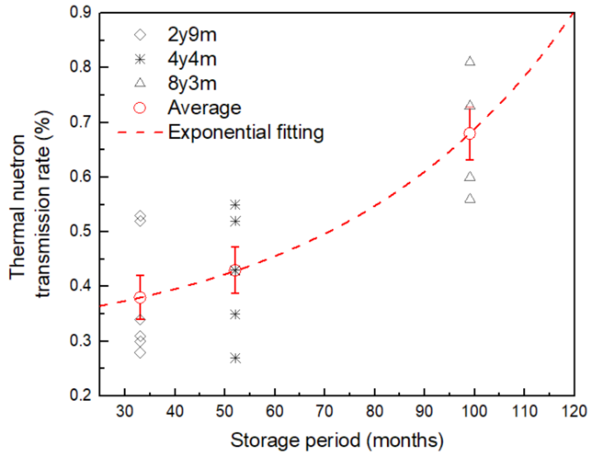

Fig. 3. Thermal neutron attenuation test results of neutron absorbers

4. Conclusion

Numerous helium bubbles were found from aluminum matrix near B_4C particles, which underwent microcracks and pits. These highly radiation damaged features are suspected due to energetic helium and lithium ions emitted from $^{10}B(n, \alpha)^{7}Li$ reaction at or near boron carbide particles, which could accelerate the corrosion of neutron absorber in SFP. The thermal neutron attenuation test showed the stepwise reduction of the boron-10 concentrations in the order of storage periods.

ACKNOWLEDGEMENT

This work was supported by Korea Hydro & Nuclear Power Co., Ltd (2017-Tech-18).

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