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Diffusion couple test of irradiated U-Zr-Ce fuel with T92 cladding at high temperature

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1. Introduction

U-Zr alloys fuel and ferritic-martensitic stainless (FMS) steel claddings have been considered as the most promising fuel for the sodium-cooled fast reactor (SFR) [1]. In this study, to investigate the fuel cladding chemical interaction (FCCI) of U-Zr-Ce fuel under a transient condition, high-temperature diffusion couple tests were conducted with irradiated U-10Zr-5Ce fuel slugs with T92 cladding at hot-cell in Korea Atomic Energy Research Institute (KAERI).

2. Experimental

The fuel rod of U-10wt%Zr-5wt%Ce (U-10Zr-5Ce) with T92 (NF616) cladding was irradiated in the HANARO test reactor at KAERI [2]. The fuel rods were irradiated for 182 effective full power days (EFPDs) and the average burn-up of 2.9 at% was achieved. Fig. 1 shows the X-ray image of the irradiated U-Zr-Ce fuel rod. The fuel slug was cut into more than five segments using low speed saw for four specimens for FCCI tests and one specimen for observation of as-irradiated state of the specimen.

Fig. 1. Transmitted X-ray image of the irradiated U-10Zr - 5Ce fuel rod.

A special jig for a transient test was designed and manufactured to facilitate easy handling by manipulators in hot-cell. Fig. 2 shows a schematic diagram of the jig. As shown in the figure, the top and the bottom surfaces of the specimens can get into contacts with the FC92, and HT9 plates, which enables to induce an inter-diffusion reaction of the fuel slug with T92, FC92, and HT9, simultaneously. The diffusion couple test was conducted at 800 ºC for 1 hr.

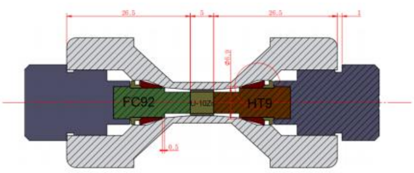

Fig. 2. Schematics of the jig for fuel cladding chemical interaction.

To observe microstructure of the specimen, both sides of the dog bone type of the jig was cut and mounted. The microstructures of the fuel slug and clad material were observed using optical microscopy (OM) and scanning electron microscope (SEM) equipped with wavelength dispersive X-ray spectroscopy (WDS) in an electron probe micro analyzer (EMPA, JXA-8320 JEOL).

3. Results and discussion

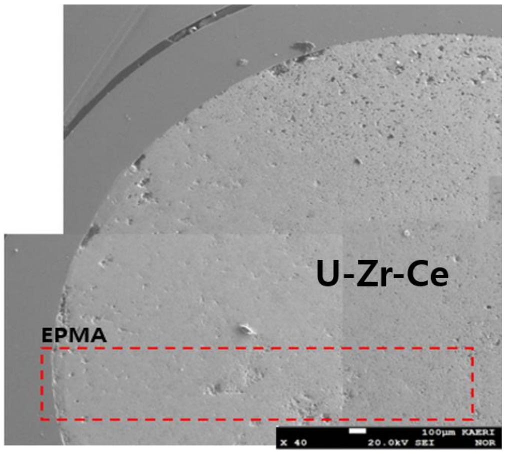

Fig. 3 SEM image of as-irradiated U-10Zr-5Ce.

Fig. 3 shows the transverse cross section of as-irradiated U-10Zr -5Ce/T92. X-ray mapping was conducted in red box in Fig. 3 for the major fuel and cladding elements U, Zr, Fe, Cr, and Ce. As shown in Fig. 4, the concentration of Zr is highest at the center and decreases with increase in distance from the center, whereas U concentration seemed to be a little complicated but U is deemed to follow the trends that U balances the total mass. It is noted that the maximum centerline temperature of this specimen during irradiation was calculated to be 549 °C [3], which is far below the phase transition temperature of the U-Zr phase diagram [4], and therefore the fuel slug will be operated in the single $\alpha+\delta$ phase during HANARO irradiation.

The distribution of Ce in the as-fabricated U-Zr-Ce fuel is uniform, and the shape of Ce in as-fabricated U-Zr-Ce shows a globular precipitate due to miscibility gap between Ce and U, whereas, the morphology of Ce in irradiated U-10Zr-5Ce fuel is not a globular but irregular shape, and Ce particles are locally concentrated in the middle and periphery of the irradiated U-10Zr-5Ce fuel. In general, lanthanides have been observed in pore and periphery of the irradiated fuel slug. It is known that lanthanide fission products tend to migrate toward the peripheral zone of fuel through the inter-connected pores. However, such a migration of Ln was not clearly observed in this work.

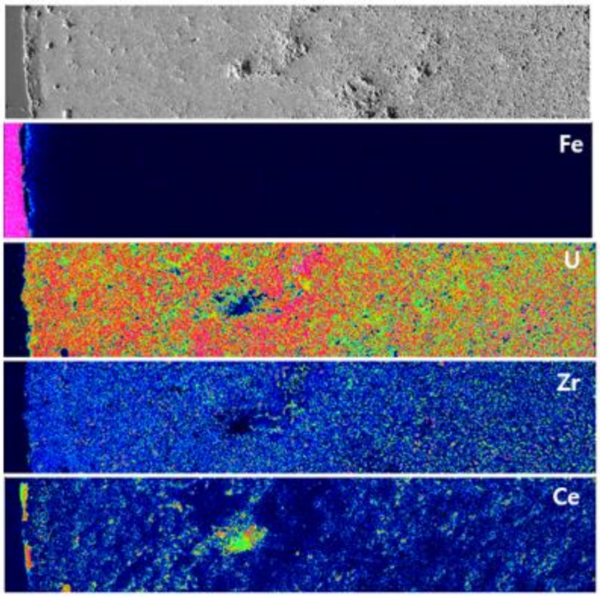

Fig. 4. X-map of as-irradiated U-Zr-Ce in Fig. 3 for Fe, U, Zr, and Ce.

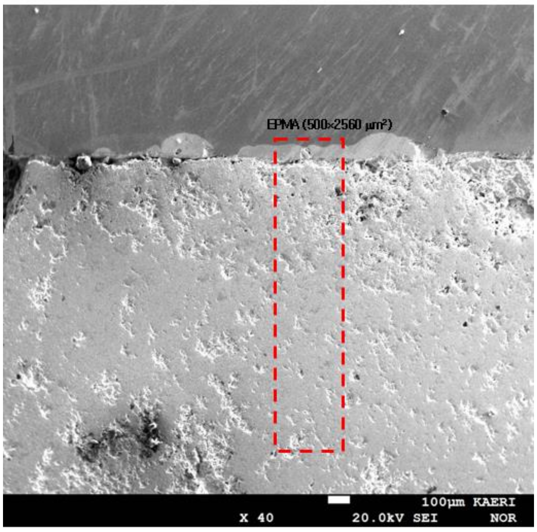

Fig. 5. SEM image of the U-10Zr-5Ce fuel rod after FCCI test

Fig. 5 shows SEM image of the U-Zr-Ce with FC92 specimen after the high temperature FCCI test, and Fig. 6 shows X-ray map of U-Zr-Ce in Fig. 5 for U, Zr, Fe, Cr, and Ce. U penetration into cladding is clearly obserbed and penetration depth of U into cladding is around 50 um and diffusion depth of Fe into U-Zr-Ce is around 560 um.

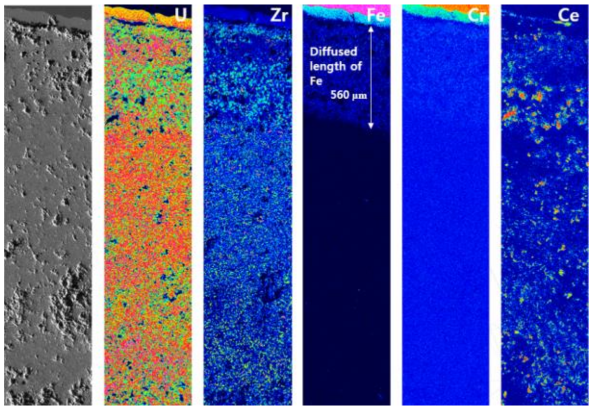

Fig. 6 SEM of U-Zr-Ce, and X-ray maps for U, Zr, Fe, Cr, and Ce in the red box in Fig. 5

Element distribution of Ce in Fig. 6 is similar to that of as-irradiated one, which may indicate that Ce does not play any significant role on FCCI in this study.

4. Summary and conclusions

High temperature heating test was conducted with irradiated U-10Zr-5Ce and T92 cladding in hot-cell. Following conclusions can be drawn from this study.

- During the 1 hr at 800 °C, penetration depth of U into Fe-Cr cladding matrix was approximately 50 µm ,and Fe diffused 560 µm toward U-Zr-Ce matrix.
- Dispersed Ce from the manufacture did not interact with iron and it does not play important role on FCCI.

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