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Performance of electroplated Cr as a FCCI barrier material for a sodium-cooled fast reactor (SFR) cladding

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1. Introduction

Metallic fuel composed of U, Zr, and transuranic elements (TRU) has been developed as a fuel material for a sodium-cooled fast reactor (SFR). Although it has many advantages such as a good thermal conductivity, compatibility with sodium, actinide management, etc., a fuel cladding chemical interaction (FCCI) can occur at a relatively low temperature. It deteriorates the performance of a metallic fuel and affects the integrity of the cladding material.

To retard a FCCI, insertion of barrier material between the fuel rod and cladding was proposed, so many refractory materials were considered as a barrier material. However, most of the materials were inappropriate because they were expected to react with fuel or cladding according to the analysis of phase diagrams. Some researchers tested the performance of candidate FCCI barrier materials by using diffusion couple annealing techniques [1-4]. Because earlier studies on FCCI barriers have focused mainly on Zr and V, the performance of Cr was not fully investigated yet. Recently, Ryu et al. [4] reported that V and Cr exhibited good FCCI barrier performance when compared to Zr, Nb and Ti.

In this study, electroplating of Cr on the inner wall of a cladding was proposed due to its advantages such as a diffusion barrier performance, manufacturing feasibility, compatibility with a cladding fabrication, irradiation performance, and economy. Cr of 20 μm in thickness was electroplated on ferritic/martensitic steel (FMS) in order to evaluate its diffusion barrier performance between a metallic fuel and FMS.

2. Experimentals

2.1 Specimen

U-10wt%Zr was used as a fuel material. It was fabricated by an induction melting of elemental lumps of U and Zr. Each rod with a diameter of 6 mm was cut into a disk with 1 mm in thickness. HT9 (Fe-11.5Cr-1Mo-0.5W-0.5Ni-0.3V-0.2C-0.55Mn-0.4Si) disks were used as a FMS cladding material. Their diameter and thickness were 8 and 1.5 mm, respectively. Cr was plated on the surface of HT9 in bath containing 250 *g/l* of chromic acid and 2.5 *g/l* of sulfuric acid.

2.2 Diffusion couple test

The U-10Zr vs. HT9 diffusion couple was wrapped in Ta foil to prevent reaction with stainless steel screw bolts. Assembled diffusion couple set was heat-treated at temperature of 700 and 740°C for 96 h and 800°C for 25 h in a vacuum tube furnace. During the test, the inside of heater was maintained under a vacuum of 10^{-3} ~ 10^{-4} Pa. After the test, the diffusion couple set was water-quenched to room temperature. The cross-sections of the diffusion couple interfaces were observed by using a scanning electron microscope (SEM) and an energy dispersive X-ray spectroscope (EDS).

3. Results and Discussion

Before the diffusion couple test with Cr-plated HT9, the test between as-received HT9 and U-10Zr was conducted. Only little part of interaction region below 1 μm was observed when annealed at 700°C for 96 h. Fig. 1 shows the results of test at 740 and 800°C. Although the thickness of interaction region was different from Keiser's observation [5], the microstructures were similar to their results. Gray phase of UFe_2, dark one of Zr rich-line layer, and mixed phase with U and Zr were observed as shown in Fig. 1(a). Fig. 1(b) shows the interaction result of a test at 800°C for 25 h. All of U-10Zr region was reacted with HT9 because eutectic melting temperature between U-10Zr and Fe is around 725°C. Gray phase of UFe_2 was formed between the initial interface and HT9. The complex intermetallic compounds mixed with U, Zr, Fe, Cr, and Ta were observed at the region of U-10Zr.

To form Cr layer on the surface of HT9, two plating methods of Cr were used in this study, 'hard Cr' and 'crack-free Cr'. Hard Cr has been applied in various industries because of its high hardness. However, it has many cracks which can deteriorate the corrosion resistance. Sohi et al. studied crack-free Cr plating to improve the corrosion resistance of Cr layer [6]. In their study, only change of bath temperature can possible to form a crack-free Cr layer. Hard Cr plated at a bath temperature of 50°C might generate many cracks, so it might affect integrity of Cr layer. A crack-free Cr layer was formed at a bath temperature of 80°C. At crack-free Cr plating, the higher current density was needed than hard Cr plating because of the drop of current efficiency by the temperature increase. Electroplating of Cr on the inner wall of a FMS cladding tube with 50 mm in length was also demonstrated successfully by using a circulation plating method.

Cr layers of 20 μm in thickness were plated by a hard Cr and a crack-free Cr condition to compare the diffusion barrier performance between U-10Zr and HT9. Both Cr layers inhibit the interaction between U-10Zr and HT9 at all temperature ranges of 700, 740, and 800°C. No eutectic melting was observed in diffusion couples with a Cr-plated barrier layer. Fig. 2 shows the results of diffusion tests between U-10Zr and Cr-plated HT9. The penetration of U into the Cr layer was observed. Many cracks developed in a hard Cr layer play as diffusion paths as shown in Fig. 2(a). When a crack-free Cr layer was formed, only a few cracks were observed in the crack-free Cr layer as shown in Fig. 2(b). Crack-free Cr plating was more effective in prohibiting the FCCI.

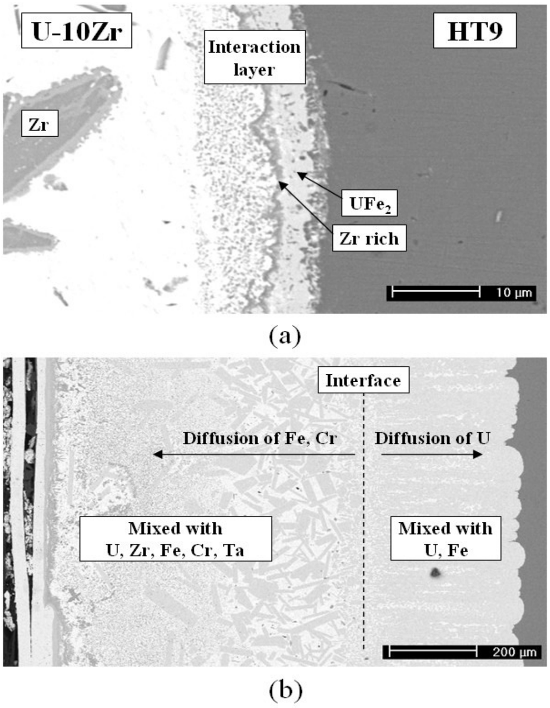

Fig. 1. Back-scattered electron images of diffusion couple test samples between U-10Zr and as-received HT9 annealed at (a) 740°C for 96 h, and (b) 800°C for 25 h

4. Conclusion

To prevent a FCCI between a metallic fuel and a cladding material, electroplating of Cr on the inner wall of a cladding was proposed. Diffusion couple tests using Cr-plated FMS were conducted at temperatures of 700, 740, and 800°C and compared with diffusion couple tests without a Cr-plated layer. Plated Cr layer inhibited an eutectic melting between U-10Zr and FMS effectively up to 800°C for 25 h. Because a penetration of U along the cracks in the conventional hard Cr layer was observed, electroplating conditions were modified to form a crack-free Cr layer. Crack-free Cr showed a better performance as a FCCI barrier with less U penetration during the diffusion couple tests.

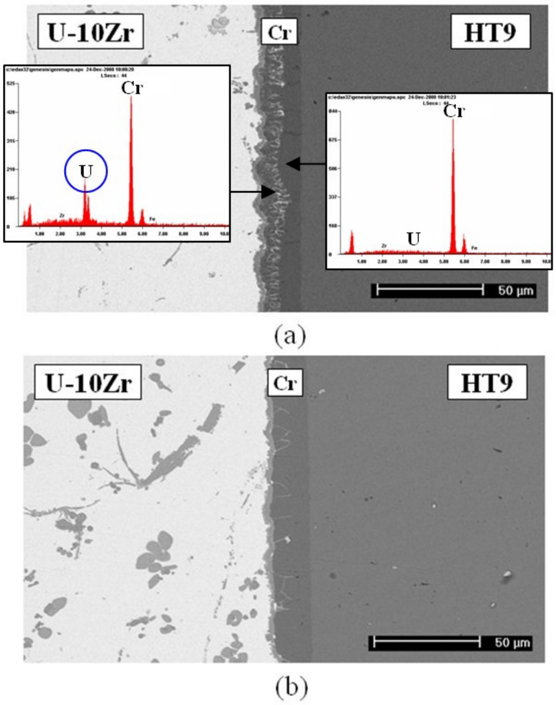

Fig. 2. Back-scattered electron images of diffusion couple test sample annealed at 800°C for 25 h with U-10Zr between (a) U-10Zr and Hard Cr plated HT9, and (b) U-10Zr and Crack-free Cr plated HT9

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