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Comparison studies between Cr-coating and Zr-liner on HT9 cladding for fuel and cladding chemical interaction (FCCI) barriers in SFRs

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1. Introduction

Fuel and cladding chemical interactions (FCCI) occurred during the operation of reactors have been a concern in the development of sodium-cooled fast reactors (SFRs), which are a type of generation-IV nuclear reactor have conceived for their ability to recycle spent nuclear fuels. Most SFRs are fueled by U-Zr metallic fuel containing TRUs (transuranium isotopes) and REs (rare-earth elements), and ferritic martensitic type steels such as HT9 have been considered as a primary candidate for cladding material. The fuel and cladding are chemically reacted at their interface under reactor operating conditions resulting in brittle and lower strength intermetallic compounds. This FCCI is a main factor decreasing the safety margin of SFRs. To overcome FCCI, the introduction of barriers between the fuel and cladding has been aroused as a simple method to hinder the fuel and cladding chemical interaction (FCCI). The Cr-coating at the inner-surface of HT9 cladding is a well-known suggestion [1], while the introduction of Zr-liner between the fuel and cladding also has been investigated for decades [2].

Although the excellent barrier properties of both Cr-coating and Zr-liner barriers have been demonstrated in the various diffusion couple tests, further investigations are required to confirm their applicability to the inner-space of cladding, interfacial characteristics, and microstructural and mechanical properties of barrier-applied HT9 cladding. In this paper, Cr-coated and Zr-linered HT9 cladding were manufactured using electroplating and sequential co-pilgering methods. Their various properties including microstructures and mechanical properties were investigated. Untreated HT9 is also prepared to be utilized as base specimen for comparison studies. Finally, diffusion couple tests were conducted to compare their barrier properties under severe conditions.

2. Methods and Results

2.1 Methods

HT9 cladding (valance Fe, 12.0 Cr, 1.0 Mo, 0.6 Ni, 0.6 Mn, 0.52 W, and 0.3 V in wt%) with the inner and outer diameters of 5.6 mm and 6.8 mm, respectively, was fabricated from HT9 ingot through hot extrusion, cold pilgering, cold drawing, and subsequent heat treatments. The inner-surface of the HT9 cladding was coated by Cr using an electrodeposition system as already described in our previous publication [1]. The manufacturing of Zr-liner HT9 cladding was carried out through various mechanical and thermal procedures including pilgering and heat-treatments. A Zr-tube was inserted into the prepared HT9 cladding and the couple was physically attached by conjunction pilgering procedure. The outer diameter and thickness of the specimen was 7.4 mm and 0.55 mm, respectively, while the length was 50—75 cm after the procedure.

To investigate the influence of Cr-coating and Zr-liner on mechanical properties of cladding, tensile tests were performed. Creep tests were performed only on the Cr-coated cladding. In light of the fact that the creep is the main failure mechanism of cladding in a reactor, creep tests will be performed on the Zr-liner cladding as well. The diffusion barrier property of Cr-coating and Zr-liner was examined using diffusion couple tests performed at 650 °C for 25 h. The simulated fuel alloy consisted of Ce and Nd (1:1 in wt%). As the eutectic temperature of the Ce-Fe system is 592 °C, the utilized test conditions simulated severe reactor core condition.

2.2 Results

Fig. 1 shows hoop stress and hold time to failure curve derived from creep tests performed at 700 °C and 800 °C. The Westinghouse Hanford Company's (WHC) creep data obtained using HT9 specimen was utilized as a reference in this study [3]. The trend lines at both temperatures were drawn by the WHC data and experimentally obtained untreated HT9 data were not far from the obtained trend lines. This result indicates the creep property of manufactured HT9 cladding in KAERI is comparable to that of reference HT9. As expected, the specimen was fractured earlier at 800 °C. The WHC, and experimentally obtained HT9 and Cr coated HT9 showed similar values and trends showing well agreements. Therefore, it is reasonable to address that untreated and Cr-coated HT9 cladding obtain comparable creep properties; the influence of Cr-coating barrier on the creep property is negligible.

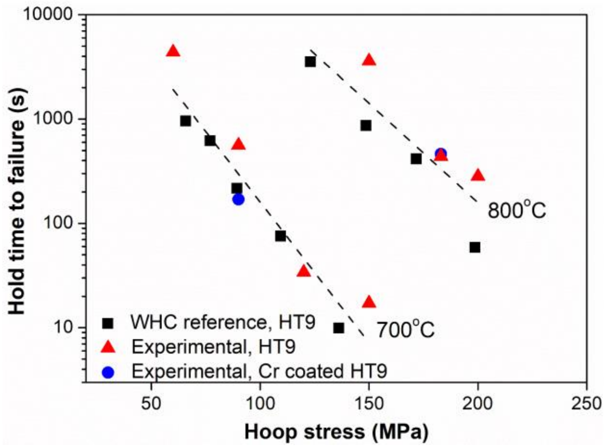

Fig. 1. Hold time to failure of untreated and Cr-coated HT9 cladding obtained from creep tests.

Fig. 2 shows tensile test results performed at 650 °C. Liner cladding revealed the highest yield strength and ultimate tensile strength (UTS) compared to those of untreated and Cr coated HT9. The yield strength and UTS of liner cladding is 400% and 190% higher than those of untreated HT9 cladding. Meanwhile, the Cr coated HT9 obtained 80% and 18% higher yield strength and UTS, respectively, than those of untreated HT9. These results indicate that the barriers have very high influence on the tensile tests and increase yield strength and UTS. As expected, the elongation behavior is generally reverse when compared to those of strengths so that the liner has the lowest elongation. It could be expected that the coating adhesion of Cr-coating and Zr-liner was excellent because if the adhesion was poor, the tensile property would be similar to untreated HT9 cladding.

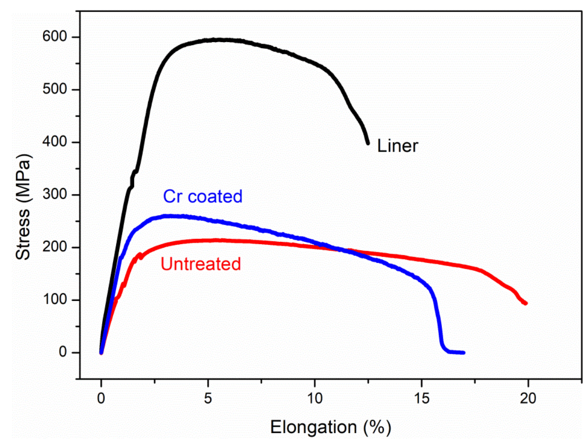

Fig. 2. Stress and elongation curves of untreated, Cr-coated, and Zr-liner HT9 cladding.

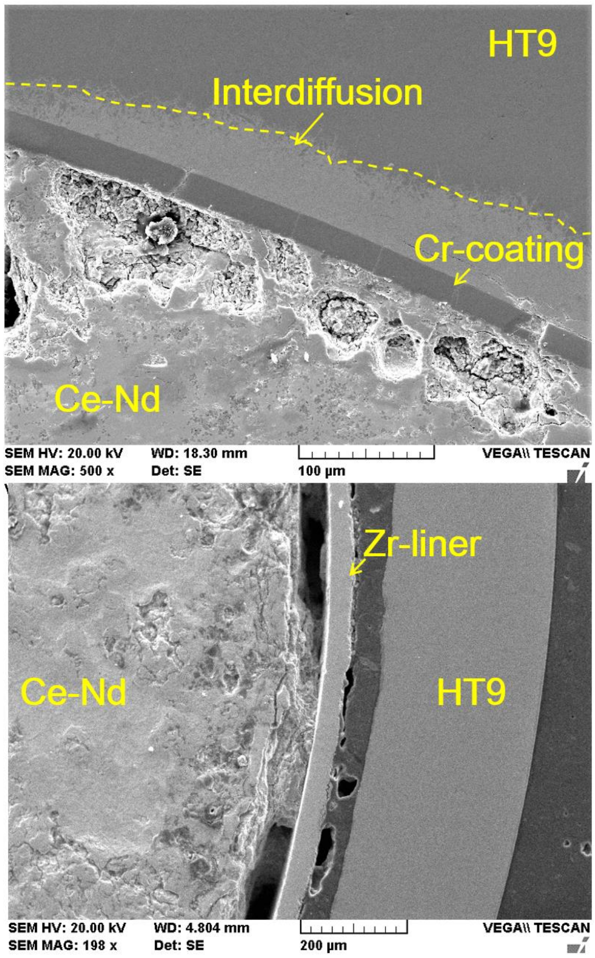

Fig. 3. Diffusion barrier properties of Cr-coating and Zr-liner from diffusion couple tests with Ce-Nd alloy.

Fig. 3 shows the diffusion couple test results of Cr-coating and Zr-liner cladding. Inter-diffusion area was clearly observed in the Cr-coated HT9 as indicated in the figure, while no inter-diffusion region was observed in Zr-liner cladding. The Cr-coating may not enough for the entire reduction of interdiffusion of Ce and Nd elements in a transient state of reactors. The Zr-liner works very well to prevent the chemical reaction between HT9 and Ce-Nd. However, the observed interfacial gap between HT9 and liner may decrease thermal conductivity of cladding. Further research is necessary to increase the barrier property of Cr-coating and reduce the interfacial gap between Zr-liner and cladding.

3. Conclusions

Mechanical properties including creep and tensile behaviors, and diffusion barrier properties of Cr-coating and Zr-liner HT9 cladding were investigated and compared. The creep property of Cr-coated HT9 cladding was comparable to that of untreated HT9 cladding. Zr-liner HT9 cladding showed the highest yield strength and UTS than those of Cr-coated and untreated HT9 claddings. Finally, diffusion couple tests revealed a lack of barrier property of Cr-coating, while excellent barrier property was observed in Zr-liner cladding without any inter-diffusion area. However, the observed interfacial gap between Zr-liner and HT9 cladding is a disadvantage to be overcome in future work.

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