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Investigation of interface property of Cr-coated Zircaloy-4 by micromechanical testing

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1. Introduction

Zirconium-based alloy is a key material for fuel rod cladding, because of its advantageous properties, such as its low neutron absorption cross-section. One significant drawback of the zirconium-based alloy is its low oxidation resistance, and to address this issue, extensive research has been conducted on coating the cladding surface with chromium(Cr) to improve oxidation resistance under both normal and accident conditions.

To maintain the oxidation resistance of the Cr, it is important that the Cr coating layer remains well-adhered and does not delaminate. Consequently, previous studies have evaluated its adhesion properties at a macroscopic scale. Kim et al. (2015) examined the adhesion behavior of Zircaloy-4 coated with 3D laser-deposited chromium, showing that the Cr-coated specimens exhibit superior strength compared to uncoated samples and good interfacial adhesion under both ring compression and tensile testing [1]. Umretiya et al. (2020) evaluated the integrity of Cr coatings by conducting scratch tests on specimens coated via PVD and cold spray methods [2].

In this study, micromechanical testing was employed to evaluate zirconium-chromium interface characteristics like interfacial bonding strength. Among various micromechanical tests, a microtensile test—conducted on the micron scale—was performed to evaluate the interfacial characteristics of the coating layer.

2. Methods and Results

2.1 Sample preparation

In this study, microtensile specimens were fabricated using a Zircaloy-4 tube coated with a Cr layer of approximately 10 µm in thickness, deposited by arc ion plating(AIP). Microtensile specimens were fabricated in two different ways: one with the interface at the midpoint of the gauge section (Zr-Cr sample) and another with the interface at the end of the gauge section (Cr sample). The detailed geometries are shown in Figure 1. After the final fabrication, the SEM images and EDS analysis results for the samples are presented in Figure 2.

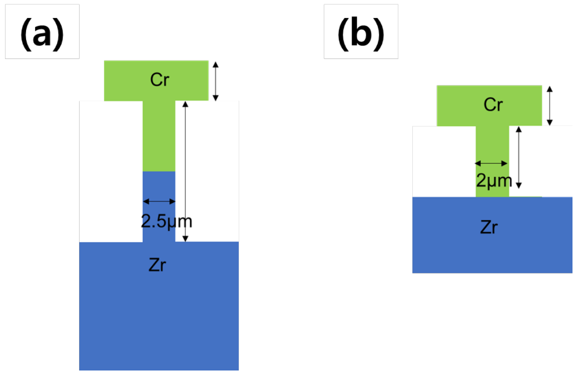

Fig. 1. Schematic of the microtensile specimen (a) interface on the middle of the gauge section (Zr-Cr sample) and (b) interface on the end of the gauge section (Cr sample)

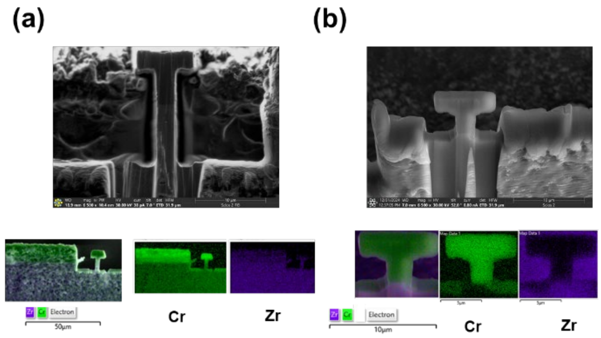

Fig. 2. Microtensile specimen fabrication SEM and EDS results of (a) Zr-Cr sample and (b) Cr sample

2.2 Microtensile test results

Microtensile specimen tests were conducted under displacement-controlled loading at 10^{-3} /s using the Hysitron PI-88 pico-indenter. Figure 3 shows the SEM images of the fractured specimens after testing. As shown in Figure 3(a), fracture occurred in the lower part of the specimen, within the relatively soft Zr layer, without delamination at the Zr/Cr interface. Similarly, in Figure 3(b), fracture did not initiate at the interface, but instead occurred at the head of the tensile bar, where stress concentration was observed. Figure 4 presents the stress-strain results for each sample. For Cr 1 sample shown in Figure 4(b), the specimen experienced tearing rather than brittle fracture, resulting in relatively high fracture stress. However, for most other samples (including both Zr-Cr and Cr samples), the fracture stress ranged from approximately 700 to 900 MPa, which is comparable to the failure stress of Zr (around 700 MPa) obtained from previous micropillar tests [3].

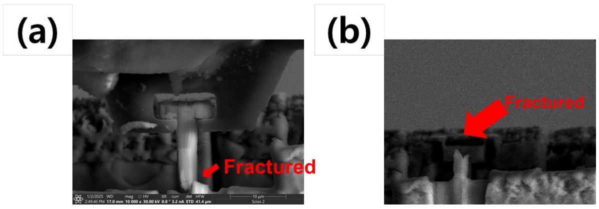

Fig. 3. SEM image of fractured microtensile specimen after tensile test of (a) Zr-Cr sample and (b) Cr sample

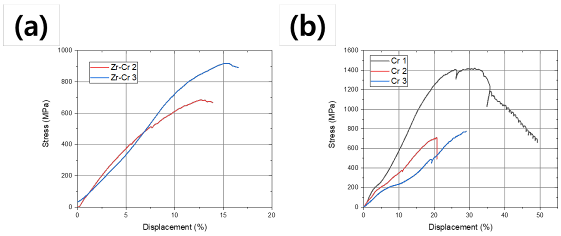

Fig. 4. Microtensile test enigneering stress-strain results of (a) Zr-Cr sample and (b) Cr sample

3. Conclusion

In this study, microtensile tests were conducted to investigate the interfacial characteristics of Cr-coated Zircaloy-4 cladding, focusing on the adhesion behavior and mechanical performance at the microscale. Microtensile specimens were fabricated using a Zircaloy-4 tube coated with a Cr layer deposited by arc ion plating.

The test results showed that fracture consistently occurred in the relatively soft Zr layer or at the head of the tensile bar, not at the Zr/Cr interface, which indicates that there is a strong interfacial bonding between the coating and substrate. These results show that the Cr coating layer maintains excellent adhesion under tensile loading. Future work will focus on modifying the microtensile specimen geometry, such as introducing hourglassing or notches near the interfaces, to further enhance interface debonding and enable a more direct evaluation of interfacial adhesion properties.

ACKNOWLEDGMENT

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