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Ballooning Behavior of an Improved Zr Fuel Cladding with Oxidation Resistant Coating under High Temperature Steam Environment

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1. Introduction

After the Fukushima nuclear accident, it was demonstrated that Zr-based alloys do not maintain their integrity under uncontrollable conditions [1,2]. The reaction between zirconium and steam at high temperatures is accompanied by the release of large amounts of hydrogen gas [3,4]. In the case of Fukushima, this resulted in explosions, which severely damaged external plant buildings. There have been various attempts to reduce hydrogen related risks in light water reactors (LWRs) and the related issues have been widely discussed [5-7]. A simple solution to prevent or reduce the possibility of hydrogen explosions in severe accidents (such as a loss-of-coolant accident (LOCA) and beyond design basis accident may be to replace the current Zr-based alloy fuel cladding with other materials exhibiting much lower oxidation rates, such as SiC, Mo alloys, and FeCrAl alloys. However, fuel claddings using these materials are still in the very early stages of development and testing and there remain a number of critical challenges to be solved. Unfortunately, it seems that it is very difficult to eliminate some drawbacks using a single material. In this respect, applying an oxidation resistant layer on the outer surface of current Zr fuel cladding may be a faster approach to enhance the safety of fuel claddings under accident conditions. In this study, we evaluate Cr as coating materials and the cold spray technique for fabricating coated Zr fuel cladding. To evaluate the feasibility of the coated claddings, the high temperature oxidation behavior of Cr-coated Zr was studied under simulated accident conditions and understood by characterization of the microstructure. For comprehensive understanding of phenomena such as ballooning, burst failures, and oxidation for the coated Zr cladding during a LOCA scenario, integral LOCA testing was carried out.

2. Methods and Results

A cold spraying technique was used to apply the coating layers on the surface of Zr alloy tube samples. The powders were accelerated in a N2 process gas stream at 800℃ and a pressure of 2.94 MPa through a de Laval type nozzle before impacting the Zr alloy substrate. The nozzle was placed at a distance of 40 mm from the Zr substrates. The deposition angle was 90°; and the nozzle traveling speed was 100 mm/s. Before coating, the surfaces of all Zr alloy specimens were ultrasonically cleaned in deionized water, acetone, and alcohol to remove any organic substances on the surfaces. For the integral LOCA tests, 400 mm long tubular Zr alloy cladding samples were filled with 10 mm long alumina pellets to simulate the heat capacity of the fuel. The furnace was heated to a pre-test hold temperature of 300℃ within 240 s, where the steam flow and sample temperature were stabilized for 500 s. A heating rate of 5℃/s from 300℃ to 1200℃ was used. After exposure at 1200℃ for 300 s, the tube was cooled slowly to 800℃ and then quenched by flooding from the bottom of the chamber with water. Further details of the test equipment and experimental procedures can be found in our previous paper [8]. Ballooned and oxidized tube samples were subjected to 4-point bend tests at room temperature to evaluate the mechanical properties. 400 mm long cladding samples were placed on two supporting pins 250 mm apart and two loading pins, 150 mm apart, applied force to the sample. After the 4-point bend tests, 8 mm long ring samples were sectioned 50 mm away from the ballooned region and used for ring compression tests.

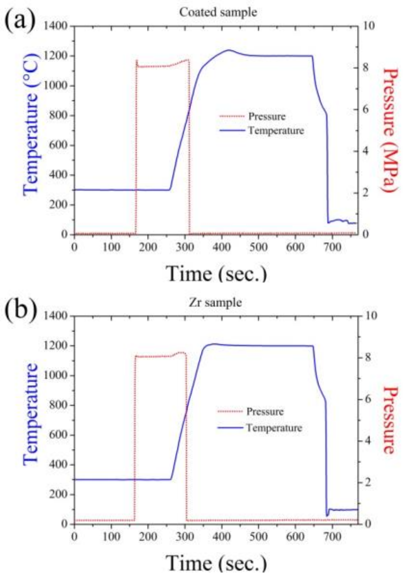


Fig. 1. Temperature and internal pressure profiles for the Zr cladding specimens (a) with and (b) without a Cr coating layer during integral LOCA tests.

We investigated the ballooning behavior of the coated tube samples using single rod geometry during simulated LOCA conditions. Figs. 1(a) and 1(b) show the temperature and internal pressure profiles for the LOCA tests conducted using an uncoated or Cr-coated Zr alloy cladding tube, respectively. The Cr-coated tube and Zr alloy cladding sample burst at 839.5℃ and 754.8℃, respectively.

As shown in Figs. 2 (a) and 2(b), The Cr-coated tube showed a much smaller burst opening than the Zr alloy cladding sample. The circumferential strains at the burst mid-plane of the Cr-coated sample and the Zr alloy cladding were 115.9% and 123.2%, respectively. The higher circumferential strain results in a decrease in the wall thickness during burst failure.

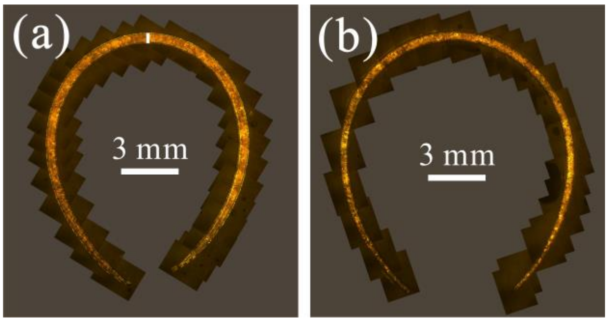
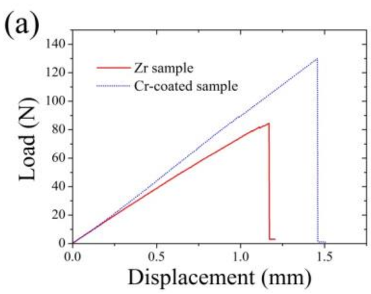


Fig. 2. Optical microscopy images of cross sections at the burst mid-planes of a (a) Cr-coated and (b) uncoated Zr cladding tube, respectively.

To assess the effects of the Cr coating on the mechanical performance of the cladding which suffered ballooning and rupture under LOCA conditions, 4-point bend and ring compression tests were carried out. The load displacement curves obtained from 4-point bend tests are shown in Fig. 3(a). The maximum load for the Cr-coated tube sample was higher than that of the uncoated Zr sample. Offset strains determined from the load-displacement curve for a Cr-coated tube and an uncoated Zr alloy cladding sample were 4.7% and 1.67%, respectively [Fig. 3(b)].



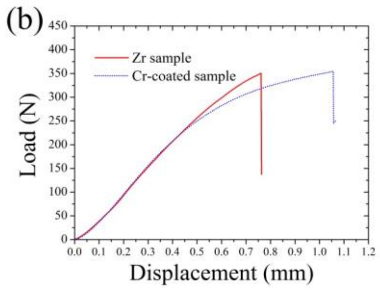


Fig. 3. Load-displacement curve for the (a) 4-point bend and (b) ring compression tests on ballooned Zr cladding sample with and without a Cr coating.

3. Conclusions

The Cr coatings improved the oxidation resistance compared to the uncoated Zr alloy when exposed to a steam environment at 1200°C. The ballooning behavior and mechanical properties of the coated cladding samples were studied after simulated loss-of-coolant accident conditions. The coated samples showed higher burst temperatures, lower circumferential strain, and smaller rupture openings compared to the uncoated Zr. Although 4-point bend tests of the coated samples showed a small increase in the maximum load, ring compression tests of a sectioned sample showed increased ductility.

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