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Fe-based Alloy for LWR Fuel Cladding and its Mechanical Properties under LOCA Condition

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1. Introduction

Interest in the development of a new concept and materials for application as nuclear fuel cladding in a conventional light water reactor (LWR) has been drastically increasing since the fukushima nuclear reactor accident. Many advanced materials such as MAX phases [1], Mo [2], SiC [3], and Fe-based alloys [4] are being considered a possible candidate to substitute the Zr-based alloy cladding has been used in light water reactors. There are also many concepts and approaches for accident tolerant cladding, such as SiC triplex cladding, protective coating, SiC ceramic matrix composite fuel rod cladding with a metal liner, and fully ceramic microencapsulated Fuel. Among the proposed candidate materials, Fe-based alloy is one of the most promising candidates owing to its excellent formability, very good high strength, and corrosion resistance at high temperature.

The integrity of the fuel cladding should be maintained not only during normal operation but also in a postulated design-based accident. In terms of this, a loss-of-coolant accident (LOCA) is treated as one of the most important design-basis accidents in a LWR. Therefore, it is necessary to understand clearly the mechanical behavior of candidate materials under LOCA condition for their application to the fuel cladding material in LWRs.

In this study, a LOCA simulation test with Fe-based alloy claddings was carried out at high temperature of 1200℃ in a steam environment. The effects of high temperature oxidation and quench on the oxidation kinetics and mechanical behavior of Fe-based alloy were investigated. Post quench ductility of Fe-based alloy and zircaloy-4 cladding was analyzed by a ring compression test. For a detailed microstructural characterization, polarized optical microscopy, scanning electron microscopy (SEM), x-ray photoelectron spectroscopy (XPS), and x-ray diffraction (XRD) analyses before and after oxidation tests are presented.

2. Methods and Results

In this section some of the techniques and experimental apparatus used to simulate the LOCA situation are described. The highlight data will then be shown with a detailed explanation.

2.1 Experimental Procedure

Zircaloy-4 and Fe-based alloy tubes which have a 40 mm length were used in this study, and the temperature of the specimen was measured by a thermocouple located near the sample ends. The steam flow was initiated at a test chamber temperature of ≈30ºC. Following the introduction of steam into the chamber, furnace heating started for a pre-test hold temperature of 300℃. Steam flow and a 300℃ sample temperature were stabilized within 180 s. After oxidation, the tube was cooled slowly and quenched at ≈800°C by bottom flooding. Several short ring specimens having a 8 mm length were cut from the tube for the testing of post-quench ductility. Slow ring-compression tests were performed at 135℃ at a compression rate of 0.033 mm/s.

2.2 Simulated LOCA Test

Fig. 1 shows the appearance of zircaloy-4 and Fe-based tube after oxidation at 1200C for 883 sec. While a zircaloy-4 cladding tube shows a clear oxide layer with a black outer surface, the Fe-based alloy tube shows little change in the color of its outer surface.

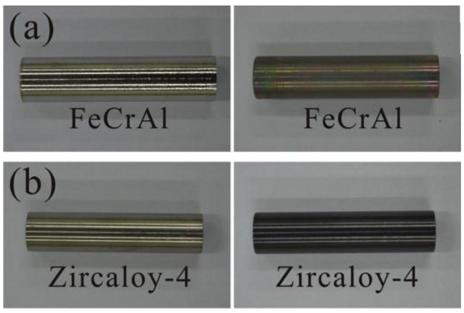

Fig. 1. Appearance of outer surface of (a) Fe-based alloy and (b) zircaloy-4 tube oxidized at 1200°C for 883 sec.

Metallography was performed for zircaloy-4 samples oxidized up to 883 s. This oxidation time correspond to a CP-ECR value of 30%. The results for these times are shown in fig. 2 at low magnification. Zircaloy-4 cladding clearly shows the oxide layers increasing with the exposure time. Fe-base alloy, however, shows no oxide layer on its outer surface in a characterization study using optical microscopy. This is probably due to a very thin oxide layer formed on the surface of the Fe-base alloy.

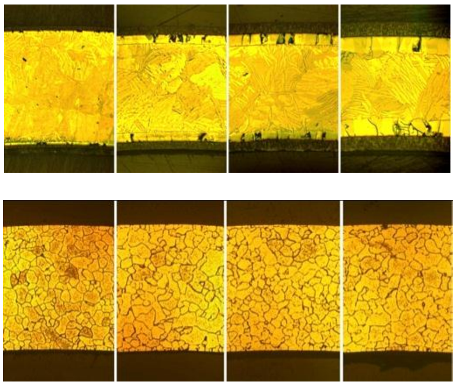

Fig. 2. Low magnification of inner- and outer-surface oxide layers for zircaloy-4 cladding (upper) and Fe-based alloy (lower) oxidized at 1200C with different oxidation time.

The change in weight of the sample after a LOCA test is plotted as a function of CP-ECR in Fig. 3. While the weight of zircaloy-4 sample drastically increases after the test, Fe-based alloys show only a few gram of weight change after the test, and a little increase with an increasing test time.

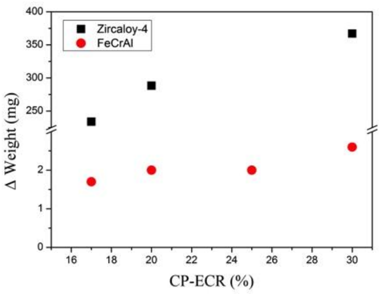

Fig. 3. Low magnification of inner- and outer-surface oxide layers for zircaloy-4 cladding (upper) and Fe-based alloy (lower) oxidized at 1200C with different oxidation time.

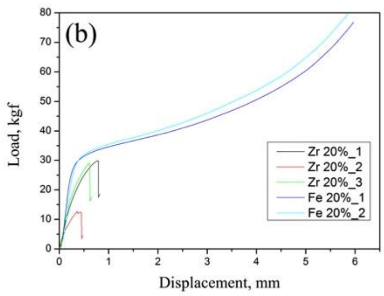

Fig. 4. Load-displacement curve for zircaloy-4 cladding and Fe-based cladding oxidized to 20% CP-ECR.

To measure the post-quench ductility of both zirclaoy-4 and Fe-based alloys, 8 mm long ring-compression tests were conducted and shown in Fig. 4. All zircaloy-4 ring samples showed an early failure with a single tight crack. In contrast, Fe-based alloy show no cracks and a failure during ring compression test up to a CP-ECR value of 30%. This indicates that integrity of Fe-based alloy cladding under accident conditions can be maintained even in the upper limit of the current LOCA safety criteria.

3. Conclusions

A LOCA simulation test with Fe-based alloy and zircaloy-4 claddings was carried out at high temperature of 1200°C in a steam environment. Fe-based alloy cladding showed an extremely low weight gain and maintained their integrity after the simulated LOCA test

ACKNOWLEGEMENT

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