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Hydrogen pickup and its effects on the embrittlement of fuel cladding during simulated loss-of-coolant accident test

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1. Introduction

Current loss-of-coolant accident (LOCA) embrittlement criteria (i.e., 17% oxidation limit and 1204℃ peak cladding temperature limit) was established in the1973 AEC Hearing. At that time, effect of large hydrogen uptake was not known, primarily because data on post-quench mechanical properties were available only for Zircaloy cladding tubes that contained hydrogen no more than ≈100 wppm [1]. Now days, however, it is known that some of the liberated hydrogen from the interaction with water is absorbed in the fuel cladding material and large hydrogen uptake may also occur under steam environment at high temperature during transient or accident condition such as LOCA [2].

The effect of hydrogen on oxygen solubility in the β-phase greatly affects the post-quench ductility of high burn-up cladding and on post-quench ductility of ballooned cladding having absorbed hydrogen in the oxidation reaction on the inside surface of the cladding. Similar effects also arise in long term transients at about 1000℃ when breakaway oxidation leads to significant hydrogen pickup. Therefore, there has been a need to revise criteria because many effects mentioned above are not addressed by the present regulatory criteria [3]. However, the exact embrittlement mechanism of fuel cladding by hydrogen uptake is not well known and different embrittlement behaviors of fuel cladding containing similar hydrogen contents under various cooling scenarios are still a controversial subject.

In this paper, how absorbed hydrogen affects the LOCA properties in fuel claddings is described. Finally, mechanical properties of fuel cladding after a high temperature oxidation test and a thermal quench test were evaluated.

2. Methods and Results

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

2.1 Experimental Procedure

Fig. 1 shows an illustration of a apparatus used for simulated LOCA test. A Zircaloy-4 tube which has a 40 mm length was used in this study and specimen temperature was measured by thermocouple located near the sample ends. Steam flow was initiated at a test chamber temperature of ≈30ºC. Following introduction of steam into the chamber, furnace heating started for a pre-test hold temperature of 300℃. Steam flow and 300℃ of sample temperature were stabilized within 180 s. After oxidation, the tube was cooled slowly and quenched at ≈800°C by bottom flooding. Representative thermal benchmark results from several LOCA tests were shown in Fig.2. Several short ring specimens were cut from the tube for testing of post-quench ductility. Slow ring-compression tests were performed at 135℃ at compression rate of 0.033 mm/s.

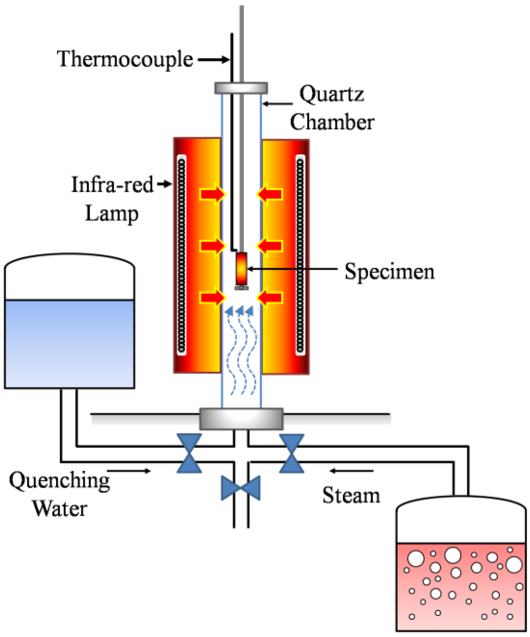

Fig.1. Schematic illustration for the simulated LOCA facility, (b) typical temperature profile of simulated LOCA quench test.

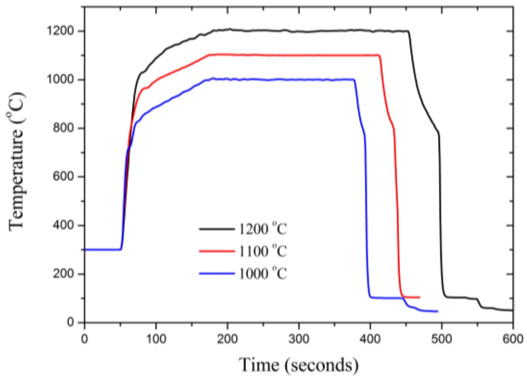

Fig.2. Thermal benchmark results from three LOCA tests

2.2 Results

Zry-4 samples oxidized at 1200°C compressed at RT and 0.0333 mm/s. Post-test appearance is shown in Fig. 3(a) and ECR (equivalent cladding reacted) values below each sample are calculated using the Cathcart-Pawel weight gain correlation. The 5.3% CP-ECR (Cathcart Pawel-ECR) sample were intact at the maximum Instron displacement for these samples. However, when oxidized over 13% of ECR, the cladding showed severe embrittlement property. That is, it could not maintain the first load drop and showed a brittle failure. Offset stains of each sample were obtained from load-displacement curve. Fig. 3(c) shows the changes of the offset strain and absorbed hydrogen contents with CP-ECR. In comparison with previous results, this large hydrogen uptake during LOCA tests is uncommon phenomenon. Although 3.7% CP-ECR sample oxidized at 1200℃ had relatively lower oxidation time, it showed very poor post-quench ductility due to its high hydrogen uptake of ≈500 wppm (not shown here). Therefore, it seems likely that not only oxidation but also hydrogen uptake during LOCA situation would affect embrittlement behavior of fuel cladding after LOCA situation.

3. Conclusions

In order to investigate the effects of hydrogen uptake on embrittlement behavior after LOCA situation, water quenching followed by oxidation on fuel cladding and subsequent ring-compression test were performed. It is observed that large hydrogen uptake could be occurred under LOCA condition in spite of relatively low ECR. In addition to oxidation, hydrogen uptake also affects ductility of fuel cladding after simulated LOCA test.

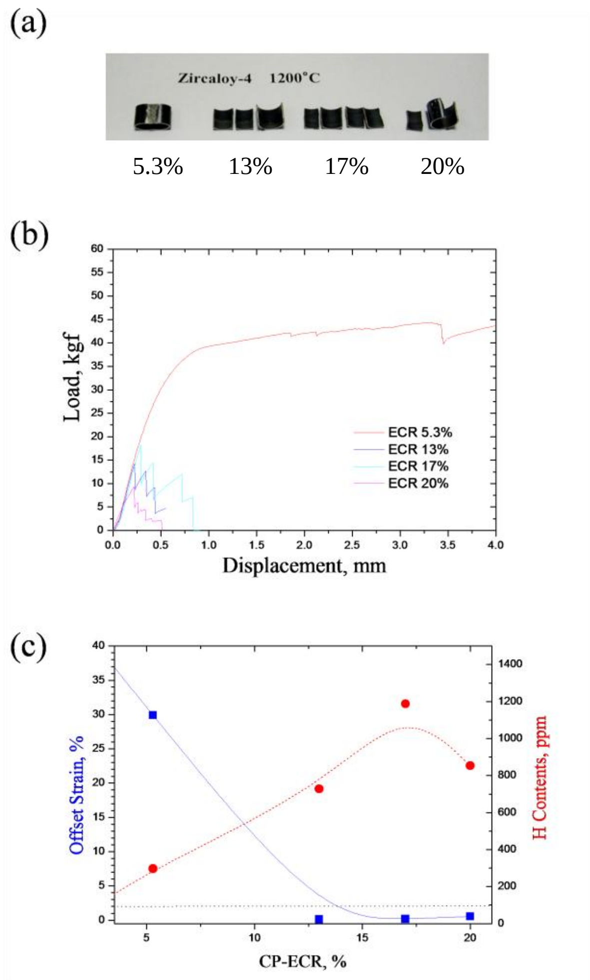

Fig. 3. (a) Post-test appearance of Zircaloy-4 samples compressed at RT and 0.0333 mm/s, (b) their load-displacement curves, (c) and Offset strains vs. CP-ECR

REFERENCES

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