Failure Analysis of Zircaloy-4 Cladding after LOCA Thermal Shock

Jun Hwan Kim, Myoung Ho Lee, Byoung Kwon Choi, and Yong Hwan Jeong[a]
a Advanced Core Materials Lab., Korea Atomic Energy Research Institute, Daejeon, 305-353, Republic of Korea
junhkim@kaeri.re.kr

1. Introduction

It is of importance that the fuel cladding should maintain its fuel integrity in a postulated design-based accident, as well as during a normal operation. In terms of this, a Loss of coolant accident (abbreviated as LOCA) is treated as one of the most important design-basis accidents in a light water reactor (LWR). When a LOCA occurs, the temperature of the fuel system rises so that the cladding undergoes an oxidation caused by an interaction of the mixture of water and steam. After a certain time interval, the emergency core cooling system activates, and water is injected to cool down the hot core, which is inevitably accompanied by a thermal shrinkage of the cladding. When the embrittled cladding cannot stand the stress involved, the cladding fragments, which result in a loss of the barrier preventing a fission product release.

The objectives in this study are to analyze the failure behavior of the fuel cladding more quantitatively and to construct a failure map of the fuel cladding under a LOCA situation from a performance-based point of view. Cladding was oxidized at various temperatures and times followed by an injection of cool water. Mechanical test, like the 3-point bend test was carried out to determine the failure behavior of the oxidized cladding in a quantitative manner.

2. Experimentals

2.1. LOCA test

A detailed explanation on the LOCA test facility is described elsewhere [1]. A Zircaloy-4 tube which has a 200 mm length was used in this study. In this study, two kinds of tests were introduced. First, the claddings were oxidized at different temperatures but with the same time at 300sec (Called '1-dimensional failure analysis') Second, the claddings were oxidized at various temperatures and times (Called '2-dimensional failure analysis').

2.2. Mechanical test

After the thermal shock test, 3-point bend test were performed to evaluate the oxidized cladding ductility. The cladding after the LOCA test was put into the bending jig then it was bent at the rate of 1mm per minute until a fracture. Span (distance between the loading jigs) length of the test was 70mm. All the tests were performed at room temperature.

2.3. Microstructural analysis

To determine the oxidation rate more quantitatively, the term ECR (Equivalent Cladding Reacted) was introduced to define the ratio of the converted metal thickness to the initial cladding thickness. Detailed definition on the ECR value is shown elsewhere [1]. Absorbed hydrogen content in the oxidized cladding was measured by a gas analysis. To measure the oxygen content inside the beta layer, an oxidized specimen after a mechanical test was cut into small parts. They were ground on both sides to a thickness of 50μ m to remove the surface oxide then it was analyzed.

3. Results and Discussions

3.1. 1-dimensional failure analysis

Fig. 1 is the changes of the material parameters of the Zircaloy-4 cladding with the oxidation temperature. Ductile bending is shown when the cladding is oxidized at a relatively low temperature ('Ductile' region). Successive load drops caused by a fracture of the surface oxide appeared when the cladding was oxidized at the intermediate temperature region. ('Load drop' region) Finally, a brittle fracture which could not sustain the first load drop appeared when the cladding was oxidized at a high temperature. ('Brittle failure' region) Absorbed energy can be defined as the area under the load-displacement curve which has a dimension of the energy. Energies obtained by the 3-point bend tests decreased with the oxidation temperature, and they showed an abrupt decrease between 1100^{o}C and 1150^{o}C. Both the absorbed hydrogen content and the oxygen content inside the beta layer increased with the oxidation temperature. Absorbed hydrogen content gradually increased in all the temperature regions. When the absorbed hydrogen content exceeds around 270ppm, the Zircaloy-4 cladding showed a brittle fracture for the mechanical test. Oxygen content inside the beta layer increased smoothly up to 1150^{o}C then it increased rapidly above this temperature. The oxygen content to cause a ductile bending of the cladding is below 0.3wt%. When the oxygen content inside the beta layer reaches between 0.3 and 0.5wt%, the Zircaloy-4 cladding begins to decrease in its energy and show a load drop caused by a decrease of the load bearing area as well as the embrittlement itself. Above 0.5%, the cladding cannot withstand the load, and it shows a nil ductility.

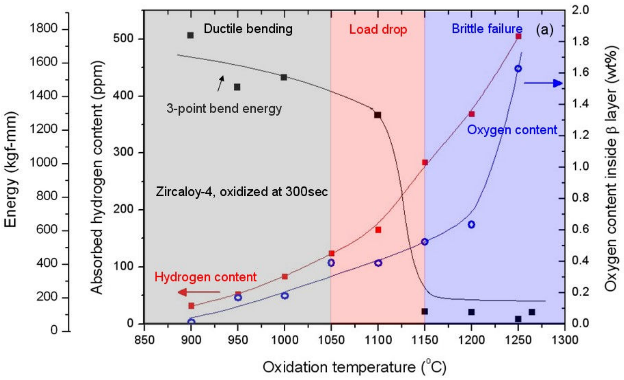

Figure 1. Changes of the material properties of the Zircaloy-4 cladding with the oxidation temperature.

3.2. 2-dimensional failure analysis

Fig. 2 is the 2-dimensional failure map of the Zircaloy-4 cladding. Closed symbol represents the failed cladding during the water quench. 'Ductile bending' (blue region in Fig. 2) means that the cladding can maintain its mechanical ductility after a thermal shock, not to mention a survival during a water quenching. 'Brittle fracture at the mechanical test' (green region in Fig. 2) means that although the cladding at first survived the water quenching, it has already lost its mechanical ductility so that it could fail during a handling, such as refueling or transporting the fuel bundles to the spent fuel storage [2]. 'Brittle failure at a thermal shock' (red region in Fig, 1) indicates that the cladding is too brittle to withstand even a thermal stress during a water quenching. From the diagram, 'Ductile bending' region decreases with the oxidation temperature. For instance, a ductile bending occurs irrespective of the oxidation time when oxidized below 950°C. Oxidized cladding at 1000°C loses its mechanical ductility above 5000sec. Finally, oxidized cladding at 1150°C shows its mechanical ductility only at 300sec. This implies that the maximum ECR to withstand a ductile bending is around 15% when oxidized at 1000°C. It gradually decreases to have a ductility below 10% when oxidized above 1100°C.

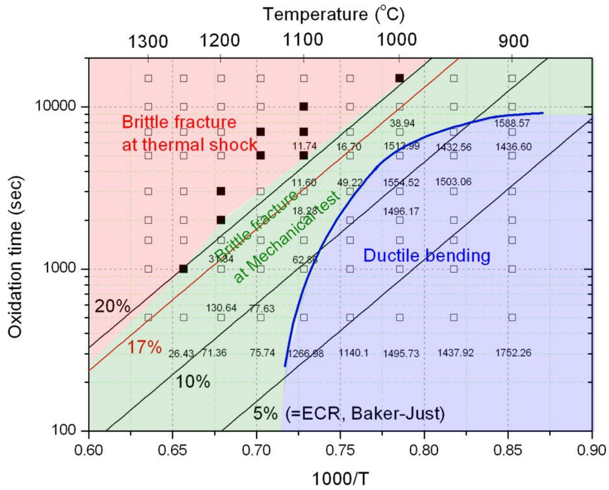

Figure 2. 3-point bend fracture energy diagram of the Zircaloy-4 cladding with the oxidation temperature and time.

4. Conclusions

The followings are the summaries of the failure behavior of Zircaloy-4 cladding under a LOCA condition.

1) Threshold ECR of the Zircaloy-4 cladding to cause a brittle fracture is around 20%, where it has a mechanical ductility with an ECR value around 15%.

2) Behavior of the absorbed hydrogen contents was similar to that of the failure during a water quenching. On the other hand, behavior of the absorbed oxygen contents inside the beta layer was similar to the behavior of the mechanical energy.

Acknowledgement

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