Deformation and Thermal Quench Behavior of K-Claddings in a Simulated LOCA Transient

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1. Introduction

It is important to maintain the fuel integrity in a postulated design-based accident, as well as during a normal operation. Loss of coolant accident (abbreviated as LOCA) is an important accident in the design of a light water reactor (LWR). When LOCA occurs, pressurized coolant is discharged so that the pressure vessel is filled with a water-steam mixture. Fuel cladding balloons and even ruptures due to the pressure differences across the cladding thickness. During the LOCA, temperature of the fuel system rises so that the cladding undergoes oxidation caused by the mixture of the water and steam. After a time interval, the emergency core cooling system is activated, water is injected to cool down the hot core, which inevitably accompanies thermal shrinkage of the cladding. When the embrittled cladding cannot stand the stress involved, the cladding fragments, which results in the loss of the barrier preventing fission product release. To maintain the fuel integrity under postulated LOCA conditions, the Nuclear Regulatory Commission (NRC) established the fuel safety criteria related to a LOCA, where the peak fuel temperature and total oxidation cannot exceed 1204°C and a 17% level [1]. The objectives of this study are to investigate the behavior of newly developed alloy, namely K-claddings in LOCA conditions. Studies were focused on the high temperature deformation and thermal quench behavior.

2. Experimentals

2.1. Specimen

The cladding used in this study is the K-claddings developed by KAERI. K1 (Zr-0.4Nb-0.8Sn-TRM), K4 (Zr-1.5Nb-0.4Sn-TRM) and K6 (Zr-1.2Nb-0.1Cu-TRM) was used. Commercial low Sn Zircaloy-4 was used as a reference material.

2.2. LOCA experiment

The detailed explanation of LOCA simulating facility was described elsewhere [2]. It is divided by heating, pressurizing, and water injection. Two types of tests were performed, namely the transient ballooning test and the thermal quench test. Transient ballooning was conducted, where the pressurized cladding was heated at a rate of 1, 10, 100 °C per second until rupture. The other is the quench test where the specimen was oxidized in a flowing steam at a desired temperature and time followed by water quenching. 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 initial cladding thickness. Using a simple dimensional conversion [3], the ECR value of zirconium can be derived according to the relationships;

$$ECR(\%) = 2.693 \times 10^{-3} \Delta m_{Zr} \quad (1)$$

where Δm_{Zr} is the total mass change of zirconium calculated by the Baker-Just equation [4].

3. Results and Discussions

3.1. High temperature ballooning

Fig. 1 shows the total elongation of the Zircaloy-4 under the transient heating condition. It showed a peak at 800 °C, which can be explained by the phase transformation of the zirconium. As the temperature increases from 600 °C to 800 °C, an increase of the alpha grain size accommodates the mobile dislocation so that it glides more easily, which leads to the increase of elongation. However, when the temperature reaches the two-phase region, the formation of the beta phase around the alpha phase may prohibit the grain elongation of the alpha phase. Hence, its elongation becomes smaller as the temperature gradually increases to reach the temperature where the fraction of the alpha and beta phase is equal. Above 900°C, the elongation increases again until it shows a peak at 1100 °C. At a temperature above the beta phase transformation, the beta phase moves first, with the aid of the alpha phase which acts as a lubricant. Such a grain boundary sliding leads to an increase in the elongation, which is inversely proportional to the grain size. In case of K-cladding, where the Nb added in common to minimize corrosion rate, addition of Nb expands beta phase to decrease alpha grain size, total elongation in alpha phase is larger than that of Zircaloy-4, whereas total elongation of beta phase is reversed due to the small beta grain size caused by the slow diffusion of Nb. Smaller grain size can provide easy movement in case grain boundary sliding mechanism dominates. Nevertheless, the effect of Nb was relatively small in that the diffusion of Nb is too low to affect deformation process in simulated LOCA process.

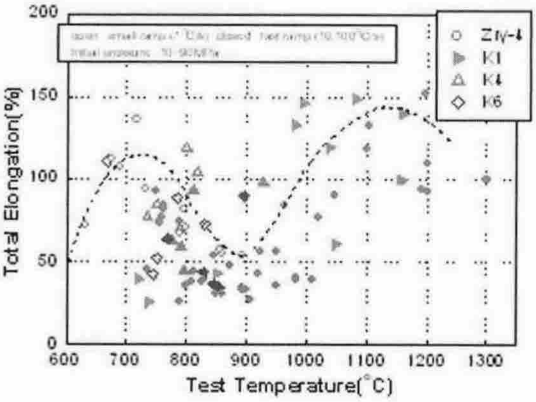

Figure 1. Total elongation of zirconium claddings with the burst temperature. Open symbol represents small thermal ramp rate (=1 °C/sec), closed symbol represents fast thermal ramp (=10, 100 °C/sec)

3.2. Thermal Quench behavior

Fig. 2 shows a failure map of the thermally quenched Zircaloy-4 and K-cladding after subsequent high temperature oxidation. An open symbol represents the specimen that survived during the water quenching after a high temperature oxidation. A closed symbol represents the specimen that failed. Threshold ECR value of K-cladding greatly increased to the value of 35% compared to the conventional value of 17% in Zircaloy-4. The reason why the threshold ECR of Nb-containing K-alloys increases can be stated that; Slowly diffusing Nb can supress the oxygen stabilized alpha region by making needle-like oxygen stabilized zone, also Nb accomodates maximum hydrogen contents in residual beta phase region by expanding beta phase region to resist hydrogen embrittlement against thermal shock.

4. Conclusions

Simulated LOCA test was performed zirconium claddings to evaluate the property of newly developed K-claddings under the design based accident. High temperature ballooning and thermal quench test was carried out and the followings can be concluded.

1) The deformation behavior of K-claddings was similar to that of Zircaloy-4 during postulated LOCA transient.
2) Addition of Nb can retard oxide growth as well as hydrogen pickup, therefore threshold ECR value can be increased in case of K-cladding.

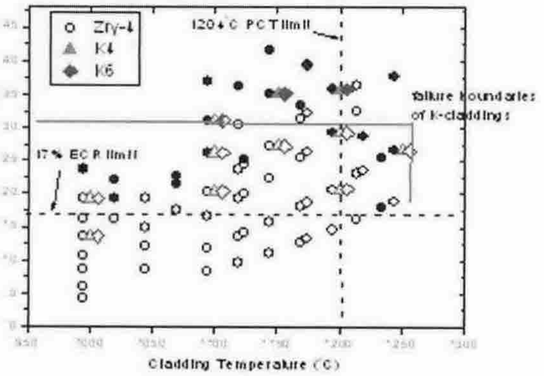

Figure 2. Failure map of zirconium claddings with respect to the oxidation temperature and ECR value. Open symbol represents cladding survived during water quenching. Closed symbol failed.

Acknowledgement

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