Crack Initiation Mechanism in the Pellet-Cladding Interaction of a Nuclear Fuel Cladding

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1. Introduction

Since the 1960's, the fractures of a cladding induced by Pellet-Cladding Interaction (PCI) in BWR and CANDU-type reactors have been reported. With the changes in pellet shapes and the development of a barrier cladding using an inner layer of pure zirconium in a BWR fuel design in the 80's, PCI has since received little attention, except for the power transient conditions in a PWR[1]. Nowadays, many power plants adopt high burn-up operation which includes high power, enlarged fuel cycle, and so on. At a high burn-up, the cladding becomes more brittle because of the hydride formed by a waterside corrosion and its possibility of a fracture by PCI is increased. So, a newly developed cladding designed for a high burn-up operation needs a higher resistance against PCI.

But the microcrack nucleation or crack initiation mechanism during the early stage of a PCI is not known. The objectives of this study are to elucidate the microcrack nucleation and crack initiation during a PCI reaction of a nuclear fuel cladding. Internal pressurization tests were carried out with and without pre-cracked Zircaloy-4 claddings in a iodine environment, and the crack propagation rates and threshold stress intensity factor were evaluated.

2. Experimental

2.1 Specimen and sample preparation

Test specimens of about 130 mm in length were cut from the Zircaloy-4 cladding. Pre-crack is made at the inner surface of the tube by a 4-point bent beam fatigue technique. Cyclic loading with a frequency of 5Hz, mean load of 50 kgf, and amplitude of 50 kgf create a longitudinal pre-crack. After 5000 cycles, maximum depth of the crack is about 25 ~ 50% of the total tube thickness and the shape of the pre-crack is elliptical. The crack was measured after the I-SCC test by a optical microscope (OM) and a scanning electron microscope (SEM).

2.2 PCI simulation test

To evaluate the PCI resistance of the specimens, a internal pressurization technique was used in a iodine environment at 350°C. Pressurization can be achieved by a high purity helium compressed-air-driven pressure booster. Helium was rapidly pressurized at the sample right after the temperature reached 350°C. The amount of iodine was added at an amount of 1.0 mg/cm^2. It was introduced as small crystals of ultra-pure iodine placed in a quartz U-shaped crucible. The stress range of the test was selected with the condition for a plane strain with a pre-cracked specimen and in the range of 310 MPa.

3. Results and Discussion

Williford [2] has reported that a pre-existing flaw and a damaged region mainly affected the crack nucleation, rather than a grain boundary attack and a pitting. Fig.1 shows the SEM image of the inner surface of the cladding when exposed to an iodine environment. A great number of pits with various sizes were found in each cladding. The size and number of each pit increased with the exposed time, showing that the pits which exceed 10 μm coalesced with each other to form a lateral crack. Such a lateral crack may act as a nucleation site to concentrate the stress as well as propagate it in the radial direction.

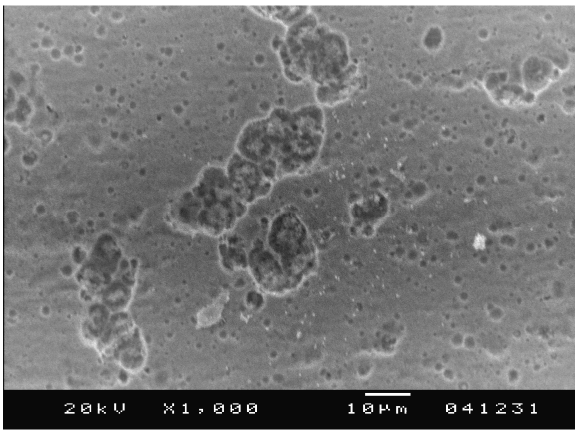

Figure 1 SEM photographs of the inner surface after test in a 350°C 280 MPa iodine environment.

Fig. 2 shows the SEM image of the fractured surface of the recrystallized Zircaloy-4 after the ISCC test to evaluate the pitting coalescence phenomena. Both intergranular (IG) and transgranular (TG) patterns were observed at the same time, showing that a lot of pits were developed on the IG surface. Average size of the pits was approximately below 2 ㎛. Regarding the TG surface, however, a few pits were shown, to only form around the grain boundary.

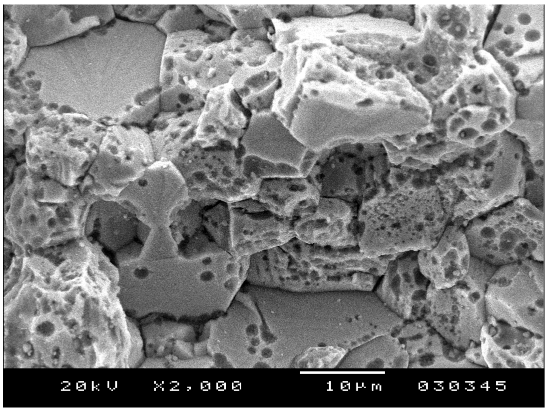

Figure 2 ISCC Fracture surface of the Zircaloy-4(RX) pressurized in an iodine environment.

As the grains are elongated along the axial direction in the case of the SR microstructure, their long grain boundaries are easily attacked by the iodine to become a macro-crack site. Such a crack initiation process may be governed by a grain-boundary pitting coalescence (GBPC). From the standpoint of the GBPC, a crack initiation caused an ISCC is not influenced by a micro-flaw inside the cladding which is inevitably generated during the manufacturing process but by the grain size, shape, and orientation which are mainly affected by the heat treatment process.

4. Conclusions

Time-to-rupture test and its associated crack propagation test under an iodine environment were performed for a Zircaloy-4 cladding with either SR or RX microstructures to investigate the ISCC process and the following can be summarized.

1. When Zircaloy-4 cladding is exposed to a high temperature, high pressure iodine environment, pits will generate preferentially around the grain boundary. They will coalescence with each other to form a microcrack to accommodate a site for a crack initiation. (grain boundary pitting coalescence, GBPC model) Microcrack will be developed into an incipient crack that initiates and propagates along the grain boundary.
2. From the GBPC model, the grain size as well as its orientation rather than a mechanical micro-flaw mainly affected a crack initiation

Acknowledgement

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Reference

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