Cooling Effect on Ductility of Zircaloy-4 Cladding after a LOCA-simulated Test

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1. Introduction

During a loss-of-coolant accident (LOCA) the fuel rods in a nuclear reactor faced on the high temperature condition at a steam environment, the fuel cladding was oxidized quickly and then quenched by the cold water, which was supplied by an emergency core cooling system (ECCS) activity [1]. From this event, oxide (ZrO_2) and oxygen-stabilized α-Zr (α-Zr(O)) layers were formed on the cladding surface [2]. Since these two layers decreased the cladding ductility, the thickness of these two layers had been limited as a regulation [1]. It could be summarized that the peak cladding temperature (PCT) was limited to 1204°C and the equivalent cladding reacted (ECR) value was up to 17% (17%ECR). These criteria were established based on the ring compression test for the Zircaloy-4 cladding by Hobson [2]. Also, the hydrogen absorption during LOCA event as well as normal operating conditions was treated as a mechanism on the cladding embrittlement behavior [3].

On the other hands, the ductility of fuel cladding could be affected by a cooling rate during water quenching, since the mechanical property of zirconium alloys was affected by the microstructural characteristics caused by a diffused and non-diffused transformation during cooling at a high temperature.

So, it could be expected that the ductility of cladding after LOCA event was affected by a cooling rate and a cooled temperature. For this reason, the object in this work is studied on the mechanical property with the cooling rate by investigating the micro-structural observation and ring compression test after LOCA-simulated test.

2. Methods and Results

Commercial Zircaloy-4 cladding (Zr-1.5Sn-0.2Fe-0.1Cr) in a length of 200 mm were oxidized at the temperature of 1200 ℃ and exposed at time of 300 s. And it was cooled by three different conditions like this; 1) water quenching at test temperature of 1200℃, 2) air cooled from 1200℃ to the intermediate temperature of 700 ℃ and then water quenching, 3) air cooling from 1200℃. Fig. 1 shows an illustration of LOCA test scheme and cooling sequence. The cladding is oxidized only outside surface, and a direct heating by ohmic resistance was applied to heat the cladding. The test temperature was controlled by the computer based on the pyrometer result for the cladding surface.

The ring compression test was carried out to evaluate the ductility for the simulated LOCA tested claddings with the cooling conditions. For the ring compression test, the oxidized claddings were cut in to 10 mm length, and tested by using an Instron test machine at the pressing rate of 1 mm per min at room temperature. The optical microscope observation was performed to observe the microstructural characteristics of the ZrO_2 phase, the oxygen stabilized α-Zr layer and and prior β-phase region with the test conditions.

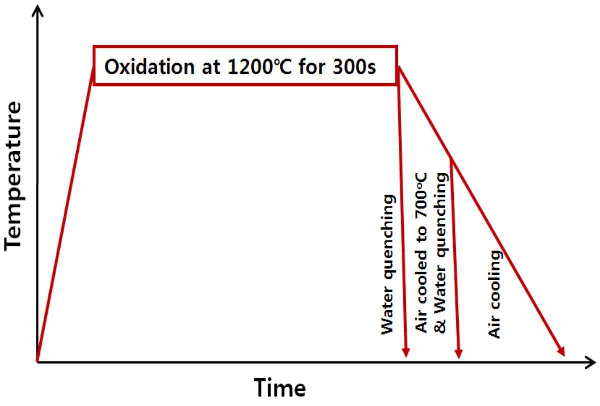


Fig. 1 Illustration of the LOCA-simulated oxidation and water quenching test scheme

In the surface appearances of the cladding tubes in the middle area after the LOCA-simulated test, the black oxide was observed at the Zircaloy-4 cladding without cooling conditions and the cracks were not observed at the cladding surface in the full test length. So, the Zircaloy-4 cladding maintained their integrity by the cooling conditions after the oxidation at 1200℃ for 300 s.

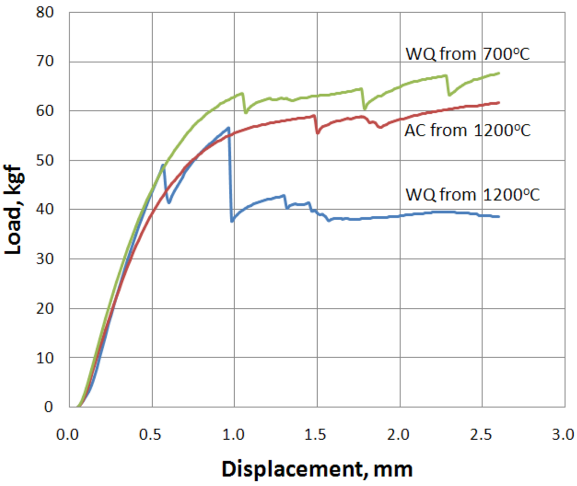
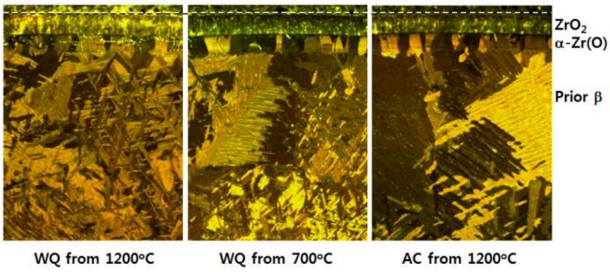


Fig. 2 Load-displacement curves of the Zircaloy-4 cladding after the LOCA-simulated oxidation and different cooling conditions

From the ring compression test after oxidized and cooled claddings as shown in Fig. 2, the load drop in the stress-strain curve was observed in the Zircaloy-4 cladding after the 300 s oxidation at 1200℃. It is observed that the displacement at load drop point was changed with the cooling conditions. The first drop of claddings showed at 1.5 mm in displacement in the water quenching from 1200℃, that drop showed at 0.6 mm in the water quenching from 700℃, and that drop showed at 0.6 mm in the air cooling from 1200℃. So the ductility of Zircaloy-4 cladding was influenced by the cooling condition after high temperature oxidation.



WQ from 1200°C WQ from 700°C AC from 1200°C

Fig. 3 Optical micrographs of Zircaloy-4 cladding after the LOCA-simulated oxidation and different cooling conditions

From the observation of the ZrO_2 phase, the oxygen stabilized α-Zr layer by using the optical microscope, it was revealed that the oxide microstructure was grown as columnar grain from the outer surface and the α-Zr(O) layer was shown as the block shaped large grains. And the thickness of these two layers was similar without cooling condition. However, the microstructure of prior β-phase region was different with respect to the cooling conditions. The martensite structure was formed in the water quenched condition from 1200℃, and the mixed structure with martensite and Widmanstätten was formed in the water quenched condition from 700℃, and the Widmanstätten structure was formed in the air cooled condition from 1200℃. From this, it was recognized that the oxide and α-Zr(O) layers were not changed with the cooling conditions, whereas, the prior β-phase region was considerably changed with the cooling conditions.

After the compare between ring compression test and microstructure, the decrease of ductility after the high temperature oxidation and cooling was related to the cooling conditions. By a formation of martensite structure, which was formed by quick cooling condition from β-phase region in zirconium alloys [4], the ductility was decreased in the Zircaloy-4 cladding. So, the cooling condition after high temperature oxidation was considered during the LOCA event.

3. Conclusions

To evaluate the cooling effect on ductility of Zircaloy-4 cladding, the LOCA-simulated high temperature oxidation and differnt cooling test was conducted. The load-displacement behavior of Zircaloy-4 cladding was influenced by the cooling condition after high temperature oxidation, since the microstructure of prior β-phase region was changed by cooling rate. When the matrensite structure was formed by fast cooling from high temperature, the ductility of cladding was decreased.

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