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Effect of Final Heat Treatment and Hydrogen on the Burst Properties of Cladding Tubes at 350℃

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1. Introduction

After having developed some HANA cladding tubes for high burn-up fuel rod, KAERI has been doing a lot of out-of pile tests including in-pile test to verify their good performance. The hydrogen effect on the burst properties of HANA-4A3 and HANA-6A3 (the added A3 to HANA-4 or 6 stands for having been finally heat-treated for 2.5hours at 510℃) at 350℃ was already studied as a kind of high burn-up simulation test[1]. This study was done on the burst properties of HANA-4B1 and HANA-6B1 (the added B1 to HANA-4 or 6 stands for having been finally heat-treated for 2.5hours at 470℃) at 350℃ as a follow-up action to the prior hydrogen effect study [1]. The additional burst tests were also done on both Zircaloy-4 (Zr-1.26Sn-0.23Fe-0.12Cr) and A (Zr-1.0Nb-0.99Sn-0.11Fe) cladding tubes in commercial grade to compare the hydrogen effect on their burst properties with that on the burst properties of HANA-4B1 and HANA-6B1.

2. Methods and Results

All the tube specimens with outer diameter 9.60mm, inner diameter 8.36mm and 150mm in length were charged with hydrogen gas as much as 500ppm and 800ppm for each one at 400℃ and then were heat-treated for 30 minutes at 410℃ in order to homogenize the hydrogen distribution in the specimens. Actual hydrogen content in the hydrided specimens was analyzed by using the LECO RH600 equipment to be 374ppm to 1181ppm. The burst test of the specimens was carried out at 350℃ according to the requirements of ASTM B811-97 pressurizing Ar gas with 50 bars per minute. The burst properties such as ultimate hoop stress (UHS) and total circumferential elongation (TCE) of the specimens were also calculated in accordance with the requirement of ASTM B811-97.

2.1 Hydrogen absorbability

The terminal solubility of hydrogen in Zircaloy is about 150 ppm at 350℃ which is near the coolant temperature of pressurized power reactor [2]. But the local hydrogen content in the irradiated Zircaloy-4 cladding tube can be over 1000 ppm [3]. The hydrogen absorbability (HA) for each specimen can be defined as the actual charged hydrogen amount after analysis over the trial charged hydrogen amount before analysis when the specimens were charged with hydrogen at the same charging condition. The average HA of HANA-4A3, HANA-6A3, HANA-4B1, HANA-6B1 was 102%, 96%, 84% and 75%, respectively. But that of Zircaloy-4 and A was 147% and 106%, respectively. So, the resistance to hydrogen absorption of HANA-4 and HANA-6 specimens was better than that Zircaloy-4 and A specimens.

2.2 Burst properties of the hydrided claddings

Fig. 1 shows that the burst properties of HANA-4B1, HANA-6B1, Zircaloy-4 and A specimens with hydrogen content. It was known that Zircaloy-4 and A specimens were also finally heat-treated at around 470℃. At 350℃, the hydrogen charged up to about 700ppm (even 1200ppm in case of Zircaloy-4 specimen) in the cladding tubes has not much effect on their UHS. But their TCE tends to decrease a little with hydrogen. Since circumferential hydride does not act as a critical crack-initiating site [4], it seems that the UHS of the specimens would not so much depend on the charged hydrogen but the TCE would reduce with hydrogen charged in the specimens because the number of void nucleation site increase as the volume fraction of hydrides increases [3].

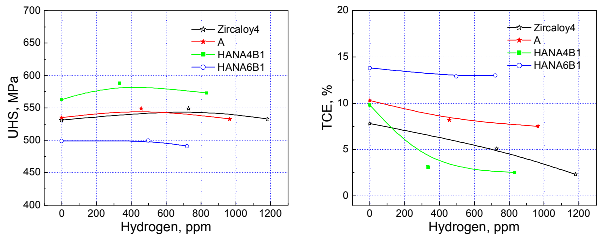

Fig.1. Burst properties of cladding tube specimens with the change of hydrogen content at 350℃

2.2 The effect of hydrogen on the different final heat treatment of HANA cladding tubes

Fig. 2 shows the effect of both hydrogen and final heat treatment on the burst properties of HANA cladding tube specimens at 350℃. The effect of hydrogen on burst properties of HANA-4 and HANA-6 specimens does not so much depend on final heat treatment. The UHS of HANA cladding tubes which were given the stress-relived (SR) heat treatment (B1) is higher than that of HANA cladding tubes which were given the partial re-crystallized (PRX) heat treatment (A3) because B1 heat-treated HANA cladding tubes would has more dislocation density than A3 heat-treated HANA cladding tubes. So, the effect of final heat treatment is still valid regardless of the amount of charged hydrogen until about 800 ppm H.

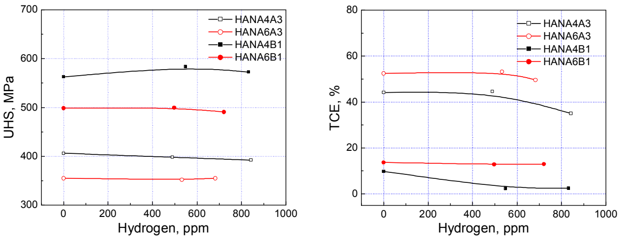

Fig.2. The effect of hydrogen and final heat treatment on the burst properties of HANA cladding tube specimens at 350℃

2.3 Fracture Surfaces of the Specimens

Fig. 3 shows the fracture surfaces of specimens in axial direction when the specimens were burst at 350℃. HANA specimens have less crack cleavage than Zircaloy-4 and A specimens. The macroscopic burst openings of HANA specimens also do show less axial running. So, the matrix ductility of HANA specimens might prevent the crack from easy propagation even though the specimens were hydrided. Because crack goes along the length of hydride platelet when it is normal to the applied stress direction [5], it seems that the cracks tend to go along the axial direction.

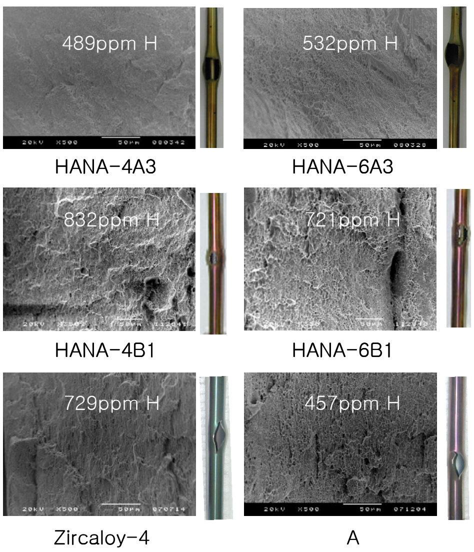

Fig. 3. Fractographs of the hydrided specimens (x500)

Several large crack openings are found in the Zircaloy-4, A and HANA-4B1, HANA-6B1 (SR condition) specimens that were finally heat-treated at 470℃ but less and fewer cracks are found in HANA-4A3, HANA-6A3 (PRX condition) specimens that were finally heat-treated at 510℃. It will be able to explain that the mutual interaction between dislocations and hydrogen atoms in SR condition would lead to more crack development and propagation than those in PRX condition due to the enhanced hardening.

3. Conclusion

To study the effect of hydrogen on the burst properties of cladding tubes, the burst tests were done at 350℃ for HANA cladding tube specimens as well as Zicaloy-4 and A specimens after they were charged with 374 to 1181 ppm hydrogen. The test results can be summarized as follows;

(1) The resistance to hydrogen absorption of HANA-4 and HANA-6 specimens was better than that Zircaloy-4 and A specimens. It was 4 ~29% better than A and 31~49% better than Zircaloy-4.

(2) The effect of hydrogen on burst properties of HANA-4 and HANA-6 specimens does not so much depend on final heat treatment. The effect of final heat treatment is still valid regardless of the amount of charged hydrogen until about 800 ppm H.

(3) Burst cracks can be more easily formed and propagated when the cladding tubes had been SR(470℃) heat teat-treated than PRX(510℃) heat-treated.

Acknowledgement

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