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Hydrogen Effect on the Circumferential Mechanical Properties of HANA-4 and HANA-6 Cladding Tubes

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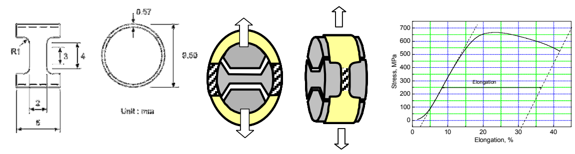
1. Introduction

KAERI has been doing a lot of out-of pile tests including an in-pile test to verify the performance of HANA cladding tubes for a high burn-up fuel rod, developed by them. When a zirconium alloy is used in a nuclear reactor, hydrides form in it from not only external hydrogen sources such as a waterside corrosion, dissolved hydrogen in a coolant, water radiolysis but also internal sources such as the hydrogen content in fuel pellets and the moisture absorbed by a uranium dioxide fuel pellet [1]. Hydrides may act as a sudden failure at a very low strain [2]. For low and medium hydrogen content, the hydrides crack during a tensile loading and accelerate the ductile fracture process [3]. As a kind of simulation test to obtain the estimated data of HANA cladding tubes in a high burn-up state, the hydrogen effect on the axial tensile properties of a HANA-4(Zr-1.5Nb-0.0.4Sn-0.21Fe-0.1Cu) cladding tube and that on the burst properties of HANA-4 and HANA-6 (Zr-1.1Nb-0.05Cu) cladding tubes was already studied [4-6]. This study was also done to characterize the effect of hydrogen on the circumferential mechanical properties of HANA-4 and HANA-6 cladding tubes by a ring tension test at both room temperature and 350℃. Additional 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 of a commercial grade to compare the hydrogen effect on their circumferential properties with that on the properties of the HANA-4 and HANA-6 cladding tubes.

2. Methods and Results

All the tested tube specimens with an outer diameter of 9.50mm and inner diameter of 8.36mm, which were annealed at about 470℃ to be stress-relieved, were charged with hydrogen gas from about 20ppm to 2850ppm at 400℃ and then they 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. The hydrided specimens of 5mm in length were machined by an electron discharge as ring specimens with the dimensions of 2mm in the reduced width, and 3mm in the length of the gage section. The tensile tests of the ring specimens were done with a strain rate of 10^{-4}/s at both room temperature and 350℃ [7]. The ultimate tensile stress and yield stress were calculated from the recorded load-displacement curves. The yield stress was determined by the 0.2% offset method and the elongation was done as shown in the Fig.1.



(a) Specimen *(b) test* *(c) elongation*
Fig.1. Ring tension test of cladding tube specimens

2.1 Hydrogen effect on the circumferential mechanical properties of cladding tubes

Fig. 2 shows the change of the circumferential mechanical properties of claddings at both room temperature and 350℃ with a change of the hydrogen content.

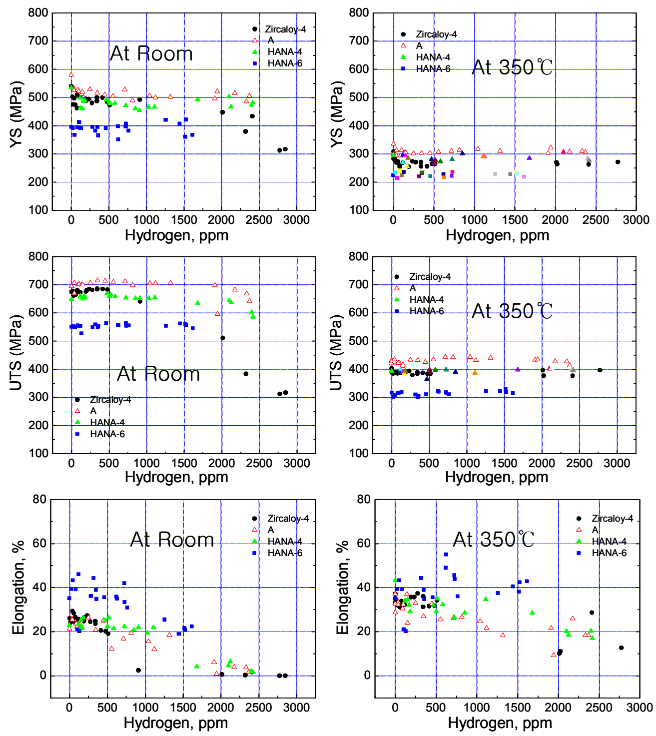


Fig.2. Circumferential mechanical properties of claddings at both room temperature and 350℃ with the change of hydrogen content

The reported effect of hydrogen on mechanical properties of zircaloy is not the same. For the stress-relived Zircaloy-4 sheet at room temperature, the yield strength(YS) decreased by a small amount as the hydrogn content increased up to 1200ppm but the ultimate tensile strength(UTS) increased by a small amount as the hydrogn content increased up to 600ppm and decreased for a higher hydrogen content while the ductile-brittle transition occured at about 1050ppm hydrogen [3]. For the stress-relived Zircaloy tube, the increase in the circumferential UTS was 11% at 300℃ and 6% at 20℃ when the hydrogen content changed from 0 to 1000 ppm and the reduction of the area at room temperature decreased from 50% to 0% when the hydrogen content was changed from 1500 to 2400 ppm [8]. HANA cladding tubes have no significant strength change at both room temperature and 350℃with hydrogen to about 1600ppm. When they were charged with hydrogen of more than 2000 ppm, the strength of the HANA-4 and A claddings decreased by a small amount with the hydrogen content while that of the Zircaloy-4 decreased much more. The elongation of Zircaloy-4, A and HANA-4 cladding tubes decreased linearly with the hydrogen at both room temperature and 350℃ while that of the HANA-6 cladding tube at 350℃ did not decrease. Such a difference bewteen Zircaloy-4 and the other cladding materials seemly comes from that the Zr-Nb based alloy systems more so than the Zr-Sn based ones have a lesser hydrogen content in metal and higher ductility and a fracture toughness at a high burnup[9].

2.2 Fracture Surfaces of the Specimens

Fig. 3 shows the fracture surfaces of the HANA-4 and Zircaloy-4 cladding tubes which were charged with different hydrogen contents. The dimple fracture was created when the cladding tubes were not charged with hydrogen while the cracks or cleavage fractures were made when they were charged with hydrogen at more than their solubility. Zircaloy-4 has more cracks than HANA-4 at around 500 ppm in hydrogen. The cracks were propagated along the axial direction because the hydrides failed in the parallel direction in the normal loading direction [3].

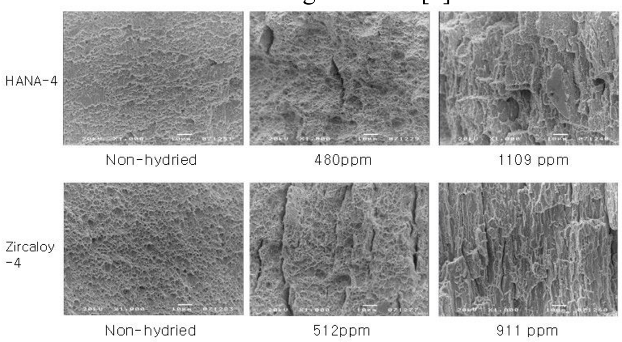


Fig.3. fracture surfaces of HANA-4 and Zircaloy-4 claddings at room temperature

3. Conclusion

To characterize and obtain data on the effect of hydrogen on the circumferential mechanical properties of the HANA-4 and the HANA-6 cladding tubes, ring tension tests were implemented for the cladding tubes at both room temperature and 350℃ after they were charged with hydrogen from about 20ppm to 2850ppm. The results are summarized as follows.

(1) The circumferential mechanical properties of the HANA-6 cladding tube are not sensitive to the charged hydrogen at both room temperature and 350℃.
(2) The effects of hydrogen on that of the HANA-4 cladding tube are equivalent to that of the A cladding tube
(3) It was confirmed that the hydrogen effect on the circumferential mechanical properties of the Zr-Nb based alloy systems is less than that of the Zr-Sn based ones at a high hydrogen content.
(4) It was also confirned that the cracks on the hydrided cladding tube are propagated along the axial direction.

Acknowledgement

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