Hydrogen Effect on the Ductile-Brittle Transition of HANA Claddings in the Circumferential Direction

Myung Ho Lee, Jun Hwan Kim, Sang Yoon Park, Byoung Kwon Choi, Yong Hwan Jeong
Mhlee2@kaeri.re.kr
Advanced Core Materials Lab., KAERI, P.O.Box 105, Yuseong, Daejon, 305-353, Republic of Korea

1. Introduction

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 were already studied [1-3]. Further, the effect of hydrogen on the circumferential mechanical properties of HANA-4 and HANA-6 cladding tubes was also studied by the use of a ring tension test at both room temperature and 350℃[4]. In this study, the hydrogen effect on the circumferential mechanical properties of the HANA cladding tubes was reviewed comparing to that of Zircaloy-4 (Zr-1.3Sn-0.2Fe-0.1Cr) cladding focusing on the difference in the stress-elongation curves and the ductile-brittle transition between the HANA claddings and the Zircaloy-4 cladding.

2. Methods and Results

The specimens of HANA-4, HANA-6 and Zircaloy-4 claddings had a dimension with an outer diameter of 9.50mm and inner diameter of 8.36mm. The HANA-4 and HANA-6 claddings were finally annealed for 2.5 hours at 470℃. The Zircaloy-4 cladding was in a commercial grade to be stress-relieved. The specimens were charged with hydrogen gas to 2850ppm at 400℃ before 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 axial length were machined by an electron discharge as ring specimens with the dimension of 2 mm 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 room temperature using the prior test jig set [4, 5]. To reduce the friction effect, the inner surface of the test rings and the outer surfaces of the test devices were coated with a lubricant Molykote P37 which can be used in the range of -30^{o}C to 1400^{o}C before the ring specimens were tensile-tested. The ultimate tensile stress and yield stress were calculated from the plot of the recorded load-displacement data. The yield stress was determined by the 0.2% offset method. The stress-elongation curves of the ring specimens lagged behind on the stage of an early elastic deformation when they were kept within the elasticity limit to accommodate a grip arrangement. So, the elongation data of the claddings were obtained by the definition of elongation which was described in a prior report [4].

2.1 stress-elongation curves of the claddings

Figure 1 shows the stress-elongation curves of the claddings with different hydrogen content at room temperature including what were not charged with hydrogen. In case of no charging, the circumferential ultimate tensile stress (UTS) of the Zircaloy-4 cladding was a little higher than that of HANA-4 cladding but their elongations were not so much different from each other. The UTS of the HANA-6 cladding was 19% less than that of the Zircaloy-4 cladding while its elongation (EL) was 11.7% larger.

For hydrogen-charged claddings, there were not so much differences in the change of UTS of claddings with hydrogen content but remarkable reduction in the EL with the increase of hydrogen content at the level of more than about 900 ppm. HANA-6 cladding had the least effect on the elongation but Zircaloy-4 cladding had the worst effect among the tested claddings.

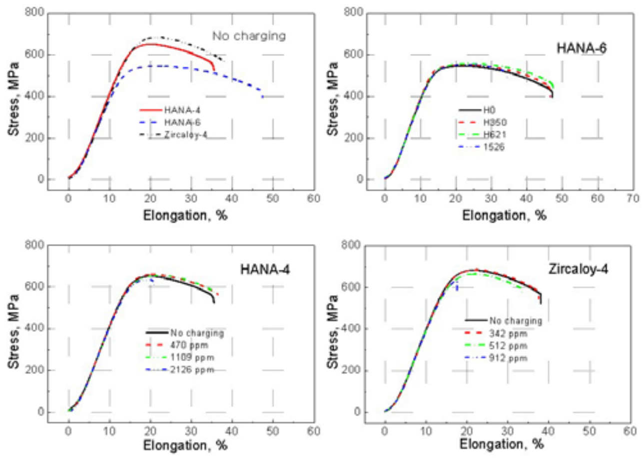

Fig.1. Stress-elongation curves of the claddings at room temperature

2.2 Ductile-brittle transition curves of the claddings

The ductile-brittle transition of the claddings was reviewed from the data of the elongation change with the hydrogen content. A diagram is plotted in Figure 2 to review the circumferential ductile-brittle transition.

As shown in the plot, the transition hydrogen content (H_T) was defined as the middle point on the slope of the elongation-hydrogen content curve. The lower part elongation (E_L) was defined as the starting point of the tangential line on the lower part of elongation-hydrogen content curve.

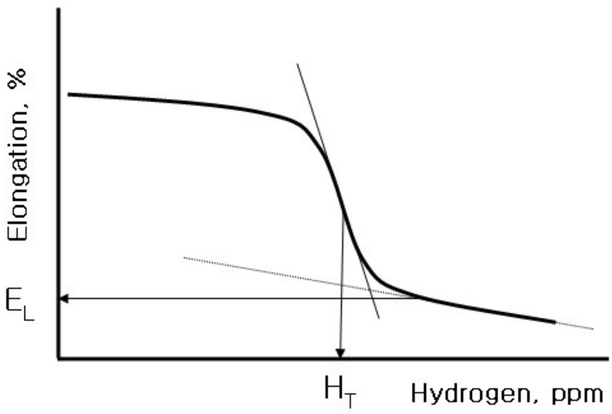

Fig.2 Diagram for the explanation of ductile-brittle transition of the cladding with hydrogen content

Figure 3 shows the transition hydrogen content which was needed for initiating the ductile-brittle transition of the claddings. The H_T of HANA-6 cladding and HANA-4 cladding was 870ppm and 905ppm, respectively while that of Zircaloy-4 cladding was 608ppm. So, HANA claddings need more hydrogen content than Zircaloy-4 cladding to initiate hydrogen embrittlement.

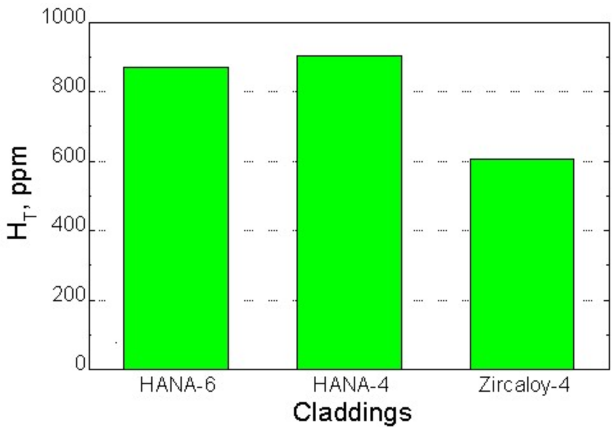

Fig.3 Change of transition hydrogen content (H_T)

Figure 4 shows the lower part elongation in the ductile-brittle transition of the claddings. The lower part elongation of the Zircaloy-4 cladding was less than 1%, but that of HANA-4 was 6% and that of HANA-6 was as much as 21.6%. So, in a high burn-up environment the resistance to the ductile-brittle transition of the Zr-Nb based HANA-4 and HANA-6 claddings would be higher than that of Zr-Sn based Zircaloy-4 cladding.

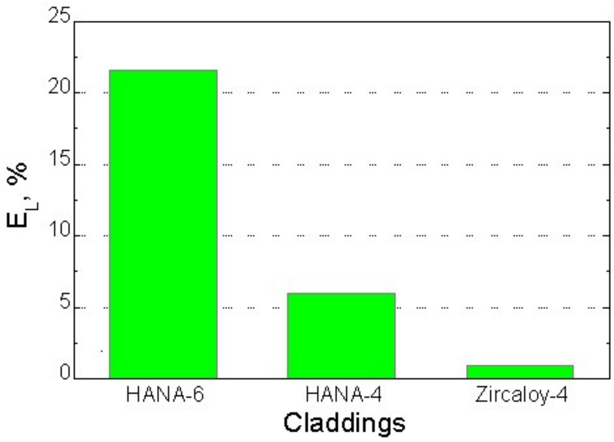

Fig. 4 Change of lower part elongation (E_L)

3. Conclusion

The hydrogen effect on the circumferential mechanical properties of HANA claddings was reviewed to study the difference in the stress-elongation curves and the ductile-brittle transition between the HANA and the Zircaloy-4 claddings under a simulated high burn-up environment. The results can be summarized as; (1) The mechanical integrity of the Zr-Nb based HANA-4 and HANA-6 claddings in the circumferential direction could be better than that of the Zr-Sn based Zircaloy-4 cladding in a high burn-up environment. (2) The Zr-Nb based alloy like HANA claddings would be less sensitive to a ductile-brittle transition than the Zr-Sn based alloy like Zircaloy-4 cladding in a high burn-up environment.

Acknowledgement

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