Effects of Hydride Rim on Ductility of Zircaloy-4

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1. Introduction

Zirconium alloys have been chosen as Light Water Reactors (LWRs) for fuel cladding materials because of their low neutron absorption cross-section, satisfactory strength at the operating temperature and high corrosion resistance. Nevertheless, oxidation and hydrogen absorption of cladding are critical problems with increasing burn-up [1]. During the operation of nuclear power plants, the reaction of water with zirconium alloys produces hydrogen, which is absorbed and picked-up inside the cladding. When the concentration of hydrogen exceed terminal solid solubility (TSS) in Zr-matrix, the hydrides which are brittle will be precipitated [2]. Because of the temperature gradient between outer and inner surface of cladding, hydrides are precipitated on the outer surface of cladding, in the form of a continuous layer/rim including a high content of discrete hydrided particles. Under this condition, hydride rim may form. These 'hydride-rim' yields a deterioration of ductility with increasing hydrogen content and/or hydride rim thicknesses [3].

The objective of this research is to discover behavior and mechanical properties of Zircaloy-4 with hydride rim. To examine the effect of hydride rim on mechanical properties of Zircaloy-4, ring compression tests (RCTs) were performed in this study.

2. Methods and Results

2.1 Samples

In this study, non-irradiated, cold worked stress relieved (CWSR) Zircaloy-4 tube of length 100 mm with an outer diameter of 9.5 mm and 0.57 mm wall thickness was used. For increasing the rate of hydrogen absorption on the cladding material, the Zircaloy-4 tube was plated with Ni and was welded by tube cap at end of both side of tube. This material plated with Ni was charged in Sievert-type apparatus at 320 ℃. Before-charging, the air present inside the reaction chamber was evacuated until $\sim 10^{-6}$ Torr. After that, chamber was heated up at 300 ℃ for 1 hour. When the temperature was stabilized, hydrogen was injected into the reaction chamber. Since then, when the pressure of reaction chamber was reached to required value, the reaction chamber was evacuated again. Finally, material was slowly cooled with 0.5-1 ℃/min cooling rate. Fig 1 shows morphology of the hydride rim using optical microscopy (OM) in the specimen. The thickness of hydride rim was 70-75 µm. After charging, the material was cut into 10 mm for RCT specimen.

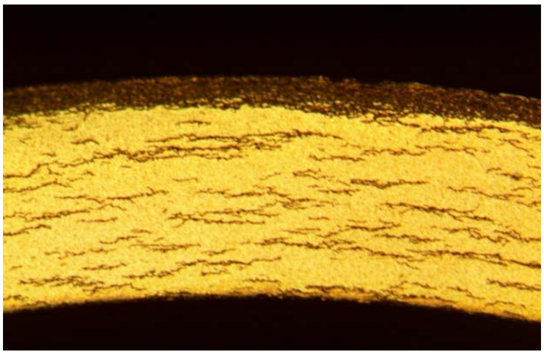


Fig. 1. Morphology of hydride rim in Zircaloy-4.

2.2 Ring compression test

RCT was done with universal testing machine (Instron model 5582) at room temperature. Fig. 2 shows the ring compression machine and sample. The tests were performed with the two kinds of specimens: the specimen with hydride rim and the as-received specimen plated with Ni. All the tests were performed at room temperature with cross head displacement rate of 1 mm/min.

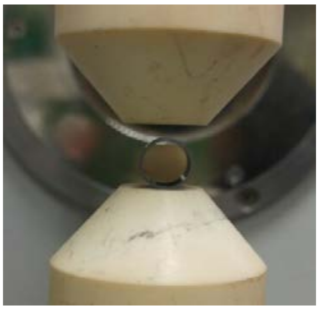


Fig. 2. Ring compression machine and sample.

2.3 Results

RCTs were performed at room temperature to compare as-received specimen and the specimen with hydride rim. Fig. 3 shows experimental results of ring compression tests. The specimens with hydride rim showed results different from the as-received specimens. The results indicate that the hydride rim deteriorates the ductility of Zircaloy-4 because the specimens with hydride rim rupture earlier than the as-received specimens.

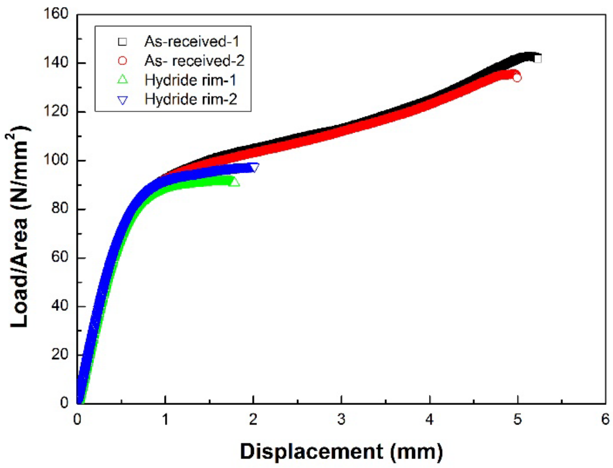
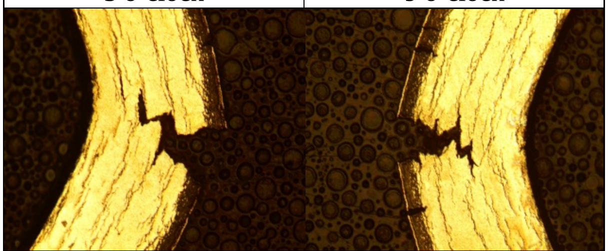


Fig. 3. Normalized load-displacement curve of Zircaloy-4 with hydride rim at room temperature.

Hydride rim specimen, Room temperature	
3 o'clock	9 o'clock



As-received specimen, Room temperature	
3 o'clock	9 o'clock

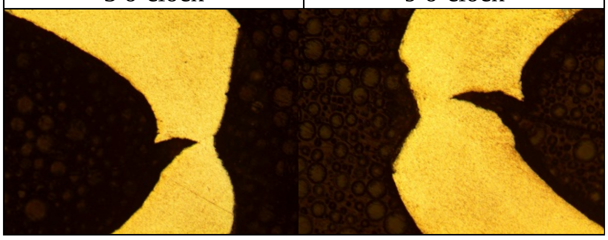
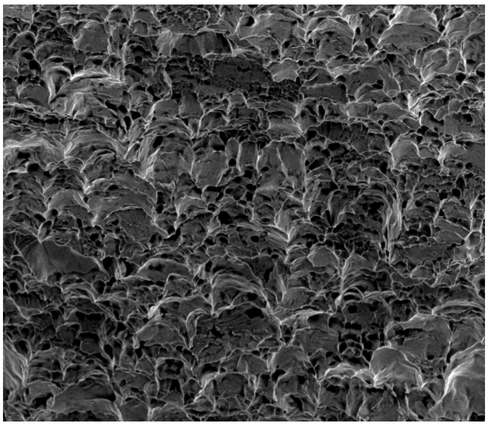


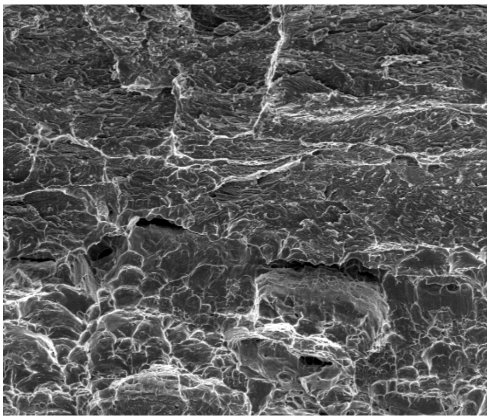
Fig. 4. Morphology and crack development in the specimen according to existence of hydride rim.

In addition, Fig.4 shows that morphology and crack development in specimens. This results were observed using OM. In case of specimen with hydride rim, cracks developed at 3 and 9 o'clock. Also, the cracks of the as-received specimen developed at 3 and 9 o'clock. Furthermore, cracks initiated at the cladding outer surface which is formed hydride rim. However, the crack imaged in the specimen with hydride rim propagated different from as-received specimen. In region of hydride rim, the crack extended clearly in the radial directions. As the crack extended inside, the crack propagated along circumferential hydrides. On the other hand, for the as-received specimen, the crack developed both of inner and outside surfaces.

Fig. 5a shows fractography of the as-received specimen. The figure was observed using scanning electron microscope (SEM). As shown in this figure, the surface contains many dimples and micro-voids which are characteristic of ductile fracture. Fig. 5b shows fractography of the specimen with hydride rim. As shown in figure, transgranular cleavage is observed with dimples. This type of fracture indicates that the specimen with hydride rim is brittle. Therefore, the hydride rim deteriorates the ductility of Zircaloy-4.



(a) As-received specimen.



(b) Specimen with hydride rim.

Fig. 5. Fractography of the Zircaloy-4 specimen.

3. Conclusions

A test procedure was developed to examine the behavior and mechanical properties of hydride rim in Zircaloy-4. The ring compression test was performed with two kinds of specimens: as-received specimens and the specimens with hydride rim. The specimen with hydride rim ruptures earlier than as-received specimens. Also, the fractography of the specimen with hydride rim depicts transgranular fracture which is characteristic of brittle fracture. These results demonstrate that the hydride rim deteriorates the ductility of Zircaloy-4.

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