*Transactions of the Korean Nuclear Society Autumn Meeting*
*Gyeongju, Korea, October 24-25, 2013*

# Hydride effects on the ductility of Zircaloy-4 by Ring compression test

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## 1. Introduction

During long-term dry storage, the cladding temperature slowly decreases with decreasing decay heat. Previous investigations showed when hydride platelet normal is parallel to axis of tensile stress which can reduce a cladding ductility even as little as 40 ppm of hydrogen content [1], whereas when platelet normal is perpendicular to the stress axis has relatively little effect [2-4]. However, the radial hydrides can be precipitated during dry storage which reduce cladding ductility [5, 6] and also cause a radial hydride assisting-DHC [7]. In addition, the ductile-brittle transition temperature (DBTT) of zirconium alloy is known between 100-200 $^{o}$C which indicates that the cladding ductility can be reduced significantly at the end of dry storage..

## 2. Experimental

### *2.1 Material*

Cold worked stress-relieved (CWSR) Zirclaoy-4 with an outside diameter of 9.5 mm and wall thickness of 0.57 mm was used. The specimens were charged with hydrogen at 400 $^{o}$C by a gaseous charging method. As a result, circumferential hydride embedded specimen with hydrogen in the range of 40–1036 wppm was obtained. On the other hand, in order to make the radial hydrided specimen, the internal pressurization method was used. The radial hydride treatment is as follows: the 25 cm long tube specimen was heated up to 400 ºC and maintain 1 hour for temperature stabilization. After the temperature stabilization, a constant hoop stress of 120 MPa was applied by pressurization of Ar gas. Then, specimen was cooled to room temperature at cooling rate of ~0.5 ºC/min with maintaining the hoop stress. Finally, the tube was cut into 10 mm long specimens without a notched section

### *2.2 Ring Compression Test*

The RCTs were performed using universal testing machine (Instron 5582) at room temperature and 150 ± 5 ºC and 300 ± 7 ºC by a cross head displacement rate of 1 mm/min. At high temperatures, RCTs were performed in Ar environment to minimize the oxidation effect, and after the RCT the specimens were cooled rapidly to room temperature. Fig.1 shows the ring compression device and specimen.

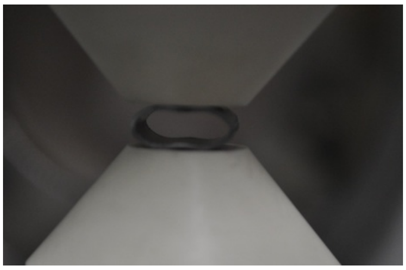

Fig. 1. Ring compression device and specimen

## 3. Results and discussions

### *3.1 Ring compression test with circumferential hydrided specimen*

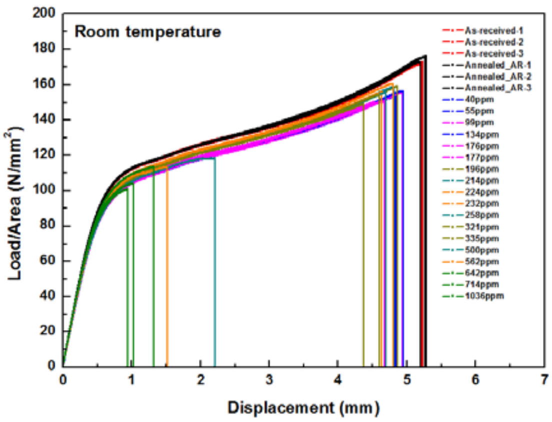


Fig. 2. RCT curve at room temprature.

Figure 2 shows the load-displacement responses of hydrided ring specimen at room temperature. The load-displacement curve is very sensitive to the cladding wall thickness and length. In order to normalize the thickness effect, the loads are divided by cross sectional area. As shown Fig. 2, the hydrided specimens are quite brittle at room temperature. but become more ductile at 150 ºC. Figure 3 shows the metallographic images of specimen after the RCT. When the specimen is subjected to compression, tensile stresses are built at the inner surface of 12 o'clock and the outer surface of 3 o' clock position; whereas, compressive stresses are generated at the outer surface of 12 o'clock and the inner surface of the 3 o' clock position. Consequently, the cracks occurred at the 3 and 9 o’clock with 134 wppm specimen; whereas, the cracks were developed at the 12, 3 and 9 o’clock with 562 wppm specimen indicating brittle fracture. It is evident that zirconium hydrides are very brittle at room temperature; therefore, it is believed that theses brittle hydrides could act as a defect which induces a brittle fracture of zirconium matrix. On the contrary, the radial crack did not occur at 12 o' clock position at 150 °C and maintain its shape until large deformed bending which indicates the specimen becomes more ductile at 150 °C.

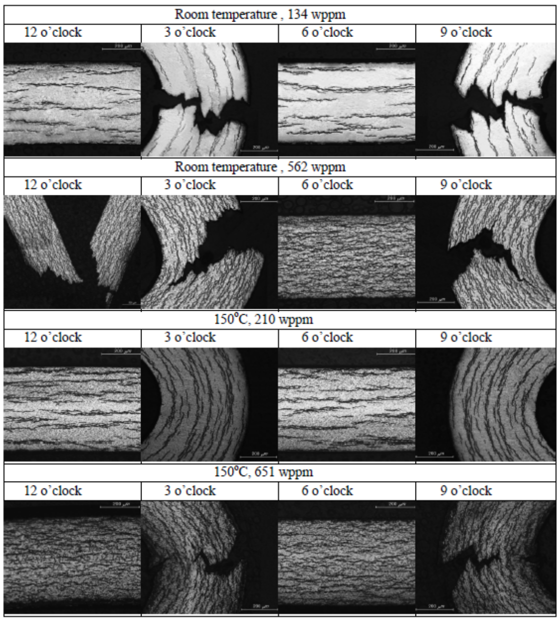


Fig. 3. Metallographical images with circumferential hydrided specimen after the RCTs

*3.2 Ring compression test with radial hydrided specimen*

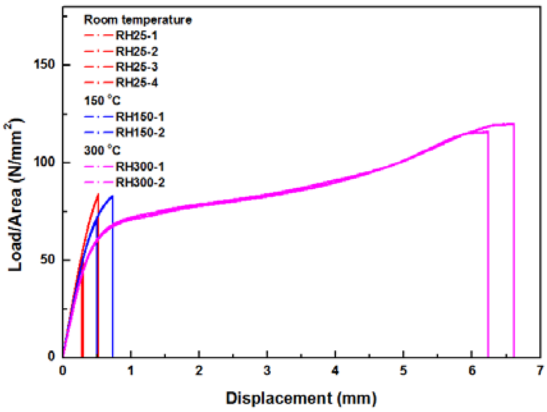


Fig. 4. Ring compression device and specimen

As shown Fig. 4, it is evident that the ductility of radial hydride specimen reduces significantly with respect to circumferential hydrided specimen. However, radial hydride containing specimens are brittle at room temperature and 150 °C which are different from the circumferential hydrided specimen. On the other hand, RCT curve at 300°C shows that the radial hydrided specimen can deform significantly without cracking. Figure 5 shows the morphology of radial hydride specimen before and after RCT. The morphologies of the specimen clearly show that the radial hydrides act as a crack initiation path at room temperature and 150 °C; whereas, the specimen can deform plastically at 300 °C even the radial hydrides are present at that temperature.

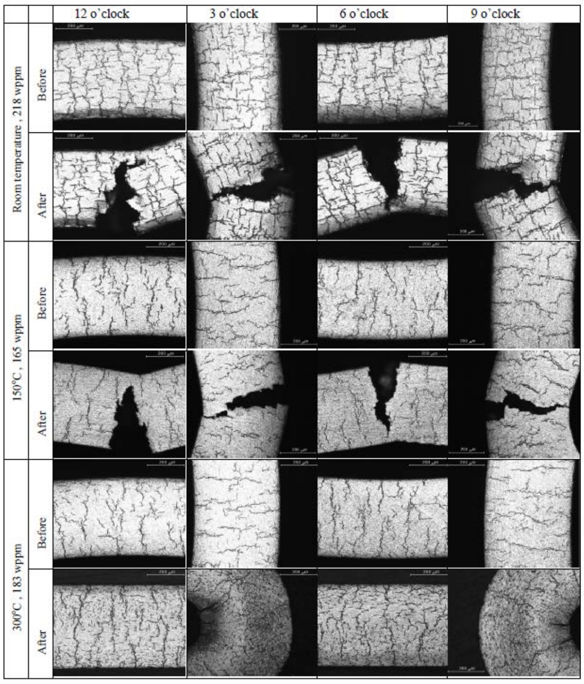


Fig. 5. Metallographical image with radial hydrided specimen before and after the RCTs

## 4. Conclusions

The circumferential hydrided specimens are quite brittle at room temperature but become more ductile at 150 °C and 300 °C. However, RCTs with radial hydride specimen showed that hydride is brittle at 150 °C but ductile at 300 °C. Therefore, brittle-ductile transition temperature of radial hydride embedded Zircaloy-4 is between 150 and 300 °C.

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