The Effect of Peak Temperatures and Hoop Stresses on Hydride Reorientations of Zirconium Alloy Cladding Tubes under Interim Dry Storage Condition

Hyun-Jin Cha*, Ki-Nam Jang, Kyu-Tae Kim
Nuclear and Energy Engineering Department, Dongguk University
123, Dongdea-Ro, Gyeongju, Republic Of Korea, 780-714
**Corresponding author: chahyunjin@dongguk.ac.kr*

1. Introduction

Spent fuels are stored in wet storage pit for a few years at temperature less than 60℃ and transferred to dry storage cask. Hydrides in zirconium alloy fuel cladding are dissolved because cladding temperature increased from 60℃ to 400℃ in dry storage cask and rod internal pressure is raised to 15.5MPa. The fuel cladding temperature may decrease by 100℃ per 10 years during the dry storage. Radial hydride can be precipitated during the cooling process if hoop tensile stress on cladding is larger than a threshold stress. The precipitated hydride in radial direction severely degrades mechanical properties of spent fuel rod. Hydride reorientation is related to cladding material, cladding temperature, hydrogen contents, thermal cycling, hoop stress and cooling rate. US NRC established the regulation on cladding temperature during the dry storage, which is the maximum fuel cladding temperature should not exceed 400℃ for all fuel burnups under normal conditions of storage. However, if it is proved that the best estimate cladding hoop stress is equal to or less than 90MPa for the temperature limit proposed, a higher short-term temperature limit is allowed for low burnup fuel. In this study, 250ppm and 500ppm hydrogen-charged Zr-Nb alloy cladding tubes were selected to evaluate the effect of peak temperatures and hoop tensile stresses on the hydride reorientation during the dry storage. In order to evaluate threshold stresses in relation to various peak temperatures, four peak temperatures of 250, 300, 350, and 400℃ and three tensile hoop stresses of 80, 100, 120MPa were selected.

2. Experimental Setup

2.1 Specimen Preparation

The chemical compositions of the Zr-Nb alloy cladding used in this study are given in Table I.

Table I: Chemical Compositions of Zr-Nb Alloy(wt%)

Nb	Sn	Cr	Fe	Zr
1.0	1.0	-	0.1	Bal.

The 250ppm hydrogen-charged (250ppm-H) and 500ppm hydrogen-charged (500ppm-H) Zr–Nb alloy cladding tubes were selected in this study. The 200mm long tubes were charged with hydrogen in a vacuum furnace at 400^{o}C containing a mixture gas of hydrogen(150torr) and argon(200torr) and heat-treated in a furnace at 410^{o}C containing argon(350torr). The hydrogen concentrations of specimens were analyzed by ELTRA ONH-2000. The hydrogen concentrations were 250ppm and 500ppm, respectively. Fig. 1 shows a schematic configuration of the test specimen and jig used in this study. The external diameter and thickness of the ring test specimen are 9.5mm and 0.57mm, respectively.

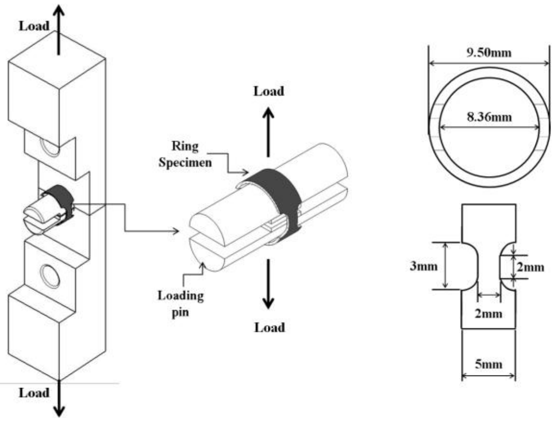

Fig. 1. Specimen and jig used in this study

2.2 Experiment Procedure

The hydride reorientation tests were performed using the KLES 500-S creep tester. The test specimens were respectively heated up with 3.0℃/min to four peak temperatures of 250, 300, 350 and 400℃ and remained for 2 hours at that temperature. Then, the test specimens were cooled down with cooling rate of 0.3℃/min under three tensile hoop stresses of 80, 100 and 120MPa. After the hydride reorientation tests, tensile tests were carried out to evaluate mechanical properties using the Instron model 3366 mechanical testing machine. The fracture surfaces of the specimens were examined by scanning electron microscope and the gage length regions were examined by optical microscope. The etchant used for metallographic examination was composed of HF, HNO_3, H_2SO_4 and H_2O in a volume ratio of 10:30:30:30.

3. Results and discussion

Figure 2 and 3 show the optical micrographs of 250 and 500ppm-H specimens after the cool-down process with the cooling rate of 0.3℃ /min under the tensile hoop stresses of 80, 100 and 120MPa, respectively. It can be seen that the higher hoop tensile stress generated the larger radial hydride fraction. In addition, the higher peak temperature generated the longer radial hydride and larger radial hydride fraction.

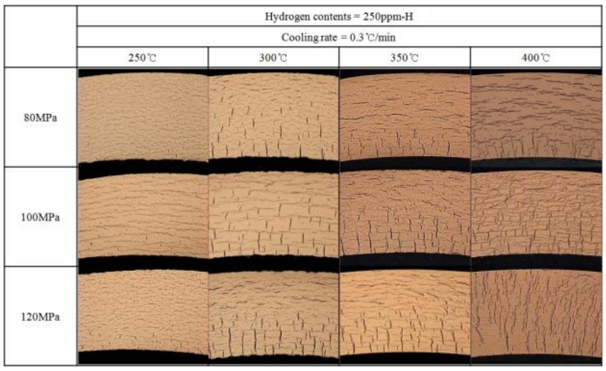

Fig. 2. Optical micrographs of 250ppm-H specimens after the hydride reorientation test under 80, 100 and 120MPa

As seen in Fig.2 and 3, the 250ppm-H specimens generated larger radial hydride fractions than the 500ppm-H specimens. It may be explained by solid solubility of hydrogen in the zirconium. There are larger amount of the undissolved circumferential hydrides of the 500ppm-H specimens at the heat-up temperature of 400℃. The undissolved circumferential hydrides may block up the growth of the radial hydrides.

In addition, 250ppm-H specimen experiencing the highest peak temperature of 400℃ and the highest tensile hoop stress of 120MPa generated the largest number of radial hydrides and the longest radial hydride length. This phenomenon may be explained by terminal solid solubility for dissolution at terminal heat-up temperature, radial hydride nucleation energy, and the effect of undissolved circumferential hydrides at peak temperature on the radial hydride precipitation during the cool-down process.

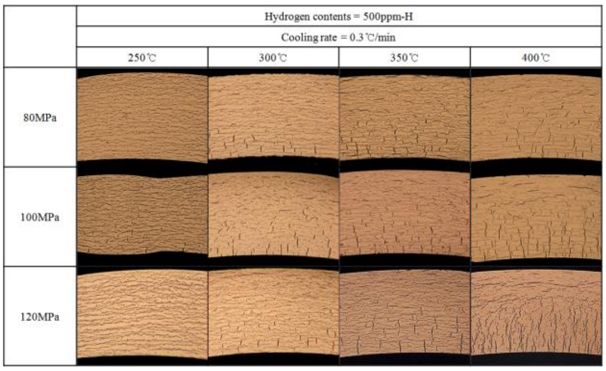

Fig. 3. Optical micrographs of 500ppm-H specimens after the hydride reorientation test under 80, 100 and 120MPa

Figure. 4 and 5 show the fracture surfaces and ultimate tensile strengths of 250 and 500ppm-H specimens after the hydride reorientation tests under 80MPa, respectively. It can be seen that the ultimate tensile strength decreases with the increase in peak temperature, as expected. In addition, the ultimate tensile strengths of 500ppm-H specimens are larger than those of 250ppm-H specimen. This may be caused by the impact of the circumferential hydrides on the dislocation movement. Ultimate tensile strength of specimen experiencing higher peak temperature is lower because radial hydride may accelerate the crack propagation.

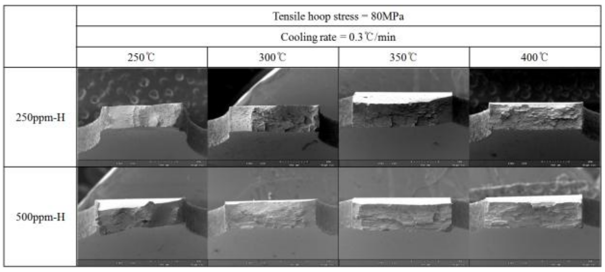

Fig. 4. Scanning electron micrographs of 250 and 500ppm-H specimens after the hydride reorientation tests under 80MPa

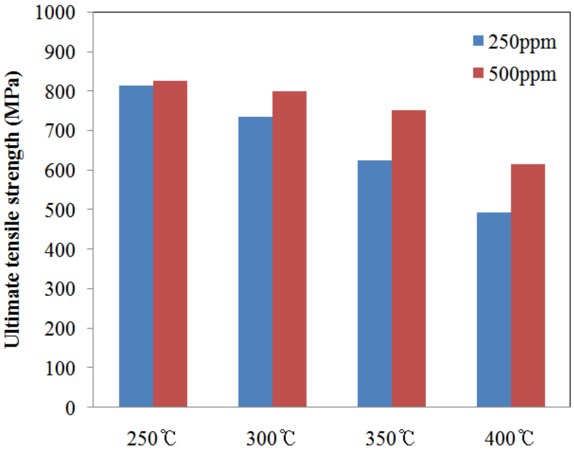

Fig. 5. Ultimate tensile strength of 250 and 500ppm-H specimens after the hydride reorientation tests under 80MPa

4. Conclusions

In this study, the effect of peak temperatures and hoop tensile stresses on hydride reorientation in cladding was investigated. It was shown that the 250ppm-H specimens generated larger radial hydride fractions and longer radial hydrides than the 500ppm-H ones. In addition, the higher hoop tensile stress and peak temperature generated the larger radial hydride fraction. It may be explained terminal solid solubility for dissolution at terminal heat-up temperature.

REFERENCES

[1] H. Chung, "Understanding Hydride- and Hydrogen-related Processes in High-burnup Cladding in Spent-fuel Storage and Accident Situations," Proceedings of the International Meeting on LWR Fuel Performance, Orlando, FL, U.S.A., pp. 470 (2004).
[2] S. Kim, S. Kwon, Y. Kim, J. Nucl. Mater. 273 (1999) 52.