Cladding Integrity Evaluation of Simulated Spent Fuel during Dry Storage Conditions

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I. INTRODUCTION

A systematic program, funded by the Ministry of Trade, Industry & Energy (MOTIE), Republic of Korea, was initiated to verify the integrity of low burn up spent fuel which makes up over 80% of the PWR spent fuel used in Korea. The goals of the project are to develop technologies that evaluate degradation and mechanical behaviors of low burnup spent fuel during dry storage. As a part of this program, the spent fuel cladding integrity during dry storage has been extensively evaluated through a model development and an analysis of the experimental results. To provide confirmatory data for degradation model validation, experiments for the possible degradation mechanisms, such as creep, hydride reorientation (HR), and delayed hydride cracking (DHC) have been performed for un-irradiated and irradiated materials. In this paper, the status and interim results of experiments for un-irradiated materials are described.

II. EXPERIMENTAL

II.A. Test Material

The test material used in this study was Zircaloy-4 cladding of the ASTM B811 standard, which has been used in PWR fuel cladding. The initial cladding thickness (t) and outer diameter (OD) are 0.57 mm and 9.5 mm, respectively (Westinghouse 17X17 type). A Zircaloy-4 cladding was obtained as cold-worked and stress-relieved at 480°C for 3.5 hours. The chemical compositions of the test material were analyzed using an inductively coupled plasma (ICP) method, as shown in **TABLE I**.

TABLE I. Chemical Compositions of Zircaloy-4 cladding (wt.%)

Zr	Sn	Fe	Cr	O	C	Si	N	H
Bal.	1.32	0.21	0.11	0.13	0.013	0.0093	0.0031	0.0006

II.B. Test Conditions and Methods

To investigate of the hydrogen effect on cladding degradation, hydrogen was charged using a gaseous technique under mixed argon/hydrogen conditions at 400°C. The amount of hydrogen absorption was analyzed using a hot extraction method (ELTRA ONH-2000). Samples for the hydrogen analysis were polished to remove the surface oxides and cleaned in carbon tetrachloride to exclude any detectable errors.

II.B.1. Creep

Actually, experimental data of irradiated spent fuel are needed to analyze and predict the creep behaviors of real spent fuel. However, the number of specimens is limited, and the hydrogen content is uncontrollable. Hence, the tests of the irradiated specimens only considered constant stress and temperature conditions to reduce the number of variables. Instead, tests using un-irradiated specimens consider stress, temperature, and hydrogen contents (**Fig. 1**).

Un-irradiated

Stress (MPa)	Temp (°C) 330	360	400
50			o
70	o	o	o
90	o	o	o
120	o	o	o
150	o	o	o
~~180~~	x	x	
~~200~~	x		o

Completed	
On progress	
Not performed	

Materials	Hydrogen contents (ppm)	
Zry-4 (CWSR)	10 (As-received)	400
	100	600

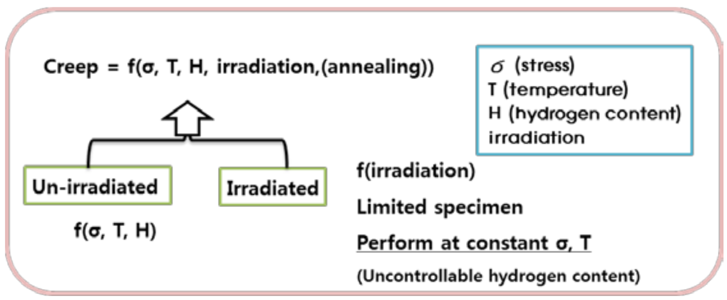

Fig. 1. Creep test plan and progress.

Creep tests were performed in a muffle furnace using an internally pressurization method with 150 mm long specimens, because this method applies the stress uniformly without a stress concentration at specific points. The creep test conditions are as follows: 340-400°C in temperature, 70-150MPa of stress, and 10-600+ ppm of hydrogen concentration (**Fig. 1**). Meanwhile, the applied hoop stress is calculated using the measured mean diameter. The assembled specimens were constantly pressurized with Ar gas to achieve the hoop stresses. The temperature was continuously monitored and maintained at an accuracy of ± 4°C. The creep strain was calculated from the average outer diameter measurements which were performed 10 times (5 points axially and 2 points circumferentially per specimen). A schematic illustration of the sample and fixtures for the creep test are shown in **Fig. 2.** HR test condition is similar to creep test condition with various cooling rate. On creep and HR analysis, microscopic analysis and ring compression tests of cladding were also performed after degradation tests.

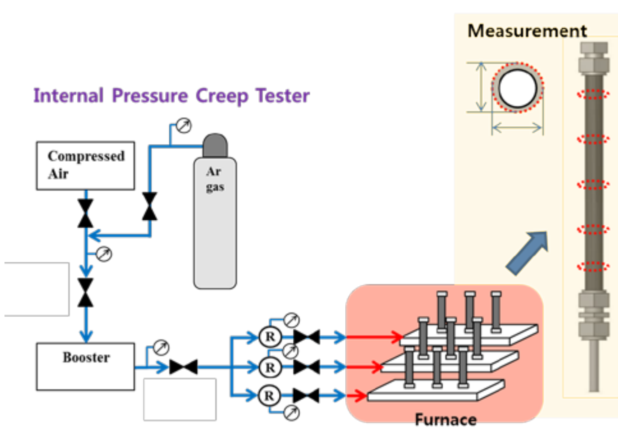

Fig. 2. Creep tester and test methods.

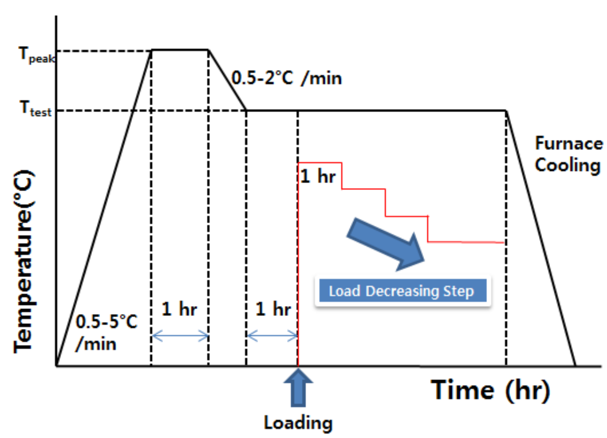

Fig. 3. DHC test procedures.

II.B.2. DHC

Because the crack growth rate of DHC is quite high within the range of 10^{-7}m/s, it is essential to suppress the crack growth of DHC (Ref. 1,2). Hence, DHC tests have been performed to find the threshold stress intensity factor (K_{IH}) through unloading test methods using a PLT-13 type specimen (**Fig. 3**). The tests were performed under various temperatures (150-300°C) with constant hydrogen content. To detect the crack growth, the axial extension was detected using LVDT, also the *in-situ* crack length was monitored using a DCPD system.

III. RESULTS AND DISCUSSION

III.A. Creep

Creep strain as a function of time at 400°C is shown in **Fig. 4**. Fresh (As-received) and 100 ppm H specimens showed 1% strain in 120 hours, and the creep strain decreased as the hydrogen content in the specimen increased. The 600 ppm H specimen reached 1% strain in about 1500 hours. This tendency is consistent with previously reported data (Ref. 3). According to previous results (Ref. 3,4), hydrogen leads to a significant creep strengthening. In addition, some experiment results suggest that precipitated hydrides act as obstacles to the dislocation glide, increasing the hardening of the material, which leads to a decrease in creep rate (Ref. 3).

After creep deformation, circumferential hydrides distribute uniformly on the microstructure and their amounts increase with the charged hydrogen content**. Fig. 4** shows the results of a ring compression test at RT, 100°C, and 300°C after creep deformation. As the hydrogen content decreased, the creep deformation increased. The as-received specimen had 5 times more deformations than the 600 ppm H specimen owing to the creep, but still maintained a high ductility after deformed. In addition, similar to the no-deformation condition, as the temperature decreased and hydrogen content increased, offset strain decreased. This implies that creep deformation does not affect the ductility.

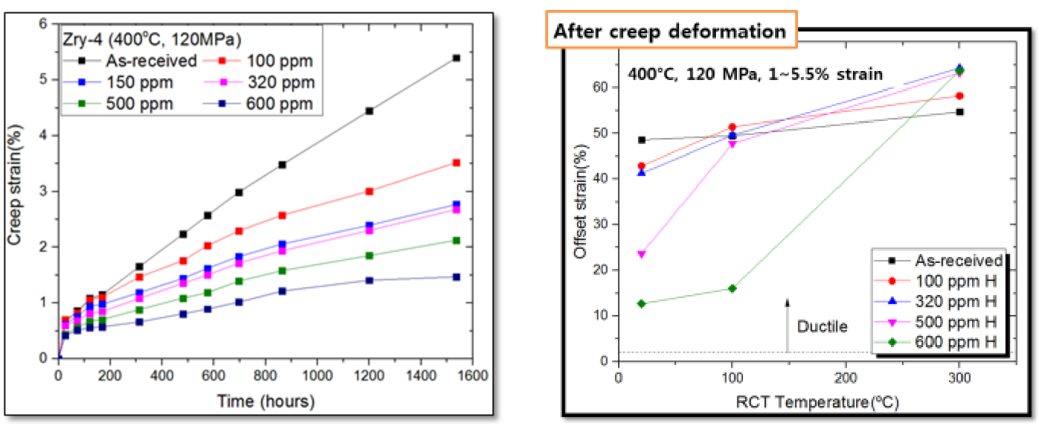

Fig. 4. Results of creep test and ring compression test after creep deformation.

III.B. DHC

A DHC test system with DCPD, and LVDT used to monitor the crack length and axial displacement was established. We performed test to evaluate threshold stress intensity factor and crack growth rate by load decreasing method. Crack growth was monitored by the LVDT on crack opening and DCPD voltage. (**Fig. 5**). Shortly, the accumulated results of the threshold stress intensity factor depending on the temperature will be produced.

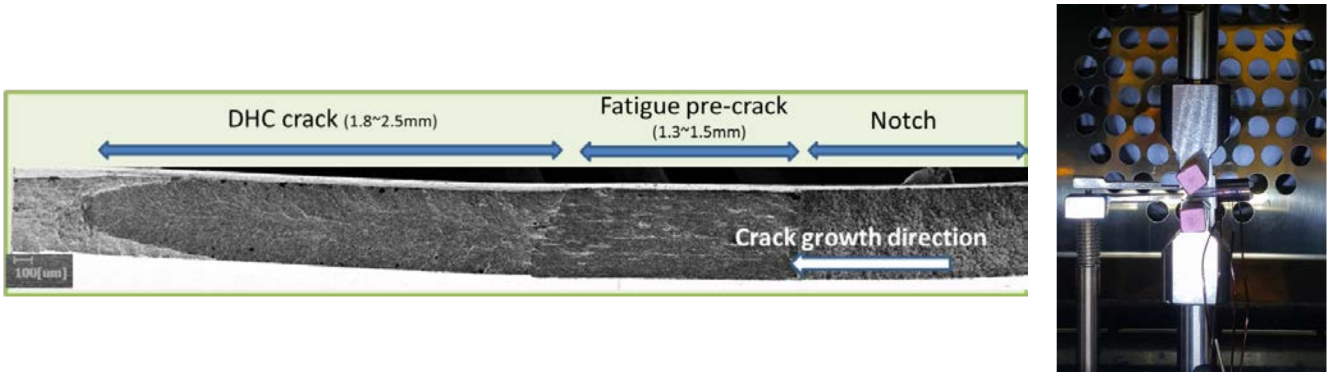

Fig. 5. Pictures of DHC crack and test set-up.

IV. CONCLUSIONS

A systematic program, funded by the Ministry of Trade, Industry & Energy (MOTIE), Republic of Korea, was initiated to verify the integrity of low burn up spent fuel during dry storage. As a part of this program, the cladding integrity when considering creep, HR, and DHC has been extensively evaluated based on our own experimental results. The results of degradation tests and the material properties after degradation were evaluated. The status and interim results of the experiments for un-irradiated materials were described.

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