Hoop Deformation and Fracture Behavior of Zircaloy-4 Cladding with Different Hydrogen Contents under EDC Tests

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Keywords : Pellet-Cladding Mechanical Interaction, Expansion Due to Compression, Digital Image Correlation

1. Introduction

During a power ramp, thermal expansion of the fuel pellets induces pellet-cladding mechanical interaction (PCMI), resulting in hoop deformation of the cladding. In addition, the hydrogen content in zirconium alloy cladding increases with fuel burnup, and hydrogen-induced embrittlement can degrade the mechanical properties of the cladding. Therefore, the deformation and failure behavior of the cladding with respect to hydrogen content should be quantitatively evaluated under PCMI conditions. Various studies have investigated the deformation and failure behavior of fuel cladding considering hydrogen content, hydride distribution, and hydride blisters [1–4]. In this study, EDC-DIC tests were conducted on as-received and 300 ppm hydrogen-charged Zircaloy-4 cladding. The hoop strain and failure behavior were compared to evaluate the effect of hydrogen content on the hoop deformation behavior of the cladding.

2. Experimental methods

2.1 Material

Cold-worked and stress-relieved (CWSR) Zircaloy-4 cladding with an outer diameter of 9.5 mm and a wall thickness of 0.57 mm was used in this study. The hydrogen content was set to 300 ppm based on the amount of introduced hydrogen gas, and the cladding was hydrogen-charged using a gaseous hydrogen charging system. The cladding was heated to 400 °C under vacuum, and hydrogen gas was subsequently introduced into the chamber to a predetermined pressure. After a decrease in the chamber pressure was observed, the remaining hydrogen gas was evacuated. The cladding was then held at 400 °C for 8 h under vacuum and naturally cooled to room temperature.

2.2 EDC tests

The EDC test consists of axially compressing a pellet simulant inserted into the cladding to induce radial expansion, thereby generating hoop deformation of the cladding. The EDC specimen consisted of a 27-mm-long Zircaloy-4 cladding tube, a PTFE pellet, and SUS304 disks. The PTFE pellet had a height of 14 mm and a diameter of 8.36 mm, while the SUS304 disks had a height of 2.5 mm and a diameter of 8.34 mm.

The EDC tests were conducted at room temperature with a strain rate of approximately $10^{-4}/s$. Three tests were conducted using three as-received specimens and three specimens with a hydrogen content set to 300 ppm. The maximum crosshead displacement was set to 6 mm, and if a specimen fractured before reaching 6 mm, the test was terminated upon fracture. During the tests, 3D-DIC was applied to measure the hoop strain on the cladding surface. Fig. 1 shows the experimental setup and a schematic of the EDC test.

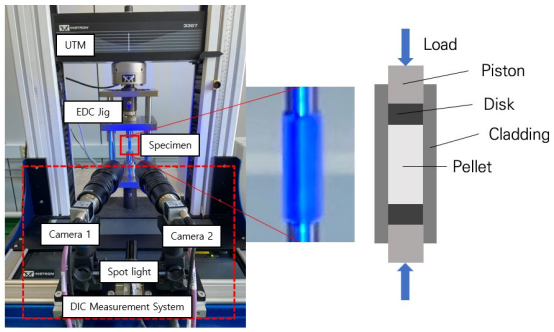


Fig. 1. Experimental setup and Schematic of the EDC test.

3. Experimental Results

Fig. 2 shows the hoop strain fields measured by DIC for the 300 ppm specimen before and at fracture. Before fracture, the maximum hoop strain was measured at the center of the specimen, while at fracture, part of the DIC measurement region became discontinuous.

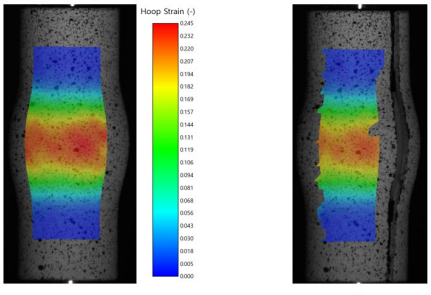


Fig. 2. Hoop strain field: (a) before fracture, (b) at fracture.

Fig. 3 shows the load–crosshead displacement curves for the as-received and 300 ppm specimens. The as-received specimens did not fracture up to a crosshead displacement of 6 mm, whereas the 300 ppm specimens fractured at 4.61–5.03 mm.

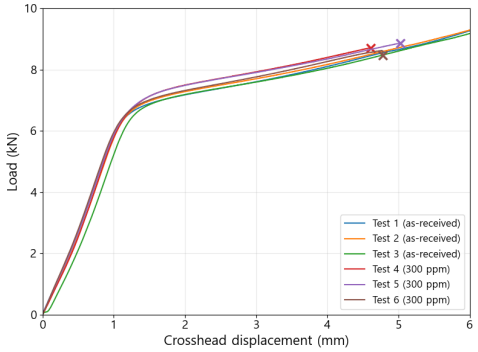


Fig. 3. Load-crosshead displacement curves under EDC tests.

Fig. 4 shows the changes in hoop strain measured during the EDC tests. The hoop strain of the as-received specimens increased until the end of the tests, whereas the 300 ppm specimens fractured at hoop strains ranging from 0.1994 to 0.2504.

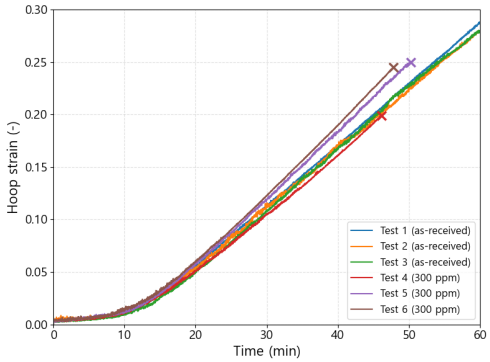


Fig. 4. Hoop strain-time curves under EDC tests.

Fig. 5 compares the maximum hoop strains of the as-received and 300 ppm specimens. The mean maximum hoop strain of the as-received specimens was 0.2837 at the maximum crosshead displacement of 6 mm without fracture, whereas the 300 ppm specimens fractured at a mean hoop strain of 0.2316.

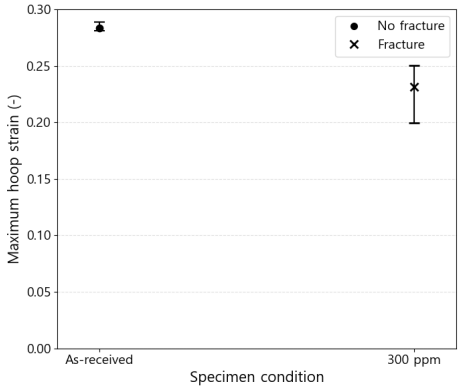


Fig. 5. Comparison of maximum hoop strain under EDC tests.

4. Conclusions

In this study, three EDC-DIC tests were conducted on each of the as-received and 300 ppm Zircaloy-4 cladding specimens to compare their hoop deformation and fracture behavior. Under the same test conditions, the as-received specimens did not fracture up to the maximum crosshead displacement of 6 mm, whereas all 300 ppm specimens fractured before reaching 6 mm. In addition, variations in fracture strain were observed among the 300 ppm specimens. Further repeated tests, additional tests on 600 ppm specimens, and measurements of the actual hydrogen content are required to quantitatively evaluate the relationship between hydrogen content and fracture strain.

Acknowledgements

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (Ministry of Science and ICT) (No. RS-2024-00422848 & No. RS-2022-00144002).

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