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Effects of Hydride Rim on Ductility of Zircaloy-4 using Ring Compression Test

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1. Introduction

Spent nuclear fuel (SNF) management is a critical issue for all countries which use nuclear power. In Korea, interim storage to manage the SNF is inevitable since government adopted a 'wait and see' strategy. Especially, dry storage among the interim storage types has been considered as realistic method.

Zirconium alloy cladding inevitably absorbs hydrogen during reactor operation and the absorbed hydrogen precipitates into a hydride platelet. Unfortunately, hydride-related phenomena such as hydride reorientation and delayed hydride cracking (DHC) are expected as major degradation mechanisms, threatening the SNF integrity during dry storage [1]. Accordingly, extensive studies have been conducted on deleterious effects of the zirconium hydride on mechanical properties of the cladding [2, 3].

However, most of previous works have been tested using un-irradiated zirconium alloy cladding that hydrides are uniformly distributed over the bulk region, rather than as-irradiated one due to experimental difficulties and limitation of resources. In case of cladding for high burnup fuel, contrary to un-irradiated one, localized hydrides around the outside wall, so-called 'hydride rim', exist [4]. Since thermal gradient resulting from temperature difference between inside and outside cladding surface during reactor operation is taken as the driving force for hydrogen migration toward the outside wall. This means that experimental results related to the hydrides in the out-of-pile conditions may be different from reality by the absence of the hydride rim. For this reason, in an experimental effort to simulate high burnup SNF cladding, several techniques have been studied and recently it was reported that successive formation of hydride rim using nickel coating on the outer surface of cladding [5,6].

The objective of this preliminary study is to form hydride rim around the cladding outside wall typically observed for high burnup fuel cladding. In addition, ring compression test (RCT) that simulates pinch-type loading subjected to cladding during SNF transportation is conducted to investigate separate effects of hydride rim on mechanical properties of the cladding.

2. Experimental

2.1 Specimen preparation

In this study, non-irradiated, commercial cold worked stress relieved (CWSR) Zircaloy-4 cladding tube with an outer diameter of 9.5 mm and wall thickness of 0.57 mm was used. The tube was cut into 150 mm in length and welded by tube cap at the end of both sides. In order to form hydride rim, prior to charge, outer surface of the specimen was plated with nickel which promotes hydrogen absorption to the specimen due to its hydrogen affinity. Then the specimen was charged with hydrogen using gaseous hydrogenation method at 320 ℃ and slowly cooled down to room temperature with cooling rate of 0.5 ℃/min. Finally, it was cut into 10 mm long tube segment for RCT. The hydrogen content in this study is 500-1400 wppm. Fig. 1 shows a typically observed hydride morphology with uniformly distributed circumferential hydrides in bulk region and hydride rim formed on outer surface of the specimen with the help of coated nickel. The hydride rim thickness used in this work was varied from 0 (as-received) to 95 μm.

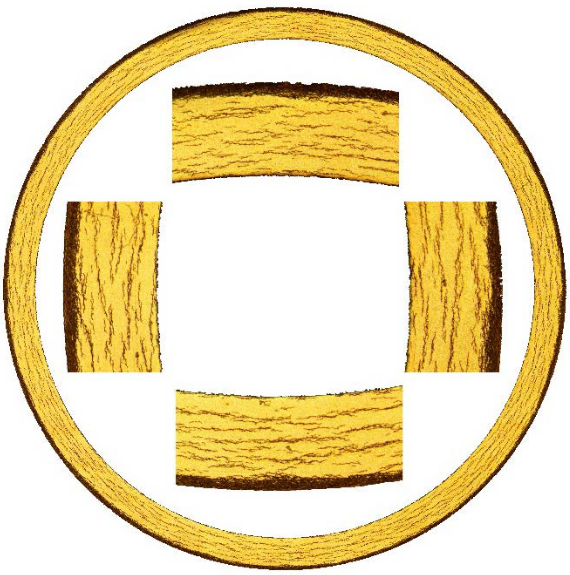

Fig. 1. An example of hydride morphology with hydride rim formed on outer surface of the cladding, whose average thickness is about 70 μm.

2.2 Ring compression test

RCTs were performed at room temperature using a universal testing machine (Instron model 5582). Fig. 2 shows a specimen placed on the ceramic device used for RCTs. The compressive load was applied to the specimen with displacement rate of 1 mm/min. Consequent mechanical responses depending on the rim thickness were acquired and analyzed.

Fig. 2. Ring compression device and specimen.

3. Current Results

Fig. 3 shows normalized load-displacement curve depending on hydride rim thickness. As the hydride rim thickness increases, the specimen ruptures earlier. This indicates although Zr-matrix maintains its ductility, quite brittle hydride layer, i.e. hydride rim contributes that cracks are easily initiated at outer surface in response to compressive stress. On the other hand, at the 80 μm hydride thickness level, fracture takes place at nearly same displacement regardless of thickness.

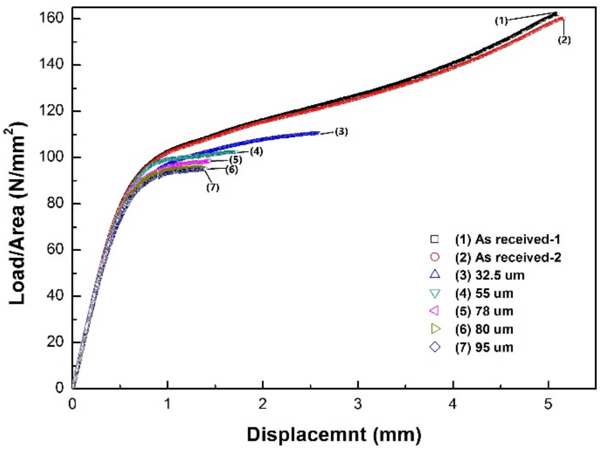

Fig. 3. Normalized load-displacement curve depending on rim thickness at room temperature.

In order to correlate rim thickness with ductility, offset strain which is used to quantify the ductility was measured. Offset strain is the engineering strain at which a test specimen fractures during RCT. Fig. 4 presents that normalized offset strain is inversely proportional to hydride rim thickness. It is indicated that the remaining ductile webs (beneath the hydride rim) are thinner. Since the ductile webs are thinner, a small level of plastic deformation are occur before fracture.

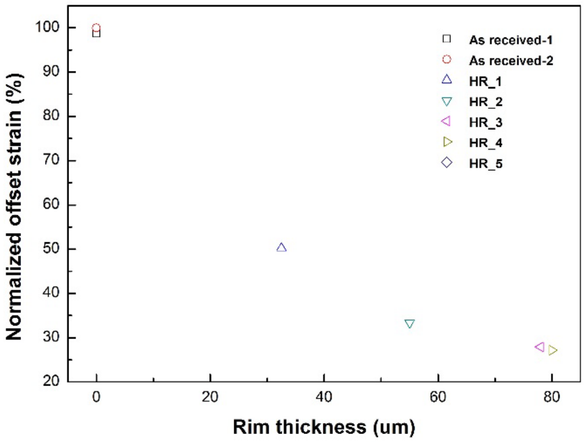

Fig. 4. Normalized offset strain with varying hydride rim thickness at room temperature.

4. Conclusions and Future plans

In this preliminary study, in order to simulate high burnup fuel cladding, hydride rim was attempted to form around the cladding outside wall. Encapsulated 150 mm long Zircaloy-4 tube which was plated with nickel at outer surface was used and then it charged with hydrogen using gaseous hydrogenation method. Finally, hydride rim whose thickness is 0~95 μm at outer cladding surface was successively formed. On the other hand, ring compression tests which simulate pinch-type loading were conducted to investigate the mechanical property degradation depending on the hydride rim thickness. The results showed that as the thickness increases, the specimen ruptured earlier and fracture strain decreases. These results demonstrate that the hydride rim deteriorates the ductility of zirconium alloy cladding. Also, hydride rim thickness is a predominant factor in causing fracture.

In the future, fracture surface analysis and characteristics analysis of hydride rim by means of hydrogen concentration determination and hydride phase identification will be conducted to back up experimental results. Also, in order to investigate effect of hydride rim on mechanical properties of the cladding, experiments with other temperature conditions will be conducted.

ACKNOWLEDGMENTS

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REFERENCES

[1] D.-H. Kook, J.-W. Choi, J.-S. Kim, Y.-S. Kim, Nucl. Eng. Technol. 45 (2013) 115-124.

[2] J.-S. Kim, T.-H. Kim, D.-H. Kook, Y.-S. Kim, J. Nucl. Mater. 456 (2015) 235-245.

[3] R.S. Daum, S. Majumdar, Y. Liu, M.C. Billone, J. Nucl. Sci. Technol. 43 (2006) 1054-1067

[4] M.C. Billone, T.A. Burtseva, R.E. Einziger, J. Nucl. Mater. 433 (2013) 431-448.

[5] T. Kido, M. Sugano, Trans. of Atomic Energy Society of Japan, 1 (2002) 469-471.

[6] O.N. Pierron, D.A. Koss, A.T. Motta, K.S. Chan, J. Nucl. Mater. 322 (2003) 21-35.