Micro-cantilever Tests on Hydride Blister and Zirconium Matrix of Zircaloy-4 Cladding Tube

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1. Introduction

During nuclear reactor operation, claddings shall be suffered corrosion. Owing to the temperature gradient between cladding inner wall and outer wall, it can cause hydride blister in outer surface of the cladding. It is reported that hydride blister is critical to integrity of fuel cladding due to its fragility. The integrity of spent nuclear fuel (SNF) should be maintained against potential shocks and vibrations during handling, storage and transportation. Most of experiments evaluating cladding integrity do not specifically consider the effect of hydride blister because it is difficult to measure the mechanical property of itself, but it is important to know how hydride blister can erode the ductility of claddings. In this study, micro-cantilever tests were introduced to evaluate the fracture toughness of local hydride blister and zirconium matrix of the cladding.

2. Experimental

2.1 Specimen Preparation

Recrystallized annealed (RXA) Zircaloy-4 cladding tube was used in this study. Two specimens were used: one is as-received (AR) and the other is hydride blister (HB) specimen. HB specimen was charged with hydrogen using a Sievert type apparatus, and hydride blister can occur through the excessive hydrogen charging process. Scanning electron microscope (SEM) image of the HB specimen is shown in Fig. 1.

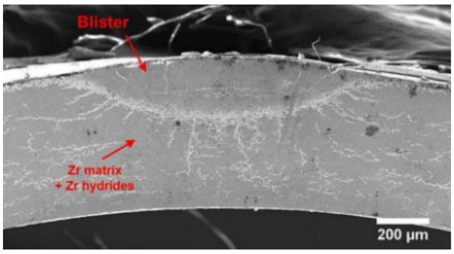

Fig. 1. Scanning electron microscope image of the specimen.

2.2 Micro-cantilever Test

Micro-cantilever tests were conducted using PI 85 pico-indenter (HYSITRON) with four-sided conductive diamond flat tip (1 μm × 1 μm) at a speed of 5 nm/sec. Micro-cantilevers and pre-cracks were ion-milled with Ga^+ ion beam of FEI Helios 600 at 30 kV acceleration voltage from hydride blister region and zirconium matrix region in Fig. 1. Dimension of the micro-cantilever and test images are shown in Fig. 2 and Fig. 3.

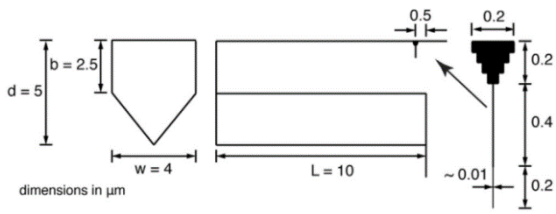

Fig. 2. Dimension of the micro-cantilever [1].

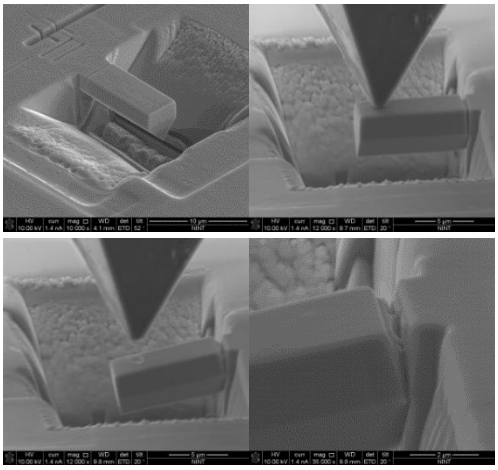

Fig. 3. Images of micro-cantilever test procedure.

3. Results and Discussions

3.1 Micro-cantilever Tests Results

Fig. 4 shows a load-displacement curve of the micro-cantilever tests. A black line indicates as-received specimen, and red and blue lines indicate the hydride blister specimens. Fracture of the as-received specimen occurred in plastic deformation region, but that of the hydride blister specimen occurred in elastic deformation region.

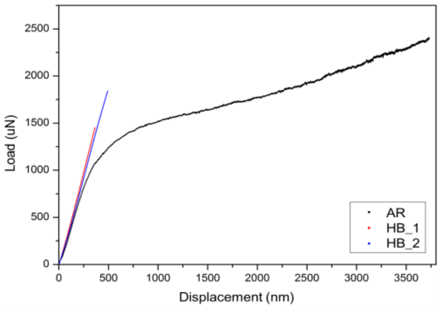

Fig. 4. A load-displacement curve of the test results.

3.2 Fracture Toughness Calculation

$$K_C = \sigma_0 \sqrt{\pi a}\, \mathrm{F}\left(\frac{a}{2\bar{y}}\right) \qquad (1)$$

$$\sigma_0 = \frac{P_0 L_0 \bar{y}}{I} \qquad (2)$$

Where σ_0 is the fracture stress, a is the crack length, and $\bar{y}$ is the vertical distance between the upper surface and the centroid of the cross-section. $\mathrm{F}(a/2\bar{y})$ is the dimensionless shape factor determined by finite element analysis [1-3]. P_0 is the fracture load, L_0 is the longitudinal distance between the pre-crack and the indenter tip loading point, and I is the second moment of area. Table 1 shows the calculated fracture toughness of the specimens. The results show that fracture toughness of the hydride blister specimen could drop up to 60% of fracture toughness of the as-received specimen.

Table 1. Fracture toughness of the specimens

Specimen	AR	HB_1	HB_2
Fracture toughness (MPa$\sqrt{m}$)	2.91	2.11	1.76

4. Conclusions

To evaluate the fracture toughness of local hydride blister and zirconium matrix of cladding on a microscale, micro-cantilever tests were introduced and well performed. The hydride blister specimen could be fractured in elastic deformation region, and fracture toughness of the hydride blister specimen could drop up to 60% of fracture toughness of the as-received specimen. Thus, the effects of hydride blister on the mechanical integrity of claddings should be taken into account when evaluating failure criteria of claddings during handling, storage and transportation of SNF.

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REFERENCES

[1] H. Chan, S.G. Roberts, J. Gong, J. Nucl. Mat., 475, 105-112 (2016).

[2] K. Matoy, H. Schonherr, T. Detzel, T. Scho berl, R. Pippan, C. Motz, G. Dehm, Thin Solid Films, 518(1), 247-256 (2009).

[3] D. Di Maio, S.G. Roberts, J. Mater. Res., 20(2), 299-302 (2005).