

## Fretting Wear Behavior of Pre-hydrated Zr Fuel Cladding

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### 1. Introduction

Zirconium (Zr) alloys is recognized as unreplaceable materials of nuclear fuel system due to their high corrosion resistances, reasonable mechanical properties and neutron absorption in PWR operating conditions. However, the outer surface can incur the corrosion damages in operating conditions, which introducing hydrogen uptakes and finally generates hydride precipitates in Zr matrix. At this time, mechanical properties can be degraded significantly, which was affected by their distributions, directions and the coverage of precipitates [1,2]. When considering fuel failure mechanism in PWR core, grid-to-rod fretting (GTRF) damages are still maintained the root cause [3], which is due to flow-induced vibration (FIV) and time-dependent contact conditions between fuel rod and spacer grid. It was confirmed that the Zr oxide on the outer surface of Zr fuel cladding, which were formed in high temperature water without irradiation damages, showed the outstanding wear resistance due to their high hardness [4]. If the Zr oxides were failed due to changed contact conditions under neutron irradiation, fretting wear damages can be generated by mechanical contact between Zr matrix with hydride precipitates and spacer grid. In this study, fretting wear mechanism of Zr fuel rod with hydride precipitates was examined, focusing on the comparison of fretting wear damages with and without hydride precipitates.

### 2. Experimental Methods and Results

#### 2.1 Specimen Preparation and Test Condition

In this study, in order to manufacture the wear samples with hydride precipitates, Zircaloy-4 (Zr4) cladding was used and its thickness and outer diameter are 0.57 mm and 9.5 mm, respectively. The hydrogen is charged using the gaseous method by using mixed argon/hydrogen condition at 400°C and this charged sample is heat-treated at 410°C for 1 day to prevent phase transformation and irregular hydride distribution. The fretting wear tests were performed on pre-hydrated Zr4 (PH-Z4) claddings wherein hydrogen concentration was about 220 ppm as shown in Fig. 1. From the image analysis results, the coverage of hydride precipitates in the Zr4 matrix was about 9% when considering the size of 10  $\mu\text{m}^2$  or more. In the fretting wear tests, initial normal force of 10 N, a frequency of 30 Hz and a relative slip amplitude of 100  $\mu\text{m}$  were applied up to number of cycles of  $10^6$  in room temperature distilled

water. The details of the fretting wear experiments including test method, spacer grid samples and test conditions were described in the previous studies [5,6].

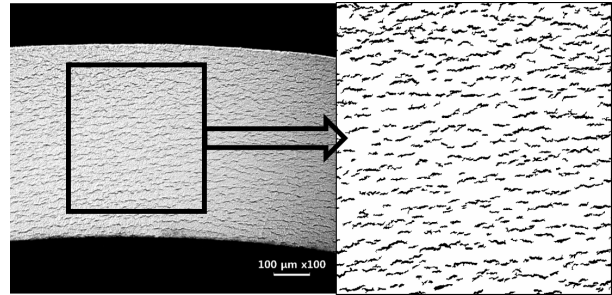


Fig. 1. Hydride distribution and typical image analysis result of Zr4 sample used in the fretting wear tests.

#### 2.2 Fretting Wear Mechanism

Fig. 2 shows typical results of worn area examination after the tests. Interestingly, the wear damages of as-received Zr4 (AR-Zr4) increased significantly compared to those of PH-Zr4, which can be distinguished by the amount of localized wear in entire worn area. When generated wear debris can be trapped between contact surfaces, severe wear can be incurred due to third-body abrasion phenomenon as shown in Fig. 3. In particular, because wear debris can be detached from both surfaces after experienced severe plastic deformations, Zr oxide can be formed due to the frictional heat and water lubricant, which has relatively higher hardness value than Zr matrix. Since the hydride precipitation initiates above the hydrogen solubility limit of the Zr4 cladding, some amount of hydrogen is dissolved in the Zr cladding. If the dissolved hydrogen influenced the mechanical properties of the Zr matrix, the surface hardness of PH-Zr4 will slightly change depending on the amount of the pre-charged hydrogen.

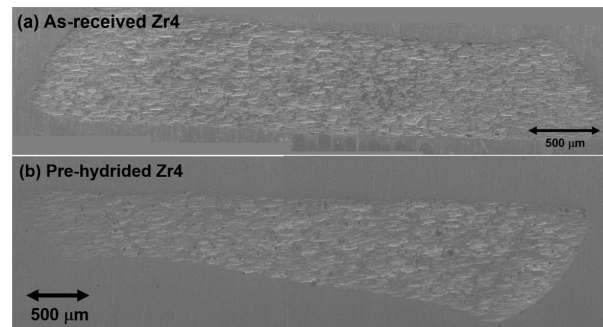


Fig. 2. Worn area of Zr4 cladding with and without hydride precipitates after the fretting wear tests (i.e.,  $10^6$  cycles in room temperature water).

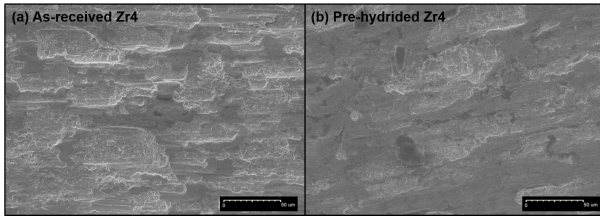


Fig. 3. Detailed fretting wear mechanism of both cladding samples.

### 2.3 Scratch Hardness Effects

After manufacturing pre-hydrided samples, scratch hardness was measured using a constant load scratch hardness tester, which can simply evaluate the resistance to severe plastic deformation under scratch conditions. It was reported that the hydrogen within Zr matrix was found to lead a reduction of the micro-hardness [7]. However, this reduction can increase in ductility with hydrogen addition. This result indicates that the PH-Z4 specimen with hydrogen pre-charging and heat-treatment process shows the resistance to wear due to improved ductility and deformation resistance at the outer surface. However, if the hydride precipitates were exposed to the contact surfaces, localized wear damages can be accelerated due to fracture of hydrides. In addition, the hydrides exposed to the contact surfaces caused a lot of error in the wear measurement results.

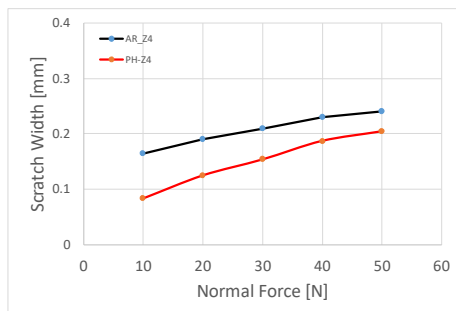


Fig. 4. Measurement results of scratch width.

## 3. Conclusions

Fretting wear characteristics of pre-hydrided Zr4 cladding was experimentally examined. The wear damages of as-received Zr4 increased significantly compared to those of pre-hydrided Zr4, which can be distinguished by the amount of localized wear in entire worn area. The pre-hydrided Zr4 specimen with hydrogen pre-charging and heat-treatment process shows the resistance to wear due to improved ductility and deformation resistance at the outer surface until the hydride precipitates are exposed to the contact surfaces.

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