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Development of Fracture Prediction Model for Spent Nuclear Fuel Cladding under Pinch Load Based on Continuum Damage Mechanics

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1. Introduction

The damage ratio of Spent Nuclear Fuel (SNF) is a very important intermediate variable for dry storage risk assessment which require an interdisciplinary and comprehensive investigation. It is known that the pinch load applied to the cladding can lead to Mode-3 failure and the cladding becomes more vulnerable to this failure mode with the existence of radial hydrides and other forms of mechanical defects. In this study, the failure resistance of Zircaloy-4 cladding against the pinch load is investigated using numerical simulations assuming the existence of radial hydrides. The simulation model is constructed from the microscopic images of cladding with hydrides. A pixel-based finite element model was created by separating the Zircaloy-4, hydrides, and hydride-zircaloy matrix interface using the image segmentation method. In this study, advantages, limitations, and challenges of a developed simulation model is discussed with the aimed to evaluate the resistance of a SNF cladding to pinch load through a continuum fracture approach considering the microscopic configuration of hydrides.

Fig. 1. Hydride rearrangement process of irradiated cladding

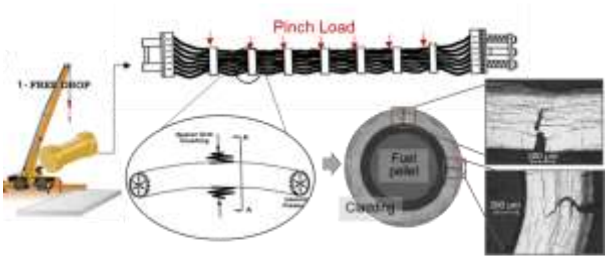

Fig. 2. SNF assembly deflected shape under drop pinch load

2. Methods and Results

The pinch load can have a decisive effect on the structural integrity and performance of the SNF rod. In this section, a pixel-based simulation model for microstructural and fracture behavior considering the effect of hydride reorientation of SNF rods under the pinch load is developed.

2.1 Failure evaluation method under pinch load

The pinch load applied to the cladding can lead to Mode-3 failure and the cladding becomes more vulnerable to this failure mode with the existence of radial hydrides and other forms of mechanical defects. The resistance of the cladding under pinch loads can be evaluated with the Ring compression test (RCT). The effect of hydride reorientation can be analyzed using the RCT. In general, radial hydrides have lower resistance to tensile hoop stress than circumferential hydrides. So, the cracks propagate along radial hydrides. The hydrides have the property of being generated close to each other, and hydrides of fine sizes are stacked under a microscope. The inhomogeneity of the cladding composition has a significant influence on fracture behavior.

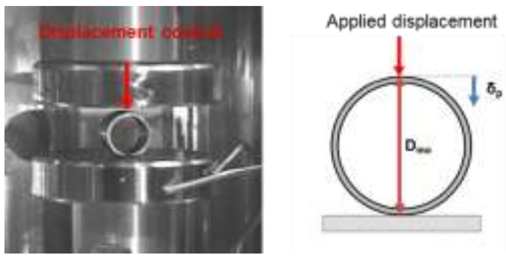

Fig. 3. RCT of a sectioned cladding ring specimen in ANL [1].

2.2 Crack propagation of mixed microstructures cladding

In general, radial hydrides have lower resistance to tensile hoop stress than circumferential hydrides. Therefore, the cracks propagate along radial hydrides. The δ-hydride form within the α-zircaloy matrix with the orientation relationship of (0001)//(111) direction causes a large expansion strain due to the volume difference. The expansion strain causes cracks in the hydride-zircaloy matrix interface of the cladding due to the increase in tensile hoop stress in the fuel rod. Also, though the hydride is stronger than the matrix. Therefore, established the three type of microstructure crack propagation analysis methods that can simulate fractures for hydride, zircaloy matrix, and hydride-zircaloy matrix interface.

2.3 Image segmentation method

A pixel-based finite element model was created by separating the zircaloy-4, hydride, and zircaloy/hydride interface using the image segmentation method. The image segmentation method uses a morphology operation basis, which is a preprocessing method through erosion operation after image expansion to enable normal segmentation by emphasizing pixels corresponding to hydrides. The segmented images are converted into a finite element model by assigning node and element numbers together with corresponding material properties. Using the generated hydride cladding finite element model to simulate crack propagation and cladding failure under pinch load.

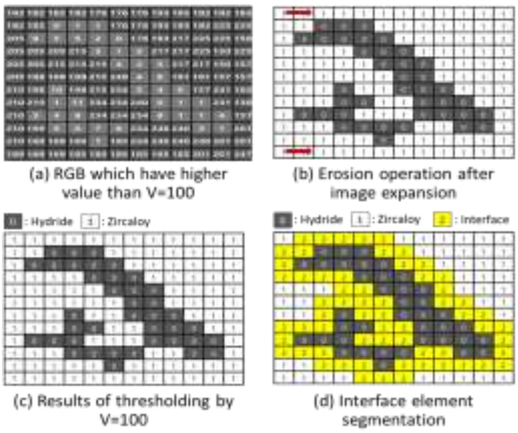

Fig. 4. Image segmentation method of morphology operation basis

2.4 Continuum damage mechanics

There is a need to simulate the fracture in pinch load using a fracture initiation criterion based on the above microstructural observations for the hydride, zircaloy matrix, and hydride-zircaloy matrix interface. Continuum Damage Mechanics (CDM) is a theoretical framework used to study the gradual failure and degradation of materials and structures under different types of loading conditions. CDM is based on the assumption that the material or structure is made up of a continuum of small elements that can undergo damage, leading to a progressive loss of their load-carrying capacity [2]. Using CDM, it is possible to simulate the hydride/matrix cracking in a continuum model and grain cracking in hydride or zircaloy matrix based on cladding deformation.

2.5 Computational modeling for fracture behavior

A computational model was developed considering the test conditions of RCT conducted in ANL. The pixel-based finite element model of the hydride reorientation cladding used in the simulation used the metallographic image high-burnup Zry-4 cross section form 400℃ test sample 605C6G [3]. The mechanical material model according to PNNL-17700 is applied to the ring section except for the 3, 6, 9, and 12 o'clock positions where major cracks occurred [4]. In this study, the elastic modulus and yield stress of zircaloy-4 and delta hydride using the nanoindentation technique were used as material properties [5]. However, the experimental studies on the fracture parameters of hydride and zircaloy-4 are difficult to obtain in irradiated cladding. Therefore, the initial fracture parameters were selected by using elastic modulus and yield stress. The fracture parameters are calibrated using sensitivity analysis and inverse engineering.

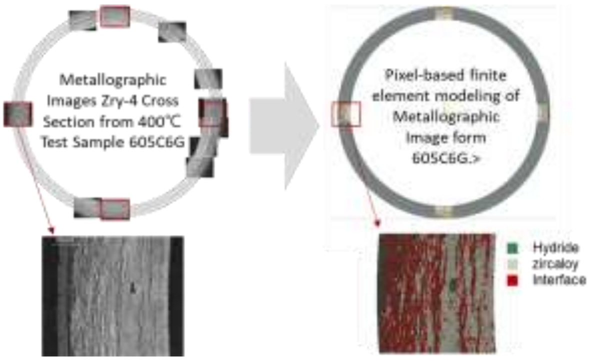

Fig. 5. Pixel-based finite element model of the hydride reorientation cladding

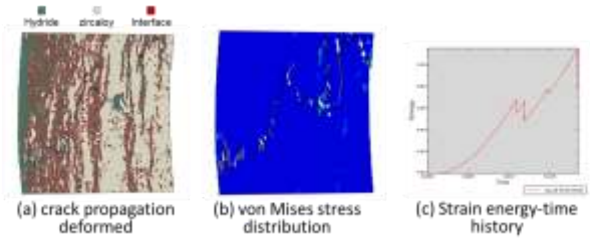

Fig. 6. RCT simulation result for fracture behavior.

3. Conclusions

In this study, a simulation model was developed to evaluate the resistance of SNF cladding to pinch loading through a continuum fracture mechanics approach considering the microscopic composition of hydrides. The developed pixel-based finite element model can simulate crack propagation for various rearranged hydride cladding based on the deformation of the continuum model. Therefore, the radial/circumferential hydride fracture resistance of the irradiated cladding can be evaluated using the developed computational model.

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