Predicting Hoop Mechanical Properties of Nuclear Fuel Cladding from the Ring Compression Test (RCT) Result

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1. Introduction

Hoop mechanical properties are the important mechanical properties to be studied for the hydride nuclear fuel cladding during operation, accident scenarios, and spent fuel storage. However, due to the tubular and thin-walled geometry of the fuel cladding, obtaining the hoop mechanical properties via the conventional uniaxial tensile test (UTT) can be difficult. A simpler and direct way, which is the ring compression test (RCT) can be employed where the modification of specimen geometry for testing is not necessary. However, mechanical properties could not be extracted directly from the RCT result, which is in the form of load-displacement curve. This work aims to predict the hoop mechanical properties from the RCT load displacement curves result rather than going through the tedious tensile testing via the application of a finite elemental (FE) model and the aid of iteration software which can help to provide an optimized deformed model for mechanical properties extraction.

2. Methods and Results

The specimen preparation, testing procedures, simulation, and prediction process are explained in this section. This prediction work is based on the experimental work done by the D. Woo and Y. Lee [1].

2.1 Sample Preparation

The specimen used in this work is nuclear reactor grade cold work stress-relief (CWSR) Zr-Nb alloy tube. Its geometry is 9.5 mm outer diameter, 0.57 mm thick, and 25 cm long. The chemical composition of the alloy is shown in Table 1.

Table 1: Chemical composition of the Zr-Nb alloy. [2]

Elements	Zr	Fe	Sn	O	Nb
Wt % (%)	Bal.	0.09-0.13	0.6-0.79	0.09-0.16	0.8-1.2

2.2 Hydrogen Charging and Reorientation

The charged hydrogen contents were in a range of around 0 to 1200 wppm. Charged cladding tubes were then treated for hydride reorientation (from circumferential orientation to radial orientation) via the pressurization method. The applied internal pressures fall in the range of 7.5 to 18.5 MPa to achieve hydride reorientation. The radial hydride fraction (RHF) which is the fraction of radial hydrides among the total hydrides in the specimen was calculated based on the definition proposed by Raynaud et al [3].

2.3 Ring Compression Test

The cladding tubes were cut into 7 mm sub-specimens and then were tested at room temperature (25°C) using the Instron 8516 tensile and compressive testing machine. The displacement rate is 0.033 mm/s.

2.4 Simulation and Prediction Process

An inverse model proposed by Reddy and Raid [4] was applied with modified optimization technique and iteration conditions were applied to predict the hoop mechanical properties. Firstly, two values, which are the initial yield stress, σ_y and elastic modulus, E can be obtained via the values extracted from the load-displacement curves as in Fig. 1.

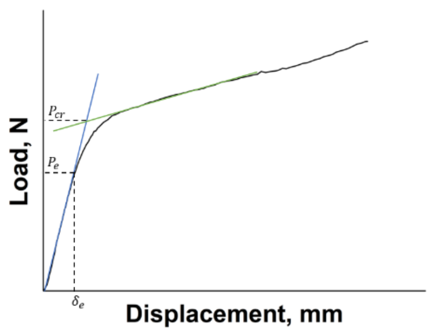

Fig. 1. Experimental load-displacement curve and the extracted parameters to obtain initial yield stress and elastic modulus.

Initial yield stress, σ_y can be obtained via equation (1) where p_{cr} is the collapse load, r_o is the initial outer radius of the specimen, t_0 is the thickness of specimen, and l is the specimen length [4, 5].

$$(1)\ \sigma_y = \frac{\alpha p_{cr} r_o}{t_0^2 l}$$

Elastic modulus, E can be obtained via the equation (2) where δ_e is the elastic range, p_e is the elastic load, and β

is the function of Poisson's Ratio which can be calculated via $\beta = (1 - v^2)/l$ [5].

$$(2)\ E = \frac{24\beta p_e r_o^3}{\delta_e t_0^3}\left(\frac{\pi}{8} - \frac{1}{\pi}\right)$$

Elastic modulus was input into the FE model to represent elasticity while the strain hardening region of the FE model is based on the strain hardening power law with the elastic limit strain, $\sigma = k(\varepsilon + \varepsilon_0)^n$ [6]. Three of the material constants, which are k, ε_0, and n are fitted with the experimental load displacement curve using an iteration software until the optimized one were determined. The optimized material constants were then input into the model to obtain an optimized deformed model.

2.5 Validation with Experimental Results

Predicted strain energy density (SED) calculated by the model was compared with the experimental SED which was based on the load-displacement curve. They exhibit well agreement as shown in Fig. 2. This proves the predicted result to be experimentally justifiable.

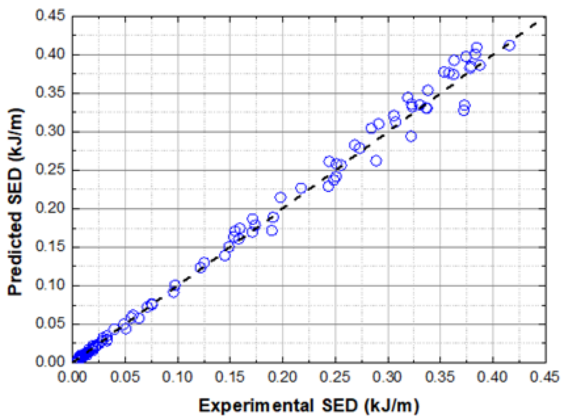

Fig. 2. Agreement between the predicted SED and the experimental SED.

2.6 Mechanical Properties Analysis Results

Mechanical properties like the fracture hoop strain and the fracture hoop stress were extracted from the optimized-deformed FE model. The mechanical properties were then plotted against to parameters such as the hydrogen content, maximum radial hydride length, and the radial hydride fraction (RHF).

Hydride content is a straightforward parameter as it represents the extent of hydride precipitation in the cladding. Maximum radial hydride length is the maximum length of the radial hydride (hydride in the radial direction) in a specimen. RHF is the fraction of radial hydrides over the total hydrides.

From Fig. 3, we can observe that the hydride content has very weak predictability on both mechanical properties in general except those with RHF<2% which exhibits certain extent of linear correlation. This can be caused by the insignificant influence from the radial hydrides as hydrided specimens that did not undergo hydride reorientation gave RHF around 2% due to the background noise [1].

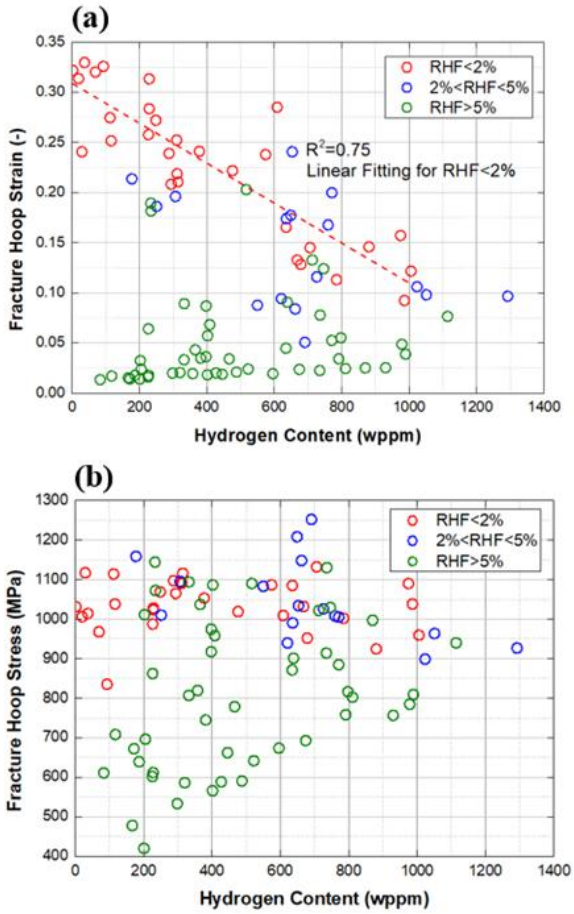

Fig. 3. (a) Fracture hoop strain versus hydride concentration, (b) Fracture hoop stress versus hydride concentration.

From Fig. 4, maximum radial hydride length has a much better predictability on the mechanical properties. The trend of the data points in Fig. 4. (a) can be described by the Equation (3) which can be treated as a prediction model for the radial hydride fracture based on the plate-shaped inclusion theory [7, 8]. The maximum radial hydride length is divided by the constant hydride thickness for the x axis to be suited into the model. Hydride is treated as plate inclusion in the zirconium alloy matrix. ε_{Zr}^f is the fracture strain, σ_T is the total stress of hydride fracture, σ_a is the applied stress, σ_{GB} is the stress due to grain boundaries interaction, E^{Zr} is the zirconium matrix elastic modulus, ε_N is the stress-free strain, v is the Poisson's ratio, a is the radial hydride length, c is the radial hydride thickness, and E_p is the plastic equivalent of zirconium matrix elastic modulus. This model provides a direct correlation between the hydride crack length with the fracture strain of the matrix based on the inclusion theory. The predicted results from the Equation (3) were plotted in Fig. 4. (a).

$$(3)\ \varepsilon_{Zr}^{f} = \frac{\sigma_T - \sigma_a - \sigma_{GB} + \dfrac{\pi E^{Zr} \varepsilon_N c}{4(1-\nu^2)a}}{\left(\dfrac{8a}{9\pi c} - \dfrac{2}{3}\right) E_p}$$

For Fig. 4. (b), a model based on the fracture mechanics and stress intensity factor from the literature [9] was developed as the Equation (4). The stress intensity factor is based on the specimen geometry that can closely describe the hydride cracking of the cladding specimen. The model was then fitted with the predicted results. The fitting result shows an R^2 up to 0.61. σ_a^f is the fracture hoop stress, $l_{Rad,Max}$ is the maximum radial hydride length, and both A and B are the fitting constants.

$$(4)\ \sigma_a^f = \frac{A l_{Rad,Max} + B}{l_{Rad,Max}^{\frac{1}{2}}}$$

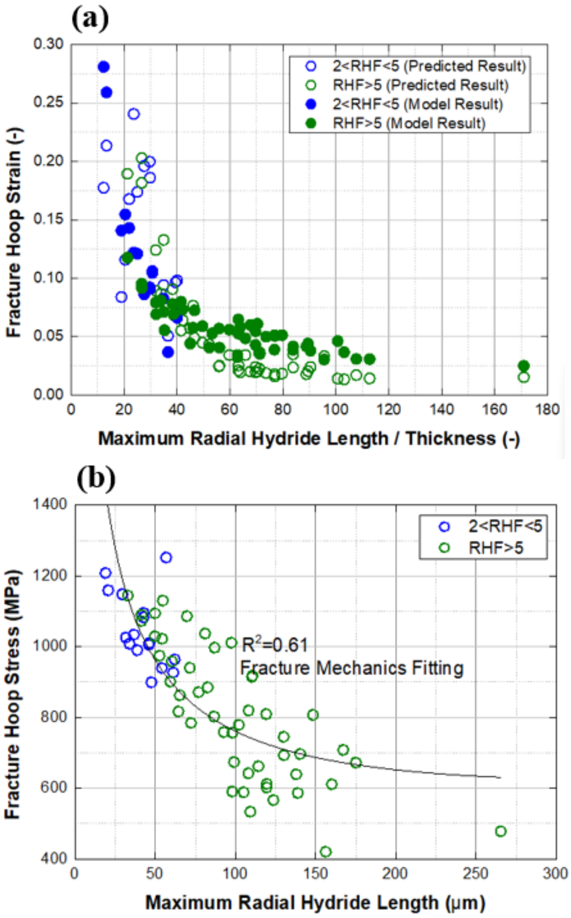

Fig. 4. (a) Fracture hoop strain versus maximum radial hydride length/hydride thickness, (b) Fracture hoop stress versus maximum radial hydride length. Only data points with RHF larger than 2% are included.

For Fig. 5. (a), RHF shows a good predictability for the fracture hoop strain with a decreasing exponential correlation. Although the decreasing trend seems similar with that of Fig. 4. (a), there is no physical correlation between the maximum radial hydride length and the RHF as a certain fraction of radial hydride cannot ensure the presence of certain length of radial hydride. For Fig. 5. (b), the trend of the correlation between the fracture hoop stress and RHF is weaker.

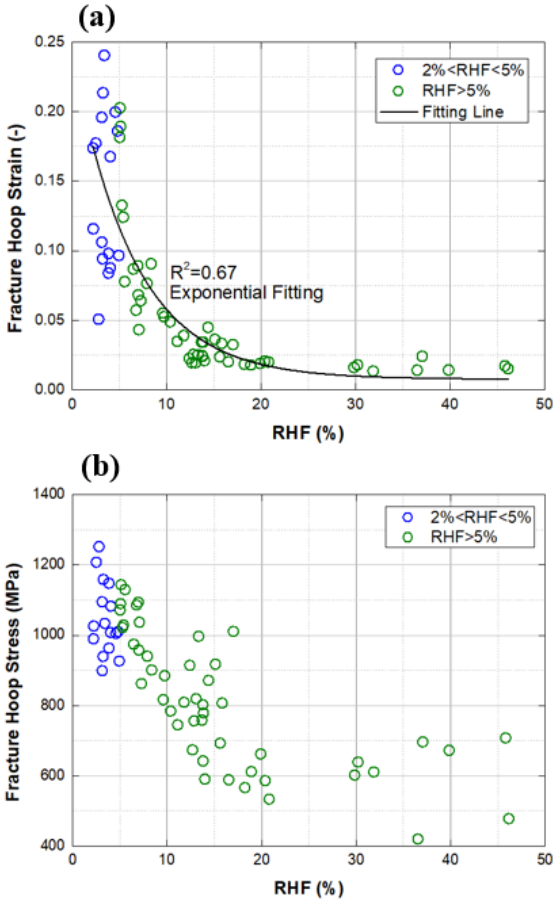

Fig. 5. (a) Fracture hoop strain versus RHF, (b) Fracture hoop stress versus RHF.

4. Conclusions

This work provides an approach to obtain hoop mechanical properties from the optimized deformed model without going through the tensile testing that requires difficult sample preparation. In general, mechanical properties decrease when maximum radial hydride length and RHF increase respectively while visibly decreasing trend can only be observed when RHF<2% for the hydrogen content. The correlations and models applied and developed here can be useful for predicting the cladding mechanical behavior under spent fuel storage conditions.

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