STUDY ON ESTABLISHING THE CRACKING CRITERION DUE TO MECHANICAL OVERLOAD OF THE ZR-2.5%NB PRESSURE TUBE SPECIMENS WITH VOLUMETRIC FLAWS

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Abstract

This paper summarizes the overload test results, performed at typically temperature on C-shape specimens with V-notch tip hydrides, prepared from un-irradiated CANDU pressure tube. The general test procedure included two steps: hydride formation and overload tests. Hydride formation involved a preconditioning treatment to realize the reorientation of the hydrides at notch-tip, consisting of thermal cycling of the specimens under a constant load. Overload tests involved determining the fracture stress on the specimens with notch-tip hydrides under monotonically increasing load conditions at typically temperatures in the field of CANDU reactor operation. An analytical relationship that correlates the applied effective stress intensity factor for the notched C-shape specimen during hydride formation, K_f, and those from overload testing, K', is obtained as function of two parameters, namely the notch depth and the hydrogen concentration. The results can be used for the structural integrity analyses of pressure tubes in CANDU fuel channels subjected to periodic inspections.

Keywords: *Overload test, CANDU pressure tube, Zr-2.5%Nb*

Introduction

During CANDU reactor operation, hydrides at a blunt flaw can form under a constant load, where the hydrogen diffusion and precipitation conditions are met. Under certain operation scenarios, the hydrided region can be subjected to a load level higher than the load at which hydrides are formed. This is known in the scientific literature as ″hydrided region overload″ phenomenon.

There are two types of overload scenarios in the operating CANDU pressure tubes. One is associated with the depressurization (to about 80% full pressure) before reactor cooling; the other situation of overload is when the transient load of up to about 15% above the normal operating pressure.

This paper summarizes the overload test procedure and the results carried out on the C-shape specimens with V-notch tip hydrides, prepared from un-irradiated CANDU pressure tube.

The tested samples have a hydrogen concentration in the area of interest for a normal operation of the reactor. The general test procedure included two steps: hydride formation and overload tests. Hydride formation involved a preconditioning treatment to realize the reorientation of the hydrides at notch-tip, and consisting of the thermal cycling of the specimens under a constant load. Overload tests involved determining the fracture stress on the notch-tip hydrides under monotonically increasing load conditions at typically temperatures in the field of operation of the CANDU reactor.

An analytical relationship that correlates the applied effective stress intensity factor for the notched C-shape specimens during hydride formation, K_f, and those from overload testing, K', is obtained as function of two parameters: notch depth and hydrogen concentration [1-6].

The results can be used for the structural integrity analyses of pressure tubes in the CANDU fuel channels subject to periodic inspections in order to make a lifetime prediction.

Mechanical overload test matrix

The expression of the applied effective stress intensity factor K_{Eff} for the notched C-shape specimen (Fig.1) from which we obtain the specific values (K_f -during hydride formation and the K' overload testing) is given below according to [1, 2]:

$$K_{Eff}=\frac{P}{B\sqrt{W}}\left[3\frac{x}{W}+1.9+1.1\frac{a}{W}\right]\cdot\left[1+0.25\left(1-\frac{a}{W}\right)^2\left(1-\frac{r_1}{r_2}\right)\right]\times$$
$$\times\frac{\sqrt{\frac{a}{W}}}{\left(\frac{a}{W}\right)^{3/2}}\left[3.74-6.30\frac{a}{W}+6.32\left(\frac{a}{W}\right)^2-2.43\left(\frac{a}{W}\right)^3\right] \quad (1)$$

where: P = applied load during hydride formation (P_f) or overload test (P'); a = notch depth; r_1 = pressure tube inner radius; r_2 = pressure tube outer radius (= r_1 +W); B = specimen width (pressure tube width); W = specimen thickness; x = loading line distance for C-shape specimen.

A factor that is often used to quantify the overload fracture resistance, particularly for very small root radius V-notches, is Φ_{Kov} which is defined as:

$$\Phi_{kov} = \frac{K'}{K_f} \quad (2)$$

K_f and K' are obtained from Eq.(1).

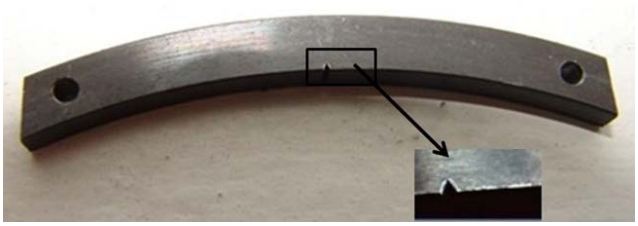


Fig.1. Experimental C-shape specimen with a V-notch

Experimental program

The overload test is performed on the C-shape specimens with V-notch tip hydrides, prepared from un-irradiated CANDU pressure tube in the radial – axial plan. The general test procedure included two steps: *specimen's preparation* (hydride formation) and *overload test*.

Hydride formation involved thermal cycling of the specimens under a constant load (P_f) to obtain the accumulation and reorientation of the hydrides at notch-tip. Overload tests involved determining the fracture load (P') on the notch-tip hydrides under monotonically increasing load conditions at typically temperatures.

The overload factor (given by Eq.(3)) that correlates the applied effective stress intensity factor for every notched C-shape specimen during hydride formation, K_f, and those from overload testing, K', is obtained. An analytical relationship was obtained by experimental values interpolation with a polynomial form [4-6].

Specimens preparation

The samples preparation includes the following items:

a) *The blank specimens*: were prepared from as received pressure tube section;
b) *Specimens hydriding*: the electrolytic technique was used to deposit a hydride layer on the specimen surfaces;
c) *The hydrogen concentration* of the hydrided samples was determined using the hot inert gas extraction technique;
d) *The V-notch geometry*: was machined on the inside diameter (ID) surface of the blank specimen in radial - axial plan;
e) *Hydrides formation*: The specimens were subjected in a loading frame, to a specified load P_f and ratcheting cycle with a peak temperature of typically 250^{o}C, to form the notch-tip hydrides;
f) *Metallographic examination* before overload tests. The notch-tip hydrides were examined in an optical microscope. Thus, the hydrides morphology, the notch depth and root radius have been determined (Fig.2).

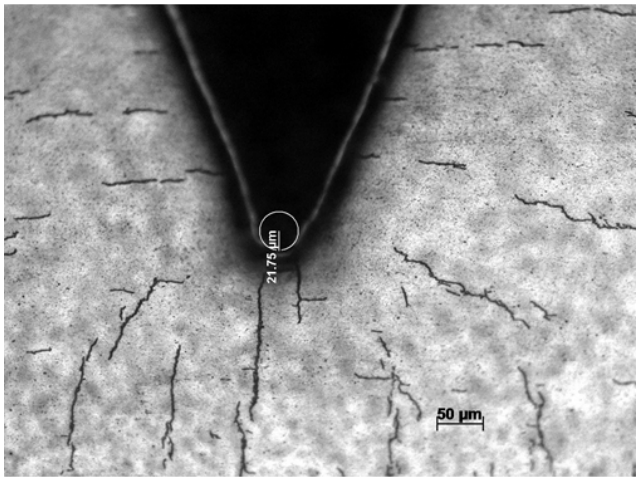


Fig.2. Metallographic examination of notch-tip hydrides

After the process area is formed, the samples were subjected to mechanical overload tests.

Overload test details

The overload tests were performed by means of Walter+Bai Materials Testing System, at 3 temperatures of interest: room temperature (20 ^{0}C), 200 ^{0}C and 300 ^{0}C, respectively. For high temperatures testing, a thermal chamber was used.

The tested specimens have the hydrogen concentrations in the specific range up to 100 ppm. The V-notch nominal depth has the values of 0.5, 0.7 and 1 mm. Every specimen was subjected to incremental loading with a loading rate of 0.8MPa/s, until the cracking has been detected. The crack initiation process was monitored by both visual examination (Fig.3) and sharp drop of load techniques (Fig.4). The value of load applied (P') is retained and it is used for overload factor (Φ_{kov}) computation.

For each testing temperature, a number of 18 specimens were tested.

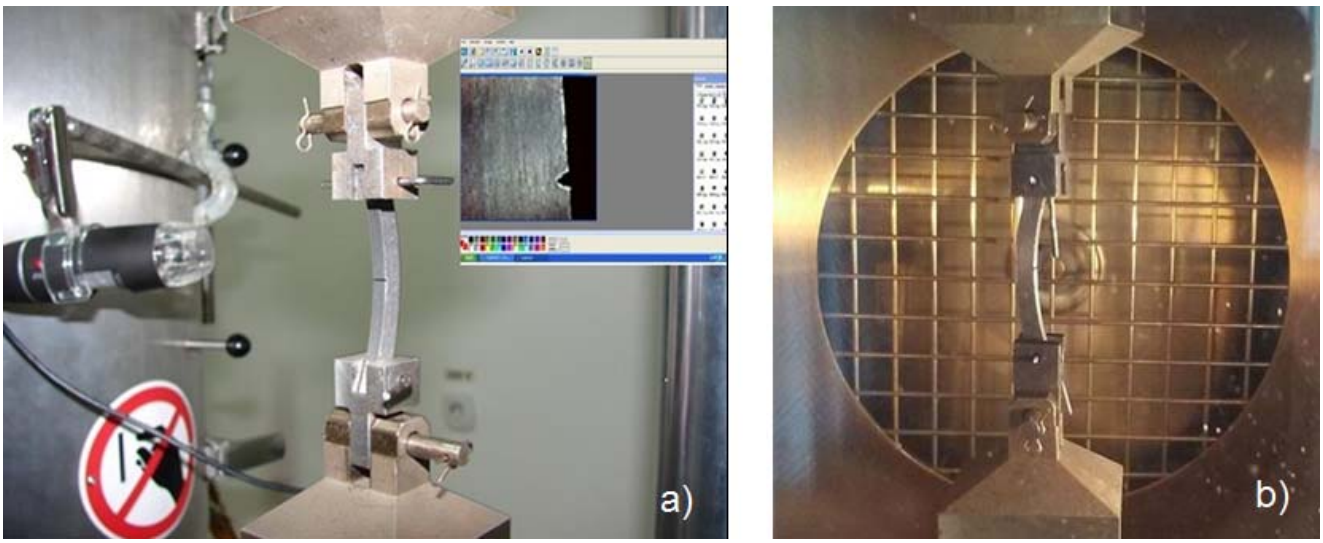


Fig.3. Experimental arrangement for the overload test: a) in air at room temperature, b) in thermal chamber

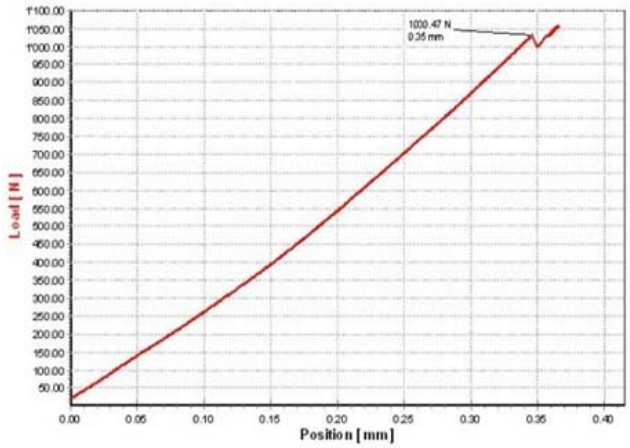


Fig.4. Load-displacement from the overload test

Metallographic examinations

After overload tests, the specimens were metallographic examined. To obtain the hydrides morphology at the crack-tip, the tested specimens were examined in the optical microscope. The typical aspect is revealed in the figure below.

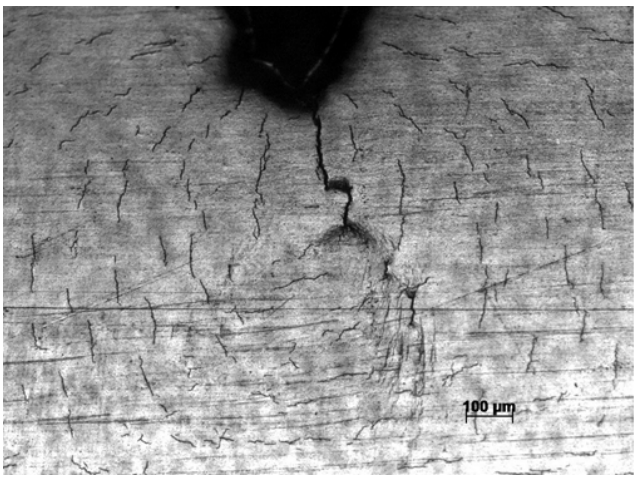


Fig.5. Optical micrograph of crack-tip hydrides, close to flaw root (C_H=34 ppm)

Results

At each testing temperature the experimental values of the overload fracture resistance parameter (Φ_{kov}) were processed and graphic represented as function of the V-notch depth and hydrogen concentration. The dependence of the overload parameter (Φ_{kov}) on the main parameters is given by the polynomial expression:

$$\Phi_{kov} = p_{00} + p_{10} \cdot a + p_{01} \cdot C_H - p_{11} \cdot a \cdot C_H - p_{02} \cdot C_H^2 \quad (3)$$

where: Φ_{kov} = overload fracture resistance parameters; a = notch depth; C_H = hydrogen concentration from material.

The coefficients from Eq. (3) were obtained with a high level of confidence, and from brevity reasons they are not shown here. To see more confident, the dependence of Φ_{kov} on the notch depth and hydrogen concentration, the three-dimensional representation has been preferred at the room temperature and 200 °C and 300 °C [4-6].

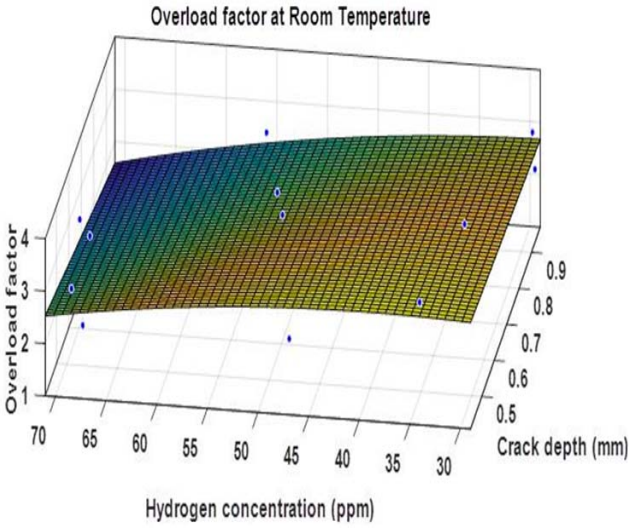


Fig.6. Dependence of the overload fracture resistance factor (Φ_{kov}) at room temperature

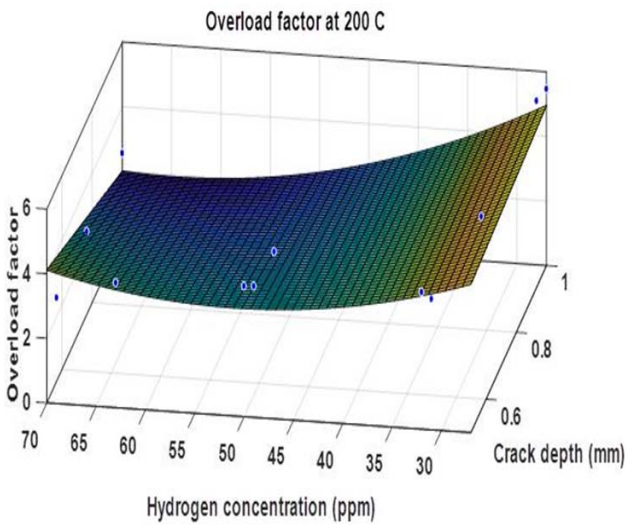


Fig.7. Dependence of the overload fracture resistance factor (Φ_{kov}) at 200^{o}C

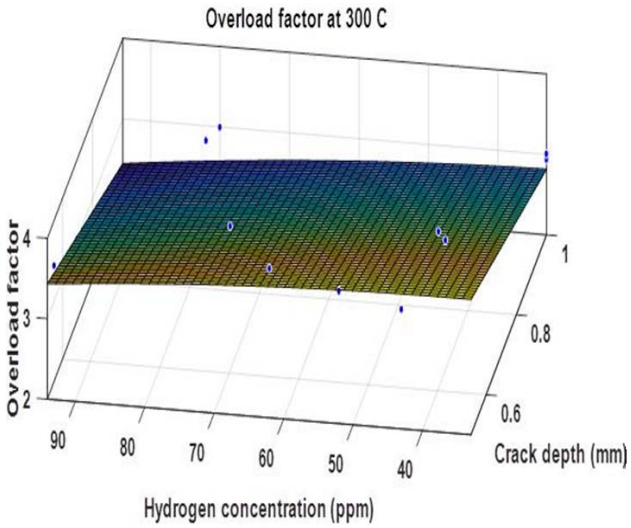


Fig.8. Dependence of the overload fracture resistance factor (Φ_{kov}) at 300^{o}C

Conclusions

The present study on the establishing the cracking criterion due to the mechanical overload of the Zr-2.5%Nb pressure tube specimens with volumetric flaws, emphasizes the main results focused on the overload parameter Φ_{kov}.

The maximum values of the overload factor (when $K' > K_f$), that is meet for simultaneous minimum values of the notch depth and the hydrogen concentration (light shades of colors in Figs. 6, 7, and 8, respectively) means that cracking has a lower probability to be initiated.

The minimum values of the overload factor (when $K' < K_f$) this is meet for simultaneous maxima of the notch depth and the hydrogen concentration (dark shades of colors in Figs. 6, 7, and 8, respectively) means that the cracking starts easier.

By modeling the overload factor with the polynomial form as function of the notch depth and hydrogen concentration, a suitable criterion for the structural integrity assessments of the CANDU pressure tubes is obtained.

References

[1] Cui, J., Shek, G.K. (2005) ″Overload Fracture of Hidrured Region at Simulated Blunt Flaws in Zr-2.5%Nb Pressure Tube Material″, PVP2005-71273, Proceed. of PVP2005, ASME Pressure Vessels and Piping Division Conf., Denver, Colorado, USA

[2] Canadian Standard Association (2010) ″Technical Requirements for in-service evaluation of Zirconium alloy pressure tubes in CANDU reactors″, CAN CSA N285.8-05, Canada.

[3] Radu, V. (2015) ″Information Report on COG Operational Plan Projects in the Domain of Fuel Channel regarding the cracking initiation due to mechanical overload″, Institute for Nuclear Research (RATEN ICN) Pitesti, internal report, no. 10491 (in Romanian).

[4] Ionescu, V., Nitu, Al., Ion, Al., Olaru,V. (2016) ″Study on the mechanical overload behaviour of the hydrated areas at the top of the defects on the CANDU pressure tube″, Institute for Nuclear Research (RATEN ICN) Pitesti, internal report, no. 11037 (in Romanian).

[5] Ionescu, V., Nitu, Al., Ion, Al., Olaru,V. (2017) ″Experiments regarding the initiation of cracking in CANDU pressure tube samples at the mechanical overload of hydrated areas″, Institute for Nuclear Research (RATEN ICN) Pitesti, internal report, no. 11515 (in Romanian).

[6] Ionescu, V., Nitu, Al., Ion, Al., Olaru,V. (2018) ″Study of the initiation of mechanical overload cracking in Zr-2.5% Nb samples at a temperature of 300 ^{o}C″, Institute for Nuclear Research (RATEN ICN) Pitesti, internal report, no. 11787 (in Romanian).