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Anisotropic delayed hydride cracking velocity of CANDU Zr–2.5Nb pressure tubes

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Abstract

Delayed hydride cracking (DHC) tests were conducted on CANDU[1] Zr–2.5Nb tubes containing hydrogen with a microstructure of elongated α-Zr and semi-continuous β-Zr at temperatures ranging from 100 to 300 °C. DHC velocity (DHCV) was found to be around two times higher in the axial direction than that in the radial direction even on the same cracking plane. According to Kim's DHC model that DHCV at temperatures lower than 300 °C is governed mainly by hydrogen diffusion and to a lesser extent by the hydrogen concentration gradient at the crack tip, we suggest that the enhanced DHCV in the axial direction arises from a faster hydrogen diffusion in the axial direction with a semi-continuous distribution of β-Zr. Evidence to this suggestion is provided by Levi's experiment that Zr–2.5Nb tubes or plates with a fully discontinuous β-Zr due to annealing at 400 °C for 1000 h or 650 °C for 9 h has no anisotropic DHCV with the orientation. Hence, we conclude that Kim's DHC model is plausible. An anisotropic DHCV of irradiated CANDU Zr–2.5Nb tubes is discussed based on their microstructural evolution with the neutron fluence and operating temperatures.

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1. Introduction

Since many failures of Zr–2.5Nb pressure tubes by delayed hydride cracking (DHC) were reported in Pickering 3 and 4 nuclear power plants in 1974 [1], one of the items to be examined during regular overhauls of operating CANadian Deuterium Uranium (CANDU) reactors is if the surface flaws will grow by delayed hydride cracking (DHC) to through-wall cracks. Further, the size of the flaws should be evaluated by accounting for anisotropic DHC velocity (DHCV) till the evaluation period in order to assure the mechanical integrity of the pressure tubes. It should be noted that DHCV is faster in the axial direction of the CANDU Zr–2.5Nb pressure tubes than that in the radial direction. According to Sagat's result [2], especially, irradiated CANDU pressure tubes showed a strong temperature dependency of the anisotropic DHCV which surprisingly disappeared at as high a temperature as 300 °C.

According to previous DHC models that a driving force for DHC is a stress gradient [3,4], an anisotropic DHCV and its temperature dependency in CANDU pressure tubes cannot be satisfactorily understood. By demonstrating a larger extent of the textural change and higher strain hardening after yielding in the axial direction of a CANDU Zr–2.5Nb pressure tube when compared to that in the radial direction, Kim suggested that a steeper stress gradient ahead of the crack tip in the axial direction is the cause of an anisotropic DHCV with orientation [5]. However, his hypothesis has some defects because it was suggested based on the previous DHC models. Recently, Kim has proposed a new DHC model that the driving force for DHC is not a stress gradient but a hydrogen concentration gradient induced by a stress-induced precipitation of hydrides at the crack tip and DHCV is governed by the product of a hydrogen diffusion and a hydrogen concentration gradient

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[6–8]. Furthermore, by comparing DHCV of Zr–2.5Nb tubes with different distributions of the β-Zr phase and yield strengths, Kim demonstrated that hydrogen diffusion mainly governs DHCV at below 300 °C [9]. Thus, Kim's new DHC model implicitly suggests that the anisotropic DHCV in CANDU pressure tubes may be attributed to an anisotropic hydrogen diffusion in the corresponding temperature range.

The aim of this study is to elucidate the cause of an anisotropic DHCV in CANDU pressure tubes by correlating it with hydrogen diffusion with orientation and thereby to demonstrate the plausibility of Kim's DHC model [6–8]. To this end, we determined axial and radial DHCV's using compact tension and cantilever beam specimens containing hydrogen which were taken from a CANDU pressure tube with an anisotropic distribution of the β-Zr. As decisive evidence for the role of an anisotropic hydrogen diffusion in the anisotropic DHCV, we cited Levi and Sagat's experiment [10] where DHC tests were conducted on annealed Zr–2.5Nb tubes and plates with a fully discontinuous β-Zr.

2. Experimental procedures

2.1. Materials

Compact tension (CT) specimens of 17 mm long and cantilever beam (CB) specimens of 38 mm long, as shown in Fig. 1, were taken from a CANDU Zr–2.5Nb tube with elongated α-Zr grains in the axial direction. According to the microstructural analyses by TEM and SEM, the CANDU Zr–2.5Nb tube had the non-uniform distribution of the β-Zr phase lying semi-continuously between the elongated α-Zr grains in the axial direction of the tube

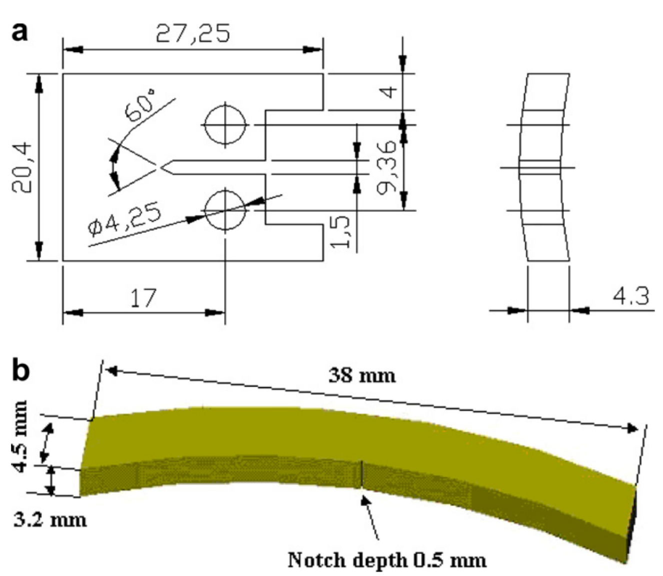

Fig. 1. Schematic drawings of (a) 17 mm compact tension specimens and (b) 38 mm cantilever beam specimens used for the delayed hydride cracking tests in the axial and radial directions of a CANDU Zr–2.5Nb tube.

(Fig. 2(a), which appears white on the SEM, as shown in Fig. 2(b). The compact tension and cantilever beam specimens were used for determining the DHC velocities and the threshold stress intensity factors, K_{IH}'s for the onset of delayed hydride cracking, respectively, in the axial and radial directions of the CANDU Zr–2.5Nb tube. Both the specimens were not given any prior heat treatments to affect the distribution of the β-Zr phase. All the specimens were subjected to electrolytic charging to form a thick hydride layer on their surface followed by homogenization treatment at different temperatures to dissolve hydrogen concentration ranging from 27 to 100 ppm H. At the end of homogenization treatment, they were water-quenched or furnace-cooled to change the size and phase of the hydride precipitates. The details of the hydrogen charging procedures have been reported elsewhere [11]. The real hydrogen content of the specimen was obtained by averaging a set of 5–7 data measured with a LECO RH 404 analyzer. A pre-fatigue crack of 1.7 mm was introduced using an Instron 8501 for the CT specimens to set the ratio of the pre-fatigue crack length and the specimen length or a_o/W equal to 0.5, but not for the CB specimens. The CB specimens had just a sharp notch of 0.5 mm depth in the radial direction with the crack tip radius of 0.05 mm since the DHC velocity was found to be unaffected by a notch tip size smaller than 0.15 mm [12].

2.2. DHC tests

DHC tests were conducted using a creep machine to apply a constant load to the 17 mm CT specimens or using a cantilever beam tester to apply constant stress intensity factors to the CB specimens with a 0.5 mm deep notch and the notch root radius of 0.05 mm, as shown in Fig. 1. The initiation and growth of a crack was monitored by a direct current potential drop method for the CT specimens and by an acoustic emission method for the CB specimens. The stress intensity factor ranging from 6.13 to 18.4 MPa$\sqrt{m}$ was applied during the DHC tests on the CB specimens through an auto-control program where the applied load was reduced in proportion to the crack length obtained from the cumulative AE counts using a step-motor [13,14]. Most of the specimens were subjected to a thermal cycle during the DHC tests where the test temperatures were approached from an upward direction by a cooling as shown in Fig. 3. The specimens were heated up to a peak temperature by 0.5–1 °C/min., held there for 1–20 h and cooled down to the test temperature followed by applying a load 30 min after reaching the test temperature. The peak temperature was set at 10 °C higher than the TSSD temperature to completely dissolve all the charged hydrogen. The water-quenched specimens after a homogenization treatment of hydrogen were not subjected to a thermal cycle but they approached the test temperature directly by a heating. The threshold stress intensity factor, K_{IH} was determined by the load-decreasing mode [2] where the applied load decreased from 20 MPa$\sqrt{m}$ step-wise by