The Effect of Testing Direction on DHC Growth Rate Using a Zr-2.5Nb Plate

Authors: Sean Hanlon, Carleton University, Scott Read, Carleton University, Alain Douchant, Atomic Energy of Canada Limited (AECL), Mona Primeau, AECL, Ken Kidd, AECL, Patrick Wilson, AECL, Glenn McRae, Carleton University, Christopher Coleman, AECL

During the corrosion of zirconium alloys hydrogen is released, some fraction of which is absorbed by the component. When the Terminal Solid Solubility of Precipitation (TSSP) for hydrogen in zirconium is exceeded, brittle disk-shaped hydrides are formed that can crack under certain conditions. This cracking can be time-dependent due to the movement of hydrogen in solution in the gradient of chemical potential, which can be written in terms of gradients of concentration, temperature, alloying elements and stress. Delayed Hydride Cracking (DHC) is the time-dependant mechanism of fracture responsible for several failures of zirconium alloy components in nuclear reactors. This mechanism requires a component to contain a stress-raiser, such as a crack or notch, and a source of tensile stress. DHC has limits associated with hydrogen concentration, stress intensity factor and temperature history. Staying within these limits and utilizing conservative safety margins allow for safe operation of zirconium components [1]. There are three basic steps involved in DHC. These are (1) the diffusion of sufficient hydrogen to nucleate a hydride at the stress raiser followed by (2) growth of the hydride until (3) fracture occurs. These steps then repeat as the crack grows [2].

In early CANDU reactors, high hoop stresses or very high hydrogen concentrations resulted in cracks in some pressure tubes. The normal to the crack plane was parallel to the hoop stress. Cracking occurs in the longitudinal and through-thickness directions in pressure tube material. The longitudinal direction is parallel to the extrusion and drawing directions. The crack could travel from the inside surface to the outside or vice versa in the through-thickness direction and lead to leakage of water from the heat-transport system. There have been several studies to determine the DHC velocities in pressure tubes for reactor conditions. Based on the data provided to the Canadian Standards Association (CSA), the current CSA standard acknowledges that longitudinal cracks generally have higher velocities than through-thickness cracks [3]. The longitudinal velocities are used to defend leak-before-break in the reactors; this approach ensures the reactor remains safe if a through-thickness crack develops. The reason for the difference in crack velocities is not well understood. This study investigates the reason for the difference.

The material used in this study was Zirconium-2.5% Niobium plate. The plate was thoroughly tested to ensure it had similar strength, texture and microstructure to that of pressure tube material. The longitudinal, transverse and through-thickness directions in the plate are equivalent to the axial, circumferential and radial directions in a tube, respectively. The geometry of the test specimens is shown in Figure 1. The strength in the transverse direction is provided in Table 1. Hydrogen was added to the plate to provide a concentration of approximately 64 parts per million by weight (ppm). Cantilever beam samples were machined from the plate and notches, with a root radius of 50 micrometers, were cut into the sample using electrical discharge machining (EDM). Half of these notches were parallel to the longitudinal direction while the other half were parallel to the through-thickness direction. During testing the samples were brought to a maximum temperature of 360 °C for an hour to dissolve all the hydrogen and then cooled to their respective test temperatures at a rate of approximately 1 °C per minute. Samples were then held at the test temperature for an hour before the load was applied. The applied load was held constant during each test and created an initial stress intensity factor of 17 MPa$\sqrt{m}$ in each sample. Tests were concluded when the acoustic emissions, or the displacement of the cantilever arm reached pre-determined values. On cooling, the specimens were broken open and the fracture surfaces were examined. Figure 2 shows examples of these fracture surfaces for both through-thickness and longitudinal cracks at 250 °C. The crack growth was estimated by measuring the area of cracking and dividing by the specimen thickness. The rate of crack growth was calculated from the amount of crack growth divided by the cracking time. A graph of crack velocity versus test temperature was produced to observe whether the expected behaviour would be produced and to determine a range for the maximum value. Current data are shown in Figure 3.

A factor controlling the difference between the longitudinal and through-thickness velocities is the orientation of the bulk hydrides. For the material used in this study, the normal vectors to the disk-like bulk-hydrides are parallel to the through-thickness direction, which means that cracks propagating in the through-thickness directions will interact with the plane of the hydride while the longitudinal cracks will only interact with the edge of the hydride. Analyses of crack faces show that radial DHC cracks travel around the transverse rupture of bulk hydrides rather than passing through them, suggesting these cracked hydrides act as obstructions that reduce the overall through-thickness crack velocity. This process only applies at temperatures where many large hydrides are present. This hypothesis suggests that the crack growth rates in each direction will be the same for a given temperature above the solubility limit but will begin to diverge at temperatures just below this limit. This method can be used to determine TSSP directly from DHC experiments. Preliminary results shown in Figure 3 are consistent with the given hypothesis. At temperatures below 270 °C the longitudinal crack growth rates are consistently higher than the through-thickness crack growth rates, while above 270 °C the velocities at specific temperatures in either direction are indistinguishable. The temperature for the solubility limit based on an examination for the fractured large hydrides in the fracture surfaces is in the range of 260 to 280 °C while Differential Scanning Calorimetry (DSC) shows a solubility limit range of 250 to 265 °C, depending on the criterion used to evaluate it. Figure 3 indicates that the maximum crack growth rate is between 275 and 285 °C.

Experiments on Zr-2.5Nb plate material have shown that this material is a suitable surrogate for pressure tube material. At temperatures below the solubility limit for precipitation of hydrides (TSSP), in the plane normal to the transverse direction, delayed hydride cracking is faster parallel to the plate rolling direction than in the through-thickness direction. When tested above TSSP little difference in the effect of testing direction can be discerned. Above a critical temperature, all cracking ceases. The testing is to be extended to hydrogen concentrations other than 60 ppm to confirm or refute the principle being explored in this work.

Acknowledgement

S.H and S.R would like to thank AECL for access to experimental facilities and both AECL and NSERC for financial support.

	Sample 1	Sample 2
Temp	20 °C	250 °C
UTS (MPa)	844	577
0.2% Yield (MPa)	732	501
Elongation	14.40%	11.40%

Table 1 - Tensile Test Results

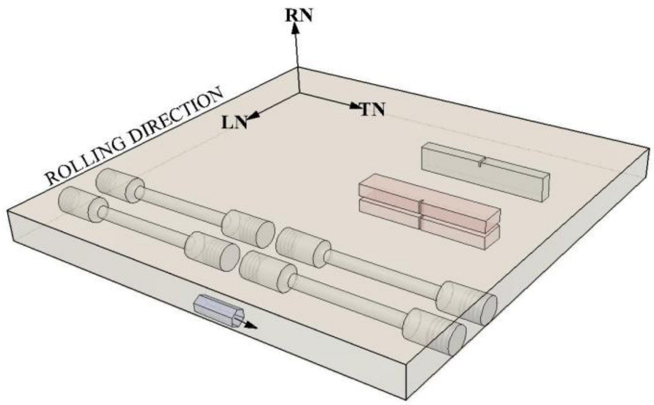

Figure 1 - Plate and Sample Geometry

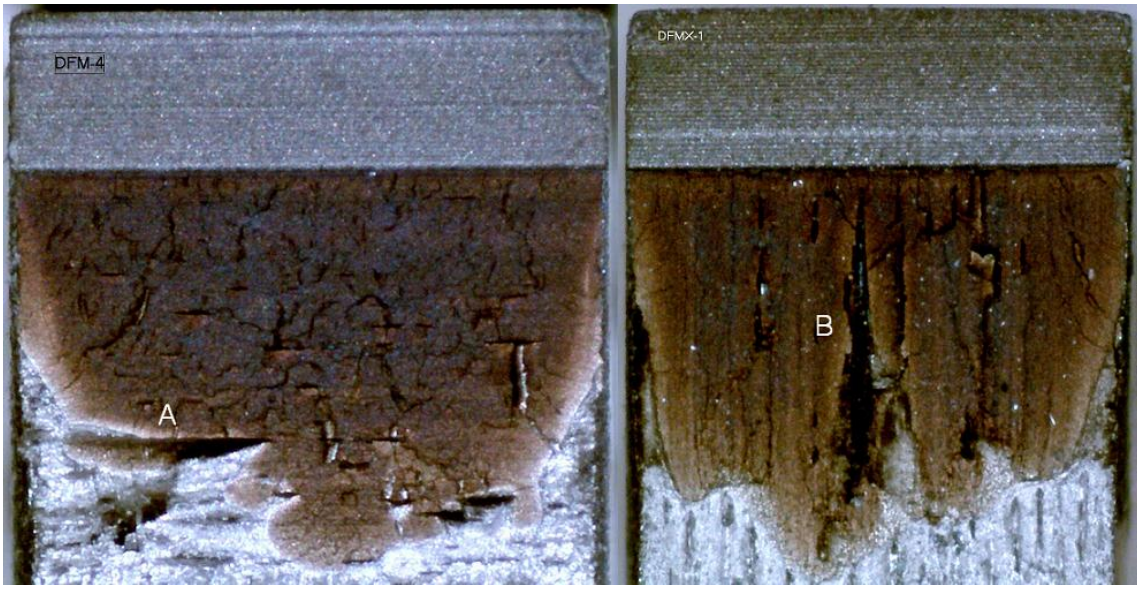

Figure 2 - Fractured Surfaces: Through-thickness (left) and Longitudinal (right). Fractured bulk hydrides shown at A and B. Samples tested at 250 °C.

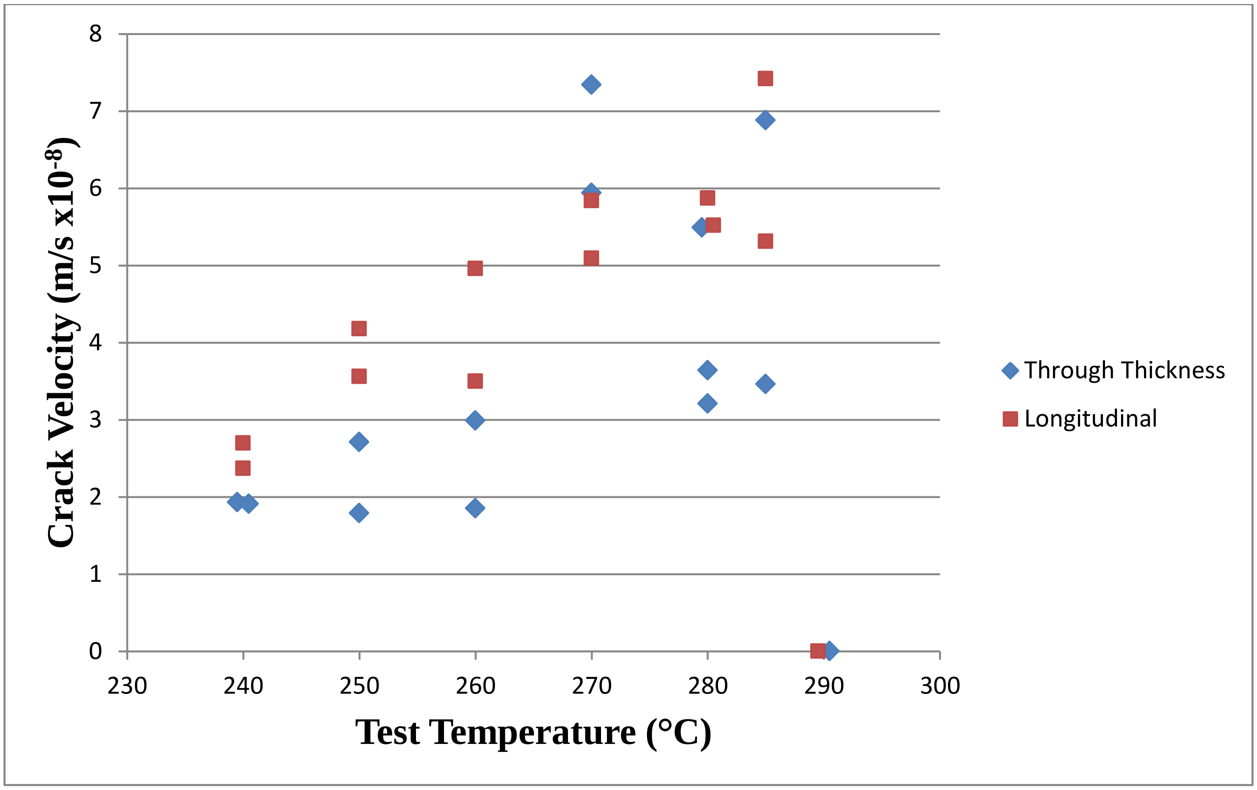

Figure 3 – Longitudinal and Through-Thickness Crack Velocities as a function of temperature. Data with superimposed symbols were moved +/- 0.5 °C for clarity.

References:

[1] Coleman, C.E., McRae, G.A., Leitch, B.W., "Evaluating the risk of delayed hydride cracking in components made from zirconium alloys", Eighth ATI Corrosion Solutions Conference, Lake Louise AB (2011).

[2] McRae, G.A., Coleman, C.E., Leitch, B.W., "The first step for delayed hydride cracking in zirconium alloys", J. Nucl. Mater., 396, (2010),130-143.

[3] Canadian Standards Association, Technical requirements for in-service evaluation of zirconium alloy pressure tubes in CANDU reactors, N285.8-05, (2005).