

Article

Evaluation of the Zirconium Hydride Morphology at the Flaws in the CANDU Pressure Tube Using a Novel Metric

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Abstract: The Zr-2.5%Nb alloy used to manufacture the pressure tubes for the CANDU 600 power plant experiences continual corrosion when the reactor's fuel channels are functioning normally. Analysis of the hydrogen accumulation circumstances, the creation of zirconium hydride platelets, evaluation of the platelets' reorientation in the thermo-mechanical field at volumetric flaws, and determination of the hydrogen morphology are therefore significant goals of the worldwide research being conducted in this field. In this paper, pressure tube alloy samples with artificial V flaws were hydrided by the technique of electrolytic deposition of a hydrogen film layer, followed by a specific thermal treatment. Micrographs of the Zr-2.5%Nb alloy samples in the radial cross-section were taken to examine the hydride reorientation phenomenon that occurred when the samples were heated under mechanical stress. The complex stress field around a tip flaw promoted the formation of some circles from hydride filaments. To characterize the zirconium hydride morphology in the reorientation zone at the volumetric flaw tip, image analysis and processing techniques were applied. To better characterize the reorientation zone from the point of view of embrittlement and mechanical behavior, this paper proposes a novel metric for the morphology of hydrides located in the reorientation zone. This work's findings are beneficial for the investigation of CANDU fuel channels' structural integrity.

Keywords: CANDU pressure tube; hydride cracking; reorientation hydrides; novel metric



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1. Introduction

In the CANDU nuclear power plant, pressure tubes are made from Zr-2.5%Nb alloy with the following dimensions: a length of 6.4 m, an inner diameter of 0.104 m, and a wall thickness of approximately 4.2 mm. In normal conditions, the internal coolant has 10 MPa of pressure, and the temperature ranges between 260 °C at the D₂O agent's entrance and 310 °C at the coolant's outlet at the opposite end of the pressure tube. The hard impurities trapped between the fuel bundle-bearing pad and the pressure tube, forming marks (volumetric flaws) on the inner surface of the pressure tube, are constantly connected to the fuel bundles even when the pressure tube is moving, which happens during the refueling process [1]. Based on operating experience with pressure tubes, it was found that some

inspected tubes had faults that exceeded the permitted limits; of these, many were caused by hard contaminants that came into contact with the fuel-bearing pad or pressure tube.

In the Zr-2.5%Nb alloy CANDU pressure tube, zirconium hydride platelets form when the equivalent hydrogen concentration is above the solid solubility limit. These are delta hydrides ($\text{ZrH}_{1.6}$), which arise from mechanical and thermal stress conditions during regular CANDU fuel channel operation [2,3]. It is important to remember that the hydride front that forms in the material when coolant enters the pressure tube will travel toward the mandrel area's high-stress locations due to the mechanical stress gradient [4]. The changes caused by hydrogen precipitation in zirconium alloys have been previously modeled using finite elements in the specialized literature. Numerous profile articles, particularly those concerning zirconium alloys, which are crucial for nuclear energy, have examined the impact of mechanical stress on hydrogen solubility [5,6].

The zirconium matrix experiences a certain degree of brittleness as a result of the brittleness of the hydride platelets. As a result, part of the material's initial ductility and fracture resistance is lost. The degree of material fragility in the case of hydride platelet formation should be noted in light of the possibility of the platelets' reorientation under specific thermo-mechanical conditions (thermal cycling under continuous mechanical stress) [7–9]. When zirconium hydride platelets reach critical conditions, which are related to their size and the stress intensity factor K_I , they fracture, and the cracks extend through the adjacent brittle hydride filaments in the pressure tube wall until they are stopped in the ductile matrix of the Zr-2.5%Nb alloy [6,10,11].

These features of the morphology of zirconium hydride platelets and their impact on crack initiation and propagation have been described by several microstructural parameters in the pertinent scientific literature [12]. Several measures, often referred to as metrics, have been defined in the scientific literature to quantify and characterize the morphology of zirconium hydrides in the material volume and to describe their impact on crack initiation and propagation, such as the total hydrogen content, zirconium hydride volume fraction [13], radial hydride fraction (RHF) [14], hydride continuity coefficient (HCC) [15], radial hydride continuity factor (RHCF) [16], and radial hydride continuous path (RHCP) [12]. It should be noted that all of the metrics defined above address uniform reorientation according to zircaloy-4 sheath thickness or pressure tube thickness. These metrics are less applicable for hydride reorientation zones located at the tips of volumetric flaws on a pressure tube, where the reorientation zone has a specific shape. These hydride reorientation zones located at the volumetric flaws on the Zr-2.5%Nb alloy CANDU pressure tube are rather circular, with a radius approximately corresponding to the defect depth in the radial direction. At the same time, they are quite fragile given that they are a conglomerate of radial hydrides and have a very high potential for the initiation of a crack, even when the mechanical stresses are in the range of nominal stress at normal operation in the reactor.

In this paper, a new metric is defined for the hydride continuity factor in the reorientation zone, HCC (RZ), which can better characterize the crack initiation potential in the CANDU pressure tube wall at volumetric flaws.

2. Materials and Methods

2.1. Characterization of the Stress Field Around Volumetric Flaws

Metallic structures subjected to mechanical stresses may present geometric imperfections, which in turn constitute mechanical stress concentrators. A factor, K_c , representing the mechanical stress concentrator, can be defined as the ratio between the maximum value of the mechanical stress at the defect tip, σ_{max} , and the value of the nominal stress, σ , from the net section of the studied component. The nominal stress, σ , is the mechanical tension in areas far from the defect area.

Mathematically, this ratio is defined as follows:

$$K_c = \frac{\sigma_{max}}{\sigma} \quad (1)$$

The severity of the mechanical stress concentrator depends on the geometrical configuration of the analyzed flaw [17]. For the special case of a circular gap with a radius of a , the solutions for the radial and circumferential stresses can be obtained depending on the distance r and the angle θ [18].

The normalized mechanical stresses for this situation are described by the following equations:

$$\tilde{\sigma}_r = \frac{\sigma_r}{\sigma_\infty} = \frac{1}{2} \left(1 - \frac{a^2}{r^2} \right) - \frac{\cos 2\theta}{2} \left(\frac{3a^4}{r^4} - \frac{4a^2}{r^2} + 1 \right) \quad (2)$$

$$\tilde{\sigma}_\theta = \frac{\sigma_\theta}{\sigma_\infty} = \frac{1}{2} \left(1 - \frac{a^2}{r^2} \right) - \frac{\cos 2\theta}{2} \left(\frac{3a^4}{r^4} + 1 \right) \quad (3)$$

where σ_r represents radial stress, and σ_θ represents hoop stress.

Figure 1 shows the distribution of the normalized stress, $\tilde{\sigma}_\theta$, as a function of the normalized radius r/a along the x axis ($\theta = 0$). The normalized stress drops quite quickly from value 3 to value 1 with an increase in the r/a ratio. We consider this kind of mechanical stress distribution around a defect in the analysis of the morphology of the hydrides located at the tips of the volumetric defects on the Zr-2.5%Nb alloy CANDU pressure tube.

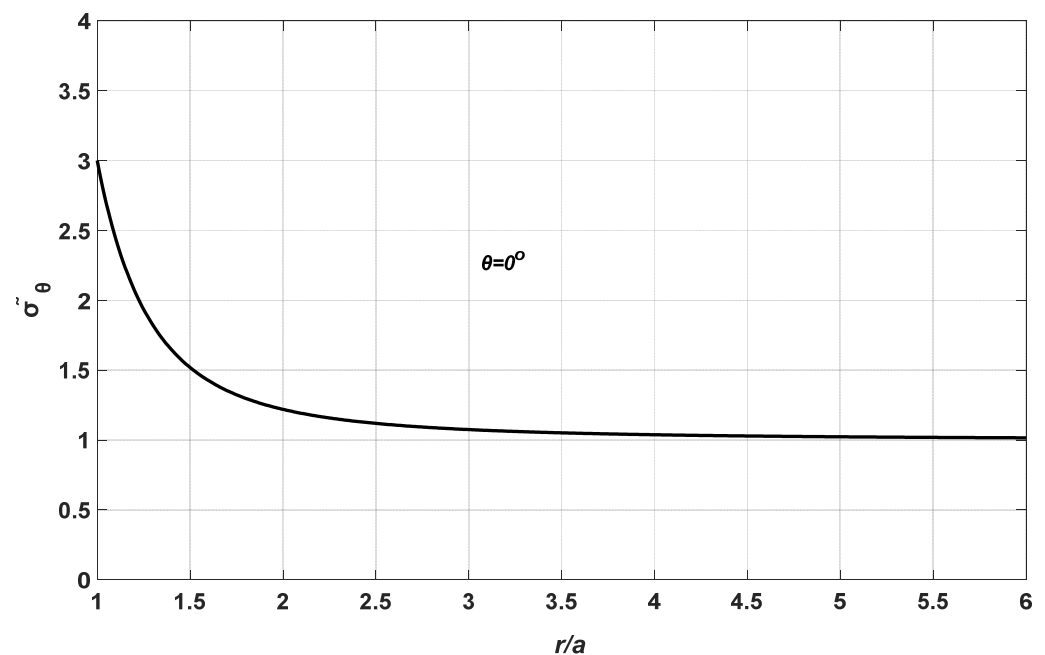


Figure 1. Distribution of normalized stress ($\tilde{\sigma}_\theta$) as a function of distance.

Also, the stress field generated at the flaw tip, considering planar dimensions, could be characterized by the fracture mechanics parameter K_I , which is the stress intensity factor for *Mode I* (opening mode) of the crack faces. The samples tested in this work were of the SENT (single-edge notched tension) type and were mechanically subjected to tensile stress, as schematically shown in Figure 2.

The stress intensity factor for *Mode I* (opening mode) of the crack faces, K_I , is given by the following relationship [20]:

$$K_I = \frac{P}{B\sqrt{W}} f\left(\frac{a}{W}\right) \quad (4)$$

with:

$$f\left(\frac{a}{W}\right) = \frac{\sqrt{2 \tan\left(\frac{\pi a}{2W}\right)}}{\cos\left(\frac{\pi a}{2W}\right)} \left[0.752 + 2.02\left(\frac{a}{W}\right) + 0.37\left(1 - \sin\left(\frac{\pi a}{2W}\right)\right)^3 \right] \quad (5)$$

Relationships (4) and (5) were used to calculate the stress intensity parameter, K_I , for the experimental samples made of the Zr-2.5%Nb alloy CANDU pressure tubes used in the present study.

To analyze the stress field influence around the stress concentrator, that is, the flaw tip, on the zirconium hydride morphology, both parameters, K_c and K_I , were used.

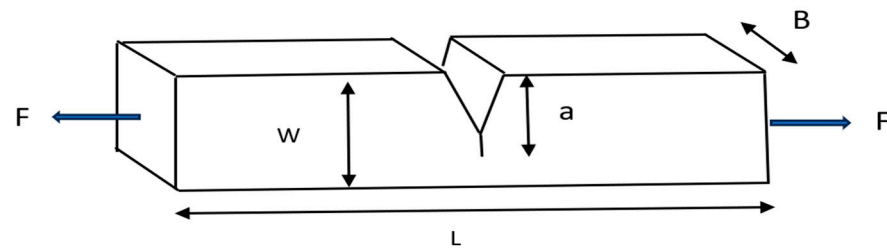


Figure 2. Single-edge notched tension-type sample [19].

2.2. Experiments for Zirconium Hydride Reorientation

Processed around the pressure tube's ring, the Zr-2.5%Nb pressure tube alloy samples had a SENT shape, as shown in Figure 3. The specimen roughness was an as-received value for the pressure tube.

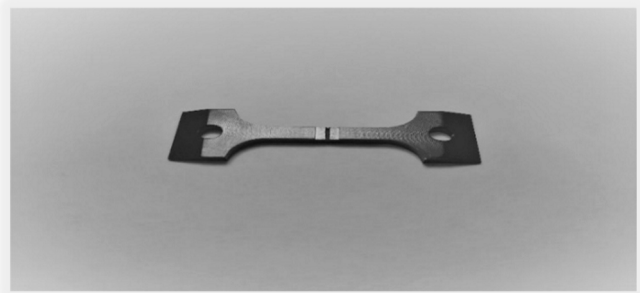
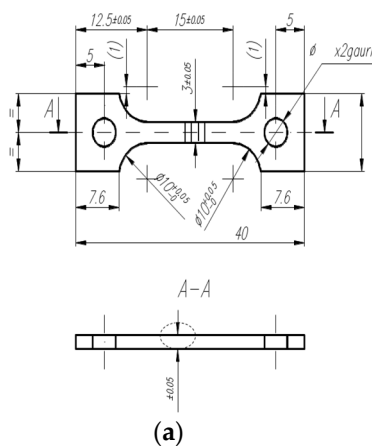


Figure 3. Single-edge notched tension-type sample: (a) dimensions in mm; (b) specimen.

An electrolytic bath containing a 0.1% H_2SO_4 solution deposited the hydride layer on the raw samples. The polished Zr-2.5%Nb samples served as the cathode, while a 5 mm thick lead plate served as the anode. The current density used was 100 mA/cm². Eight hours were allotted for holding, and the working temperature was 90 °C in the electrolytic bath. After this treatment, a homogeneous layer of hydride was produced. This was followed by a thermal homogenization treatment, which caused hydrogen to diffuse throughout each sample's volume. The period of hydrogenation was determined to obtain the required final hydrogen concentration in the samples. The samples were heated for two hours at 425 °C in a vacuum chamber as part of the hydride heat treatment.

To determine the hydrogen concentration in the samples, the "ELEMENTRAC OH-p" analyzer was used, which provided the measurement results directly in parts per million. The measuring principle of the ELEMENTRAC OH-p elemental analyzer allows a wide measuring range. To analyze each sample, it was weighed and placed on the sample port. The graphite crucible was outgassed in the impulse furnace of the analyzer to

reduce possible contamination. For hydrogen analysis, a nitrogen carrier and a sample gas were passed through a Schuetze reagent. With an absolute inaccuracy of ± 5 ppm, the controlled hydrogen in the samples was within the range of 30–80 parts per million (ppm) in this work considering how the hydrogen concentrations in the pressure tubes of the CANDU reactor changed. Established metallographic procedures were applied to highlight the hydrides and ascertain their orientation. Specifically, the samples were polished and subjected to a chemical attack (a solution consisting of 45% nitric acid, 45% distilled water, and 10% hydrofluoric acid; $t = 20$ s). A particular chemical attack—immersion in a mixture of 25 mL of lactic acid, 25 mL of nitric acid, and 3 to 4 drops of hydrofluoric acid—was used to highlight the hydrides. The samples' microstructure was examined under a light field metallographic microscope. Certain heat cycling tests were carried out to acquire the hydride reorientation phenomenon. To enable a thermal cycling treatment under the controlled load of samples with artificial flaws, such as V-type flaws, an experimental setup was employed at the testing facility.

Thermal cycling treatments under continuous mechanical load were used to observe the hydrides in the location of reorientation. The operating procedures were as follows:

1. The instrumented and hydride samples were installed in the clamping mechanism typical of the SENT sample type;
2. The samples were heated to 300 °C for a full day to dissolve the hydrides. Subsequently, the temperature was lowered to 185 °C at a rate of 1 °C per minute, and the holding period was extended to three hours. Following this, the cooling process was maintained at a rate of 1 °C per minute until 90 °C was reached. Then, the samples were heated to 250 °C at a rate of 1 °C per minute for one hour.

The parameters for testing were managed with the aid of appropriate software. The number of heating cycles under constant mechanical stress varied between 9 and 25. Based on initial experiments conducted on samples containing a hydrogen concentration greater than 30 ppm, the threshold stress for hydride reorientation was determined over a temperature range of 280 to 350 °C.

2.3. Image Analysis of Zirconium Hydride Morphology at Volumetric Flaws

Micrographs of the Zr-2.5%Nb alloy samples in the radial cross-section were taken to examine the hydride reorientation phenomenon that occurred when the samples were heated under constant mechanical stress. The Zr-2.5%Nb alloy's phenomena of hydride reorientation were caused by the requirement that the material's hydrogen concentration be higher than the solid solubility limits at a particular temperature. The hydrides appeared as tiny filaments in the radial–transverse plane with varying orientations. Hydride platelets with their orientation direction positioned at an angle different from the transverse direction (45–90°) are known as reoriented hydride platelets, as defined in Figure 4a. Examination of the micrographs of the zirconium hydride platelets showed that the hydride continuity coefficient (HCC) metric, a dimensionless measure, provides an estimate of the hydrides' reorientation [15]. The subsequent steps needed to obtain the HCC were as follows:

3. A rectangular-shaped surface with dimensions of roughly 0.1 mm $\times$ 1.0 mm was selected in the radial–transverse plane for analysis;
4. Radial projections, L_k , of the hydride platelet lengths were constructed on this surface;
5. Together with the total length of the investigated rectangular surface, L_{total} , the projected lengths, L_k , were measured;
6. The following relationship was used to compute the HCC:

$$HCC = \frac{\sum_{k=1}^n L_k}{L_{total}} \quad (6)$$

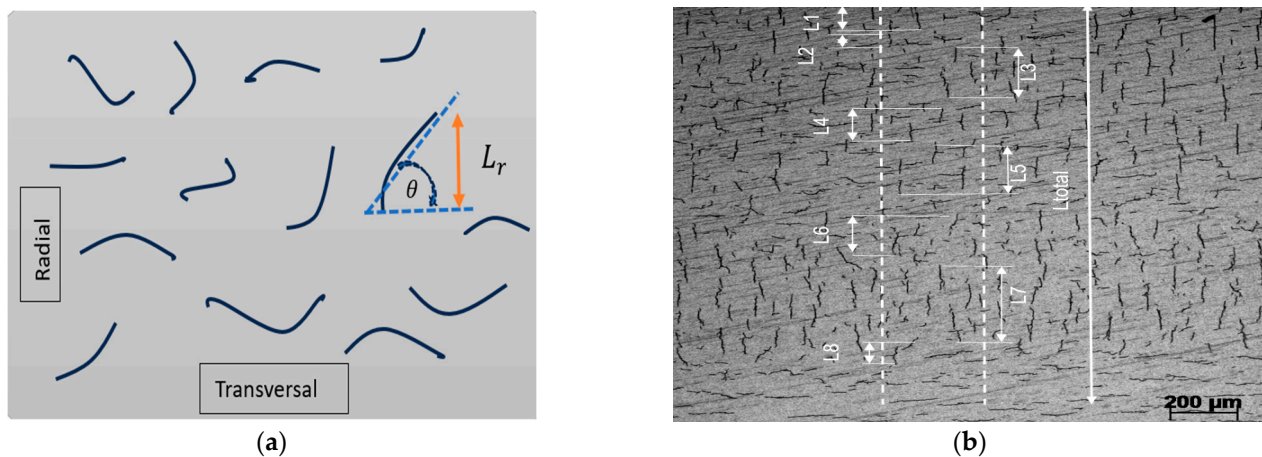


Figure 4. (a) Quantification in the zirconium alloy of the hydrides' reorientation effect using the HCC metric; (b) example of HCC computation [15].

An example of HCC computation is presented in Figure 4b. At higher hydrogen concentrations and with a greater number of thermal cycles that induce hydride reorientation, the HCC became easier to calculate and increased significantly.

From the Canadian scientific literature [7], the values of the tensile stress at which this reorientation phenomenon occurs are above 110 MPa if the stress state is biaxial or 120–155 MPa for uniaxial traction ([7,21]). To meet the threshold stress criterion, some thermal cycles under continuous load were performed with the mechanical stress $\sigma > 120$ MPa at the notch tip. The hydride platelets were seen to be clearly orientated in the pressure tube's radial direction as the number of cycles increased. Their lengths extended in this direction as a result, and their HCC values increased.

The reorientation of zirconium hydrides resulted in a particular shape in the tests using hydrided specimens manufactured from a CANDU pressure tube that included the V-type notch, as shown in Figure 5a. The hydride platelets were oriented normally, parallel to the direction of tensile stress, but the complex stress field around a tip flaw promoted the formation of some circles from hydride filaments. Starting from the tip flaw in the radial direction, we defined a "reorientation zone" (RZ), with a circular form, until its border was tangential to the un-orientated hydrides.

From Figure 5, it was also estimated that the radius of the reorientation zone had a depth of approximately 2 times the depth of the V-type flaw. Also, from the finite element analysis, we found that the area with such higher mechanical stresses, approximately 120 MPa, had a depth of approximately 2 times the depth of the defect for normal circumferential stresses to which the CANDU 600 pressure tube wall was subjected. By intercomparison with the metallographic analyses, it was observed that the radius of the reorientation zone could be approximated by 2 times the depth of the defect, which was largely confirmed.

The importance of characterizing the morphology of the hydrides in the reorientation zone lies in the fact that the initiation of a crack and its subsequent propagation occurred from the tip of the defect to the radially brittle reoriented platelets, as shown in Figure 5b. Also, when the stress conditions were met (fatigue, thermal cycling, etc.), crack propagation extended through the reorientation zone, as demonstrated in Figure 5c. To characterize the zirconium hydride morphology in the reorientation zone at the volumetric flaw tip, first, image analysis and processing techniques were applied by using the public domain software ImageJ [22]. The reorientation zone was divided into 10 slices, as shown in Figure 6a. After defining the "hydride unit", with a size of ten microns, the hydrides in

each slice were counted. Finally, the reoriented hydride density in a form normalized to the maximum value obtained in a zone was visualized, as shown in Figure 6b.

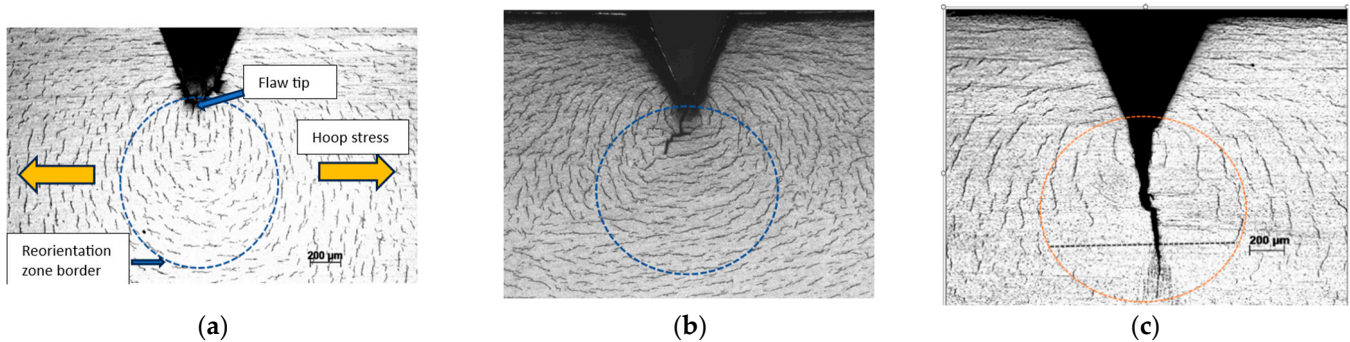


Figure 5. Particular shape of the reorientation zone (RZ): (a) at the V-type notch flaw; (b) with the crack initiated by hydrides in the RZ; (c) with the crack crossing the RZ.

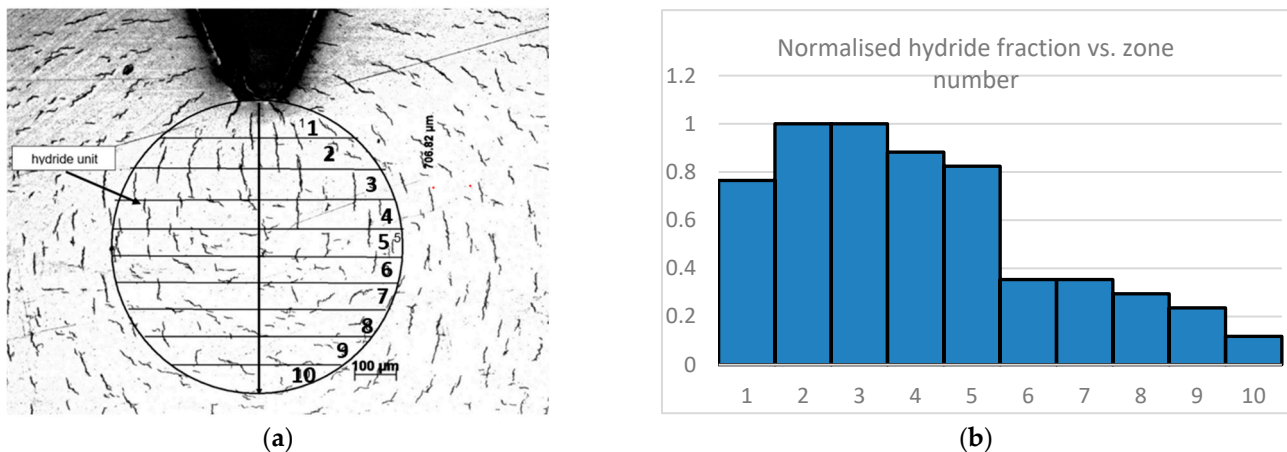


Figure 6. Image analysis: (a) the RZ divided into 10 slices; (b) statistical data processing.

One may see from the statistics in Figure 6b how the brittle aspect provided by the density of the reorientated hydrides is higher close to the flaw tip and decreases radially with distance. However, the normalized hydride fraction offers only a qualitative aspect of the brittleness of the reorientation zone. This should be determined with a more representative parameter quantitatively.

3. Results

To better characterize the reorientation zone from the point of view of embrittlement and mechanical behavior, this paper proposes a novel metric for the morphology of hydrides located in the reorientation zone. Finite element analyses were performed on SENT specimens with flaws to evaluate the stress field around the notch tip (Figure 7a) to infer the stress concentrator factor K_c . In the same picture, the principal stress graph is superimposed in front of the notch. The depth of the zone with stress greater than 120 MPa, that is, the threshold stress to start the reorientation process, was approximately 2 times the notch depth. In this sense, in the development of the model on which the novel metric is based, the characteristics specified in Figure 7b were taken into account. The circular area from the tip of the flaw was delimited, and it had a radius approximately equal to the depth of the defect, $r \approx a$. This was also based on the hypothesis that at a distance equal to $2a$ measured radially from the tip of the defect, the effect of stress concentration decreases, as demonstrated in Figures 1 and 7a.

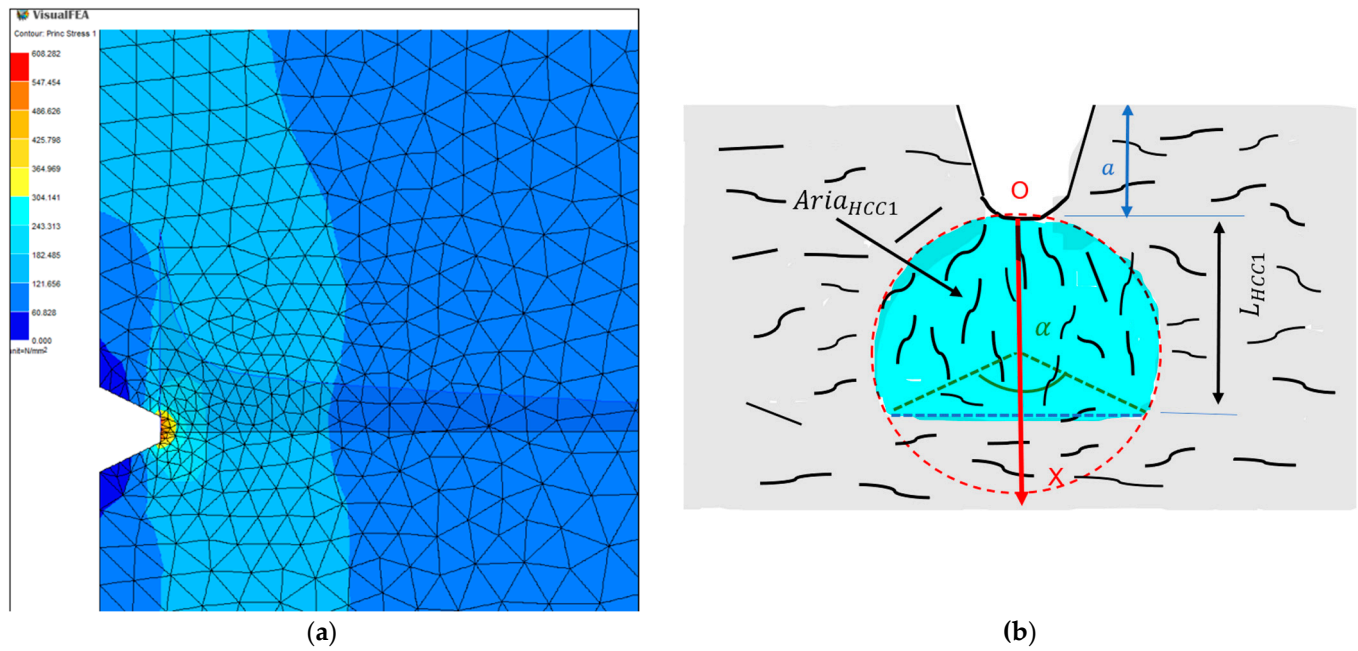


Figure 7. (a) Principal stress field around the notch tip by FEA (unit = N/mm²); (b) characterization of the hydride reorientation zone (RZ) with the model HCC.

Considering the cracking potential of the reorientation zone of localized hydrides, a novel metric is proposed for the hydride continuity coefficient in the reorientation zone, noted as $\Phi_{HCC(RZ)}$. It is based on Figure 7b with the following considerations:

7. The radius of the circular hydride reorientation zone located at the tip of a volumetric flaw in the wall of the CANDU pressure tube was approximately equal to the depth of the volumetric notch ($r \approx a$), taking into account the stress concentration at the tip of the defect.
8. All hydride filaments contained in the circular area of localized hydrides projected in the radial direction (Ox), and thus, a segment was constructed along the OX axis, a segment without discontinuities, L_{HCC1} , as shown in Figure 7b. The coefficient HCC_x in this area was $HCC_x = 1$.
9. The circle segment of the angle, α^0 , was delimited, where $HCC_x = 1$, as denoted by the blue color in Figure 7b.
10. The novel metric $\Phi_{HCC(RZ)}$ proposed for the $HCC(RZ)$ was defined as the ratio between the area of the circle segment defined by $HCC_x = 1$, as shown in Figure 7b, and the area of the circle with a radius equal to the depth of the defect ($r \approx a$), as follows:

$$\Phi_{HCC(RZ)} = \frac{\pi \cdot r^2 - r^2 \left(\frac{\pi \cdot \alpha^0}{360^\circ} - \frac{\sin(\alpha^0)}{2} \right)}{\pi \cdot r^2} \quad (7)$$

The value of the $\Phi_{HCC(RZ)}$ metric better quantitatively defined the embrittlement of the area where the hydrides reoriented at the tips of volumetric defects on the Zr-2.5%Nb alloy CANDU pressure tube.

Two examples of $\Phi_{HCC(RZ)}$ metric calculation for samples with different hydrogen concentrations and flaw dimensions, which were subjected to various thermo-mechanical conditions, are displayed in Figure 8.

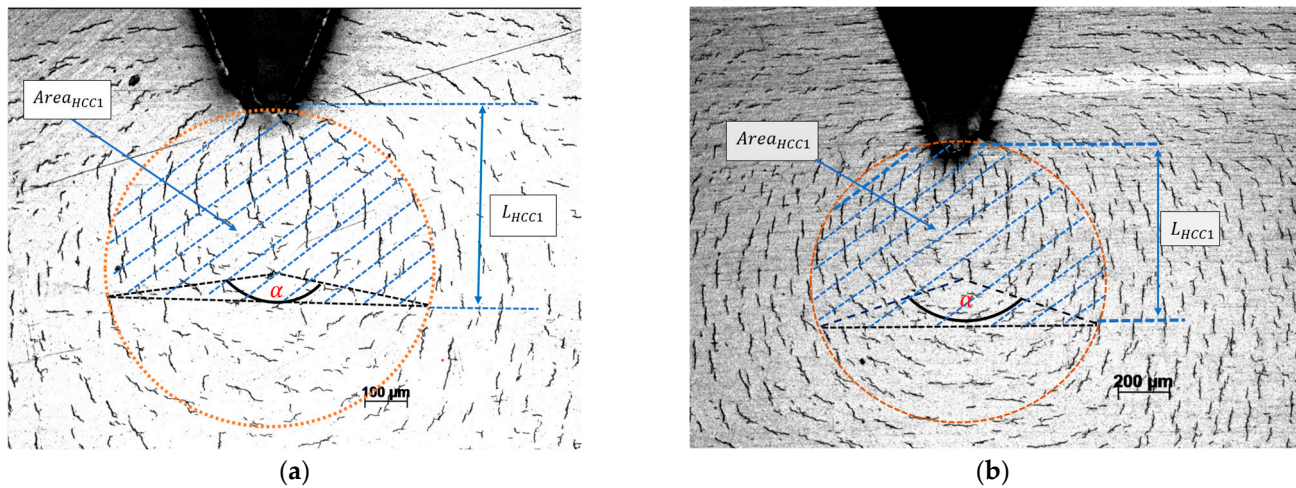


Figure 8. Examples: (a) metric $\Phi_{HCC(RZ)} = 0.58$ at a 60 ppm hydrogen concentration, flaw depth $a = 0.5$ mm, root radius $\rho = 0.05$ mm; (b) metric $\Phi_{HCC(RZ)} = 0.80$ at a 80 ppm hydrogen concentration, flaw depth $a = 0.7$ mm, root radius $\rho = 0.05$ mm.

To highlight the attributes of the novel $\Phi_{HCC(RZ)}$ metric compared to the HCC metric, Table 1 lists the values of these metrics for the same evaluated samples, together with the values of the stress intensity factor, K_I , and the volumetric flaw's tip stress concentration factor, K_c .

Table 1. Comparison between two reorientation zones with metrics for hydride morphology.

Reorientation Zone Parameters	K_I (MPa $\sqrt{m}$) (Relation 4)	K_c (FEA)	$\Phi_{HCC(RZ)}$ (Relation 7)	HCC (Relation 6)
$C_H = 60$ ppm $a = 0.5$ mm $\rho = 0.05$ mm	3.22	9.65	0.58	0.53
$C_H = 80$ ppm $a = 0.7$ mm $\rho = 0.05$ mm	4.25	10.46	0.80	0.42

It can be seen from Table 1 that the values of the $\Phi_{HCC(RZ)}$ metric better characterize the density of hydrides at the tip of the volumetric V-type flaw, being more connected with the influencing parameters of the reorientation phenomenon of localized hydrides, namely, K_I and K_c , as well as with the hydrogen concentration absorbed in the sample.

The new metric defined for hydride morphology assessment at a volumetric flaw in a Zr-2.5%Nb alloy pressure tube could be used in the framework of fracture mechanics analyses by considering an “equivalent flaw like a crack”. This equivalent flaw like a crack has an updated depth, a_{eq} , which also considers the influence of the $\Phi_{HCC(RZ)}$ metric value in the following way:

$$a_{eq} = a + \Phi_{HCC(RZ)} \cdot 2a = a \cdot (1 + 2\Phi_{HCC(RZ)}) \quad (8)$$

Figure 9 shows two examples considering the a_{eq} depth versus actual a depth of a volumetric flaw obtained with relationship (8) using the $\Phi_{HCC(RZ)}$ metric. Also, one may see that there are already radial hydrides connected in the form of a crack in the $Area_{HCC1}$ zone. In this way, the embrittlement induced by hydride reorientation at the flaw tip is more appropriate for further evaluation of the stress effect under fatigue or other loadings.

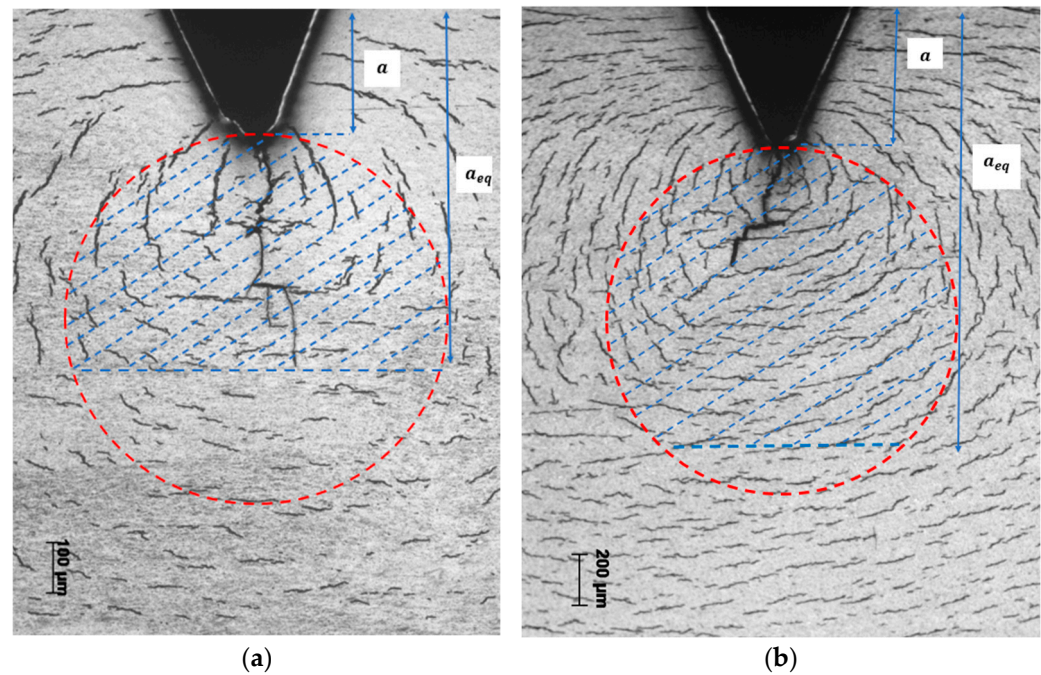


Figure 9. (a) HCC(RZ) with $\Phi_{\text{HCC(RZ)}} = 0.66$, $a_{\text{eq}} = 2.33a$; (b) HCC(RZ) with $\Phi_{\text{HCC(RZ)}} = 0.93$, $a_{\text{eq}} = 2.86a$.

Thus, with this approach using the HCC(RZ), the stress intensity factor K_I can be defined much more accurately for an equivalent flaw like a crack instead of an actual volumetric flaw. In this way, the embrittlement induced by hydride reorientation at the flaw tip is more appropriate for further evaluation of the stress effect under fatigue or other types of thermal or mechanical loadings. Consequently, this can be used in structural integrity evaluations of CANDU pressure tubes following in-service inspections.

4. Discussion

The new metric defined for hydride morphology assessment at a volumetric flaw in a Zr-2.5%Nb alloy pressure tube could be used in the framework of fracture mechanics analyses by considering an equivalent flaw like a crack. This equivalent flaw like a crack has an equivalent depth, a_{eq} , that replaces the actual volumetric depth, a .

With this approach for the HCC(RZ), the stress intensity factor K_I can be defined much more accurately for an equivalent flaw like a crack instead of an actual volumetric flaw. In this way, the embrittlement induced by hydride reorientation at the flaw tip is more appropriate for further evaluation of the stress effect under fatigue or other types of thermal or mechanical loadings. Consequently, this can be used in structural integrity evaluations of CANDU pressure tubes following in-service inspections.

Of course, in a real scenario, the definition of the reorientation zones of localized hydrides must take into account the type of defect, which, in the case of pressure tubes, can be a “bearing pad fretting flaw” (BPFF), a “debris fretting flaw” (DFF), or a combination of these, as revealed by the periodic inspections carried out on the fuel channels in CANDU nuclear power plants. Therefore, further development of the model in this article must take into account the specific configuration of the defects revealed by periodic inspections, as stipulated in the Canadian standard [1].

5. Conclusions

Vibrations due to an agent’s flow through fuel bundles and corrosion phenomena cause volumetric flaws on the inner surface of the CANDU pressure tube, which is more

likely during normal operation. In the pressure tube, zirconium hydride platelets, or delta hydrides ($\text{ZrH}_{1.6}$), develop when the equivalent hydrogen concentration is above the solid solubility limit. Reorientation of the hydride platelets under specific thermo-mechanical settings (thermal cycling under continuous mechanical stress) is a relevant factor in determining the degree of material fragility in this situation.

To more accurately describe the crack initiation potential in the pressure tube wall at volumetric flaws, a novel measure for the hydride continuity factor in the reorientation zone is defined in this research.

To characterize the zirconium hydride morphology in the reorientation zone at the volumetric flaw tip, the image analysis and processing techniques were first applied. The normalized hydride fraction offers a qualitative aspect of the brittleness of the reorientation zone.

To better characterize the hydride continuity coefficient in the reorientation zone, HCC (RZ), from the point of view of embrittlement and mechanical behavior, this paper proposes a novel metric, $\Phi_{\text{HCC(RZ)}}$. The value of the $\Phi_{\text{HCC(RZ)}}$ metric better defines the crack initiation potential at the tips of volumetric flaws on the Zr-2.5Nb alloy CANDU pressure tube.

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