CHARACTERIZATION OF THE DHC CRACK PARAMETERS IN ZIRCONIUM ALLOYS

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Abstract. Zirconium alloys are used in heavy water-cooled reactors due to their low thermal neutron capture cross-section and good mechanical and corrosion properties. At the beginning of their operation, hydrogen was identified as an embrittlement agent. The source of the embrittlement was hydride precipitates that formed as platelets. Hydrides were associated with the cracks and the process was called Delayed Hydride Cracking – DHC. This research aims to develop a reproducible procedure concerning DHC $K_{HI}$ parameter measurements on Zirconium claddings, by using the Pin Loading Test (PLT) technique. Experimental activities including sample preparation, adding hydrogen, testing and results are presented in detail.

Key words: zirconium alloys, DHC mechanism, hydrogen embrittlement, tensile test.

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1. INTRODUCTION

The Fukushima accident highlighted the need to evaluate and fully define the factors responsible for hydrogen absorption on the structural integrity of these components as a matter of priority.

Zirconium alloys are widely used in nuclear reactors because of the physical and mechanical properties they recommend. In general, zirconium alloys are used for pressure tubes and fuel element tubes. For safety and economy in operation, it is necessary to maintain the structural integrity of these components. During operation, the components are subjected to an aging process generated by thermal and pressure changes, fast neutron bombardment, and corrosion at the water/metal interface leading to the release of a small fraction of hydrogen during the corrosion reaction which is absorbed into the alloy of zirconium. When the hydrogen concentration in the material exceeds the solubility limit, zirconium hydride is formed. These hydrides, which are less ductile than the metal matrix, can have negative effects on the mechanical properties of components when present in large amounts.

In the initial studies [1] it was shown that at a low hydrogen content in the material, there may be a time-dependent cracking mechanism (known as Delayed Hydride Cracking – DHC) which involves the local increase of the hydrogen content due to some hydrogen concentrators. The local increase in hydrogen concentration...
can lead to the formation of a dense hydride region with the effect of crack initiation and propagation.

The study of the integrity of zirconium alloys used as cladding material focuses on the effect of the presence of a large volume of hydride precipitates.

The fact that the rupture of some fuel elements is suspected to have occurred through the DHC mechanism and the need to predict the integrity of the fuel bundle under long-term storage conditions led to studies on the mechanism of slow cracking under load in the presence of hydrogen [2].

2. THE DHC MECHANISM

During operation in the nuclear reactor, the components in the active zone made of zirconium alloys are subjected to several types of degradation, associated with the aggressive conditions of the operating environment, namely creep, degradation induced by irradiation, embrittlement due to hydrogen, etc.

The normal and safe operation of nuclear facilities requires the understanding and monitoring of these degradation mechanisms.

Between metallic zirconium and the coolant (water or heavy water) of the reactor, a corrosion reaction occurs according to the relationship:

\[
\begin{align*}
\text{Zr} + 2\text{H}_2\text{O} & \rightarrow \text{ZrO}_2 + 4\text{H} \\
\text{Zr} + 2\text{D}_2\text{O} & \rightarrow \text{ZrO}_2 + 4\text{D}
\end{align*}
\]  

and some of the hydrogen/deuterium is absorbed into the zirconium matrix.

During operation in the reactor, the hydrogen content of the component increases resulting in reduced mechanical properties due to embrittlement in the presence of hydride plaques [3]. These brittle hydride plates precipitate when the solubility limit is exceeded causing the component to break.

There are two major ways in which a component can break:

- The first way is a fast process that depends on the breaking tenacity of the material;
- The second is a slower process generated by the diffusion of an atomic constituent in the material toward a stress concentrator. Increasing the concentration of that constituent produces a local decrease in fracture toughness.

The latter process is composed of two stages that usually have different time dependence:

1. Crack initiation stage;
2. The repeated propagation stage during which the subcritical crack produced in the first stage slowly grows in length until it reaches a critical length from which unstable propagation occurs.
Favoring the embrittlement process is the individual breaking of the hydride precipitates located in the zirconium matrix. Thus the key parameter for understanding and modeling the conditions of loss of fracture toughness as a result of the presence or the possibility of localized formation of hydride precipitates is the fracture resistance of hydride precipitates.

Zirconium alloy components can break through a time-dependent cracking process if hydrides form preferentially and then crack in areas of high mechanical stress (Fig. 1).

This process, called Delayed Hydride Cracking (DHC) is based on the mechanism of diffusion of hydrogen to regions with higher mechanical stress, followed by the phenomenon of nucleation, growth, and cracking of the hydride region [5, 6].

Observations of the fracture surfaces at low magnifications showed rows of crack growth (striations), moving parallel to the fracture front (Fig. 2).
Rupture of the hydrate zone produces rapid crack growth, growth that stops at the boundary between the hydrate zone and the ductile matrix. The striations represent physical evidence of this interruption of crack growth and the distance between each row of striations represents the critical crack length of the hydrate region.

The DHC crack growth rate confirms that this process occurs due to the diffusion phenomenon. The presence of these striations (ductile fracture zones) after each crack growth stage suggests that the first step for the DHC mechanism to proceed is the nucleation of new radial hydrides.

3. EXPERIMENTAL

3.1. THE HYDRIDING PROCESS OF THE ZIRCALOY-4 ALLOY

To obtain hydrided Zircaloy-4 tubes with different hydrogen concentrations, necessary to study its influence on the mechanical properties of the zirconium matrix, the tubes are subjected to a complex hydridation process, composed of two distinct stages.

The initial hydrogenation stage of the samples consisted in depositing a hydride layer on the base matrix-Zircaloy-4 alloy in an electrolytic bath containing an H₂SO₄ solution. The parameters are monitored through the acquisition and control system (Fig. 3).

![Control panel « Electrolit-1 »](image)

Using a specific homogenization thermal treatment, the diffusion of hydrogen from the layer deposited on the sample and the formation of hydride precipitates in the form of hydride plates are ensured.
The homogenization duration was set at 24 hours in stages at a temperature of 365°C. The homogenization treatment diagram used is presented in Fig. 4.

![Homogenization treatment diagram](image)

Fig. 4 – Homogenization treatment diagram.

3.2. DETERMINATION OF HYDROGEN CONTENT

The hydrogen content of zirconium alloys consists of the hydrogen present as an impurity due to the manufacturing process or of the introduced hydrogen controlled by experimental tests [8]. The determinations are made using the hydrogen/oxygen analyzer ELTRA OH-900 (Fig. 5).

![ELTRA OH-900 hydrogen/oxygen analyzer](image)

Fig. 5 – ELTRA OH-900 hydrogen/oxygen analyzer.
Before starting the determination of the hydrogen content of the samples, the apparatus is calibrated. The calibration is carried out with titanium standards, which are indicated for hydrogen determinations in zirconium alloys. The process computer calculates the result obtained after burning the standard plate, which it saves in a text file. If the obtained values satisfy the requirements, proceed to the examination of the samples and if not, clean the gas path of the analyzer and resume the calibration procedure.

After calibrating the apparatus, the sample is placed in a graphite crucible and heated to a temperature higher than the melting temperature of the zirconium alloy. By melting, oxygen and hydrogen are released from the material, the hydrogen being detected by a thermal conductivity cell.

Figure 6 presents the text file with the results obtained in the case of the calibration tests. The calibration was carried out with 4 standards with different hydrogen content (28±3, 47±4, 62±5, 110±7 ppm H).

<table>
<thead>
<tr>
<th>Standards</th>
<th>ppm O 2/0</th>
<th>ppm H 4/0</th>
</tr>
</thead>
<tbody>
<tr>
<td>x/001</td>
<td>250.0 mg</td>
<td>0.00</td>
</tr>
<tr>
<td>xx/002</td>
<td>250.0 mg</td>
<td>0.00</td>
</tr>
<tr>
<td>xxx/003</td>
<td>250.0 mg</td>
<td>0.00</td>
</tr>
<tr>
<td>blanc/004</td>
<td>250.0 mg</td>
<td>0.00</td>
</tr>
<tr>
<td>T-2/006</td>
<td>238.7 mg</td>
<td>0.00</td>
</tr>
<tr>
<td>28 ± 3/006</td>
<td>253.5 mg</td>
<td>0.00</td>
</tr>
<tr>
<td>47 ± 4/007</td>
<td>264.2 mg</td>
<td>0.00</td>
</tr>
<tr>
<td>62 ± 5/008</td>
<td>234.9 mg</td>
<td>0.00</td>
</tr>
<tr>
<td>110 ± 7/009</td>
<td>231.9 mg</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Fig. 6 – Measurement results for calibration tests.

The results obtained by the analyzer fall within the tolerance ranges offered by the standards, and thus we move on to the determination of the hydrogen content of the samples we have to analyze. The ppm H values obtained are shown in Table 1.
Table 1

Hydrogen content in the analyzed samples

<table>
<thead>
<tr>
<th>Sample code</th>
<th>Hydrogen content (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A17-2</td>
<td></td>
</tr>
<tr>
<td>A17-3</td>
<td></td>
</tr>
<tr>
<td>A17-4</td>
<td>123</td>
</tr>
</tbody>
</table>

3.3. PLT SAMPLES PREPARATION

To determine the fracture mechanics parameters in the case of thin-walled tubes, as in the case of Zircaloy-4 fuel tubes, it is necessary to make PLT (Pin Load Tension) samples [9]. These samples are drawn from hydrated tubes (section 3.2.) and have a length of 13 mm. Figure 7 shows the layout of a PLT sample.

![Fig. 7 – Zircaloy-4 CANDU fuel element tube PLT sample.](image)

At both ends, the sample has two groups of slits positioned diametrically opposite. The widths of the two groups of slots are different. The larger widths (FM) are made by diamond disc cutting and have the technological role of allowing the material to move during testing. The narrower slits (Fm) are obtained by EDM (Electrical Discharge Machining) and constitute the part of the sample from which the crack propagation test begins.

The slits were measured using an optical microscope and Table 2 and Fig. 8 shows the results of some measurements.

Table 2

Measurement results of the slits of the PLT samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>Side A (µm)</th>
<th>Side B (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FM length</td>
<td>FM width</td>
</tr>
<tr>
<td>A17-2</td>
<td>2208</td>
<td>546</td>
</tr>
<tr>
<td>A17-3</td>
<td>2126</td>
<td>548</td>
</tr>
<tr>
<td>A17-4</td>
<td>2107</td>
<td>539</td>
</tr>
</tbody>
</table>
Fig. 8 – Metallographic aspects with slit measurements of PLT samples.
Preparation of the samples for testing continues by making the cycling pre-crack at the narrow slot end. The purpose of making the pre-crack is to obtain an artificial defect with a very sharp tip [10].

3.4. THE FRACTURE MECHANICS TEST TO DETERMINE THE $K_{IH}$ FACTOR AND DHC VELOCITY

The $K_{IH}$ parameter is defined in the literature as the stress intensity factor below which the DHC mechanism does not occur. In most tests, the measurement of the $K_{IH}$ factor consists of determining the highest value of the stress intensity at which no crack growth is observed.

For the precipitated hydrides to reach a critical size from which cracking occurs, through the combined effect of the properties of the hydrides and the matrix of the material, the time of application of the force must be sufficiently long. The American standard describing the method for determining the stress intensity threshold factor, E 1681 (Standard Test Method for Determining Threshold Stress Intensity Factor for Environment-Assisted Cracking of Metallic Materials) does not provide information regarding the time of force application. From the literature [11] it has been found that 24 hours or more are required for crack initiation.

**Charging Method (Charging Effect).** From the point of view of applying the force on the sample, there are two ways to determine the $K_{IH}$ factor. In one method, the $K_{IH}$ is measured by increasing the force from a low value until the crack is initiated. The increase is done every 24 hours and the $K_{IH}$ is defined as the maximum load at which the crack is initiated. For this case, in general, it is necessary to make a pre-crack [11].

The second method consists in gradually decreasing the force, from a value at which the crack is well established until propagation stops. The test is considered completed when the crack stops propagating for 24 hours. In this case, the intensity factor is considered the minimum load at which the crack closes.

In both situations, recording the arrest of crack propagation depends on the sensitivity of the method used.

In this work, the tests were carried out according to the force reduction method, and the testing stages are presented below [12]:

- Pre-tensioning of the sample for loading the entire system;
- Heating with 4°C/min at a temperature of 380°C;
- Holding at 380°C for 1 hour to dissolve the hydrides;
- Controlled cooling with 1°C/min to test temperature (250°C);
- Keeping the temperature constant throughout the test. The DHC – $K_{IH}$ tests were performed on the creep machine by gradually reducing the load as the DHC crack grew to a specified length of 70 µm, at a value of 97%.
The load reduction is carried out until the DHC crack stops propagating for 24 hours;
- Free cooling of the sample in the furnace.

The stress intensity factor at the crack tip, for the PLT-type samples, is calculated according to the relationship:

\[ K_I = \left( \frac{P}{2tW} \right) f\left( \frac{a}{W} \right) \]  

(2)

where: \( P \) = load applied to the sample (N); \( t \) = wall thickness of the tube (mm); \( W \) = width of the sample – gripping system assembly (mm); \( a \) = effective crack length (mm), equal to the sum of the mechanical crack and the cycling crack \( a_f \);

\[ f\left( \frac{a}{W} \right) = -360.99\left( \frac{a}{W} \right)^3 + 787.15\left( \frac{a}{W} \right)^2 - 468.73\left( \frac{a}{W} \right) + 92.203 \]  

(3)

The parameters involved are also indicated in Fig. 9.

![Fig. 9 – PLT sample layout.](image)

The mechanical test for determining the KIH threshold factor involves starting the test from an initial \( K \) given by the relation:

\[ K_I = \left( \frac{P}{2t\sqrt{W}} \right) f\left( \frac{a_f}{W} \right) \]  

(4)
where: $a_0 = a_n + a_f$ – the sum of the nominal crack length (obtained mechanically) and the fatigue crack length (obtained by cycling).

From relation (4) we extract the force $P$:

$$P_{\text{max}} = \frac{K_{\text{I max}} 2t\sqrt{W}}{f(a_0/W)}$$  \hspace{1cm} (6)

The obtained value will represent the maximum force that will be applied to the sample and from this value, the force will decrease by a percentage of 3% for each increase of the crack by 70 $\mu$m. This decrease satisfies the condition imposed on $K$:

$$K_n = 0.97K_{n-1}$$  \hspace{1cm} (7)

From where we have:

$$P_n = 0.97P_{n-1} \frac{f(a_n/W)}{f(a_{n-1}/W)}, \hspace{0.5cm} n > 2$$  \hspace{1cm} (8)

The $K_{\text{I max}}$ value from relation (6) is obtained through successive tests. For PLT-type Zircaloy-4 tube samples the established value for $K_I$ is 15 MPa m$^{1/2}$.

The test continues until the crack stops propagating for 24 hours. After this period, the sample is subjected to a mechanical cycling test to highlight the DHC crack zone. To be able to analyze the fracture surface, usually using optical microscopy, the sample is broken through a classical tensile test.

The calculation of the $K_{\text{IH}}$ value is done taking into account the total length of the crack composed of the mechanical crack, fatigue crack, and DHC crack.

Measurement of DHC velocity ($V_{\text{DHC}}$) can provide information on the DHC mechanism and is also the most studied parameter. In the literature, the determination of $V_{\text{DHC}}$ is carried out by different methods.

The most common method that allows accurate measurement of DHC velocity is the direct determination method. In this sense, after the fracture mechanics test is completed, the sample is broken through a fatigue test to delimit the DHC crack. The DHC velocity is measured by dividing the DHC crack length by the propagation time.
Other methods try to estimate the DHC velocity directly using the potential difference signal or acoustic emission. These methods are less accurate due to the uncertainties introduced by the crack length measurement.

The crack propagation velocity is strongly influenced by the temperature as well as the temperature scenario experienced by the sample. In general, there are four factors of interest influenced by the temperature scenario of the sample:

- The hydrogen concentration in the solution;
- The amount of supersaturated hydrogen;
- The diffusion coefficient of hydrogen in solution (increases with temperature);
- The yield strength of the zirconium matrix (decreases with temperature).

Experimental [13], it was observed that for high supersaturations, the crack velocity increases by 3–5 times compared to lower supersaturations of 50%. Thus it appears that a high content of hydrogen in the solution is associated with an increase in the cracking velocity due to the improvement of the hydrogen diffusion ability at the crack tip.

Consequently, the temperature scenario of the sample has a significant effect on the cracking behavior of the material, and both the increased hydrogen content in the solution and the high supersaturated hydrogen content are associated with a high crack growth rate.

4. RESULTS AND DISCUSSIONS

The testing was carried out at a temperature level of 250°C, after previously dissolving the hydrides through a thermal ramp, carried out at 385°C. The mechanical stress was initiated under the conditions of applying a value of $K_I = 15 \text{ MPa} \cdot \text{m}^{1/2}$ at the tip of the crack, corresponding to a stress load that is calculated according to relation (2). The test was run continuously until the crack propagated.

For the calculation of the KIH parameter, the value of the last load step for which the crack did not propagate for 24 hours was taken into account, and the crack length was measured by optical metallography by averaging the lengths of the DHC cracks on the two fracture surfaces of each tested sample. The calculation is carried out using the 5-segment method (Fig. 10) [14].

![Fig. 10 – Measurement of crack lengths on the surface of a sample tested under KIH conditions (sample A17-3).](image-url)
Table 3 shows data on the tested samples (sample code, hydrogen concentration, initial crack sizes, etc.) and measurement values (DHC crack size, stress intensity factor value).

In the first part of the test (Figs. 11–13), when the load value is high, the crack growth rate is higher. As the load decreases, the DHC rate also decreases to a point where crack propagation no longer occurs. The temperature, for all tests, has a peak at 385°C for the dissolution of hydrides and then decreases to the test value – 250°C.

Table 3

Results of fracture mechanics tests

<table>
<thead>
<tr>
<th>Sample</th>
<th>Hydrogen concentration (ppm)</th>
<th>Temperature peak (°C)</th>
<th>Testing temperature (°C)</th>
<th>Initial crack length (mm)</th>
<th>Initial load (N)</th>
<th>KI_initial (MPa·m½)</th>
<th>Load reduction steps</th>
<th>KI_reduction (%)</th>
<th>Crack growth estimation (µm)</th>
<th>Load reduction steps</th>
<th>Final crack length (mm)</th>
<th>Final load (N)</th>
<th>KI_final (MPa·m½)*</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>A17-2</td>
<td>3.35</td>
<td>124</td>
<td>12.74</td>
<td>34</td>
<td>3</td>
<td>70</td>
<td>1.07</td>
<td>70</td>
<td>1.07</td>
<td>4.42</td>
<td>33.32</td>
<td>6.14</td>
<td>Mean value 7.42 MPa·m½</td>
<td></td>
</tr>
<tr>
<td>A17-3</td>
<td>2.63</td>
<td>137</td>
<td>11.45</td>
<td>24</td>
<td>3</td>
<td>70</td>
<td>1.97</td>
<td>70</td>
<td>1.97</td>
<td>4.60</td>
<td>40.12</td>
<td>7.71</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A17-4</td>
<td>120 +/- 5</td>
<td>385 +/- 6</td>
<td>124</td>
<td>34</td>
<td>3</td>
<td>3</td>
<td>70</td>
<td>1.48</td>
<td>1.48</td>
<td>4.94</td>
<td>44.52</td>
<td>8.42</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 11 – Test for determining the KIH factor Sample A17-2, temperature 250°C.
In the literature [15] there is a recommendation that the length of the DHC crack should be 1.5 mm. For the samples presented in the paper, the DHC crack lengths are close to the recommended value (1.07 mm; 1.97 mm; 1.48 mm) and the average value is 1.506 mm. There is also a recommendation for $K_I$'s value. These recommendations [15, 16], provide for $K_I$ the value of 15 MPa·m$^{1/2}$. In the case of the tested samples, the average value of $K_I$ is 12.23 MPa·m$^{1/2}$. 
Based on the results obtained and the measurements of the fracture surfaces, the propagation velocity of the DHC crack was determined. The velocity calculation was done with the relation:

\[ V_{DHC} = \frac{l_{DHC}}{t} \]  \hspace{1cm} (9)

where \( l_{DHC} \) = the length of the crack formed by the DHC mechanism measured metallographically; \( t \) = crack propagation time.

In the case of the tested samples, the crack propagation time is represented by the interval between the moment of application of the load and the moment of the last decrease of the load.

Next, the results obtained for the calculation of the DHC velocity are presented.

Sample A17-2:

\[ V_{DHC} = \frac{l_{DHC}}{t} = \frac{l_{DHC}}{t_f - t_i} \left[ \frac{m}{s} \right] \]

\[ l_{DHC} = 1.07 \text{ mm} = 1.07 \times 10^{-3} \text{ m}; \ t_f = 580448 \text{ s}; \ t_i = 18013 \text{ s} \]

\[ V_{DHC} = \frac{1.07 \times 10^{-3}}{580448 - 18013} = 1.9 \times 10^{-8} \frac{\text{m}}{\text{s}} \]

Sample A17-3:

\[ V_{DHC} = \frac{l_{DHC}}{t} = \frac{l_{DHC}}{t_f - t_i} \left[ \frac{m}{s} \right] \]

\[ l_{DHC} = 1.97 \text{ mm} = 1.97 \times 10^{-3} \text{ m}; \ t_f = 1236523 \text{ s}; \ t_i = 18019 \text{ s} \]

\[ V_{DHC} = \frac{1.97 \times 10^{-3}}{1236523 - 18019} = 1.6 \times 10^{-8} \frac{\text{m}}{\text{s}} \]

Sample A17-4:

\[ V_{DHC} = \frac{l_{DHC}}{t} = \frac{l_{DHC}}{t_f - t_i} \left[ \frac{m}{s} \right] \]

\[ l_{DHC} = 1.48 \text{ mm} = 1.48 \times 10^{-3} \text{ m}; \ t_f = 1177666 \text{ s}; \ t_i = 180078 \text{ s} \]

\[ V_{DHC} = \frac{1.48 \times 10^{-3}}{1177666 - 180078} = 1.48 \times 10^{-8} \frac{\text{m}}{\text{s}} \]
In Table 4, the results obtained for $K_{\text{initial}}$ and $V_{\text{DHC}}$ are structured.

**Table 4**

$K_{\text{initial}}$ factor and $V_{\text{DHC}}$ values

<table>
<thead>
<tr>
<th>No.</th>
<th>Sample</th>
<th>$L_{\text{DHC}}$ [m]</th>
<th>$K_{\text{initial}}$ [MPa $\sqrt{W}$]</th>
<th>$V_{\text{DHC}}$ [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A17-2</td>
<td>$1.07 \times 10^{-3}$</td>
<td>12.74</td>
<td>$1.9 \cdot 10^{-8}$</td>
</tr>
<tr>
<td>2</td>
<td>A17-3</td>
<td>$1.97 \times 10^{-3}$</td>
<td>11.45</td>
<td>$1.6 \cdot 10^{-8}$</td>
</tr>
<tr>
<td>3</td>
<td>A17-4</td>
<td>$1.48 \times 10^{-3}$</td>
<td>12.49</td>
<td>$1.48 \cdot 10^{-8}$</td>
</tr>
</tbody>
</table>

The average value of the DHC velocity obtained during the tests is $1.7 \cdot 10^{-8}$ m/s. This value is comparable to the specialized literature for temperatures in the range of 250–280°C. In reference [16] the average value of the DHC velocity is $3.3 \cdot 10^{-8}$ m/s for Zircaloy-4 CANDU tubes tested at a temperature of 250°C, but the results are scattered (Fig. 14). Possible causes of the scatter are the differences between the metallurgical methods of obtaining and the differences between the testing procedures.

The fact that the obtained results are similar to those provided by the specialized literature (Table 5) confirms that the test procedure is adequate for the testing requirements in the nuclear field and is recommended for future investigations of material properties.

**Table 5**

Comparative presentation of the values of the fracture mechanics parameters

<table>
<thead>
<tr>
<th>Source</th>
<th>DHC crack length [mm]</th>
<th>$K_{\text{initial}}$ [MPa]</th>
<th>$V_{\text{DHC}}$ [10^{-8}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>this work</td>
<td>1.5</td>
<td>15</td>
<td>3.3</td>
</tr>
<tr>
<td>literature</td>
<td>1.506</td>
<td>12.23</td>
<td>1.7</td>
</tr>
</tbody>
</table>

![Fig. 14 – Distribution of DHC velocity values for Zircaloy-4 tubes.](image)
5. CONCLUSIONS

The objective of the work was to determine the interest fracture mechanics parameters through specific tests on the material used as a cladding tube – Zircaloy-4 alloy.

To achieve this objective, it was necessary to go through several stages:

- Through an electrolytic deposition process, followed by a diffusion treatment, hydrogen was introduced into the Zircaloy-4 tubes. The hydrogen concentration obtained was 120+/–5ppm. The hydrogen content was determined using the ELTRA hydrogen analyzer;
- PLT samples were drawn and processed from the hydrated tubes;
- The tests to determine the fracture mechanics parameters were carried out on the creep machine equipped with a stepper motor capable of gradually reducing the applied load;
- Previously, the samples were subjected to cyclic stress to create the fatigue crack, which represents the crack initiation point through the DHC mechanism;
- The load was applied continuously until the crack propagation ceased, at which point the test is considered complete;
- The aim was to determine the value of the stress intensity factor at the crack tip, KIH, and the crack propagation velocity DHC – VDHC;
- The results obtained are comparable to those in the specialized literature, which shows that the method of obtaining the sample, the test procedure, and the methods of investigation and processing of the results are adequate for the testing requirements in the nuclear field.

REFERENCES


