

Fracture Mechanics Tests on CANDU Pressure Tubes Samples

IONESCU Silviu, MINCU Marin, MAN Ion, DINU Laurentiu¹, PRISECARU Ilie²

¹*Institute for Nuclear Research Pitesti, RATEN, Romania;*

²*University Politehnica of Bucharest, Romania.*

Corresponding author's e-mail: silviu.ionescu@nuclear.ro

INTRODUCTION

There are two types of tests for Pressure Tubes (PT) properties characterization and to define the mechanisms responsible for their degradation: tensile tests and fracture mechanics tests.

Tests of fracture mechanics on pressure tube samples

The high-strength materials, which rupture is preceded by low levels of plastic deformation associated with brittle fracture type, one accepts the hypothesis of linear elastic behavior in the region of the crack tip. Here the crack is primed and the break develops. The material feature is given by the stress intensity factor "K" size, which is a measure of the stress increase in the presence of cracks, compared to the stress in absence of cracks. [1], [2].

Crack propagation takes place when breaking surfaces situated on either side of the crack plane are moving with respect to each other. Depending on the relative displacement of the crack surfaces there are three modes of propagation: by opening (mode I), by front sliding (mode II) and sideways sliding (mode III).

If brittle fracture crack extension takes place according to the mode I, then the characteristic parameter of this method of breaking is K_I .

Regardless of the crack propagation mode, the stress intensity factor K is given by:

$$K = f(g)\sigma\sqrt{a} , \quad (1)$$

Where: $f(g)$ - parameter depending on the geometry of the sample and crack;

σ - applied tension;

a - crack length.

According to the principles of the breaking mechanics, if the K factor at the crack tip reaches the critical value, K_{IC} [3], then the rupture is unstable.

K_{IC} is related to the intrinsic ability of the material to withstand the intensity of the field voltage on the tip of a crack during its extension, where plane strain conditions apply. The factor K_{IC} is also called fracture toughness.

The K_{IC} value can be considered a material characteristic which reflects the resistance to the initiation of the propagation for an existent crack. Achieving plane strain condition for determination of K_{IC} is possible only in thick plates where the deformation is prevented (plastic constraint) in the direction of the crack front (across the plate) for mode I of propagation.

TESTS OF FRACTURE MECHANICS ON PRESSURE TUBE SAMPLES

Types of fracture mechanics tests:

- Uniaxial tensile tests;
- K_{IH} type testing and DHC (Delayed Hydride Cracking)
- Fracture mechanics: Tenacity determination - K_I factor

Uniaxial tensile tests

Depending on the interest temperature range, ambient temperature respective high temperature, the tensile test will be performed according to ASTM E 8M, respective ASTM E 21. One uses plain samples, obtained out of the pressure tube (on transversal and longitudinal direction) in order to determine:

- Tensile test diagram (load - extension);
- Specific material diagram (tensile stress – tensile strain);
- Tensile strength;
- Yield strength (offset=0.2%)
- Ultimate tensile strength (UTS);
- Elastic limit;
- Elongation.

K_{IH} type testing and DHC

The initiation of DHC type crack, the associated limit load setting, and the determination of its propagation velocity are highlighted in specific fracture mechanics tests, namely K_{IH} and DHC type tests [1], [2]. Mechanical tests are carried out in conditions of heat cycling coupled with an uniaxial mechanical stress on the CT or C-ring type specimen [5].

The K_{IH} test comprises the following sequences:

1. Fast heating to approx. 3-5 °C/min up to a temperature threshold value which must be present to provide the initial dissolution of the hydride material. The maximum temperature is chosen so that it is larger than the temperature corresponding to the solubility threshold TSS of hydrides in the Zr-Nb base matrix.
2. Maintaining sample temperature in landing for at least 30 minutes;
3. Cooling by 1÷2 °C/min until reaching the targeted heat temperature of interest, corresponding to the intended test material;
4. Applying a load so that the value of stress intensity factor at the crack tip is approximately 14 MPa · m^{1/2}.
5. Effort under constant load until the crack propagates along a length of a few tens of microns (eg 30 µm), when the load is reduced by about 3%;
6. Making of mechanical cycles under constant load associated with crack length increases;
7. Re-start of the cycle until the crack is no longer propagated for 24 - 36 hours;
8. Applying an uniaxial stress until the rupture of the sample;
9. Fracture surface analysis and determination of the crack length.

The DHCV test includes:

The first 4 steps have to be done exactly as in the case of the K_{IH} test.

5. Effort under constant load corresponding to $K_I = 14 \text{ MPa} \cdot \text{m}^{1/2}$ until the crack reaches a length of 1-1.5 mm;
6. Applying an uniaxial stress until the rupture of the sample;

7. Analysis of breaking surface and determination of the crack length.

In Figure 1 is shown the PC display during data acquisition for the K_{IH} test.

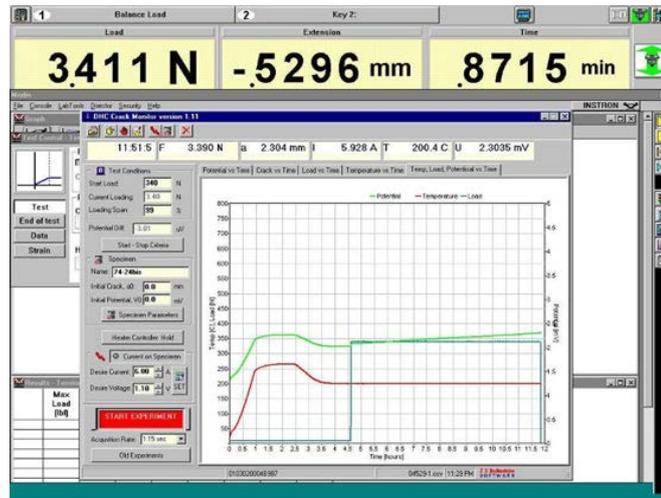


Figure 1: DHC test charts

The DHCV and K_{IH} tests can be coupled and the testing is carried out on a single sample.

In this case, one performs the 1-6 steps of the K_{IH} test, then the load is increased to a value corresponding to the intensity factor of the stress at the crack tip of about 14 $\text{MPa}\cdot\text{m}^{1/2}$ and the testing continues until the DHC crack reaches 1-1.5 mm in length. In the end, the sample breaks under uniaxial load.

Regardless of the type of test performed, K_{IH} or DHC, one assesses the fracture surface in order to measure the actual crack length $a_{K_{IH}}$, a_{DHC} .

For this purpose, the method of 9 equidistant segments (9 equi-spaced reference lines) is used. The method consists in measuring the length of nine equidistant segments drawn on the breaking surfaces of the tested sample and the length will be:

$$\Delta a = \frac{1}{9} \sum_{i=1}^9 a_i, \quad (2)$$

if the front looks like the one presented in Figure 2a (constant velocity)

$$\Delta a = \frac{1}{8} \left(\frac{a_1 + a_9}{2} + \sum_{i=2}^8 a_i \right) \quad (3)$$

if the front looks like the one presented in Figure 2b (variable velocity).

The DHC crack velocity is the ratio between the DHC crack length a_{DHC} and the time t while the sample was under constant load:

$$Velocity_{DHC} = \frac{a_{DHC}}{t} \quad (4)$$

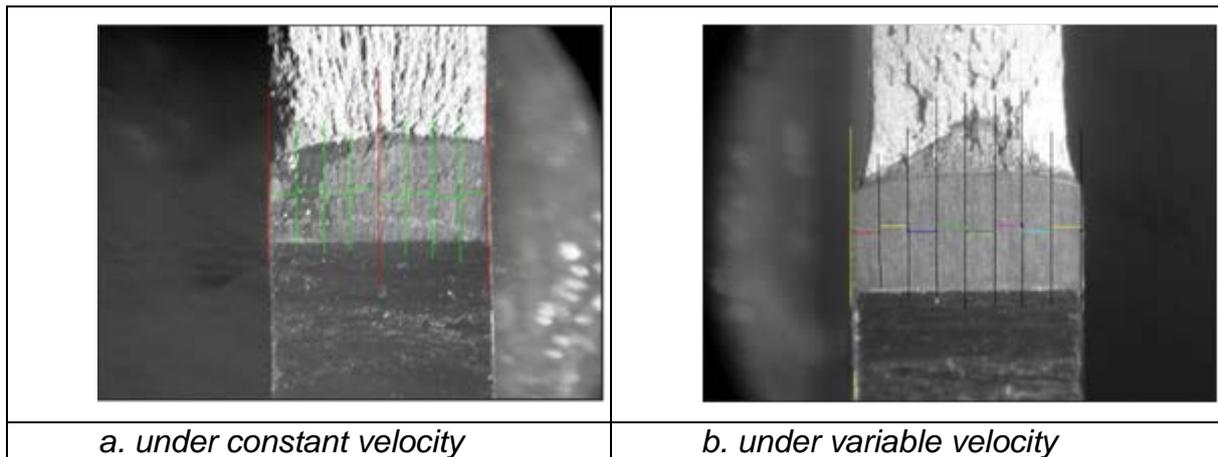


Figure 2: Aspect of the DHC crack propagation

Tenacity determination - K_{Ic} factor

For high-strength materials (including Zr -2.5 % Nb alloy) or conditions that lead to decreased plastic deformation (e.g. due to hydrogen embrittlement, neutron irradiation) the K_{Ic} criterion is valid for initiation of unstable crack propagation.

The factor of the critical intensity of the stress K_{Ic} for mode I of breaking (defined as the resistance opposed by the material at the extension of the crack under plain strain conditions) is determined by the method developed in ASTM E- 399, [4].

This standard uses the finding that the K_{Ic} factor decreases with increasing sample thickness reaching a constant minimum value K_{Ic} under the conditions of a plane state of deformation. In such situations, the crack instability leads to complete rupture of the material immediately following the crack initiation phase. Initial crack growth occurs at the same stress intensity value for a given material.

Given the foregoing considerations, ASTM E- 399, [4] impose restrictive conditions:

- selecting the shape and dimensions of the specimen (thickness greater than 1.6 mm);
- making and sizing the mechanical notch obtained by cycling;
- working with actual experimental curve for determination of K_{Ic} .

The recommended standard mentions two types of samples:

- Samples type CT or C –ring - tensile required;
- Sample type "notch - bend specimen" - bending required.

These types of samples shows a stress concentrator in the form of prolonged mechanical notch made by a fatigue crack.

ASTM E- 399 imposes severe restrictions on the sample size to satisfy plane strain conditions and to enable the application of fracture mechanics assumptions -approximately linear – elastic behaviour.

The test procedure includes the following steps:

- selecting the type of sample;
- establishment of critical dimensions depending on the material thickness, "B", which also is chosen based on its elasticity modulus and flow stress;
- one has to achieve compliance with the conditions of initial notch (it has to be between 0.45 to 0.55 W) in cycling conditions in order to obtain an ideal plane crack with zero radius. The cycle -induced fracture length should extend from at least 0.05 W to no more than 1.3 mm in order to eliminate the effects of the mechanical construction of the

notch. The number of cycles is around 104-106, depending on the notch depth, mechanical type specimen and stress.

- the testing itself - tensile or bending tests – is done by applying a static load so that the growing speed of the factor KI is between 0.55-2.75 MPa m^{1/2}/s [2]. These curves are not perfectly linear. In order to determine the critical force corresponding to the value K_{IC}, one uses different criteria such as: the deviation from linearity, the peak load value, the offset method, the secant offset method. In ASTM E-399 is recommended the method of the secant whose slope is 5 % lower than the slope of the initial tangent of the linear segment (Figure 3). The intersection of the secant with the P- Δ curve represents the P5 force that is used when calculating the critical value K_{IC}. It is assumed that the value of P5 corresponds to the force which leads to an extension of the crack of 2% from its initial value.

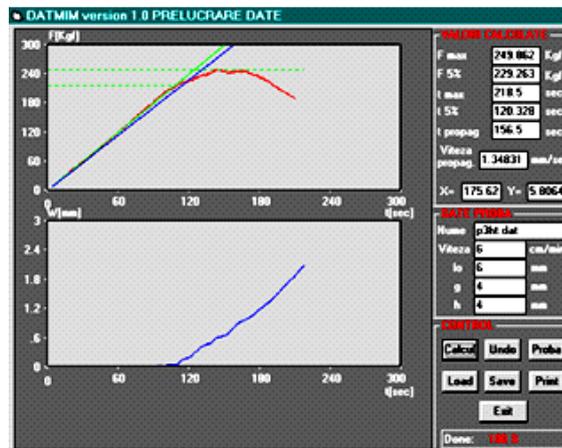


Figure 3: K_{IC} determination

- the calculated ratio Pmax/P5 must satisfy the condition

$$P_{max}/P_5 \leq 1.1 \tag{5}$$

If the above condition is met, then K_Q is calculated with standard formulas. Here is an application example for uniaxial tensile test and a CT type sample:

$$K_Q = \frac{P_5}{BW^{1/2}} \left[29.6 \left(\frac{a}{W} \right)^{1/2} - 185.5 \left(\frac{a}{W} \right)^{3/2} + 655.7 \left(\frac{a}{W} \right)^{5/2} - 1017.0 \left(\frac{a}{W} \right)^{7/2} + 638.9 \left(\frac{a}{W} \right)^{9/2} \right] \tag{6}$$

where: P₅ is the force corresponding to a crack extension of 2%;
 K_Q - value of stress intensity factor corresponding to P₅ force;
 a, B, W - specimen initial crack size, type CT.
 One checks if the value K_Q satisfies the condition:

$$a, B \geq 2.5 \left(\frac{K_{IC}}{\sigma_{flow}} \right)^2 \tag{7}$$

in which case K_Q = K_{IC}.

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The testing for measuring the crack initiation and the speed of crack propagation is done by the monitored potential variation method. The testing includes steps 1-4 of testing for evidence of type DHC crack initiation after the request is made under constant load (14 to 15 MPa) until the crack aDHC measured by the variation in potential reaches 1-1.5 mm.

During the assay, one monitors the evolution in time of the temperature distribution $T = f(t)$, the applied load $F = f(t)$ and the change in the potential $P = f(t)$ to measure the DHC fracture.

The initial load value corresponds to the applied stress intensity factor at the crack tip about $14\text{-}15 \text{ MPa}\cdot\text{m}^{1/2}$ and is calculated as:

$$K_I = P_Q / (BW^{1/2}) \cdot f(a/W) \quad (8)$$

where: P = applied load on sample (N);

t = thickness of the tube wall (m);

W = width of the sample (m);

a = initial crack length (m);

$f(a/W)$ = dimensionless relationship whose expression is given in ASTM E-399 depending on the geometry of the test sample.

For K_{IH} calculation we consider the value of the last stage for which the crack never propagated for at least 24 hours.

Tests are performed on CT or C-ring sample types, depending on the PT direction on which the tenacity has been determined (either axial or transversal direction).

RESULTS

Sampling

For each type of testing method, specific standard samples were manufactured [6].

So, for K_{IH} , DHC type tests the geometry samples meet the requirements of specific standards fracture mechanics tests [4] being used samples of the C-ring or CT type.

The C-ring samples have a certain configuration so that the direction of crack propagation is radial.

Figure 4 shows the shape and dimensions of the "C" specimens:

- a - crack depth 0.75 mm;
- W - material thickness 4.1 mm;
- B - width is 3.3 mm;
- X - distance between the loading axis and the surface cracked 0.75 mm.

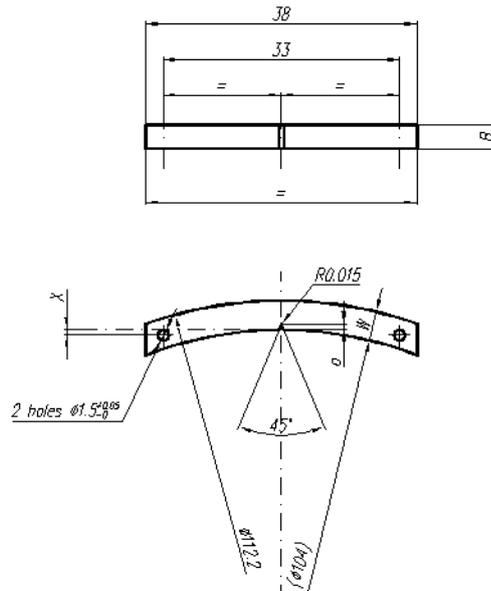


Figure 4: Geometry of "C" type sample

The "C" type sample is obtained by cutting the arcs of a ring. Taking into account the recommendations of the ASTM 399 [4] and the pressure tube dimensions, the specific dimensions of the "C" type sample are those given in Figure 4.

The main characteristics of the specimens are:

- Crack depth ($a = 0.75$ mm);
- Material thickness ($W = 4.1$ mm);
- The width of the material ($B = 3.3$ mm);
- The distance between the axis of the load and the cracked surface ($X = 1$ mm);
- The angle between the crack flanks ($\alpha = 45^\circ$);
- The radius of the crack tip ($r = 0.015$ mm);
- Total length ($l = 38$ mm);
- Diameter mounting holes ($F = 1.5$ mm);
- The distance between the mounting holes ($l_g = 33$ mm).

The CT type samples are taken in the axial direction of the pressure tube, Figure 5, whereas the C-ring type samples are cut in the transverse direction of the PT wall. The choice of specimen is based on the direction of the pressure tube on which correspond the measurement of parameters of interest (K_I , J, DHC velocity).

According to ASTM E-399 [4], the main characteristics of the CT type sample are:

- $W = 17$ mm (width of the sample);
- $A = 8.25 \div 8.5$ mm (crack depth, including the pre-notch, min. 1.5 mm);
- $B = 4$ mm (width of the sample).

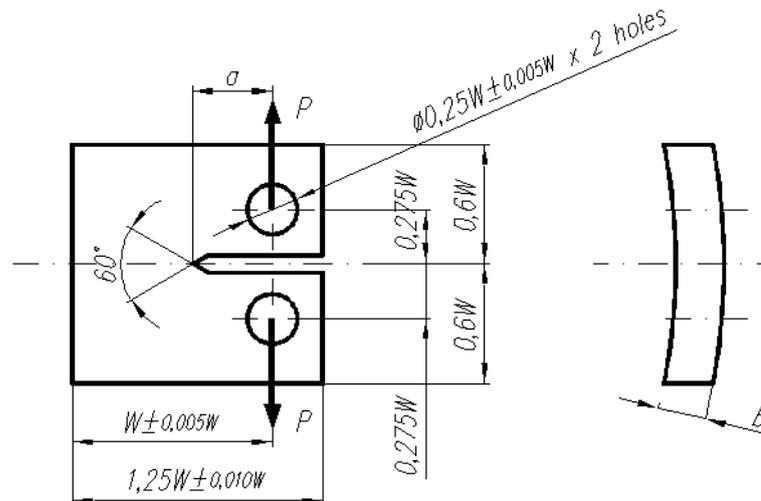


Figure 5: Geometry of CT type sample

CONCLUSIONS

The main purpose of this paper is the implementation of fracture mechanics tests on "C" and CT type samples in PIEL. These tests will be part of the assessment methodology for the PT out of service from Cernavoda NPP and will be used to define the mechanisms responsible for their degradation.

This paper refers to investigative techniques used in Post -Irradiation Examination Laboratory in INR Pitesti for the analysis of pressure tubes.

We designed devices needed for the tests to be performed on "C" and CT type samples using the Instron Model 5569 tensile machine existing in PIEL.

This paper has applicability by supporting research topics proposed within the Cernavoda NPP - INR Pitesti protocol cooperation, part of the Program for the development of the methodology for the analysis and evaluation of critical components of CANDU fuel channels.

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