# FATIGUE CRACK INITIATION AT COMPLEX FLAWS IN HYDRIDED Zr-2.5%Nb SAMPLES FROM CANDU PRESSURE TUBES

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## ABSTRACT

The paper addresses the phenomena which occur at locations where the oxide layer of the inner surface of CANDU tube pressure is damaged by the contact with the fuel element or due to the action of hard particles at the interface between the tube pressure and bearing pad of fuel element. In such situations generate defects, which most often are defects known as "bearing pad fretting flaws" or "debris fretting flaws". In this paper the experiments are completed in a series of previous works on the mechanical fatigue phenomenon on samples prepared from the pressure tube Zr-2.5% Nb alloy. The phenomenon of variable mechanical stress (or fatigue) may lead to initiation of cracks at the tip of volumetric flaws, according to the accumulation of hydrides, which then fractures and can propagate through the tube wall pressure due to the mechanism of type DHC (Delayed Hydride Cracking).

**Key words: Zr-2.5% Nb, hydrides, DHC, mechanical fatigue, volumetric flaws**

## Introduction

The pressure tube is made of Zr-2.5% Nb alloy which is an alloy of zirconium with a high susceptibility to corrosion from aqueous temperatures and mechanical stresses in the CANDU reactor. During normal operation there is a potential of certain defects to start on the interior surface of the pressure tube.

The flaws on the wall of the pressure tube, including the type and BPFF and DFF, promote setup the fragile zirconium hydrides (called platelets δ- hydrides or $Zr\text{-}H_{1.66}$) in areas of their tip, where it exceeds the solubility limit of hydrogen / deuterium absorbed for a given temperature. These components are fragile and they fracture in some specific mechanical and thermal stress conditions, especially when there is the phenomenon of continuous accumulation of hydrogen / deuterium in the volume of material. Fracturing process may continue in the typical sequence process, which is known as the "phenomenon of sequential slow hydride cracking under mechanical stress traction". This is also known in the scientific literature under the generic name "phenomenon DHC" (Delayed Hydride Cracking) [1].

- *Description Basquin curves (S-N) to characterize the phenomenon of fatigue in the presence of flaws*

One of the criteria in the assessment of phenomena of mechanical fatigue in metal component is given by the dependence of the mechanical stress cycles to failure (N) on the applied mechanical stress (S) (or stress amplitude), so-called S-N curves. They can characterize the fatigue behavior on broad area, namely from low cycle fatigue (elasto-plastic range - $10^3$ cycles) to areas of high cycle (elastic range – $10^6$ cycles).

From the mathematical point of view, the lifetime relationship represented by the number of cyclic loading (N) and applied stress amplitude (S) is given by Basquin relationship:

$$S_a^k \cdot N = const. \qquad (1)$$

where *a* and *k* are constants obtained from experimental tests.

A flaw found on the inner surface of the pressure tube at periodic inspections performed on the fuel channels, is subjected to analysis according to the Canadian standard CAN / CSA N285.8.

## Experimental test program test for the mechanical fatigue cracking initiation

In the experimental program of fatigue testing the samples cut from Zr-2.5%Nb rings were used at different hydrogen concentrations. Each sample has been prepared as “C shape” type specimen with complex defects (BPFF combined with DFF) (Figure 1). The following steps were applied:

a. The samples were hydrided up to the 30-90 ppm concentration;
b. Thermal cycling under constant load has been applied in order to achieve reorientation hydride hydrides at the flaw tip.

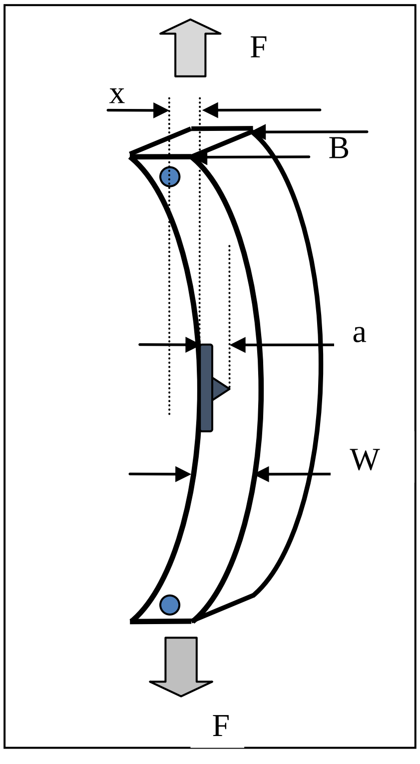

**Fig.1**. *The C-type specimen having complex-type defects (BPFF combined with DFF)*

The C-type specimen preparation for fatigue testing has been described in previous works devoted to the subject [2,3]. Rings were initially charged mechanically by turning a pressure tube segment, Zr-2.5% Nb alloy. To obtain the reorientation phenomenon hydrides the specific tests have been carried out by thermal cycling [2,3]. Thus, the creep ADAMEL machine was used with an experimental setup to allow thermal cycling treatment of the samples under controlled load type defects hydride complex, which is shown in Figure 2.

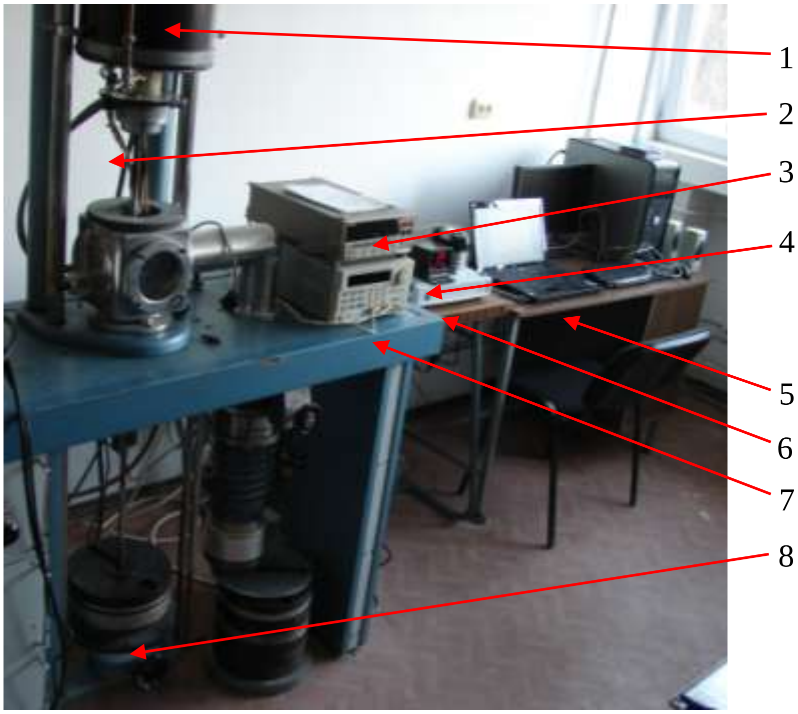

**Fig. 2.** *Experimental for achievement the re-orientation of the hydrides at complex flaw tip (BPFF combined with DFF)*

The experimental setup described in previous papers [2,3] is shown in Figure 2 and contains the following components of the experimental chain:

1. the oven;
2. sample clamping device;
3. digital multimeter;
4. temperature regulator;
5. PC data acquisition;
6. signal amplifier (Spider);
7. AC power;
8. Load sample platters.

By means of the optical microscopy, the microstructure characterization of specimens was performed after treatment of localized reorientation of hydrides and after mechanical fatigue testing. Some comments are given in the next.

- Characteristics of defects before fatigue testing. To characterize the initial flaw geometry and the reorientation of hydrides at flaw tip the following actions were done: the digital measurements on both sides of the samples for V flaw depth and root radius, and of the angles between the flaws planes as well.
- Characterization of the microstructural morphology of the tested specimens. It was considered to highlight the first crack which started on the one specimen side following the hydrides located at the flaw top, and appearance of fatigue crack growth path.

From Figures 3 to 5, one may note that there are small differences between defect depths in V at the flaw region, but errors are small. Also, the examinations performed on both sides of the samples, show a quite geometric uniformity throughout the sample thickness.

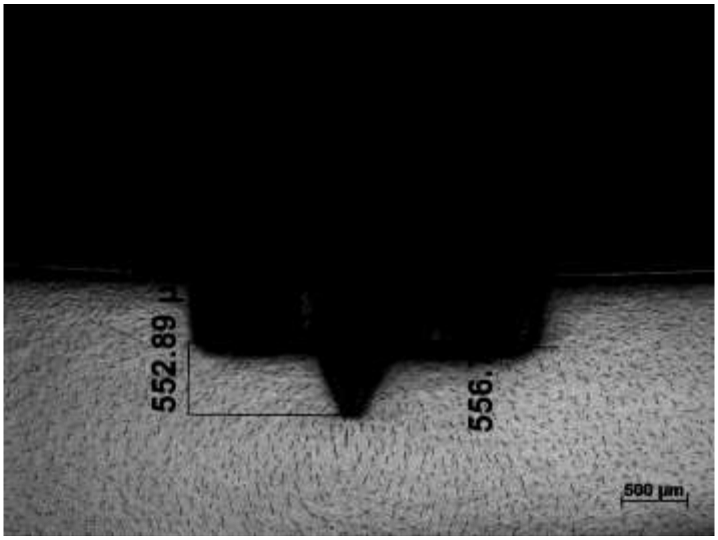

**Fig. 3.** *The micrograph R19, with 30 ppm hydrogen and complex flaw*

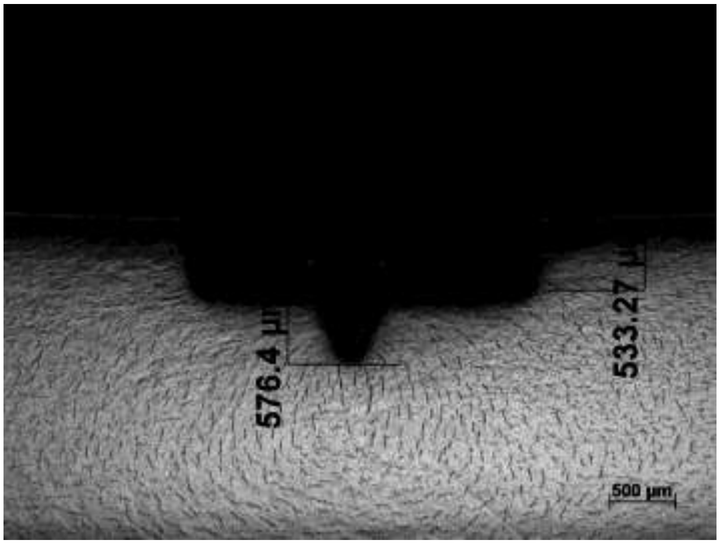

**Fig. 4.** *The micrograph R15, with 50 ppm hydrogen and complex flaw with hydride reorientation*

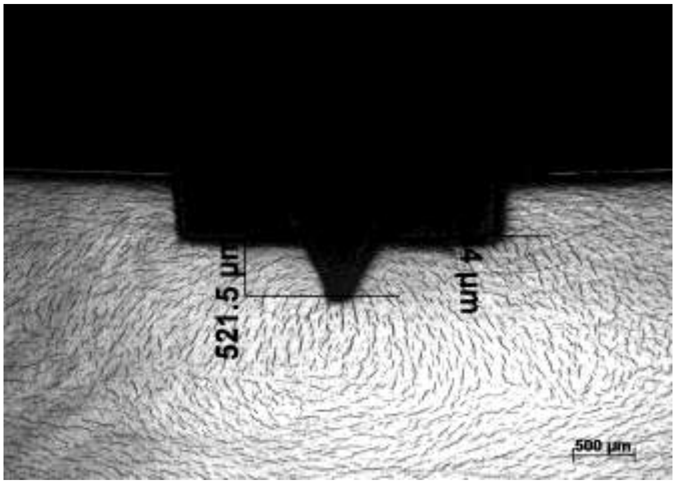

**Fig.5.** *The micrograph R31, 90 ppm hydrogen, micro aspect of the localized hydrides*

Micrographs of the samples with complex defect (3 to 5) before fatigue testing, showed the reorientation of hydrides located at the flaw. The reorientation of hydrides has a specific form of the platelets disposition and it can be seen that regardless of the concentration of hydrogen introduced into evidence at the flaw region exists platelets oriented perpendicular to mechanical stress, more precisely, platelets having radial orientation in the tube pressure. This induces an intrinsic fragility of this area, which will be subject to high mechanical stresses during cyclic stressing, and therefore the fatigue crack initiation in this area is obvious.

Mechanical stresses of the mechanical fatigue tests induce high stresses in the DFF area located at the V flaw tip that acts as a mechanical stress concentrators. Thus, fatigue cracks will be initiated in these areas.

Figure 6 for a sample with a concentration of 30 ppm, suffered a crack initiation effect "tunneling" practically hydrides located at some distance from the flaw of the defect have suffered the phenomenon of the-cohesion and were broken.

To concentrations of 90 ppm (Figure 7) the initiation of fatigue cracks occur simultaneously in several hydrides favorably oriented (perpendicular to the direction of mechanical stress). Moreover, it can be said that the area of the crack flaw is full of "initial cracks" because each hydride platelet, with appreciable thickness could be itself a crack.

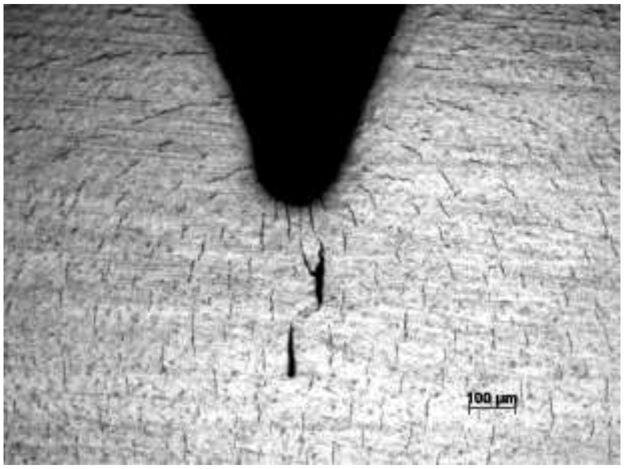

**Fig. 6.** *Metallographic appearance of cracks in the sample R19, 30 ppm hydrogen, after fatigue*

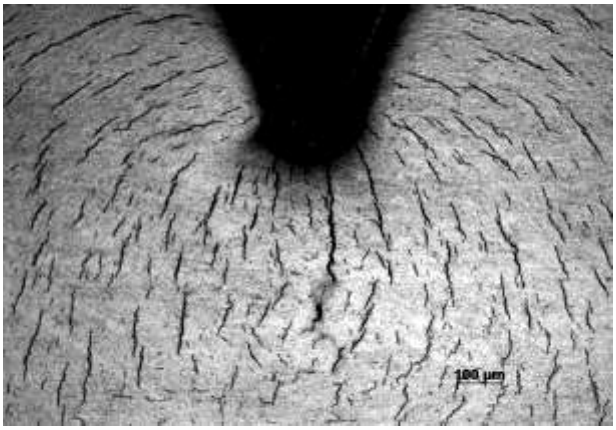

**Fig. 7.** *Metallographic appearance of cracks in the sample R31, 90 ppm hydrogen, after mechanical fatigue*

From the metallographic examinations the initiation of fatigue cracks occurs only at the V-type flaw tip (DFF), placed on the flaw bottom. This is due to the higher mechanical stresses at the flaw of the region in V.

The experimental fatigue data obtained from present studies were prepared for an inter-comparison with fatigue curve prescribed in this Canadian standard CAN / CSA N285.8-05 .

The Canadian standard CAN / CSA 285.8 [1] requires the evaluation of inspection data on fuel channels, blunt flaws (or volumetric) and analyses for the fatigue crack initiation. The assessment methodology is based on the inter-comparison with the curve of fatigue crack initiation for blunt flaws. The generic name of "blunt flaws", which refers to the Canadian standard is based only on the experimental tests with samples with V- type flaws (DFF).

The results of the fatigue tests (complex flaws) from present work are processed and are shown in Figure 8. There are symbolized distinct hydrogen concentrations of specimens. Important to note that the results obtained in this paper are reported to the fatigue curve as they are described by the Canadian standard CSA N285.8-05.

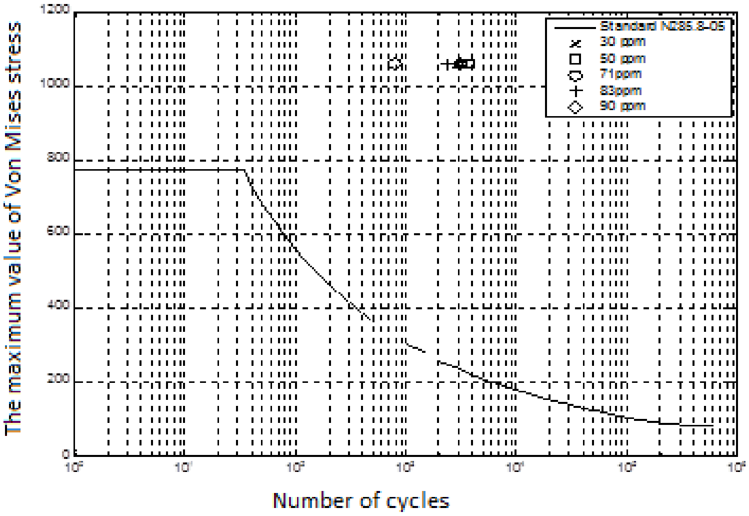

**Fig.8.** *The experimental results of the fatigue on Zr-2.5%Nb specimens with complex flaws and fatigue curve from N285.8*

The experimental results concerning of the life time are shown by the number of N cycles up to crack initiation versus the Von Mises amplitude stress. Moreover, it appears that the lifetime points displayed in the Figure 8 are in the safe region relatively away from the curve that separates the safe from un-safe region, for complex flaws (BPFF with DFF). Thus, one can see that the experimental results obtained in this paper are in good agreement with the standard assessment methodology.

## Conclusions

1. The C-type specimens were prepared from the circumferential direction of the pressure tube CANDU Zr -2.5% Nb alloy with different hydrogen concentrations (30 ppm - 90 pp), and further subjected to an initial heat treatment in order to achieve hydride reorientation at the complex flaw tip (BPFF combined with DFF).
2. The specimens were subjected to the mechanical fatigue tests with specific parameters.
3. The microstructural investigations reveal both the morphological appearance of hydride platelets orientation and the characteristics of initial crack propagation.
4. The experimental results concerning of the life time are shown by the number of N cycles up to crack initiation versus the Von Mises amplitude stress (Basquin curve). It appears that the lifetime points for complex flaws (BPFF with DFF) are in the safe region relatively away from the curve, which separates the safe from un-safe region.
5. Thus, we may conclude that the experimental results obtained in this paper are in good agreement with the N285.8 standard assessment methodology.

## References

[1] CAN/CSA Standard N285.8-05: “Technical requirements for in-service evaluation of zirconium alloy pressure tubes in CANDU reactors”, 2005

[2] V. Radu, “The study of the impact of damage to the oxide layer on the inner face of the tube by the pressure of the coolant impurities hard to contact pressure tube “, RATEN ICN internal Report.

[3] V. Radu, „The study of fatigue crack initiation at Debris Fretting Flaw in the pressure tube”, RATEN ICN internal Report.