THE INITIATION OF FATIGUE CRACKING IN ZR-2.5%NB CANDU PRESSURE TUBE AT TYPICAL END-OF-LIFE HYDROGEN CONCENTRATIONS

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Abstract

In-service inspections of CANDU Zr-2.5%Nb pressure tubes may reveal blunt flaws that include debris fretting flaws (DFF), fuel bundle bearing pad fretting flaws (BPFF). Although the flaws are not an immediate threat to the tube integrity, a fatigue crack may initiate flaws due to cyclic loads. For this reason, it is necessary to evaluate the flaw in fatigue crack initiation. The CSA Standard N 285.8 contains acceptance criteria to evaluate DFF and BPFF type of flaws. The paper presents a methodology of the mechanical fatigue tests performed in RATEN ICN on the Zr-2.5%Nb pressure tube specimens containing complex flaws. The lifetime is determined at the mechanical fatigue stress by a Basquin type relation, as fatigue crack initiation curve in the number of cycles and mechanical stress coordinates. The results can be used for the structural integrity analyses of pressure tubes in CANDU fuel channels subject to periodic inspections.

Keywords: *Mechanical fatigue test, Basquin equation, CANDU pressure tube, Zr-2.5%Nb*

Introduction

In-service inspections of CANDU Zr-2.5Nb pressure tubes may reveal blunt flaws that include debris fretting flaws (DFF), fuel bundle bearing pad fretting flaws (BPFF), mechanical damage flaws and crevice corrosion marks. Although the flaws are not an immediate threat to the tube integrity, a fatigue crack may initiate flaws due to cyclic loads. Fatigue crack initiation must be accounted for in design and during service when blunt flaws are dispositioned. For this reason, it is necessary to evaluate the flaw in fatigue crack initiation. In the relevant Canadian scientific literature, it is also mentioned that it is necessary to treat the curves specific to each type of defect separately.

This paper presents a methodology developed in RATEN ICN for mechanical fatigue tests performed on Zr-2.5%Nb pressure tube specimens containing complex flaws (debris fretting flaw combined with fuel bundle bearing pad fretting flaw) with a given depth. The specimens of interest are C-shape type with complex flaws and hydrogen concentrations exceeding terminal solid solubility, in the interest range for pressure tube end-of-life.

The experimental procedure consists in the following main steps: specimen preparation (formation of notch-tip hydrides), mechanical fatigue tests and data processing. Hydride formation involves the hydrogen migration under thermal cycling and stress gradient, hydrides precipitation and reorientation in the region of the stress spots. The mechanical fatigue test for this study consists of cycling loading with a given mechanical load amplitude, up to the fatigue crack initiation. The lifetime is determined at the mechanical fatigue stress by a Basquin type relation, represented graphically as fatigue crack initiation curve in the number of cycles & mechanical stress coordinates. The Basquin equation was obtained by fitting the experimental fatigue points, having the coordinates (alternating von Mises stress vs. number of cycles up to the fatigue crack initiation). The results can be used for the structural integrity analyses of pressure tubes in CANDU fuel channels subject to periodic inspections.

Experimental work

The following test parameters and conditions are investigated for their potential effect on fatigue crack initiation properties: specimen type, notch root radius, hydride formation thermal cycle, test temperature, minimum load/maximum load cycle, loading frequency, and specimen orientation. The general test procedure included two steps: specimen preparation (formation of notch-tip hydride) and fatigue test.

Specimen's preparation

These tests are performed on transverse C-shape type specimens (Fig.1) prepared from an as-received CANDU pressure tube, with the complex notch (debris fretting flaw combined with fuel bundle bearing pad fretting flaw) and hydrogen concentrations exceeding terminal solid solubility. Orientation of hydrides at the tip of the notch involves a pre-conditioning procedure that consists of thermal cycles of the samples under constant loading.

Sample preparation consists of following operations [1-3]:
a) *Blank specimens*: were prepared from the as-received pressure tube section;
b) *Specimens hydriding*: material was first hydrided by electrolytic technique and diffusion - annealed at 365 ºC;
c) *Hydrogen concentration* of hydrided samples was determined by using the hot inert gas extraction technique;
d) *Complex notch geometry*: was machined on the inside diameter (ID) surface of the blank specimen in radial - axial plan as in Fig. 1 (nominal notch depth is up to 1 mm and the range of root radius is 20÷50 μm);



Fig. 1. Image of the C-shape specimen with a complex notch

e) *Hydride formation*: The hydrogen concentrations of test specimens have values in the interest range for pressure tube end-of-life. In order to obtain the notch-tip hydrides, the specimens were subjected to some pre-conditioned hydride formation thermal cycles before fatigue testing, under the specified load P_f. The thermal cycle (creep cycle at 360 ºC and ratcheting cycle with a peak temperature of typically 340 ºC) is illustrated in Fig. 2.

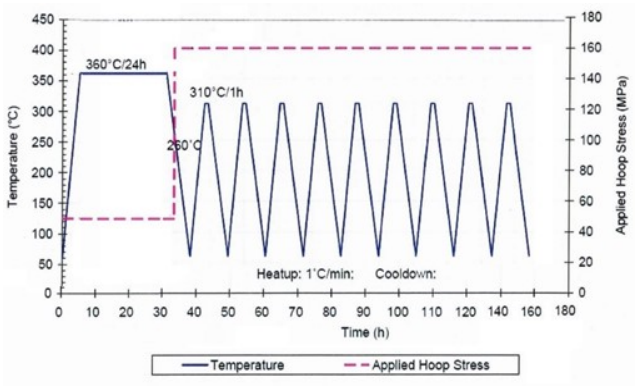


Fig. 2. Schematic diagram for the ratcheting thermal cycles

f) *Metallographic examination*: before the overload tests the specimens were metallographically examined. The notch-tip hydrides were examined in an optical microscope. Thus, the hydrides morphology, the notch depth and root radius have been determined (Fig. 3).

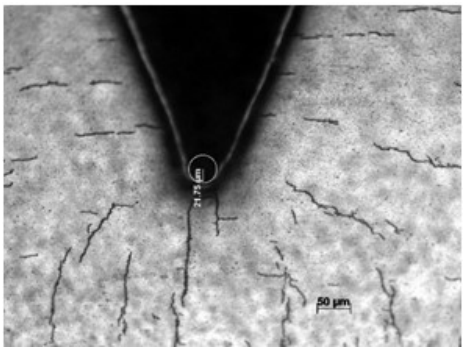


Fig. 3. Metallographic examination of notch-tip hydrides (50 ppm)

After the process area was formed, the samples were subjected to mechanical fatigue tests.

Fatigue tests set-up

The mechanical fatigue tests consist of application of elastic stress at the notch-tip on individual samples until fatigue crack initiation. The elastic stress structure for this study consists of mechanical cycles with the same loading amplitudes (Fig. 4).

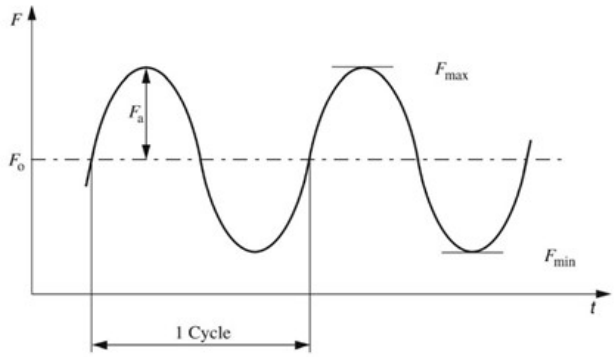


Fig. 4. Fatigue testdiagram by mechanical cycles (the field of mechanical demand $F_{min} \div F_{MAX}$)

Fatigue crack initiation tests were performed in an air environment at a given working temperature of maximum 360 ºC, using a Walter+Bai hydraulic testing machine (Fig. 5).

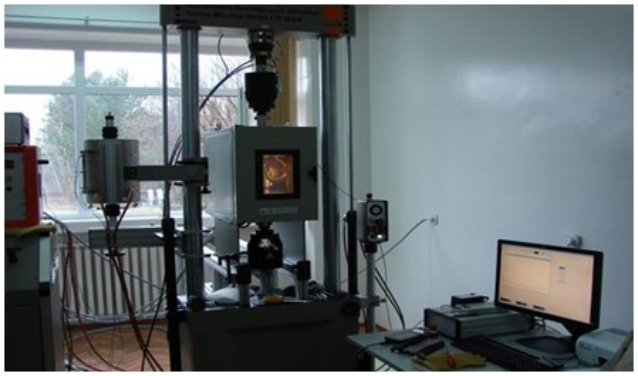


Fig. 5. Walter+Bai hydraulic testing machine

Metallographic examinations

After performing the overload tests, the specimens were metallographically examined. The flaw-tip hydrides were examined with the optical microscope. Thus, the cracked hydrides morphology has been determined (Fig. 6).

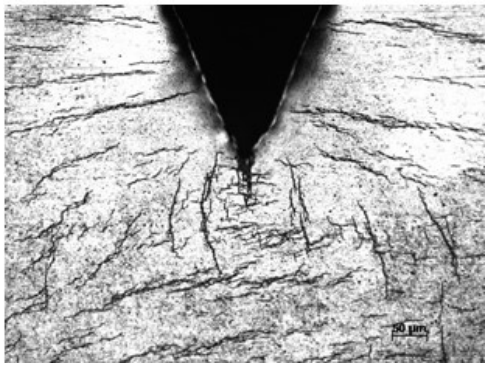


Fig. 6. Crack-tip hydrides optical micrographs close to flaw root (70ppm)

Experimental data processing

To characterize the initiation of fatigue cracking at a complex defect (the lifetime prediction), after performing the fatigue tests for each sample, several stages of processing the experimental data obtained are needed and will be given in the following.

(1) Calculation of the significant parameters characterizing the fatigue stress of samples with a complex defect (debris fretting flaw combined with fuel bundle bearing pad fretting flaw), such as:

- extreme values of load applied to the specimen F_{min} and F_{MAX};
- nominal mechanical stresses $\sigma_{n\min}=\frac{F_{min}}{S_0}$, $\sigma_{nMAX}=\frac{F_{MAX}}{S_0}$ in [MPa], where S_0 = specimen area (width x thickness);
- the von Mises stress fields are obtained at the minimum nominal stress ($\sigma_{n\ min}$) and maximum nominal stress ($\sigma_{n\ MAX}$), respectively, (see Fig. 7), by simulating using with the finite element method and the VisualFEA software [4-6];
- for each von Mises stress field, the von Mises stress maximum value at the notch tip is determined (elastic minimum peak stress $\sigma_{n\min}^{V\,MAX}$ and elastic maximum peak stress $\sigma_{nMAX}^{V\,MAX}$);
- the range of nominal mechanical stresses ($\Delta\sigma_n$), $\Delta\sigma_n=\sigma_{nMAX}^{V\,MAX}-\sigma_{n\min}^{V\,MAX}$;
- the alternating von Mises stress $S=0.435\times\Delta\sigma_n$ [7].

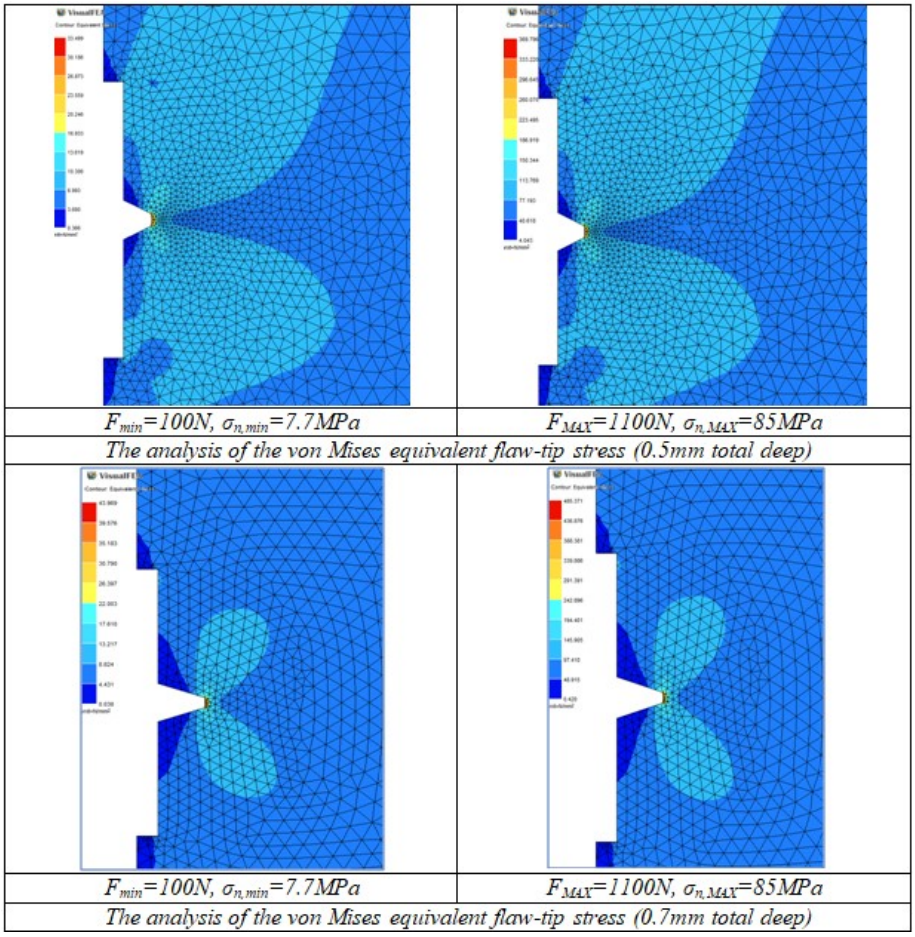


Fig. 7. Analysis of the mechanical stresses state by the VisualFEA software

(2) Graphical representation of the pairs of values for each tested sample: the alternating elastic von Mises peak flaw-tip stress (S) values vs the number of load cycles to crack initiation (N) (Mechanical stress - Number of cycles (S-N) coordinates).

By fitting experimental data with a Basquin type relation (see the equation below), a dedicated "curve of fatigue crack initiation" (fatigue curve) is obtained (see Fig. 8):

$$S_a = S_0 \cdot N^{-\sigma}$$

where the parameters have the following meanings:
S_a - the value of the alternating elastic tension von Mises amplitude;
S_0 - the coefficient of resistance to fatigue (which usually depends on the minimum radius of curvature of the defect and possibly on the angle between the flanks of the defect);
α - a constant obtained from experiments;
N - the number of cycles of stress on mechanical fatigue.

Thus, the initiation of the fatigue crack (the lifetime of the material) can be characterized.

The FFSG (Fitness For Service Guidelines) fatigue crack initiation evaluation curve - «Fatigue Crack Initiation Evaluation Curve», from Canadian standard CAN/CSA N285.8 ensures the prediction of the initiation and non-initiation of the fatigue crack in the material of the pressure tube, Zr-2.5 %Nb, during operation.

In the relevant Canadian scientific literature, it is also mentioned that it is necessary to treat separately the curves specific to each type of defect. The Basquin curves must be customized for each type of defect, depth, hydrogen concentration, and working temperature. These are more permissive failure criteria but with a high level of safety, which represent a conservative approach to fatigue crack initiation compared to the FFSG fatigue crack initiation evaluation curve. To obtain these determinations (specific curves) with high precision, a sufficiently large number of tested samples is required, i.e. pairs of values of the effective alternating stress (von Mises), S_a, and the number of corresponding load cycles, N.

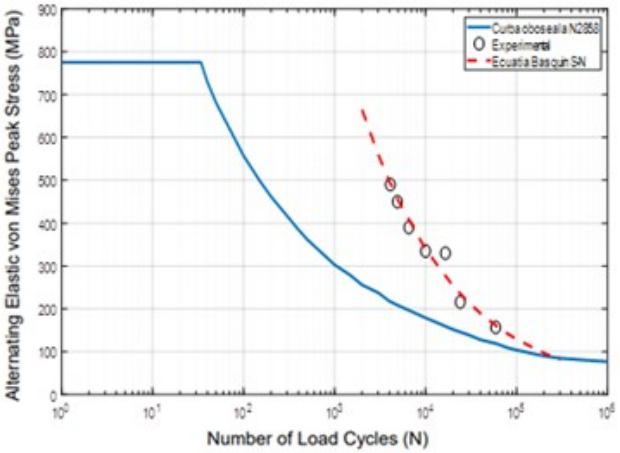


Fig. 8. Prediction of Fatigue Crack Initiation Curves and intercomparison with the CSA N285.8 standard evaluation [5], experimental values

Conclusions

Based on the experimental results presented in this work, several conclusions can be pointed out.

Using the finite element method, by means of VisualFEA software, the alternating von Mises flaw-tip stress, required to obtain the Basquin equation, was determined for each tested sample.

By fitting the experimental fatigue data (Von Mises equivalent stress amplitude vs. number of cycles to fatigue crack initiation), a Basquin curve was obtained.

The Basquin equation approaches the requirements imposed by the Canadian standard N285.8, regarding the $S - N$ range of values, which ensures the prediction of the initiation / non-initiation of fatigue cracking on Zr-2.5% Nb samples with defect and implicitly of the tube life.

The results can be used for the structural integrity analyses of pressure tubes in CANDU fuel channels subject to periodic inspections.

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