PRELIMINARY DEVELOPMENT OF FLAW EVALUATION PROCEDURES FOR DELAYED HYDRIDE CRACKING INITIATION UNDER HYDRIDE NON-RATCHETING CONDITIONS

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ABSTRACT

The flaw evaluation procedure for Delayed Hydride Cracking (DHC) initiation currently provided in the CSA Standard N285.8 was developed for hydride ratcheting conditions, in which flaw-tip hydrides do not completely dissolve at peak temperature. Test results have shown that hydrided regions formed under non-ratcheting conditions, in which flaw-tip hydrides completely dissolve at peak temperature, have significantly higher resistance to cracking than those formed under ratcheting conditions. This paper presents some preliminary work on the development of a procedure for the evaluation of DHC initiation for flaws under hydride non-ratcheting conditions.

1. INTRODUCTION

Zirconium alloy pressure tubes are susceptible to Delayed Hydride Cracking (DHC) when the diffusion of hydrogen in the zirconium to a service-induced flaw results in the formation and subsequent growth of a hydrided region at the flaw tip. The hydrided region can fracture to the extent that a crack forms, at which point DHC is said to have initiated. Hydrided regions can form under ratcheting or non-ratcheting conditions. Ratcheting conditions refer to the situations where the flaw-tip hydrides do not completely dissolve at the operating peak temperature and incremental build-up of flaw-tip hydrides is predicted to occur with each reactor heatup/cooldown cycle. In contrast, non-ratcheting conditions refer to the situations where the flaw-tip hydrides are completely dissolved at the peak temperature, and no incremental hydride accumulation occurs from reactor heatup and cooldown cycles. Whether ratcheting or non-ratcheting conditions occur at a pressure tube flaw is mainly determined by the hydrogen concentration and the operating temperature at the flaw location. The CSA Standard N285.8 [1] requires the demonstration of no DHC initiation for in-service flaws in CANDU reactors. The flaw evaluation procedures for DHC initiation currently available in the Standard are for hydride ratcheting conditions. Flaw evaluation for hydride non-ratcheting conditions is permitted in the Standard, but a flaw evaluation procedure for non-ratcheting conditions is currently not provided.

Test data have shown that hydrides formed under non-ratcheting conditions have significantly higher resistance to cracking than those formed under ratcheting conditions [2]. As a majority of debris fretting flaws are located in the region of the pressure tubes which will not have sufficient hydrogen isotope concentration for hydride ratcheting to occur at the planned end of pressure tube life, it would be overly conservative to evaluate such flaws for crack initiation using procedures based on hydride ratcheting conditions. Flaw evaluation procedures for DHC initiation under hydride non-ratcheting conditions are currently under development based on experiments, modeling and engineering judgment [3]. This paper reports some preliminary work on such development.

2. DHC INITIATION AND FLAW EVALUATION

Precipitation of hydrides in zirconium occurs when the solubility limit of hydrogen in the zirconium is exceeded, such as during cooldown from reactor normal operating temperature to room temperature. In addition, hydrogen diffuses to a stress concentration, such as at a flaw tip. This results in hydrided region forming at the flaw tip. The hydrided region is comprised of zirconium hydrides intertwined with ductile zirconium matrix. The size and density of a hydrided region have significant impact on the susceptibility of DHC initiation at the flaw. Figure 1 shows a Scanning Electron Microscope (SEM) micrograph of a hydrided region in an un-irradiated pressure tube material formed under ratcheting conditions. In the hydride ratcheting situation when some hydrides in the vicinity of the flaw tip do not dissolve at the peak temperature in a thermal cycle, incremental build-up of flaw-tip hydride with each reactor thermal cycle is predicted to occur. For the non-ratcheting situation, all hydrides dissolve at the peak temperature and there is no incremental build-up of flaw-tip hydride with each thermal cycle. Hydride non-ratcheting conditions are believed to be less susceptible to DHC initiation compared to hydride ratcheting conditions. Figure 2 shows the notch-tip hydrided region formed at a similar loading condition as Figure 1 but under non-ratcheting conditions. It is seen from the figure that the hydride platelets in the hydrided region become dispersed as a result of non-ratcheting cycles, resulting in a decrease in hydride density and a hypothesized increase in resistance to cracking.

In-service evaluation of a detected flaw in pressure tubes includes an analysis to demonstrate that DHC will not initiate from the flaw. A threshold peak stress evaluation or explicit process-zone evaluation shall be performed in accordance with the CSA Standard [1]. To apply the threshold peak stress evaluation procedure, the peak principal flaw-tip stress σ_p is determined from a method of stress analysis such as finite element analysis, as illustrated in Figure 3. Prevention of DHC initiation is demonstrated by satisfying the following relation

$$\sigma_p < \sigma_{th} \tag{1}$$

where σ_{th} is the threshold peak flaw-tip stress for the onset of DHC initiation. Values of σ_{th} provided in the CSA standard were developed for ratcheting conditions.

Alternatively, to apply the explicit process-zone evaluation procedure, the hydrided region at the flaw tip is evaluated as a process zone with a uniform stress p_H in the process zone, as illustrated in Figure 4. The stress distribution at the flaw tip is determined from a method of stress analysis, due to the applied load, and in the absence of the process zone. The process zone displacement v_T is then determined for the stress distribution due to the applied load and the process zone uniform stress p_H. Prevention of DHC initiation is demonstrated by satisfying the following relation

$$C_v \, v_T < v_c \tag{2}$$

where C_v is the process-zone displacement factor, v_c is the critical process-zone displacement for the onset of DHC initiation. The process-zone analysis procedure currently available in the CSA standard was developed for hydride ratcheting conditions.

Although flaw evaluation based on hydride non-ratcheting conditions is permitted by the CSA standard, the corresponding threshold stress and process-zone analysis procedure are currently not provided. On the other hand, as discussed earlier, flaw evaluation procedures for hydride ratcheting conditions are overly conservative for flaws that are under non-ratcheting conditions. Therefore, there is a need to develop a flaw evaluation procedure for hydride non-ratcheting conditions.

3. CURRENT TEST DATA UNDER NON-RATCHETING CONDITIONS

Some DHC initiation tests have been conducted and the results were collected in a database [2]. Table 1 summarizes the test data for DHC initiation under hydride non-ratcheting conditions on machined V-Notches with depth of 0.75 *mm* and root radius of 15 μm. The data includes three sets of tests on pre-irradiated pressure tube material and two sets of tests on un-irradiated pressure tube material. Groups of cantilever beam or C-shape specimens were loaded to different stress levels and thermally cycled under hydride non-ratcheting conditions, by choosing an appropriate peak temperature, for cracking to occur. The fourth column in the table provides the information about applied load levels in terms of the effective stress intensity factors (K_{EFF}), and the number of cracked specimens at the given load level as well as the total number of specimens. K_{EFF} were calculated by treating the notch as a crack with the same planar dimensions. For example, "14 (1/5)" for Tube D means that there was 1 specimen experiencing crack initiation among all 5 specimens tested, at the load level of K_{EFF} = 14 *MPa*. In the tests where no cracking was detected at the highest load level, the thresholds are shown with the symbol ">", indicating that thresholds are higher than the applied load levels. Measured threshold K_{TH} given in the table are the effective stress intensity factors K_{EFF} at DHC initiation. The corresponding measured K_{TH} under ratcheting conditions are also given in the table. The last column in the table gives $F_{NR}(exp)$, the ratios of non-ratcheting K_{TH} to ratcheting K_{TH}. $F_{NR}(exp)$ reflects the improvement to DHC initiation resistance under non-ratcheting conditions as compared to under ratcheting conditions. Note that the threshold values are taken as the mean of the two load levels which straddled the threshold level for cracking. For example, in the last row, the K_{TH} for tube E is taken as 10.5 MPa√m under non-ratcheting conditions, and is 8.5 MPa√m under ratcheting conditions. Since K_{EFF} is linearly proportional to nominal stress σ_n, the same values of $F_{NR}(exp)$ would be obtained if nominal stress is used to measure the thresholds for DHC initiation. The non-ratcheting improvement factor of DHC initiation resistance obtained from tests for hydride non-ratcheting conditions and ratcheting conditions can be defined as

$$F_{NR}(exp) = \frac{\sigma_{nTH}(exp, non-ratcheting)}{\sigma_{nTH}(exp, ratcheting)} \quad (2)$$

where σ_{nTH} is the threshold nominal stress at DHC initiation.

It is evident from Table 1 that hydride non-ratcheting conditions provide significant increase in DHC initiation threshold stress levels when compared to ratcheting conditions. The improvement factor on V-notches with 15 μm root radius is greater than 1.20 based on available test data. It is noted that current test data are limited and more series of tests are currently underway or planned for the near future.

4. PRELIMINARY DEVELOPMENT OF EVALUATION PROCEDURES

The engineering procedures for DHC initiation evaluation under hydride non-ratcheting conditions are under development based on experiments, modeling and engineering judgment, and will be validated against experimental results. It is assumed that factors affecting DHC initiation such as flaw geometry under hydride non-ratcheting conditions are consistent with those under hydride ratcheting conditions, and the difference in fracture resistance under non-ratcheting conditions is largely due to hydride morphology. It is expected that the engineering procedures will be developed in a staged approach, from empirical, simple and conservative to more detailed and less conservative. Only the preliminary work on the simplest and most conservative procedure will be discussed in this section.

The first level of the engineering evaluation procedure involves the determination of an adjustment factor for non-ratcheting conditions which will be applied to threshold nominal stress for DHC initiation prediction under hydride ratcheting conditions. Experimental values of threshold nominal stress $\sigma_{nTH}(exp)$ for DHC initiation under hydride non-ratcheting conditions for a given pressure tube are determined from DHC initiation databases. The corresponding threshold stress $\sigma_{nTH}(pzr_e)$ is predicted from process-zone analysis for hydride ratcheting conditions and elastic material behavior, in accordance with the explicit process-zone evaluation procedure in the CSA standard. The hydride non-ratcheting adjustment factor $F_{NR,e}$ for elastic material behavior is then calculated using

$$F_{NR,e} = \frac{\sigma_{nTH}(exp)}{\sigma_{nTH}(pzr_e)} \quad (3)$$

The calculated values of $F_{NR,e}$ will be sorted into separate bins, based on flaw root radius, hydrogen isotope concentration, and possibly other factors. A representative and conservative value of $F_{NR,e}$ will be determined for each bin.

The application of adjustment factor $F_{NR,e}$ for flaw evaluation is straightforward. The predicted threshold nominal stress $\sigma_{nTH}(pzr_e)$ for hydride ratcheting conditions is first calculated using the process-zone analysis procedure. The adjustment factor $F_{NR,e}$ is selected based on flaw root radius and hydrogen isotope concentration from the corresponding bin. The predicted threshold nominal stress for hydride non-ratcheting condition is then calculated as

$$\sigma_{nTH}(nr_e) = F_{NR,e}\,\sigma_{nTH}(pzr_e) \tag{5}$$

The predicted threshold peak stress $\sigma_{th}(nr_e)$ under non-ratcheting conditions can then be determined from the corresponding nominal stress $\sigma_{nTH}(nr_e)$. With the known threshold peak stress under non-ratcheting conditions, prevention of DHC initiation for flaws under non-ratcheting conditions can be demonstrated using equation (1).

5. CONCLUDING REMARKS

Current DHC initiation test results for hydride non-ratcheting conditions show a minimum 20% improvement to cracking resistance for flaws with 15 μm root radius, as compared to hydride ratcheting conditions. Work is underway to develop flaw evaluation procedures for DHC initiation under hydride non-ratcheting conditions. Work in this direction will allow less conservative evaluations of flaws that are under hydride non-ratcheting conditions.

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Table 1: DHC initiation experiments under hydride non-ratcheting conditions on V-notches with depth of 0.75 *mm* and root radius of 15 *μm*.

Pre-irradiated or Un-irradiated	Pressure Tube ID	Nominal Notch Root Radius (μm)	Non-ratcheting Test			Measured Threshold K_{TH} under Ratcheting Conditions (MPa √ m)	F_{NR} *(exp)* (ratio of non-ratcheting K_{TH} to ratcheting K_{TH})
			Applied Effective Stress Intensity Factor K_{EFF} (Failures/No. Specimens in Group) (MPa √ m)	Total Number of Test Specimens	Measured Threshold K_{TH} (MPa √ m)		
Pre-irradiated	A	15	8 (0/6), 9 (0/6)	12	> 9	7 ~ 8	> 1.2
Pre-irradiated	B	15	6 (0/5), 6.5 (0/5), 7.5 (0/5), 8.5 (0/5), 10 (0/6)	26	> 10	7.5 ~ 8.5	> 1.25
Pre-irradiated	C	15	5 (0/7), 6 (0/7), 7 (0/5), 8 (0/4), 9 (0/4)	27	> 9	7 ~ 8	> 1.2
Un-irradiated	D	15	11 (0/4), 12 (0/8), 13 (0/5), 14 (1/5), 15 (1/5)	27	13 ~ 14	9 ~ 10	1.42
Un-irradiated	E	15	9 (0/6), 10 (0/6), 11 (1/12), 12 (2/12), 14 (1/6)	42	10 ~ 11	8 ~ 9	1.23

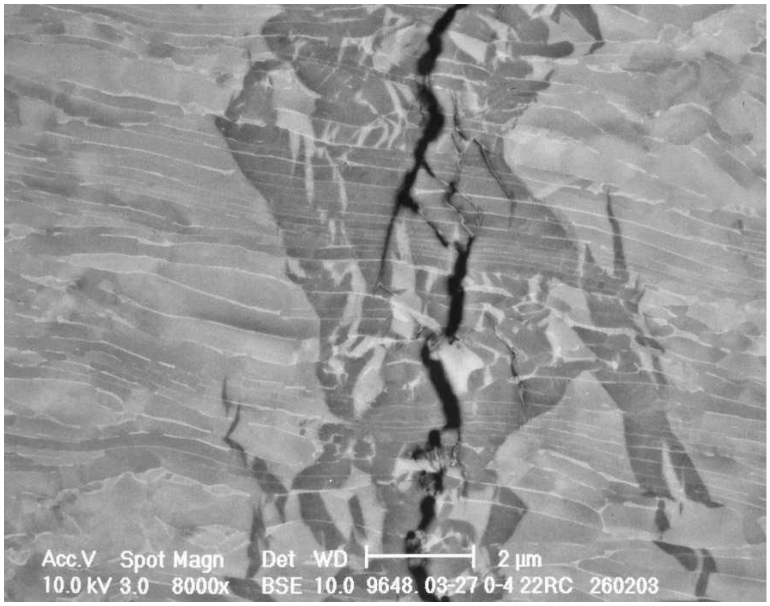

Figure 1. SEM (Scanning Electron Microscope) micrograph of notch-tip hydrided region in an un-irradiated tube material, $K_{EFF} = 12\ MPa\sqrt{m}$, 22 ratcheting cycles.

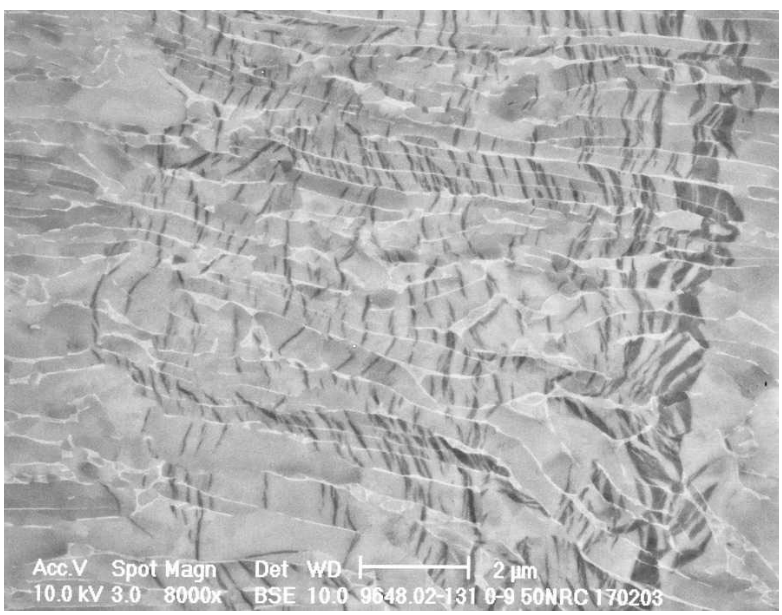

Figure 2. SEM (Scanning Electron Microscope) micrograph of notch-tip hydrided region in an un-irradiated tube material, $K_{EFF} = 12\ MPa\sqrt{m}$, 50 non-ratcheting cycles.

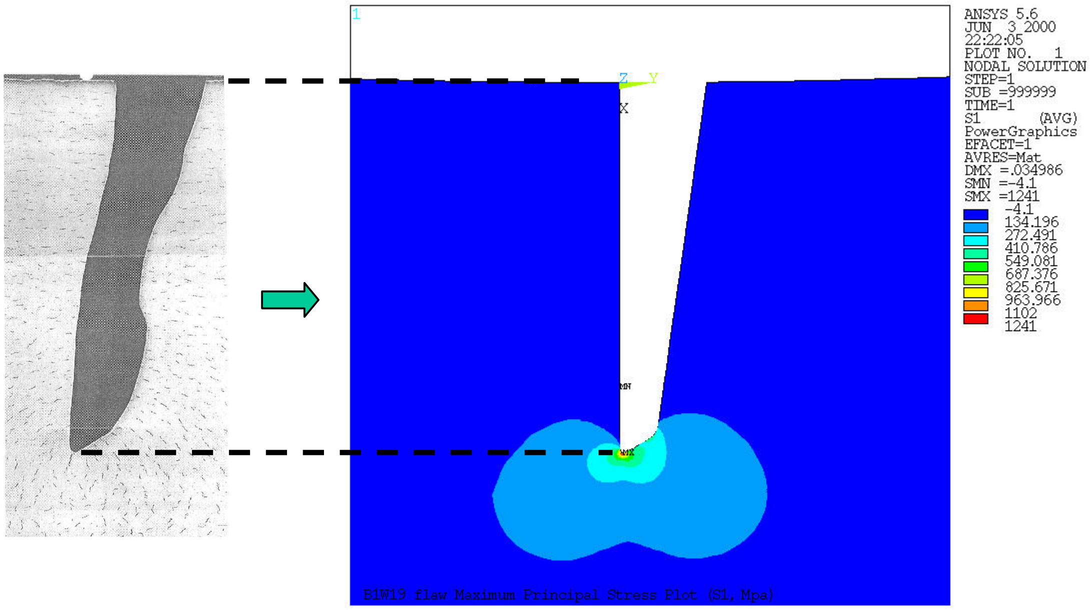

Figure 3. Metallograph and finite element stress analysis of an ex-service debris fretting flaw for DHC initiation evaluation.

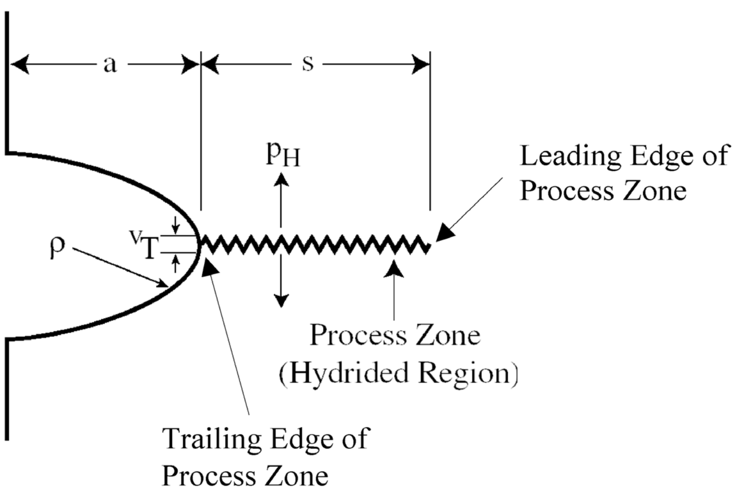

Figure 4. Process Zone at a Flaw Tip