

## Velocity of Delayed Hydride Cracking with Stress Intensity Factor in Zr-2.5Nb Pressure Tube

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### 1. Introduction

Delayed Hydride Cracking (DHC) has led many Zr-2.5Nb pressure tubes to be replaced or fail during their operation in heavy water reactors. DHC was known to occur by diffusion of hydrogen to a crack tip, nucleation and growth of hydrides followed by fracturing of hydrides. Since some incidents of tube failures by DHC in 1970s, lots of researches have been conducted to understand its mechanism. Dutton and Puls suggested that a driving force for DHC is the tensile stress gradient formed at the crack tip [1]. However, this model can't explain the unique phenomenon of DHC or the constant crack growth rate independent of the applied stress intensity factor or K, as shown in Fig.1, Fig. 2 and Fig. 3. The DHC crack starts to grow only if the applied K exceeds the threshold stress intensity factor (or  $K_{IH}$ ) and its velocity increases quickly, which is termed Stage I. At Stage II, the DHC velocity becomes constant with an increase in the applied K. Besides, the spacing of striation lines on the fractured surfaces after DHC tests is wider close to the notch, becomes smaller gradually with increasing K and levels off to a constant at Stage II. [2]. The aim of this paper is to explain the cause for a change of the DHC velocity with increasing K based on the analysis of the stress state at the crack tip using a finite element method (FEM).

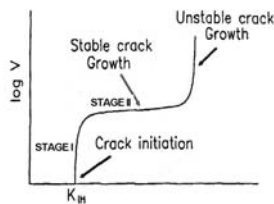


Fig. 1. Dependence of the crack growth velocity with K.

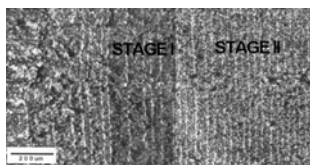


Fig. 2 Striation lines on the fractured surfaces of DHC CT specimen

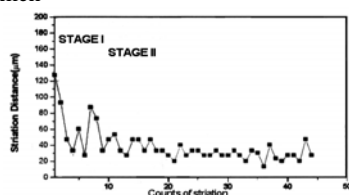


Fig. 3. Variation of the striation spacing of DHC.

### 2. Methods and Results

Using FEM, the elements near the crack tip are modeled and compared with the previous experimental data [3]. Also, the plastic zone size near the crack tip is calculated for checking the effects of the plastic constraint and notch strengthening.

#### 2.1 Materials and Specimen

The material used is a cold-worked Zr-2.5Nb pressure tube and its room temperature mechanical properties are represented in Table 1. The detail dimension of CT specimen (thickness=4.2 mm) is shown in Fig. 4.

Table 1 Mechanical properties of the Zr-2.5Nb alloy used in finite element analysis

Elastic Modulus (MPa)	Poisson's Ratio	Yield Strength (MPa)
102000	0.38	869

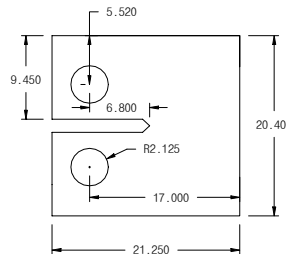


Fig. 4. Dimension of compact tension specimen.

#### 2.2 FEM Model

IDEAS code for FEM analysis and 10240 elements of solid linear brick is used. 3D FEM model is shown in Fig. 5. and includes pre-fatigue crack length of 1.7 mm. The element length near crack tip is 130 μm of the maximum length which the hydride is able to grow at Stage I [2].

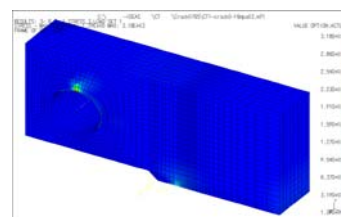


Fig. 5. 3D Finite Element Modeling of CT specimen.

### 2.3 Hydride behavior at Crack Tip

The stress and displacement at elements near a crack tip is examined in increasing load (K). The elements near a crack tip are moved in the direction of  $-X$  as shown in Fig. 6. Also, the tensile force in the direction of  $-X$  and  $+Y$  is acted at that. This means that the tensile force restrains the hydride growth in the direction of  $+X$  and promotes the hydride growth in the direction of  $+Y$ . Up to now, Puls and Scarth had considered the stress in the direction of  $Y(\sigma_y)$ . But, actually,  $\sigma_x$  is not small value in comparing with  $\sigma_y$ . Table 2 represents the stress level of a crack tip element according to each K value. When  $\sigma_x$  is the small value, the hydride grows in the direction of  $+X$ . If  $\sigma_x$  attains some value, the growth of the hydride length stops and hydride grows in the direction of  $+Y$  of the thickness direction of hydride. Thus, the maximum length of the hydride growth is to be  $127 \mu\text{m}$  at Stage I[2].  $\sigma_x$  value is gradually large in increasing load and the growth of hydride length is restrained. Thus, the striation spacing is gradually narrow. Finally, when  $\sigma_x$  becomes  $725 \text{ MPa}$  ( $K=10 \text{ MPa}\sqrt{m}$ ), the length growth of hydride stops and the hydride grows in the direction of the thickness (Y direction) at stage II as shown in Fig. 2, Fig. 3 and table 2. Thus, spacings of striation lines become constant.

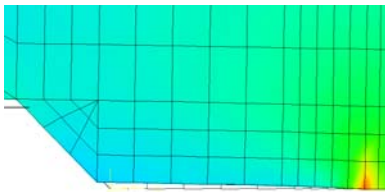


Fig. 6. Behavior of the elements near the crack tip.

Table 2 Stress level of the crack tip element according to each K value.

K	5	6	8	10	12	14	16
$\sigma_x$ (MPa)	363	435	580	725	870	1015	1164
$\sigma_y$ (MPa)	571	685	913	1142	1370	1598	1832

When K value increases, the experimental data of which the hydride length is gradually large, become constant and the hydride thickness increase at some value ( $K=9.7 \text{ MPa}\sqrt{m}$ ), is represented in table 3.

Table 3 Hydride thickness and length according to each K value.

K	Hyd. Thickness(mm)	Hyd. Length(mm)
3.5	0	0
8.65	2	23.5
9.2	2	53.0
9.7	4.5	103.0
11.1	8.75	102.0

### 2.4 Size of Plastic Zone at Crack Tip

The size of the plastic zone at the crack tip according to each K value is represented in Table 4. The crack length in each K value is reflected in calculating the size of the plastic zone. As shown in Table 4, the size of the plastic zone is in proportion to K value. This means that the energy of the load (K) increased is spent in increasing the plastic zone. Thus, DHC velocity is constant at Stage II even if K value increase. The more the size of plastic zone is increasing, the more the force of the plastic restraint is increasing. This means that the compression force increased near the crack tip restrains the growth of the hydride. Also, the effect of the notch strengthen (the more the crack length is increasing, the more the fracture toughness is increasing) assists to explain the fact that DHCV is constant at Stage II even if the K value increase.

Table 4 Plastic zone size according to each K value

K	Crack Length(mm)	Plastic Zone(mm)
16	0.765	0.85
20	1.015	1.33
24	1.310	1.84

### 3. Conclusion

When  $\sigma_x$  is the small value, the hydride grows in the direction of  $+X$ . If  $\sigma_x$  attains some value, the growth of the hydride length stops and hydride grows in the direction of  $+Y$  of the thickness direction of hydride. Thus, spacings of striation lines become constant at Stage II. the size of the plastic zone is in proportion to K value. This means that the energy of the load (K) increased is spent in increasing the plastic zone. Also, the plastic restraints and the effect of the notch strengthen assist to explain the fact that DHCV is constant at Stage II even if the K value increase.

### Acknowledgements

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