FEM Analysis for the Mechanism of a Delayed Hydride Cracking (DHC) in Zr-2.5Nb Pressure Tubes

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ABSTRACT

Delayed Hydride Cracking (DHC) tests are conducted in this study by using CT specimens of Zr-2.5Nb at 250 ^{o}C. The test data is used for the FEM model. Two models, while not considering and considering a hydride expansion, are constructed. Hydride stresses and average stresses of the plastic zone of the two FEM models are calculated and two results are compared. That results show that the hydride fracture is due to a hydride expansion and that the hydride fracture is related to a relation between an increment of the hydride expansion stress and an increment of the average stress of the plastic zone on the hydride. Also, the same results show that a hydride expansion is the most important factor of a DHC. Now, Stage I and Stage II of the unique DHC phenomenon can be explained through an analysis of an increment of a hydride expansion and a plastic constraint force in the plastic zone.

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 has been known to occur by a diffusion of hydrogen to a crack tip, a nucleation and growth of hydrides followed by a fracturing of the hydride. Since some incidents of tube failures by a DHC in the early 1970s, lots of researches have been conducted to understand its mechanism. Dutton and Puls suggested that a driving force for a DHC is the tensile stress gradient formed at the crack tip [1]. However, this model can’t explain the unique phenomenon of a DHC or a constant crack growth rate independent of the applied stress intensity factor or K, as shown in Fig.1, Fig. 2 and Fig. 3 respectively. 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 as Stage I. At Stage II, the DHC velocity becomes constant with an increase in the applied K. Besides, the spacing of the striation lines on the fractured surfaces after the DHC tests is wider close to the notch and it becomes gradually smaller with an increasing K as shown in Fig.2 and levels off to a constant at Stage II as shown in Fig.1 [2]. The aim of this paper is to explain the cause for a change of the DHC velocity and the cause for a change of the spacing of the striation lines with an increasing K based on an analysis of the stress state at a crack tip by using a finite element method (FEM).

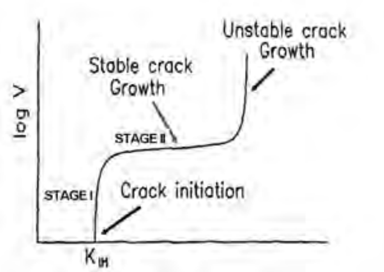

Figure 1. Dependency of the crack growth velocity with K.

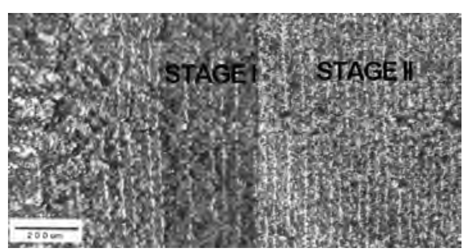

Figure 2. Striation lines on the fractured surfaces of the DHC CT specimen

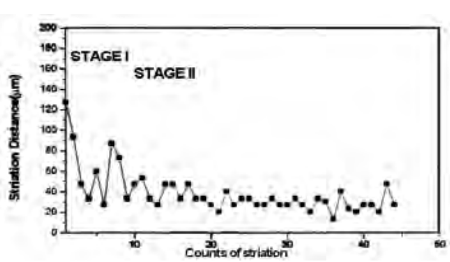

Figure 3. Variation of the striation spacing of a DHC.

2. METHODS AND RESULTS

The experimental data is used for the FEM model. The stresses of the hydride and Zr-2.5Nb elements near a crack tip of the FEM model are examined. Also, the plastic zone size and average stresses near a crack tip are calculated for evaluating the effects of a plastic constraint.

2.1 Experimental Data

Delayed Hydride Cracking (DHC) tests are conducted by using CT specimens of Zr-2.5Nb at 250 ^oC. Hydrogen concentration of the CT specimens is 60 ppm. Striation lines on the fractured surfaces of the DHC CT specimen are shown in Fig. 2 and the spacing of that is measured. Variation of the striation spacing of a DHC is represented in Fig. 3 [2]. Fig. 4 is the tensile stress-strain curves of the Zr-2.5Nb in the transverse and longitudinal direction specimens from the un-irradiated tube [3]. The transverse data of 250 ^oC is used for the elastic-plastic analysis. The threshold stress intensity factor, K_{IH} is 7.0MP$\sqrt{m}$. This value is obtained by repeating the test of three times.

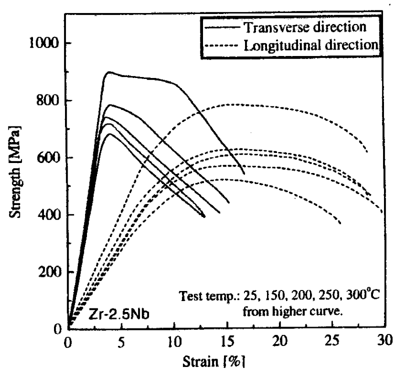

Figure 4. Tensile stress-strain curves in the transverse and longitudinal directions of the specimens

2.2 Materials and Specimen

The material used is a cold-worked Zr-2.5Nb pressure tube and the mechanical properties at 250 ^oC are represented in Table 1 [4]. The mechanical properties of the hydride are represented in Table 2 [5]. The detail dimensions of the CT specimen (thickness=4.2 mm) are shown in Fig. 5.

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

Elastic Modulus (MPa)	Poisson's atio	Yield Strength (MPa)
81550	0.329	700

Table 2. Mechanical properties of a hydride

Elastic Modulus (MPa)	Poisson's Ratio
131700	0.322

2.3 FEM Model

ABAQUS code is used for the FEM analysis. 3D-FEM model includes about 70000 elements of a solid linear brick. This model is shown in Fig. 6 and includes a pre-fatigue crack length of 1.7 mm. The element length and thickness of the hydride near a crack tip is 30 μm and 1 μm respectively.

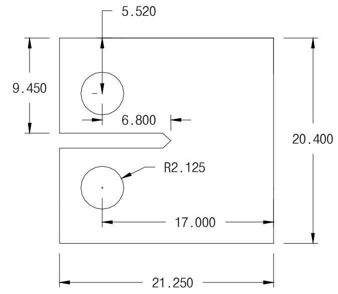

Figure 5. The Dimensions of the CT specimen.

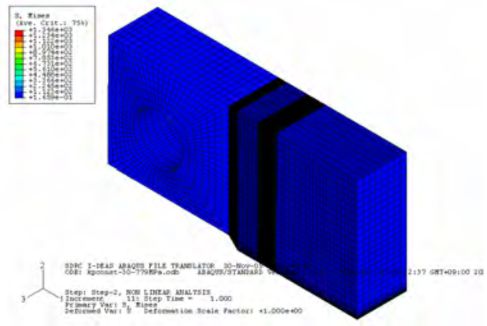

Figure 6. 3D Finite Element Modeling

The spacing of the striation lines on the fractured surfaces is wider at first and becomes gradually smaller at Stage I with an increasing K as shown in Fig. 2. Finally, it becomes constant (30 μm) at Stage II with an increasing K as shown in Fig. 2. K value is calculated by the formula of ASTM E399.

$K=P/BW^{0.5}\times f(a/W)$

2.4 Analysis by not considering a hydride expansion

It is known that a generation and a expansion of a hydride brings about an increment of its volume. To establish if a hydride expansion is an important factor of a DHC mechanism, firstly, FEM analysis by not considering a hydride expansion is performed. In the case that the hydride grows to 60 μm at Stage I ($K=7.52MP\sqrt{m}$), the stress distribution of when the hydride growth is 10 μm is shown in Fig. 7 and that of when it is 20 μm is shown in Fig. 8.

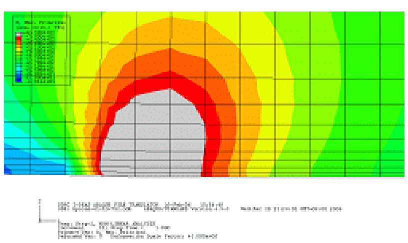

Fig. 7 Plastic zone in the case of a hydride growth of 10 μm (Stage I, $K=7.52MP\sqrt{m}$)

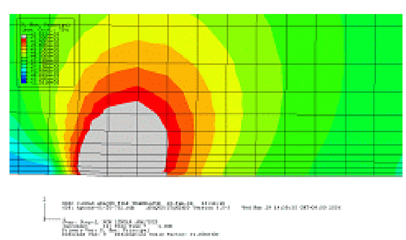

Fig. 8 Plastic zone in the case of a hydride growth of 20 μm (Stage I, $K=7.52MP\sqrt{m}$)

The gray color in the figures is the plastic zone which exceeds 700MPa of the stress value. Similarly, a stress analysis, when the hydride growth is 30, 40, 50 and 60 μm, is performed. When the hydride grows, the σ_y value of the hydride element near a crack tip and the average σ_y ($\sigma_{y.ave}$) of the plastic zone which exists on the hydride element is represented in Table 3.

Table 3 Stress distribution near a hydride (Stage I, $K=7.52MP\sqrt{m}$)

	σ_y of hydride (MPa)	$\sigma_{y.ave}$ of plastic zone (MPa)
10 μm	1673	1077
20 μm	1647	1078
30 μm	1657	1076
40 μm	1654	1076
50 μm	1654	1076
60 μm	1654	1076

In the case that a hydride growth is 30 μm at Stage II, the stress distribution, when the hydride growth is 10 μm, is shown in Fig. 9. Similarly, a stress analysis, when the hydride growth is 20 and 30 μm, is performed.

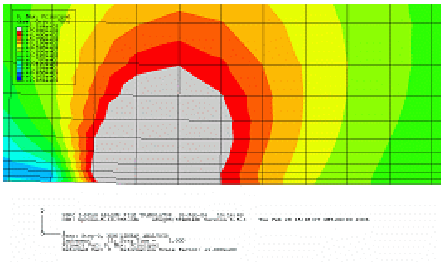

Fig. 9 Plastic zone in the case of a hydride of 10 μm (Stage II, K=7.88MP$\sqrt{m}$)

When the hydride grows at Stage II, the σ_y value of the hydride element near a crack tip and the average σ_y ($\sigma_{y.ave}$) of the plastic zone which exists on the hydride element is represented in Table 4.

Table 4 Stress distribution near a the hydride (Stage II, K=7.88MP$\sqrt{m}$)

	σ_y of a hydride (MPa)	$\sigma_{y.ave}$ of a plastic zone (MPa)
10 μm	1748	1129
20 μm	1718	1130
30 μm	1729	1129

As shown in Table 3 and Table 4, when not considering a hydride expansion at Stage I and Stage II, the hydride stress near a crack tip is not really changed even if the hydride grows. This means that a hydride growth and existence is not able to fracture the hydride. Therefore, it implies that a hydride growth and expansion is able to fracture the hydride.

2.5 Analysis by considering a hydride expansion

When the hydride expands, the increase of the hydride volume is 16%. The following equation is made.

$X^3+3aX^2+3a^2X=0.16a^3$

Where, a=1 μm

X=ε=0.051 μm

Therefore, when a hydride length of 1 μm grows in the X, Y and Z directions, ideally, the hydride volume increases by 0.000051 mm in one direction. Since the displacement load in the Y direction is important for considering a hydride fracture, this value(0.000051 mm) is applied to the FEM model.

In the case that a hydride grows to 60 μm at Stage I (K=7.52MP$\sqrt{m}$) and the hydride expansion is considered, the stress distribution, when the hydride growth is 10 μm, is shown in Fig. 10 and that, when it is 20 μm, is shown in Fig. 11. The gray color in the figures is the plastic zone which exceeds 700MPa of the stress value. Similarly, a stress analysis, when the hydride growth is 30, 40, 50 and 60 μm, is performed.

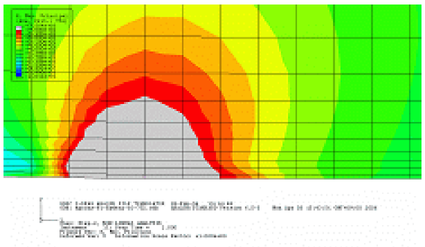

Fig. 10 Plastic zone in the case of a hydride growth of 10 μm (Stage I, K=7.52MP$\sqrt{m}$)

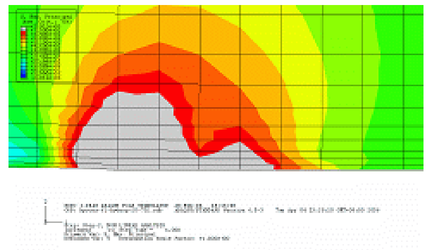

Fig. 11 Plastic zone in the case of a hydride growth of 20 μm (Stage I, K=7.52MP$\sqrt{m}$)

Table 5 includes the following data. When a hydride grows, the σ_y of the hydride element near a crack tip, the average σ_y ($\sigma_{y.ave}$) of the plastic zone which exists on the hydride element, the average stress increment of the plastic zone on the hydride elements ($\Delta\sigma_{yave.p}$), the stress increment of a hydride in the Y direction ($\Delta\sigma_y$) and the difference in the value between $\Delta\sigma_y$ and $\Delta\sigma_{yave.p}$ (Δ) is represented.

Table 5 Stress distribution near to the hydride when considering a hydride expansion (Stage I, K=7.52MP$\sqrt{m}$)

	σ_y	$\Delta\sigma_y$	$\sigma_{y.ave}$	$\Delta\sigma_{yave.p}$	Δ
10 μm	7488		994		
20 μm	7633	145	1047	53	92
30 μm	7682	194	1074	80	114
40 μm	7695	207	1086	92	115
50 μm	7707	219	1091	97	122
60 μm	7712	224	1095	101	123

In the case that a hydride grows to 30 μm at Stage II (K=7.88MP$\sqrt{m}$) and a hydride expansion is considered, the stress distribution, when the hydride growth is 10 μm, is shown in Fig. 12. The gray color in figures is the plastic zone which exceeds 700MPa of the stress value. Similarly, a stress analysis, when the hydride growth is 20 and 30 μm, is performed.

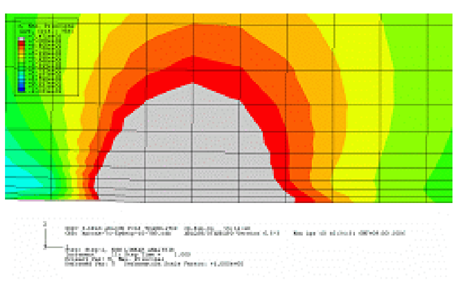

Fig. 12 Plastic zone in the case of hydride 10 μm when considering a hydride expansion (Stage II, K=7.88MP$\sqrt{m}$)

Table 6 includes the following data. When a hydride grows at Stage II, the σ_y of the hydride element near a crack tip, the average σ_y ($\sigma_{y.ave}$) of a plastic zone which exists on a hydride element, the average stress increment of the plastic zone on the hydride elements ($\Delta\sigma_{yave.p}$), the stress increment of a hydride in the Y direction ($\Delta\sigma_y$) and the difference in the value between $\Delta\sigma_y$ and $\Delta\sigma_{yave.p}$ (Δ) is represented. Δ values mean the actual increment of a hydride expansion.

Table 6 Stress distribution near to a hydride when considering a hydride expansion (Stage II, K=7.88MP$\sqrt{m}$)

	σ_y	$\Delta\sigma_y$	$\sigma_{y.ave}$	$\Delta\sigma_{yave.p}$	Δ
10 μm	7464		1001		
20 μm	7597	133	1037	36	97
30 μm	7645	181	1055	54	127

As shown in Table 5 and Table 6, when a hydride expansion at Stage I and Stage II is considered, the hydride stress near a crack tip considerably increases and $\sigma_{y.ave}$ also increases according to the hydride growth. This means that the resultant stress is increased by a hydride expansion and the average stress value in the plastic zone is also increased. The increment of the average stress value in the plastic zone means an increment of the plastic constraint force. This plastic constraint force restrains a hydride expansion. As shown in Table 5 of the analysis result at Stage I, when the difference in the value between the hydride stress increment value ($\Delta\sigma_y$) and the increment of $\sigma_{y.ave}$ in the plastic zone becomes 123 MPa, a hydride is fractured. As shown in Table 6 of the analysis result at Stage II, when the difference in the value between the hydride stress increment value ($\Delta\sigma_y$) and the increment of $\sigma_{y.ave}$ in the plastic zone becomes 127 MPa, a hydride is fractured. Therefore, the difference in the value between the hydride stress increment value ($\Delta\sigma_y$) and the increment of $\sigma_{y.ave}$ in the plastic zone, that is, the Δ value means the actual increment of a hydride expansion stress. When this attains certain values, a hydride is fractured. Therefore, a hydride expansion is the most important factor of a DHC and Stage I and Stage II of the unique DHC phenomenon can be explained through an analysis of the plastic constraint force in a plastic zone and a hydride expansion.

3. CONCLUSION

The experimental data from this study was used for the FEM model. The stresses of the hydride and Zr-2.5Nb elements near a crack tip of the FEM model were examined. Also, an analysis of the plastic constraint force in a plastic zone by a hydride expansion was performed. The following conclusions were obtained.

1) When the difference in the value between the hydride stress increment value ($\Delta\sigma_y$) and the increment of $\sigma_{y.ave}$ in the plastic zone attains certain values, a hydride was fractured

2) The hydride expansion force was the most important factor of a DHC.

Acknowledgements

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