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FRACTURE TOUGHNESS OF IRRADIATED ZR-2.5NB CANDU PRESSURE TUBE USING LOAD RATIO METHOD

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Abstract

The fracture toughness of irradiated Zr-2.5Nb CANDU pressure tube material in Wolsung CANDU site has been evaluated by means of Load-ratio method. In case of irradiated pressure tube, measurement of crack extension is very difficult because it is not easy to install conventional measuring instruments. In load ratio method, however, initial crack length, final crack length and load-load line displacement curve are needed to measure crack extension in load ratio method. In this study, Load-ratio method was applied to evaluate fracture toughness.

Curved Compact Tension (CCT) specimen was manufactured with axially notch in outlet and inlet of pressure tube. Fracture test performed at temperatures between room temperature and 300 .

At low temperature, the load-load line displacement in the fracture test showed the discontinuous abrupt decreases caused by crack jumping. In crack resistance curve, unstable crack growth stage was showed due to irradiation damage and hydride. The fracture characteristic value ($J_{0.2}$, dJ/da) in the irradiated are lower than those of the unirradiated.

Key words: load-ratio method, pressure tube, Zr-2.5Nb alloy, fracture toughness, irradiation

1. Introduction

CANDU pressure tube absorbs hydrogen in manufacturing process and from heavy water during reactor operation. Hydride is precipitated in CANDU pressure tube during long term operation time so the hydride deteriorates fracture toughness of CANDU pressure tube. So study for hydride embrittlement of CANDU Pressure tube is performed from now on.

Test methods for hydride embrittlement of CANDU pressure tube are unloading compliance method and Direct Current Potential Drop (DCPD) method based on elastic-plastic fracture mechanics.

Fracture toughness test of Unirradiated pressure tube is performed actively. However, it is difficult to perform fracture test of irradiated pressure tube because it was not easy to install measuring instruments on irradiated materials in hot cell. In addition to difficulty of test, DCPD method is excepted from ASTM standard method when ASTM standard is revised in 2001.

Test methods have been developed to determine J-R curve characteristic without measuring instrument since 1980's.

Normalization method(1) based on Key-Curve method(2) and Load-ratio(3) method based on Load-drop method(4) are developed.

If J-R curve (or crack resistance curve) is determined by the methods, fracture toughness test can be performed without various measuring instruments. So safety for test will be increase highly and many data for fracture toughness of irradiation with various test condition will be obtained.

In this study, fracture test of irradiation CANDU pressure tube materials was performed and J-R curve was determined by load ratio method without measuring instruments in hot cell.

2. Back ground

2.1 Concept of load ratio (3)

According to deformation theory for J-integral analysis, load-load line displacement curve (LLD) of specimen with crack propagation can be expressed as shown Fig. 1

With fracture test, LLD curve, OAB can be obtained. If there is no crack growth with fracture test, strain hardening curve will be OA'B'. When crack grows from a_0 to a_i, real strain curve, OA can be separated to OA' and A'A. OA' is strain hardening curve with only plastic deformation and A'A is crack growth with no plastic deformation. When Crack length is a_i, compliance C_i is the reciprocal of the slope of O'A. Then Elastic displacement, v_e can be expressed

$$v_e = P_i^* C_0 = P_i C_i \tag{1}$$

If we know strain hardening curve with no crack growth, compliance, C_i can be obtained. Crack growth a_i can be calculated from Comliance, C_i (5)

2.3 Limit load analysis of CT specimen [6]

Reference hardening curve is determined by limit load analysis. In numerical analysis of fracture mechanics [7], Load line displacement of CT specimen can be expressed by

$$\Delta_L = \alpha \cdot \varepsilon_0 \cdot a \cdot h_3(a/W, n) \cdot \left(\frac{P}{P_0}\right)^n \qquad \text{Eq. (2)}$$

$$P_0 = 1.455\sigma_{ys} \cdot B \cdot \beta \cdot b \qquad \text{Eq. (3)}$$

$$\beta = \sqrt{4\left(\frac{a}{b}\right)^2 + 4\left(\frac{a}{b}\right) + 2} - \left(\frac{2a}{b} + 1\right) \qquad \text{Eq. (4)}$$

Δ_L: Load Line Displacement

a: Crack length

W: Width of specimen

P: Load

P_0: Limit load of specimen

α, ε0, n: Material constant

h3: Non dimensional function by numerical analysis

b (=W-a): Ligament

As shown Eq. (3), P_0 is a function of crack length and decrease with crack growth.
Therefore, Normalized load, P/P_0 can be assumed to be hardening condition in ligament.

2.4 Determination of reference hardening curve

In initial deformation region, effective crack length increases because crack tip is blunted by plastic deformation. So correction for blunting is needed. Using limit load analysis proposed by Merkel [8] Relationship between CTOD (Crack Tip Opening Displacement) and LLD is given by

$$CTOD = \frac{(1+\beta)}{(\frac{2W}{b} + \beta - 1)} \cdot \Delta_P \qquad \text{Eq. (5)}$$

$$\Delta_P = \Delta_L - C_0 \cdot P \qquad \text{Eq. (6)}$$

Blunting correction crack (a_b) is assumed to half CTOD. P_0 is calculated using a_b and Load-LLD curve is normalized as shown Fig.2.

Reference hardening curve is given by tangent line between the normalized curve and final crack point as shown Fig.2

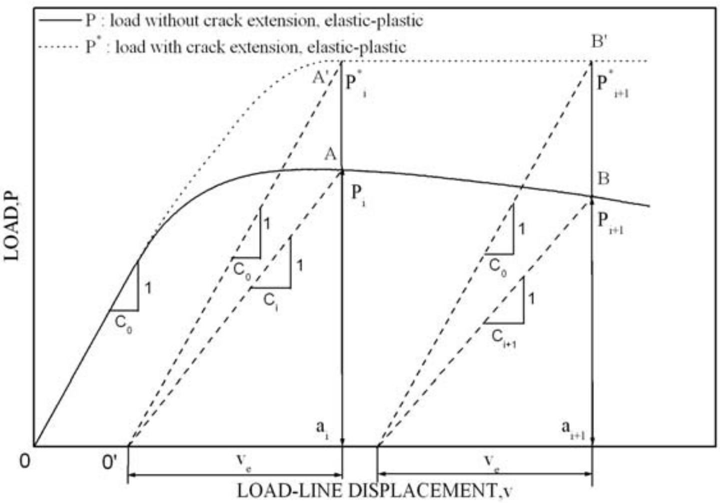

Fig. 1 Concept of load-ratio-method for direct determination of the elastic compliance

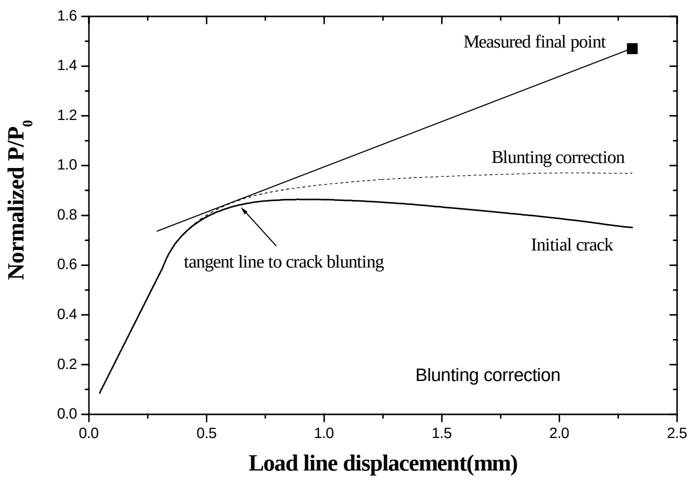

Fig. 2 Determining the reference hardening curve by a tangent line approximation

3. Material and Experimental Procedure

3.1 Material and Specimen

The used material was irradiated CANDU pressure tube materials operated in Wolsung Unit-1. Table 1 shows operation history and cutting ring position

a cold worked Zr-2.5Nb alloy which is pressure tube material from Wolsung CANDU reactor unit-1. The pressure tube is cold worked Zr-2.5Nb alloy which has chemical composition as shown Table 2[(9)].

Fig. 3 shows the Curved Compact Tension (CCT) specimen used in the present study. The specimen has a thickness (B = 4.2 mm) and Width (W = 17 mm). The specimen is manufactured by Electro Discharge Machining (EDM) in Hot Cell.

3.2 Experimental procedure

Fracture test was performed using universal type test machine which be able to control remotely in Hot cell. Precrack of specimen for fracture toughness test was inserted with ΔK=15~11 MPa√m, R (P_{max}/P_{min}) =0.1 and loading cycle=3~5Hz. In order to insert regular precrack of curved specimen, pin with 1.5° slope was used. Load line displacement speed was 0.2mm/min and test temperature was controlled by chamber which have the range from -150 to 300°C. crack length was measured after heat-tinting(30min.). Test temperature condition, precrack length, initial crack length and final crack length is shown as Table 3.

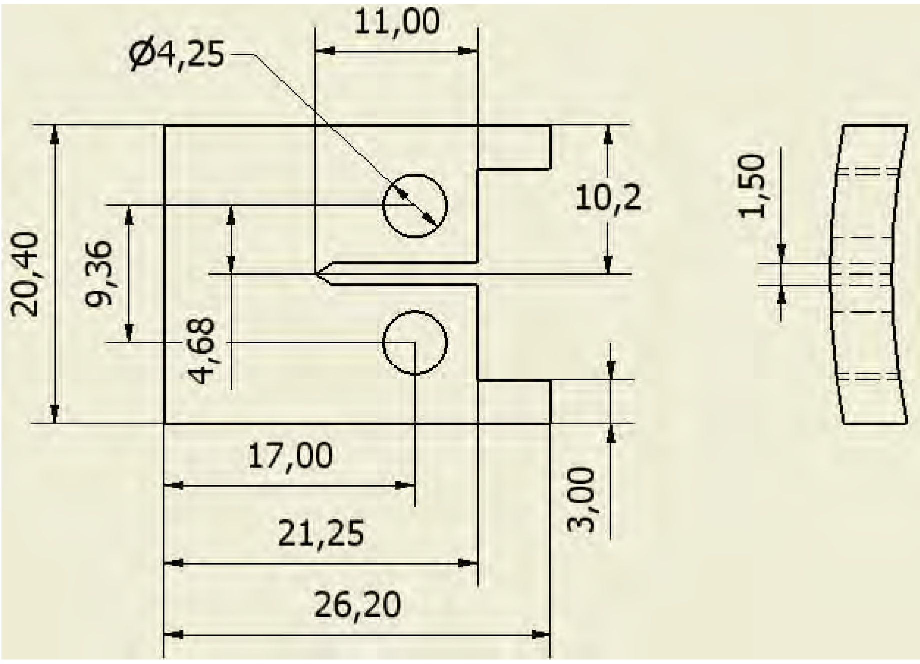

Fig. 3 Configurations of 17 mm curved compact tension specimen

Table 1 Operation history and cutting ring position in pressure tube

Accumulated neutron fluence	Operating Temperature	Effective full power years(EEPY)	Annual load factor	Ring position
8.91×10^{25} n/m^2	285.5ºC	9.3 years	100.8%	Inlet & Middle & Outlet

Table 2 Chemical compositions of cold-worked Zr-2.5Nb pressure tube materials (unirradiated)

Nb	O	C	Cr	H	Fe	Ni	N	Si	Ta	Zr
2.4 ~ 2.8 wt%	900 ~ 1300 ppm	< 270 ppm	< 200 ppm	< 25 ppm	< 1500 ppm	< 70 ppm	< 65 ppm	< 120 ppm	< 200 ppm	Balance

Table 3 Fracture test condition and crack length of irradiated specimen

Specimen ID	Temp(°C)	W	B	a_{pre}	a_0	Δa	a_f
EMFL-01	Room Temp.	17	4.207	1.24	8.04	4.56	12.60
EMFL-02	200	17	4.285	1.49	8.29	2.89	11.19
EMFL-03	250	17	4.316	1.12	7.92	2.62	10.54
EMFL-04	300	17	4.2	1.45	8.25	2.80	11.05
EMFR-01	Room Temp.	17	4.3085	1.58	8.38	3.64	12.02
EMFR-02	200	17	4.247	1.16	7.96	2.64	10.60
EMFR-03	250	17	4.269	1.71	8.51	2.94	11.45
EMFR-04	300	17	4.4595	1.84	8.64	3.23	11.87
EMFR-05	150	17	4.29	1.77	8.57	2.62	11.19

4. Result and Discussion

4.1 Load-load line displacement

Load-LLD curve of irradiated specimen was compared with that of unirradiated specimen as shown Fig.4. At room temperature, maximum load (P_{max}) of irradiated specimen reduces by 37% comparing with unirradiated specimen. However, at 300°C, P_{max} of irradiated specimen increase by 12% comparing with unirradiated specimen. At room temperature, LLD when load is P_{max}, reduce by 48% (0.94mm to 0.46mm). LLD between irradiated and unirradiated specimens have no difference at 300°C.

Fig.5 and Fig.6 shows load-LLD curve and crack growth – LLD at room temperature and 300°C.

At room temperature, load-LLD curve have unstable load drop behavior. This behavior is due to irradiation damaged matrix and hydride precipitation. At high temperature, damaged matrix is recovered, and hydride is dissolved so resistance curve show stable crack growth and no crack jump

4.2 Crack resistance curve (J-R curve)

Fig. 7 shows that crack resistance curve (J-R curve) of irradiated specimen. Crack resistance curve at room temperature have unstable crack growth like crack jump. Crack resistance curve at high temperature (150°C to 300°C) have stable crack growth. Crack resistance curve with specimen which is tested at high temperature (except 250°C) shows similar behavior as show Fig. 7. So it is thought that irradiation defect is recovered above 150°C. Final crack length at room temperature is 30% longer than that of 300°C in spite that LLD of P_{max} at room temperature is smaller than that of P_{max} at 300°C as shown Fig. 4 because there are unstable crack growth stages due to brittle fracture at room temperature as shown Fig. 7.

Fracture toughness characteristic shows in Fig. 8 and Fig. 9. dJ/da and $J_{0.2}$ have small value due to crack jump. dJ/da and $J_{0.2}$ at high temperature are recovered because irradiation defect is recovered. However, at 250, the fracture toughness reduces slightly.

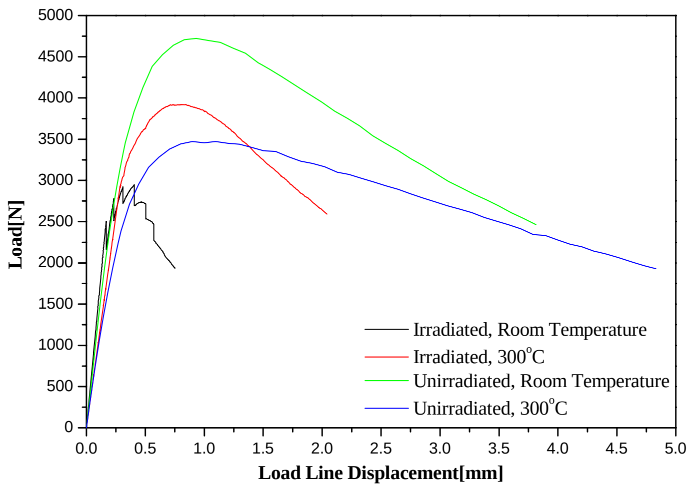

Fig. 4 Typical behaviors of load and LLD in irradiated and unirradiated specimens at room temperature and 300°C

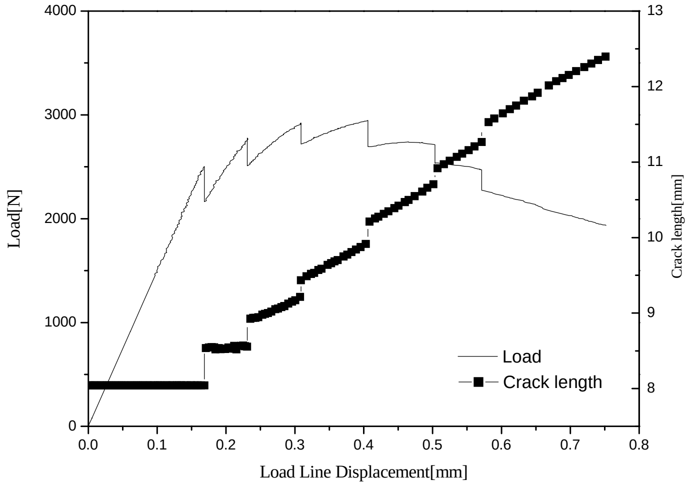

*Fig. 5 The unstable load change and crack jumps referenced from irradiated specimen under room temepratur*e

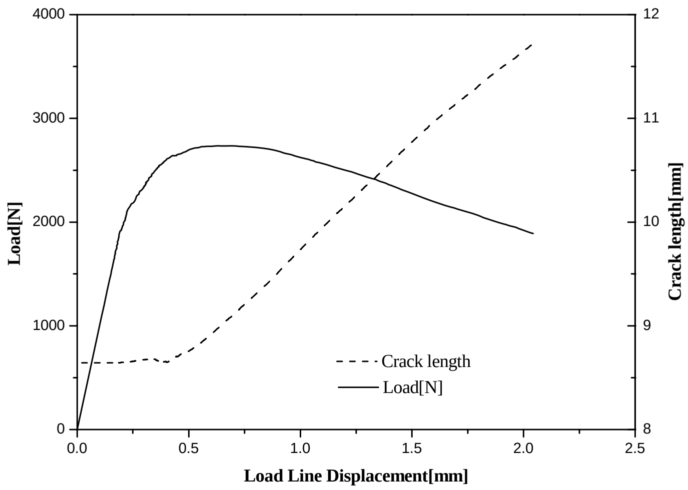

Fig. 6 The stable load and crack growth from irradiated specimen at 300°C

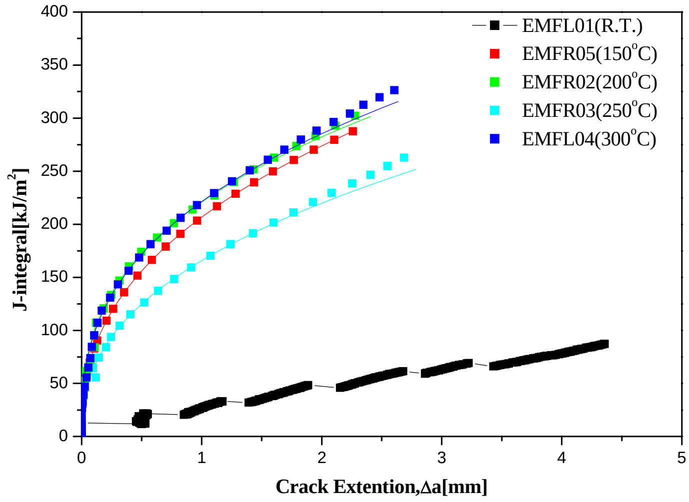

Fig. 7 Typical crack resistance curves of irradiated and unirradiated specimens at room temp.

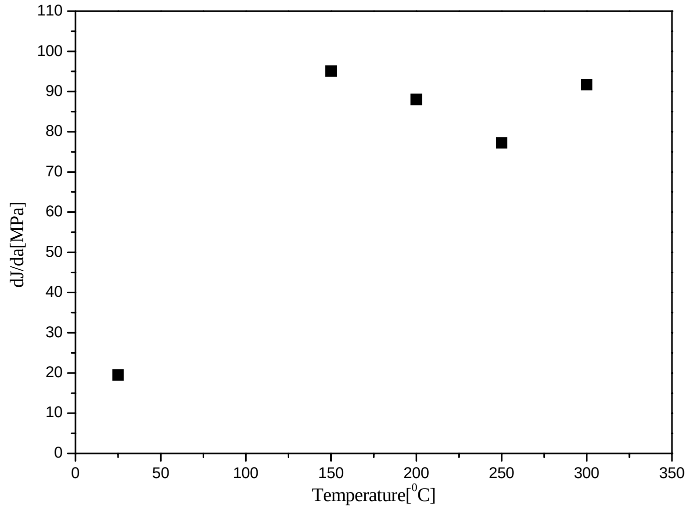

Fig. 8 dJ/da of irradiated specimen with temperature

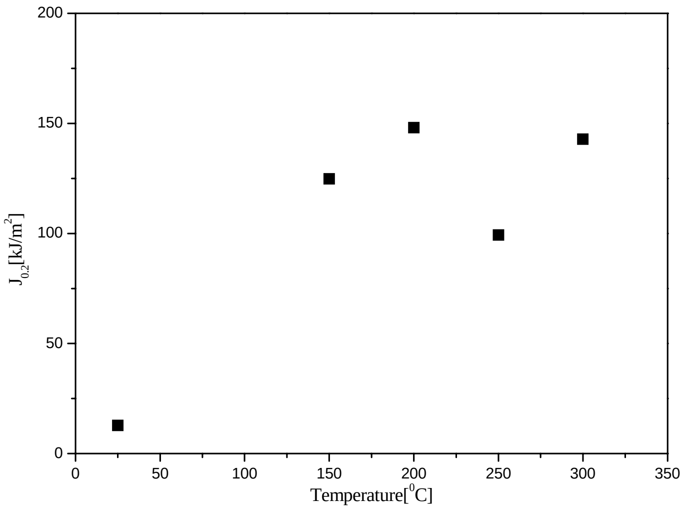

Fig. 9 dJ/da of irradiated specimen with temperature

5. Conclusion

Fracture toughness test of irradiated CANDU pressure tube which is obtained from Wolsung unit-1 is performed using load-ratio method. In Load –LLD curve, Pmax of irradiated specimen decrease at room temperature. However, Pmax of irradiated specimen increase at 300°C comparing with unirradiated specimen. At room temperature, fracture toughness is very low due to unstable crack growth. Unstable crack growth is shown as load drop in Load-LLD curve and crack jump in crack resistance curve. The reason of this behavior is that irradiation defect of matrix and hydride embrittlement. Above 150°C, there is stable crack growth because irradiation defect is recovered.

Reference

(1) Landes, J.D., Zhou, Z., Lee, K., and Herrera, R., "Normalization Method for Developing J-R Curves with the LMN Function," Journal of Testing and Evaluation, JTEVA, Vol. 19, No. 4, July 1991, pp. 305-311.

(2) Ernst, H. A., Paris, P. C.,Rossow, M., and Hutchinson, J. W.,"Analysis of Load-Displacement Relationship to Determine J-R Curve and Tearing Instability Material Properties", Fracture Mechanics, ASTM STP 677, American Society for Testing and Materials, Philadelphia, 1979, pp. 581-599

(3) Hu, J. M.,Albrechtm P., and Joyce, J. A., "Load Ratio Method for Estimating Crack Extension,"Fracture Mechanics : Twenty-Second Symposium(Volume I), ASTM STP 1131, H. A. Ernst, A. Savena, and D.L. McDowell, Eds., American Society for Testing and Materials, Philadelpia, 1992, pp. 880-903.

(4) Kapp, J. A., "J-R curve Determination Using Precracked Charpy Specimens and the Load-Drop Method for Crack Measurements", Fracture Mechanics: Sixteenth Smposium, ASTM STP 868, M. K. Kenninen and A. T. Hopper, Eds., American Society for Testing and Materials, Philadelphia, 1985, pp. 281-292.
(5) ASTM E1820-01 Standard Test Method for Measurement of Fracture Toughness
(6) B.S. Lee and J. H. Hong, "J-R Characterization of CT specimens by the Load ratio method", the Korean Society of Mechanical Engineers Spring meeting (1997)
(7) V. Kurmar, M. D. German, and C.F. Shih, An Engineering Approach for Elastic-Plastic Fracture Analysis, EPRI NP-1931(1981)
(8) J. G. Merkle and H. T. Corten, Trans. ASME: Journal of Pressure Vessel Technology, pp286-292(1974)
(9) Davies, P. H., Shewfelt, R. S. W. and Jaevine, A. K., 1995, "Constraint Effect in Testing Different Curved Geometries of Zr-2.5Nb Pressure Tube Material," Zirconium in the Nuclear Industry, ASTM STP 824, pp. 88~105.

