DEVELOPMENT OF MECHANICAL TEST TECHNIQUES ON AN OPERATED CANDU PRESSURE TUBE MATERIAL IN A HOT CELL

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ABSTRACT

Various mechanical property data are required to evaluate the operation safety based on the LBB criterion for an operated (irradiated) CANDU pressure tube. The mechanical test techniques as of a tensile, a fracture toughness, and an axial delayed hydride cracking velocity (DHCV), and furthermore a specimen fabrication technique are developed to acquire them in hot cells. The operated tube was pulled out from a reactor core, cut to be the rings with 300mm in a total length, and transported to the hot cell facility. They are machined to various shapes of specimen using the electric discharge machine (EDM) and the CNC milling machine specially designed for the hot cell usage. Tensile tests are conducted with shoulder girder type specimens, which are easily fitted to the jig. The curved 17mm compact tension (CT) specimens retaining an original tube radius are machined to conduct fracture and DHCV tests. They are pre-cracked to 1.7 mm in a crack length. During the test in an UTM, a crack growth length is continuously measured using the direct current potential drop (DCPD) system. The specimens for DHCV tests are charged with 50 ppm in hydrogen content by the electro-chemical method. The crack velocity is continuously measured to be divided the crack advanced length by a loading time in a fixed range. The characteristic values from tests are successfully adopted to evaluate the LBB criterion for the operation tube in reactor.

1. Introduction

In Korea, 4 PHWRs (Pressurized Heavy Water Reactors) are currently under operation since the Wolsung Unit 1 has started operation in 1983. Thin-walled pressure tube of Zr-2.5Nb material, which is nominally 6.3m long, 103mm in a diameter, and 4.2mm thick, is used as the primary containment for the uranium dioxide fuel in a PHWR as shown in Figure 1. Heavy water flows through the tubes to cool the fuel, under an internal pressure of about 10 MPa, and at a temperature range from about 260 to 320°C[1]. Over the expected lifetime, the pressure tube is subjected to degradation due to exposure to high stresses, temperature and neutron flux. One criterion for lifetime of a tube would be an inability to defend leak-before-break (LBB). This condition can be met a LBB if a crack initiate, penetrates the tube wall and leakage of heavy water is detected before the crack grows the critical crack length(CCL) and become unstable. To get an LBB available time the CCL and DHCV are necessary, and the CCL is governed by a crack driving force (CDF) and a fracture toughness [2]. The CDF can be calculated using an elastic constant, flow stress decided from tensile

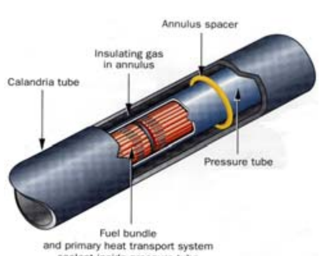

Fig.1 Tensile specimen cutting plan from the irradiated tube

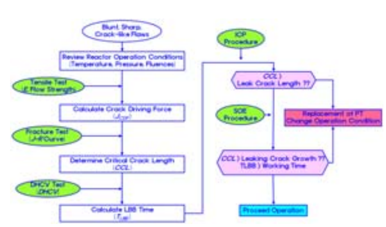

Fig. 2 Flow chart to evaluate the safety based on a LBB criterion.

tests as shown in Figure 2. To acquire the experimental data above mentioned various mechanical test techniques for the irradiated tube were developed in this paper.

2. Specimen fabrication techniques

The fabrication techniques on a transverse tensile specimen and a 17mm compact tension specimen are developed to use in the tests. The electric discharge machine (EDM) has been designed to cut out the specimens directly from the irradiated tube, which is shown in Figure 3. It has mainly two parts, one is a body to discharge cutting specimens including a filter unit, and the other is an electrical control part. The whole size of a main body is 1000(W) x 905(D) x 800(H) mm. A tube fixing device can be rotated to position the electrode on the tube. The electrode is fixed to an air chuck head with a 6-bar compressed air. The specimen deserves a heating up, a dimension change, and a surface coarseness during discharging. To decide the optimum discharging conditions the measurement tests as dimensions, surface roughness, heat affected layer, heat-up temperature are performed in the conditions of a different input current and on-time. Through the tests the optimum conditions are acquired to be an input current 6~7 amperes and an on-time 2 μsec. In these conditions the specimen has about 100μm the heat affected zone size, 5~7μm and 30~60μm in an average and the maximum roughness respectively, and heated up to 90 degC in the maximum temperature. Figure 4 and 5 shows the electrodes.The CNC milling machine cuts out the round area part to be flat in a tensile specimen.

3. Development of test techniques

3.1 Tensile test

The shape of a transverse tensile specimen is chosen as the shoulder girder type due to the convenience of specimen installation on the jig in a hot cell. Detailed shape and

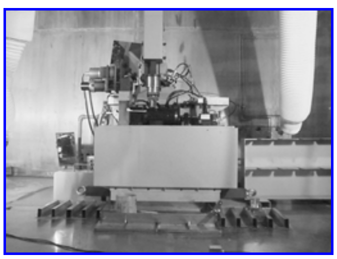

Fig. 3 The shape of EDM in a hot cell.

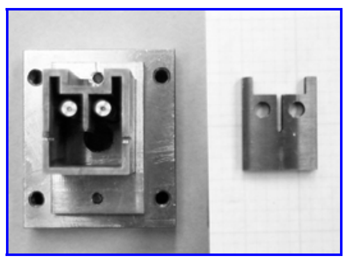

Fig. 4 The electrode of an 17 mm curved CT specimen

Fig. 5 The electrode of a tensile specimen

dimensions of specimen are shown in Figure 6 and 7. The specimens are collected from the six and nine o'clock positions in a vertical viewpoint from the coolant inlet side. To get a flat part in a gauge section in the specimen, the curved areas caused from a tube diameter are machined by a CNC milling machine. The tensile tests are performed by a dynamic UTM manufactured by Instron Co. with a specially designed chamber. The test speed is 0.12mm/min, and the test temperatures are a room temperature (RT), 100, 150, 200, 250, and 300 degC. Instead of the attachment of an extensometer on a specimen during main tests, dummy specimen tests are performed to get a compliance value for the machine system including the jig. Finally the load and displacement curve after test is compensated using the compliance value from the dummy tests. In addition, the microstructures of tube materials were observed by TEM which has 20kV in a power. The example of the stress and strain curves through tests is shown in Figure 8 [3].

3.2 Fracture toughness test

The specimen shape to measure a fracture toughness, which is a crack resistance curve (J-R curve), is a 17mm curved CT proposed by AECL staffs [4]. The detailed dimensions of it are shown in Figure 9 and 10. Except for the thickness and the curvature of the tube, the in-plane dimensions of specimen are in the same proportions to a compact specimen used in ASTM E 813. It has been shown that the curvature of the specimen does not introduce significant errors when the flat specimen equations were applied because of the small specimen size. Unpublished finite element calculation by B. Leitech has confirmed this conclusion [5]. It is directly machined from a tube retaining the original curvature by EDM. The discharging conditions were 6 Ampere in a current and 0.2μsec in an on-time.

The specimens are fatigue-precracked to about 1.7mm in a crack advanced length using

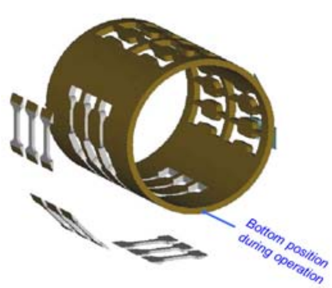

Fig.6 A cutting plan of the tensile specimen in the irradiated tube

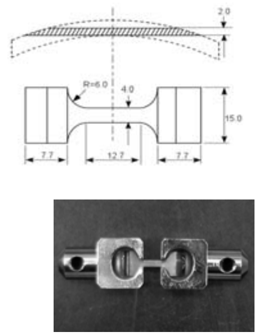

Fig. 7 Detailed shape of a transverse tensile specimen

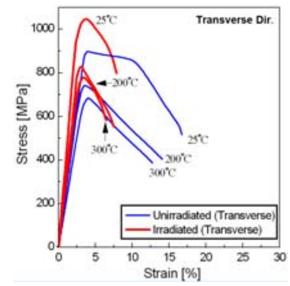

Fig. 8 Result example of transverse tensile test

the Instron 8502 machine. An *a/W* value in a precracked length is about 1, where *a* is the crack length and *W* the width of the specimen. A simple analytical calculation estimates that the maximum curvature-induced stress was less than 10% of the in-plane tensile stress at the crack tip [5]. It induce that the crack front line is slanted to the inside direction of tube. Therefore the tapered connecting pins between the specimen and the jig to produce a straight front line are used. The tapered angle in the pin is optimized to be 1.5^o through tests for various taper pins. The fatigue precracking is carried out in the spirit of ASTM E 399 section A22. The loading cycle is 5 Hz to initiate the fatigue crack evenly, an initial stress intensity factor range (ΔK) about 15 $MPa\sqrt{m}$ with the load ratio(R) of 0.2. Once the fatigue crack is generated, ΔK is continuously decreased to be about *10* $MPa\sqrt{m}$ at the final precracking stage.

During the fracture toughness test the amount of crack growth is measured by the reverse direct current potential drop (DCPD) system. The test fixtures which are consisted of pull rods and grips to be insulated to prevent electrically short circuiting from DCPD currents. The power supply lines are attached to the upper and lower edges using brass cap. The lead wires to measure a dropped voltage are Nickel-Copper electric lines in a diameter 0.6mm and are spot-welded to the crack mouth of the specimen in a lead glove box. The spot-welding condition is 3,000 Amperes in a current and 0.2 sec in a pressuring time. After welding the specimen is carefully handled in the grips, and connected it with the pins so as not to disturb the potential leads. The DCPD system are switched on and allowed to be stabilized until the potential drop indicated that there are no more voltage changes for at least 20 minutes.

The compliance value caused by the jig deflection with loading is measured before tests using a rigid steel body over a full load range. The load and displacement curve from the fracture test is finally compensated with the compliance value.

The fracture test is carried to advance the crack between 3.0 ~ 4.0 mm in a length. The test speed in a displacement is 0.25mm/min. Through the test, the values of a load, a load point displacement, a dropped voltage and ambient temperature were continuously to be monitored and recorded. After test the specimen is heated to 280~290°C in a temperature to be tinted on the fractured surface. A small load (approximately 50% of the final load) is applied to the specimen to prevent a crack closure during the heat-tinting. The initial and final crack lengths are measured by the nine point average method with highscope system. From the total dropped voltage and the crack growth, the calibration constant is derived to calculate the crack increments during the test. The J-integral values according to the crack length are calculated to generate the crack resistance curve (J-R curve) based on ASTM E-1152. The example of the crack resistance curves are shown in Figure 11.

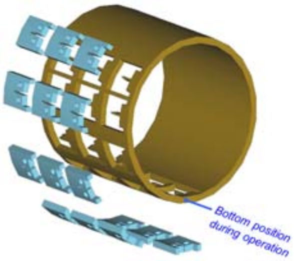

Fig. 9 The cutting plan of CT specimens.

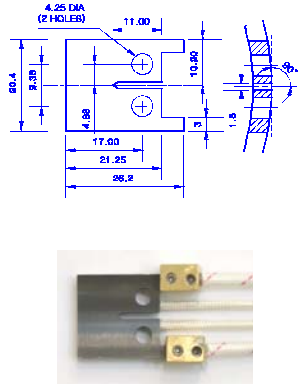

Fig. 10 Detailed shape of a CT specimen

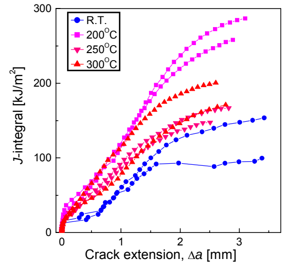

Fig. 11 Result example of the fracture tests

3.3 Longitudinal DHCV test

The specimen to perform a DHCV test is a curved 17 mm CT, which is the same as that of fracture toughness test. Before doing a precracking procedure the specimens are charged with hydrogen in an amount of 50 ppm using an electro-chemical diffusion method.

The specimens were polished up to 1200 grit emery paper to obtain oxide free surface. Subsequently they are submerged into the stirrer with 0.1 mol sulphuric acid solutions. The solutions are continuously mixed and maintained at 90 ^{o}C during 24 hours. The direct current is supplied to the specimen which is connected to the minus pole. Hydrogen dissolved from water gathered on the surface of specimen, and piled up the hydride layers. The next annealing procedure to diffuse the surface hydrogen into the specimen is executed at 275 ^{o}C during 30 hours. According to McMinn's study this annealing temperature get 50 ppm in the hydrogen solubility [6]. After annealing process the specimen surface is again cleaned to remove unsolved hydride. Finally the amount of hydrogen solubility is chemically measured, and the proper specimens to test are picked up.

Specimens are pre-cracked to about 1.7mm (a/w = 0.1) in a crack length with the value of 0.1 in a load ratio (R) and 5Hz in a loading cycle. A static UTM, a direct current potential drop device, a heating furnace and a data acquisition system are set up to perform a DHCV test. The input current lines in a DCPD system are screwed to the each edge of specimen, and the dropped voltage lines are spot-welded to the area of a crack mouth. A tubular heating furnace controls the test temperature in the precision of ± 2^{o}C. The thermal route on the specimen in the process of a heat-up, a homogenization, a cool-down and a test are as shown in Fig. 13. The furnace is heated up to 275 ^{o}C in 20 ~ 30 minutes with care not to overshoot the designated temperature in the first stage. If the homogenization temperature is higher than 275 ^{o}C, the hydrogen solubility may excess to the designated 50 ppm, it give a different DHCV value. After a homogenization stage in 1~1.5 hours the furnace temperature is cooled down to start the DHCV test. After maintaining 1 hour in the test temperature following the cool-down step, a load is applied and the dropped voltage is measured. The amount of the load is 13~15 $MPa\sqrt{m}$ determined from the base on the specimen size in the compliance with ASTM E 399. The supply current to the specimen in the DCPD system is 6 Ampere, and the dropped voltages are varied between 2~3 mV with the test temperature and the crack growth length. During test the crack growth length can be predicted according to the equation $\Delta a/W = (1.1 \sim 1.2) \cdot \Delta V/Vo$ that was determined from the calibration process before the test. The crack growth length should be continuously calculated from the monitored dropped during the test. When the calculated crack growth length is reached up to 3.4 ~ 4.2 mm the test is finished. Some specimens having the shorter crack length than the above mentioned value can be repeatedly tested in the different test temperature condition considering the scarce and the fabrication hardness for the irradiated specimen. In the repeated tests the heating route should be fully reiterated except for the test temperature shown in Figure 13. After finishing the test the specimen is heat-tinted in the temperature of 250 ^{o}C. The specimen is separated into two pieces on the basis of the cracked line as shown in Figure 13. The final crack length is measured on the fractured surface using the high-scope system with x20 in magnification.

The example of test result is shown in Figure 14. During the test in figure a load line displacement and a dropped voltage under a fixed load are continuously increased. We can match the initial crack length to the initial dropped voltage and the final crack length to the final dropped voltage during the test period. The instantaneous DHCV is constantly calculated by the equation as (final crack length – initial crack length) / (fixed period time). The DHCV can be decided as shown in Figure 14 according to the K-value with the crack length and DHCV with a fixed period.

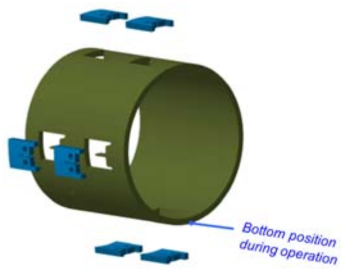

Fig.12 The cutting plan of DHCV specimens

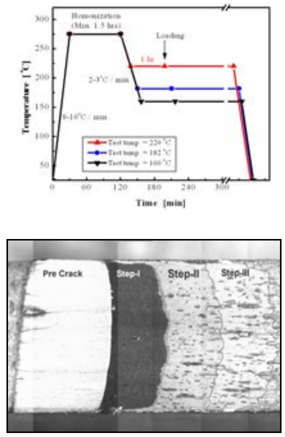

Fig. 13 Thermal heating routes during a DHCV test, and a fractured surface configuration

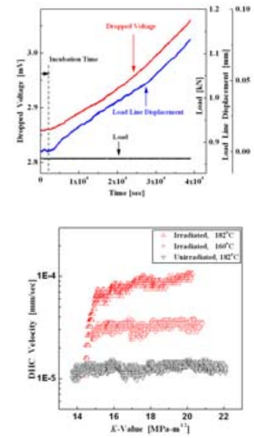

Fig. 14 Result example of DHCV tests

4. Conclusions

The mechanical test techniques for the operated CANDU pressure tube material are successfully developed in a hot cell. The electric discharge machine and the CNC milling machine are specially designed and introduced to fabricate specimens from a tube. The techniques on the crack length measurement using a reversed DCPD system and the precracking procedure of the 17 mm curved CT specimen are developed to perform the fracture toughness tests. The hydrogen charging method, the heating route and the DHCV calculation method from raw test data also developed for the DHCV test. We will effort to enhance the developed techniques in this paper, and finally these will be adopted to evaluate the tube operation safety for PHWR in Korea

References

[1] Puls, M. P., 1997, Nuclear Engineering & Design Vol. 171, pp.137-148
[2] Moan, G. D., 1990, Int. J. Pres. Ves. & Piping Vol 43, pp 1-21
[3] Ahn, Sangbok et al, 2005, Key Engineering Materials Vols 297-300, pp. 421-427.
[4] Chow, C. K. et al, ASTM STP 945, 1988, pp 419-439
[5] Chow, C. K. et al, ASTM STP 1132, 1991, pp 246-275
[6] Mcminn, A et al, ASTM STP 1345, 2000, pp. 173-195