2.5 The Development of Crack Measurement System Using the Direct Current Potential Drop Method for Use in the Hot Cell

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ABSTRACT

The crack length measurement system using the direct current potential drop (DCPD) method was developed for the detection of crack growth initiation and subsequent crack growth. The experimental precautions and data processing procedure required for its application were also described and discussed. The system presented herein was specially built for use in fracture toughness testing of unirradiated or irradiated pressure tube materials from nuclear reactor.

The application of this system for fracture toughness determination was illustrated from the test of curved compact tension specimens removed from CANDU reactor pressure tubes. The crack extension was monitored using the DCPD method. It is found that the changes of the potential drop and the changes of the crack length have a linear relationship. The final crack front was marked by heat-tinting after the test and the specimen broken open for determination of the initial and final physical crack length. The physical crack lengths, obtained by the 9-point average method described in ASTM E1737-96 on heat-tinted fracture surface, were used to calibrate the DCPD method for each test on an individual basis by matching the change in voltage to the crack extension. It is found that this system can be recommended for determination of the $J$-integral resistance ($J-R$) curve of unirradiated or
irradiated materials in the hot cell, especially when testing at elevated temperature and in the environment chamber or furnace.

INTRODUCTION

Precise measurements of crack extension are crucial for the determination of reliable fracture toughness and fatigue crack growth rates. Various crack measurement techniques have been applied, including optical (visual and photographic), ultrasonic, acoustic emission, electrical (eddy current and potential difference), and compliance (COD and back face strain gages) methods. Optical, compliance and electrical potential difference are the most common laboratory techniques. The optical technique [1] is simple and inexpensive, and calibration is not required. Accurate measurements can be performed provided the specimen is carefully polished and does not oxidize or corrode during the test. However, crack length is usually underestimated with this method. The process is time consuming and can be automated only with complicated and expensive video-digitizing equipment. In addition, many fracture mechanics tests are conducted in simulated-service environments that obscure direct observation of the crack. The trend toward laboratory automation has resulted in the development of indirect methods of determining crack extension, such as specimen compliance and electric potential difference monitoring.

The methods used to measure changes in compliance [1-3] include crack-opening displacement (COD), back-face strain, and crack-tip strain measurements. Among those, the COD method is less expensive, the specimen need not be visually accessible, and it provides an average crack length figure where crack-front curvature occurs. Also, it can be used as a remote method and is easily automated. However, the COD technique has its limitations: it is use for specimens where time-dependent, time-independent, and reversed plasticity effects are small, and has difficulty in attaching clip gage to small specimens in environmental chambers or furnaces.

On the other hand, the electric potential difference (EPD) methods are applicable to virtually any electrically conducting material in room-temperature applications as well as high-temperature applications. It can be used for detecting crack initiation and measuring crack growth in the laboratory. Both direct current (DC) and alternating current (AC) techniques have been used to measure crack size in test specimen. For the more common direct current potential drop (DCPD) technique [4-10], it is simple, robust, and of relatively low cost. This method is amenable to automation and for long-term high-temperature testing but is well established for only certain specimen geometry. However, the method has the limitation of not distinguishing between the crack extension and external dimensional changes.
of the specimen that would typically occur during general yielding and is not suitable for large specimens. Its application is totally dependent on an accurate calibration relating output voltage to crack length.

This study describes the development and application of a direct current potential method of crack length monitoring for use in fracture toughness testing in the hot cell. The crack length measured by DCPD method is compared with the observed crack length on the specimen surface. And this system is verified through the $J$-integral test using curved compact tension (CCT) specimen removed from the CANDU pressure tube.

**FRACTURE TOUGHNESS TESTING SYSTEM**

The elastic-plastic fracture toughness, $J$-integral, test procedure requires simultaneous and continuous measurement of load, load-line displacement and crack length during the test.

The direct current potential drop (DCPD) technique is a widely accepted method of monitoring crack initiation and growth in controlled laboratory tests. In its simplest form it involves passing a constant current through the test piece and accurately measuring the electrical potential across the crack plane. As the crack propagates, the measured potential drop (PD) increases due to the reduction in uncracked sectional area of the test piece. Typical apparatus for the DCPD technique is illustrated in Figure 1. The basic equipment for the DCPD method consists of a source of constant dc current, a voltmeter of measuring the potential differences that are produced across the crack plane and DCPD IEEE reversing current unit.

A very stable source of constant electrical current is required to maximize the sensitivity of the apparatus. HWD 20-10 Transistorized Regulated Power supply manufactured by Mid-Eastern Industries, Inc. was used to supply a constant DC current to the specimen. This supply can be set to any current between 0 to 10A with excellent long-term stability and very low noise levels. The voltage measuring circuit was required to measure continuously changes of the order of microvolts in a signal of several millivolts. Initially, the potential leads were connected to a Hewlett-Packard 3457A multimeter with 6.5 digits of resolution. EPD data was taken in the following procedures. A digital pulse from the INSTRON 8500 Plus occurs at the maximum load. This pulse then triggers the Hewlett-Packard multimeter to capture data. Using a small area (20%) allow the EPD voltage to be captured at the maximum load. Maximum load corresponds to maximum crack opening and gives the best resolution for crack length determination during test. In addition, for improving voltage measurement precision, voltage lead wires were twisted and were held to reduce stray voltage induced by changing magnetic fields. Grounding of all devices (current supply, voltmeter, and so on) was
made properly. For DCPD system the thermoelectric effect was taken into account by measuring voltage while reversing the direction of current flow [11].

Testing was conducted on INSTRON 8500 Plus hydraulic testing machine. The pull rods and the grips are machined from heat-treated steel. Test fixture for J-integral tests was electrically insulated from the test machine to prevent short-circuiting of the DCPD apparatus used for crack extension measurement. This can be achieved by making and inserting the Teflon insulation plates between the test fixture and load cell and actuator.

Load-point displacement was measured continuously by the two linear variable differential transducer (LVDT) attached at the both load-line of the CCT specimen during the J-integral test, Figure 2. The elastic displacement of the load train was excluded by using the LVDT signal [12, 13]. The average value of the corrected LVDT readings is taken as the load-line displacement for calculating J-integral.

**MATERIAL AND TEST PROCEDURES**

Zr-2.5%Nb CANDU pressure tube materials were tested in this study. The inside diameter and nominal wall thickness of the pressure tube were 103mm and 4.3mm, respectively.

The specimen used in J-integral fracture toughness tests was cut from CANDU pressure tube by electric discharge machining. The dimensions of specimens are shown in Figure 3. Except for the thickness and the curvature of the tube, the in-plane dimensions of curved compact tension (CCT) specimen are in the proportions described for compact tension specimen in ASTM Standard Test Method E1737-96 for J-integral Characterization of Fracture Toughness [14].

For the measurements of crack extension during J-integral test, the DC current leads were asbestos-covered nickel-copper wire, 2.1mm in diameter, screwed into the appropriate places of specimen allowing 6A to be carried. The voltage measuring leads were nickel-copper wires, 0.6mm in diameter, spot-welded to opposite side within 1mm of the crack mouth as shown in Figure 4.

Before J-integral testing, the CCT specimens were fatigue-precracked for about 4.76mm at room temperature so that the final crack depth \((a/W)\) was about 0.53, where \(a\) is the crack length and \(W\) is the width of specimen. The initial maximum stress intensity factor and the final maximum stress intensity factor were about 16.3 and 12.7MPa m\(^{1/2}\), respectively. The fatigue precracking was performed with sinusoidal waveform having stress ratio (minimum to maximum load ratio, \(R\)) of 0.1. The tapered loading pins with 1.5 degrees of taper were used for producing straighter fatigue precrack. In order to monitor the fatigue crack growth, at first a small area on surface of the specimen ahead of the crack tip was polished, and then the
crack growth was observed with a magnifying (X80) travelling microscope.

The $J$-integral tests were performed in air using a constant displacement rate of 0.25mm/min. The crack extension was measured by DCPD method. The tests continued until the PD indicated that the crack had propagated for about 3 to 4mm. After completing the final loading, the area of slow-stable crack extension at the end of the test was heat-tinted for 30minutes at 300°C and observed by optical measuring microscope. The initial and final crack lengths were measured by the ASTM E1737-96 nine-point average method. The ratio of the total change in crack length to the total change in PD was used to interpolate the crack length during the test, assuming a linear relationship. The $J$-$R$ curve was then calculated using ASTM Test Standard E 1737-96.

### RESULTS and DISCUSSION

The DCPD technique relies on the relationship between the crack length and the measured potential, which can be determined either by empirical or theoretical means. The typical closed form expressions of a voltage versus crack length relationship that applies approximately for the CT specimen geometry is given in ASTM E1737-96 and E647-95a [15]. However, if wire placement (current or voltage) or testing environment has been altered, the suggested relationship is no longer valid, and a new relationship must be developed. Some researchers have used the saw-cut method to obtain the calibration curve [4]. In practice, the possibility of short circuits across the crack opening exists, especially due to the roughness of the fracture surface. Also, there could be some problems to apply the saw-cut method to the irradiated materials. Alternatively, we have observed optically the crack length on the specimen surface. Although the optical surface measurements can not give an average crack length along the crack front, the relationship between the crack length and the potential drop can be obtained. The fatigue crack growth was monitored by polishing a small area on surface of the specimen ahead of the crack tip and by observing the crack growth with a magnifying (X80) travelling microscope as shown in Figure 5.

Figure 6 shows the crack length monitored on the specimen surface by a magnifying (X80) travelling microscope with PD signals measured during the fatigue crack growth test for CCT specimen at room temperature. As expected, the crack length is linearly increased with an increase in PD.

We found the linear relationship between the crack length and the PD. But, the proportional factor determined in Fig. 6 can not be used to established the $J$-$R$ curve because of the effects of the plasticity on the measured potential during the $J$-integral test. Therefore, we assumed that the change of potential drop was proportional to the change of crack length. Then the
proportional factors were obtained for each specimen by measuring the total potential change during the test and the total stable crack growth. The total stable crack length was measured by the nine-point average method in ASTM E1737-96 on the heat-tinted fracture surface after the test.

A typical heat-tinted fracture surface is shown in Figure 7, in which three regions can be observed. The fatigue crack fronts were usually quite straight, indicating that the curvature of the curved specimen did not change the stress distribution significantly. The stable crack had a thumbnail shape, which is quite symmetric with respect to the thickness of the specimen, indicating again that the curvature did not modify the stress field near the crack tip significantly.

A computer program was developed to generate the $J-R$ curve using the procedures described in earlier. Typical $J-R$ curve of unirradiated CANDU pressure tube at room temperature is given in Figure 8.

**CONCLUSIONS**

1. The DCPD system developed in KAERI has been successfully used to measure the crack length of curved compact tension specimen in the hot cell.
2. A quite straight fatigue crack and stable crack fronts were obtained on the fracture surface of curved compact tension specimen by using the 1.5° tapered pin.
3. Assuming the linear relationship between the changes of potential drop and the changes of crack length measured by nine-point average method and using computer program developed in this study, $J-R$ curve can be established.

**REFERENCES**

Fig. 1  Schematic diagram of the DCPD system

Fig. 2  Pull rod assembly for Hot cell testing
Fig. 3  Configurations of curved compact tension specimen

Fig. 4  Placements of current wires, voltage wires and LVDTs
Fig. 5  Measurement of crack length on the specimen surface

Fig. 6  Potential drop as a function of crack length for curved compact tension specimen at room temperature. For 0.50 < a/W < 0.75, the relationship can be taken as linear.
Fig. 7 Fracture surface of a specimen tested at room temperature

Fig. 8 J-R curve of curved compact tension specimen