

Results of Fracture Toughness Tests for the Round Robin Test Program Using Mini-Compact Specimens

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Light Water Reactor Sustainability

Results of Fracture Toughness Tests for the Round Robin Test Program Using Mini-Compact Specimens

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INTRODUCTION

Small specimens are playing the key role in evaluating properties of irradiated materials. The use of small specimens provides several advantages. Typically, only a small volume of material can be irradiated in a reactor at desirable conditions in terms of temperature, neutron flux, and neutron dose. A small volume of irradiated material may also allow for easier handling of specimens. Smaller specimens reduce the amount of radioactive material, minimizing personnel exposures and waste disposal. However, use of small specimens imposes a variety of challenges as well. These challenges are associated with proper accounting for size effects and transferability of small specimen data to the real structures of interest.

Any fracture toughness specimen that can be made out of the broken halves of standard Charpy specimens may have exceptional utility for evaluation of reactor pressure vessels (RPVs) since it would allow one to determine and monitor directly actual fracture toughness instead of requiring indirect predictions using correlations established with impact data. The Charpy V-notch specimen is the most commonly used specimen geometry in surveillance programs.

The Central Research Institute of Electric Power Industry (CRIEPI) had developed the test technique for the miniature C(T) specimens (Mini-CT), whose dimensions are 4 x 10 x 10 mm, and verified the basic applicability of the Master Curve approach by means of Mini-CT for the determination of fracture toughness of a typical RPV steel. A round robin program is organized with the participation of Japanese and International academia, industries and government institutes. The program aims to verify the reliability and robustness of experimental data of the Mini-CT, and to pick out further investigation items to be solved before the actual application of the technique. The advantage of this Mini-CT specimen technique is that multiple specimens can be machined from one half of a broken Charpy specimen, used in a standard surveillance capsule of a reactor pressure vessel.

This report summarizes the results of the round robin testing program performed at ORNL. The report is prepared in satisfaction of Milestone M3LW-15OR0402012 – Complete Report Detailing the Results of Fracture Toughness Test for the Round Robin Test Program Using Mini-Compact Specimens.

MATERIAL AND EXPERIMENTAL PROCEDURE

The tested material is Japanese RPV steel forging, SFVQ1A [1], with chemical composition shown in Table 1. As a result of previous investigation [2] on several Japanese RPV materials including SFVQ1A, Young's modulus E (GPa) and yield stress σ_y (MPa) of the material in the temperature range of RT to -150°C is represented by the following equations:

$$E = 208.74 - 0.063T \quad (1)$$

$$\sigma_y = 84 + 271 \exp \{110 / (T + 273.15)\} \quad (2)$$

where, T is temperature in $^\circ\text{C}$.

The original material used for the round robin is one of the broken halves of a 4T-C(T) specimen, which is taken from the center part of a 160mm thickness forging. After the fracture toughness testing on the 4T-C(T) specimen at -100°C , blocks of $12 \times 12 \times 100\text{mm}$ were machined from the broken half (Fig. 1). Each block was sliced into 20 pieces of $10 \times 10 \times 4\text{mm}$ (Fig. 2). Every piece was numbered as specimen 01 to 20 according to its location in the block.

Table 1. Chemical composition of tested material, wt% [3].

Material	C	Si	Mn	P	S	Ni	Cr	Mo	V
SFVQ1A	0.18	0.18	1.46	0.002	<0.001	0.90	0.12	0.52	<0.01

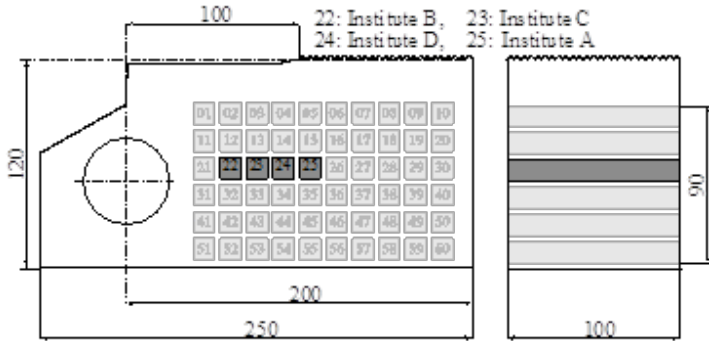


Figure 1. Numbering and location of blocks in 4T-C(T) specimen [4].

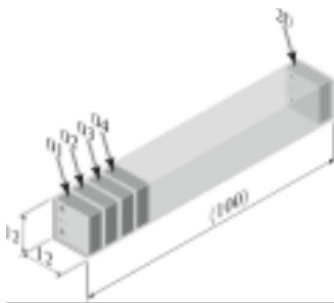


Figure 2. Location of Mini-CT specimens in block [4].

Each small piece was machined into Mini-CT specimen in T-L orientation. The geometry of Mini-CT (Fig. 3) follows the specifications in ASTM E1921-10 with an exception in the width of the wire-cut notch. Because of the limitation in available minimum wire diameter (0.1mm) used in notch machining, the notch width is about 0.2mm instead of 0.01W (0.08mm in Mini-CT) as shown in ASTM E1921-10.

The specimens were fatigue pre-cracked up to an a/W ratio of 0.5. The total crack length with the machined notch length on the side surface was maintained to be 3.8 mm to consider some amount of crack tunneling toward the thickness direction. CRIEPI machined and pre-cracked all the specimens before the distribution of them to the participating organizations. The test temperature was prescribed by CRIEPI to be -120°C based on results of preliminary testing in Japan [2].

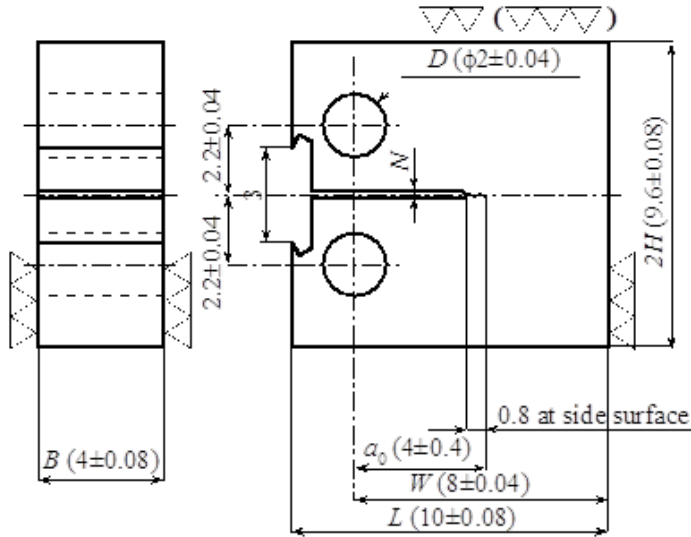


Figure 3. Geometry of Mini-CT specimen tested in this program [4].

EVALUATION OF FRACTURE TOUGHNESS AND THE REFERENCE TRANSITION TEMPERATURE, T_0

Fracture toughness and reference temperature T_0 was evaluated following three steps of the Master Curve evaluation in ASTM E1921-10 [5].

Step 1 is evaluation of fracture toughness K_{Jc} . K_{Jc} was evaluated by equation (3) using the J integral value at fracture, J_c , which was obtained from the relationship between load and load line displacement:

$$K_{Jc} = (J_c E / (1-\nu^2))^{0.5} \quad (3)$$

where, E is Young's modulus, ν is Poisson's ratio. J_c is given as the sum of its elastic and plastic components, J_e and J_p :

$$J_c = J_e + J_p \quad (4)$$

$$J_e = (1-\nu^2) K_e^2 / E \quad (5)$$

$$J_p = \eta A_p / (B b_0) \quad (6)$$

where, K_e is the stress intensity factor at the start of cleavage, b_0 is the initial ligament length ($W - a_0$), A_p is the area under the load - load line displacement curve; that corresponds to the plastic deformation. The parameter η is determined according to the shape of the specimen. For a C(T) specimen $\eta = 2 + 0.522 b_0/W$. K_e can be obtained by equations (7) and (8) for C(T) specimen without side grooves.

$$K_e = P / (BW^{0.5}) f(a_0/W) \quad (7)$$

Where:

$$f(a_0/W) = \frac{2 + a_0/W}{(1 - a_0/W)^2} \times \left[\begin{array}{l} 0.886 + 4.64(a_0/W) - 13.32(a_0/W)^2 \\ + 14.72(a_0/W)^3 - 5.6(a_0/W)^4 \end{array} \right] \quad (8)$$

where P is the load at the cleavage fracture starting point.

Step 2 is the conversion of K_{JC} into $K_{JC(1Teq)}$, which is the fracture toughness equivalent to a 1T C(T) specimen with thickness $B_{1T}=25.4\text{mm}$. Following the Master Curve method, in this round robin it is considered that the fracture toughness follows a Weibull distribution with three parameters, K_{min} (location parameter, fixed to $20 \text{ MPa m}^{0.5}$), Weibull exponent (shape parameter, fixed to 4) and K_o (scale parameter). Then, $K_{JC(1Teq)}$ is determined as follows:

$$K_{JC(1Teq)} = K_{min} + [K_{Jc} - K_{min}] (B/B_{1T})^{1/4} \quad (9)$$

Step 3 is evaluation of the reference temperature, T_o . The Master Curve is described as a function of temperature, T, as follows:

$$K_{Jc(med)} = 30 + 70 \exp [0.019 (T - T_o)] \quad (10)$$

where, $K_{Jc(med)}$ is the median value of $K_{Jc(1Teq)}$ at a single test temperature, and with the single test temperature dataset, K_o , obtained as follows:

$$K_o = \left[\sum_{i=1}^N \frac{(K_{Jc(1Teq)(i)} - K_{min})^4}{r} \right]^{1/4} + K_{min} \quad (11)$$

where subscript i represents i -th data, N is the total number of data, r is the number of valid data. Valid data are data that satisfy the restrictions on the plastic deformation of the specimen in order to maintain high strain constraint at the crack tip. A data point exceeding the $K_{Jc(limit)}$ is considered as invalid data.

$$K_{Jc(limit)} = [E b_o \sigma_Y / \{30 (1 - \nu^2)\}]^{0.5} \quad (12)$$

Data points determined to be invalid should be replaced with $K_{Jc(limit)}$ as the censored data in the determination of $K_{Jc(med)}$.

$$K_{Jc(med)} = K_{min} + (K_o - K_{min}) [\ln(2)]^{1/4} \quad (13)$$

The reference fracture toughness temperature, T_o , was evaluated by equation (14):

$$T_o = T - (1/0.019) \ln [(K_{Jc(med)} - 30) / 70] \quad (14)$$

where T is the test temperature of -120°C in this round robin test program.

TEST RESULTS

Test results for the Mini-CT specimens are summarized in Table 2. A total of 12 specimens were tested as part of this round robin. All 12 K_{Jc} data were determined to be valid according to ASTM E1921-10. The calculated value of the reference fracture toughness temperature for this set is -87°C . This is in very good agreement with the $T_o = -94^\circ\text{C}$ value determined by testing 1T C(T) specimens at CRIEPI [4].

Table 2. Test results of Mini-CT specimens at -120°C.

I.D.	K_{Jc} , MPam ^{0.5}	$K_{Jc(1Teg)}$, MPam ^{0.5}	Yield Stress, MPa	a_o , mm	$K_{Jc(limit)}$, MPam ^{0.5}
F0208-4	128.3	88.2	640	3.95	143.4
F0208-5	102.3	71.8	640	3.99	142.6
F0215-20	73.3	53.6	640	3.94	143.4
F0215-4	124.4	85.8	640	3.97	142.9
F0215-17	92.2	65.5	640	4.47	133.7
F0215-18	92.2	65.5	640	3.94	143.4
F0215-20	98.5	69.5	640	4.21	138.6
F0216-1	102.4	71.9	640	3.87	144.7
F0216-3	95.2	67.4	640	3.83	145.4
F0216-19	101.4	71.3	640	3.87	144.6
F0216-20	82.8	59.6	640	3.91	144.1
F0215-3	95	67.2	640	3.98	142.8

SUMMARY

Testing of the miniature compact tension specimen, Mini-CT, has been completed as part of the international round robin testing exercises organized by CRIEPI, Japan. This design of the specimen has an advantage for long-term operation of LWRs. It can be machined from a broken half of surveillance Charpy specimen and be used for direct measurement of fracture toughness of RPV. It can also be placed in supplemental capsules for extended life monitoring purposes. The ORNL results are in very good agreement with results derived from large, 1T C(T), specimens at CRIEPI.

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