Crack-Arrest Toughness Determination from Stub-Panel Specimen Tests

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ABSTRACT

The Heavy-Section Steel Technology Program at the Oak Ridge National Laboratory is conducting experiments to improve the ability to predict crack run-arrest behavior in reactor pressure vessel steels under nonisothermal situations. Dynamic fracture data are obtained from a relatively small double-tension stub-panel specimen of A533 grade B class 1 steel that is sized between conventional ASTM crack-arrest specimens and very large HSST wide-plate specimens. Elastodynamic finite element analyses are used to determine dynamic fracture toughness values from measured data. Test techniques have been carefully established and the crack arrest toughness from the first test is consistent with that from the wide-plate and other large-specimen test results.

INTRODUCTION

The Heavy-Section Steel Technology (HSST) Program at the Oak Ridge National Laboratory (ORNL) under the sponsorship of the U.S. Nuclear Regulatory Commission is continuing to improve the understanding of conditions that govern the initiation, rapid propagation, arrest, and ductile tearing of cracks in nuclear reactor pressure vessel (RPV) steels. In pressurized-thermal-shock (PTS) scenarios, inner surface cracks in an RPV have the greatest propensity to propagate because they are located in the region of highest thermal stress, lowest temperature and greatest radiation damage. If such a crack begins to propagate radially through the vessel wall, it will extend into a region of higher fracture toughness due to the higher temperatures and lower radiation damage. Because crack initiation is a credible event in a PTS transient, assessment of vessel integrity requires the ability to predict <u>all</u> phases of a fracture event. These phases included crack initiation, nonisothermal propagation, arrest, cleavage reinitiation, stable or unstable ductile tearing, and structural instability.

This paper addresses the important objective of generating sufficient data for material properties such as the crack-arrest fracture toughness, K_{Ia}, and dynamic fracture toughness, K_{ID}, to meet the requirements of analytical concepts describing crack-arrest behavior. In particular, values for these quantities

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must be known for temperatures that range above those corresponding to the onset of the Charpy upper-shelf behavior for RPV materials. The fracture-toughness correlations contained in the ASME Boiler and Pressure Vessel Code assume that the material cannot exhibit arrest toughness above 220 $\text{MPa}\cdot\sqrt{\text{m}}$. The imposition of this limit is based in part on the fact that insufficient K_{Ia} data existed above this level, and because Charpy tests showed that impact energy levels exhibit an upper-shelf behavior. This limit does not impose difficulties for analysis of RPVs undergoing thermal-shock transients with low accompanying pressure levels, but PTS scenarios could lead to conditions where the driving force on a propagating crack increases to levels well in excess of the current ASME limit.

The K_{Ia}-data obtained from conventional ASTM Standard E1221-88 crack-arrest specimens (transverse wedge-loaded rectangular compact specimen) cover the region below 200 $\text{MPa}\cdot\sqrt{\text{m}}$, which usually corresponds to temperatures below those where arrest is likely to occur in a PTS scenario. Experiments (Bryan et al., 1986) with pressure vessels containing long axial cracks and subjected to PTS loading have shown that high K_{Ia} values (300 $\text{MPa}\cdot\sqrt{\text{m}}$) do exist at the temperatures of interest. Since the K_{Ia} measurements by means of PTS experiments provide only a few data points at high costs, a series of large (1 × 1 × 0.1 m) wide-plate tests (Pugh et al., 1988; Naus et al., 1988) were performed to provide a significant number of K_{Ia}-values and K_{ID}-values in the temperature range of interest. Those experiments were designed to have a driving force that increases with crack extension. A rising toughness field for these crack-arrest tests is produced by applying a temperature gradient across the specimen. The wide-plate experiments indicate that very high toughness values (exceeding 500 $\text{MPa}\cdot\sqrt{\text{m}}$) can be attained and measurements have been made at temperatures more than 30°C above the onset of the Charpy upper shelf.

DESCRIPTION OF STUB-PANEL SPECIMENS

Stub-panel crack-arrest specimens have been devised by the HSST Program to close the gap between conventional crack-arrest tests in a decreasing K_I-field and the large wide-plate tests. Two stub-panel specimen geometries are utilized, one of which was designed by ORNL and the other by the National Institute of Standards and Technology (NIST), Boulder, Co. Design of the ORNL specimen geometry [Fig. 1(a)] was based on requirements for providing crack-arrest toughness measurements higher than 200 $\text{MPa}\cdot\sqrt{\text{m}}$ in a rising field of stress-intensity factor and with a testing machine capacity of 2.5 MN. The 45.1 × 99.1 × 3.39 cm plate is side grooved on each face to a depth of 12.5% of the thickness, resulting in a net thickness of 2.54 cm at the crack plane. Precracking of the specimen is done by hydrogen charging an electron-beam (EB) weld located at the base of the premachined notch in the plate.

A gradient in fracture toughness is achieved by cooling the stub region and heating the panel edge to produce a nonuniform steady-state temperature distribution across the plate. A tensile load is applied to the panel to produce a rising driving force. The stub is mechanically loaded to provide K_I levels that are high enough for initiation of the chilled crack in cleavage. Arrest of the fast-running crack then occurs in the ductile high-temperature region of the panel. Static and dynamic analyses (Stamm et al., 1986) carried out for the stub-panel configuration of Fig. 1(a) indicated that crack-arrest toughness values >200 $\text{MPa}\cdot\sqrt{\text{m}}$ could be attained in a rising K_I field by using available testing machines and appropriate thermal boundary conditions.

The second stub-panel specimen geometry being tested under the HSST Program is depicted in Fig. 1(b). This NIST-designed specimen, with dimensions 76.2 × 45.7 × 2.54 cm, represents a modification of a specimen developed previously (Teramoto et al., 1986) to study crack arrest in a rising K_I field.

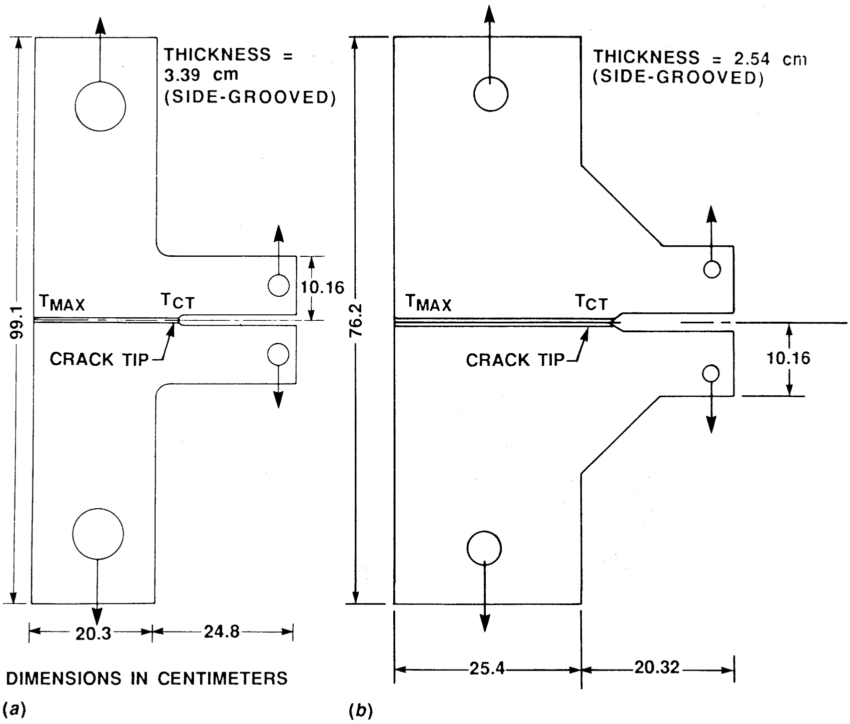

Fig. 1 Geometry and loading system of stub-panel crack-arrest specimens: (a) ORNL-designed specimen; (b) NIST-designed specimen.

Like the ORNL geometry of Fig. 1(a), the NIST specimen is of the double-tension type and is side grooved on each face to a depth of 12.5% of the plate thickness. In a previous cooperative study under the HSST Program, NIST - Boulder performed dynamic crack-arrest tests on three specimens of this type and made from A533 grade B class 1 steel. Those specimens were fabricated at ORNL and taken from the same source material as the HSST wide-plate specimens (Pugh et al., 1988).

The stub-panel specimens now being fabricated for testing at ORNL use two different steels. One set of specimens, designated as series SP-1, is taken from the same plate of A533 grade B class 1 steel as that used in the NIST specimens and the WP-1 series of HSST wide-plate tests (Pugh et al., 1988). For this material, RT_{NDT} = -23°C and Charpy upper-shelf energy is 160 J with its onset occurring at ~55°C. The second series (SP-2) of specimens is taken from the 2 1/4 Cr-1 Mo steel plate used in the WP-2 series of HSST wide-plate tests (Naus et al., 1988); this plate was specially heat treated to obtain a Charpy upper-shelf energy equal to or less than 68 J (50 ft-lb).

INSTRUMENTATION AND TESTING PROCEDURES

For each specimen, a significant number of strain gages are positioned adjacent to the crack-propagation plane to provide dynamic strain-field measurements for determination of the crack-tip velocity. For example, the strain-gage layout employed in test SP-1.3 is shown in Fig. 2. The strain signals are recorded by transient digital oscilloscopes. The temperature gradient across the specimen is monitored by eleven thermocouples positioned adjacent to the plane of crack propagation. Additional instrumentation includes capacitance-based gages to indicate relative displacement of the stub and panel load pins during the

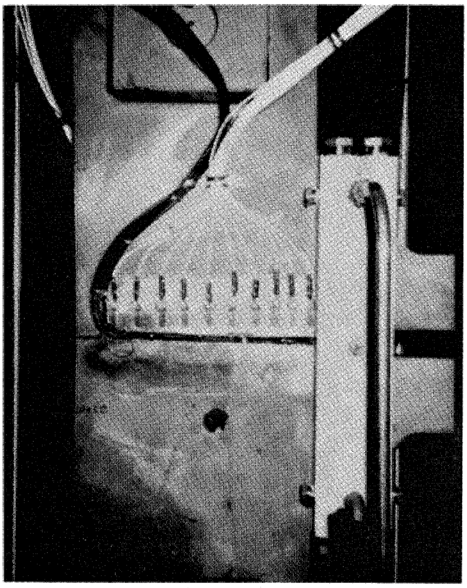

Fig. 2 Strain-gage layout and liquid nitrogen chill block employed in stub-panel test SP-1.3.

dynamic event. Load cell output and crack-mouth opening displacement (CMOD) are also recorded during each test.

Specimen heating is provided by electrical resistance elements (300- to 500-W) mounted on an aluminum bar that is attached to the back edge of the specimen. Cooling is provided by a liquid nitrogen reservoir chill block that is positioned around the specimen in the region of the crack tip (shown in Fig. 2 for test SP-1.3). The heating-cooling system is controlled by a microcomputer linked to selected thermocouple sensors.

In each test, liquid nitrogen flow and power to the heaters are continuously adjusted to obtain the desired thermal gradient. Final calibration of the strain gages, load-pin displacement gages, CMOD gages and the load cell are completed just prior to specimen loading. A predetermined tensile load is applied to the panel by a 2.5 MN-capacity testing machine, and loading is applied monotonically to the stub by an auxiliary system until crack initiation is achieved.

SUMMARY OF STUB-PANEL TEST SP-1.3

Specimens SP-1.1 and -1.2 of the ORNL design were used to establish instrumentation techniques and load requirements. Because the stub load required for initiation of the ORNL-designed specimen exceeded the capacity of the available auxiliary system, the third test utilized a NIST-designed specimen which could be loaded by a simple jack technique. The geometry of the SP-1.3 specimen is depicted in Fig. 1(b). The temperature gradient imposed on the specimen included a crack-tip temperature of T_{CT} = -95°C and a maximum temperature of T_{MAX} = 130°C on the heated edge. After the thermal gradient was established, a tensile mechanical load of 1.059 MN was applied monotonically to the panel. Then, auxiliary loading was applied to the stub via a pressurized jack until cleavage crack propagation initiated at an estimated auxiliary load of 0.2 MN. Crack propagation terminated in a stable arrest. Posttest examination of the fracture surface indicated that the crack arrested in cleavage approximately 18 cm from the initiation site, where the crack-tip temperature would have been

44°C. The entire fracture took place within the side-grooved region, with some evidence of shear lips extending 1 to 2 cm from the point of arrest.

Posttest analyses of test SP-1.3 were performed using elastodynamic fracture mechanics techniques (Bass et al., 1988) and measured data. First, the strain vs time curves from crack-line strain gages 1 through 8 were used to construct the crack vs time history (see Fig. 3). The measured data in Fig. 3 indicate an initial crack-tip velocity of $\dot{a} \geq 520$ m/s, with arrest of the crack occurring beneath gage 8 approximately 0.4 ms after cleavage initiation. Then an elastodynamic analysis was performed using the measured crack-time curve, and it indicates an arrest toughness value of $K_{Ia} = 176$ MPa•$\sqrt{m}$. This value is compared in Fig. 4 with K_{Ia} data from several types of large-scale tests that collectively

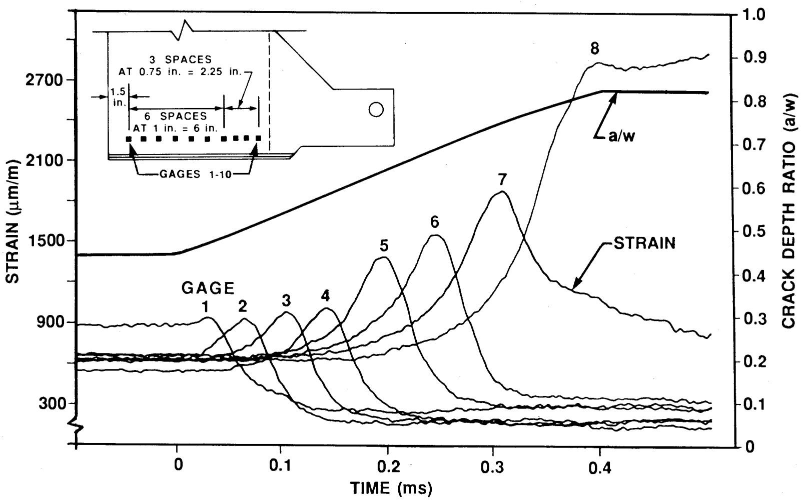

Fig. 3 Crack depth vs time curve inferred from strain vs time data recorded by crack-line strain gages 1-8 in stub-panel test SP-1.3.

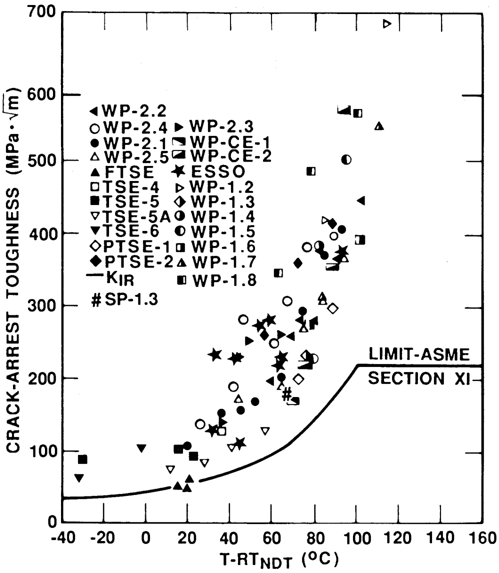

Fig. 4 Crack-arrest toughness data vs temperature (T - RT_{NDT}) from stub-panel and large specimen tests.

exhibit a trend extending above the ASME Section XI limit of 220 MPa•$\sqrt{m}$ for this and other heats of RPV steels. The ORNL-designed specimen is expected to give noticably higher K_{Ia} test capability.

CONCLUSIONS

This test study demonstrates that high-quality dynamic fracture data can be obtained from relatively small stub-panel specimens under nonisothermal test conditions. Strain-gage techniques have been shown to be very satisfactory for trigger and dynamic fracture measurements. It has also been demonstrated that these specimens can be used to determine crack-arrest toughness values for temperatures corresponding to the Charpy upper-transition region. Analytical studies indicate that the imposition of higher panel loads will produce K_{Ia} values in excess of the ASME Section XI limit of 220 MPa•$\sqrt{m}$ for either the ORNL-designed or NIST-designed specimen.

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