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DYNAMIC FRACTURE ANALYSIS OF HSST CRACK RUN-ARREST EXPERIMENTS WITH NONISOTHERMAL WIDE PLATES*

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Summary

Dynamic fracture analysis results from Heavy-Section Steel Technology (HSST) wide-plate crack-arrest tests are summarized. These tests relate to assessing nuclear reactor pressure vessel integrity under pressurized-thermal-shock (PTS) conditions. Computed results for five tests are compared with measurements of strain versus time, crack propagation speed, and the arrest location. Crack arrest toughness values determined by various analytical methods are compiled for test temperatures that range from mid-transition into the Charpy upper-shelf region for the test material.

Introduction

The Heavy-Section Steel Technology (HSST) Program, a major safety research program sponsored by the U.S. Nuclear Regulatory Commission at the Oak Ridge National Laboratory (ORNL), is concerned with the technology and data needed for structural integrity assessments of pressure vessels for light-water-cooled nuclear power reactors. Central to these studies is understanding conditions that would initiate growth of an existing crack and conditions that would lead to arrest of a moving crack. Prior studies of crack arrest have utilized small specimens and focused on reducing dynamic effects of the running crack. Small specimens, however, provide limited constraint of deformation in the crack-plane region and permit the generation of data only at temperatures below those where arrest is likely to occur in some pressurized-thermal-shock (PTS) scenarios. The HSST Program is continuing to provide crack-arrest data over an expanded temperature range through tests of large thermally-shocked cylinders, PTS vessels, and wide-plate specimens. The wide-plate tests [1] allow a significant number of data points to be generated at affordable costs.

A series of five HSST wide-plate crack-arrest tests (WP-1) has been performed at the National Bureau of Standards (NBS), Gaithersburg, MD, using specimens from HSST Plate 13A of A533 grade B class 1 steel. The WP-1 series was aimed at providing crack-arrest data at temperatures up to and above that corresponding to the onset of the Charpy upper-shelf, as well as providing information on dynamic fracture (run and arrest) processes for use in evaluating improved fracture analysis methods.

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Dynamic finite element fracture analyses have been completed for the first five tests in the WP-1 series. This paper describes analysis procedures and compares the computed results with data for crack-line strain-time response, crack-propagation speed, and crack-arrest location. Arrest toughness calculations are given for the test temperatures that extend to upper-shelf values for the wide-plate material.

Specimen Geometry, Material Properties, and Instrumentation

Figure 1 shows the single-edge-notched plate specimens (1 × 1 × 0.1 m) that were cooled on the notched edge and heated on the other edge to give a linear temperature gradient along the plane of crack propagation. Upon initiating propagation of the crack in cleavage, arrest was intended to occur in the higher-temperature ductile region of the specimen.

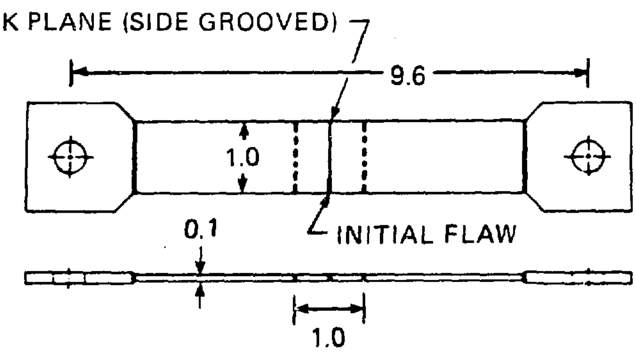

Fig. 1. Wide-Plate crack-arrest specimen and pull-plate assembly

The specimens had an initial crack depth-to-plate width ratio (a/w) of 0.2. Each surface was side-grooved to a depth equal to 12.5% of the plate thickness. The specimen was welded to pull-plates which have a pin-to-pin length of 9.6 m to minimize stress wave effects. Drop weight and Charpy test data indicate that RT_{NDT}=-23°C for this material. Temperature-dependent fracture-toughness relations for initiation and arrest, based on small specimen data, and other information on material properties are described in Ref. 2.

The specimens were instrumented with thermocouples, strain gages, and crack-opening-displacement gages. A series of eleven thermocouples and sixteen strain gages were located about 65 mm above the crack plane across the plate to record temperature and strain as functions of time and crack position.

Model Definition and Analysis Techniques

The postulated crack run-arrest event is dependent upon parameters related to plate geometry, material properties, temperature profile and mechanical loading. To investigate the interactions of parameters that impact the run-arrest event, elastodynamic analyses of the wide-plate tests were carried out with the EDF [3] computer program developed by ORNL. The EDF code is capable of performing both application mode and generation mode dynamic analyses. In an application mode analysis, the crack tip is propagated incrementally when $K_I = K_{ID}(\dot{a},T)$, where K_I is the dynamically computed stress-intensity factor, and K_{ID} is the dynamic fracture toughness relation that is taken to be a function of crack velocity $\dot{a}$ and temperature T and is given in Ref. 2. In a generation mode analysis, the crack tip is propagated incrementally according to a prescribed crack position vs time relation, and values of fracture toughness are determined from the dynamically computed K_I. For both modes of analysis, the dynamic stress-intensity factor K_I is determined in each time step from the dynamic J-integral containing the appropriate inertial and thermal terms, as described in Ref. 3.

The crack-growth modeling technique in the EDF code is essentially that described in Ref. 4. In this technique, the element immediately ahead of the crack tip is divided into N subelements, where N depends on the mode of analysis, the magnitude of the time step, the dimensions of the element, and the limiting crack velocity. During propagation, the tip is moved through these subelements in discrete jumps. The position of the crack tip relative to these subelement divisions is determined from restraining forces that are placed on the crack-plane nodes of the element adjacent to the crack tip. These forces, postulated to vary linearly with the crack-tip location, are released incrementally as the tip propagates through the element.

Test and Analysis Results

Cleavage initiation occurred at very high loads in the first two tests, but they exhibited arrest, if for only a small fraction of a second, prior to tearing instability. Test WP-1.2 was performed with slightly lower load than WP-1.1, and exhibited two such micro-arrest periods. The initiation loads were reduced further for tests WP-1.3 and -1.4. An arrest period of about 2 seconds was experienced in WP-1.3, and the arrest in WP-1.4 was completely stable. Test WP-1.4 was reinitiated by further increase in load to produce a second cleavage initiation-run-arrest event. Test WP-1.5 was initiated at a slightly lower load than WP-1.3; it exhibited two cleavage events. Table 1 shows the general conditions for these five experiments.

Table 1. Summary of HSST wide-plate crack-arrest tests for A533 grade B class 1 steel

Test no.	Crack location (cm)	Crack tip temp. (°C)	Initiation load (MN)	Arrest location (cm)	Arrest temp. (°C)	Arrest $T - RT_{NDT}$ (°C)
WP-1.1[a]	20.0	-60	20.1	50.2	51	74
WP-1.2A	20.0	-33	18.9	55.5	62	85
WP-1.2B	55.5	62	18.9	64.5	92	115
WP-1.3	20.0[b]	-51	11.25	48.5	54	77
WP-1.4A	20.7[b,c]	-63	7.95	44.1	29	52
WP-1.4B	44.1	29	9.72	52.7	60	83
WP-1.5A	20.0[b]	-30	11.03	52.1	56	79
WP-1.5B	52.1	56	11.03	58.0	72	95

[a]Specimen was intentionally warm prestressed by loading to 10 MN at 70°C, and then also preloaded to 19 MN at about -13°C.
[b]Crack front cut to chevron configuration.
[c]A pillow jack applied pressure load to specimen notch.

A posttest application mode analysis of test WP-1.5 was performed using a two-dimensional (2-D) plane stress finite element model consisting of 794 nodes and 232 eight-noded isoparametric elements. The measured fracture load of F_{in}=11.03 MN was applied at the top of the load-pin hole to determine the load point displacement. For the dynamic analysis, the load point was fixed at the displacement value of the initiation load and the time step was set at Δt=5 μs in the implicit Newmark scheme for the time integration. Figure 2 presents the dynamic factor K_I^{DYN}, the static toughness K_{Ia} (from small specimen data) and the crack velocity $\dot{a}$ as a function

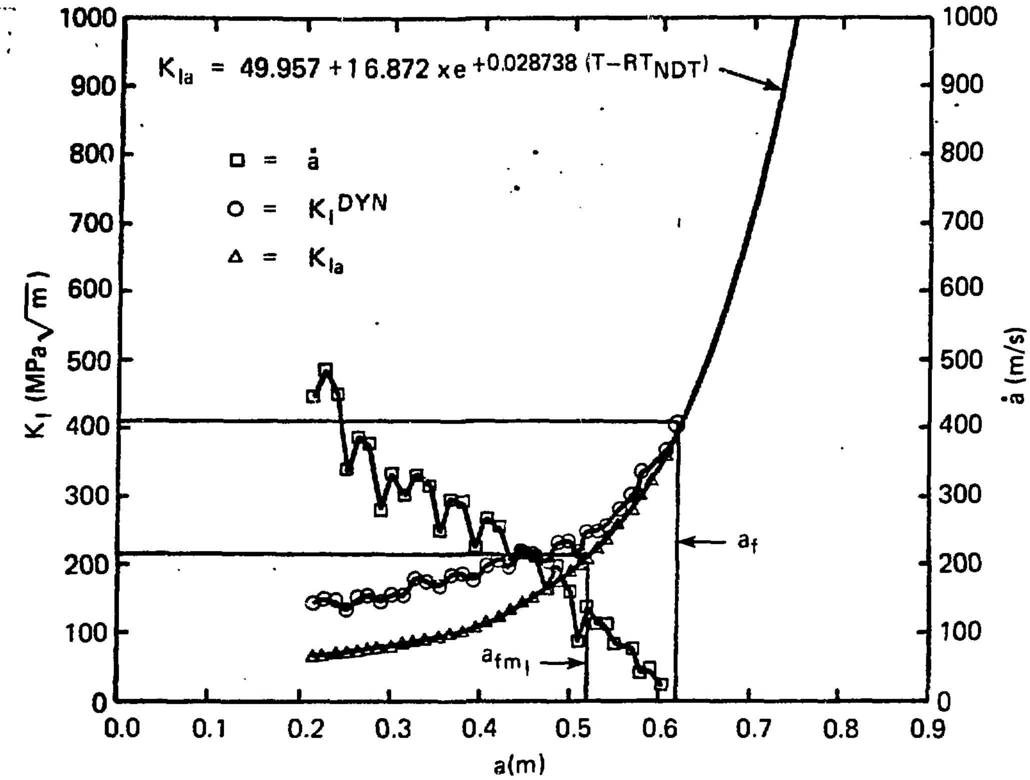

Fig. 2. Results of posttest application mode analysis of test WP-1.5

of instantaneous crack length. The crack propagates into a rising K_I field, followed by arrest at a_f=0.623 m with temperature T_f=83°C and arrest toughness K_{Ia}=405 MPa$\sqrt{m}$. The computed arrest length exceeds the measured initial arrest length of a_{fm_1}=0.52 m, with T_{fm_1}=56°C and K_{Ia}=213 MPa$\sqrt{m}$.

The estimate of crack position vs time in Fig. 3 was constructed by NBS [5] from strain-gage data and was used as input for a posttest generation mode dynamic analysis of test WP-1.5. Figure 3 shows the measured first crack arrest at a_{fm_1}=0.52 m; the second cleavage arrest at a_{fm_2}=0.58 m is not

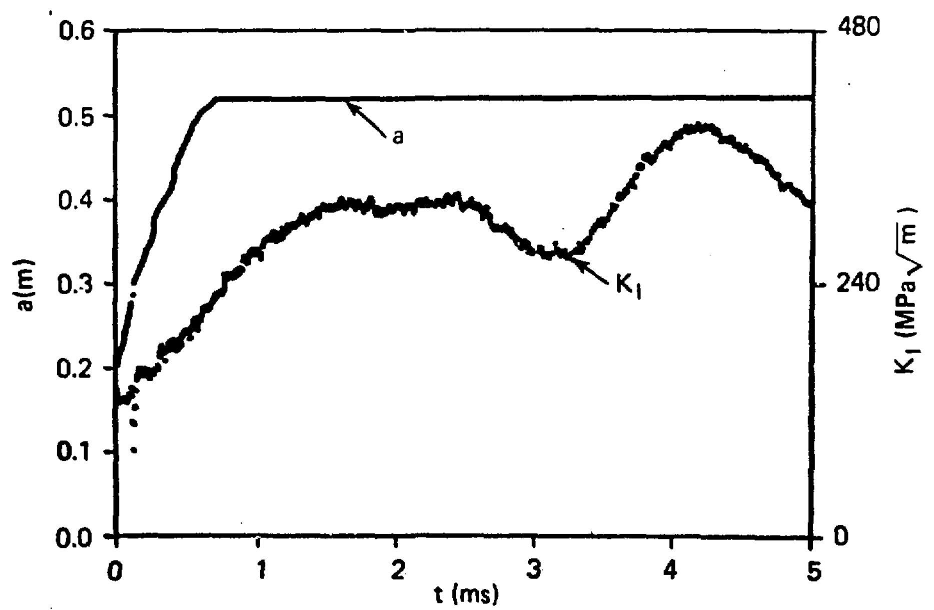

Fig. 3. Results of posttest generation mode analysis of test WP-1.5

shown. For the dynamic analysis, the load point was again fixed at the displacement value of the initiation load. From these calculations, the amplitude of the stress intensity factor as a function of time is given in Fig. 3. The analysis results for the two arrest events were: a_{fm_1}=0.52 m, T_{fm_1}=56°C, K_{Ia}=229 MPa$\sqrt{m}$; and a_{fm_2}=0.58 m, T_{fm_2}=72°C and K_{Ia}=300 MPa$\sqrt{m}$.

The computed strain-time histories for points close to three of the crack-line gages are depicted in Fig. 4 for the generation mode analysis along with measured data from the gages. The sharply defined strain peaks are associated with the fast-running crack passing under a gage point, with the peak being transformed into a more blunted curve as the crack tip slows down. The comparisons of strain histories in these figures indicate generally good agreement between measured and computed times for the occurrence of peak strain values.

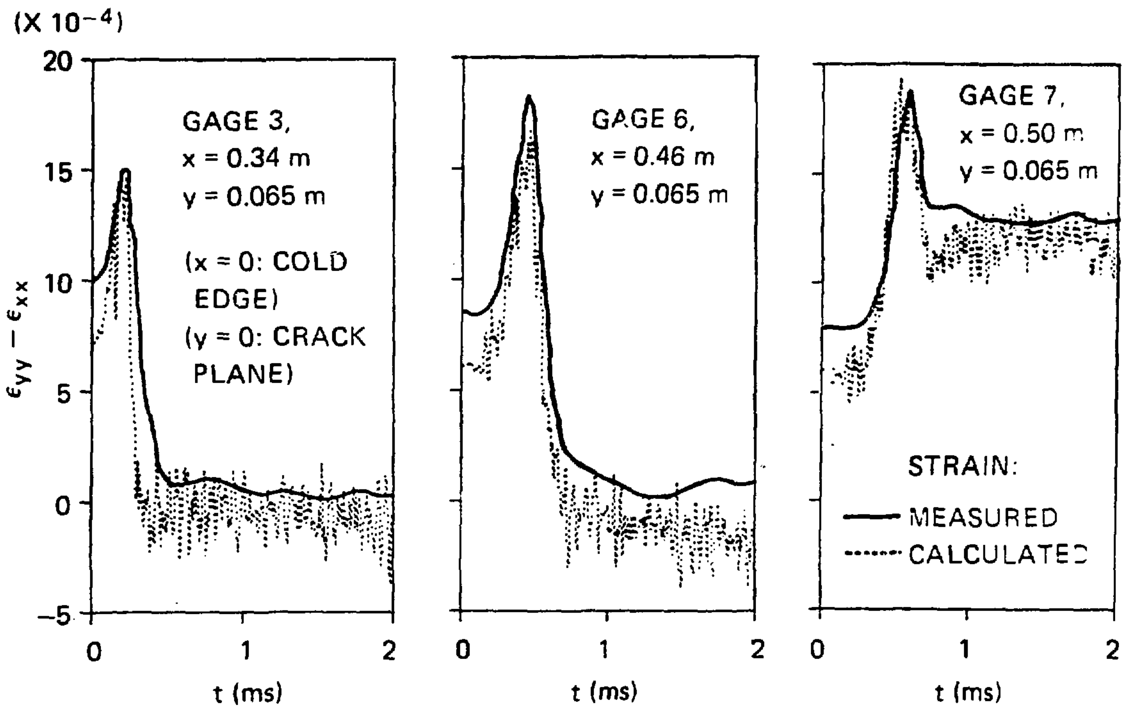

Fig. 4. Comparison between strain-time histories from measured data and generation mode dynamic analysis for test WP-1.5

Additional static and dynamic analyses have been performed for the wide-plate tests, WP-1.1 through WP-1.5, and the results reported in Ref. 1. Some of the computed values are shown in Fig. 5. Further results will be published as they become available.

Closure

The results obtained to date from the wide-plate analyses show that the essence of the run-arrest events, including dynamic behavior, is being modeled. Refined meshes and optimum solution algorithms are important parameters in dynamic analysis programs to give sufficient resolution to the geometric and time-dependent aspects of fracture analyses. Further refinements in quantitative representation of material parameters and the inclusion of rate dependence through viscoplastic modeling is expected to give an even more accurate basis for assessing the margin of safety of reactor pressure vessels under PTS and other off-normal loading conditions.

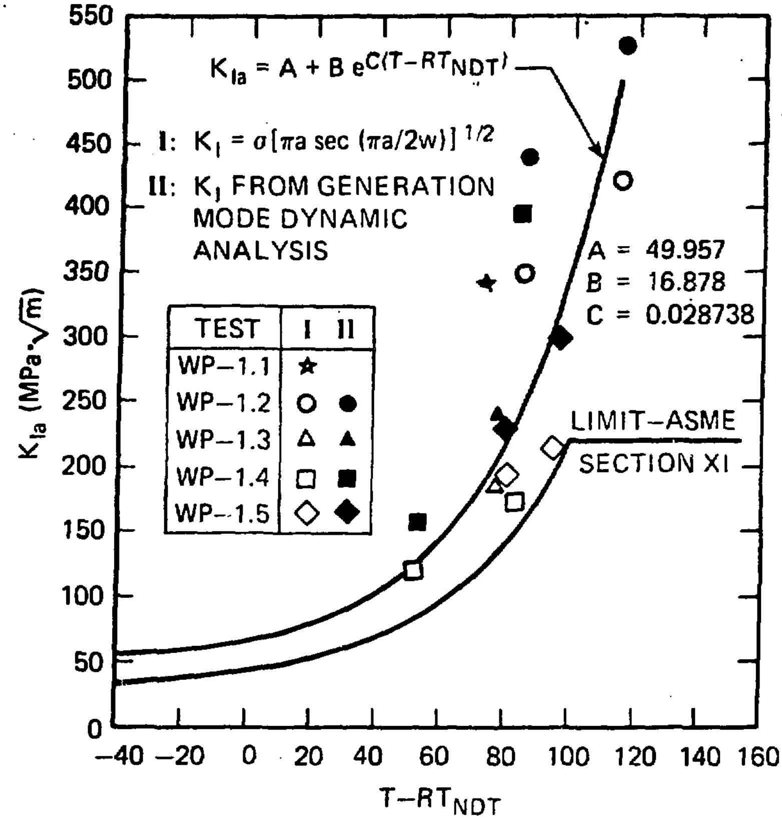

Fig. 5. Comparison of wide-plate crack-arrest data with curves representing small-specimen K_{Ia} data and ASME Section XI curves

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