Advanced Analytical Methods for Interpreting Crack Run-arrest Events in Reactor Pressure Vessel Steels*

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ABSTRACT

Experimental and analytical studies to improve the understanding of conditions that govern the initiation, rapid propagation, arrest and ductile tearing of cracks in reactor pressure vessel (RPV) steels are presented. Large-scale experiments are performed to generate crack-arrest toughness data for RPV steels at temperatures approaching and above the onset of Charpy upper-shelf behavior. Analytical studies included considerations of the role of nonlinear rate-dependent effects in crack run-arrest events in these ductile materials. A summary of experimental results and analytical interpretations of two series of large nonisothermal wide-plate crack-arrest tests is presented. The importance of incorporating viscoplastic effects as well as dynamic modeling into the analyses of the wide-plate data is examined.

KEYWORDS

Crack-arrest toughness; dynamic fracture; wide plates; viscoplasticity

INTRODUCTION

In pressurized-thermal-shock (PTS) scenarios, inner surface cracks of reactor pressure vessels (RPVs) have the greatest propensity to propagate because they are located in the region of highest thermal stress, lowest temperature and greatest irradiation 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 less irradiation damage. The Heavy-Section Steel Technology (HSST) Program at the Oak Ridge National Laboratory (ORNL) under the sponsorship of the Nuclear Regulatory Commission (NRC) is conducting experimental and analytical studies

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aimed at modeling the circumstances that would initiate the growth of an existing crack in an RPV and the conditions that can lead to the arrest of a propagating crack. A vital component of these studies is the wide-plate crack-arrest tests which are conducted for the HSST Program by the National Bureau of Standards. A total of thirteen nonisothermal wide-plate experiments have been performed using two steels. Objectives of these tests are to: (1) extend the existing K_{Ia} data bases to values above the limit in the ASME Code, (2) clearly establish that crack-arrest does occur prior to fracture-mode conversion, (3) provide data to improve and validate elastic and viscoplastic dynamic fracture-mechanics models, and (4) develop improved experimental dynamic fracture methods.

The analytical crack-arrest studies are addressing the development of computational analysis methods incorporating nonlinear and strain-rate dependent (i.e., viscoplastic) effects for use in interpreting crack run-arrest events in these ductile materials. Various viscoplastic constitutive models and several proposed nonlinear fracture criteria have been installed in HSST-developed finite element computer programs. The capabilities of these nonlinear techniques are being compared and evaluated, in part, through applications to the wide-plate tests.

The following sections provide a summary of the test conditions, results, and analyses of the two series of wide-plate crack-arrest tests. This is followed by a discussion of the importance of incorporating viscoplastic effects into dynamic fracture analyses of crack run-arrest events in these strain-rate sensitive ductile steels.

TEST CONDITIONS FOR WIDE-PLATE SPECIMENS

The initial series of wide-plate crack-arrest specimens (WP-1) is taken from HSST plate 13A of A533 grade B class 1 steel that is in a quenched and tempered condition (Naus *et al.*, 1987). Drop-weight and Charpy V-notch test data indicate that RT_{NDT} = -23°C, and Charpy upper-shelf energy is 160 J with its onset occurring at 55°C. The second series of wide-plate specimens (WP-2) is taken from a plate of 2 1/4 Cr-1 Mo steel that has been heat treated to produce a low upper-shelf Charpy impact energy (Naus *et al.*, 1988). Based on a limited number of tests, the tentative drop-weight nil-ductility temperature for the material is > 60°C, and the Charpy upper-shelf energy is about 50 J with its onset occurring at about 150°C.

The 1 by 1 by 0.1 m specimens (1 by 1 by 0.15 m for specimens WP-1.7, WP-2.1 and WP-2.3), shown schematically in Fig. 1, were machined and pre-cracked by ORNL. The total crack length for each specimen was nominally 0.2 m (a/W ~ 0.2). Each side of a specimen was side grooved to a depth equal to 12.5% of the plate thickness. Each specimen was welded to pull plates which have a pin-to-pin length of 9.6 m to minimize stress wave effects. Up to 25 gages have been utilized to provide dynamic strain-field measurements for determining crack velocity and assessing boundary conditions. Thermocouples were positioned on each specimen and sequentially monitored to insure that the desired temperature distribution was achieved throughout the plate assembly.

In each wide-plate test, a fracture toughness gradient was achieved across the plate by LN_2 cooling of the notched edge while heating the other edge. Tensile load was then applied to the specimen at a rate of 11 to 25 kN/s until fracture occurred.

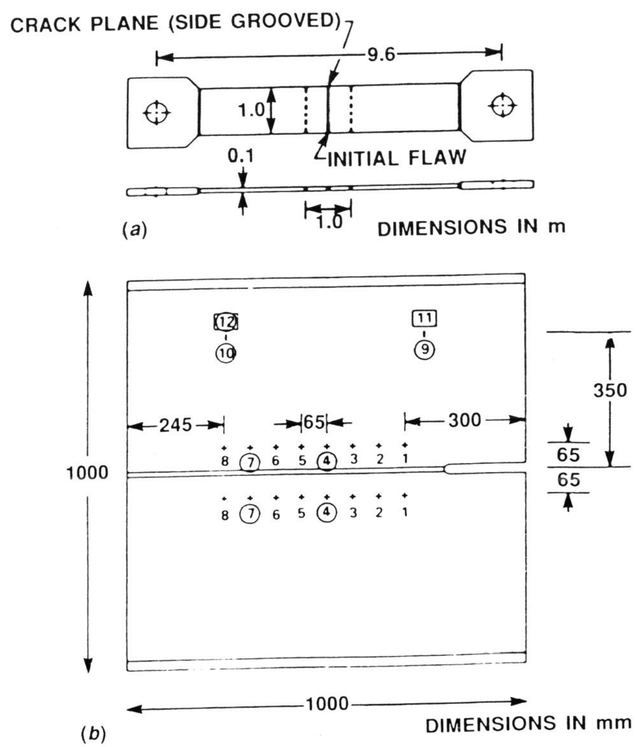

Fig. 1. Wide-plate assembly and crack-arrest specimen: (a) pull-plate assembly; (b) specimen with strain-gage locations.

SUMMARY OF TEST RESULTS AND POSTTEST ANALYSES

Previous descriptions of the wide-plate tests include those of Naus *et al.* (1987, 1988) for WP-1 and of Naus *et al.* (1988) and Pugh and Naus (1987) for WP-2. Table 1 presents a summary of conditions for each test in the WP-1 series; similar data for WP-2 is given by Naus *et al.* (1988). Posttest elastodynamic fracture analyses were conducted for each wide-plate test to investigate the interaction of parameters that affect the crack run-arrest events. Figure 2 summarizes crack-arrest toughness values for the WP-1 and WP-2 series which were computed in fixed-load, generation-mode dynamic finite element analyses. (In the generation-mode analysis, the crack tip is propagated according to a prescribed crack position vs time relation obtained from measured data.) Results for both test series exhibit a significant increase in toughness at temperatures near and above the onset of Charpy upper shelf ($T - RT_{NDT}$ = 78°C for WP-1; $T - DW_{NDT}$ = 90°C for WP-2). Crack-arrest toughness values obtained from this series of tests extend consistently above the ASME reference fracture-toughness curve. The increase in arrest-toughness values which occurs at an accelerating rate with temperature near and above the onset of Charpy upper shelf suggests that a temperature limit exists at or below which cleavage

Table 1. Summary of HSST wide-plate crack-arrest test conditions for A533 grade B class 1 steel: WP-1 series

Test parameter	1.1	1.2	1.3	1.4	1.5	1.6	1.7
Crack temperature (°C)	-60	-33	-51	-63	-30	-19	-24
Initiation load (MN)	20.1	18.9	11.25	7.95	11.03	14.5	26.2
Arrest location (cm)	50.2	55.5	48.5	44.1	52.1	49.3	52.8
Arrest T - RT_{NDT} (°C)	74	85	77	52	79	77	84

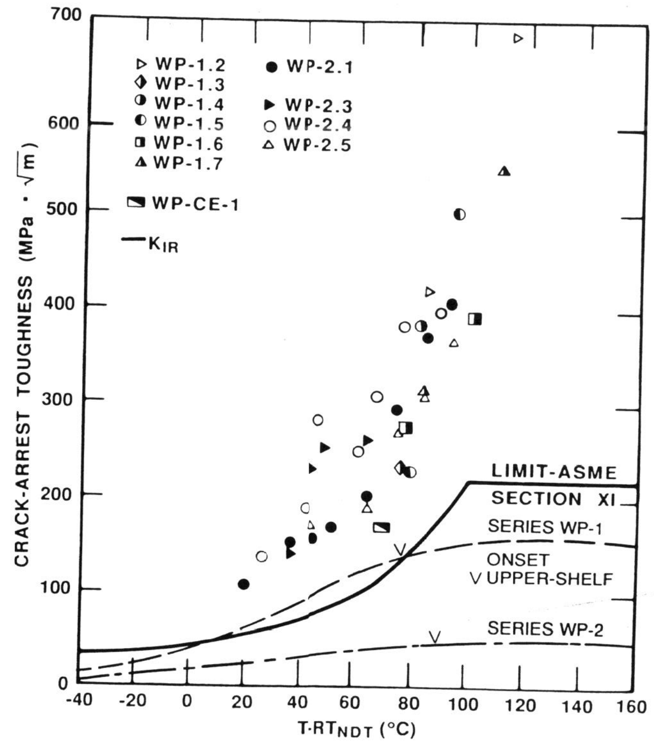

Fig. 2. Charpy V-notch energy and wide-plate crack-arrest toughness data versus temperature (T - RT_{NDT}) for test series WP-1 and WP-2.

crack propagation will arrest, no matter how high the applied driving force. Results presented in Fig. 2 also show that arrest of cleavage crack propagation can and does occur at temperatures above the onset of Charpy upper shelf. These trends observed in K_{Ia} values from the wide-plate tests are further substantiated by data from other types of large-scale tests (Pugh and Naus, 1987).

The importance of the analysis method (static vs dynamic) and boundary conditions (fixed load or fixed load-pin displacement) utilized to interpret the wide-plate crack-arrest tests is demonstrated by comparing the values given in Fig. 3 for specimen WP-2.4. Values of K_{Ia} determined using the secant equation (Fedderson, 1967) and the Tada fixed load condition (Tada *et al*, 1973) represent approximate lower and upper bounds, respectively, to the dynamic results in Fig. 3. For long-duration crack run-arrest events (>20 ms), such as could occur for the low Charpy upper-shelf material, considerable load adjustment can take place as a result of specimen/pull-plate compliance. Therefore, the most meaningful values of K_{Ia} under such conditions must reflect this occurrence and involve a dynamic finite-element analysis. The dynamic generation-mode (fixed load) analysis results represent one such calculation.

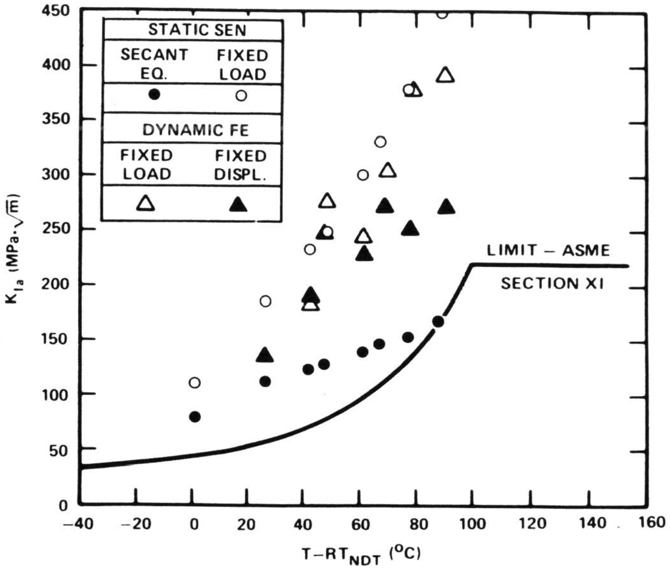

Fig. 3. Static and dynamic crack-arrest toughness determination vs temperature (T - RT_{NDT}) for specimen WP-2.4.

APPLICATIONS OF VISCOPLASTIC DYNAMIC FRACTURE METHODS

Until recently, linear elastic fracture mechanics (LEFM) concepts have been dominant in applications of dynamic analysis techniques to the crack-arrest studies described in the previous sections. However, except for very short crack jumps, LEFM assumptions are not strictly valid characterizations of rapid crack propagation (Kanninen and Popelar, 1985). In particular, a wake of residual plasticity left behind the moving crack tip violates the K_I-dominance requirement of LEFM. An indication that LEFM conditions are not satisfied occurs when elastodynamic analyses of crack run-arrest data lead to geometry-dependent fracture toughness relations. Dahlberg *et al.* (1980) performed elastodynamic fracture analyses of crack run-arrest tests of single-edge-notched (SEN) tension panel specimens of different lengths. Their results for different panel lengths coincide for low crack velocities, but show a definite geometry dependence at higher velocities where nonlinear effects are more pronounced. However, Brickstad (1983) has demonstrated that this geometry dependence can be removed through application of an inelastic fracture model that incorporates plasticity and strain-rate effects (i.e., viscoplasticity).

These studies indicate that strain-rate effects ($\sim 10^4$ s^{-1}) can be important for rapid-loading situations such as cleavage crack propagation events in ductile RPV steels. The HSST Program research efforts at ORNL and several subcontracting groups are developing viscoplastic-dynamic finite element analysis techniques and validating their utility through analyses of data from the carefully controlled wide-plate experiments. Various viscoplastic constitutive models and several proposed nonlinear fracture criteria have been installed in general purpose (modified ADINA) (Bathe, 1984; Bass *et al.*, 1988) and special purpose (VISCRK) (Dexter *et al.*, 1987) finite element computer programs. The constitutive models implemented in these computer programs include viscoplastic formulations of Bodner and Partom (1975) and of Perzyna (1966); the proposed fracture criteria include three parameters [T* from Atluri *et al.* (1984), $\hat{J}$ from Kishimoto *et al.* (1980), and γ from Brickstad (1983)].

The combined predictive capabilities of these nonlinear techniques are being evaluated through applications to the crack propagation and arrest events of the wide-plate tests. As an example, results from viscoplastic dynamic analyses of one such wide-plate crack-arrest test (WP-1.2) utilizing the modified ADINA and the Bodner-Partom constitutive model are shown in Fig. 4. Generation-mode fixed load analyses were performed using data from Table 1 and the estimate of crack position versus time given by Naus *et al.* (1987). The time history of the parameter T* is expressed in terms of pseudo-K_I values for purposes of comparison with elastodynamic values, as shown in Fig. 4. In the viscoplastic calculations, a small rectangular

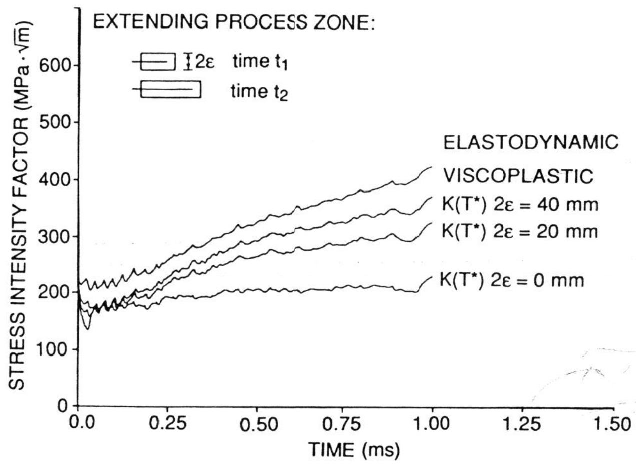

Fig. 4. Amplitude of stress-intensity-factor versus time from proposed fracture parameters in elastodynamic and viscoplastic analyses of wide-plate test WP-1.2.

domain of height 2ε was defined around the crack tip [see Fig. 4] to approximate a finite fracture process zone. This process zone was chosen such that ε equals the height of one or two rows of elements along the plane of crack propagation in the finite element model. During the dynamic analyses, this rectangle was extended in length (but not in height) to include part of the plastic wake behind the advancing crack. Motivated by the objective of computing a convergent non-zero value of the T*-integral for viscoplastic models, Nishioka (1988) advocates excluding the integration of the volume term of the T*-integral (see Atluri *et al.*, 1984) from this extending process zone. According to a study by Nishioka (1988), the T*-integral should be essentially invariant with respect to the size of this extending domain provided ε is sufficiently small. However, in application of this technique to wide-plate test WP-1.2, significant variation in the time history of K_I (T*) for two different heights of the extending process zone (2ε = 20 and 40 mm in Fig. 4) indicates that T* cannot be considered independent of ε for the finite element model employed in this study (crack plane elements had dimensions 10 × 20 mm). The question of mesh-size dependence of the (T*,ε) parameter will be investigated further using finite element models having greater refinement near the crack plane and, consequently, smaller extending process zones.

CONCLUSIONS

In conclusion, the HSST program has an integrated effort underway to extend the range of applicability of current state-of-the-art crack-arrest practices and to develop alternatives where improvements are needed. Fractographic examinations confirm that the crack propagation in the wide-plate tests occurred by a predominately cleavage mode and that the arrest events were not preceded by conversion to ductile tearing. Arrest may be followed by stable or unstable ductile crack growth, but these modes of fracture may be analyzed independent of the cleavage run-arrest events. A consistent trend is formed when the crack-arrest data from HSST wide-plate tests are combined on a plot of K_{Ia} vs $T - RT_{NDT}$ with other large-specimen data (Naus *et al.*, 1988). Dynamic effects must be included in the analysis techniques to obtain meaningful calculations for the relatively thin plate-type specimens. Collectively these data show that arrest can and does occur at temperatures up to and above that which corresponds to the onset of Charpy upper-shelf behavior, and the measured K_{Ia} values extend above the limit included in Section XI of the ASME code. Further, the data suggest the existence of a limiting temperature above which a cleavage crack cannot propagate no matter how high the applied driving force.

The role of nonlinear rate-dependent effects in the interpretation of crack run-arrest events in these ductile materials is being investigated through development and applications of viscoplastic dynamic finite element analysis techniques. Comparisons of elastodynamic and viscoplastic dynamic fracture analyses of tests from the WP-1 series indicate that the effects of including viscoplasticity in the fracture parameter calculations are significant for certain crack run-arrest events. Future development plans include mesh refinement studies to determine whether the proposed fracture parameters converge to non-zero values in viscoplastic analyses or whether they are mesh dependent. Planned applications of alternative crack-modeling techniques, such as moving variable-order singular elements, will possibly lead to better resolution of stress and strain fields ahead of the propagating crack and thus to improved understanding of the significance of the proposed fracture criteria.

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