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A FRACTURE MECHANICS PRACTICE FOR CRACK ARREST

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SUMMARY

This paper describes part of an extensive program at Battelle-Colombus concerned with measuring propagating crack toughness, K_D, and defining the conditions under which a rapidly moving crack will arrest. Earlier publications have discussed the K_D data that have been generated and the testing procedures, including specimen size requirements. Here we concentrate on describing a method for determining the relation between K_D and crack velocity which bypasses the need for direct velocity measurements. As a result the test procedures are considerably simplified.

The test method involves wedge-loading of duplex double cantilever beam specimens containing a blunt starter notch. Particular care is taken to approach fixed-grip conditions as closely as possible. As a result it is possible to initiate a rapidly moving crack and to arrest it. The results are analyzed with the aid of a finite difference procedure. A key result of the analysis, which has been confirmed experimentally, is that the crack length at arrest under fixed-grip loading is a single-valued function of the crack-velocity/bar-wave-speed ratio for fixed specimen dimensions. Of equal importance the ratio K_D/K_Q (K_Q = stress intensity at crack initiation) depends only on crack velocity, again for fixed specimen dimensions. Combining these two results. it is seen that the two desired quantities (K_D and velocity) can be found if K_Q and crack length at arrest are measured. The use of duplex specimens to facilitate rapid crack initiation complicates, but does not invalidate, the procedure.

The paper describes how these procedures have been verified in tests on three heats of A533B pressure vessel steel in the temperature range (NDT -66 °C) to (NDT $+34$ °C). Comparisons will be made of K_D values measured for crack length at arrest and K_D values measured using direct velocity measurements. The arrest-length K_D is found to be slightly ($\sim 10\%$) conservative.

Attention is then drawn to K_{Im}, the least value of K_D at any given temperature. This quantity is probably the most useful parameter for use in design. It represents a lower bound of the energy consumed in a propagation/arrest event. Application of the procedure outlined above to measure K_m is discussed. Finally, alternative estimates of K_{Im} are explored. These include K_d (the fracture toughness associated with crack initiation under rapid loading) and K_{Ia} (the static value of stress intensity at crack arrest). Some consideration will be given to the relative values of K_{Ic}, K_{Id}, K_{ID}, and K_{Ia} at temperatures in the vicinity of NDT, and to the ratios between them and K_{Im}.

In summary, a new method of measuring propagating crack toughness, K_{ID}, has been devised. It is shown that it is possible to measure K_{ID} without measuring crack velocity directly.

1. Introduction

Fracture safety analyses of nuclear pressure vessels which operate at elevated temperatures involve problems arising both from radiation embrittlement and from the well-known ductile/brittle transition in steel. As a result a region which is significantly cooler and more highly irradiated than the bulk of the structure may also be significantly less crack resistant. This effect may become important during the thermal shock accompanying emergency core cooling when a crack formed at a local cold spot will run into warmer, less embrittled, and hence, tougher material. This situation gives rise to the question as to under what conditions will such a running crack be arrested.

The research being carried out at Battelle-Columbus is concerned with the problem of the arrest of a fast-moving crack. Because crack propagation is a dynamic event, a dynamic analysis of the experiments is required. The analysis and the associated data developed in our laboratory reveal that the most useful property for describing rapid crack propagation and arrest is K_{Im}, the minimum value of propagating crack toughness at any given temperature [1 - 3]. To date, we have developed specimen designs and experimental procedures to measure the value of K_{IDm}, the minimum stress intensity associated with a rapidly propagating crack. It is believed that K_{IDm} provides the closest approximation to K_{Im} currently available. As such, K_{IDm} should be useable in structural design calculations concerning the condition under which running cracks will arrest.

This paper provides a short summary of the test procedures which have been developed for the double-cantilever-beam (DCB) specimen. The data are expressed in terms of K_{IDm}, which is the lowest point on the K_{ID}/velocity curve at any give temperature. Attention is then drawn to comparison among K_{IDm} and other measures of fracture toughness, in particular K_{ID} (the post-crack-arrest stress intensity), K_{Ic} (the static-loading plane strain fracture toughness, K_{Id} (the dynamic-loading plane strain fracture toughness), and K_{IR} (the ASME pressure vessel design curve).

2. Recommended Practice

The procedures have been reported in detail [2, 4] and will only be briefly outlined here. The various specimen designs which are being considered for inclusion in crack arrest test procedures are shown in Figure 1. The compact specimen is of the same proportions (except thickness) as in ASTM-E399. Its application to crack arrest measurements is nearing completion at Battelle-Columbus. The rectangular DCB specimen has been studied extensively and is the source of the data discussed in this report. The contoured specimen has been used by Crosley and Ripling [5] to measure the post-crack-arrest stress intensity as discussed below.

Figure 2 is a photograph of a test arrangement for the DCB specimen. Loading is accomplished by forcing the wedge between two pins. The pins rest in rectangular slots of a "tie-down device" which is intended to prevent vertical motion of the specimen relative to the pins. Earlier experiments without the tie-down device had shown that such motion can occur and is due to elastic energy stored in the system. The result is additional crack propagation and a serious departure from stiff wedge loading conditions.

An experimental result on A533B steel is shown in Figure 3. Two major experimental observations arising from this procedure are that:

(1) The crack velocity is close to a constant value in a homogeneous specimen. In a duplex specimen each section exhibits extended propagation at a steady-state velocity. The value of steady state velocity will vary with K_Q, the stress intensity at crack initiation, which, in turn, will be controlled by the root radius of the blunt starter notch.

(2) The steady-state crack velocity and the crack length at arrest are uniquely related for any given specimen design. In a duplex specimen the arrest crack length will depend on the starter section material as well as the test section material. However, for a given starter section material the crack length at arrest can be uniquely related to the test section velocity.

The model which has been used to analyze these results focuses on the strain energy release rate associated with a rapidly moving crack. The computations are in accord with both of the above items, giving confidence that it provides an accurate description of the experiments. In particular the model allows evaluation of K_D either from measurements of crack velocity and/or from crack length at arrest. When applied to a series of experiments on two heats of A533B pressure vessel steel at several test temperatures the agreement between these two methods (given in Figure 4) was found to be good. Note that the two measures are mostly within 10% of one another with the K_D value determined from arrest length being generally lower than the value obtained from crack velocity. This observation simplifies the experiments since the difficult task of measuring velocity can be eliminated in favor of just measuring arrested crack length. It also provides a measure of conservatism since K_{ID}, and with it K_{IDm}, measured from crack length tend to be lower than the values measured more directly using steady-state velocity.

3. Comparison of K_{IDm} with Other Measures of K_{Im}

3.1 Post-Crack-Arrest Stress Intensity

The term, K_{Ia}, is taken to mean the value of stress intensity immediately after static equilibrium has been achieved following the arrest of a rapidly propagating crack. The original technique for measuring K_{Ia} is due to Crosley and Ripling [5], and involves use of the machine-loaded contoured specimens for which the static value of stress intensity for a given load is independent of crack length within the contoured section. Calculations performed at Battelle-Columbus suggest that under very special conditions K_{Ia} measured in this way is a good approximation of K_{Im}. The major restrictions are that K_{Im} is close to the K_{Ic} values used to initiate the crack and that K_{Im} corresponds to a low velocity. Since Crosley and Ripling [6] have reported that the value of K_{Ia} will increase with increasing crack jump length, the reported K_{Ia} scatter bands include, at least in part, a systemmatic dependency.

Our experimental arrangement provides another source of K_{Ia} data. The crack jumps are somewhat longer than those of Crosley and Ripling and also occur at close to fixed-grip conditions because of the stiff loading system. The difference in the two techniques produces a difference in dependence on crack jump length as shown in Figure 5. Note that these include two heats of steel common to both laboratories [2, 4, 7].

It is noted that the lowest K_{Ia} points are those obtained with the long jumps in the rectangular specimens. As pointed out before, these data can only characterize the dynamic run-arrest event to the extent that they can be related to the situation obtaining at arrest via the appropriate dynamic analysis. The actual value of stress intensity at the instant of arrest is equal to K_{Im}. For A533B steel at temperatures around NDT K_{Ia} for duplex DCB is typically 0.7 K_{ID} with somewhat lower ratios for larger crack jumps [4]. To the extent that $K_{ID} \approx K_{Im}$, our K_{Ia} values are believed to be considerably below K_{Im} in this region.

3.2 Comparison with Other Measures of Dynamic Toughness

The most widespread method of measurement dynamic fracture is K_{Id}, the stress intensity associated with the extension of a stationary crack under rapid loading. This procedure produces the lowest reported stress intensities of any method over a wide range of temperatures. However, it currently has two drawbacks:

(1) While the measurements are made dynamically, the event is analyzed as if it were static, neglecting inertia forces. The magnitude and direction of the resulting error are currently unknown.

(2) Fracture is initiated from a fatigue crack, which is not naturally a propagating crack. The magnitude and direction of this effect are also unknown.

An alternative possibility of some appeal would be to relate K_{Ic} values to K_{Im}. The K_{Ic} measurement techniques are much more highly developed and the first objection above is no longer valid. The problem is that one is attempting to use a static experiment to describe a dynamic event. However, it is possible that a rate/temperature shift technique can be developed, such as is common on polymers [8] and has been used for Charpy V-notch tests on steels [9]. Recently, impressive empirical correlations between K_{Ic} and Charpy V-notch tests have been developed [10, 11], involving both a temperature shift and a normalization. Therefore, the possibility of a shifted K_{Ic} value deserves attention.

Figure 6 shows K_{IDm}, K_{Ic}, and K_{Id} measured on A533B steels [4, 12]. Note that the point marked with a cross (x) on the K_{IDm} plot is the lower of only two tests at that temperature and is subject to being moved downward as more data become available. The K_{Ic} data on the figure are limited to the same heats as the K_{IDm} data. Note that the two curves are rising at about the same rate at temperatures slightly above NDT. In contrast, the K_{Id} data tend to rise much more rapidly in this region, which is indicated by the dashed line in Figure 5(c), and which corresponds to the onset of large non-linearities in the load records.

In order to examine whether the rate/temperature shift has any possible validity, the data in Figure 6 were shifted according to the following scheme:

$$\left.\begin{aligned} K_{IDm}(T) &= K_{Ic}(T-20) \\ K_{IDm}(T) &= K_{Id}(T+50) \end{aligned}\right\} \quad \text{Temperatures in C} \qquad (1)$$

The result is shown in Figure 7. Here the K_{IR} curve of the ASME Boiler Code [13] was chosen as the reference. Since it has been shown previously that the K_{Id} "initiation values" on Figure 6 agree closely with K_{IR}, K_{Id} was not shifted at all. The other points were shifted according to Equation (1).

This result must be treated with some caution and considered only preliminary. There is a conceptual problem in understanding why parameters which are based on either initiation, propagation, or arrest, which involve either static or dynamic loading and analysis, and which employ either fatigue or antural cracks, all apparently exhibit the similar temperature dependence. However, the possibility should be explored that various toughness tests can be related by a simple shift along the temperature axis, provided the appropriate precautions are taken (e.g. assurance of plane strain behavior).

4. Conclusions

1. A K_{ID} test method has been developed which does not require crack velocity measurements. The method can provide a close estimate of K_{Im}.

2. Further evidence of a dependence of K_{Ia} or crack jump length has been obtained. However, K_{ID} and K_{IDm} can be obtained from K_{Ia} provided the proper analysis is applied.

3. The values of K_{IDm}, K_{Ic}, and to a limited extent, K_{Id}, measured for A533B steel in the ductile/brittle transition region appear to be equal provided an appropriate shift in temperature is made. Specifically, $K_{Id}(T) = K_{IDm}(T-20) = K_{Ic}(T-70)$.

5. Acknowledgements

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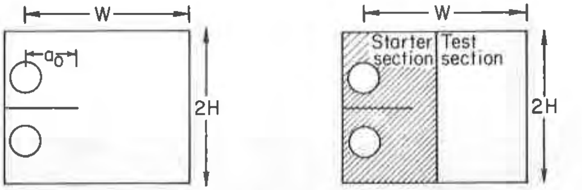
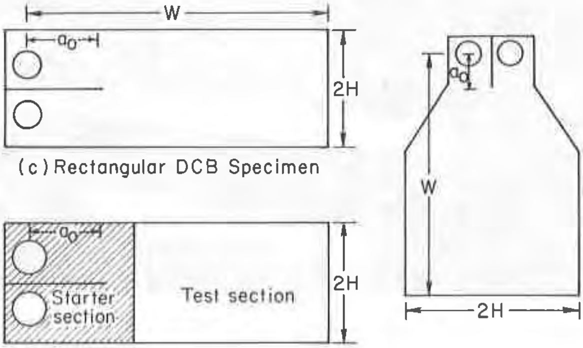


(a) Compact Specimen (b) Duplex-Compact Specimen



(c) Rectangular DCB Specimen

(d) Rectangular Duplex-DCB Specimen (e) Contoured DCB Specimen

Figure 1. SCHEMATIC DRAWINGS OF POSSIBLE CRACK ARREST SPECIMENS
The starter sections of duplex specimens are made of a hardened steel electron beam welded to the test section. The starting crack in duplex specimens is purposely blunted to obtain high K_Q-values, and this eliminates the need for fatigue precracking.

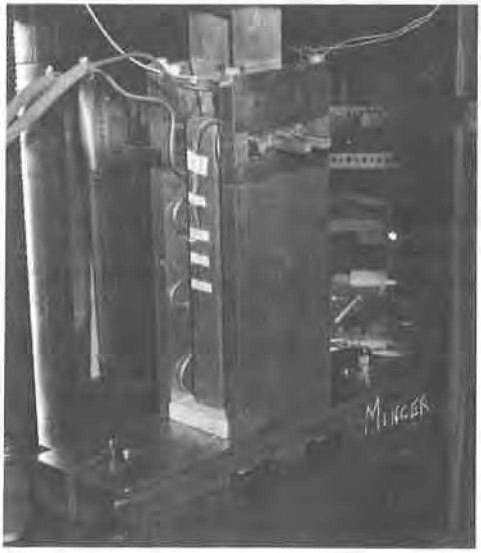
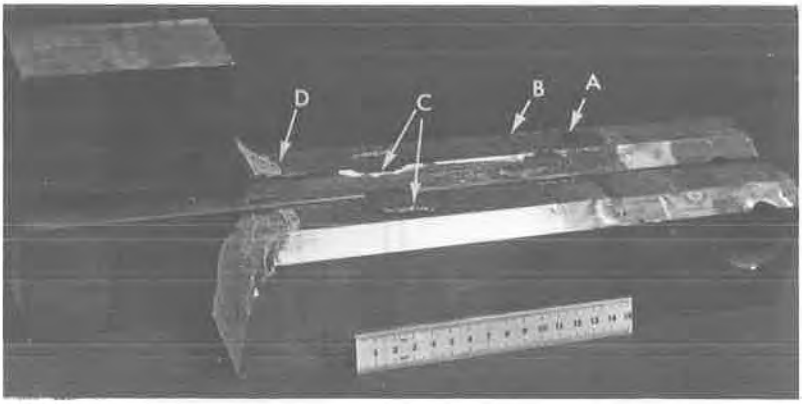
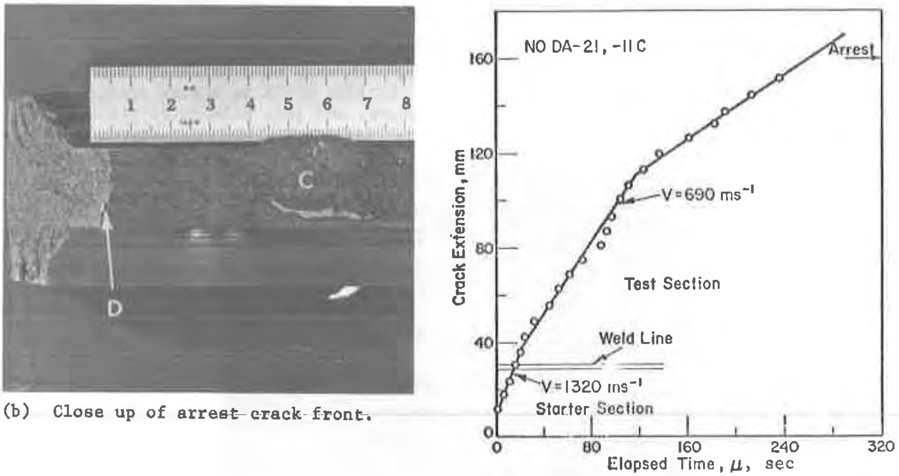


Figure 2. TEST ARRANGEMENT FOR THE WEDGE-LOADED DOUBLE CANTILEVER BEAM SPECIMEN
Cooling is provided by cold nitrogen gas fed to the copper coils on either side of the specimen. Stress intensity is derived from a clip gage on top of the specimen and from measured crack length.



(a) Specimen after heat tinting fracture surface dark and breaking open at -78°C to expose fracture surface.



(b) Close up of arrest crack front.

(c) Measurement of crack position versus time derived from resistance grid.

Figure 3. EXAMPLE OF AN AISI 4340/A533B DUPLEX DCB SPECIMEN (No. DA-21) TESTED AT -11C

(a) Specimen after heat tinting fracture surface dark and breaking open at -78°C to expose fracture surface,
(b) Close up of arrested crack front and,
(c) Measurement of crack position versus time derived from resistance grid.

The photographs show the position of the starting slot (A), weld line, (B), knot-like perturbation (C) and unbroken ligament (untinted region near (C) cuased by branching attempt and arrested crack front (D). Note that the reduction in crack velocity observed after about 120 mm of crack travel corresponds with the branching attempt (C).

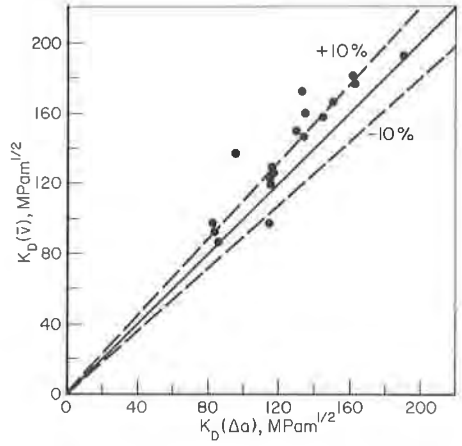


Figure 4. COMPARISON OF K_D DERIVED FROM MEASUREMENT OF CRACK EXTENSION IN TEST SECTION, $K_D(\Delta a_T)$, WITH K_D DERIVED FROM CRACK VELOCITY MEASUREMENTS, $K_D(\bar{V})$ IN TEST SECTION

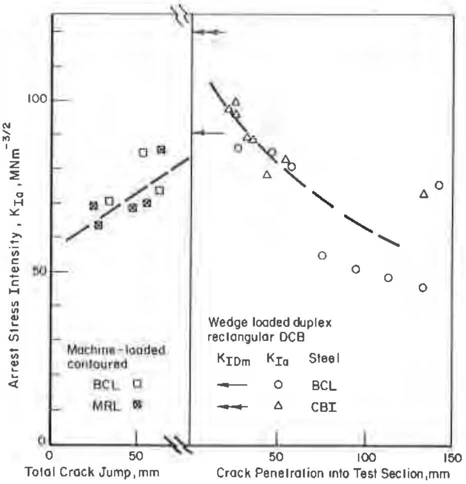


Figure 5. RELATION BETWEEN CRACK JUMP LENGTH AND POST-ARREST STRESS INTENSITY FOR TWO DIFFERENT SPECIMEN DESIGNS AND TWO HEATS OF A533B STEEL Data of Hahn, et al.[4] and of Crosley and Ripling [7].

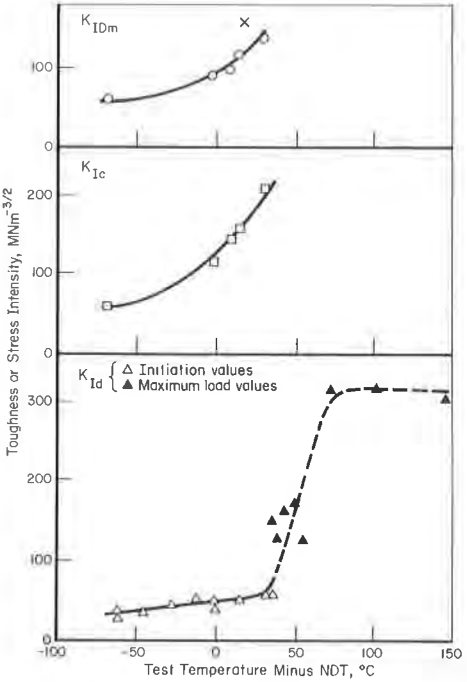


Figure 6. TEMPERATURE DEPENDENCE OF FRACTURE PARAMETERS OF A533B PRESSURE VESSEL STEEL

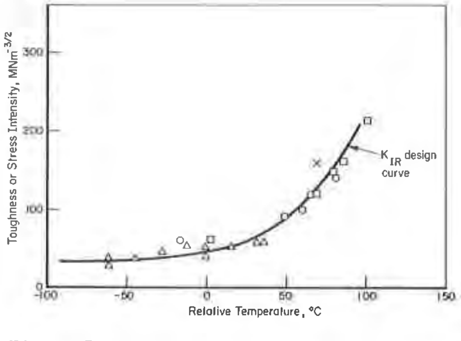


Figure 7. FRACTURE PARAMETERS OF FIGURE 6 DISPLACED ALONG THE TEMPERATURE AXIS TO PRODUCE SUPERPOSITION. K_{IR} CURVE HAS BEEN HELD FIXED.