THE EFFECT OF TRIAXIALITY ON DUCTILE-CLEAVAGE TRANSITIONS IN A PRESSURE VESSEL STEEL

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ABSTRACT

The effect of triaxiality on the fracture toughness of a pressure vessel steel has been studied over the brittle-ductile fracture mechanism transition. Specimens with a variety of widths, thicknesses, and crack lengths were tested over the temperature interval -70°C to +50°C. All but one specimen failed by a cleavage instability even though the cracks extended initially by ductile mechanisms at higher temperatures. The small specimens consistently displayed a higher fracture toughness than the large specimens when crack growth initiated by cleavage. In contrast the ductile crack growth resistance was size independent for the range of specimen sizes and crack growth increments studied. An increase in the stress triaxiality occurred during ductile crack growth which frequently resulted in a transition to cleavage fracture after some amount of ductile crack extension. Then the apparent fracture toughness was independent of specimen size and was determined by the ductile crack growth resistance at the crack extension necessary to induce the fracture mechanism transition.

INTRODUCTION

There are two important aspects to failure of ferritic steels in the ductile-brittle transition regime. The first is the effect of size and geometry on the fracture toughness. For unstable crack initiation (cleavage), the elastic plastic fracture toughness, K_{IJ}, evaluated from small specimens is often in excess of the scatter band of the linear elastic fracture toughness, K_{IC}, evaluated from large or valid specimens. The second is the frequently observed transition from the ductile to the cleavage mode of cracking when cracks first extend by ductile mechanisms. This also can lead to an apparent excessive value for K_{IJ} if the ductile crack growth is not recognised.

These two aspects of failure were addressed by Milne and Chell (1977, 1979a) and it was concluded that they could both be explained in terms of stress triaxiality effects at the crack tip. The model of Ritchie, Knott and Rice (1973) was invoked to show that the excessive plasticity of a non-valid geometry can make the conditions for cleavage difficult to attain and thus result in an increase in the measured fracture toughness. This is equivalent to a lowering of the ductile brittle transition temperature, T_{D-B} with decreasing specimen size. Eventually the conditions for cleavage cannot be attained and the crack grows by ductile mechanisms.

As it grows, the changing shape and sharpness of the tip combine with other effects to increase the stress triaxiality local to the growing crack tip and in effect to raise T_{D-B}. The transition from a ductile to a cleavage mode of cracking while the ductile crack is growing occurs if and when T_{D-B} is raised sufficiently.

An alternative explanation for the size effect on K_{IJ} has been advanced by Landes and Shaffer (1979). In a small specimen the amount of material adjacent to the crack tip is less than in a large specimen. Thus where material scatter is large, and this is generally the case for cleavage fracture, a sampling effect can be invoked to explain the higher values in the smaller specimens. Using Weibull statistics Landes and Shaffer attempted to predict large specimen behaviour from small specimen tests. This approach however does not explain the effects observed by Milne and Worthington (1976) and Chell and Gates (1977) where the state of triaxiality was varied by varying the crack depth, but keeping the specimen thickness, and hence the amount of material sampled at the crack tip, constant. Moreover the statistical approach of Landes and Shaffer relied on test data from specimens which had not failed by cleavage, a rather unsatisfactory situation.

In the following the ideas of Milne and Chell (1977) are tested on a pressure vessel steel by varying crack length and specimen size.

EXPERIMENTAL

Two series of 3-point bend specimens were cut from an 80mm thick plate of BS1501-271 steel. Series A had a constant width W of 80mm and a crack length a of 0.4W. The thicknesses, B, were 75, 40 and 20mm. Series B had W=40 and B=20mm, but crack lengths were 0.2, 0.3 and 0.5W. All the specimens were tested with a span of 4W under displacement control at a rate of 10^{-5}m sec^{-1} while monitoring load, actuator displacement and temperature. The testing temperature ranged from -70 to +50^{o}C.

ANALYSIS

A linear elastic fracture mechanics analysis was performed at the maximum load of each test in the usual way using the original crack length. This produced a result which we shall define as K_{IE}. For specimens with cracks of depth 0.4 and 0.5W a post yield analysis was also performed at this maximum load to determine the elastic-plastic stress intensity factor at failure, K_{IJ}. This analysis used the curve fitting procedures of Milne and Chell (1979b). No post yield analysis was performed for specimens with cracks of 0.2 and 0.3W, as non-linearity in the load displacement curves of these specimens cannot be attributed solely to the presence of the crack when there is a possibility of yielding in the outer fibre. The elastic-plastic effects occurring in these specimens have to be inferred from observations of general trends.

RESULTS

Series A

One specimen, with B = 20mm, was tested at +50^{o}C, and this one failed progressively by ductile mechanisms. All the other specimens in this series failed with a discontinuous load drop, by cleavage mechanisms. Non linearity in the load displacement curves was evident at the higher test temperatures, but this diminished as the temperature was lowered. This non-linearity was due entirely to plasticity below

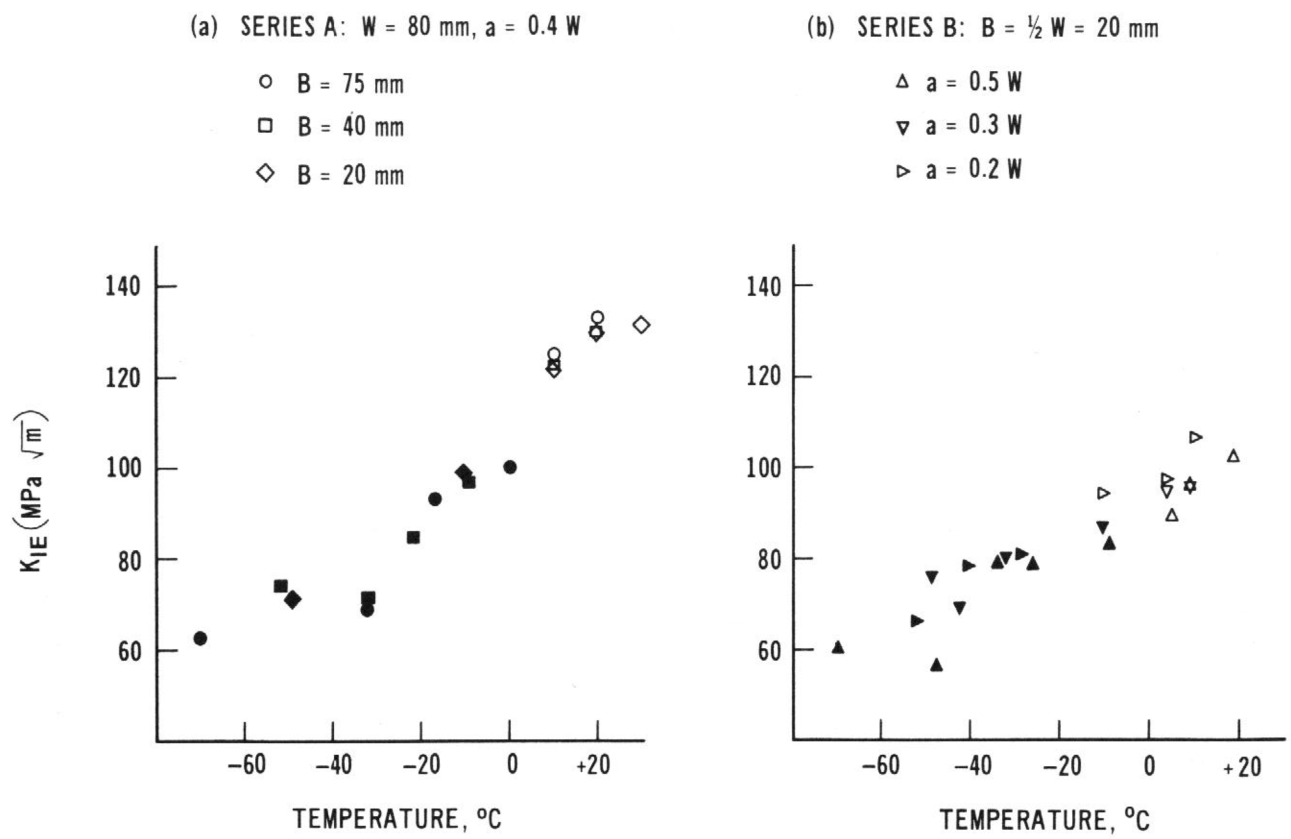

FIG. 1 ELASTIC STRESS INTENSITY FACTOR AT INSTABILITY AS FUNCTION OF TEMPERATURE ALL FAILURES BY CLEAVAGE. OPEN SYMBOLS INDICATE SOME PRIOR DUCTILE CRACK EXTENSION

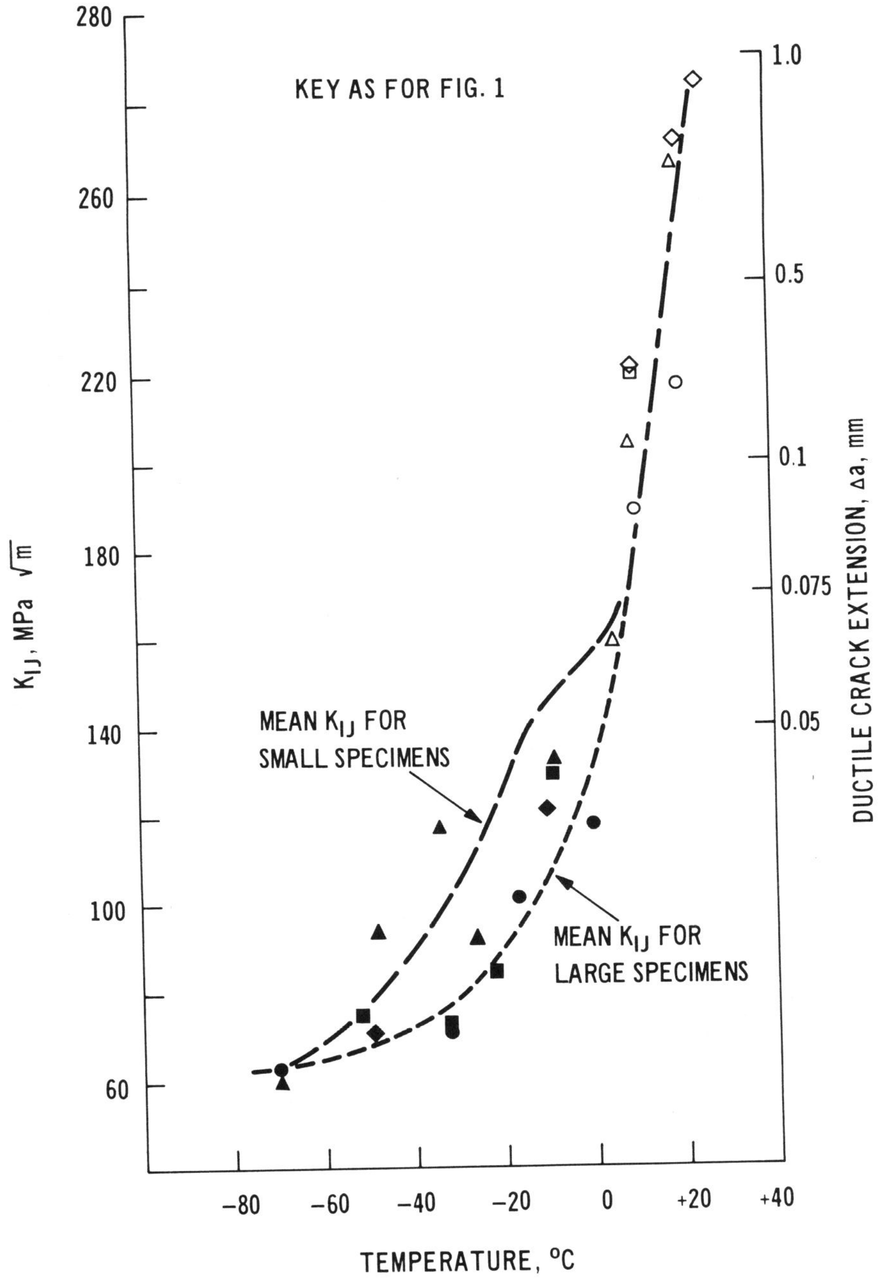

FIG. 2 PLOT OF K_{IJ} AS FUNCTION OF TEMPERATURE. ALL FAILURES BY CLEAVAGE. OPEN SYMBOLS INDICATE SOME PRIOR DUCTILE CRACK EXTENSION

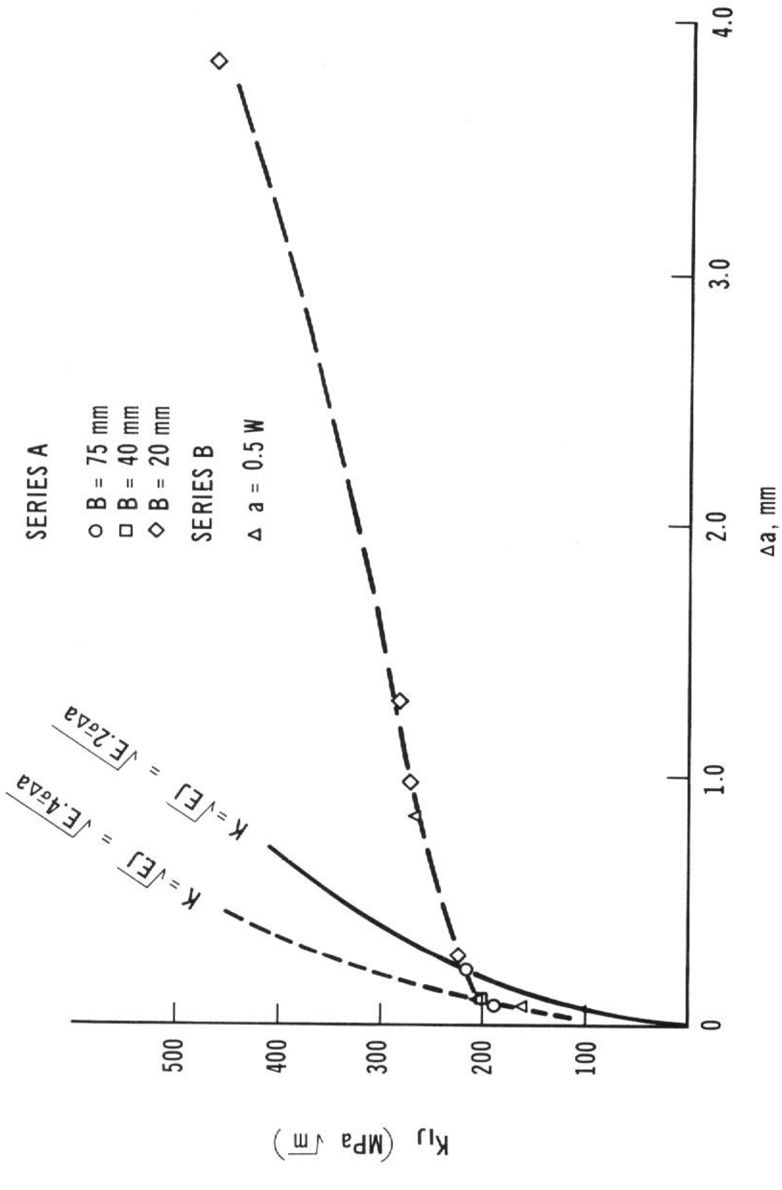

FIG. 3 PLOT OF K_{IJ} AS A FUNCTION OF DUCTILE CRACK EXTENSION, Δa

$+10^oC$, but additional contributions from ductile crack extension occurred at and above this temperature. At all temperatures but $+50^oC$ the final failure mode was cleavage. At any one temperature the extent of the ductile crack growth, where it preceded cleavage, decreased with increasing B. However, even for the 75mm thick specimen a ductile fringe was observed on the fracture surface at $+10^oC$.

The value of K_{IE}, although increasing with temperature, showed no variation with B, Fig. 1a. However, K_{IJ}, being dependent on the non-linearity in the load-displacement curves, showed a tendancy to increase not only with increasing temperature but also with decreasing B, Fig. 2.

Series B

All of these specimens were tested at temperatures where failure occurred with a discontinuous load displacement trace. Non-linearity prior to failure in the load displacement curves was extensive at the higher temperatures, again diminishing as the test temperature was reduced. This non-linearity also tended to increase with decreasing crack size. Although the final failure was always by cleavage mechanisms, some prior ductile crack extension was observed at temperatures as low as $+4^oC$. Indeed for a = 0.2W there was a hint of a ductile fringe at the fatigue crack tip at -10^oC.

From Fig. 1b it can be observed that the temperature dependence of K_{IE} is not so strong as for Series A, and again there is no clear effect due to $^a/W$, although at the higher temperatures where ductile cracking preceded cleavage the shorter cracked specimens produced the higher values of K_{IE}. In this temperature range K_{IE} never reached the levels achieved in the Series A tests.

In this series, K_{IJ} was only calculable for $^a/W = 0.5$, and these values have been included on Fig. 2. The tendency was for these values of K_{IJ} to be above the scatter band obtained from the largest specimens from Series A, and in many cases above K_{IJ} obtained from the thinnest specimens in Series A. This effect was particularly noticeable below -20^oC, but seemed to diminish as the temperature for ductile crack initiation was approached.

DUCTILE CRACK GROWTH RESISTANCE

In Fig. 3, K_{IJ} is plotted as a function of the amount of ductile crack extension, Δa, observed on the final fracture surfaces. All the data, including that obtained at $+50^oC$ fall on the same curve, indicating negligible effects due to both temperature and geometry. A stretch zone line was drawn to the most commonly used equation, $K^2 = E'J = E'.2\bar{\sigma}\Delta a$, where E' is Young's Modulus, E, for plane stress and $E/1-\nu^2$ for plane strain, ν being Poisson's ratio. The flow stress, $\bar{\sigma}$, is the arithmetic mean of the yield and ultimate tensile stresses. As can be seen from Fig. 3, several points fell above this line. A better equation for the stretch zone line is $K^2=E'J=E'4\bar{\sigma}\Delta a$, as shown. However, the intercept between even this latter line and the crack growth resistance curve does not define the onset of ductile cracking, as is evident from the Fig. 3.

DISCUSSION

The trends in the data are better illustrated by plotting the results in terms of the CEGB failure assessment diagram (Harrison and Milne, 1976). This has the added advantage of allowing study of elastic plastic effects in those specimens for which K_{IJ} was not calculated. In Fig. 4a, two parameters were calculated, $K_r = K_{IE}/K_{IJ}$

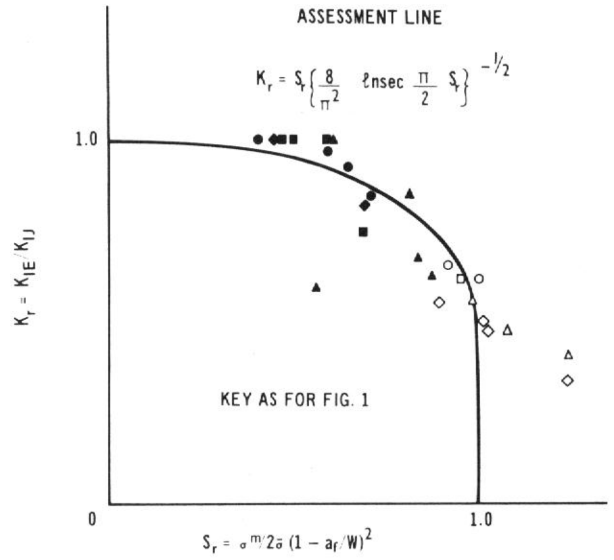

FIG. 4(a) PLOT OF K_{IE}/K_{IJ} VERSUS $\sigma^m/2\bar{\sigma}\,(1 - a_f/W)^2$
OPEN SYMBOLS INDICATE FAILURE PRECEDED BY DUCTILE CRACK GROWTH

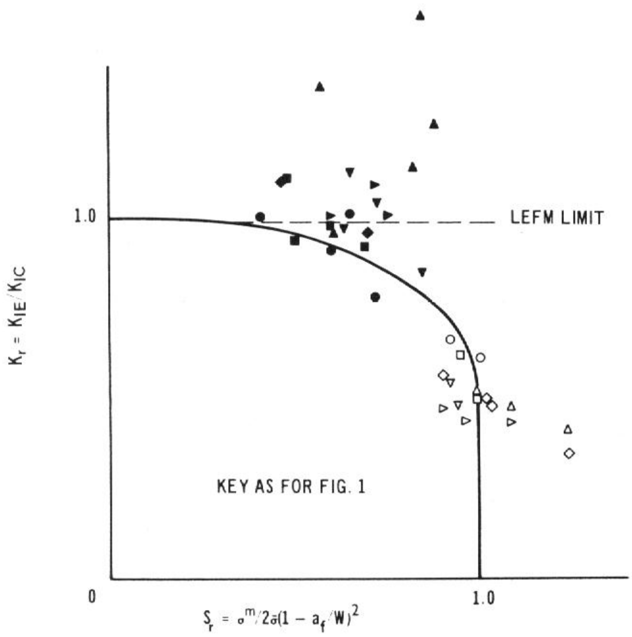

FIG. 4(b) K_{IE}/K_{IC} VERSUS $\sigma^m/2\bar{\sigma}(1 - a_f/W)^2$. OPEN SYMBOLS INDICATE FAILURE PRECEDED BY DUCTILE CRACK GROWTH, EVALUATED AT K_{IJ}

and $Sr = \sigma^m/2\bar{\sigma}(1-{}^a/W)^2$. This latter expression defines how close each specimen was to plastic collapse at the maximum (failure) stress, σ^m. The value for a was taken to be the final crack length including the extent of ductile cracking for evaluating both S_r and K_r. This Fig. simply validates the general concept of the failure diagram using the expression of $2\bar{\sigma}(1-{}^a/W)^2$ for the collapse stress with the arithmetic mean of yield and ultimate stresses for $\bar{\sigma}$. As required, the data scatters reasonably evenly about the assessment line. In Fig. 4b the results are replotted using the same value for S_r but $K_r = K_{IE}/K_{IC}$. In this case K_{IC} is the average K_{IJ} obtained from the largest test specimens (the small dashed line in Fig. 2), B = 75, W = 80mm, where cracking was initiated by cleavage, and from the K_{IJ} resistance curve where ductile crack growth intervened. These points fall into two distinct groups, depending on whether or not ductile crack growth preceded the final fracture.

Where ductile crack growth was absent, the filled symbols in Fig. 4(a) indicate a distinct effect of specimen geometry. Three points only fall inside the assessment line, and two of these are for the largest specimens. The remaining 19 points fall above the assessment line, 13 of these above the dashed line which defines the LEFM limit. Those points furthest from the line are for the series B specimens with a = 0.5W. The remaining series B specimen data fall closer to the assessment line, somewhat in conflict with the observations of Milne and Worthington (1976) and Chell and Gates (1977) on the effect of crack size on K_{IJ} but their relative positions still imply an increased K_{IJ} over that for the largest specimens.

Where ductile crack growth preceded cleavage, the open symbols in Fig. 4b, the data scattered fairly evenly about the assessment line. The size effect observed for cleavage initiation was thus absent when cleavage occurred after some amount of ductile crack growth. This indicates that here the measured toughness is obtained from the size independent ductile crack resistance curve, Fig. 3, rather than from the cleavage fracture toughness. The growing ductile cracks clearly created the conditions for cleavage, through a combination of effects due to prestraining, changes in the crack front shape and sharpening of the initially blunted crack.

In Fig. 2, the right hand ordinate has been scaled in terms of Δa, obtained using the best fit curve to the data of Fig. 3. The light dashed line is the mean line for all the large specimens and the heavy dashed line is drawn through the mean of the small specimen data. This illustrates how the size effect disappears when ductile crack growth precedes cleavage failure, and how the resultant level of K_{IJ} is a measure of the ductile resistance toughness at the crack extension where cleavage occurs.

This is an important point, and explains the frequent reports of excessive fracture toughness when relatively small (possibly undetected?) amounts of ductile cracking exist. Moreover the loss of the size effect in this regime also explains the inability of many observers, particularly during the days when elastic plastic fracture mechanics was in its infancy, to recognise the effect of size on cleavage initiation. The fact that this size effect has disappeared lends further powerful support to the triaxiality explanation for the effect of specimen geometry on the value of K_{IJ}, as proposed by Milne and Chell (1979) rather than the statistical model, since the statistical model would predict that the size effect is retained.

CONCLUSIONS

1. For cleavage initiation the plastically corrected fracture toughness of small specimens can greatly exceed the plane strain fracture toughness, K_{IC}.
2. The cleavage mechanism of fracture is always in competition with the ductile mechanism in the transition region.
3. Cleavage failure which is preceded by ductile crack extension can be regarded

as being due to an upward shift in the ductile brittle transition temperature resulting from the ductile crack extension.

4. Prior to a cleavage instability, ductile crack growth occurs at a toughness determined by the crack growth resistance curve at the appropriate extent of crack growth. In this material the crack growth resistance was size independent for the range of specimen sizes and crack growth increments investigated.

ACKNOWLEDGEMENT

The authors are grateful to J.R. Haigh for help during the early stages of this work. The work was performed at the Central Electricity Research Laboratories and is published by permission of the Central Electricity Generating Board.

REFERENCES

Chell, G.G. and Gates, R., (1977) Int. J. of Fracture 14 233.
Harrison, R.P. and Milne, I. (1976) Proc. of Conf. on Fracture Mechanics in Eng. Practice, Sheffield, p. 69.
Landes, J.L. and Schaffer, D.H. (1979) Proc. Twelfth U.S. National Fracture Mechanics Symposium, ASTM.
Milne, I. and Chell, G.G. (1977) Proc. E.C.F. 2, Darmstadt, Germany, p. 116.
Milne, I. and Chell, G.G., (1979a) ASTM STP 668 586.
Milne, I. and Chell, G.G. (1979b). CSNI Specialist Meeting on Ductile Tearing Instability, St. Louis, paper II (2), NUREG/CP-0010, CSNI report No. 39.
Milne, I. and Worthington, P.J. (1976) Mats. Sci. & Eng. 26 185.
Ritchie, R.O., Knott, J.F. and Rice, J.R. 1973. J. Mech. Phys. Sol. 21 395.