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THE USE OF THE J INTEGRAL TO MEASURE THE RESISTANCE OF MILD STEEL TO SLOW STABLE CRACK GROWTH

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INTRODUCTION

The development of yielding fracture mechanics allows the extension of the resistance (R) curve concept [1] to situations involving large scale plasticity. There are thee main advantages in this: firstly the possibility arises of predicting R curves for large structures from small specimens: secondly, an improvement in the accuracy of resistance curve measurements is attainable (since the build up of resistance is accompanied by an increase in plastic zone size, linear elastic fracture mechanics is inadequate): and finally, the measurements of "plane strain" R curves for low strength materials becomes feasible despite extensive yielding.

It is the purpose of this paper to examine the use of the J contour integral [2] as a measure of the resistance of mild steel to slow stable crack growth.

THEORY

From Rice [3] the area ΔU_p in Figure 1 can be related to J, for non-linear elastic material, by

$$\Delta U_p \simeq J_{1-2}\, B\Delta a \qquad (1)$$

where opq represents the load deflection curve for an initial crack length a_1 and orq for a longer crack $a_2 = a_1 + \Delta a$. All the energy released is available to propagate the crack. J_{1-2} is the average value of J between the two crack lengths, and B is thickness. Begley and Landes [4] and Bucci et al [5] have extended this concept to elastic/plastic materials as a means of evaluating J, although the simple energetic meaning of energy available to drive the crack is not then maintained.

A technique for developing a J resistance (J_r) curve was derived for three point bending in [6], in which the three parameters of load, deflection and final crack length are all matched in the derivation of J. The basis of the method is the construction of a series of non-linear elastic curves to describe the history of the specimen as the crack extends (such as orq in Figure 1). This technique avoids the criticism that irreversible stress relaxation at the crack tip invalidates the J concept. Due, however, to the irreversible nature of plastic deformation the curves such as orq (Figure 1) are purely notional. Assuming a linear variation of the R curve for the increment of crack extension, and using the relationship between J and work done (U), as developed by Sumpter and Turner [7] for the three point bend geometry, the value of J at the new crack position can be

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found without the precise form of orq (Figure 1) being known. The expression is

$$J_2 = J_1 \frac{(W-a_2)}{(W-a_1)} + \frac{2\Delta U_d}{B(W-a_1)} \qquad (2)$$

where ΔU_d is the extra energy put into the specimen as the crack grows from a_1 to a_2 (see Figure 1) and W is the width of the specimen (Figure 2).

This equation can be applied for subsequent increments of crack growth to give the general form:

$$J_n = J_{(n-1)} \frac{(W-a_n)}{(W-a_{(n-n)})} + \frac{2(U_n-U_{n-1})}{B(W-a_{(n-1)})} \qquad (3)$$

Similar expressions may be obtained for all geometries where J : U estimates can be determined.

EXPERIMENTAL PROCEDURE

All tests were conducted at room temperature (~ 21°C). The properties of the mild steel (En32) used are listed in Table 1. Specimens were tested in three point bending. Both side grooved and plain types were used (Figure 2). All specimens were fatigue cracked at loads less than half the yield value. Initial crack lengths and subsequent amounts of crack growth were measured at ten points along the crack front and averaged to give mean values. Loading rate was constant at 1mm/min. A transducer was used to obtain load point displacement. As the technique relies on the load-displacement record, a correlation was made for the extraneous displacement due to roller indentation.

The three parameter technique is best suited to a one specimen test where crack extension is monitored together with load point displacement. However, due to the inadequacies of current techniques for detecting slow growth in the presence of large scale plasticity, a multi-specimen programme was adopted. Ten or so specimens were bent to give gradually increasing amounts of crack growth. Care was taken to ensure at least one specimen had crack growth $\leq$ 0.1mm. The specimens were then fractured in liquid nitrogen to facilitate measurement of the ductile crack extension. Crack growth determinations were made ignoring the stretch zone width (typically $\ll$ 0.1mm). Thus the initiation value of $J(J_i)$ is given by the intersection of the resistance curve with the Δa (the amount of slow growth measured) = 0 axis. Load-displacement areas were measured with a planimeter. The use of the formula:

$$J_o = \frac{2\,U_{total}}{B(W-a_o)} \qquad (4)$$

shown by Sumpter and Turner to be valid for a_o/W ranging from 0.4 to 0.7 precludes the need to subtract the energy attributable to the uncracked body recommended by Rice et al [8]. To begin with specimens of identical initial crack lengths were prepared but in later tests it was found sufficient to compensate for slight variations by making adjustments to the energy values.

The test method devised by Landes and Begley [9] was used to plot the $J_o : \Delta a$ curves (J_o is calculated using the initial crack length regardless of the amount of crack growth) in Figure 3. For larger increments of crack growth these curves overestimate the true J resistance (J_r) curve, but for small amounts the curves converge to give the same value for J_i. The $J_o : \Delta a$ curve was used as a check for any specimen behaving extraordinarily (due to blunted notch, preloading of bifurcation, for example). Any such point was omitted from the J_r calculation using the three parameter technique as it was found to affect subsequent points in the analysis. The first point on the J_o curve was taken at the J_1 value in equation (2) and the J_r curve was generated as in equation (3).

RESULTS

The effect of remaining ligament depth on the J_o curve for specimens with a side groove ratio (S.R. is defined in Figure 2) of 0.56 is shown in Figure 3. The variation of J_o with initial crack length translated into a J_r curve (Figure 4) which is independent of the remaining ligament for the values chosen. As expected J_o and J_r curves diverge after ~ 1mm crack growth. Both curves extrapolate to give a J_i for the material of 0.12 Jmm^{-2} (120 Nmm^{-1}). This value of J_i was found to be constant for all configurations of bend specimens tested. The side groove ratio of 0.56 was chosen to eliminate 3 mm deep shear lips present in the plain specimens. However when specimens of double the dimensions but with the same side groove depth were tested a steeper J_r curve was found (Figure 5). Essentially the same curve is produced for differing value of W. The curve for the smaller W however reaches a plateau as the crack moves into the plastic region of the loading roller. Figure 6 indicates that it is the S.R. ratio which is the over-riding factor, rather than the removal of shear lips, in the production of a lowest bound or "plane strain" resistance curve. The ratio of 0.56 appears sufficient to provide this curve whereas 0.25 is not.

Plain sided specimens (S.R. = 0) of varying thicknesses with constant W (Figure 7) show the expected dependence, i.e., the greater the amount of shear to flat rupture, the steeper the resistance curve.

Shear lip size was found to vary with specimen thickness and width in a rather complicated manner which is reflected in the resistance curves. Altering W with B constant gives very different J_r curves (Figure 8) attributable entirely to the variation of shear lip size in the two cases. Maintaining the W/B ratio constant (Figure 9) produces identical results.

CONCLUSIONS

By use of the three parameter technique, J_r curves of form similar to K_r curves are found. J_r curves are greatly affected by the presence of shear lips. Shear lip size is geometry dependent. This is reflected in the resistance curves of non side grooved specimens. It is not sufficient merely to eliminate the shear lips to produce the lowest bound curve. It would appear that the side groove ratio is itself a governing factor of the J_r curve obtained but by choice of a side groove ratio S.R. = 0.56 a "plane strain" curve is produced that is independent of initial crack length in three point-bending over the range of sizes tested.

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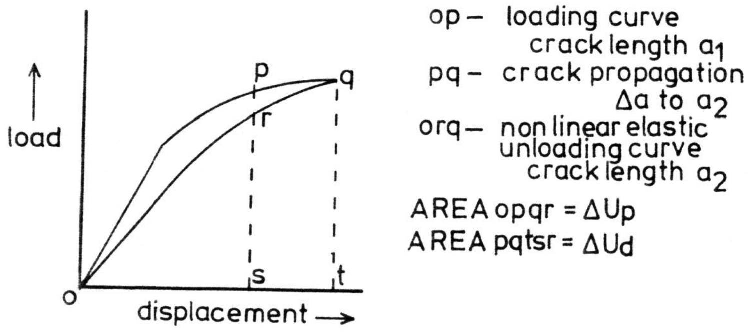


Figure 1

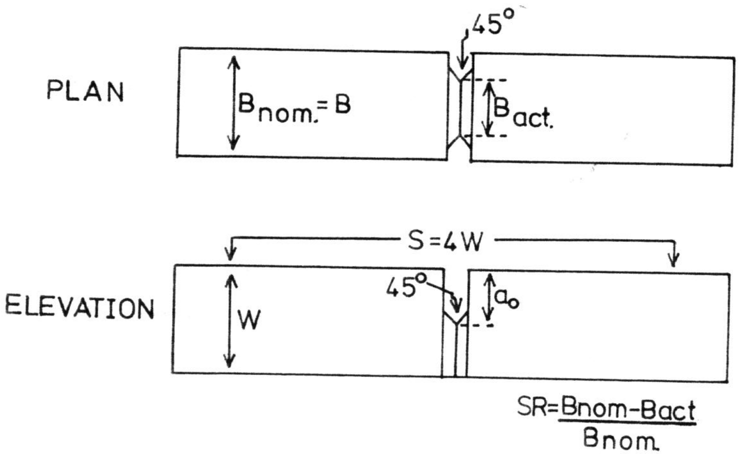


Figure 2

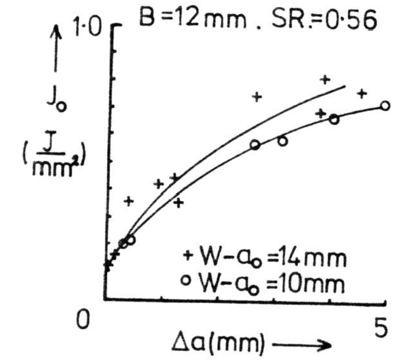
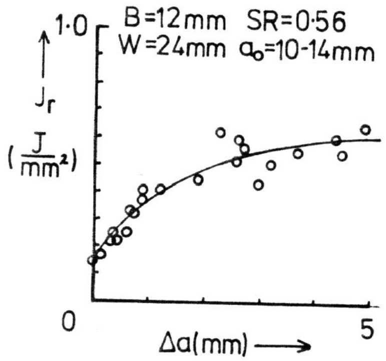


Figure 3



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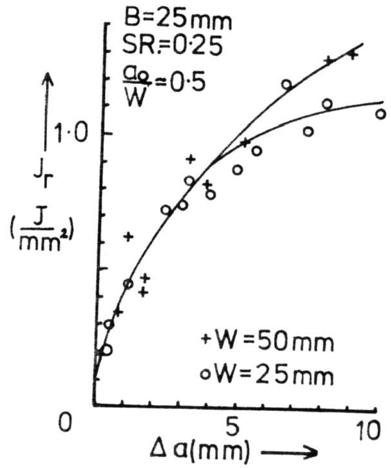

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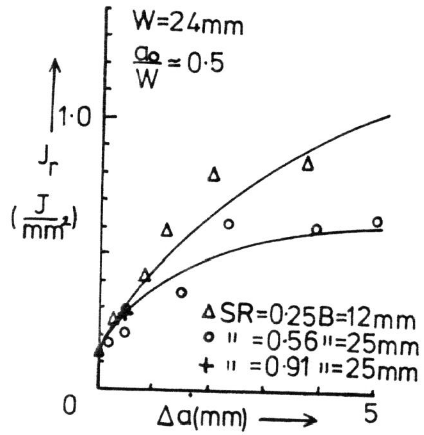

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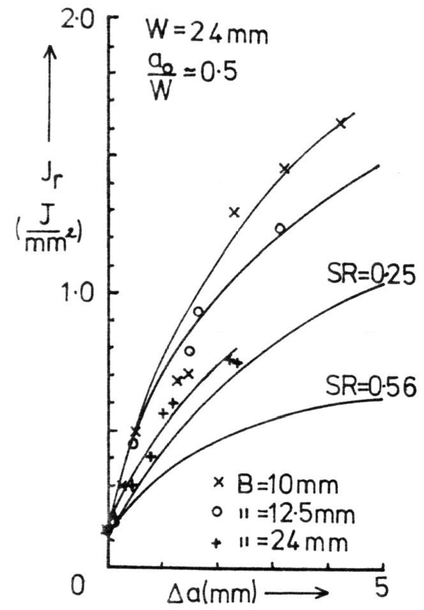

Figure 7

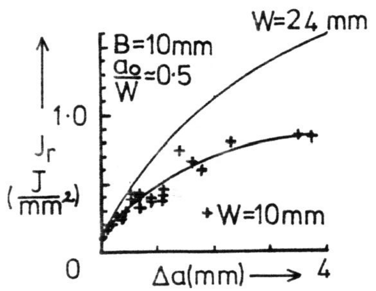

Figure 8

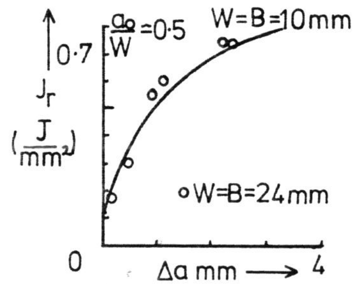

Figure 9

Table 1

MATERIAL	CONDITION	YIELD STRESS MN/m^2
En 32 steel (C - 0·17% Si - 0·23% Mn - 0·74%)	Normalised (900°C, 1hr, air cooled)	290