The Relationship between Dynamic Fracture Toughness and the Conditions for Crack Arrest in a Large Structure

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1. THE CONCEPT OF DYNAMIC FRACTURE TOUGHNESS There are three essentially different processes which are linked by the fact that fracture is occurring under a high local strain rate: shock fracture initiation from a sharp notch; fast propagation of a crack; crack arrest. If we take the simple-minded view that fracture is controlled by the value of an effective surface energy, the three processes become closely related. Shock initiation depends on the value of the applied stress exceeding the Griffith's value:

$$\sigma = \sqrt{\frac{2E\,\gamma_{eff}}{\pi C}} \quad \ldots\ldots (1)$$

Where C is the length of the initiating notch, or crack, E is Young's modulus and γ_{eff} is the effective surface energy, consisting mainly of the work needed to stretch to fracture the layer of material next to the fracture surface. On this simple hypothesis the excess strain energy released during propagation becomes kinetic energy, only 4 BC γ_{eff}, the amount needed to make the fracture surfaces, being used (B is the plate thickness). Crack arrest occurs if the strain energy release rate falls below 4 B γ_{eff}, i.e. if (Cottrell, 1964)

$$\sigma < \sqrt{\frac{2E\,\gamma_{eff}}{\pi C}} \quad \ldots\ldots (2)$$

Very similar to the Griffith's condition (equation 1).

This simple model suffers from many drawbacks but the practical usefulness of dynamic toughness must depend on some such simple model applying. Therefore, our comprehensive series of dynamic tests on one steel (a common C/Mn steel in the normalised condition, to BS1501 - 221) will be examined to see how far it applies.

2. SHOCK FRACTURE INITIATION Specimens were in the form of bars broken in three-point bending. Each contained two notches equidistant from the central loading point. They were fractured by impact and the notch opening displacement (δ_D) measured at the unbroken notch tip. This is a measure of the dynamic toughness since this notch must have been near its fracture condition when it was unloaded by fracture at the other notch. Using the simple model we have:

$$\gamma_{eff} = \frac{\sigma_y \delta_D P}{2} \qquad \ldots\ldots (3)$$

Where σ_y is the dynamic yield stress and P is the plastic constraint factor of value between 1 and 3, depending on the amount of yielding.

Tests of this type were carried out on our standard 25 mm thick C/Mn steel plate by courtesy of the Gas Council and on some 76 mm thick specimens at the Safety in Mines Research Establishment. Both types of specimen were prepared with 150μm root radius notches and δ_D was measured by feeler gauge. The results are compared below with the dynamic toughness in crack propagation (section 3) and in arrest (section 4).

3. FAST CRACK PROPAGATION A method for finding propagation toughness from an impact test is the temperature wave method invented by Wells. The temperature wave emanating from the fracture is measured by thermocouples. On the assumption, based on other work, that most of the energy needed to deform a metal appears as heat, this temperature wave can be used to calculate the propagation toughness, γ_{eff}. Montgomery and Wells (1972) have used this method to find the propagation toughness of our 25mm C/Mn steel. The results compare well in the lower shelf region with values of γ_{eff} calculated for crack arrest in the pressure vessel tests described in section 4.

The propagation toughness measured in a wide plate or a vessel test should be more reliable than that obtained from impact tests, because more stable fast crack conditions will be achieved. A method of measuring propagation toughness in this circumstance has been developed in this investigation. It depends on relating the amount of plastic deformation, the traces of which remain after fracture, to γ_{eff}. One way of measuring the deformation is via the local thickness contraction near the fracture. For a moderate or high toughness giving nearly plane stress conditions the amount of thinning is approximately equal to the local plate stretch, δ_D. This is because shear occurs in bands at 45° to the plate surface (Hahn and Rosenfield, 1965). Equation (3) relates δ_D to γ_{eff}. The results on our 25mm C/Mn steel, obtained by taking plate thickness measurements after the series of pressure vessel burst tests, span the brittle-ductile transition region. Agreement with the double-notched impact δ_D (section 2) is remarkably good - the transition occurs over approximately the same temperature range (0-40°C) in both cases and values of δ_D agree well in magnitude. (For example, at 20°C the value of δ_D in double-notched impact is 0.76mm and is 0.6mm in wide plate propagation.)

4. CRACK ARREST We see from the quasi-static model in equation (2) that crack arrest occurs if the applied stress is less than some value which depends on γ_{eff} and instantaneous crack length. To find this value and hence γ_{eff} it is necessary to measure a condition in which the crack just stops. The inertia of the loading system of a tensile testing machine would be such as to make uncertain the stress acting at the instant of arrest. Our 25mm C/Mn steel was therefore tested in the form of gas-loaded pressure vessels so that the full stress would be acting throughout the process and would last until gross fracture had occurred. This work has been reported briefly elsewhere

(Edmondson, Formby, Jurevics and Stagg, 1969; Edmondson, Formby and Stagg, 1969) but before the full results were available.

A 305mm (12 in) long running crack was produced in each of the 1.52m (5 ft) diameter cylindrical vessels by cooling an axial 305mm groove. This was repeated at a succession of increasing internal pressures on each vessel by repairing and rotating, until the crack no longer stopped near the groove ends but ran on to give a complete burst. Repetition to cover a range of overall vessel temperatures allowed the full transition curve to be obtained in terms of fracture stresses. The lower bound is given by the highest stress at which the running crack emerging from the artificially induced brittle region was found to arrest. The upper bound is the lowest stress at which the crack was found to continue to run, giving a complete burst. The bounding stresses can be converted to δ_D values via the empirical formula of Cowan and Kirby (1969). This crack arrest toughness can be compared with shock initiation toughness (section 2) and with propagation toughness (section 3). The transition spans the temperature range 0 to 35°C and the value of δ_D at 20°C is 0.5mm (0.020 in) in excellent agreement with the shock initiation and propagation cases (section 3).

Some standard Robertson Crack Arrest Tests were carried out by R.E.M.L. Risley on our steel for comparison. The crack arrest temperatures did in fact occur near in temperature to the δ_D transition, but the result obtained at the more usual applied stress (124 MN/m^2; 8 tsi) lay slightly below the main part of the transition. These results show that the Robertson Crack Arrest Test does give a feel for the position of the dynamic toughness transition, but a test for dynamic toughness would give much more information.

5. DISCUSSION The similarity found between the shock initiation, propagation and arrest toughnesses is remarkable when account is taken of the diversity of process and test type, and of the complications caused by inertia and strain rate effects. The simple argument given in section 1 of the equivalence of the three processes must be sufficiently valid. Moreover, the fact that the crack arrest conditions of the 1.5m diameter gas-loaded vessels were predictable even from the impact tests, in which the energy released was orders of magnitude smaller, shows that crack arrest is controlled by dynamic toughness rather than stored energy release. Thus dynamic toughness can be regarded as a material property in its own right, independent of the test details. The only requirements seem to be an acute notch, full plate thickness and a loading rate in the right range.

A straightforward way of incorporating dynamic toughness into safety arguments would be via the Pellini Fracture Analysis type of approach (Pellini, 1971). This approach could be improved by the application of a standardised test for dynamic toughness. The dynamic toughness could then be used in conjunction with the standard fracture mechanics formulae, familiar from static fracture initiation, to make quantitative predictions of the size of shock loadings or brittle volumes which can be allowed in a structure.

6. CONCLUSIONS

(1) Shock fracture initiation, rapid crack propagation and crack arrest are equivalent in the sense that they are controlled by the same effective surface energy, γ_{eff}.

(2) The dynamic toughness, γ_{eff}, can be a useful material property, specifying tolerance of shock loadings and brittle areas.

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