CRACK ARREST BEHAVIOUR AND TOUGHNESS IN DUCTILE MATERIALS

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ABSTRACT

A test procedure has been developed to study fast crack propagation and arrest in ductile materials. The extent of crack jump can be controlled readily and crack velocity measured. The load and displacement at instability and arrest can be determined, which permits determination of the work done during the instability period. Arrest toughness based on "static" considerations allows evaluation of the ductile toughness.

The value of arrest toughness has been found to vary with crack speed as has the rate of change of crack velocity over the arrest period.

KEYWORDS

Crack propagation, dynamic fracture, crack arrest, arrest toughness, ductile material.

INTRODUCTION

The arrest of running cracks has been of considerable interest since the catastrophic wartime failures of welded Liberty ships. More recently, attention has been focused on crack arrest following initiation from a loss of coolant accident in a pressurised water reactor. This work has been based upon the application of linear elastic fracture mechanics. Propagation and crack arrest in gas pipelines has also received considerable attention and, in contrast, relates to thin sections exhibiting considerable ductility. Recently, the crack arrest philosophy has been considered in terms of providing a degree of redundancy in the safety argument applied to the design of tanks for the bulk storage of liquified gases.

Since these latter interests lie in the evaluation of ductile material, a test procedure was felt desirable, because the Crosley (1976) and Hoagland (1976) specimens are not suited to ductile fracture and have unstable crack direction, unless heavily side grooved. The large wide plate tests are deficient in as much as test machine response and energy available are near to uncontrollable.

In response to the need to examine ductile fast fracture and arrest, a procedure has been developed, based upon use of the conventional compact tension specimens. It should be borne in mind that in propagating ductile cracks, the ability to do plastic work on the specimen following initiation is critical. In what follows, results and details are presented of experiments conducted to establish a method of propagating cracks, measuring velocity and evaluating arrest. The measure of arrest toughness includes the contribution due to plastic deformation.

THE TEST PROCEDURE

The initial objective was to be able to initiate a crack under well defined conditions, eg. at a desired load or displacement. To this end liquid metal embrittlement was seen as a simple means. As a result, the tests described in this paper are based on the use of brass in which cracks can be initiated using mercurous nitrate. A specimen containing a blunt notch could be loaded to a prescribed state, recording equipment checked and a crack started by passing a thin thread soaked in mercurous nitrate across the notch. This worked successfully on the trial samples.

Instability and control of the crack jump was achieved by displacement controlled loading of the specimen in series with a quantity of Belleville washers, see Fig. 1. This system evolved because the amount of plastic work done in propagating the crack could not be achieved by the strain energy introduced into the specimen or accurately controlled through test machine operation on load control.

The specimens were standard CTS configuration, with W = 100 mm and B = 8.15 mm. They were prepared by overloading the uncracked plate to plastically deform the pin holes. A sharp notch was then introduced with a/W values of 0.5 and 0.6. The specimen was set up with a specified number of Belleville washers in series. Load pin separation as a measure of total work done was recorded. Washer displacement was also measured. Crack length and hence velocity were measured using the AC potential drop method. A timing interval spike was imposed on the standing voltage. All events were recorded on a multi-track tape recorder at 60 ins. per minute, with a playback facility of 15/16 ins. per minute.

In the defined test program a different brass was used, which was much tougher and though cracks would form initially, controlled instability could not be achieved. As a result, the test procedure to emerge, which is applicable to all materials, was as follows. Using a very slow displacement control the crosshead of the test machine moved against the Belleville washers. At the onset of instability from a sharp notch, which could be seen from the load displacement trace, the machine was stopped. Run and arrest was then dependent on the load maintenance of the Belleville washers.

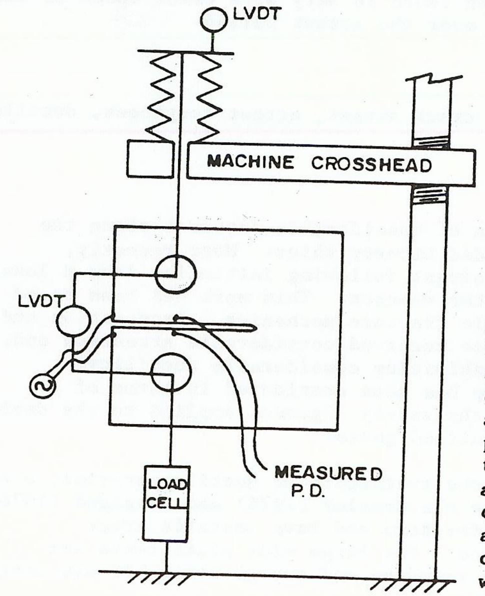

Fig. 1 Test Specimen Set-up

Using the playback facility it was possible to plot any two variables against each other. In addition, the potential drop was plotted as a function of time, to show the changes in velocity at instability and arrest. A typical summary of records is shown in Fig. 2. After arrest the specimens were heat tinted and broken open to obtain crack length data.

An initial series of tests using the J integral method of analysis was conducted to provide a measure of the initiation toughness. Also, some preliminary dynamic system tests were carried out to establish the pattern of crack initation upto the point of instability. The J/da results are plotted in Fig. 3.

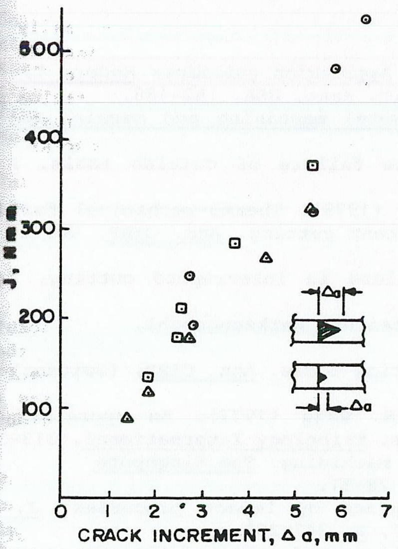

Fig. 3 J – Δa Results

THEORETICAL BASIS OF FRACTURE AND ARREST

In considering a rigorous analysis of the dynamic behaviour of cracks, Kanninen (1974) and Hahn (1974) have proposed that a total energy balance is essential. This requires account to be taken of kinetic energy effects. In a finite size specimen stress waves will radiate from the crack tip and be reflected back from the boundaries. Thus the kinetic energy contribution at any time will play an important role in the dynamic fracture event. Consequently it was proposed that the energy balance equation should take the form

$$\frac{dF}{da} - \frac{dU}{da} - \frac{dE}{da}\,\mathrm{kin} - \frac{dW}{da} = 0 \qquad (1)$$

where F is the work done, U is the elastic energy, W is the energy required for crack extension and E_{kin} is the kinetic energy contribution. Thus the dynamic driving force

$$G_d = \frac{dF}{da} - \frac{dU}{da} - \frac{dE}{da}\,\mathrm{kin} \qquad (2)$$

If R_d denotes the dynamic energy dissipation rate per unit of crack extension, then crack propagation will only occur when

$$G_d\,(t,V) > R_d\,(V) \qquad (3)$$

where t denotes time and V crack velocity.

It can be seen from the energy balance, that if a static analysis is applied to the dynamic arrest event, then the apparent arrest toughness, will be a variable quantity depending on what proportion of E_{kin} is recovered.

The detailed energy balance evaluation can only be undertaken analytically with difficulty for linear elastic fracture mechanics and requires data or assumptions about the relationship between crack velocity and fracture resistance. To undertake an extension of such an analysis into the regime of large scale plasticity is not presently feasible. Consequently, one must resort to a "static" arrest analysis, thus reverting to the static energy balance equation

$$G_A = \frac{dF}{da} - \frac{dU}{da} \tag{4}$$

$$= \frac{1}{B}\,\frac{Pdv}{da} - \frac{dU}{da} \tag{5}$$

where B is the plate thickness and v the load displacement. At this juncture one must recognise that while dU/da relates to the elastic properties of the specimen, P dv/da is a function of the elastic-plastic properties. These latter quantities can be determined from experimental results, which makes it possible to determine an arrest toughness that includes the contribution due to large scale plastic deformation.

ANALYSIS OF EXPERIMENTAL RESULTS

It should noted at the outset that, in attempting to analyse the results of these tests a difficulty over the shape of the arrested crack front arises. The final crack front was found to tunnel on the centre plane of the specimen a distance almost equal to thickness. Neale (1978) has shown that tunnelling has a significant effect on crack tip stress intensity and specimen compliance. Though not strictly correct, calculated values quoted in this paper involving crack length are based on surface measured length. From the J evaluation tests and prematurely terminated dynamic tests, it was observed that the starter crack would tunnel initially to instability, so that during the rapid growth period the crack front shape was essentially unchanging. From a test, the following quantities could be measured.

TABLE 2

LOAD	CRACK LENGTH	DISPLACEMENT
Maximum Instability Arrest	Initial Edge arrest Tip arrest	Load point Spring

Of course all intermediate data is known, so that total work done, final rate of change of load with displacement at arrest and load point displacement with crack length increment can all be determined. Also from the load displacement record the compliance indicated crack length can be calculated.

Because of the extent of load point displacement, a conventional clip gauge could not be used and it was also considered that it may not follow the fast event accurately. To measure load point displacement, a two part fixed transducer across the load pins was used. Having preloaded the unnotched specimens it is considered that only small elastic extraneous displacement was likely to be measured during a test.

Calibration of the AC potential drop indicated crack length, has not proved straightforward. Because of changes due to plastic deformation, which in these tests was large, the saw cut method of calibration indicated a completely different voltage change per crack increment, than was realistic from the arrest results. From evaluation of the arrest test changes in voltage and crack length, a value of 1.78 mm per volt was obtained.

Table 1, records the summary of experimental results and various crack arrest toughness values obtained. The following definitions are applicable, from

$$K = \frac{PY}{BW^{\frac{1}{2}}} \tag{6}$$

K_{in}	maximum load, initial crack length and elastic Y calibration.
K_{ElAr}	arrest load, final edge crack length and elastic Y calibration.
K_{CoAr}	arrest load, compliance indicated crack length and elastic Y calibration.

From the static energy balance equation, the value of G_A (K_A) was determined using the values of dv/da obtained from the results of displacement and crack increment, shown in Fig. 4., together with P arrest. The value of dU/da, being the elastic strain energy release rate, can be obtained from the value of K_{Elar}.

Since crack initiation was from a sharp notch, it was thought than an average value of dynamic toughness could be obtained by considering work done and strain energy difference between specimens of the same initial crack length.

$$G_{ave} = \frac{(F_i - U_i) - (F_j - U_j)}{\Delta a_i - \Delta a_j} \tag{7}$$

Through this route the initial work done upto instability is assumed identical and does not enter into evaluation of the dynamic event. Unfortunately, such values appeared to be very inconsistant.

CONCLUDING REMARKS

From the preliminary trials which led to the evolution of the test program providing the results described, it emerged that the ability to do plastic work, to produce ductile instability was important. For this reason, it maybe that brittle/ductile duplex specimens could give misleading, but high, results on arrest toughness. When the fast moving crack with its small plastic zone reaches the ductile material it may have a dynamic stress intensity greater than required. However, since propagation can only continue with a much larger plastic zone, arrest may occur because insufficient energy is available to change the plastic zone size sufficiently. In contrast the "static" analysis would underestimate arrest toughness.

Observations on crack speeds, as indicated by the change in voltage, show that a crack accelerates and achieves a maximum velocity. The arrest that follows can be abrupt or gradual. For greater qunatities of Belleville washers, and hence higher crack speeds, the arrest event occured suddenly. Fewer washers produced a lower maximum velocity and showed a definite decceleration period. The abrupt arrest was seen as a step change within the plotter scale used to record the event. These cracks reached their maximum velocity in less than 0.2 secs. The maximum velocity recorded was 0.75 m/sec over a distance of 25 mm.

It should be noted that the arrest toughness G_A (K_A) appears to be related to the number of springs and hence crack velocity. The higher the velocity the lower the toughness. It has also been shown by Kalthoff (1976) that Araldite wedge loaded specimens behaved in the same way.

From the results of Table 1, it can be seen that a simple linear elastic analysis of arrest toughness considerably underestimates ductile crack arrest toughness. Both the "static" rate of change of work and strain energy, and the complicance indicated arrest toughness are in reasonable agreement, being of the order five times greater than the elastic value.

The J initiation results also indicate a much lower toughness than the ductile arrest values.

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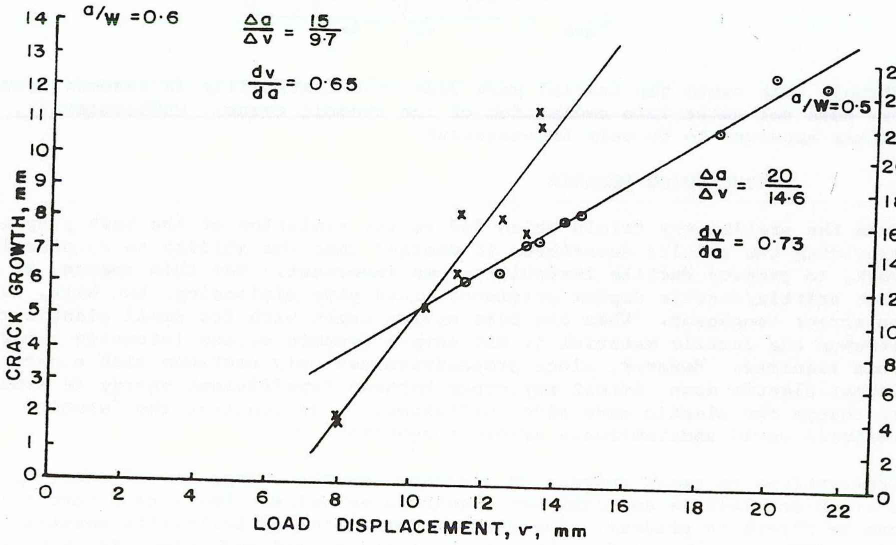

Fig. 4 Load pin displacement against crack growth

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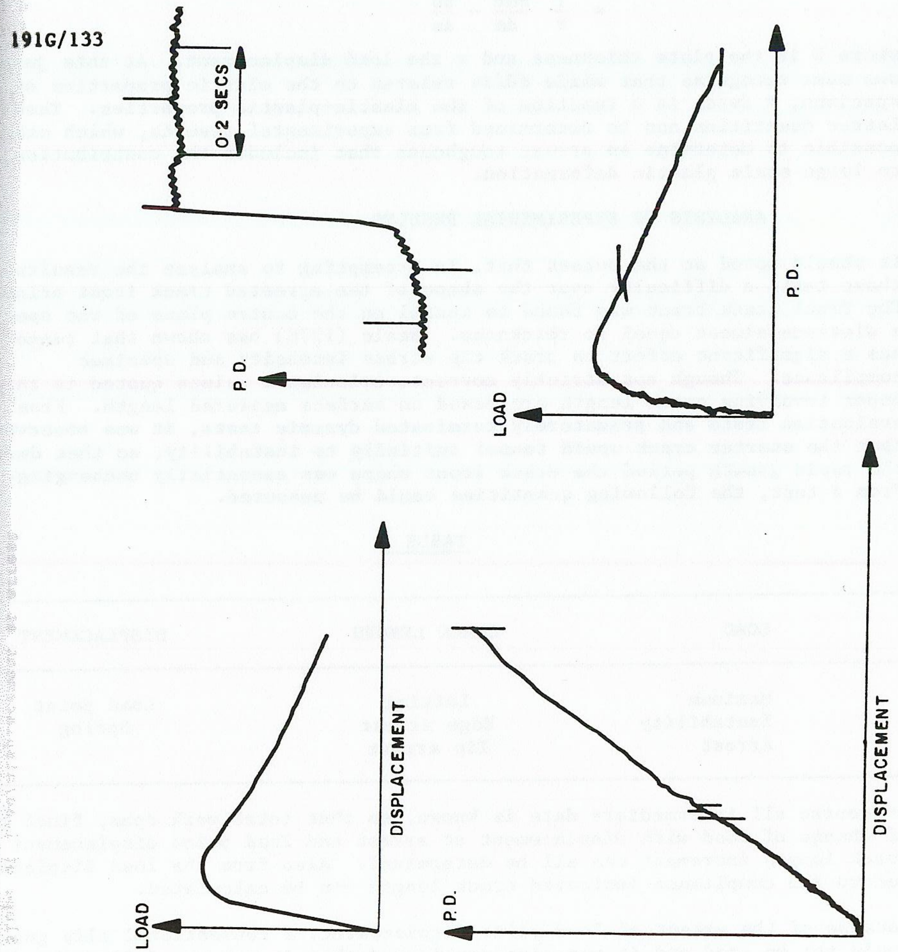

Fig. 2 Sample Test Records

TABLE 1 Test Results

Spec. No.	LOAD KN		CRACK LENGTH mm			CRACK TIP STRESS INTENSITY MN $M^{-3/2}$				F − U $X10^{-3}$	No. of Spring pairs *Note 1	$\frac{dP}{dW}$ *Note 2 KN mm
	max	arrest	initial	edge	tip	K_{In}	K_{ElAr}	K_{CoAr}	K_A	N mm		
16	14.6	8.9	60.0	65.5	73.2	77.3	59.5	313	259	116.7	8	0.98
17	14.7	11.7	60.0	62.0	68.6	77.8	67.5	285	298	92.0	8	0.96
23	14.25	7.0	60.0	71.4	78.4	75.4	63.9	424	227	138.9	10	0.77
24	23.8	3.7	50.0	75.2	82.7	89.1	41.9	402	177	277.4	13 (D)	0.84
25	23.9	10.1	50.0	64.9	72.4	89.5	65.7	400	293	227.6	11 (D)	1.3
26	23.7	9.7	50.0	66.3	73.4	88.7	67.3	407	287	231.6	12 (D)	1.14
27	22.4	9.6	50.0	64.7	73.0	83.8	61.9	386	286	209.2	12 (D)	1.19
28	23.0	6.7	50.0	69.4	77.1	86.1	54.2	407	239	243.8	12 (D)	0.99
30	23.4	5.8	50.0	71.9	78.8	87.6	53.9	425	221	263.1	13 (D)	0.92
33	23.0	9.0	50.0	66.6	74.0	86.1	63.3	413	277	232.2	12 (D)	1.1
34	24.5	11.5	50.0	63.0	70.4	91.7	68.8	395	313	221.8	10 (D)	1.39
35	23.6	11.9	50.0	62.4	69.6	88.4	69.4	370	319	197.7	10 (D)	1.46
36	23.3	3.7	50.0	74.7	82.2	87.3	40.6	410	177	298.5	14 (D)	0.76
37	14.9	8.1	60.0	68.1	75.1	78.8	61.7	352	247	124.7	9	0.98
38	16.0	12.5	58.6	60.5	67.5	80.2	65.1	485	309	89.7	7	1.18
39	15.5	8.4	58.1	66.3	73.3	77.2	58.3	333	252	119.9	5	1.1
41	16.0	8.2	60.0	67.7	75.1	84.7	60.9	372	248	155.7	9	0.86
43	15.5	7.0	60.0	71.0	77.2	82.0	61.7	372	228	155.0	9	-
45	14.9	8.9	60.0	66.6	73.4	78.8	62.9	346	259	130.3	9	0.84

NOTE 1. Belleville washers are stacked to form a pair

D stands for doubled to double stiffness

NOTE 2. Slope of load/displacement at arrest