THE RELATIONSHIP BETWEEN ACOUSTIC EMISSION AND FRACTURE MECHANISMS ILLUSTRATED BY A STUDY OF CLEAVAGE IN MILD STEEL

C. B. SCRUBBY, H. N. G. WADILFY AND J. E. SINCLAIR
Atomic Energy Research Establishment, Harwell, Didcot, Oxon

The MS of this paper was received at the Institution on 30 November 1978 and accepted for publication on 18 January 1979

SYNOPSIS A theoretical and experimental approach to the relationship between acoustic emission and fracture mechanisms is presented. Acoustic emission waveforms are recorded during the cleavage fracture of mild steel, using a calibrated, broad-band detection system. Source strengths are deduced as time-varying crack volumes using a Green's function derived for an elastic half-space. A typical source is modelled as a cleavage crack of diameter ~50 µm and opening ~0.4 µm, which propagated at ~20% shear wave velocity. The model is in broad agreement with fractographic analysis of the specimens.

INTRODUCTION

1. The fracture of metals is accompanied by localised strain relaxations which may cause energy to be released as transient elastic waves (acoustic emissions) that propagate away from the fracture source to the test-piece surface. By using suitable detection methods, it should therefore be possible not only to detect and locate fracture events, but also to assess their severity by analysis of the recorded signals. Thus the acoustic emission technique has great potential as a practical nondestructive testing tool for engineering structures. It has in addition often been suggested that by suitable analysis of the acoustic emission waveforms new insights might be gained into the dynamics of microdeformation and fracture.

2. There has been little shortage of applications for acoustic emission: it has been applied to the monitoring of a wide range of structures from aircraft components to nuclear pressure vessels. Nevertheless, the technique continues to have two major problems associated with it. Firstly, it suffers from poor reliability: some minor flaws emit, while others do not. Secondly, it has proved difficult to characterise growing defects on the basis of recorded emission measurements alone.

3. The first problem is crucial: acoustic emission can only be used with confidence if it is known that the critical defects in a given structure are going to emit. It is thus important to determine which deformation and fracture processes act as sources of emission, and how they are influenced by microstructural variation. Extensive laboratory experiments have shown that a wide range of defects may generate detectable emission (Ref.1). In most commercial materials several different types of source may be present, but if specimens are prepared with care it is often possible to isolate a single emission source process. For example, in pure Al, 4 wt% Cu in solution treated, and aged for varying times at about 170°C to produce a range of microstructures (Refs.2,3), it can be shown that the detected emission is associated with shear of weak Guinier-Preston zones. The absence of these weak obstacles to dislocation motion in the solid solution, or the presence of very strong obstacles in the peak hardened condition results in almost no emission. These tests demonstrate that a rapid release of strain energy is required to give detectable acoustic emission. Other systematic tests with aluminium alloys have shown that composition, purity and microstructural variables such as grain size can have a very strong influence on the character of the acoustic emission (Ref.4).

4. In ferritic steels few systematic studies have been reported. However, it is clear that the decohesion and fracture of inclusions is an important source of emission in commercial steels (Refs.5,6,7). The cracking/decohesion of carbides (Refs.8,9) and the escape of dislocations from interstitials, either at yield (Ref.10) or during dynamic strain aging (Ref.8), are further possible sources of emission during deformation. During fracture a similar complex situation exists. Brittle crack growth processes such as cleavage (Ref.11), stress corrosion cracking (Ref.12), hydrogen (Ref.13) and temper embrittlement (Ref.14) all generate detectable emission, though the level of activity is dependent upon metallurgical and testing conditions. However, the normal mode of crack growth in medium and low strength structural steels by slow weld coalescence tends to be quiet. When the same steels are tested in a high strength condition there is evidence that the alternating shear mechanism of fracture does generate emission (Refs.15,16).

5. During service, emission may be detected from a range of defects, only some of which are critical, and it is important therefore to be able to characterise the emission and assess the severity of the defect source, especially if it is located on a part of the structure which is inaccessible to other NDE techniques. Workers have attempted to relate amplitude distributions (Ref.17) and frequency spectra (Refs.18,19,20) to source processes, but usually with only very
limited success. The reasons for this are firstly that the ultrasonic pulse carrying the information about the defect must pass through the test-piece to the surface. As it does so there are reflections, mode conversions and attenuation which degrade the pulse so that no simple relationship exists between the surface motion and the source event. Secondly the detection system, and the transducer in particular, may distort the data further by non-linearities and reductions in bandwidth. Finally, such A.E. data is expressed in units, such as "counts", which are not defined in absolute terms, so that results often cannot be more than qualitative. This unfortunately makes it difficult to compare data from different laboratories.

6. To overcome these difficulties, Wadley and Scruby (Ref.14) used a broadband detection system and showed that differences in recorded waveform could be correlated with changes in crack growth mechanism. The objective of the current Harwell study is to examine in more detail the relationship between acoustic emission waveform and fracture process. In the following section the theoretical basis for the study is outlined, while in the third section the broadband system for waveform measurements is described. For this series of tests one fracture process, cleavage, in mild steel was chosen, and in the fourth section are presented the acoustic emission results when the position of the source was varied within the gauge section of the specimen. Finally in the fifth section the data is discussed and used to produce a model of the emission source process, and this is compared with the results of fractography.

THEORETICAL CONSIDERATIONS

7. Theoretical studies have not been applied to acoustic emission in a consistent manner until very recently, although the analogous problem of characterising seismological sources (e.g. earthquakes) has received extensive study (Refs.21, 22).

8. The aim of the theoretical studies is to deduce quantitative information about deformation and crack growth processes by analysis of acoustic emission waveforms. This can be tackled in three equally important stages:

(i) A mathematical description is required of the various deformation or fracture processes of interest. The description can be, for instance, in terms of the time varying distribution of forces which would have to be applied to a perfect body to produce the same elastic disturbance as the process of interest. An alternative, which is more easily related to fracture events, is to model a source in terms of imaginary dislocation distributions. The two schemes are formally related in a simple way through the elastic constants (Ref.23).

(ii) A transfer function is required to relate given source functions to the surface displacements which will be observed. In space-time problems, such a transfer function is usually called a "Green's function", and expresses the elastic displacement at a given time and position due to a unit impulse of force applied at zero time at a given point. The response to sources extended in space and time can then be obtained by convolution process. Analytical expressions for elastic Green's functions are however known only for the very simplest of bodies.

(iii) To work back from observed displacements to a source description poses both a mathematical problem (the inversion of stage (ii), i.e. deconvolution) and an experimental one (the accurate measurement or sufficient displacement wave-forms). Clearly, to determine n independent source parameters as a function of time, we need at least n separate records from the same event.

The Source

9. Even the simplest of metal fracture processes comprises a complex combination of crack extension and plastic flow, and we have not yet attempted theoretically to model such events. Rather, restricting attention to the growth (or creation) of planar microcracks, it can be deduced that all such processes will appear from a distance to be equivalent to the appearance of a small dislocation loop. For instance, a crack loaded normally (in mode I) will be equivalent to an edge loop whose strength bA (Burgers vector x loop area) is equal to the crack volume. The dislocation loop may in turn be equivalently represented in terms of three orthogonal force dipoles (Ref.22). This type of microcrack model is in general characterised by two constant orientation parameters and three time dependent amplitudes (the crack opening volume and equivalent quantities for two shear modes). For a crack in a half-space, normal displacement measurements at the epicentre can only detect the mode-I opening, and only one orientation, the inclination of the crack to the horizontal, can be distinguished. Thus, a two-parameter (one constant, one time varying) model is appropriate.

The Green's Function

10. Several authors (Refs.24,25,26) have given solutions for elastic point force problems in a half-space, and corresponding solutions for an infinite plate have recently been computed (Refs. 27,28). More complicated geometries appear as yet to be intractable. For the half-space, the solutions at the epicentre assume closed analytic form, and the spatial derivative of the solution of Willis (Ref.25) were calculated to give surface displacements from force dipoles, quadrupoles, etc. The dipole solutions were combined to give solutions for the dislocation loop models discussed above. Figure 1 shows the result for a horizontal loop (crack) of volume V = bA H(t) ("switching on" at t = 0) buried at a depth d. At early times, the delta function part of the longitudinal arrival dominates; its strength is

\[ S = \frac{c_2^2}{2} \frac{bA}{c_0} \]  

where \( c_1 \) and \( c_2 \) are the longitudinal and shear wave speeds, respectively.

Deconvolution

11. For a given crack orientation, the above procedure yields a solution \( I(t) \) for the surface displacement when the source strength (volume) is a unit step function \( H(t) \). If a function \( Q(t) \) can now be found which, when convoluted with \( I(t) \),
gives the source function \( H(t) \), then the same "operator" \( Q(t) \) will also transform any measured surface displacement waveform \( U(t) \) into the corresponding source volume \( \delta V(t) \). The equation for \( Q(t) \) is

\[
Q(t) \ast U(t) = H(t)
\]  

(2)

12. In the discrete time sampled representation used for the experimental data, this becomes

\[
\sum_{m=0}^{n} Q_m U_{n-m} = 1 \quad \text{for} \quad n = 0, 1, 2, \ldots
\]  

(3)

where \( Q_m \) is the mth sampled value of \( Q(t) \), and similarly for \( U \). This series of equations can readily be solved for each \( Q_m \) in turn, starting from \( Q_0 = 1/U_0 \).

13. Finally, from any given sampled displacement record, \( U_t \), the convolution

\[
\delta V(t) = \sum_{m=0}^{n} Q_m U_{n-m}
\]  

(4)

gives the source volume history \( \delta V_n \).

EXPERIMENTAL PROCEDURE

14. It was found to be necessary to develop both a special specimen geometry and a broadband detection system in order to relate acoustic emission waveforms to known fracture events. Careful specimen preparation to provide a well characterised acoustic emission source was considered to be equally important.

Specimen Geometry

15. The ideal specimen shape for applying the theory of Section 2 would be a half-space, while testing considerations require the choice of a geometry such as a dumb-bell. The specimen chosen for these tests, the Yobell (Ref.29) (Fig.2) is a compromise between these requirements. First, in order to reduce signal loss by ultrasonic attenuation and geometrical spreading, the source to transducer distance was kept to a minimum (18 mm). Secondly, in these tests the waveforms were to be measured at one point, the epicentre, and deformation and fracture were restricted to a 2 mm long, 3 mm diameter, gauge section vertically below the transducer. Thus the specimen transfer function remained approximately constant for all recorded waveforms. Finally, the diameter of the section between source and transducer was made large enough (60 mm) to prevent interference from reflected wave fronts to the first 8 \( \mu s \) of recorded signal.

16. It was realised that the presence of a gauge section could lead to some distortion of the waveform which would vary with source depth. In order to examine this effect, three specimens were therefore tested, with 0.5 mm deep, 600 notches at the top (A), middle (B) and bottom (C) of the gauge section (see Fig.2).

Measurement of Surface Motion

17. In order to calculate the time history of an acoustic emission source, we must accurately measure the motion of the specimen surface over the full frequency spectrum of the source. Typical surface displacements may be \( 10^{-7} \)m and source spectra can extend beyond 10 MHz (Ref.29). The piezoelectric transducers used for conventional ultrasonics fulfill the sensitivity criterion, but do not have adequate bandwidth, nor are they straightforward to calibrate (Ref.30). A parallel plate capacitor can be made to satisfy both requirements for use as a detector of acoustic emission (Ref.31).

18. The surface of the specimen forms one plate, and the second circular plate of area \( A \) is held a distance \( x \) above the surface and at a potential \( V \) so that the displacement \( dx \) due to the arrival of an elastic wave causes a small change, \( dq \), in the charge stored in the capacitor. The sensitivity is

\[
\frac{dq}{dx} = \frac{-\varepsilon AV}{x^2}
\]  

(3)

where \( \varepsilon \) is the dielectric constant of the gap between the plates.

19. The spherical wavefronts from the source do not reach all parts of the transducer simultaneously. The consequent time delays lead to loss of phase coherence and limit the effective bandwidth. The bandwidth of the transducer can be shown to be inversely proportional to \( A \) (Ref.31). The capacitance transducer used for the current tests had \( A = 28.3 \text{ mm}^2 \) and \( \varepsilon = 2.7 \). With \( V = 50 \text{ V} \) and \( \varepsilon_{\text{air}} = 8.85 \times 10^{-12} \text{ F m}^{-1} \), the sensitivity was 1.72 x 10^{-3} C m^{-1} surface displacement. The transient response of the transducer has also been measured using a laser interferometer (Ref.30).

20. The transducer was coupled to a wide-band low-noise charge amplifier (Ref.29), and the signal from this was conditioned by a 35 kHz - 45 MHz band-pass filter, further amplified, and recorded with a Biomation 8100 transient recorder (Fig.2). The recorder digitised the acoustic emission waveform at 10 ns intervals with 8-bit precision. The digitised waveform was stored, for later analysis, on a magnetic disc in a PDP8/E computer. For the current experiment, the detection system had a rise time of 20 ns and a sensitivity of 8.5 x 10^{-3} V pm^{-1}. Steps were taken to ensure that the sensitivity remained constant for all three tests. The electrical signal from the amplifier was also monitored with a R.F. power meter to give a qualitative guide to the rate of emission energy release as a function of applied load.

Materiels Preparation

21. Cleavage fracture of ferrite generates acoustic emission and is metallurgically one of the best defined fracture processes. It is known generally to involve the fast fracture of single grains (Ref.32). Cleavage is usually only observed at low temperatures, which makes it inconvenient for acoustic emission experiments. However it can sometimes be induced at room temp-
erature using notched specimens and a rapid quench rate.

22. Thus for the experiments reported here, three notched Yobell specimens were machined from a bar of commercial mild steel, composition as shown in Table 1. After annealing at 850°C for 30 minutes, they were quenched in water to produce a martensite structure with a prior austenite grain size of 21 μm. The specimens were tested to failure in an Instron 1195 screw-driven tensile testing machine at a crosshead displacement rate of 0.1 mm min⁻¹. The load and R.F. power meter output were plotted on a chart recorder as a function of time. The fracture appearance of each specimen was examined by scanning electron microscopy.

EXPERIMENTAL RESULTS

Load and A.C. Power Data

23. The load and acoustic emission power are shown as a function of time for all three tests in Fig.3. At low load, a non-linear load-time relation was observed due to the high compliancy of the gripping system (which contained electrical insulation). Beyond this region a linear relation was observed, indicative of only limited plastic deformation. The first detected emissions occurred at a load of 40.5 kN for each test, and their rate of generation increased as final fracture was approached. Specimen B, with the notch at the centre of the gauge length, generated more emissions (236) than either specimen A (108) or C (91). The origin of the difference may have been the lower stress concentration in specimen B, the consequent need for a larger critical crack length to initiate catastrophie fracture, and hence a greater quantity of subcritical crack growth.

Fracture Appearance

24. All three specimens underwent a mixed fracture mode. The fracture faces were covered with isolated cleavage facets connected by shallow, large diameter dimples, Fig.4. The area of a typical cleavage facet was ~1000 μm² and was generally consistent with cleavage cracks extending over one or two grains.

Measured Waveforms

25. Typical acoustic emission waveforms from each test are shown in Fig.5a; it can be seen that A resembles the theoretical waveform for a dislocation loop source (Fig.1) when account is taken of the removal of the low frequency component by signal conditioning. It can also be seen that the δ-function of the calculated L arrival is replaced by a pulse of finite duration and height, as a consequence of the finite spatial extent and lifetime of a real source.

26. Comparison of typical waveforms from specimens B and C with specimen A shows that a second pulse followed the first when the source was located deep within the gauge. This “echo” pulse was consistently present during tests B and C and never during A, and must be associated with the acoustic response of the gauge section. The time difference between the two pulses was almost always larger for C, suggesting that the origin of the echo was a reflection from the top of the gauge section where there is a sudden change in cross-sectional area.

INTERPRETATION

27. The time dependence of emission activity (Fig.3) and fractographic results (Fig.4) strongly suggest that the source of acoustic emission was the formation of subcritical cleavage cracks, with a range of areas typically ~1000 μm².

28. We now apply the analysis of Section 2 to determine the acoustic emission source from each measured waveform by deconvolution (2,3). The Green's function was assumed to be that for a half space (1.2), taking the distance from epicentre to notch root as source depth, d. The source was modelled as an infinitesimal dislocation loop, oriented parallel to the surface (2.1).

29. Deconvolution resulted in a source volume history for each wave-form (Fig.5b). The fall in calculated volume to zero and negative values at long times is a result of high-pass filtering at 35 kHz. The small error introduced for short duration events has been neglected.

30. From each deconvolved waveform, the maximum volume attained (V₁) was measured as shown in Fig.6. Physically this should represent the maximum volume reached by a freshly nucleated microcrack. In order to facilitate comparison between the three tests, histograms of volume, V₁, were plotted (Fig.7a). The extent of the distribution was restricted by the limited dynamic range of the 8-bit precision transient recorder. A percentage of waveforms overloaded the recorder in each test and could not be used to calculate source volumes.

31. A peaked distribution, weighted towards smaller values of V₁, is observed for all three specimens. However, the histograms for B and C also exhibit an increasing proportion of large volume sources, so that the mean value of V₁ apparently increases with depth (Table 2). This effect is due to the second, echo peak discussed above, which gives a volume contribution that adds on to that of the longitudinal peak. This serves to emphasise the great care that must be taken in interpreting acoustic emission sources when no account is taken of nearby specimen boundaries.

32. In order to reduce the effect of echo pulses a different volume parameter, V₂, was chosen (Fig.6). The volume value was measured at the time of the first peak in the transient and then assuming that the peak was symmetrical this value was doubled to give V₂. This assumption leads to inaccuracy in V₂ as a measure of the final volume of a freshly nucleated microcrack. In particular it can be seen from Fig.6 that the longitudinal peak is often asymmetrical so that the source apparently takes considerably longer than time τ to reach maximum volume. The long trailing edge of the longitudinal peak may possibly be a feature of the crack growth process itself, which would suggest that there are significant slow relaxations around the crack tip; however, interference from the circular notch cannot be discounted. When histograms of V₂ are compared (Fig.7b) it is seen that the three specimens now give the same source volume distribution within statistical limits. Thus,
neglecting any effect due to the proximity of the circular notch, \( V_2 \) can be considered as a system independent source parameter.

33. A further parameter, the source lifetime \( T \) can also be measured for each emission. The effect of gauge echoes again needed to be reduced and \( T \) was calculated as twice the time for the first pulse to rise from zero to its maximum value (Fig.6). The assumptions implicit here are the same as those for calculating \( V_2 \) above. The lifetime histograms for the three tests (Fig. 8) were statistically indistinguishable suggesting that \( T \) is also a system independent parameter, and can be used together with \( V_2 \) in attempts to model the emission source.

34. The mean values, \( V_2 \) and \( T \), for all the recorded transients were calculated from the values from each test (Table 2) and can be used to model an acoustic emission source during these tests. Thus a typical source event was a microcrack whose volume increased by 600 \( \mu \text{m}^3 \) (\( V_2 \)) in 88 ms (T).

35. If we assume a horizontal, circular, elastic crack of radius a (Fig.9) then we can find the crack faces will open a distance \( 2b \) given by (Ref.33)

\[
\gamma = \frac{2(1-\nu^2)}{E} \sigma a
\]

where \( \nu \) is Poisson's ratio, and \( E \) is Young's modulus.

36. The tensile stress in the vicinity of a small microcrack within a notched specimen is difficult to estimate. Clearly, it will vary during the test as the applied load is raised and the uncracked ligament decreases. For the purposes of this interpretation we shall assume \( \sigma = 10^8 \text{ N/m}^2 \) (an estimated net-section stress). Using \( \nu = 1/3 \) and \( E = 2.1 \times 10^{11} \text{ N/m}^2 \), equation (6) yields \( b = 8.5 \times 10^{-3} \mu \text{m} \). Substituting for \( b \) in the formula for the volume of an oblate ellipsoid:

\[
V = \frac{2}{3} \pi a^2 b
\]

yields,

\[
V = 3.5 \times 10^{-2} a^3
\]

Thus \( a = 26 \mu \text{m} \) for the typical source volume of 600 \( \mu \text{m}^3 \), and \( b = 8.5 \times 10^{-3} a = 0.22 \mu \text{m} \).

It is noted that for given \( V \), \( a \) is proportional to \( \sigma^{-1/2} \), so that errors in the estimation of \( \sigma \) do not lead to large errors in crack radius. Crack opening however is more sensitive to errors in \( \sigma \). Allowance for plasticity would increase \( b \) and decrease \( a \).

37. The typical crack area was estimated from fractography as 1000 \( \mu \text{m}^2 \) (Section 4.2). If this were a circular crack it would have a radius of 18 \( \mu \text{m} \). The calculated value of \( a = 26 \mu \text{m} \) is in remarkably good agreement with this, bearing in mind the assumptions made in the calculation and the scatter in actual cleavage facet areas.

38. It is, finally, possible to estimate crack speed. It is assumed for this purpose that a typical cleavage crack is initiated at one grain boundary and is arrested when it reaches another, so that its mean speed is \( 2a/T = 590 \text{ m/s} \). This value, which ignores acceleration and deceleration, is 18% of the shear wave velocity. However, this estimate must be treated with the same caution as the crack radius, because of the many assumptions which have been made. Brittle fracture velocities for steel of 1300-2000 \text{ m/s} \) have been reported (Ref.34). The velocity estimated above is somewhat less, but no allowance has been made for plasticity which would have the effect of lowering crack velocity.

SUMMARY

39. This series of tests and the accompanying theoretical studies have shown that careful acoustic emission waveform measurement and careful interpretation can give valuable new insights into the nature of fast fracture events. In particular, it has been possible to deduce the strengths of the emission sources as time-varying crack volumes. From calculated average values of crack volume and lifetime a typical source has been modelled as a cleavage crack of diameter \( \approx 60 \mu \text{m} \), opening \( \approx 0.4 \mu \text{m} \) and velocity \( \approx 20\% \) shear wave velocity.

40. There remains, however, a need for further work to establish in more detail the relationship between acoustic emission and fracture mechanisms. Much needs to be done to improve experimental accuracy, in addition to increasing the number of measured fracture source parameters. It is furthermore necessary to extend these studies to more general types of testing configuration, such as crack opening geometries. If these prove successful it may then be possible to determine the physical basis for flaw characterisation by waveform analysis on engineering structures.

ACKNOWLEDGEMENTS

We wish to thank Mr. G. Shrimpton for his practical assistance, and Drs. B.L. Byrne and G.J. Curtis for many helpful discussions during this study. Finally we wish to acknowledge funding during the development of the broadband technique by the Procurement Executive (M.o.D.), through Admiralty Marine Technology Establishment.
REFERENCES

8. Holt, J., Palmer, I.C. and Goddard, D.J. Berichte 20th Symp. der Deutschen Gesell-
   schaft fur Metallkunde, Munich, 1974, 24.
28. Simmons, J. and Willis, J. Unpublished work.

TABLE 1
COMPOSITION OF MILD STEEL

<table>
<thead>
<tr>
<th>ELEMENT</th>
<th>C</th>
<th>N</th>
<th>O</th>
<th>P</th>
<th>S</th>
<th>Mn</th>
<th>Ni</th>
<th>Cr</th>
</tr>
</thead>
<tbody>
<tr>
<td>CONCENTRATION</td>
<td>0.26</td>
<td>0.007</td>
<td>0.003</td>
<td>0.019</td>
<td>0.025</td>
<td>0.7</td>
<td>0.02</td>
<td>0.01</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>No.</th>
<th>Fe</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>Nb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mo</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
<td>0.001</td>
<td>0.02</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
<td>Sn</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Specimen</th>
<th>depth</th>
<th>transients recorded</th>
<th>transients overloaded</th>
<th>mean V /m²</th>
<th>mean V /m³</th>
<th>mean t /sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>17.1</td>
<td>103</td>
<td>22</td>
<td>1120</td>
<td>600</td>
<td>92</td>
</tr>
<tr>
<td>B</td>
<td>17.7</td>
<td>236</td>
<td>52</td>
<td>1280</td>
<td>590</td>
<td>86</td>
</tr>
<tr>
<td>C</td>
<td>18.4</td>
<td>91</td>
<td>24</td>
<td>1590</td>
<td>635</td>
<td>88</td>
</tr>
</tbody>
</table>

© I Mech E 1979
Fig. 1  The dislocation loop model for the source event, and the vertical surface displacement at the epicentre, using the Green's function calculated as described in section 2.2

Fig. 2  The YOBELL specimen design, and the broad band detection system employed for the tests. The inset shows the position of the 60° notch for the three specimens tested.

Fig. 3  Showing the load as a function of time for the three notched specimens tested. No units are given for the acoustic emission because the power measurement was uncalibrated. (It is only a qualitative guide to activity.)
Fig. 4 Scanning electron micrographs of the fracture face of specimen C
a Shows both cleavage and ductile dimple fracture
b Shows an enlargement of one cleavage facet

Fig. 5a Measured surface displacement for a typical emission from each specimen. Note the echo pulse in B and C which is absent in A.

Fig. 5b Source volume calculated assuming a horizontal dislocation loop model at depth d. The volume drops from a maximum and becomes negative because of low frequency filtering.

Fig. 6 Showing how the maximum (V₁), and first peak (V₂) volumes and lifetime (τ), used in the histograms of Figs. 7 and 8, are measured from a typical transient.
Fig. 7 Histograms of source volume for specimens A, B, and C

a The mean maximum volume ($V_1$) increases with source depth due to the contribution of the echo pulses
b The volume of the first peak ($V_2$) ignores the echo pulse and the histogram is independent of source depth
Fig. 8  Histograms of source lifetime $r$ for specimens A, B, and C, where $r$ is twice the leading edge risetime (Fig. 6). The mean lifetime is independent of source depth.

Fig. 9  Ellipsoidal model for elastic crack used to estimate crack opening $B$