A new technique for the measurement of acoustic emission transients and their relationship to crack propagation

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Abstract. This paper describes a new broad-band approach to the detection of acoustic emission in which a capacitance transducer has been used to record the transient elastic waves generated by crack growth processes as surface displacements. A unique specimen geometry, the 'Yobell' has been developed to reduce interference from internal reflections of the ultrasonic pulse, so that the measured surface displacements can be compared with those calculated for a source buried below the surface of the half-space. A static source model has been used to relate the rise-time and amplitude of transients to the time-scales and magnitudes of incremental crack growth.

1. Introduction

Many experiments have been reported in recent years in which acoustic emission has been observed during the deformation and fracture of a wide class of materials including composites, ceramics and metals (for a review see Ying 1973). Because acoustic emission is generated during crack growth, it has been used as a technique both for monitoring the structural integrity of large engineering structures and for studying the dynamic aspects of crack growth in laboratory experiments.

A major advance in the assessment of structural integrity and the study of crack growth processes would be to relate the information in an individual acoustic emission signal to the crack process by which it was generated. The first step is to detect and record acoustic emission signals which are not so heavily modified by their passage through a measurement system that the source information is obscured. The second step is to develop and test the theory relating the important features of the acoustic emission signals to the details of the source processes. For reasons which we discuss later, this proves to be very difficult with a conventional acoustic emission system. This paper describes an absolute approach to the measurement of acoustic emission transients which, when combined with a carefully selected specimen geometry, enables the structure of the transients to be related to the time-scale and magnitude of the fracture events using a simple theoretical model. As an example of the application of the technique we show results from the fracture of a low-alloy steel.

The measurement technique developed for this study enables the recorded transients to be calibrated, so that they give system independent measurements of the acoustic emission signals with fundamental significance.
2. Fundamental aspects

2.1. The source

Acoustic emission is generated by rapid changes in local stress and strain fields within a material. Stored elastic strain energy is released, and some of this may propagate away from the source as elastic waves. Only a fraction of the available energy is converted into acoustic radiation, since some is also converted into heat, surface and plastic strain energy. The partition of energy among these processes depends on both the nature of the source mechanism and the properties of the surrounding material.

It is extremely difficult to model an acoustic emission source such as a propagating crack accurately since there are many factors involved, such as the extent, speed and orientation of the crack. The simplest model for an emission source due to a fracture event is a transient force pulse acting at a point inside the body. Pekeris and Lifson (1957) consider a point force which varies with time as a Heaviside step-function $H(t)$, i.e. it is ‘switched on’ at $t=0$, and acts in a direction perpendicular to the surface. The point source model is very limited. Firstly, it is clear that a single unbalanced force is unlikely to represent a typical fracture event; a force dipole or some combination of higher-order derivatives and configurations of forces would be a better representation. Secondly, a fracture event extends over a given volume which varies with time. A rapidly propagating crack front is for instance unlikely to be accurately represented by a static point source. A third consideration is phase coherence across the source. Loss of coherence is a minimum when the source is oriented parallel to the surface and a maximum when perpendicular, assuming the source is vertically below the detector (Simmons and Clough 1976). The effect is less serious for a source whose dimensions are much less than the wavelength of the radiating elastic waves.

The general case for an expanding crack has yet to be solved, although Burridge and Willis (1969) and Willis (1973) have published solutions for the motion of the surface due to expanding self-similar cracks. Roy (1975) has considered a moving point source and shown that for low source velocities (i.e. much less than wave velocities in the material) the errors resulting from assuming a stationary source are not serious. The life-time of a fracture event can be taken into account to a first approximation by replacing $H(t)$ in the point source model with a step whose rise-time is equal to the life-time of the event.

For the purposes of interpreting the results reported below, discussion will be limited to a point source model, and at this stage interpretation of the data will be restricted to the measurement of two parameters, source life-time and source magnitude.

2.2. Propagation of stress waves to the specimen surface

Pekeris (1955) and Pekeris and Lifson (1957) have calculated the displacement of the surface of a semi-infinite solid, produced by a point force proportional to $H(t)$ buried within the bulk of the material. Recent calculations using realistic values for the longitudinal ($v_L$) and shear ($v_S$) wave velocities in steel of 5960 and 3240 m s$^{-1}$ respectively show that the first arrival at the epicentre (figure 1(a)) is a vertical displacement step with amplitude $\delta \xi$ at time $h/v_L$ given by

$$\delta \xi = 0.047 \frac{\delta F}{\mu h} H(t-h/v_L)$$  \hspace{1cm} (1)

where $\delta F$ is the magnitude of the force step function, $h$ is the source depth below the epicentre, $\mu$ is the shear modulus of steel.
Figure 1(a) shows that the surface continues to rise, until the arrival of the shear component at time $h/v_s$ when there is a discontinuity in the derivative of the displacement. Pekeris and Lifson (1957) show that the displacement function rapidly becomes more complex if measurements are made away from the epicentre. At large distances from the epicentre, the displacement is dominated by surface wave modes. Interpretation of surface displacements is thus simplest if the detector is at the epicentre.

The corresponding surface displacement for a dipole source function is obtained by differentiation and is shown in figure 1(b).

Figure 1. The vertical surface displacement at the epicentre E due to a point source at a depth $h$. The source is an unbalanced force in (a) and a force dipole in (b). In each case the surface displacements are given for sources with (i) zero and (ii) non-zero ($\delta r$) rise-time. The longitudinal leading edge amplitude is $\delta c$.

In practical acoustic emission tests a bounded specimen is used; consequently the initial wavefronts reaching a detector on the surface undergo multiple reflections, interferences and mode conversions. The analysis outlined above for a semi-infinite body can no longer be applied. The displacement waveform becomes the response of the vibration modes of the specimen to transient pulse stimulation. Retrieval of information specific to the source rather than the specimen response becomes extremely difficult. In the past this problem has been considered in terms of convolution, which is valid if the two conditions of time invariance and linearity are satisfied. Thus the displacement at a point on the surface can be written as

$$ Y(t, r) = S(t, r) \ast X(t) $$  \hspace{1cm} (2)

where $X(t)$ is the source function, and $S(t, r)$ is the impulse response function for the specimen, and varies with both time and source position $r$. $Y$, $S$ and $X$ are usually considered as scalars but are strictly tensors of at least second rank.

The equation is solved for the source function $S(t, r)$ by deconvolution, which is most readily carried out in the frequency domain by taking the Fourier transform of equation (2):

$$ y(v, r) = s(v, r) \cdot x(v) $$  \hspace{1cm} (3)

where $y(v)$, $s(v)$, $x(v)$ are respectively the Fourier transforms of $Y(t)$, $S(t)$, $X(t)$. Thus $x(v)$ can be obtained by dividing $y(v)$ by the transfer function of the specimen, $s(v)$. 
There are several sources of error during numerical deconvolution, some of which arise because the specimen is a resonant body, so that its transfer function is dominated by the normal modes of vibration. As long as the source–specimen–transducer configuration does not vary between acoustic emission events, it might be possible to retrieve source information by taking into account mode conversions and phase changes at the boundary. But, because the source position can vary during a test, the distribution of the source energy amongst the modes will also vary from event to event. As a further complication, the frequency of the resonance modes of the specimen may change as a crack propagates through a specimen (Lloyd 1976).

The waveform suffers a degree of attenuation and scattering in its propagation to the detector. This is a material dependent quantity, and typical values for structural materials are given by Papadakis (1965). Attenuation increases with the distance travelled through the material, and also increases rapidly with increasing frequency. To minimise the effects of material attenuation it is essential to keep the source-transducer distance small and to be sure that metallurgical variables such as grain size are not causing changes in the frequency dependence of the attenuation.

2.3. Measurements of surface displacement

The process by which the vibration of a surface is converted into an electrical signal may also distort the source information, so that the output signal is a function of the transducer response as well as of the specimen response (equation (2)). An ideal detector measures displacement (or velocity) at a point on the surface, and has a well-defined linear response function for longitudinal and shear waves, so that truly quantitative measurements can be made. It should have a flat frequency response over the band-width of any acoustic emission source, which for a source with dimensions $\sim 10 \, \mu\text{m}$ and velocity approaching the shear velocity in the material, extends well above 100 MHz. The detector also needs to have sufficient sensitivity to detect the longitudinal components of the emission pulses. In order to determine the directionality and spatial disposition of the source it is necessary to measure the displacement at a number of points. However, most acoustic emission tests in the laboratory employ only a single transducer so that this information is not available.

Although piezoelectric transducers have good sensitivity, they fail to meet the band-width requirements. Typical piezoelectric transducer band-widths vary from 50 kHz to 1 MHz depending on damping. The signal from such a device is therefore convolved with a further transfer function due to the transducer. This proves just as serious a limitation on quantitative measurements as the effects of specimen resonances, because the sensitivity of a transducer with a resonance frequency below about 1 MHz, falls rapidly at the higher frequencies required to cover the band-width of most acoustic emission sources. This high-frequency attenuation is so severe that the original frequency content of the source cannot be recovered by deconvolution.

A number of workers have, nevertheless, attempted to measure source frequency distributions using deconvolution (Fleischmann et al 1975, McBride and Hutchinson 1976, Houghton et al 1976). Their results are difficult to interpret, and they have failed to take into account the frequency-dependent noise introduced by the deconvolution of a digitised signal.

A further parameter of interest is the acoustic energy released by the source. This, however, cannot be measured adequately if the band-width of the detection system is appreciably less than the source band-width. The acoustic energy is related to the square
of the surface velocity (i.e. the time derivative of displacement) and therefore tends to be dominated by higher frequencies. In the detection system to be described below and those used for most other reported work the terms acoustic emission 'power' or 'energy release rate' refer to the electrical power output of the detection system, measured over a limited band-width, which is a parameter-dependent on the response of the system.

3. The detection system

3.1. Testing geometry

In order to apply the theory outline in §2.2 a semi-infinite specimen, i.e. with only one free surface, is required. Practical considerations make this impossible but a specimen, called a 'Yobell', has been designed and tested, whose dimensions are chosen to approximate as closely as possible to the ideal case at least for the early part of the signal. The geometry shown in figure 2 permits about 6 μs (in steel) of the direct wavefront to be measured at the epicentre before interference from waves reflected from the sides of the specimen. The emission source is confined to a small gauge volume, so that it remains vertically below the transducer at the epicentre. There is still some interference from gauge length reflections, but these only slightly distort the leading edge. After the first 6 μs of signal, the surface displacement becomes dominated by the normal modes of vibration of the 'Yobell'.

![Figure 2. Cutaway drawing of capacitance transducer and grips used for testing 'Yobell' specimens of EN30A steel under tensile load.](image)
3.2. Choice of detector

The unsuitability of a piezoelectric transducer for detecting acoustic emission signals over a wide band-width has already been discussed (§2.3). Thus an air gap capacitance transducer (figure 2) has been developed in which the highly polished surface of the specimen forms one plate of the capacitor, and displacements of the surface cause a charge to be induced on the other plate which is held at a constant voltage. The charge induced, $\delta q$, is given by

$$\delta q = -\frac{eAV}{\xi^2} \delta \xi$$

(4)

where $\epsilon$ is the permittivity of the gap between the plates, $A$ the area of the plates, $V$ the plate voltage, $\xi$ the plate separation and $\delta \xi$ the surface displacement. The sensitivity of the transducer at constant voltage is thus inversely proportional to the square of the separation. Very small air gaps are therefore essential for a high sensitivity, and those used were typically about 4 $\mu$m. The plate diameter was chosen to be 6 mm, and the plate was held at 50 V. With these dimensions the capacitor had a sensitivity of 0.8 pC nm$^{-1}$, and a lower rise-time limit of $\sim$20 ns for a source at a depth of 20 mm (Scruby and Wadley 1978).

3.3. Recording the data

The transducer was coupled to a wide-band charge amplifier and the output from this taken through a band-pass filter (35 kHz–45 MHz) before further amplification (figure 3). The filter limits were set to remove low-frequency machine noise and to prevent high frequency signal aliasing. Radio-frequency interference was reduced by enclosing the specimen, transducer and charge amplifier in a Faraday cage. The signal was then fed into a Biomation 8100 transient recorder where it was digitised prior to storage in a recirculatory memory. The recorder was linked to a PDP8/E computer, and data were stored on magnetic disc. The accuracy with which transient signals were recorded was limited by the precision (eight-bit) and sampling frequency (100 MHz) of the analogue to

![Figure 3](image_url)
Measurement of acoustic emission transients

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digital converter. The overall sensitivity of the system (for a 4 μm transducer air gap) was 32 V nm⁻¹, while the dynamic range was limited by the eight-bit precision of the recorder to surface displacements of 1–18 pm. The acoustic emission energy release rate was recorded continuously during tests, using a Hewlett Packard 435A Power Meter, and this was plotted together with the load–extension data.

3.4. Evaluation of the system

The system was tested by fracturing glass capillaries against the lower end of a Yobell specimen, which had been cut off at the end of the gauge length remote from the transducer. The transients recorded from these fracture events resembled those reported by Breckenridge et al (1975), whose testing configuration approximated more closely to the ideal half-space. The measured surface displacements were also consistent with values calculated for a step function source, with rise-times in the range 0.2–1 μs.

Capillary fracture events are not fast enough to test the system fully and other methods of determining the transfer function of the complete system including laser calibration, are under active consideration. The rise-time of the recording system (but excluding the transducer) has been measured by applying a rectangular voltage pulse of rise-time 1 ns to the transducer, and found to be 40 ns. This limit was imposed by the band-width of the head amplifier used for these tests. This part of the system was also found to have a flat frequency response over an equivalent band-width. These preliminary tests confirmed the suitability of the system for detecting acoustic emission transients over a wide band-width.

4. Experimental results and interpretation

The system has been used to record acoustic emissions transients from a range of fracture processes in steel and the results of this study will be reported elsewhere (Wadley and Scruby 1978). Here we report the results of one test from EN30A steel, which had been quenched from 1000°C, tempered at 650°C for 1 h, and temper-embrittled at 500°C for 24 h. It was tested under tensile load at a strain rate of 4 × 10⁻⁴ s⁻¹ in an Instron Model 1195 screw-driven machine. The fracture mode was a ductile cup and cone (figure 4) and 36 emissions were recorded by the broad-band detection system during the region of the stress–strain curve immediately before failure (figure 5). Of these only 24 were within the dynamic range of the system, and three of these are shown in figure 6.

When the experimental data are compared with the theoretical surface displacement, corrected for high-pass filtering, there are a number of important differences, some of which give information about the source event. It is convenient to consider these differences under two headings: the longitudinal peak and shear arrival. The structure following each of these will not be discussed further, since it is much more difficult to interpret and is complicated by interference from reflected pulses.

4.1. Longitudinal peak

The δ-function of the theoretical longitudinal arrival has been replaced by a peak of finite height and width. There are three measurements which can be made from the leading edge of the pulse; its amplitude, rise-time (time for the amplitude to rise from 10% to 90% of its maximum) and slope. Only two of these are independent. These
measurements are related to the finite dimensions of the source, and can be interpreted in terms of simple static source models as follows. Provided that the rise-time is longer than the system response time (40 ns) it is a measure of the life-time of the source event, while the amplitude, $\delta \xi$, of the leading edge is proportional to the magnitude of the force pulse (equation (1)). If the source is a propagating crack, and if the local stress level is known, a static point source model can be used to estimate the area of new crack surface. Similarly, the slope of the leading edge is proportional to the speed of propagation of the source event.

When this analysis is applied to the transients recorded from an acoustic emission test, the rise-times and amplitudes vary. It is therefore convenient to present the data in the form of a histogram (figure 7). The lower limit of the distribution of rise-times is set by the system at 40 ns, and transients with rise-times shorter than this appear in the 40–50 ns interval. From this the mean rise-time was found to be 63 ns. The amplitudes distribution is also limited by the system as figure 7 shows. Small surface displacements were below the recorder trigger level which is controlled by the background noise level, and large displacements caused overloading. In this test the air gap was 4.2 $\mu$m, so that overloading occurred when the surface displacement exceeded 18 $\mu$m.

4.2. Shear arrival
The delay before the shear component arrives can be used to measure the depth of the source below the epicentre. For the test described, the delay was consistent with all the

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Figure 5. Load–extension curve for the test during which the transients of figure 6 were recorded. The emission energy release rate was obtained by also monitoring the output from the transducer and amplifiers with a power meter.
Figure 6. Three surface displacement transients measured during the ductile fracture of a low-alloy steel. The longitudinal leading edge (L) has variable amplitude and rise-time. There is also variation in the shear arrival (S), and the parts of the signal following L and S.

Figure 7. Normalised rise-time and amplitude distributions for the displacement transients recorded during the ductile fracture of EN30A steel. There were 24 emissions within the dynamic range of the system. Their amplitudes are interpreted as source strengths using the model referred to in the text.
emissions originating from sources in the gauge length. The height of the shear step relative to the area under the longitudinal peak varied from transient to transient. A possible explanation of this was variation in source orientation. Information about the shear component is somewhat limited at the epicentre, and data from other points on the surface are required before any firm conclusions can be made about source orientation or character.

5. Discussion

This new approach to the detection of acoustic emission has permitted us to measure, with a minimum of distortion, the vertical surface displacements due to acoustic emission events during the fracture of a low-alloy steel. In addition, because of the use of a special specimen geometry, it has also been possible to compare the measured transients with those calculated theoretically. This comparison shows that there are two features of a measured transient which are most easily interpreted in terms of the source process, the longitudinal component rise-time and amplitude.

The technique in its present form has both response time and dynamic range limitations, but even so it has been possible to obtain truncated distributions of surface displacement rise-time and amplitude associated with the ductile fracture of a low-alloy steel. From these distributions the range of transient rise-times was \( \lesssim 40-120 \text{ ns} \) and their amplitudes extended from 1 to 18 pm (0.01 to 0.18 Å). Using equation (1), the range of surface displacement amplitudes can be expressed as a range of source magnitudes if the assumptions of the theory by which this equation was derived are realistic. This leads to a range of source magnitudes between 0.03 and 0.6 N (figure 7(b)).

Let us now consider a model for the source of emission in this study. It emerges from the analysis above that a typical source has a life-time of about 60 ns and a magnitude of 0.2 N for the vertical force relaxation. Such large relaxations are most likely to be due to a crack event. The macroscopic stress at the stage at which emissions were recorded was \( \sim 10^9 \text{ Pa} \). This must be considered as a lower limit for the local stress, since there will be stress concentrations in the vicinity of cracks. Using this estimate of the stress, the transient amplitudes can be interpreted as a distribution of crack areas with a typical value of 200 \( \mu \text{m}^2 \). The duration of these crack advances is then given by the rise-time of the transient displacements. Approximate values of crack velocity follow directly by dividing each crack area increment by its duration or as the time derivative of the leading edge of the longitudinal component. A typical surface velocity of 100 pm \( \mu \text{s}^{-1} \) corresponds to a growth rate of about 3300 \( \mu \text{m}^2 \mu \text{s}^{-1} \), where the model for a typical source event is the propagation of a crack over an area of about 200 \( \mu \text{m}^2 \) during a time of 60 ns. It follows that the observed distributions of amplitude and rise-time reflect the range of crack area increments and life-times.

It has not been possible to link features of the fractured specimens observed by scanning electron or optical microscopy unambiguously with individual acoustic emission transients and so we can only speculate as to the fracture process that generated the observed emission. One fracture process that occurs during the fracture of these materials is the fast shear fracture of interinclusion ligaments prior to final fracture (Knott 1975). The distributions of crack increment areas and crack growth time-scales are consistent with likely distributions of ligament areas assuming a crack growth rate of about 0.1 \( V_b \). However, areas of intergranular fracture were also observed (figure 4), and it is equally possible that these may also have generated the acoustic emission.
6. Conclusions

(1) A calibrated broadband detection system for acoustic emission has been developed, and used to record transients emitted during the ductile fracture of a low-alloy steel. The relatively flat transfer function of the system enabled surface displacements to be measured with little interference from specimen or transducer resonance modes.

(2) The overall shape of the displacement transients is in good agreement with theory. Analysis of the transient leading edges has been shown to give information about source event life-times, magnitudes and speeds. It should be possible to characterise specific deformation and fracture events by distributions of rise-time and amplitude.

(3) When this analysis was applied to the ductile fracture of En30A steel with the heat treatment described above, it was found that the mean source event life-time was 63 ns for the emissions which fell within the dynamic range of the system. It is noted that such time-scales are too short to be observed with a conventional acoustic emission system.

(4) The measured surface displacements have been interpreted in terms of source strengths, and these have been tentatively related to crack areas, typically 200 $\mu$m$^2$. It has similarly been possible to estimate crack speeds. Conclusions about source strengths rely on the ability to measure absolute surface displacements. A conventional system using a piezoelectric transducer is unable to do this directly.

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Figure 4. Scanning electron micrographs of the fracture face of temper-embrittled EN30A steel, showing (a) a typical area of ductile dimple fracture at the centre, and (b) secondary intergranular cracks at the periphery of the fracture. Scales: (a) 1 cm = 8.2 μm; (b) 1 cm = 4 μm.