ACOUSTIC EMISSION FROM A CRACK GROWTH EVENT

L. J. Jacobs*, W. R. Scott, D. M. Granata, and M. J. Ryan
Naval Air Development Center
Advanced Metallic and Ceramic Materials Branch
Warminster, PA 18974

*Office of Naval Technology Postdoctoral Fellow

INTRODUCTION

Acoustic emission is a nondestructive testing technique that detects the stress wave emissions from deformation and fracture processes within a loaded structure; these signals are the result of various processes that occur within the body. Some potential sources of acoustic emission include: crack propagation and arrest, fretting between fracture surfaces, dislocation movement, microcracking, twinning and phase transformations. In addition to these failure related mechanisms, other phenomena such as fastener and joint fretting, structural vibration, cavitation, and electromagnetic noise can create signals which are picked up by acoustic emission instrumentation. The ability to isolate crack growth signals from other events would greatly enhance the current acoustic emission signal processing capability.

Previous laboratory studies [1] have successfully characterized acoustic emission signals using statistical pattern recognition algorithms to characterize signals on the basis of features observed in a large number of events which can be assumed valid. Normally such techniques extract features which are dependent both upon the emission event and the response of the surrounding structure to that event. However, being empirical in nature they cannot necessarily distinguish between these contributions.

Other investigators [2,3] have looked specifically at geometrical effects. Such studies have modeled dispersion effects from various simple plate geometries on the characteristics of stress waves having an assumed functional form. They considered several point source models which were used to describe the mechanism of acoustic emission. Experimentally, waves observed from such sources at various locations had similar spectral characteristics to those predicted analytically.

This paper complements previous studies by providing a development of the analytical form of an acoustic emission waveform resulting from the propagation and subsequent arrest of a planar crack and comparing it to experimental measurements. An advantage of this approach is that the source model for the acoustic emission signals is an actual crack propagation event. The interferometer used to quantify displacement response has the ability to make localized absolute measurements with very high fidelity and without acoustically loading the specimen. In addition, the experimental design minimizes the effects of geometric dispersion on the observed waveforms by interrogating the wavefront very close to the crack tip before interactions with adjacent boundaries can occur. By comparing the early part of the observed time domain waveforms to model calculations, the existence of a crack and its rate of propagation can be predicted.

Using previously developed analytical methods, predictions will be made concerning the theoretical form of the acoustic emission caused by a specified crack growth event. These results will be used to interpret the signals obtained experimentally.

Within the assumptions of linear elastic fracture mechanics, the dynamic stresses caused by a prescribed crack growth event in an infinite two dimensional body are calculated. These results can be used to calculate displacement as a function of time at any point within the body. The specific case examined is a semi-infinite crack in an isotropic body under static tension, where growth suddenly initiates, and after propagating a distance with a constant velocity, suddenly stops. The analytically obtained function models the surface displacement of a finite body for the time period prior to the arrival of stress waves reflected from the specimen boundaries. The current analytical procedure is not valid for the time period after the fastest reflected waves interfere with the unadulterated signal from the crack propagation. The results of this analysis can lead to establishing a precise, quantitative correlation between a crack growth event and the acoustic emission signal received at the surface.

ANALYTICAL METHOD

The present work employs an integral equation method which is similar to the well known technique for solving static contact problems in linear elasticity. The integral equation in the present application is in two variables, a spatial coordinate (x) and time (t). Since it employs a fixed coordinate system, the procedure can be used to solve the problem of a finite length crack. An additional advantage of the proposed method is its ability to provide relatively efficent computations for various dynamic fracture problems under more general conditions than previous analytical models.

The first step of this analysis is to determine the dynamic stress, as a function of time, caused by a crack tip propagating with a prescribed velocity. This analysis, summarized in [4], uses an influence function (or Green's function) method to formulate an integral equation that expresses the boundary conditions in the crack plane. In order to clarify the method of solution for the time dependent displacements, the steps for formulating the integral equation in terms of the unknown dynamic stresses follow. The solution presented is for a semi-infinite crack that is symmetrically loaded (Mode I).

The influence function $U_y(x-x',t-t')$, obtained in closed form, is the vertical displacement of an elastic half-space subjected to a unit concentrated impulse acting at a point normal to its edge.

Assume a crack exists at time $t=0$ with its tip located at $x=a(0)$ and $y=0$. For time $t>0$, the crack tip moves from $x=a(0)$ to $x=a(t)$. The two relevant boundary conditions are that the newly formed crack faces are stress free and that the vertical displacement in front of the moving crack tip is zero. Both of these boundary conditions are met by:

(a) Removing the existing known static stress, $\sigma_{yy}=P(x)$, and assuming that instead a new unknown time dependent stress, $\sigma_{yy}=F(x,t)$, develops.

(b) Requiring that the new stress distribution be such that there is vertical displacement continuity in front of the moving crack tip.

The continuity boundary condition can be expressed in terms of the displacement $U_y(x-x',t-t')$:

$$-\int_0^t\int_{-\infty}^{+\infty} P(x')U_y(x-x',t-t')dx'dt' + \int_0^t\int_{-\infty}^{+\infty} F(x',t')U_y(x-x',t-t')dx'dt' = 0 \qquad (1)$$

The above is a Volterra integral equation of the first kind in the variables x and t. This equation can be reduced to an integral equation in time t only and solved numerically for the unknown dynamic stress distribution, F(x,t), for any prescribed crack tip velocity. The specific problem of interest for this application is the case of a crack that suddenly starts from rest, and after propagating with a prescribed constant velocity, suddenly stops. The results obtained in this analysis agree with those of previous researchers [5,6].

The displacement at any point within the infinite body is determined using the previously calculated dynamic stress, F(x,t) and two new influence functions, $U_{xy}(x-x',y,t-t')$ and $U_{yy}(x-x',y,t-t')$. These influence functions represent the displacement u_x and u_y at point (x,y) within an elastic half-space that is subjected to a vertical unit impulse surface loading at x'. Figure 1 shows a diagram of these influence functions which are also calculated using integral transform methods. The differential arrival time of the longitudinal and shear wave fronts is evident in these plots.

Convolution integrals are set up to calculate the vertical and horizontal displacement as a function of time for any point (x,y) within the body; they determine the displacements due to the previously calculated dynamic stress distribution that is applied in the plane of the crack. The displacements are:

$$u_x(x,y,t) = -\int_0^t\int_{-\infty}^{+\infty} P(x')U_{xy}(x-x',y,t-t')dx'dt' + \int_0^t\int_{-\infty}^{+\infty} F(x',t')U_{xy}(x-x',y,t-t')dx'dt' \qquad (2)$$

$$u_y(x,y,t) = -\int_0^t\int_{-\infty}^{+\infty} P(x')U_{yy}(x-x',y,t-t')dx'dt' + \int_0^t\int_{-\infty}^{+\infty} F(x',t')U_{yy}(x-x',y,t-t')dx'dt' \qquad (3)$$

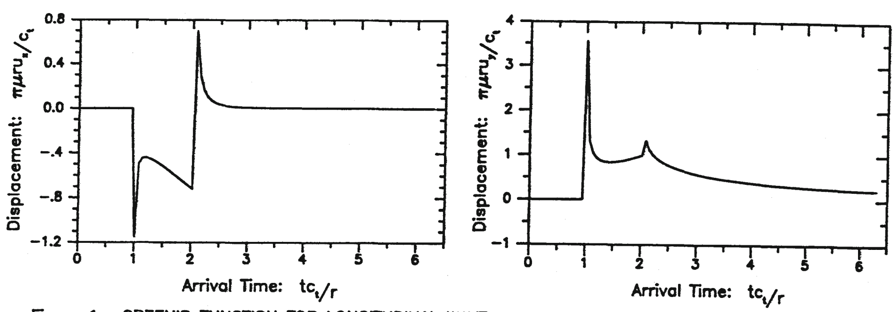

Figure 1a: GREEN'S FUNCTION FOR LONGITUDINAL WAVE Figure 1b: GREEN'S FUNCTION FOR SHEAR WAVE

Figure 1.

These integrals can be evaluated numerically to determine the displacement functions.

EXPERIMENT

Crack propagation events were produced using a Compact Tension fracture specimen with dimensional proportions as outlined in ASTM E-399. The specimen was modified to be wedged open through bolt loading as shown in Figure 2. This wedge loading is displacement controlled. Once the crack growth initiates, the bolt is advanced no further. The crack unloads as it extends and arrests before complete failure occurs. The stress intensity relationship of the ASTM standard was used to compute the critical loads required to initiate propagation. The specimens were fabricated of 1/2 in. and 1 in. thick poly methyl methacrylate. This material's low fracture toughness and nearly brittle failure mode allowed cracks to be easily propagated, and its optical transparency permitted the size, geometry and location of cracks to be readily determined.

Cracks in these specimens were initiated by driving a sharp blade into the notch of the specimen while the crack faces were clamped in compression. This permitted a short cracked region to be started without producing catastrophic failure. Further propagation was produced by tightening the bolt in the side of the specimen.

Three characteristic cracking phenomena were observed during propagation with corresponding differences apparent on the fracture surface. Fast fracture was preceded by craze formation at the crack tip. Low amplitude acoustic emissions observed during the loading portion of the test were interpreted as resulting from this crazing. Usually only one event of this type was observed. The crack growth increment in the fast fracture region averaged 1 cm and yielded an audible acoustic event with signals an order of magnitude higher than craze events. A small time lag was perceptible between craze formation and crack advance. Subsequent loading generally resulted in ductile failure, with little or no acoustic activity observed.

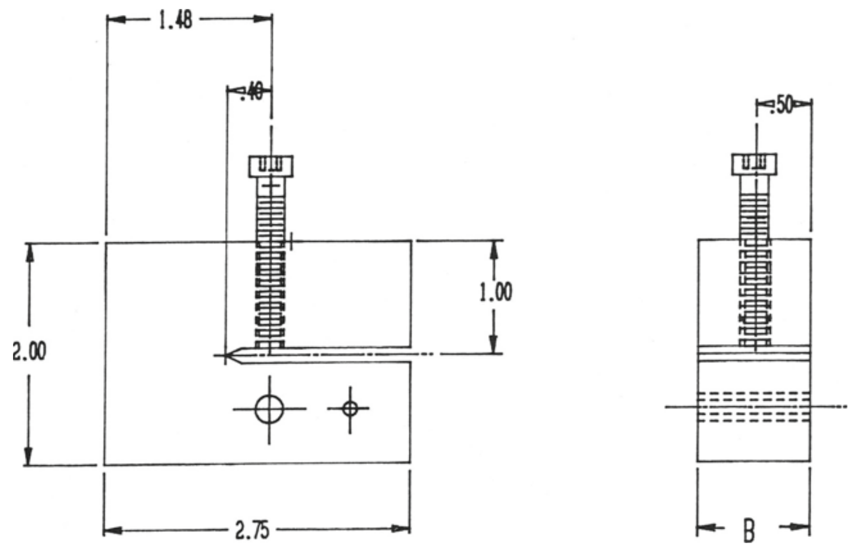

Figure 2. Wedge Opening Load Specimen

A high sensitivity heterodyne interferometer is used to detect acoustic events resulting from crack growth in the specimen. A schematic of the instrumentation is shown in Figure 3. The device used in these studies permits high fidelity localized measurement of displacements resulting from acoustic emission events arriving at various locations on the sample surface. Since this type of measurement does not acoustically load the sample, the event being observed is undisturbed by the measurement process.

The specimen face opposite the crack is polished and placed in the interferometer and becomes one mirror surface. The beam striking this face is approximately 1.5 mm in diameter and samples the average displacement taking place over this region, which is much smaller than the wavelength of the acoustic events being observed. The sample is designed so that initial acoustic emission events leaving the crack tip will arrive at this face prior to reflection from other faces of the specimen.

Lateral adjustment screws on the table supporting the sample allowed the sample face to be moved across the beam without significantly affecting the alignment of the interferometer. In this way the apparatus could interrogate displacements from wavefronts arriving at predetermined angles with respect to the plane of the crack.

The operation of the heterodyne interferometer is similar to that described elsewhere [7]. Briefly, single frequency laser light is split into two components using an acousto-optic modulator. These two components, which are separated in frequency by 40 MHz, are sent along two arms of an interferometer one of which contains the sample to be monitored. The beams are recombined on the surface of a photodetector where they beat together at a frequency of 40 MHz. Phase shifts in the light reflected from the sample surface result in equivalent phase shifts in the 40 MHz beat signal received by the photodetector. This carrier signal can then be demodulated to determine the time dependent displacement occurring at the sample surface.

The detection scheme used differs from that described in reference [7] because it uses a linear discriminator to demodulate the carrier instead of a phase locked loop. This technique was suggested to the authors by the work of Ringermacher [8]. As a result FM demodulation rather than a phase demodulation is obtained and the interferometer behaves as a doppler shift detector. The time domain waveform acquired in this way can then be integrated to determine time dependent displacement.

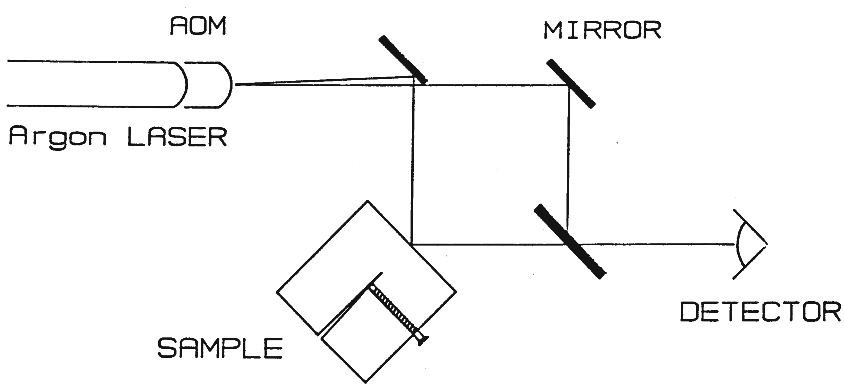

Figure 3. Interferometer

Comparisons of identical waveforms acquired using both the phase locked loop and the discriminator showed these devices to produce nearly equivalent results within the accuracy of the experiments being performed.

The detection system described has a band width of 10 MHz which was further limited to the spectral region 0 to 2 MHz in order to reduce noise in the signals. All signals were acquired on digital oscilloscopes and stored for later processing.

DISCUSSION AND CONCLUSIONS

A Green's function has been calculated which describes the dynamic stresses caused by a prescribed crack growth event in an infinite 2-dimensional body. Features of this solution are in qualitative agreement with experimental measurements of acoustic emission events reported in these studies.

A characteristic crack emission is shown in Figure 4. Based on the analytical Green's function, the duration of the initial peak should be at least a few microseconds. This is consistent with the experimental results which exhibit a peak width of about 10 - 15 microseconds. Of the six valid events recorded from short crack growth events all exhibited this initial peak followed by a double peak of lower amplitude occurring about 14 microseconds later, a negative extrema occurring approximately 60 microseconds from the onset of the emission and two more large maxima occurring at 90 and 110 microseconds.

The separation of the first two extrema (14 microseconds) corresponds roughly to the difference between longitudinal and shear waves arriving at the specimen surface, which was calculated to be about 12 microseconds for most of the specimens.

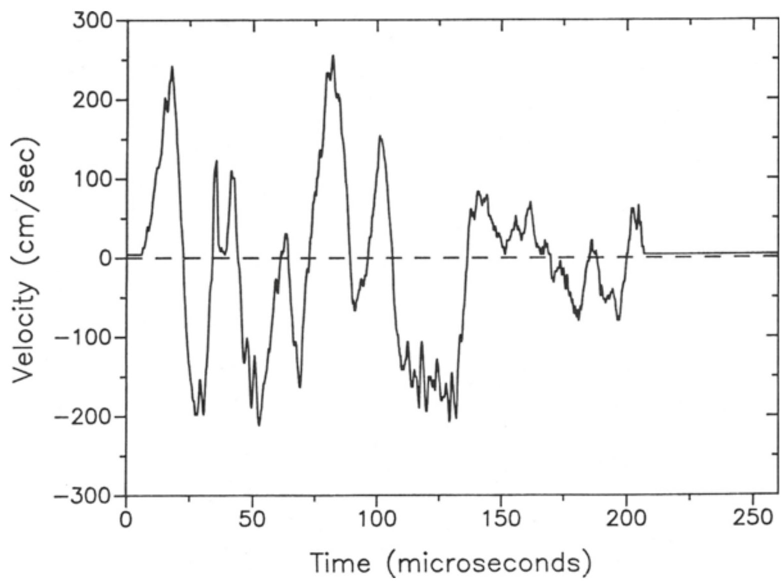

Figure 4. Acoustic Event from a Growing Crack

Care was taken experimentally to avoid the broadening effect of wave reflections and mode conversions from the specimen boundaries on this initial peak. However, these effects were probably present in later portions of the waveform. In addition, the presence of a curved crack front (tunneling) will result in variable arrival times thereby broadening all the features seen in the event. Other limitations of the experiment include the inability to measure the crack velocity and to determine exact time difference between the crack growth event and its arrival at the measurement surface.

Some correlation was exhibited between the amplitudes of the acoustic emission events and the stress intensity factors for the propagating cracks. Shorter cracks (17 to 19 mm in length) having a higher potential energy at crack initiation produced events with much higher amplitudes than were seen in longer cracks (22 to 29 mm).

Anomalies in the fracture behavior of the specimen included out of plane growth, some crack tunneling, and the evidence of crazing. Out of plane growth resulted from Mode III loading imposed by bearing stresses between the bolt and notch surfaces, which twisted the lower specimen leg outward. The loading mechanism can be modified to eliminate this effect. Tunneling comes from a stress gradient through the specimen thickness, and is less noticable in the thinner specimens. The thinner the specimen however, the more prone the measurement is to side reflections. Acoustic displacement measurements were taken from the center plane of the specimen to minimize broadening effects of side reflections and differential arrival times from a curved crack front. Both of these conditions however are relatively insignificant with respect to the assumptions of the model.

Craze event amplitudes are much smaller than fast crack growth events, and since there is a distinct time lag between craze formation and fast crack propagation, it is currently being assumed that the craze event is independent of the crack signal.

Further development of the analytical model is necessary before the experimentally obtained waveforms can be fully interpreted. Enhancement of the experimental and analytical techniques developed here are planned to clarify the relationship between acoustic emission events and crack growth. The effects associated with separation in the arrival of the longitudinal and shear wave fronts caused by the starting and stopping of crack growth are expected to dominate the calculated displacements. The numerical evaluation of the displacement functions should show the effect of the influence functions on time dependent displacement values.

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