CHARACTERIZATION OF FIBER FRACTURE
VIA QUANTITATIVE ACOUSTIC EMISSION

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INTRODUCTION

Fiber fragmentation tests\(^1,2,3\) can be used for in situ recovery of fiber-matrix interface shear strengths and/or fiber fracture spatial and strength distributions. Often neglected with the tests however, is important quantitative information (e.g. the crack volume and its history) contained in the elastic waves (acoustic emission) released during fracture. The final crack volume is related to the fiber fracture stress and the average sliding stress at the fiber-matrix interface. Thus, quantitative acoustic emission analysis provides an alternative approach for in situ recovery of these important fracture characteristics. Furthermore, knowledge of the crack volume history can help with the study of transition from the cumulative to noncumulative failure mode in composites since this transition is likely connected to the rate of stress redistribution in the fracture wake.

ACOUSTIC EMISSION FUNDAMENTALS

To model the motion caused by abrupt failure processes in elastic bodies, Burridge and Knopoff\(^4\) treated the failure as an expanding dislocation loop and expressed spatial and material characteristics of the defect in terms of a distribution of “equivalent” body forces. A single point-like source can be modeled by a source moment tensor\(^4,5\)

\[
M_{ij} = c_{ijkl}[u_{kl}]\Sigma_l
\]

where \(i\) and \(j\) indicate the direction and separation of body force dipoles. \(c_{ijkl}\) is the elastic constant tensor, \([u_{kl}]\) is the displacement discontinuity across the defect in the \(k\)-th direction and \(\Sigma_l\) is the defect surface area projected onto a plane having a normal in the \(l\)-th direction.

The time-dependent displacement in the \(i\)-th direction, \(u_i(x, t)\), at location, \(x\), and time, \(t\), caused by a source centered at \((x', r')\) is obtained by a convolution

\[
u_i(x, t) = M_{ijkl} G_{ijl} k(x-x', t-r') S(r') dt'
\]
where \( S(t) \) is the source time-dependence (e.g. the normalized crack volume history) and 
\( G_{ijkl}(x;x', t-t') \) is the spatial derivative of the dynamic elastic Green's tensor. Each 
component of the Green's tensor represents the displacement at \( (x, t) \) in the \( i \)-th direction 
due to a unit strength impulsive body force dipole concentrated at \( (x', t') \), acting in the \( j \)-th 
direction, with separation in the \( k \)-th direction.

For a unidirectional composite under tensile load in the fiber direction, mode I cracking 
of the fiber is usually accompanied by mode II shear at the fiber-matrix interface. Static 
equilibrium considerations necessitate that sliding must occur along a length, \( l = r_f T/2 \tau_s \), 
where \( r_f \) is the fiber radius, \( \tau_s \) is the average interface sliding stress and \( T \) is the fiber 
fracture stress and the remote fiber stress thereafter. The crack opening is approximately

\[
\Delta = \frac{r_f T^2}{2E_f \tau_s} \tag{3}
\]

where \( E_f \) is the Young's modulus of the fiber. Suppose the normal to the fracture surface is 
oriented in the \( x_f \) direction. Because far field contributions to the moment tensor from shear 
at the fiber-matrix interface cancel due to symmetry, Equations (1) and (3) give

\[
M_{ij} = \begin{bmatrix}
\lambda_f + 2\mu_f & 0 & 0 \\
0 & \lambda_f & 0 \\
0 & 0 & \lambda_f
\end{bmatrix}
\frac{\pi r_f^2 T^2}{2E_f \tau_s} \tag{4}
\]

where \( \lambda_f \) and \( \mu_f \) are the Lamé elastic constants of the fiber. Observing Equation (4), we see that 
the magnitude of the moment tensor is scaled by the final crack volume, \( \pi r_f^2 T^2/2E_f \tau_s \).

Solutions to the wave equation for Heaviside or unit ramp excitation are available for 
the infinite linear elastic isotropic plate. Wave dispersion, attenuation and the presence of 
the fiber are neglected. In terms of the unit ramp tensor, \( G_{ijkl}^R(t-t') \), the time-dependent 
surface displacement normal to the plate (i.e. the acoustic emission signal) has the form

\[
u_3(t) = M_{kij} \int_0^t G_{ij,k}^R(t-t') \tilde{S}(t')dt'
\tag{5}
\]

for \( \tilde{S}(0) = 0 \) where \( x \) and \( x' \) have been omitted for simplicity. Combining Equations (4) 
and (5) we find

\[
u_3(t) = \frac{\pi r_f^2 T^2}{2E_f \tau_s} \int_0^t [(\lambda_f + 2\mu_f)G_{31,3}^R(t-t') + \lambda_f G_{32,2}^R(t-t') + \lambda_f G_{33,3}^R(t-t')] \tilde{S}(t')dt'
\tag{6}
\]

**EXPERIMENTAL**

A thin groove was scribed in a Ti-6Al-4V (wt.\%) plate and a single SCS-6 fiber 
(Textrol Specialty Materials, Lowell, MA) was placed in it. An unscribed, but otherwise 
identical section of plate was placed over the fiber and the plates were electron beam welded 
in vacuum around their edges to encase the fiber. The sample was hot isostatically pressed 
for 90 minutes at 100 MPa and 900°C for microscopically complete consolidation. This 
procedure was performed identically to produce a neat (fiberless) sample. Both samples 
were machined to a dogbone geometry (with the fiber located at the center of the plate) with 
a 95 mm long, 50 mm wide and 5 mm thick gauge section. Fig. 1. A 300 kN capacity 
electromechanical testing machine with serrated face wedge action grips was used to apply 
tensile load at a constant crosshead rate of 0.1 mm/min at 25°C. Load was measured using a 
strip chart recorder.
Figure 1. Experimental arrangement for quantitative analysis of fiber fragmentation.

To measure the acoustic emission activity, eight miniature piezoelectric sensors were spring loaded to the plate surface (see Fig. 1) for measurement of displacement normal to it. Sensors were based on the broad band design of the National Institute of Standards and Technology (NIST). When calibrated (on steel using the same model 250 mV/pC charge amplifier) at NIST, a displacement response, Fig. 2, which compared favorably to that of the NIST design was achieved but with a smaller element backing. The maximum displacement sensitivity was 45 dB (RE 1 V/µm) or 178 V/µm at 450 kHz and decreased to 30 dB or 32 V/µm at 2 MHz. Signals were recorded at 1 nsec per data point with 10.5 bits voltage resolution for a 15 MHz upper frequency limit.

Figure 2. Construction details of the miniature piezoelectric sensor and its displacement response.
ACOUSTIC EMISSION ACTIVITY

During the initial stages of loading, both the neat and single fiber samples experienced a few weak, low frequency emissions. As loading progressed beyond the elastic regime, more than 35 additional strong, high frequency emissions were measured for the single fiber sample. The first of these occurred at a plate tensile stress, $\sigma$, of 773 MPa and the last at 852 MPa. Acoustic emission signals recorded during testing of the single fiber sample at $\sigma = 788$ MPa are shown in Fig. 3.

![Acoustic emission signals for a fracture event which occurred at a plate stress of $\sigma = 788$ MPa.](image)

FRACTURE SITE LOCATION

If $x', y'$ and $z'$ is the unknown location of the fracture, the $i$-th receiver located at $x_i$, $y_i$ and $c_i$ will first experience a signal when

$$(x' - x_i)^2 + (y' - y_i)^2 + (z' - z_i)^2 = (c_i t_i)^2$$

(7)

where $t_i$ is the travel time for the first compression wave to reach the $i$-th receiver and $c_p$ is its velocity. Let $t_0$ be the travel time for the wave to reach the closest receiver and $\Delta t_i$ be the
travel time difference between that receiver and the \(i\)-th receiver. Substituting \(t_i = t_0 + \Delta t_i\) into Equation (7) and subtracting any \(i\)-th equation from any \(j\)-th to generate one linear equation. For \(\eta\) receivers, there are a maximum \(N = \eta(\eta - 1)/2\) unique subtractions.

Travel time differences, \(\Delta t_i\), were found within \(-20\) nsec accuracy by observing when the AE signal magnitude first exceeded the background noise. The \(N = 28\) equations were solved using a least squares algorithm with \(c_p = 5.9\) mm/\(\mu\)sec for Ti-6Al-4V. The returned fracture location was \(x' = -6.6\) mm, \(y' = 0.0\) mm, \(z' = -2.3\) mm and \(t_0 = 1.73\) \(\mu\)sec.

This location was consistent with the centerline of the plate and the known fiber location. Note that accuracy in \(z'\) is problematic for thin plates because the straight line distance between the source and a receiver ‘far’ from it is not substantially affected by changes in \(z'\).

CRACK VOLUME HISTORY

Sensor 5 was oriented \(-4.7^\circ\) with respect to the \(x_f\) axis of the selected fracture event. This small rotation was disregarded and Equation (6) was used directly. Infinite plate unit ramp responses\(^6\) were computed for the source located at plate center (i.e. \(z = 0\)) with a radial (\(x_f - x_2\) plane) source-receiver distance of \(31.9\) mm. For Ti-6Al-4V, the shear wave velocity was \(3.1\) mm/\(\mu\)sec, the shear modulus was \(43\) GPa and again \(c_p = 5.9\) mm/\(\mu\)sec. 500 data points beyond the first wave arrival and a 5 nsec step size allowed reasonable comparison with the measured AE signal while avoiding reflections from the edges of the plate (not considered in the infinite plate model).

Equation (6) was evaluated (in terms of \(T^2 / \tau_d\)) using \(r_f = 70\) \(\mu\)m, \(E_f = 400\) GPa and a fiber Poisson’s ratio of 0.14 (Find \(\lambda_f = 68\) GPa and \(\mu_f = 175\) GPa), Fig. 4. Through trial and error involving convolution (discrete) of \(\hat{S}(t)\) with the appropriate unit ramp responses, good agreement (normalized) between the measured and modeled acoustic emission signal (see Fig. 4) was obtained with \(\hat{S}(t) = \pm 44.4\) 1/\(\mu\)sec\(^2\) and a 0.3 \(\mu\)sec rise-time. Integrating this function twice with respect to time, a crack volume history, \(\hat{S}(t)\), having the shape of a symmetrical parabolic ramp was recovered. The shape of this function is thought to correctly portray the physics of the fracture in the sense that it accelerates (i.e. nucleation and growth) and then decelerates to reach a final static value (i.e. arrest).

![CHANNEL 5](image.png)

**Figure 4.** Comparison between the measured and the modeled acoustic emission signal.
INTERFACE SLIDING STRESS

At the time of the selected fracture event, minimal plasticity had occurred. For small fiber volume fraction composites in the elastic regime, the remote fiber stress can be approximated by

$$T = \left[ \frac{\sigma}{E_m} + (\alpha_m - \alpha_f)\Delta T \right] E_f$$

where $E_m$ is the Young's modulus of the matrix, $\alpha_m$ and $\alpha_f$ are the matrix and fiber linear expansion coefficients and $\Delta T$ is the processing temperature change. For Ti-6Al-4V, $E_m = 113$ GPa and $\alpha_m = 8.5 \times 10^{-6}$ 1/°C. For SCS-6, $\alpha_f = 4.8 \times 10^{-6}$ 1/°C. Using $\sigma = 788$ MPa and $\Delta T = -875$ °C, the fracture stress is estimated to be $T = 1494$ MPa.

Observing Fig. 4, we see that the measured AE signal was dominated by sinusoids having frequencies in the neighborhood of 3 MHz (the expected upper limit for the modeled signal is approximately 1/\text{rise-time} = 3.3$ MHz which is higher than the range of frequencies (10 kHz - 2 MHz) which our piezoelectric sensors had been calibrated for (see Fig. 2). To estimate the 3 MHz sensitivity of our sensors, we note that beyond 2 MHz, the "roll off" rate for sensors of this type typically increases to about 15 dB (RE 1 V/°m)/MHz. Since the 2 MHz sensitivity of our sensors was 30 dB, the 3 MHz sensitivity should be about 15 dB or 3.6 V/°m. With this value and $T = 1494$ MPa, nearly absolute agreement between the measured and the modeled AE signal (see Fig. 4) is then obtained with an average interface sliding stress of $\tau_s = 287$ MPa. We note that recovery of $T$ for a known $\tau_s$ presents another possibility. This analysis would proceed in a similar fashion.

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