Acoustic Emissions from Rapidly Moving Cracks

Steven P. Gross,* Jay Fineberg,† M. Marder, W. D. McCormick, and Harry L. Swinney
Center for Nonlinear Dynamics and Department of Physics, The University of Texas, Austin, Texas 78712
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Linear elasticity is unable to predict completely the dynamics of a rapidly moving crack without the addition of a phenomenological fracture energy. Our measurements of acoustic emission, crack velocity, and surface structure demonstrate quantitatively similar dynamical fracture behavior in two very different materials, polymethlymethacrylate and soda-lime glass. This unexpected agreement suggests that there exist universal features of the fracture energy that result from dissipation of energy in a dynamical instability.

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The current understanding of dissipation in solids is largely phenomenological. A good example is found in the study of rapid crack propagation in brittle amorphous materials. When such a material is stretched sufficiently, it releases the stored potential energy through the creation and propagation of cracks. Though it might be expected that the energy dissipated in this way is simply proportional to the amount of surface created, experiments show that the energy required to create a unit length of surface increases rapidly with crack velocity. This rapid increase in energy cost is incorporated into standard theories of fracture mechanics through the introduction of a velocity-dependent fracture energy [1]. Fracture energies are largely empirical, and it is widely assumed that their velocity dependence involves such complicated phenomena on the microstructural level that there is little point to further investigation [2].

We examine here the dynamics of moving cracks in the two different brittle amorphous materials, polymethylmethacrylate (PMMA) and soda-lime glass. PMMA is a polymeric solid composed of long polymer chains (molecular weight $\sim 10^6$), while glass has nearly crystalline order at small length scales. It is thus reasonable to expect different microscopic mechanisms of dissipation and different crack dynamics in the two materials. However, we find that glass and PMMA show similar quantitative as well as qualitative fracture behavior. These results suggest that there is a universal aspect to the velocity-dependent fracture energy [3].

Our experiments were conducted on sheets of PMMA and soda-lime glass, 3.1 mm thick, 208 mm wide (direction of crack propagation), and 210 mm long (distance between pull tabs). The plates were fractured by applying uniform stress to four pull tabs which were metal strips, 2.5 cm wide by 220 mm wide by 3.1 mm thick, glued in opposite parallel pairs 210 mm apart; each pair was composed of two tabs parallel to each other and glued to opposite sides of the plate. The pull tabs were parallel within 0.1 mrad. Prior to each experiment the sheets were coated with a 30 nm layer of aluminum, and a short crack was seeded in the middle of one of the 210 mm long sample edges. As the crack advanced, the tip location could then be determined to within 0.1 mm by measuring the resistance of the aluminum coating [4].

Acoustic emissions from the fracture were measured with two NIST-type transducers [5] resting on the plate surface, typically 30 mm from the anticipated nearest approach of the crack, and 50 mm and 100 mm, respectively, from the side of the plate where the crack began. The transducers were sensitive to out of plane displacement with a flat frequency response to within ± 2.5 dB from 0.1 to 1.0 MHz [5], with -10 dB sensitivity at 1.1 MHz. The transducer characteristics were checked by comparing the transducer signal produced by breaking a 0.3 mm thick pencil lead on a 0.96 cm thick glass plate with the theoretical predictions of Weaver and Pao [6] for the same situation. Pencil leads produce a step function unloading as they fracture [7], and thus generate a known reproducible calibration signal. The excellent agreement between theory and experiment (Fig. 1) enables us to measure surface displacements to within $\pm 15\%$, which is the uncertainty in the breaking stress of the 0.3 mm leads. In order to compensate for slight differences in transducer coupling, calibrations were also carried out *in situ*, breaking glass capillary tubes at a fixed distance from a transducer and then looking at the amplitude of the response. There was more uncertainty in the breaking stress of the capillary tubes ($\pm 25\%$) than in the pencil leads, but their larger amplitude signal made calibration possible in PMMA, which dissipates small amplitude signals.

Plates were broken by applying stress to the rigid pull tabs. Stress was generated by a computer-controlled tensile testing device, whose jaws were parallel to within 0.2 mrad. The total stress was increased in steps of 20 N, separated by 20 s waiting periods. The plate usually broke during a waiting period. The applied stress was monitored continuously at 25 kHz by a load cell accurate to 10 N. Throughout the experiment the response of the transducers was monitored at a sampling rate of 20 MHz to 8 bit accuracy.

Previous measurements of crack velocity in PMMA [4] revealed a dynamic instability when the velocity exceeded a threshold of 300–400 m/s. The present measurements of acoustic emission, crack velocity, and surface structure demonstrate that this velocity-dependent instability oc-

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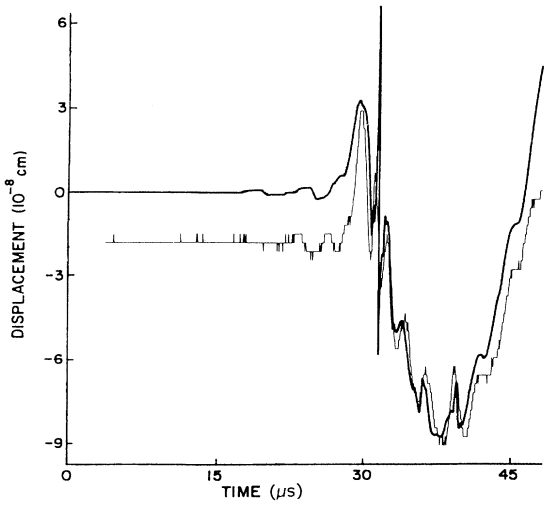

FIG. 1. Calibration of the transducer signal. The thick curve is the theoretical prediction of Weaver and Pao [6] for the out of plane displacement of a 0.96 cm thick glass plate, due to a 10 cm distant step pulse, 3.45 N downward. The thin curve is the measured transducer response for an experimental duplication of the theoretical boundary conditions, with the step pulse being provided by the fracture of a 0.3 mm diameter pencil. The difference in baselines is due to the difference in boundary conditions between theory (step loading) and experiment (step unloading).

curs in glass as well as in PMMA. In both materials the surface created by the advancing crack is initially quite smooth. The instability is identified with the point where the surface roughens, as determined with a profilometer [8]. Measurements of crack velocity versus crack length yield the crack velocity v_c at the onset of roughening; v_c (scaled by the Rayleigh wave speed in each material) is plotted in Fig. 2 as a function of the breaking stress (scaled by typical material yield strengths [9]) in Fig. 2. The measurements for both PMMA and glass show that the instability onset occurs, within the experimental uncertainty, at a velocity that is about 45% of the Rayleigh wave speed. Each material, however, does exhibit a weak dependence of v_c on the applied stress. This was not detected in the earlier (lower resolution) experiments on PMMA.

Acoustic emissions from the crack tip change character when the crack velocity exceeds v_c. Emissions from propagating cracks in PMMA and glass are shown in Fig. 3. At first the signals are dominated by low frequency components whose characteristic time is that needed for sound to travel from the crack tip to the plate boundary and return. However, when the velocity of the crack exceeds v_c, the emissions develop sustained high frequency components. The insets in Fig. 3 reveal the nearly periodic character of the high frequency PMMA signal, while the glass signal shows less obvious periodicity, possessing a number of different frequency components. In experiments where the crack velocity did not exceed v_c, acoustic

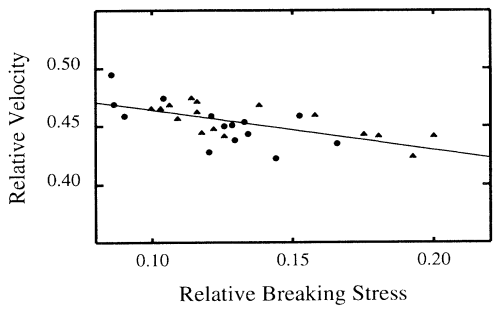

FIG. 2. The breaking stress and crack velocity at the onset of instability, expressed, respectively, relative to the typical material yield stress and to the Rayleigh wave speed (970 m/s in PMMA, 3370 m/s in glass), for plates 3.1 mm thick. Triangles are PMMA data; circles are glass. The instability onset corresponds to the first appearance of rough surface created by the propagating crack. The line is a best fit to the data.

emissions did not contain the high frequency components.

The time evolution of the acoustic power spectra is shown in the raster plots in Fig. 4. The figures were produced by taking the power spectral density of windows of

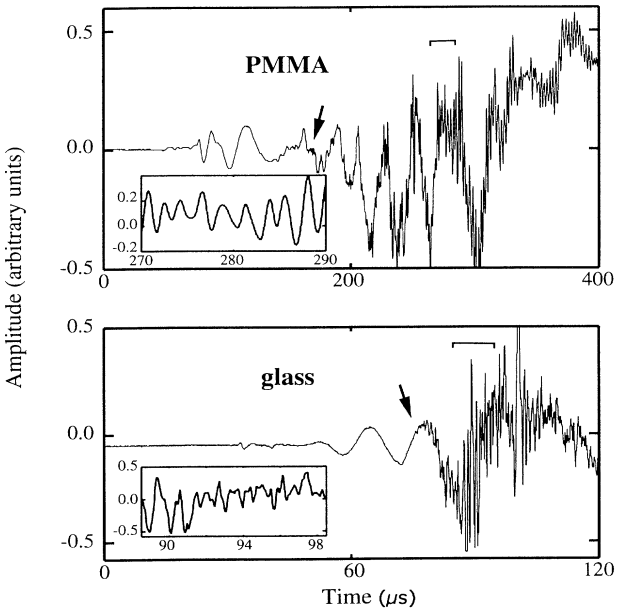

FIG. 3. Acoustic emissions from fast cracks in 3.1 mm thick plates of PMMA and glass. The time origins correspond to the start of fracture. The transducers were located near the center of the plates, 25 mm from the nearest approach of the crack. The insets, which expand the regions shown by the overbars, show the oscillations in the acoustic emissions produced when rough fracture surface is created. The arrows indicate the calculated appearance of high frequency acoustic emissions if they are emitted when the crack first creates rough surface and propagate through the plate at the transverse wave speed. The signal from glass was high-pass filtered (0.48 MHz) and amplified (×15) compared to the signal from PMMA.

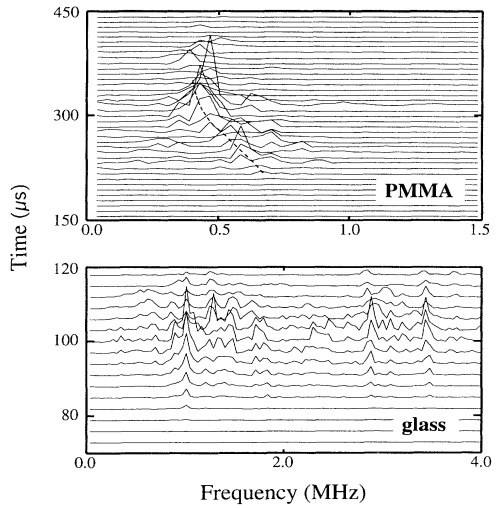

FIG. 4. Acoustic power spectra (multiplied by the square of the frequency) as a function of time, produced by propagating cracks creating rough surface structure in PMMA and glass. A Doppler shift is seen in PMMA as the crack passes the transducer (at 240 μs, though the signal arrived at 270 μs due to transmission time). The dotted line is a calculation of the expected Doppler shift (see text). In glass a Doppler shift is not observable.

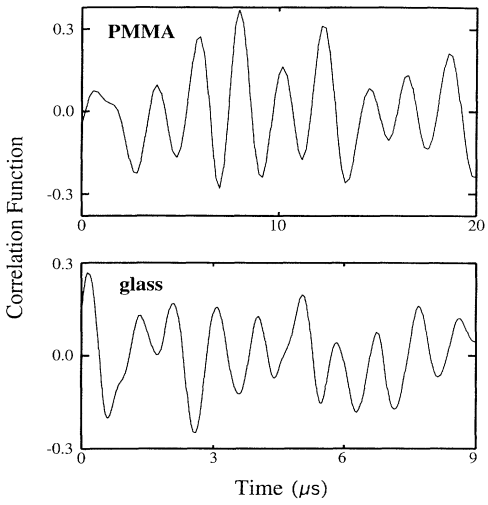

FIG. 5. Cross-correlation function between acoustic emissions and surface structure along plate center line. Surface structure was determined with a scanning profilometer.

data 26 μs long, and moving the windows progressively forward through time. Since the power transported by an acoustic wave is proportional to its frequency squared, the power spectral density was multiplied by ω^2 to give actual power carried by different frequency components. Zero on the time axis corresponds to the time at which the crack started advancing.

When the instability appeared in PMMA, it emitted power at approximately 0.7 MHz, while in glass it emitted primarily at 1.1, 1.4, 1.8, 2.9, and 3.5 MHz (see Fig. 4). In different experimental runs the principal frequency component in glass varied between 1.0 and 1.2 MHz. In PMMA this frequency component shifted to lower frequencies as the crack approached and passed the transducer. The expected Doppler shift, shown as a dotted line in the PMMA plot in Fig. 4, was calculated using the average crack velocity in each 26 μs window and the angle due to the transducer offset. The propagation speed of the signal was taken to be the transverse wave speed, and a central frequency of 0.53 MHz was assumed.

The emissions from glass did not show a change in the Doppler shift as the crack passed the transducer. This, together with the numerous spectral peaks, suggested that the crack was emitting broadband radiation and that the observed spectral peaks were due to plate resonances. To check this we excited plate resonances by breaking pencil leads and glass capillary tubes of different thickness on the plate surfaces. Of the resonances detected, the strongest were at 0.92 and 0.96 MHz, close to the frequency of a longitudinal wave reflecting from the plate surfaces (0.96 MHz); the plate resonance frequencies did not correspond to the spectral peaks in the emission data.

If an oscillatory instability is responsible for both the creation of surface structure and acoustic emission, then the two should be highly correlated. This idea is supported by determinations of the cross-correlation function between surface structure (determined by a scanning profilometer) and acoustic emission amplitude, as shown in Fig. 5. The correlation functions for both PMMA and glass are oscillatory, with the same correlation coefficient to within experimental error. The oscillation frequency in PMMA is 0.54 MHz, and for glass it is 1.0 MHz, in agreement with the acoustic emission frequencies shown in Fig. 4. The eye readily perceives this periodicity on the fracture surface of PMMA, but not on the surface of glass. Using our crack-length versus time data, we can find the fluctuations of the fracture surface profile as a function of time rather than space. This analysis of the fracture surface of PMMA yields only one frequency peak, at 0.53 MHz, as expected, while the glass surface shows spectral peaks at 1.0, 1.4, 1.8, 2.9, and 3.5 MHz, as were found in the acoustic emissions. A power spectrum of the glass cross-correlation function (Fig. 5) showed that it is not modulated by these higher frequency components, possibly indicating a lack of phase coherence over large distances.

The acoustic power emitted by the propagating cracks can be estimated since the NIST transducers give actual plate surface displacement. Following previous calculations by Boler and Spetzler [10], we assume that the energy transported by a plane wave arriving at a particular location is the material density multiplied by the velocity of elastic wave transmission times the out of plane plate velocity squared. We calculate the total radiated energy by assuming that the emissions are isotropically distributed, and that the out of plane velocity is uni-

form throughout the plate thickness. Under these assumptions, we found that a crack advancing with a well developed instability in PMMA or glass spent about 3% of its energy in acoustic emissions (this estimate neglects dissipation, which is significant in PMMA). For PMMA, these emissions contained around 4.8 J/m^2, while in glass they contained around 0.1 J/m^2. By way of comparison, the zero velocity fracture energy of PMMA is 140 J/m^2, and that for soda-lime glass is 4 J/m^2. Our estimate of the energy in the acoustic emissions is approximately 100 times larger than that of Boler and Spetzler [10], who found that the radiated energy was only 0.05% of the surface energy [11].

In conclusion, these measurements suggest that an oscillatory instability of the crack tip beyond a threshold velocity v_c is a generic feature of fracture in brittle amorphous materials. Once properly scaled, the instability appears at the same velocity v_c in both glass and plastic. The acoustic spectra for PMMA show a simple characteristic frequency, while the spectra for glass have several strong spectral components. In each case there is a good correlation between the fracture surface structure and the acoustic emissions. The fraction of the total fracture energy emitted as acoustic waves is about 3%, which means that most of the fracture energy is consumed in short time scale processes near the crack tip which manifest themselves eventually as heat [12].

We are left finally with the question of the mechanism underlying the oscillations. A theoretical explanation must predict both v_c and the characteristic frequency of oscillation. To date no theory has done both. Yoffe [13] predicts that beyond a critical velocity, a crack moving in a straight line will branch off at an angle, but the predicted critical speed is about 60% of the Rayleigh wave speed rather than the 45% observed in our experiments. Proposals for the mechanism of fracture in PMMA [14,15] focus on the way that bonds break when fracture surface structure is being formed, or on the aggregation of defects into microcracks and voids ahead of the crack tip [16], without asking why the process begins at a certain velocity, or what sets the frequency scale. Recent theoretical ideas involving lattice theories of fracture [17] predict a critical velocity for an oscillatory instability, but do not obtain the frequency or critical velocity seen in experiment. Additional theoretical possibilities now being explored include thermomechanical coupling [18] and noise-sustained instabilities of the crack front [19].

Dimensional analysis also fails to yield frequencies comparable to those observed. One possible frequency arises by dividing the sound speed by the size of microstructure (about $\sim 10^{-7}$ m in PMMA and $\sim 10^{-10}$ m in glass), giving $\sim 10^{10}$ Hz in PMMA and $\sim 10^{13}$ Hz in glass, frequencies much higher than those observed. Similarly, the material sound speed squared divided by the thermal diffusion coefficient (0.001 cm^2/s and 0.006 cm^2/s in PMMA and glass, respectively) gives frequencies of $\sim 10^{13}$ Hz and $\sim 10^{14}$ Hz in PMMA and glass, respectively. The sound speed divided by the plate thickness gives an appropriate time scale and requires further investigation, though the change in oscillation frequency with plate thickness seems to be a small effect [20]. Whether the correct explanation comes from a lattice model, a theory coupling thermal and mechanical effects, or some other theory remains an open question.

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* Electronic address: gross@chaos.utexas.edu
† Now at Department of Physics, Hebrew University of Jerusalem, Givat Ram, Jerusalem 91904, Israel.

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