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Acoustic-emission spectra from the formation of through cracks in glasses

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The results are given from experimental investigations of the acoustic-emission spectra associated with the formation of through cracks in glass plates subjected to thermal stresses. A theoretical interpretation of the empirical laws is given.

The acoustic-emission (AE) method, which is based on recording of the spontaneous acoustic emission that accompanies various irreversible processes in a solid, has recently begun to find widespread applications for investigations of the physical properties of solids in conjunction with traditional acoustic sensing techniques. The nucleation and growth of cracks, or brittle fracture processes, hold an important place in the above-mentioned class of irreversible processes. The detailed investigation of specific aspects of the acoustical phenomena that accompany the nucleation and growth of cracks at various temperatures and loads is of major interest in connection with the physical mechanisms of fracture. Here we report the results of experimental studies of the AE spectra associated with the formation of through cracks of finite length in glasses under the action of thermal stresses, and we given an interpretation of the resulting empirical laws.

In the experiments we have used \( \sim 35 \times 25 \times 0.3 \) cm plates of normal Na\(_2\)O-CaO-8SiO\(_2\) glass with line scratches of length 1-3 cm formed on the surface by means of a diamond glass cutter. Then the regions around the edges of the scratches were heated by alcohol burners (Fig. 1) until through cracks were formed at the scratch sites as a result the thermal stresses created there. The crack-forming technique proposed in Ref. 5 has the advantage that the thermal stresses created by the burners are tensile in the immediate vicinity of the scratch and are compressive along its continuation. Thus, the growing cracks were inhibited outside the scratches. For the experimental thickness of the glasses, this feature enabled us to obtain cracks of finite length, which varied between the limits of 2-4 cm, with sufficiently stability. The generated stresses for cuts of smaller length turned out to be lower than the corresponding critical values necessary for fracture, and cracks did not form. For larger cuts, on the other hand, complete fracture of the samples set in.

A longitudinal-mode piezoelectric ceramic wafer with a resonance frequency of 5 MHz was bonded by means of salol to the surface of the glass in the direction of the normal to the cut a distances of 10-15 cm in order to record the AE signals; the element in this configuration responded to the normal displacements of the glass surface. The wafer was fabricated from TsTS-19 (lead zirconate-titanate, PZT) ceramic and had dimensions \( \sim 0.8 \times 0.8 \times 0.04 \) cm. The experimentally recorded frequency response of the given glass-loaded wafer was characterized by the presence of a quasiuniform interval in the range \( \sim 20-340 \) kHz due to partially overlapping flexural-mode width resonances, which were highly damped under the influence of the load. The calculated frequency of the lowest flexural resonance in this case was \( \sim 22 \) kHz, which is in good agreement with the measured values. The sensitivity of the wafer at frequencies below 20 kHz, according to theory, tended to zero according to a \( \sim \omega^2 \) law. The upper limit of the indicated quasiuniform interval was determined by the frequency of the lowest lon-

![FIG. 1. Diagram of experimental arrangement. 1) Glass plate; 2) crack; 3) alcohol burners; 4) receiving piezoelectric wafer; wood-block supports; 6) DR 1080 programmable transient recorder; 7) graphical recording instrument; 8) oscilloscope.](image-url)
...width mode: ≈ 350 kHz. These modes were damped to a lesser degree and provided fairly strong peaks in the measured frequency response. According to theoretical estimates (see below), the main part of the acoustic energy radiated by cracks of the indicated dimensions was localized in the interval of frequencies up to 100 kHz. The experimental piezoceramic wafers did not introduce appreciable distortions in the spectra of the investigated AE signals in this frequency range, which were in the form of pulses of the lowest symmetrical (quasilongitudinal) mode and the pure shear mode SH in the glass plate. Since normal displacements of the surface exist only in the quasilongitudinal mode, the given piezoceramic wafers responded only to that part of the acoustic field. Note that each glass sample could only be used for one measurement.

The electrical pulse obtained from the output of the piezoelectric element in the event of crack formation was sent to the input of a DL 1080 programmable transient recorder, which was equipped with a long-term memory. The sweep of this recorder was triggered directly by the investigated signal, which could be stored subsequently in the recorder for a time period that was adjustable from 0 to 10 ms; the signal could also be displayed on the oscilloscope in the form of a periodic pulse train when the sweep had the necessary duration. The necessary output signal was recorded on the graphic recording instrument and used for the subsequent treatment. Total "sounding" time of the glass sample due to reflection of the excited cracks of the acoustic waves on the facings of the glass plate was 100 msec.

Typical time dependence u(t) of the recorded piezoceramic signal was recorded on the graphic recording instrument with a 250 μs sweep time; a typical trace is shown in Fig. 2. It is evident from the figure that the recorded signal has a rather complicated form, as it carries information not only about the primary acoustic signal emitted directly by the crack, but also about the transfer characteristic of the glass plate, which distorts the useful signal considerably. To separate out the latter factor, the spectrum u(ω) of the received signal was calculated on a computer for each measurement. A fast Fourier transform (FFT) algorithm was used. Figure 3 shows the spectrum u(ω) (curve 1) for the signal plotted in Fig. 2. The jaggedness of the spectrum is attributable to the resonances of the glass plate.

The degree of excitation of a particular mode is known to depend on the geometry and spatial position of the source. Inasmuch as the dimensions of the generated cracks (2-4 cm) were considerably smaller than the characteristic wavelengths of the acoustic waves emitted by them, we were able to treat the cracks as point sources for simplicity. Since the generated cracks were oriented at an angle relative to the edges of the plate and were located at some distance from them, a set of modes of the glass plate, including the lowest modes, was excited in every case. The total number N of modes with frequencies higher than some specified value ω can be estimated approximately in the case of large solid samples, for which boundary effects can be neglected, by means of the well-known Debye equation used in calculations of the lower-temperature heat capacities of solids. In the investigated two-dimensional case, this equation has the form

\[ N = \frac{5}{2} \left( \omega_{\text{max}}^2 + 1 \right) \left( \frac{1}{c_L^2} + \frac{1}{c_T^2} \right) \]

where S is the surface area of the glass plate, c_L is the velocity of shear bulk waves, and c_T is the velocity of the lowest quasilongitudinal mode in the plate, evaluated as \( \omega \to 0 \), i.e., the so-called "plate" velocity. The value of the latter is expressed in terms of the parameters of the unbounded medium by the relation

\[ c_T = 2c_L \left( 1 - \left( c_T/c_L \right)^2 \right)^{1/2} \]

in which c_L is the longitudinal wave velocity in the material. The error of the equation in the calculation of N for real solid plates with free edges is proportional to the total edge perimeter and is analogous to the error associated with neglect of the contribution of the surface to the heat capacity of a solid (surface heat capacity).

It is readily verified that, e.g., the frequency interval 10-20 kHz contains \( \sim 14 \) modes, the interval 20-30 kHz contains 29, and the interval 30-60 kHz already contains 81 modes. Thus, if our spectral range of interest 0-100 kHz is partitioned into, say, ten subintervals of 10 kHz each, then each one will contain modes with antinodes at the crack site. These modes are excited with the same maximum possible efficiency for a point source. The same considerations also apply to the receiving piezoceramic wafer, whose spatial position induces additional mode selection (the wafer, of course, can also be treated as a point element).

Thus, the transfer function of the glass plate with the crack and the piezoceramic wafer represents a comb with approximately equal maximum amplitudes of the resonances peaks corresponding to the most efficiently generated and received modes. The specific form of the comb, of course, depends on the locations of the crack and the piezoceramic wafer. All that matters in the ensuing discussion, however, is the fact of the existence of a large number of resonances of the maximum possible amplitude in the transfer characteristic.

We assume on the basis of the foregoing that the emission spectrum \( u_\text{e}(\omega) \) of the crack per se, according to the properties of the Fouriertransform.

![Figure 2](#)

**Figure 2.** Typical time trace of an AE signal recorded by the piezoceramic wafer; the crack length is 2x = 1.8 cm. 387 Sov. Phys. Acoust. 32(5), Sept.-Oct. 1986

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form, represents the envelope of the spectrum \( u(\omega) \) through the tops of the strongest resonance peaks in the spectrum of the received signal. The center frequencies \( \omega_0 \) corresponding to the spectral peaks were determined from the spectrum \( u^T(\omega) \) obtained in this manner. The observed values of \( \omega R/\omega_0 \), where \( \omega R \) is the velocity of a surface acoustic wave (SAW) that is similar to a Rayleigh wave and propagates along the plane of the crack, was represented by the points in Fig. 4 as a function of the length \( 2t \) of the generated cracks.

We now undertake a theoretical interpretation of the results. We regard the glass plate as extending to infinity in area, and we introduce a coordinate system with the \( x \) axis directed along the edge of the plate, and the \( z \) axis directed along the normal to it. We express the displacement components \( u_x \) and \( u_z \) of the acoustic field created by the crack in terms of the scalar Lamé potentials \( \varphi \) and \( \psi \):

\[
\begin{align*}
  u_x &= \varphi /\partial z - \psi /\partial x, \\
  u_z &= \varphi /\partial x + \psi /\partial z.
\end{align*}
\]

According to Ref. 6, the spectra of the potentials \( \varphi(\omega) \) and \( \psi(\omega) \) are related one-to-one with the spectrum \( u^L_2(\omega, k) \) of the normal displacements of the edges of the cracks:

\[
\begin{align*}
  \varphi(\omega) &= \frac{1}{2\pi} \int_{-\infty}^{\infty} u^L_2(\omega, k) \frac{2k^2 - \omega^2/c_1^2}{(\omega/c_1)^2 - k^2} e^{-i\omega t_1} e^{i\omega t_2} dk, \\
  \psi(\omega) &= \frac{1}{2\pi} \int_{-\infty}^{\infty} u^L_2(\omega, k) \frac{2k}{\omega/c_1^2} e^{-i\omega t_1} e^{i\omega t_2} dk,
\end{align*}
\]

where the presence of the wave number \( k \) in \( u^L_2(\omega, k) \) takes into account the geometrical growth of the crack from the nuclear stage to its macroscopic length \( 2t \).

The determination of the function \( u^L_2(\omega, k) \) poses a complex and as yet not completely solved problem in the physics and mechanics of fracture (Refs. 2, 3, and 7). Accordingly, we use a simplified model to interpret the experimental data, where it is assumed that the crack grows instantaneously (at an infinite rate) to the length \( 2t \), then its edges spread apart, and it tends to its static position (as \( t \to \infty \)). This crack-opening process is responsible for the acoustic emission from the crack within the framework of the given model. It is clear that the model does not correctly describe the behavior of the leading edge of the emitted signal. However, according to the classical concept, the growth rate of a crack can attain the Rayleigh surface wave velocity, and so the actual distortion is significant only for the first period of the oscillations in the received signal. The function \( u^L_2(\omega, k) \) in the model of the instantaneously generated crack depends degenerately on \( \omega \) and \( k \), i.e.,

\[
u^L_2(\omega, k) = u^L_2(\omega) \xi(k),
\]

where the function \( u^L_2(\omega) \) represents the spectrum of the normal displacement at the center of the crack.

Even within the framework of the above-described simplified model, the calculation of the acoustic field according to Eqs. (1) and (2), in particular the experimentally measured field \( u^T(\omega) \) of normal displacements of the surface, poses a complex problem. The integrals (2) are analytical only in the wave zone, where the steepest-descent method is applicable, i.e., for \( \omega /c_1 t_1 > 1 \) where \( t_1 \) is the distance from the center of the crack to the observation point. The main contribution to the longitudinal displacement field \( u^L_2(\omega) \), which is associated with the greater part of the energy of the crack-induced quasimodal mode, is given by the first integral (2) in this case, and if the ellipticity of the crack opening is neglected, the expression for \( u^L_2(\omega) \) acquires the form

\[
u^L_T(\omega) = u_4(\omega) \frac{\sin \omega t_1}{c_1} \left( \frac{\omega/c_1}{\omega} \sin \omega t_1 - \frac{c_1^2}{c_1} \sin^2 \omega t_1 - 1 \right)
\]

Here \( \omega \) is the angle between the normal to the surface of the crack and the direction to the observation point. Taking into account the fact that \( r \sim 10-15 \text{ cm} \) in the experiments, we find that Eq. (3) is valid for frequencies \( \omega /2t \approx c_1 /r > 10 \text{ kHz} \). In the opposite limiting case \( c_1 /r \ll 1 \), i.e., in the nonwave zone, it follows directly from the boundary conditions at the edges of the crack that the relation \( u^T(\omega) = u^L_T(\omega) = u^L_2(\omega) \) holds at \( \omega \approx 0 \). In the intermediate frequency range it is necessary to calculate the generated acoustic field numerically.

To transform from the longitudinal displacements \( u^L_2(\omega) \) to the experimentally measured normal displacements \( u^T(\omega) \) of the surface of the glass plate, it is sufficient to use the familiar relation (see, e.g., Ref. 2)

\[
\begin{align*}
  u^T(\omega) &= \frac{\nu h}{2(1-\sigma)} \frac{v h}{\nu h} \frac{\nu h}{\nu h} \frac{\nu h}{\nu h},
  d \omega^n
\end{align*}
\]

where \( \nu \) is the Poisson ratio of the plate material, and \( h \) is its thickness. As a result, the spectrum \( u^T(\omega) \) differs from the spectrum \( u^L_T(\omega) \) by a factor \( \nu h \).

The existing results of numerical calculations of \( u^L_2(\omega) \) (Refs. 2 and 7) indicate that this function has an ascending part, which is superimposed on the \( \omega^{-1} \) law characterizing the process of the crack geometry approaching its static form monotonically. In the time domain this result reflects the fact that the function

\[
u^L_2(t) = \int_{-t}^{t} u^L_2(\omega) \exp(-i\omega t) d\omega
\]

contains oscillations, i.e., the displacements of the edges of the crack tend to the static value \( u^L_2 = 2t^2/c_1^2 \), following an oscillating path. Here \( \phi \) is the stress preceding fracture, and \( \rho \) is the density of the medium. Similarly, it is obvious that the spectrum of longitudinal displacements includes the AE field \( u^T_T(\omega) \). However, the spectrum \( u^T_T(\omega) \) is

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(ω) of experimental recorded normal displacements of the sample surface now contains a conspicuous
maximum, which was observed in the experiments, at the ascending part of the spectrum. The func-
tion υT(ω) plotted according to the analytical data for u2(ω) (Ref. 2 and 7) is shown in Fig. 3 (curve
2). It is seen that the spectrum υT(ω) is qualita-
tively consistent with the experimental curve υT(ω)
frequency range. The decay of the experi-
mental curve υT(ω) as ω → 0 is explained by the experimental curve υT(ω) as ω → 0 is explained by
the influence of the frequency responses of the piezoelectric wafers used in the experiments,
whose sensitivity, as mentioned, tended to zero be-

According to the numerical calculations, the frequency of the maximum of the theoretical curve
υT(ω) depends only on the dimensions of the gen-
erated crack and on the elastic parameters of the
medium. For example, ω0 = ωL/26 (Ref. 7) for a
Poisson ratio ν = 0.25, which is typical of the
glasses used in our work.7 This leads to the hy-

The simplest approximate model of such resonance
behavior is one treating the crack as a reso-

A problem of determining the coefficient R of
reflection of the symmetrical Rayleigh mode from
the tip of the crack. According to this solution, the
value of R is equal to 0.285 exp (iπ/2) for a medium
with a Poisson ratio of 0.25. Substituting the value
R = π/2 in Eq. (4), we obtain ω0 = πν/4. We

Consider only the lowest resonance frequency here, be-
cause the influence of higher harmonics in the case
of instantaneous crack formation is negligible accord-
ing to analytical results obtained8 for a simplier model
without radiation into the volume of the plate. The
simply value of ω0 is smaller than the numerical
result by a factor of approximately 1.1/3: ω0 = ωL/26 ≈
2π/26. This indicates that the waves (or, more
precisely, waves in the plate) that are scattered
by the tips of the crack, propagated along its edges,
and decay with distance according to a -x3/2 law,10

We note that the above-described specific fea-
tures imparted to the AE spectra by surface-wave
resonances can be nonexistent in cases where sur-
face waves are unable to propagate along the edges
of the crack for one reason or another. This kind
of situation can arise, e.g., in the case of nucleate
cracks with lengths of a few tens of angstroms. In
this case, the characteristic frequencies of the
acoustic modes are close to the limiting frequencies
of the acoustic modes are close to the limiting fre-
quencies of the crystal lattice, and the influence of
capillary effects can make it impossible for Rayleigh-
type surface waves to propagate.11

Thus, the results of the present study show that
the experimental spectra of the acoustic emission
accompanying brittle fracture in finite plates are
amenable to a realistic theoretical interpretation
based on the model of an instantaneously formed

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