Interaction of Shear Waves and Propagating Cracks

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Shear waves generated from an ultrasonic transducer are used to twist dynamically growing crack fronts; the response of crack front to such external perturbations is examined in order to investigate the primary cause of surface roughening in brittle materials. The response of the crack front is found to be linear in amplitude and frequency of the perturbing wave and without persistence. The response to random perturbations, e.g., by localized material inhomogeneities at the free surface, is also discussed.

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The physical aspects of dynamic fracture continue to pose significant fundamental challenges. While the continuum theory has allowed the determination at least numerically of the energy flux into the crack tip process zone for any dynamically growing crack (see for example [1]), efforts to relate this energy flux to the response of the crack have been only partially successful [2]. Dynamically growing cracks create a crack tip structure of their own — crack surface roughening observed even in nominally brittle materials is a consequence of the fracture processes that are material specific. Such roughness generation has been investigated in different materials, with quite a few different models proposed for the underlying physical origins [3–6]. Analytical investigation of the fracture process zone structure has also elicited much recent interest, driven by the availability of analytical results for the more difficult three dimensional crack problem [7].

Fluctuations in the crack tip structure should result in the release of elastic waves that propagate both into the bulk as well as along the surface. For example, Ravi-Chandar and Knauss [3] argued that the interaction of elastic waves within the crack tip process zone provided the appropriate mechanism for the growth of the fracture process zone. Ramanathan and Fisher [8], and Rice and coworkers [9,10] examined such wave interactions in a series of increasingly sophisticated models. The possibility that in-plane and out-of-plane perturbations could persist along the crack surface, resulting in a new kind of waves — crack front waves and corrugation waves — was discovered by these authors. Such waves were suggested to be the possible sources of crack surface roughening, even in brittle materials [5]. Sharon *et al.* [11] generated dynamically growing cracks in 3 mm thick soda-lime glass plate specimens; perturbations were introduced by scribing one face of the plate with a 100–1000 μm deep groove. Postmortem examination of the crack surface indicated surface undulations that emanated from the location of the crack front perturbation, traveled across the width of the specimen, reflected off the opposite specimen surface, and bounced back and forth for a distance many times the width of the perturbation. Based on their observations, Sharon *et al.* [11] suggested that such undulations were indeed evidence of crack front waves.

We report here the results of experiments that were designed to uncover the primary cause of surface roughening in brittle materials. Rather than relying on random or uncharacterized perturbations to generate perturbation marks on the fracture surface, in our experiment stress waves of known amplitude, frequency, and polarization were introduced at specific locations along the crack path. These shear waves induce a mode III perturbation in the local loading of the crack front, and twist the crack front *without* fragmentation. This response is found to be *linear* in amplitude and frequency of the perturbation, and without any persistence when the perturbation disappears. The experimental results also suggest that the surface undulations observed by Sharon *et al.* [11] are the signature of the interaction between the crack front and the shear waves rather than the signature of the crack front wave. Implications of our experimental observations on surface roughening are also discussed.

Experimental setup.—The experimental setup is illustrated in Fig. 1. Soda-lime glass is chosen as representative of brittle materials. Parallelipedic specimen of size $51 \times 51 \times 13$ mm in the x (propagation), y (loading), and

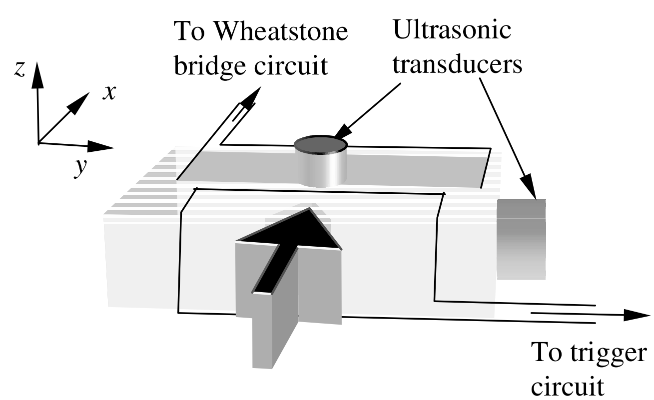

FIG. 1. Experimental arrangement.

z (sample thickness) are loaded in mode I by pushing a triangular wedge into a cut out on one of the two 51×13 mm (y-z) surfaces (Fig. 1). An initial seed crack (5–10 mm long) is introduced at the tip of the wedge cut. Blunt crack tips cut by a diamond saw generate crack speeds in the range of 900–1200 m/s. Sharp cracks introduced by a thermal quenching method [12] are used to grow cracks at speeds ranging from 300–500 m/s. The precise value of the crack speed is measured during the experiment using the potential drop technique [13,14].

Three different transducers (0.5, 5, and 20 MHz) are used to generate a short pulse (2.0, 0.2, and 0.05 μs) of a plane shear wave of spatial extent equal to the diameter of the transducers (25.4, 12.7, and 6.37 mm). Honey is used as a viscous couplant between the transducer and the specimen. The speed C_s and decay rate of shear waves in our specimen were measured to be 3444 m/s and 0.1 dB/mm, respectively. The wavelengths λ of the induced disturbances are thus expected to be 6.9 mm, 690 μm, and 172 μm, respectively. The location of the point where this pulse interacts with the crack can be timed precisely by a trigger signal generated when the crack cuts through a thin conducting line ahead of the seed crack.

Crack response to a localized mode III perturbation.— In the first series of experiments, the ultrasonic transducer is oriented such that the pulse polarized in the $\pm y$ direction propagates in the z direction. The interaction of this shear wave with the growing crack perturbs the crack front and generates tracks running along the crack surface that are readily visible to the unaided eye. These tracks are rendered visible when photographed in a shadowgraphic arrangement — a slight defocusing of the specimen enables better visualization [Fig. 2(a)]. The interaction between the shear wave and the crack front is observed to persist for quite a long time, and to continue upon sequential reflections of the shear wave from the opposite sides of the specimen. The profile of the surface perturbations is measured in an interference microscope. A reconstructed topographic image obtained with this technique is shown in [Fig. 2(b)]; details of the image processing method used are described elsewhere [14]. It is apparent that along the trace of the interaction of the shear wave with the crack front the crack surface undulates out of the x-z plane. From measurements of the peak amplitude as a function of the distance traveled by the shear wave, it is seen that the amplitude decay matches the 0.1 dB/mm decay rate of the shear wave [Fig. 3(a)]. Qualitatively similar features were observed in repeated experiments with ultrasonic modulation at 0.5 and 20 MHz; profiles of the crack surface undulation along lines $z = 0$ are shown in Fig. 3(b) for three different experimental conditions indicated. These results indicate that the amplitude and wavelength of the surface undulation depend on the perturbing shear wave as well as the crack speed.

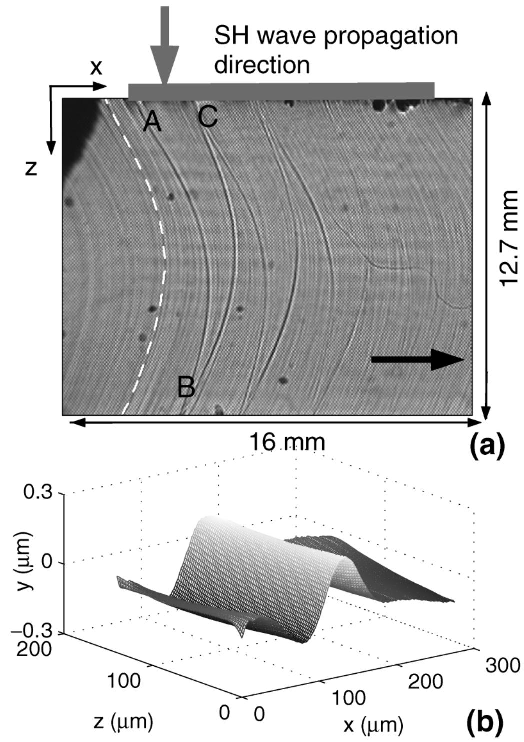

FIG. 2. (a): Shadowgraph of the fracture surface in glass indicating the line of interaction between the crack propagating from left and right ($f = 5$ MHz, $v = 480$ m/s) and the shear wave propagating in the $\pm z$ direction. Parallel lines, such as the one emphasized by the dashed white line, that appear to be translated along the direction of crack propagation are either arrest lines or undulations of the x-z plane about the z axis. The continuous line that begins at the top left part of the figure at the point marked A and reflects at the plate faces at B, C, represents the interaction between the shear wave and the crack front. (b): Topographic image measured using an interferometric microscope.

We now examine the mechanics of formation of these crack surface undulations. The spatiotemporal domain over which the shear wave and the crack front interact is indicated schematically in Fig. 4(a). Consider the crack propagating along the x direction at a constant speed v; in the thick specimens used in our experiments, the crack front is usually curved — typically of parabolic shape — and at any point the front makes an angle θ with respect to the propagation direction as indicated in the figure. The line of the common space-time interaction between the crack tip and the shear wave is indicated by the dark line in Fig. 4(a). From Fig. 4(b) it can be recognized that the perturbation provided by the ultrasonic shear wave generates a mode III loading on the crack. In response, the crack front twists about the x axis [15] with a corresponding warping of the crack surface. This twist in the crack front is carried along the moving crack front by the shear wave. Thus, the crack plane does not tilt about the z axis to produce the undulation as one might have guessed from postmortem examination of the fracture surface, but does

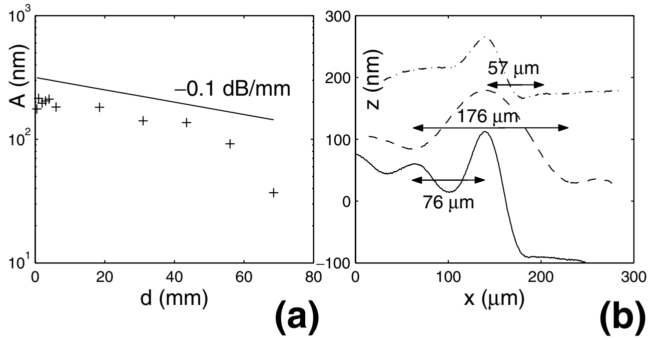

FIG. 3. Topography of the undulation of the crack surface in the x direction. (a) Variation of the amplitude A of the undulation with respect to the distance d from the transducer ($f = 5$ MHz and $v = 480$ m/s). The straight line slope is 0.1 dB/mm. (b): Influence of shear wave frequency f and crack velocity v. Plain: ($f = 5$ MHz, $v = 480$ m/s); dashed: ($f = 5$ MHz, $v = 867$ m/s); dash-dotted: ($f = 20$ MHz, $v = 895$ m/s). Data have been shifted vertically for clarity. The corresponding wavelength λ_x is marked on the figure.

a twist about the x axis. The wavelength of the crack surface perturbation can now be related quantitatively to the wavelength of the shear wave. In the time $\tau = \lambda/C_s$, the shear wave travels through a length λ in the z direction and the crack moves through a length $\lambda v/C_s$ in the x direction. From Fig. 4(a), it is clear that the shear wave interacts with the crack front over a length $\lambda_{\text{cf}} = \lambda[\sec(\theta) + v/C_s]$. When the undulation is measured along the x direction the corresponding wavelength is $\lambda_x = v\lambda/C_s$. Figure 3(b) shows the undulation of the crack surface for the following: $f = 5$ MHz, $v = 480$ m/s; $f = 5$ MHz, $v = 867$ m/s; and $f = 20$ MHz, $v = 895$ m/s. The measured wavelengths λ_x are 76, 176, and 57 μm, respectively, in agreement with the theoretical values 96, 174, and 45 μm obtained from the preceding equation. It is worth mentioning that these tracks are similar to the ones observed by Wallner [16] on fracture surfaces of glass *without any external source of shear waves*, and identified by him as interactions of the crack front with shear disturbances generated by random sources on the glass specimen.

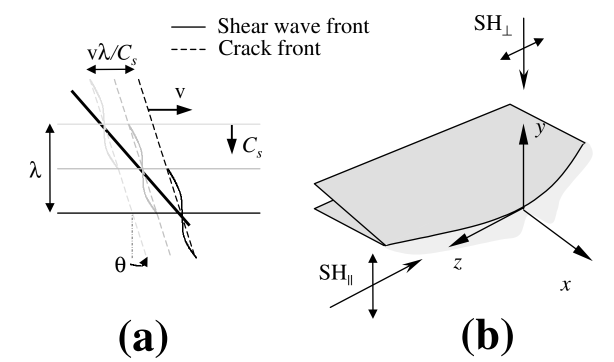

FIG. 4. (a): Sketch of the interaction of the shear wave and the crack front at three successive time steps. (b): Schematic diagram of the interaction of shear waves with crack fronts.

On the persistence of the surface markings.—In the second series of experiments, the location of the transducer was changed: with reference to Fig. 1, the transducer was placed on the x-z plane at one end of the specimen, and the shear wave was propagated in the y direction, with the polarization in the $\pm z$ direction. Now, the shear wave interacts with the crack, passes through the crack plane, then reflects from the other boundary of the specimen and arrives again at the crack plane; since the pulse length is only about 690 μm, the ultrasonic shear pulse interacts with the crack at discrete times corresponding to the arrival of the ultrasonic pulse at the crack plane, and then only for a short duration each time due to the short burst of the pulse [17]. Corresponding to each interaction of the shear wave with the crack front, a surface undulation feature was observed as shown in shadowgraph in Fig. 5(a). In the time taken for the shear wave of pulse length $\lambda = 690$ μm to move across the crack plane, the crack moves by about 96 μm and hence the track marked on the fracture surface corresponds very nearly to the shape of the crack front.

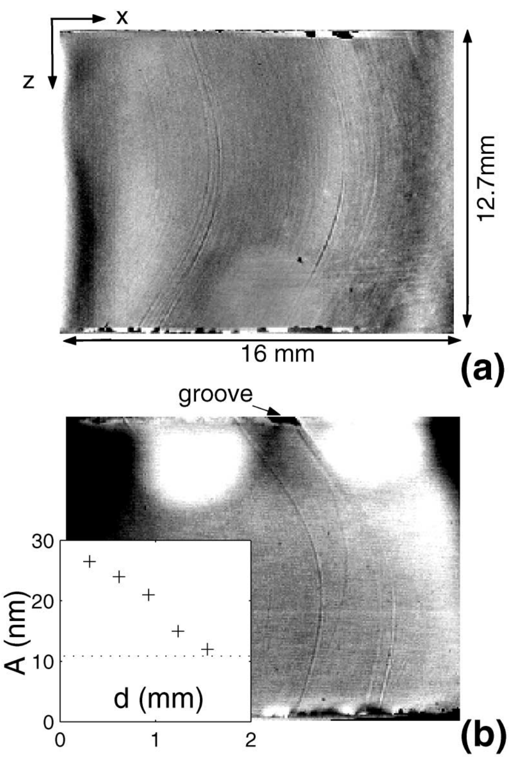

FIG. 5. Shadowgraph of the fracture surface (a) when the 5 MHz transducer is placed so that the shear wave propagates in the y direction with a polarization in the $\pm z$ direction and the fracture surface when (b) the perturbation is induced by scribing a groove. The inset shows the variation of the undulation amplitude A with respect to the distance d from the groove. The dotted line represents the limit of measurement resolution, around 10 nm.

However, when the shear wave moves beyond the crack plane, the perturbations disappear. The reflections of the tracks that were observed in the first experiment are not seen here, which allow us to relate unambiguously the persistence of the surface undulations in the first experiment to the persistence of the shear waves.

On random perturbations.—In the third series of experiments, a perturbation was introduced by scribing a groove on the surface $z = h/2$ with a diamond tool as in the experiments of Sharon *et al.* [11]. Wallner lines similar to the ones observed in the first two experiments were again seen [Fig. 5(b)]. However, the undulation amplitude decays much faster than observed in the first series of experiment [inset of Fig. 5(b)]. The amplitude becomes smaller than the resolution of the interferometric measurement (around 10 nm) after a propagating distance of the order of a few mm, although it remains visible on the shadowgraph image. This can be understood as follows: From the free body diagram of the system, one can show that any disturbance introduced through inhomogeneities on the plane $z = \pm h/2$ must induce shear stresses that produce mode III on the crack or a normal stress that is parallel to the crack line. But the groove may be considered to be a point source and hence the radiated stress waves are subject to a geometric $1/r^2$ decay (r being the distance from the point source) while the ultrasonically generated shear waves were plane waves decay without geometric attenuation below the transducer.

Discussion.—The experiments reported in this Letter explore the interaction of shear waves with propagating crack fronts and evaluate the persistence of crack front perturbations. Three main conclusions are evident: (i) shear waves introduced from the plate surfaces induce a mode III loading on the crack front, and in response the crack front twists; (ii) the interaction is linear, with the amplitude, frequency, and decay of the crack surface perturbations matching the underlying shear wave that transmits the perturbations to the crack front, and (iii) there is no persistence of the perturbations on the crack front. These conclusions enable a discussion of crack front waves and surface roughening. The similarities between the perturbations driven by the plane shear waves and the perturbations generated by a scratched groove suggest that surface undulation markings found on fracture surfaces are indeed Wallner lines and not crack front waves. In contrast to the observations of Sharon *et al.* [11], we find that the surface undulations continue to decay to levels that are below the limit of measurement resolution 10 nm. The lack of persistence of the surface undulations when the shear wave is removed from the crack plane suggests that if crack front waves were to exist, they are below the threshold of measurability; such small undulations cannot lead to roughening.

We must point out, however, that there remains the question of large amplitude perturbations. In all of our experiments, crack growth was driven primarily by an opening mode loading introduced by the wedge and the ultrasonic waves merely provided a small amplitude perturbation. Sommer's experiments [15] make it clear that under larger mode III perturbations, the crack front must fragment. The physical origin and the length and time scales of such fragmentation still require careful study.

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