INTERACTION OF PROPAGTING CRACKS AND SHEAR WAVES

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Summary: 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 to random perturbations, introduced by localized material inhomogeneities at the free surface, is also discussed.

INTRODUCTION

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. Ramanathan and Fisher (1997), and Morrisey and Rice (1998) 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 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. Sharon *et al*., (2001) generated dynamically growing cracks in soda lime glass plate specimens; perturbations were introduced by scribing one face of the plate with a 100 - 1000 μm deep groove. Post-mortem 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*., (2001) suggested that such undulations were indeed evidence of crack front waves. Here we report on an experimental investigation aimed at examining the interaction between propagating cracks and shear waves (Bonamy and Ravi-Chandar, 2003a, b).

CRACK RESPONSE TO A LOCALIZED MODE III PERTURBATION

Soda-lime glass is chosen as representative of brittle materials. Parallelipedic specimen of size 51 x 51 x 13 mm in the x (propagation), y (loading) and z (sample thickness) are loaded in mode I by pushing a triangular wedge into a cut out on one of the two 51 x 13 mm (y-z) surfaces. An initial seed crack (5-10 mm long) is introduced at the tip of the wedge cut. The precise value of the crack speed is measured during the experiment using the potential drop technique. Three different transducers (0.5 MHz, 5 MHz and 20 MHz) are used to generate a short pulse (2.0 μs, 0.2 μs and 0.05 μs) of a plane shear wave. 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.

The transducer is oriented such that the pulse polarized in the y-direction propagates in the z-direction. The interaction of this shear wave with the crack growing along the x direction in the x-z plane, 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. 1). 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. From these measurements, it was 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 was seen that the amplitude decay matched the 0.1 dB/mm decay rate of the shear wave. Qualitatively similar features were observed in repeated experiments with ultrasonic modulation at 0.5 MHz and 20 MHz. These results indicate that the amplitude and wavelength of the surface undulation depend on the perturbing shear wave as well as the crack speed.

The spatio-temporal domain over which the shear wave and the crack front interact is indicated schematically in Fig. 2a. 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. 2a. From Fig. 2b 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 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 post-mortem examination of the fracture surface, but does 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. 2a it is clear that the shear wave interacts with the crack front over a length $\lambda_{cf} = \lambda\,[\sec\theta + v/C_s]$. When the undulation is measured along the x-direction the corresponding wavelength is $\lambda_x = \lambda v/C_s$. The measured undulation wavelengths λ_x of the crack surface for ($f = 5$ MHz, $v = 480$ m/s), $f = 5$ MHz, $v = 867$ m/s) and $f = 20$ MHz, $v = 895$ m/s) are 76 μm, 176 μm and 57 μm respectively, in agreement with the theoretical values 96 μm, 174 μm, and 45 μm obtained from the preceding equation. It is worth to mention that these tracks are similar to the ones observed by Wallner, (1939) 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.

DISCUSSION

The experiments reported in this paper 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., (2001), 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 (1969) 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.

D. Bonamy and K. Ravi-Chandar, (2003a), *Phy Rev. Lett.*, **91**, 235502.
D. Bonamy and K. Ravi-Chandar, (2003b), *Int. J Fracture*, submitted 2003.
J.W. Morrissey and J.R. Rice, (1998), *J. Mech. Phys. Solids,* **46**, 467.
S. Ramanathan and D.S. Fisher, (1997), *Phys. Rev. Lett*. **79**, 877.
K. Ravi-Chandar and W. G. Knauss, (1984), *Int. J. Fracture*, **25**, 141; **25**, 247; **26**, 65; **26**, 189.
J.R. Rice Y. Ben Zion and K.S. Kim, (1994), *J. Mech. Phys. Solids*, **42**, 813.
E. Sharon, G. Cohen and J. Fineberg, (2001), *Nature*, **410**, 68.
E. Sommer, (1969), *Eng. Fracture. Mech*., **1**, 539.
H. Wallner, (1939), *Z. Physik,* **114**, 368.

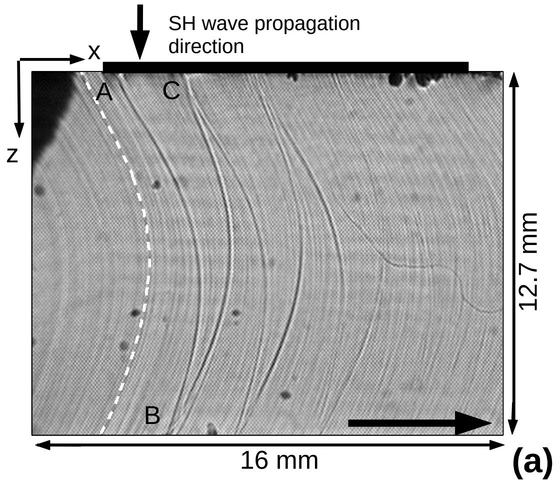

Figure 1. Shadowgraph of the fracture surface in glass indicating the line of interaction between the crack propagating from left and right ($f = 5$ MHz, $v = 480$ m/s) and the shear wave propagating in the z direction. The dashed white line indicates the instantaneous crack front. The continuous line from A to B to C represents the interaction between the shear wave and the crack front.

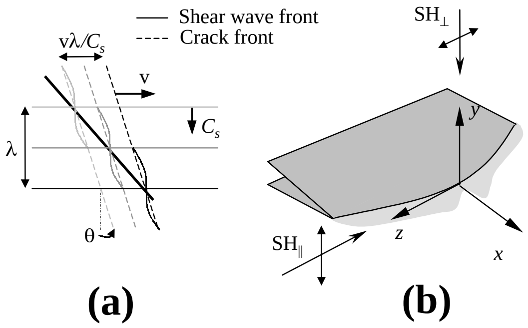

Figure 2. (a): Sketch of the interaction of the shear wave and the crack front at three successive time steps. (b): Schematic diagram of the interaction of shear waves with crack fronts.