FAST FRACTURE IN SLOW MOTION: DYNAMIC FRACTURE IN BRITTLE GELS

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Summary We present recent results of fracture experiments in poly-acrylamide gels. These gels are soft polymers in which the characteristic sound speeds are on the order of a few meters/sec - thereby slowing down fracture dynamics by 3 orders of magnitude. We first show that the dynamics of rapid cracks are universal [1]; the fracture of gels exhibits characteristic features that are identical with those seen in "classic" materials such as glass. Utilizing the "slow motion" inherent in the fracture of these materials, we show that the singular structure of the deformation fields as the tip of a dynamic crack is approached, predicted by Linear Elastic Fracture Mechanics, change their structures due to nonlinear elastic effects that dominate the near-tip region [3]. We then show that the dynamic instability [2] from a straight to an oscillatory path at a critical velocity is directly related to the size of the nonlinear zone surrounding the crack tip. These findings [5] directly verify recent theoretical predictions [4] and suggest that the nonlinear zone is not passive, but rather is closely linked to rapid crack instabilities.

INTRODUCTION

Understanding the dynamics of propagating cracks is extremely important, as crack propagation governs the stability and strength of materials. Here we investigate the fracture dynamics of brittle, amorphous materials. While the fracture dynamics of brittle materials have been the subject of intensive study for over 60 years, our detailed understanding of these critical processes has been hampered by the fact that fracture dynamics are governed by the behaviour of a microscopic and nearly singular region at the tip of a moving crack which is propagating at velocities on the order of material sound speeds. The classic theoretical framework that describes fracture dynamics, called Linear Elastic Fracture Mechanics (LEFM), assumes that materials respond to imposed deformations according to linear elasticity. This theory predicts that the deformation fields in the vicinity of the tip of a crack approach a mathematical singularity. While this theory has been very successful in predicting the motion of simple “straight” cracks, it has been unable to explain crack instabilities that have been observed at high propagation velocities. These instabilities include both “microscopic branching” in which a single crack spawns successive bifurcating “daughter” cracks as well as rapid tip oscillations that take place when the microscopic branching is suppressed.

RESULTS

By using soft materials (poly-acrylamide gels) we are able to slow down fracture dynamics by nearly 3 orders of magnitude. We first demonstrate that all of the characteristic features and instabilities of fracture dynamics that have been observed in “standard” materials, such as brittle glasses, are identical to those that develop in the fracture of brittle gels. We then utilize these materials to study the detailed structure of the deformation fields surrounding the tip of propagating cracks. We first demonstrate that the structure of the singular fields at the tip of simple cracks changes distinctly as the tip of a crack is approached and that these changes result from material nonlinearity as that large strains inherent in the singular region go beyond the regime of linear elastic behaviour. We then briefly outline a new fundamental theoretical description that accounts for elastic nonlinearity and experimentally show that this framework provides an excellent description of the deformation fields measured in the vicinity of propagating crack tips within the gels. In Figure 1 we compare the predictions of both this nonlinear theory and LEFM to the measured strains field in front of propagating cracks at progressively higher velocities. We find that the new theory (with no adjustable parameters) provides an excellent description of these singular strains whereas LEFM becomes progressively worse as the velocity increases.

We then turn to the oscillatory instability of single cracks at high propagation velocities. Figure 2 shows how a simple propagating straight crack becomes unstable to an oscillatory instability as its velocity surpasses about 90% of the shear wave speed. This instability has no explanation in conventional theoretical descriptions of fracture. One intriguing property of the instability is that the observed wavelength is wholly uncorrelated with any geometrical scale characterizing the experimental system. This suggests that the wavelength corresponds to an instrinsic scale. We demonstrate that this scale corresponds to a nonlinear dynamic scale that is incorporated within the nonlinear theory of fracture. This scale corresponds to the size of the region where nonlinear elastic effects dominate the fracture dynamics.

These results indicate that the nonlinear zone is not a passive scale, but instead is closely linked to rapid crack instabilities.

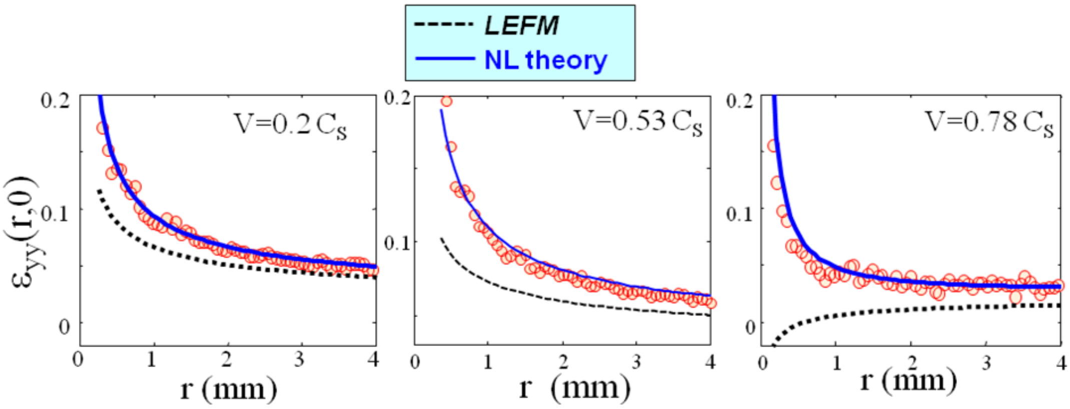

Figure 1: A comparison of the strain field component normal to the propagation direction of rapidly propagating cracks as a function of the distance, r, from the crack tips. Solid lines correspond to a new fundamental theory where elastic nonlinearity of the material is incorporated whereas dashed lines are the LEFM predictions for these fields. The dots are the direct measurements.

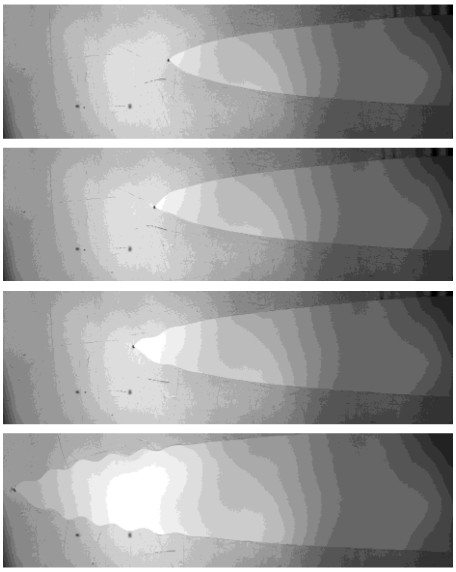

Figure 2: Instantaneous snapshots of a crack propagating in a gel at the onset of the oscillatory instability at propagation velocities approaching 90% of the material shear wave velocity. The initially featureless crack (top) undergoes an oscillatory instability whose wavelength is independent of all geometrical scales in the system. The 2nd and 3rd pictures show the onset of the oscillations, whereas the bottom picture demonstrates the nearly sinusoidal character of the well-developed crack tip oscillations. The horizontal scale of each photograph is 60mm and the photographs were taken at a frame rate of 6500 frames/sec.

References

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