

Unsteady Crack Motion and Branching in a Phase-Field Model of Brittle Fracture.

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Recommended and a commentary by Wim van Saarloos, Leiden University.

The problem of crack propagation is a very old and relevant one, but only during the last 10-15 years have physicists become interested in it. This was due to the accidental discovery by an experimentalist who dropped a piece of plexiglass in the lab, that the fracture patterns are not necessarily simple dull irregular structures. Instead, they show signs of coherent dynamical behavior. E.g., after a short transient, the speed of a propagating crack often reaches some limiting average speed, which is a good fraction (say $1/4$ to $2/5$) of the speed of sound in the material. Moreover, when the crack speed is still low, the crack surface is usually rather smooth. However, when the speed crosses a critical value of the order of the asymptotic speed, the crack surface suddenly becomes much rougher and the crack speed often exhibits strong fluctuations. Often above the critical speed inspection of the crack surface shows that the main crack has emitted smaller cracks to the sides: the cracks branch. In a recent experiment, it was found that by stressing the material in two directions, coherent snake-like oscillations of the propagating crack could be induced.

What makes a theoretical or numerical analysis of crack propagation so difficult is that one cannot get away with a continuum elastic theory only. A continuum elastic theory in which the crack is taken as a mathematically sharp cut is prone to singular behavior - one really has to put in the breaking of bonds or the dissipation of energy near the crack tip into the model to obtain a proper description. Numerically it has indeed become possible, in recent years, to do large-scale molecular dynamics simulations (sometimes matched to continuum elastic models on long scales) which do reproduce many of the experimental features, including the splitting of cracks. However, from such simulations it is still difficult to separate the essentially long-range dynamical behavior from what is intrinsic to a particular short-range molecular potential.

In a recent paper, Karma and Lobkovsky [1] report some exciting progress towards understanding crack dynamics. They use a so-called phase field model for crack propagation, which was developed recently. A phase field model is essentially what most workers in condensed matter physics would simply call a phenomenological order parameter model: one introduces a continuum "phase field" which indicates whether one has a stiff solid or a broken material which does not support stresses, and which interpolates between these two extremes in a thin zone. In the present context, this transition zone is the "process zone" where the breaking occurs. Within such a model, the

atomistic breaking of bonds is not incorporated realistically but it is mimicked by having energy dissipate there.

The numerical advantage of such a model is that simulations of it are relatively simple, and that they allow one to study coherent behavior, which is independent of the precise atomistic details. This is precisely what the authors of [1] have done. First of all, their simulations allow them to test an old engineering idea, which assumes that the instantaneous crack speed is a unique function of the rate of energy flow to the crack zone. This is essentially an adiabatic approximation. The authors find that while the crack is speeding up, there are significant deviations from this relation: significantly more energy flows towards an accelerating crack than to a crack propagating steadily with the same instantaneous speed. This is a sign that dynamical effects (increase of kinetic energy) are quite important in practice. Secondly, the simulations of the authors indicate that the transition to dynamical branching behavior is not governed by an instability, but by the disappearance of solutions that describe steadily propagating cracks. Thirdly, just above the critical speed the authors observe in their model a regime where the cracks propagate in an oscillatory fashion; the frequency is found to be close to that of the lowest harmonic standing wave in the elastic solid. For higher speeds, the crack shows irregular branching behavior. Finally, the model allows the authors to tune the relative importance of the dissipation in the process zone near the crack tip, and hence to explore the relative importance of inertia in comparison with energy dissipation.

In a related paper [2], it was found that an extension of the model allows one to study the coherent snake-like propagation of cracks under bi-axial load. Readers wanting to get a feel for the issues in the field are recommended to look at the introductory review [3] or [4].

[1] A. Karma and A. E. Lobkovsky, Unsteady Crack Motion and Branching in a Phase-Field Model of Brittle Fracture, cond-mat/0401056.

[2] H. Henry and H. Levine, Dynamic instabilities of fracture under biaxial strain using a phase field model, cond-mat/0402563.

[3] J. Fineberg and M. Marder, Instability in dynamic fracture, Physics Reports, vol. 313, pp. 1-108, 1999.

[4] M. Marder and J. Fineberg, How things break, Physics Today, vol. 49, pp. 24-29, 1996.

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