Heterogeneity in dynamic fracture (1,2)

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Abstract

Rapid cracks are the cause of catastrophic mechanical failure. The continuum theory of cracks, Linear Elastic Fracture Mechanics (LEFM), successfully predicts the propagation of cracks along a straight line in homogeneous brittle solids (3-5). Even so, the dynamic fracture of heterogeneous materials is a conundrum. Cracks are 3D entities whose leading edge, the crack front, may locally move faster or slower when cutting through weak or tough regions. The upshot is that the overall energy cost of driving the crack becomes a function of its dynamics rather than a 'static' material property. Thus, a description of the crack front's time-evolving geometry is needed to predict whether heterogeneity makes a material tougher or weaker.
I will show how LEFM can be modified to encompass the dynamics of crack fronts. The pioneering works of Willis and Movchan (6) and Ramanathan and Fisher (7), provide a general scheme for calculating the elastic stresses near a moving crack front as a perturbation series in the crack front fluctuation. However, past efforts only provided explicit tractable expressions for the linear order. We expanded the theory to the second order and obtained the local energy release rate, or the elastic energy per unit area available for fracture, as a nonlinear functional of the front geometry and history. To predict the front dynamics, we locally balance the energy release rate with the energetic cost of fracture. We model the fracture energy as a product ofo a homogeneous part that depends on crack velocity and a heterogeneous part. Energy balance then yields a 1D nonlinear equation of motion for the crack front. A custom GPU-powered code allows us to solve the equation numerically over 2D meshes with up to _˜4 million nodes.

The main result of our calculations is that heterogeneity may have a toughening or, surprisingly, a de-toughening effect. When the fracture energy weakly depends on crack velocity, the nonlinear coupling between the heterogeneous landscape and the front dynamics enhances the energy dissipation and decreases the overall crack speed. This effect is dominant when the crack is slow compared to the Raleigh wave speed, When the fracture energy strongly depends on crack velocity, the heterogeneity may decrease the dissipation and facilitate crack motion. This effect is strongest at intermediate crack speeds. I will show that insights from these solutions can be used to design toughness landscapes that create preferable crack propagation directions and discuss possible extensions of this work.

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