HOW DOES THE CRACK VELOCITY AFFECT THE CRACK FRONT DEFORMATION AND THE EFFECTIVE TOUGHNESS IN HETEROGENEOUS MATERIAL?

Bingbing Hao[1, 2]*, Ashwij Mayya[2], Julien Chopin[3], Yuelei Bai[1] and Laurent Ponson[2]

[1]National Key Laboratory of Science and Technology on Advanced Composites in Special Environments and Centre for Composite Materials and Structures, Harbin Institute of Technology, Harbin 150080, China
[2]Institut Jean Le Rond D'Alembert (UMR 7190), Sorbonne Université - CNRS, 75005 Paris, France
[3]Fisex Lab, Caminho das Arvores, Salvador, BA 41820-790, Brazil
** Presenting Author email: bingbing.hao@outlook.com*

Abstract

In brittle failure, the pinning of the crack by tough obstacles deforms the crack front and ultimately enhance the crack growth resistance of materials. In this study, we investigate the effect of the crack speed v_m on this mechanism through a combined theoretical and experimental investigation of the pinning of a crack by triangular obstacles of various shapes. Our work reveals that crack pinning is hindered when the crack speed gets closer to an intrinsic velocity v_0 that emerges from the rate sensitivity of the fracture energy. Our work suggests that the beneficial effect of collective pinning in disordered materials is optimized in the limit $v_m << v_0$ and vanishes when $v_m \approx v_0$.

1. Introduction

Understanding crack propagation in heterogeneous materials is a topic of fundamental interest as it paves the way for the rational design of tougher materials. The mechanisms controlling the fracture resistance of materials take place in a tiny region near the crack tip. As a result, predicting the effective toughness of heterogenous materials requires a full multi-scale model. In disordered materials, a collective effect is at play when a crack interacts with a random distribution of obstacles [1],[2]. Understanding this collective pinning and ultimately predict the crack growth resistance of a material from its microstructural features is therefore an important challenge for microstructure-based toughness design.

Recently, Chopin *et al.*[3] studied the spatiotemporal evolution of the crack front depinning in experiments with a single rectangular obstacle focusing on the role of toughness contrast C between the inclusion and the matrix. Using a similar experimental setup (see Fig. 1(a)), we explore here the role of the inclusion shape on the process of crack front pinning. We use triangular obstacles of varying shape that are defined by the half-angle β at their apex. We then introduce a microstructural descriptor $\varepsilon = v_{m,local}/v_0$ which is a dimensionless number depending on β that turns out to control the pinning strength. While $\varepsilon \approx 0$ corresponds to the quasi-static solution for which the crack front pinning is maximized, larger values of ε leads to different behaviors that are explored in our study.

2. Results

The change from a rectangular shape to a triangular obstacle of varying width manifests a subtle but important change in the theoretical formulation of Chopin *et al.*[3].

a. The maximum value of the local crack front speed $v_{m,local}$ varies linearly with the inclusion lateral extension rate $\dot{d} = v_{m,local} = v_m \tan\beta$, where β and $2d(x)$ are the half-angle and width of the obstacle, respectively (as shown in Fig. 1(b)). v_m is the average speed of the crack and is imposed by the loading rate of the test machine. As a result, we obtain the microstructural descriptor ε controlling the effective fracture energy of the disordered materials as $\varepsilon = \gamma \tan\beta$ where γ, which is close to 1/3 for the material used in our experiments, characterizes the driving rate sensitivity of the fracture energy.
b. We first derive the kinematic equation of the crack front $\dot{f}(z,x)$ that is moving along the x axis with external driving v_{ext}. We then obtain the evolution form of the crack front pinned by the triangular obstacles $\delta f(z,x) - \delta f(0,x)$ as shown in Fig. 1(b) where $\delta f(0,x)$ is the position along the line passing through the apex. However, the evolution is non-stationary due to the triangular shape of the obstacle. But, upon a rescaling the front amplitude by a $Cd(\mathrm{x})$ and longitudinal coordinate by the instantaneous obstacle width $d(\dot{d}) \times t$, the front collapses on a time independent shape.

c. We identify primarily two distinct regimes in the evolution form of the crack front. At distances closest to the apex axis ($z = 0$), the front assumes a parabolic shape feeling the full impact of the toughness contrast, C. Further away from the inclusion, this effect wanes, finally saturating at a height $\mathcal{H}$ that is inversely related to the microstructural descriptor, ε.

d. The dimensionless form of the microstructural descriptor has important implications. We find the extent to which the interface elasticity comes into play during the depinning dynamics can be controlled by tuning the microstructural descriptor.

e. We analyze the pinned crack fronts for cases with $\tan\beta_1 = 1$ and $\tan\beta_2 = 0.5$. Following the proposed theoretical framework, we expect a significant reduction of the front deformation in the first case ($\varepsilon_1 \approx 0.34$) in comparison to the second case ($\varepsilon_2 \approx 0.17$). Our experimental observations are shown to be in good agreement with these theoretical predictions, see Fig. 1(c).

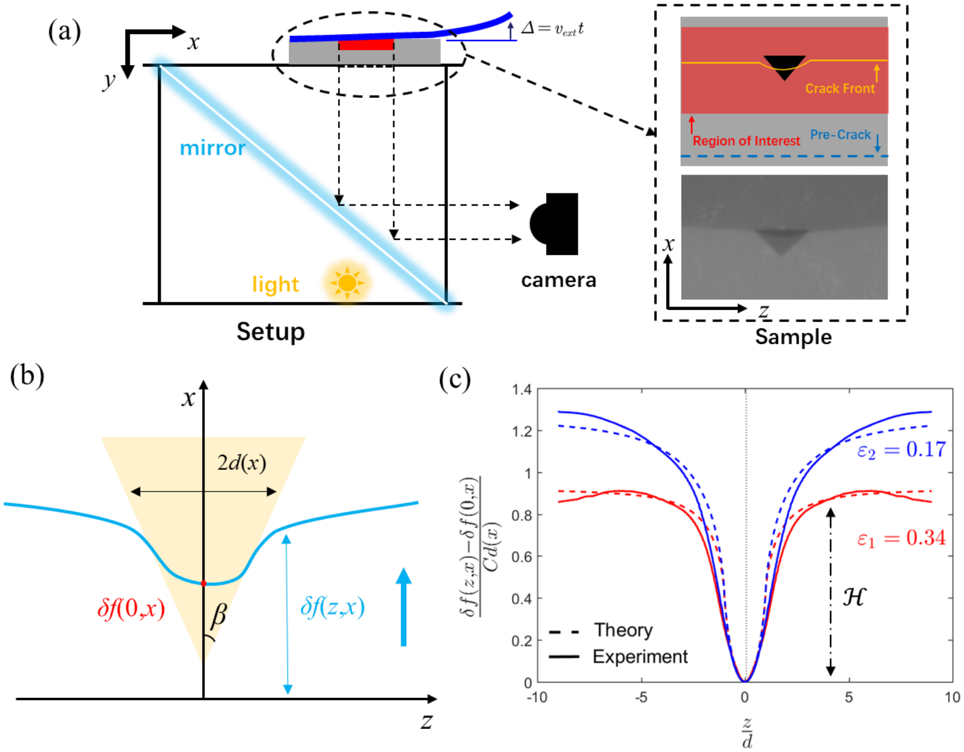

Fig. 1 (a) Schematic of peeling experimental setup and sample, (b) Schematic of a crack front pinned by a triangular obstacle, (c) Comparison of the stationary form $\delta f(z,x) - \delta f(0,x)\ /Cd(x)$ of the pinned crack front for different triangular obstacles with $\tan\beta_1 = 1$ (red line) and $\tan\beta_2 = 0.5$ (blue line).

3. Conclusions

We show that the crack front motion through a disordered media can be controlled by the shape of the heterogeneities, besides their toughness contrast. Our study lays foundation for a new mechanistic paradigm in studies of toughness design where the shape and the patterns of obstacles are chosen by considering the beneficial nature of collective effects.

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