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Morphology and dynamics of a crack front propagating in a model disordered material

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ABSTRACT

We present an experiment on the morphology and dynamics of a crack front propagating at the interface between an elastomer and a glass slide patterned with a prescribed distribution of defects. Regimes of high and low pinning strength are explored by changing the fracture energy contrast of the defects. We first analyze the roughness of crack fronts by measuring their typical amplitude in real and Fourier space. Irrespective of the pinning regime, no well defined self-affine behavior is found which may be explained by the emergence of an intermediate lengthscale between the defect size and the sample size. Then, we show that the dynamics at high fracture energy contrast results in rapid jumps alternating with periods of arrest. The distributions of speeds, displacements and waiting times are found to have an exponential decay which is directly related to the distribution of distances between defects along the direction of propagation.

1. Introduction

Due to progress in micro fabrication, microstructure of materials can be tailored to achieve unprecedented macroscopic properties such as negative Poisson ratio (Yang et al., 2004), superhydrophobicity and omniphobicity (Bonn et al., 2009), reversible and strong adhesion (Geim et al., 2003; Chan et al., 2007; Xia et al., 2012) and anti-biofouling property (Epstein et al., 2012). Regarding the mechanical properties, the addition of particles is well known to enhance mechanical properties, like in adobe, particles-loaded rubber (Mower and Argon, 1995), or nanosheets made of clay-reinforced composites (Alexandre and Dubois, 2000). Although remarkable achievements have been made over the past decade, it is still poorly understood how large-scale mechanical properties are linked to characteristics of the microstructure such as size and distribution of heterogeneities, or strength of bonding of heterogeneities and surrounding matrix. This link is crucial to predict and optimize the mechanical stability of multilayered composite materials or, in the context of safety, the service lifetime of engineering structures.

Fractography is one of the most useful tools to determine the cause and dynamics of failure of a material. It relies on a visual inspection of the postmortem cracked surfaces (Hull, 1999). Some morphological features are specific to modes of failure such as periodic strips in fatigue crack (Suresh, 1998) or facets for brittle crack (Lawn, 1993). A morphological feature

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found in heterogeneous material is the fractal (or self-affine) geometry of broken surfaces. Since the seminal work by Mandelbrot et al. (1984), numerous experimental characterizations with a wide range of materials and fracture protocols have been carried out to check the scale invariance and to measure associated roughness exponents (Bouchaud et al., 1990; Engoy et al., 1994; Plouraboué et al., 1996; Ponson, 2007; Dalmas, 2008). This specific morphology has been interpreted as the result of a critical dynamics during the crack propagation through the heterogeneous material (Bouchaud, 1997; Bonamy, 2008, 2009).

To the best of our knowledge only one experimental setup developed by Schmittbuhl and Måløy enables testing this interpretation by the direct visualization of the crack front dynamics (Schmittbuhl and Måløy, 1997). In this setup, a crack front propagates at the interface of two sintered Plexiglas plates. Before sintering, the plates are sandblasted to induce a disorder with a typical size given by the diameter of projected beads. Using a subtle statistical analysis, they obtained information on the shape and the dynamics of the crack front (Delaplace, 1999; Santucci et al., 2010). For scales larger than the typical size of heterogeneities, they found that crack propagation is well described by models first introduced by Gao and Rice (1989), and improved later on Schmittbuhl et al. (1995). Critical exponents characterizing the morphology (roughness exponent) and dynamics (scale-free avalanches) are found to agree with theoretical predictions (Bonamy, 2008, 2009). However, at smaller scale, the crack propagation is explained by another scenario based on growth by coalescence of microcracks which accounts for the unexpectedly high roughness exponent at that scale (~ 0.6). While the interpretation of their experimental results brings a coherent picture of the crack front dynamics in their setup, some aspects need to be clarified. First, there is no clear experimental evidence of a diffuse front moving by microcracks coalescence at small scale. Second, the lengthscale separating the roughness regime is located in the middle of the observation window and, thus, prevents a clear identification of both roughness regimes over a large range of lengthscales. Therefore, a better understanding of the rupture process at the microstructure scale and a better control of the disorder are needed. Along these lines, other setups have been developed to enable a better control of deterministic heterogeneities using lithographic techniques (Chopin et al., 2011) or micro-machined interfaces (Dalmas et al., 2009), and experimental results were often in quantitative agreement with models developed within the framework of Linear Elastic Fracture Mechanics (LEFM). However, the case of a completely disordered interface has not been considered yet with these approaches.

In this paper, we present an original experimental setup where the shape and dynamics of a crack front are analyzed while propagating through an interface patterned with a prescribed random distribution of defects. We address the influence of the distribution of defects on the front shape and dynamics. Our experimental results will be interpreted in the framework of LEFM for which dissipative processes are assumed to be localized in a small region around the crack tip (the process zone) and are traditionally characterized by a fracture energy Γ. The crack front will propagate if the loading is high enough to overcome the energetic cost to create a new interface which happens when $G > \Gamma$, where G is the elastic energy release rate, i.e. the elastic energy released during fracture per unit of newly created fracture surface area. Consequently, the crack is at equilibrium when $G = \Gamma$. When a material is heterogeneous because of, for example, voids or inclusions, the fracture energy presents spatial fluctuations that are responsible for the distortion of crack front shape. For moderate fracture energy contrast, the crack front is slightly distorted at the defect scale and is then amenable to perturbative approaches (Gao and Rice, 1989). In this regime, the crack front can be understood as an elastic line with a nonlocal elasticity forced by a quenched noise (see Kardar, 1998, for a review). It was found that at small scale, the crack front presents smooth deformations and continuous dynamics. Above a crossover which depends on the system size and on the characteristics of the disorder, numerical and theoretical results show that the crack front shape has scale invariant properties with self-affine behavior (Roux et al., 2003; Patinet et al., 2013; Démery, 2014). Moreover, the crack propagates intermittently through avalanches which consist of rapid events where a part of the front moves from one pinned configuration to another. This regime at large scale has been studied intensively but no clear agreement of the predicted roughness exponent with experimental data has been obtained so far (Schmittbuhl and Måløy, 1997; Delaplace, 1999; Santucci et al., 2010). Many reasons have been proposed to explain this disagreement: the influence of nonlinear terms in the elastic energy release rate (Adda-Bedia et al., 2006), finite size effects (Katzav et al., 2007; Leblond, 2003; Patinet et al., 2013), artifacts in the analysis of experimental data (Schmittbuhl et al., 1995; Bakke and Hansen, 2007), or more fundamentally the questioning of the validity of LEFM approach (Hansen and Schmittbuhl, 2003).

The paper is organized as follows. In Section 2, we describe the experimental setup, the fabrication of the sample using lithographic techniques, the method of visualization and extraction of the crack front shape over time. Two regimes of pinning strengths are explored by changing the fracture energy contrast from a high to a low value. In Section 3, we analyze the roughness of the crack front shape using statistical tools. In either regimes, the fluctuations do not show scale invariant behavior over significant ranges of lengthscales. This result is explained by the emergence of an intermediate lengthscale which is the geometrical mean of the defect size and the size of the sample. This lengthscale is derived by calculating the shape of crack front pinned by a single defect taking into account a finite crack length. In Section 4, we analyze the statistics of front dynamics by calculating the distributions of speed and displacement in both regimes. For high fracture energy contrast, we find that the crack dynamics is slaved to the distribution of defects through the distance between pinning points.