DYNAMICS OF INTER-FACIAL CRACK FRONT PROPAGATION

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Abstract. Here we report on *in situ* observations with a high speed CCD camera of an in-plane crack propagating through a transparent heterogeneous Plexiglas block. The toughness is controlled artificially and fluctuates spatially like a random noise. A stable crack in mode I was monitored by loading the system by an imposed displacement. We show that the movement of the fracture front is controlled by local instabilities triggered by the depinning of asperities even for very slow loading. Development of crack roughness is described in terms of a Family-Vicsek scaling with a roughness exponent $\zeta = 0.60$ and a dynamical exponent $\kappa = 1.2$.

Keywords: Inter facial fracture, roughness, depinning, local dynamics

Introduction

In this experiment we studied the dynamics of a slow inter-facial crack front line during its propagation through a transparent heterogeneous Plexiglas block. We found that the slip in the front line along the fracture interface is strongly correlated over scales much larger than the width of the fracture front and that the front moves in irregular bursts [1]. In contrast to the experiment presented here, most experiments are performed with unstable fractures which exhibit fast propagation of the order of the speed of sound. The fast propagation makes it very difficult to study dynamics. Direct observation of the crack front is usually impossible and an inverse description of the crack front obtained for instance from acoustic emissions is generally observed with a low spatial resolution.

Most studies on fractures have focused on homogeneous materials. The role of heterogeneities has been addressed more recently. Fracture surfaces have been found to exhibit self-affine long range correlations [2, 3, 4, 5, 6, 7, 8, 9]. However, the physical origin of it is still not fully understood. Static elasticity leads to long range interactions [8, 10] but in addition elastic waves specially recently observed crack front waves [11, 12, 13, 14, 15] may play an important role. In most modeling of fracture dynamics in heterogeneous materials the latter are ignored since a quasi static assumption is used. A recent quasistatic simulation presented by Hansen et. al [16] (see this proceeding) shows results consistent with our experiments.

Experimental method and results

In this work we present an experimental study of a stable slow fracture propagating along an annealed interface between two Plexiglas blocks [17, 18, 19, 1]. Crack fronts are directly observable because of the

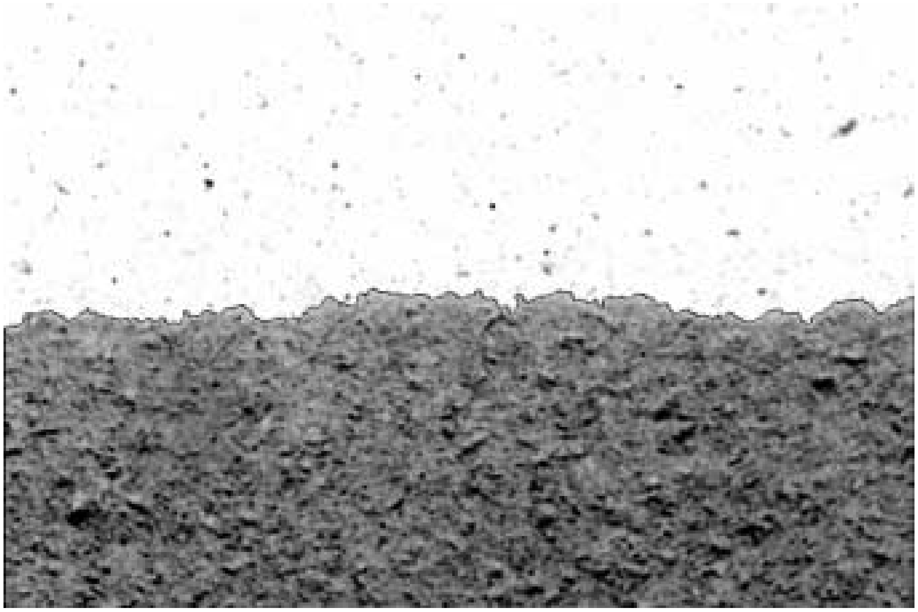

Figure 1: Sample of crack fronts. The background is an inverted raw image where the intact material appears white. In contrast, the cracked zone is dark. Crack propagates in this case from bottom to top because of a tensile load.

transparency of the material. Plates are : $32cm \times 14cm \times 1cm$ and annealed together at $205°$ C under several bars of normal pressure. The annealed surface corresponds to a weak plane which the fracture will propagate along. Before annealing, both plates are sand-blasted on the side to be annealed with $50\mu m$ steel particles. The sand-blasting procedure introduces a random roughness which induces local toughness fluctuations during the annealing procedure. Since the sand-blasting gives a cutoff of the structure in the plates of about $50\mu m$, we do not expect correlated toughness above this length scale. One of the plates is clamped to a stiff aluminum frame. A normal displacement is applied by a press to the other plate which induces a stable crack propagation in mode I at constant low speed ($68\mu m/s$). The fracture front is observed with a microscope linked to a high speed Kodak Motion Korder Analyzer camera which records 8.7s at 500 images per second with a 512x240 pixel resolution. We also performed experiments with a normal speed Kodak DCS 420 CCD camera which has a resolution of 1536x1024 pixels. This camera was used after loading when the fracture had come to rest. The visualization setup is mounted on a translation table with possible movement parallel to the propagation plane (x, y) controlled by two stepping motors.

In Fig. 1 is shown a sample image obtained with this setup. The uncracked part is seen as white while the gray region represents the open fracture. The front is defined as the contrast boundary. Let V be the local front velocity in the direction of the front normal. The velocities V at all front positions were calculated by measuring the distance δl, along the normal, to the intersection with the front that is $20ms$ later. The distributions of the velocity V is shown in Figure 2. The distribution have clear long tails at large velocities. Very high front velocities compared to the average crack speed are observed locally. Figure 3 shows the fluctuations of the crack front position : $h(x,t) - \langle h(t) \rangle_x$ in gray levels [1]. Light regions correspond to regions which are in advance of the average crack front. On the contrary, the dark gray correspond to pinned regions of the front that evolve slower than the average crack front. In the figure there are numerous sharp transitions which appear close to horizontal. These transitions are triggered after pinning periods (dark regions) and correspond to fast propagations or local instabilities along the front. The fracture front line only evolves during these fast instabilities or bursts. Apart from

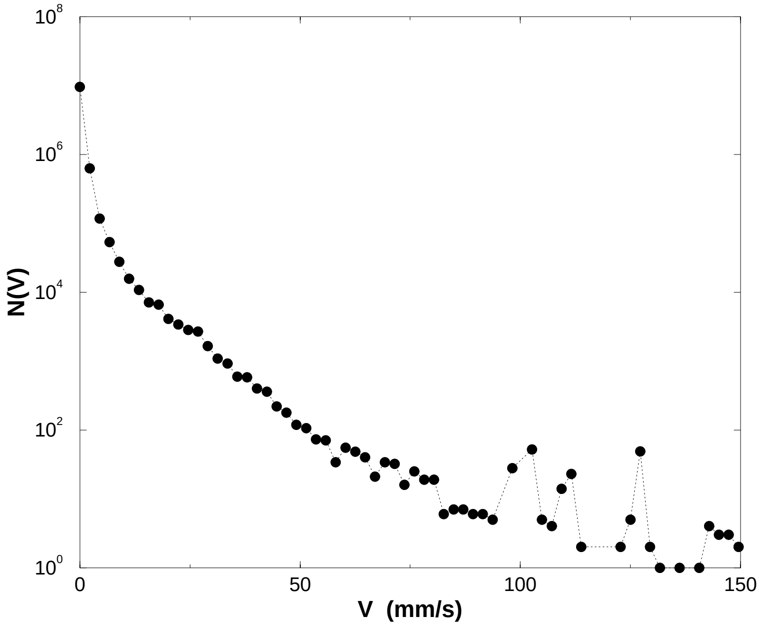

Figure 2: The distribution of the velocity V. The velocity V are calculated on the basis of fronts separated with a time interval of $\delta t = 20ms$. The largest measured local speeds are about three order of magnitude larger than the average front speed $V_f = 68\mu m/s$. It is important to note that the speeds V are average speeds within the time $\delta t = 20ms$. This means that even much higher speed fluctuations may be present with a higher resolution in space and time.

them there are almost no evolution of the front position.

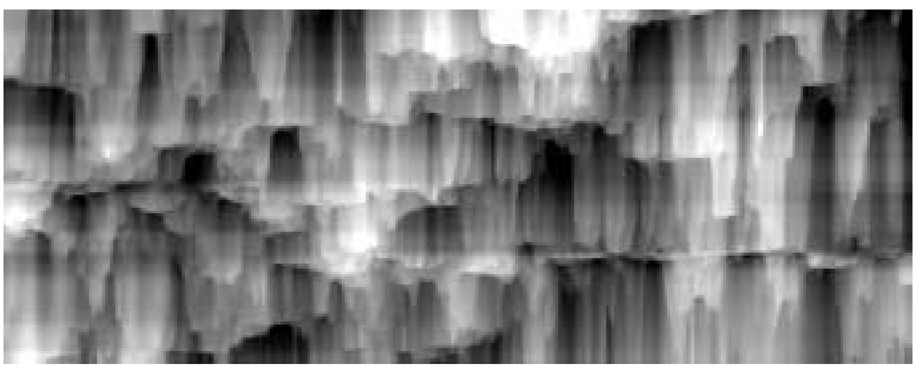

Figure 3: a) The figure shows the space (horizontal) and time (vertical) diagram ($5.12mm \times 8.7s$) of the position fluctuations $h(x,t) - \langle h(t) \rangle_x$. The gray level represents $h(x,t) - \langle h(t) \rangle_x$. Light gray corresponds to positive values of $h(x,t) - \langle h(t) \rangle_x$, while dark gray corresponds to negative values of $h(x,t) - \langle h(t) \rangle_x$.

The dynamic scaling of the fracture front has been checked by calculating the power spectrum $P(k,t)$ of the position difference $h(x,t) - h(x,t=0)$, where k is the wave-number and t is the time ($t = 0$ corresponds to the first image). The Family-Vicsek scaling [20] of the power spectrum $P(k,t)$ can be written as

$$P(k,t) = t^{(1+2\zeta)/\kappa} G(kt^{1/\kappa}) \,, \tag{1}$$

where $G(x)$ is constant for $x << 1$ and $G(x) \propto x^{-1-2\zeta}$ for $x >> 1$. The dynamic exponent κ gives the scaling with time of the horizontal correlation length $\xi_x \propto t^{1/\kappa}$.

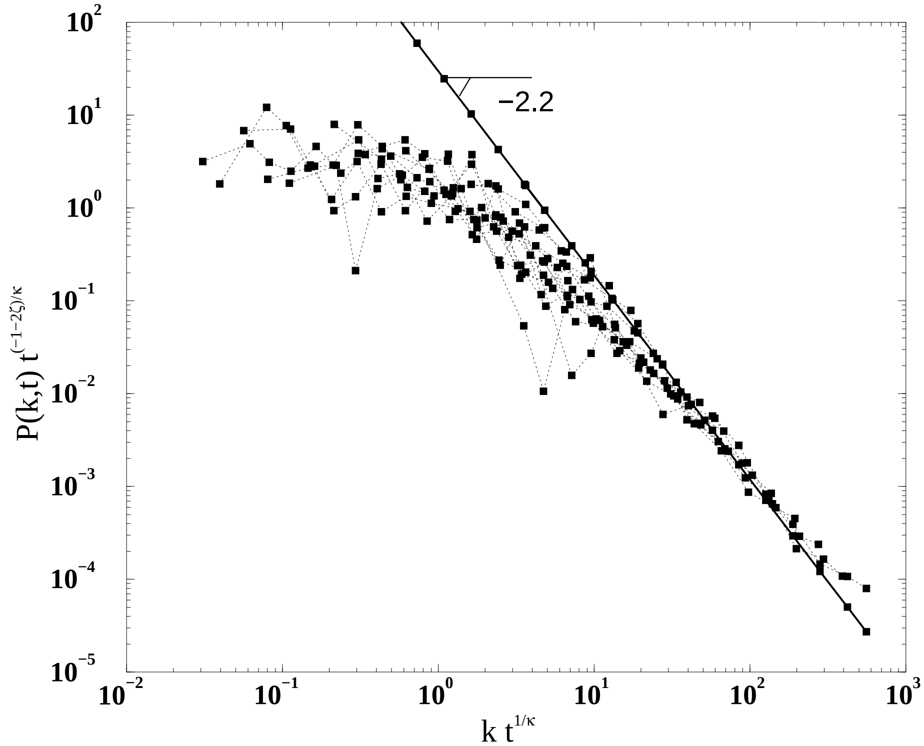

Figure 4: Family-Vicsek scaling: The dependence of the scaling function $P(k,t)t^{-(1+2\zeta)/\kappa}$ with $kt^{1/\kappa}$. This data collapse gives an estimate of the dynamic exponent $\kappa = 1.2$.

In Fig. 4, the scaling function $P(f,t)t^{-(1+2\zeta)/\kappa}$ is plotted as function of $kt^{1/\kappa}$ for different times from $0.03s$ to $7.11s$. This data collapse provides an estimate of the dynamic exponent $\kappa = 1.2$ and the roughness exponent $\zeta = 0.6$ [1]. We emphasize that the exponent may be different from the dynamic exponent obtained from an initially flat front. However the subtraction technique presented here is the only one experimentally accessible. The latter value of the roughness exponent has been extensively checked for fronts at rest over a larger range of scales ($5\mu m$ to $50mm$) [18].

The roughness exponent has also been measured after loading, when the fracture front had come to a complete rest. During each loading stop, the microscope was translated along the front and neighboring pictures were taken. By assembling up to 20 pictures we obtained front up to 2^{14} data points [18]. We found a self-affine crack front over more than three decades using several techniques[18]. The result of the power spectrum of the self-affine profile averaged over nine fronts is shown in Fig. 5. The fitted line corresponds to a roughness exponent of 0.64.

The roughness exponents obtained in our experiment is not consistent with most present theoretical models or simulations [8, 21, 11, 22]. However the theoretical model proposed by Ramanathan and Fisher [12] in which they solve the elastic problem of a planar tensile crack in a heterogeneous medium with a full elastodynamic description is consistent with our experimental work. In the ideal case where the toughness is not dependent of the velocity, they predict a roughness exponent of $\zeta = 0.5$ consistent with our experiments. This model contains elastic waves, and in particular crack front waves which will create stress overshoot along the fracture front. The results are also consistent with a recent quasi static simulation by Hansen et. al [16] (see this proceeding) who found $\zeta = 0.6$ and $\kappa = 0.9$.

Conclusion

The fast dynamics of the local scale is very different from the dynamics on large scale characterized by

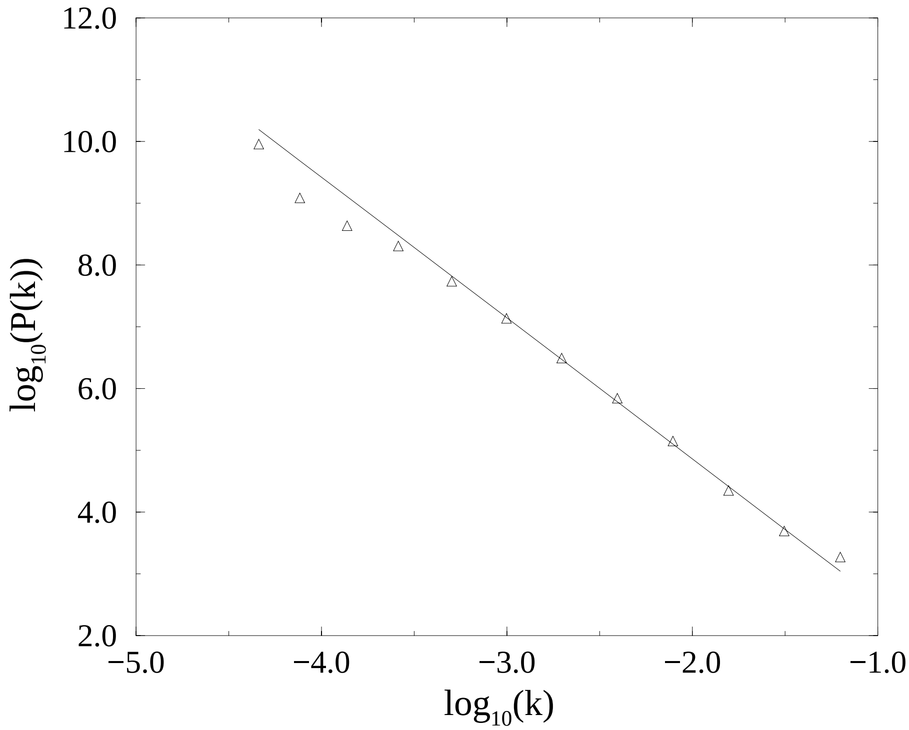

Figure 5: Average of the power spectrum analysis over nine fronts. The best fitted line has a slope of $-2.28 = -1 - 2\zeta$, where ζ is the roughness exponent.

a creeping motion. Very high front velocities compared to the average crack speed are observed locally. We show that the dynamics of the fracture is controlled by local instabilities or bursts which give rise to a self-affine fracture front line with roughness exponent $\zeta = 0.60$, and a dynamic exponent $\kappa = 1.2$. The slip along the front is found to be correlated on a length scale much larger than the asperity size.

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