

Self-Healing Slip Pulses along a Gel/Glass Interface

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We present experimental evidence of self-healing shear cracks at a gel/glass interface. This system exhibits two dynamical regimes depending on the driving velocity: steady sliding at high velocity ($>V_c \approx 100\text{--}125 \mu\text{m/s}$), characterized by a shear-thinning rheology, and periodic stick-slip dynamics at low velocity. In this last regime, slip occurs by propagation of pulses that restick via a “healing instability” occurring when the local sliding velocity reaches the macroscopic transition velocity V_c . At driving velocities close below V_c , the system exhibits complex spatiotemporal behavior.

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There has been in the last decade a sustained interest in the question of the existence, characteristics, and dynamical behavior of slip pulses propagating along sheared frictional interfaces. The relevance of such “self-healing cracks” to seismic dynamics was first demonstrated by Heaton [1] from inversion of seismic data. They have been evidenced as playing an important role in the complex sliding dynamical behavior of Burridge-Knopoff types of models [2], and are being studied by mechanicians [3], who have recently proved the essential importance, in this context, of the detailed features of the underlying friction law. These multifarious developments are to be contrasted with the much less advanced state of experimental studies in this field. Rubio and Galeano [4], studying gels sliding against Plexiglas (Lucite) in a Couette geometry, observed a regime of inhomogeneous sliding via such self-healing pulses. These have also been found by Anoshepoor and Brune [5] with an interface between dissimilar foam rubbers. However, no systematic characterization of the range of driving velocities as to where they exist, nor of their detailed structure, is yet, to our knowledge, available.

In this Letter, we report the results of such a study, performed on a gel (aqueous gelatin) sliding on glass, in a linear geometry. Total sliding force measurements evidence at low driving velocity V , a regime of periodic stick slip which bifurcates, at $V = V_c \approx 100 \mu\text{m/s}$, towards stationary sliding. Simultaneous optical observation allows us to show that, in the stick-slip regime, slip is *inhomogeneous*. It occurs via the propagation of self-healing pulses with no observable opening (in contrast with Schallamach waves [6]), nucleated periodically at the trailing edge of the sliding block. The measurement of the sliding velocity profile within these pulses shows that resticking is determined by a “healing instability” occurring at the above-mentioned critical velocity V_c . This points towards the intimate connection between pulse existence and the detailed form of the velocity dependence of the dynamic frictional stress. Moreover, the velocity of the fracturelike pulse front can be related with small scale characteristics of the gel, namely its mesh size—in agreement with qualitative arguments put forward by Tanaka *et al.* [7] to account for mode I fracture dynamics in the bulk of a gel. Finally,

in a narrow velocity bracket about V_c , *irregular stick slip* is observed. It corresponds to the alternation of pulses of the type described above and of shorter lived events nucleated “homogeneously” within the interface.

Experiments.—The gel samples are made from a 5 wt% solution of gelatin in water, stirred for 35 min at 55 °C, then poured into a parallelepipedic mold of thickness 10 mm, and kept at 5 °C for 20 h. After returning to room temperature, the block sides are cut to obtain the trapezoidal shape shown in Fig. 1. This ensures that sliding will occur at the gel/glass interface rather than along the upper driving plate. All experiments are performed at 20 °C in a water saturated atmosphere. No measurable aging of the samples occurs over the duration (≈ 3 h) of an experiment, as monitored by the stability of the low frequency shear modulus $G = 4$ kPa. Moreover, we determined from dynamic light scattering the collective diffusion coefficient of the gelatin network [8] $D = 1.8 \times 10^{-11} \text{ m}^2 \text{ s}^{-1}$.

The flat free surface of the sample (area $A = 30 \times 10 \text{ mm}^2$) is brought into contact with a carefully cleaned float glass plate. Fine control of the parallelism of the approaching surfaces, together with the strong gel/glass adhesion and the large compliance of the gel block, ensure the homogeneity of the contact. The system is driven at a controlled velocity V ranging from $10 \mu\text{m/s}$ to 2 mm/s through a double cantilever spring much stiffer than the sample. The shear force F , and thus the average shear stress $\sigma = F/A$, is deduced from the spring elongation, measured by a capacitive displacement transducer. In addition, a stiff attachment is used to work at a constant sample thickness corresponding to zero external load on the non-moving system. All experiments consist of several runs of slip distance 150 mm. The shear stress level is reproducible to better than 5%, except for the first run, which

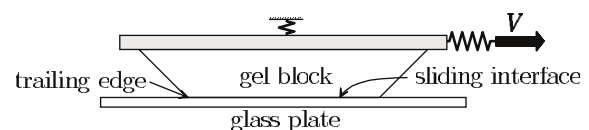


FIG. 1. Sketch of the experimental setup.

we discard since it corresponds to a systematically larger stress. The interfacial plane is observed with a CCD camera at a rate of 60 frames per second. Its motion can be observed thanks to the presence of tiny optical imperfections attached to the gel in the vicinity of its surface. This permits one to measure interfacial slip with a resolution of $20 \mu\text{m}$. Finally, sideways optical observation between crossed polarizers provides information about the deformation field integrated across the sample.

When starting to load from rest at constant V , one first observes a linear rise of the average shear stress σ , corresponding to elastic deformation of the block. This stick phase is followed by a slip one, during which σ drops. Following this transient stress peak, two dynamical regimes are observed, depending on V : (i) at low velocities, slip stops and periodic stick slip sets up (Fig. 2a). The first peak is systematically larger than the subsequent ones, indicating interfacial aging at rest [9]. Increasing V shortens the stick phase, but slip develops a sluggish “tail” of increasing duration, which diverges at a critical V_c . (ii) For $V > V_c \approx 125 \mu\text{m/s}$, no resticking occurs any more, and sliding becomes stationary (Fig. 2c). In this regime, $\sigma(V)$ (Fig. 3) is measured to be velocity strengthening, of the shear-thinning type frequently observed for complex fluids.

Upon decreasing V , *no hysteresis of the transition is observed*. However, in a narrow velocity range below V_c , the above described stick-slip peaks are aperiodic and interspersed with irregular smaller events (see below). Such a mechanical behavior seems incompatible with a 1 degree of freedom dynamics. This points toward the need for improving upon the integrated information provided by σ .

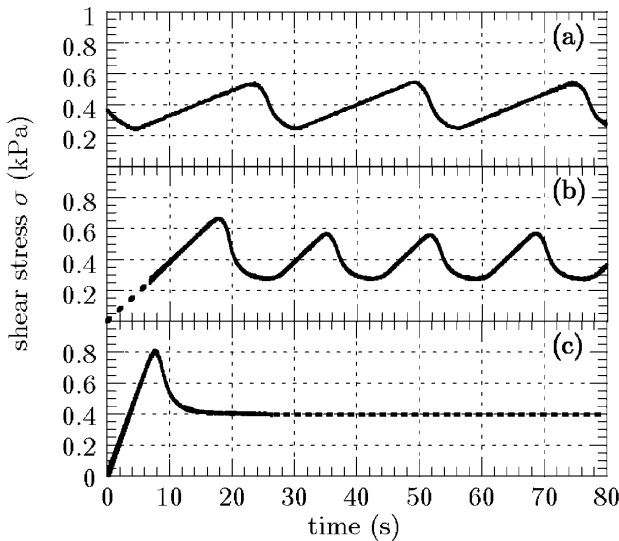


FIG. 2. Average shear stress $\sigma = F/A$ vs time showing the two dynamical behaviors of the system: Stick slip at low driving velocity: (a) $V = 50 \mu\text{m/s}$, (b) $V = 100 \mu\text{m/s}$. (c) Steady sliding at high velocity $V = 150 \mu\text{m/s}$.

This is realized by extracting the spatiotemporal slip dynamics from the CCD recording of the interface image.

Figure 4 shows the light intensity along a randomly chosen single pixel line parallel to the driving direction (horizontal axis) as a function of time (vertical axis) in the stick-slip regime ($V = 80 \mu\text{m/s}$). At the end of the stick phase ($t = t_0$) sliding nucleates at the trailing edge which, in this loading geometry and due to the finite length of the sample, is unavoidably in a state of tensile stress. The locus of slope discontinuities reveals the propagation of the head of this “slip wave.” Its velocity V_{tip} increases, as intuitively expected, as it comes close to the leading edge. During most of the traversal, $V_{\text{tip}} \approx 8 \text{ mm/s}$. This value is found to be, within experimental precision, independent of the driving velocity.

We find that all trajectories can be superimposed by shifting into coincidence the points of discontinuity at which sliding starts: the slip field is stationary in the frame of the moving tip. It is shown in Fig. 5, together with the slip velocity field. Three important qualitative features emerge: (i) the slip velocity exhibits a quasidivergence at the tip, suggestive of a fracturelike singularity. This is confirmed by the photoelastic visualization, which clearly reveals stress concentration in the tip region. It is worth noticing that no opening of the interfacial contact is observable, which leads us to think that we are dealing with a pure “frictional shear crack” (see discussion). (ii) Surprisingly, resticking occurs quasidiscontinuously. Namely, on a time scale $\Delta t < 1/60 \text{ s}$, the sliding velocity decreases from the finite value V_{stop} to zero. Moreover, whatever V in the stick-slip regime, we find that V_{stop} is equal to the critical velocity V_c which marks the transition to the regime of stationary sliding. (iii) For $V < V_c$ the slip field close behind the tip is quasi V independent (see Fig. 5), the slip velocity decreasing asymptotically towards V_c . This is reached at a distance which increases with V . This increase of the pulse width accounts for the growth of the stick-slip period.

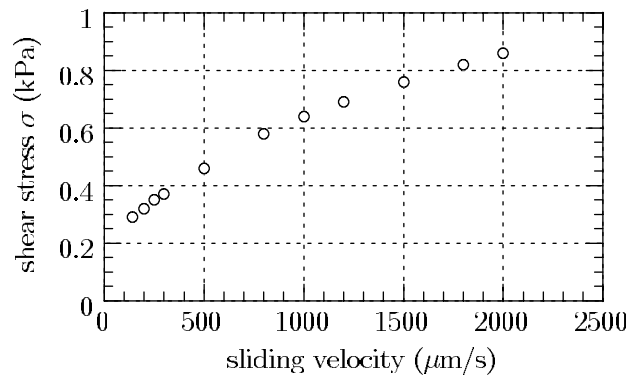


FIG. 3. Average shear stress vs the sliding velocity in the steady sliding regime ($V > V_c$).

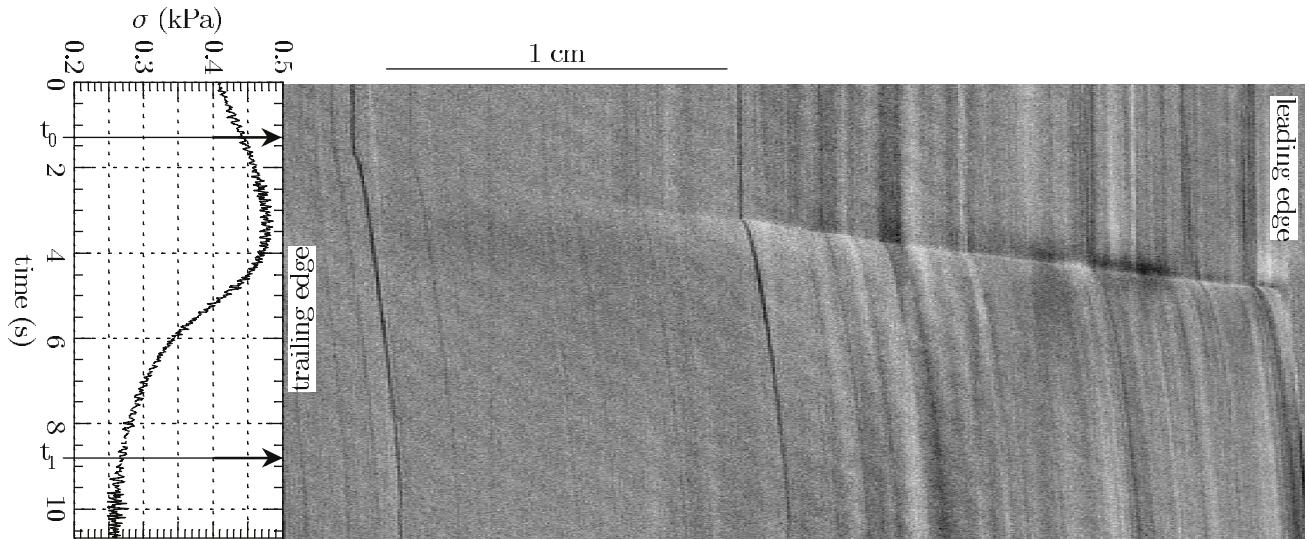


FIG. 4. Spatiotemporal diagram of interfacial motion in the stick-slip regime, with time going down, and the gel driven to the right. Dark lines correspond to the trajectories of imperfections attached to the gel surface. For $t < t_0$, they are immobile, and the gel is stuck. At t_0 , the trailing edge begins to slide, and sliding propagates along the interface. t_1 marks the beginning of resticking. The curve on the left shows the average shear stress measured simultaneously.

When $V > V_c$, the slip velocity behind the initial pulse head saturates at the driving velocity, and stationary motion sets in after the tip has emerged on the leading edge.

Finally, in a V range of order $5 \mu\text{m/s}$ below V_c , where the pulse width has become larger than the sample one, a more complex behavior is observed (see Fig. 6). Stationary sliding seemingly sets in. However, after a random time lapse, the interface resticks suddenly and practically all at once (no resticking front is observable). The average stress then starts rising again until a new pulse is nucleated at the trailing edge. Moreover, during the sliding phases between these large pulses, finite interfacial patches restick at random. Then, within these patches, slip nucleates and

propagates in either direction. These “homogeneously nucleated” events are associated with the stress fluctuations interspersing the main peaks.

Discussion.—So, it appears clearly that low-velocity sliding of the interface between our two elastically very dissimilar materials occurs via the “heterogeneous nucleation” of self-healing pulses. These sweep the contact at a quasi V -independent velocity V_{tip} on the order of 8 mm/s , much slower than the (transverse) sound velocity $c_s \approx 2 \text{ m/s}$. As was already noticed by Tanaka *et al.* [7] when studying propagation of mode I fractures in a gel, this strongly subsonic value of V_{tip} points towards the fact that the main relevant dissipative mechanism in our poroelastic medium is the so-called “slow Biot mode,” i.e., collective diffusion of the gelatin network. Indeed, this mode, of dispersion law $\omega_D = Dq^2$, is expected to become most effective when the molecular depinning signal from the crack head, of frequency $\omega = V_{\text{tip}}/d$ (with d the gel mesh size), resonates with the diffusive mode at wave vector $q \approx d^{-1}$, i.e., when $V_{\text{tip}} \approx D/d$. D is related to the gel shear modulus G , skeleton Poisson ratio ν , and mesh size d by [8]

$$D \approx 2G \frac{1 - \nu}{1 - 2\nu} \frac{d^2}{\eta} \quad (1)$$

with η the viscosity of water. One can safely assume [8] that $\nu = 0$. From our measured values of D and G , we then estimate $d \approx 1.5 \text{ nm}$, so that $D/d \approx 10 \text{ mm/s}$, in excellent agreement with the measured V_{tip} .

The fact that we observe, for driving velocities close to V_c , sudden global resticking events strongly suggests that V_c is a threshold below which sliding becomes unstable down to wavelengths smaller than our space resolution. This inference is consistent with the

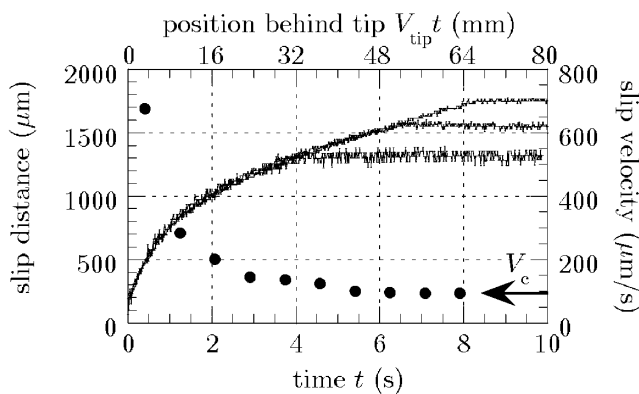


FIG. 5. Full curves: Slip distance vs time (lower horizontal axis) and distance behind pulse tip $V_{\text{tip}}t$ (upper horizontal axis). $t = 0$ refers to the local onset of sliding. From bottom to top: $V = 30, 60, 90 \mu\text{m s}^{-1}$. Dots: Velocity profile corresponding to the upper slip curve.

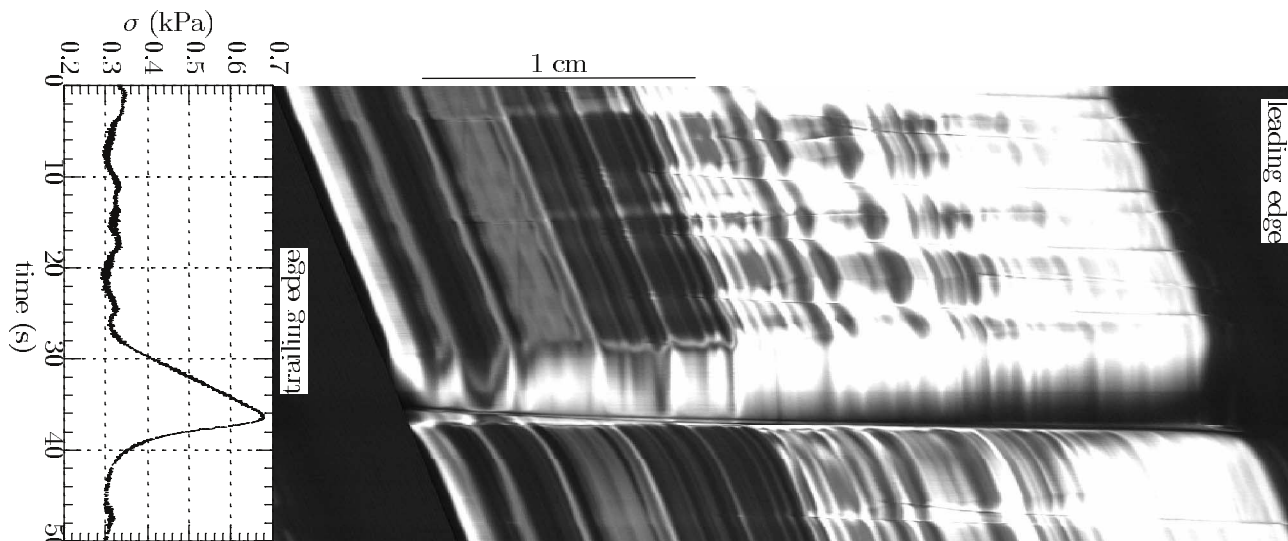


FIG. 6. Spatiotemporal diagram at a driving velocity close below V_c built from a line of the photoelastic side view of the gel block close to the interface. The presence of thickness defects on the lateral faces of the block reveals local sliding, as in Fig. 3. Photoelasticity shows waves of deformation of various sizes associated with local slip pulses responsible for the fluctuations of the macroscopic shear stress (curve on the left).

quasidiscontinuity of the slip velocity at the resticking pulse tail end in the periodic regime. In other words, we believe that, if stationary sliding could be stabilized at $V < V_c$ by, e.g., working with a very thin, hence stiff, gel layer, sliding friction should become velocity weakening.

Such a behavior must necessarily be ascribed to the underlying dynamics of a structural “state” variable. In the present case, one can reasonably associate it with the density of pinning points between polymer chains and strong adhesion sites (e.g., silanols) on the glass surface which, according to Charitat and Joanny [10], should decrease with increasing slip velocity. Note that, in this frame of interpretation, adhesion persists while sliding, which excludes that sliding occurs on top of a pure water layer. Opening of the network/glass contact is also excluded, in contrast with Schallamach waves in rubber or with “brittle” pulses studied by Gerde and Marder [11].

Our results point to the importance, for the dynamics and, possibly, the existence, of self-healing pulses in our system, of the details of the frictional dynamics. Whether or not the relation between self-healing and sliding instability might extend to a wider class of systems, of course, remains an open question. However, it is worth mentioning, in this perspective, the striking qualitative analogy between the global stick-slip dynamics of our system and that measured in some surface force apparatus experiments [12] involving thin confined layers of small molecules.

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