Jamming creep of a frictional interface

L. Bureau, T. Baumberger, and C. Caroli
Groupe de Physique des Solides, Universités Paris 6 et 7, UMR CNRS 7588, 2 place Jussieu, 75251 Paris, Cedex 05, France
(Received 24 January 2001; published 27 August 2001)

We measure the displacement response of a frictional multicontact interface between identical polymer glasses to a biased shear force oscillation. We evidence the existence, for maximum forces close below the nominal static threshold, of a jamming creep regime governed by an aging-rejuvenation competition acting within the micrometer-sized contacting asperities. The time dependence of the creep process deviates from the standard Rice-Ruina [J. R. Rice and A. L. Ruina, J. Appl. Mech. **50**, 343 (1983)] phenomenology at early times; this suggests the possibility of an aging-rejuvenation competition at much smaller scales, within the nanometer-thick adhesive junctions.

DOI: 10.1103/PhysRevE.64.031502 PACS number(s): 83.60.La, 62.20.Qp, 46.55.+d

INTRODUCTION

Solid friction between two macroscopic solids is commonly characterized in terms of (i) a static force threshold below which no relative displacement is supposed to take place, (ii) a dynamic friction coefficient, measured in stationary motion. However, recent experiments performed on multicontact interfaces (MCI), i.e., interfaces between two solids with rough surfaces, pressed together under a load N, have revealed that [1] (i) for shear forces F such that $F/N \ll \mu_s$, where μ_s is the static threshold, the pinned interface responds elastically, via the reversible deformation of the contacting asperities, (ii) for $F \lesssim \mu_s N$, creeplike irreversible sliding is observed.

Clearly, the study of the latter regime of incipient sliding should give access to precise information about the underlying pinning/depinning dynamics.

The real area of contact Σ_r for a macroscopic MCI consists of a large set of micrometer-sized contacts dilute enough to be mechanically independent. The normal stress that they bear is, typically, comparable with the yield stress of the bulk material.

It is now well established [2] that, for a MCI, the variations of the friction force $F=\sigma_s\Sigma_r$ (the stress σ_s is usually called the interfacial shear strength) are governed, at low velocities, by the competition between two effects: (i) an age strengthening effect resulting from the logarithmic creep growth, under the high normal stress, of the microcontacts between load bearing asperities. When motion starts, contacts get gradually destroyed, after a lifetime or age Φ, and replaced by fresh ones. So, while the interface sits still, it ages (strengthens), when it slides, it rejuvenates (weakens). Full refreshment occurs, on average, after sliding a micrometric memory length D_0. In stationary motion, this results in a logarithmic decrease of Σ_r with the velocity V. (ii) This velocity-weakening effect is counteracted by the velocity-strengthening interface rheology:

$$\sigma_s(\dot{x}) = \sigma_{s0}[1+\alpha \ln(\dot{x}/V_0)], \tag{1}$$

where $\alpha>0$, $\dot{x}$ is the instantaneous sliding speed, and σ_{s0} is the value of the sliding stress measured at the, *a priori* arbitrary, reference velocity V_0. We will choose $V_0 = 1\ \mu\mathrm{m\,s}^{-1}$. This rheology results from thermally activated depinning events within the nanometer-thick adhesive junctions between contacting asperities.

Both effects yield logarithmic variations of F. One thus expects creep to exhibit a strong, exponential sensitivity to forces close to the nominal static threshold.

Now, the experiments reported in [1] were performed under static loading through a spring of finite stiffness. As such, they did not provide a force control fine enough to study incipient creep accurately. So, we have chosen, in this work, to probe it via the response to a biased oscillating shear force. With a bias $F_{dc} \ll \mu_s N$, and an amplitude such that the maximum force F_{max} lies in the tangential creep range, the interface should experience, during each oscillation period, an alternation of two regimes: (i) for F close to F_{max}, a sliding phase during which rejuvenation is at work, yielding a negative age variation that we will call $\Delta\Phi_{slide}$. (ii) as F decreases, the slip velocity decreases quasiexponentially, and the slider enters, for the rest of the period, a quasistatic phase where age grows linearly with time by an amount $\Delta\Phi_{stat}$. Such a competition between rejuvenation and aging is akin to that invoked to model soft glassy rheology (SGR) [3].

If, say, $\Delta\Phi_{slide}+\Delta\Phi_{stat}<0$, i.e., if the system experiences a net rejuvenation over a period, the interface will weaken, leading to a larger slip during the next period, etc. If, on the contrary, $\Delta\Phi_{slide}+\Delta\Phi_{stat}>0$, the interface strengthens during each oscillation, leading to a smaller slip during the next one, etc, hence to self deceleration and possibly, to saturation of the average motion. One thus expects the dynamics to bifurcate between self-accelerated unlimited slip and what can be termed a jamming [4] creep regime. The experiments reported below fully confirm this qualitative scenario. Moreover, quantitative analysis of the data, based upon the Rice-Ruina (RR) model [5], allows us to show that the rejuvenation-aging process cannot be fully ascribed to variations of Σ_r, leading us to conclude that the interfacial rheology is most likely, itself, of the SGR-type.

EXPERIMENTS

The experimental setup has been fully described in [6]; it is sketched in the inset of Fig. 1(a). Two poly(methyl meth-

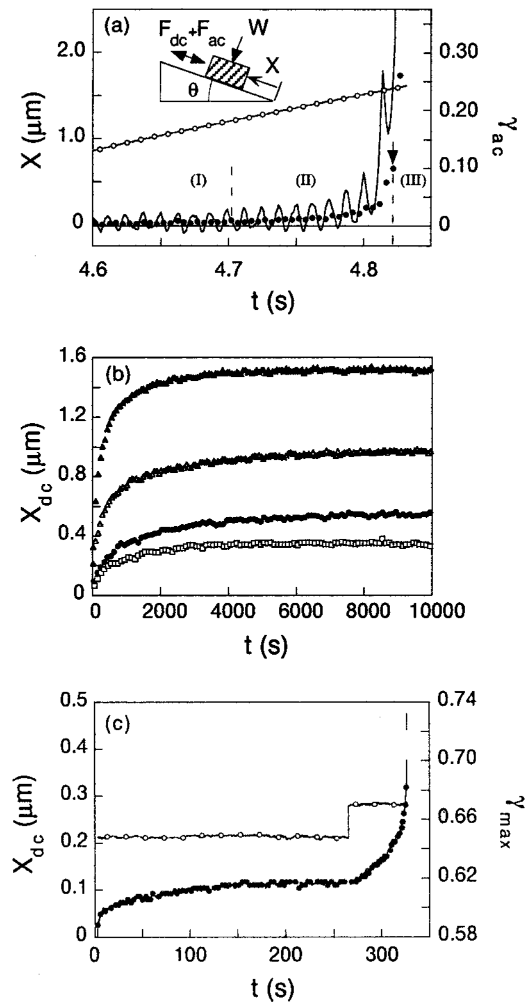

FIG. 1. (a) Instantaneous (line) and averaged (●) displacement response of the slider to a biased oscillating shear force of ramped reduced amplitude $\gamma_{ac}(t)$(○). The bias $\gamma_{dc}=0.36$. The arrow indicates the point at which the averaged velocity reaches 100 μm s^{-1}. Inset: experimental setup. (b) Recordings of the average creep displacement X_{dc} for four runs performed under identical nominal conditions: $\gamma_{dc}=0.36$, $\gamma_{ac}=0.18$, and $t_{wait}=300$ s. The wide scattering of the curves results from dynamical amplification of the statistical dispersion of the interfacial strength. (c) Transition from jamming to unbounded slip (●) triggered by a 3% jump of $\gamma_{max}=\gamma_{dc}+\gamma_{ac}$ (○).

acrylate) (PMMA) samples, with lapped surfaces of roughness $R_a=1$ μm, are glued on a slider and a track and form the multicontact interface. All experiments are performed under room conditions at relative humidity 30–40% and temperature 20–25 °C. The slider, of nominal area 4 cm^2, rests on the track, inclined at $\theta=20°$ from the horizontal. The tangential (F_{dc}) to normal (N) load ratio $\gamma_{dc}=\tan\theta=0.36$ is well below the static threshold $\mu_s\approx 0.6$ (see [2]) and no sliding occurs. Imposing a harmonic motion to the track then results in an inertial shear loading of the slider, of amplitude $F_{ac}=\gamma_{ac}N$, with $\gamma_{ac}\leqslant 0.5$. The frequency $f=80$ Hz is chosen well below the natural frequency of the slider-interface system, $f_0=800$ Hz, so that the inertia associated to its relative motion in the track frame can be neglected. We measure the displacement X of the center of mass of the slider by means of a capacitive displacement gauge, with a noise amplitude 1 nm over its whole 0–500 Hz bandwidth. In order to prepare the system in as reproducible as possible an initial state, the slider is placed on the track and a large γ_{ac} is then imposed, in order to make it slide a few micrometers in the direction of F_{dc}. The harmonic force is then suddenly stopped, which results in an elastic recoil of the contacting asperities [7]. This method reduces the relative dispersion on interfacial stiffness values (see [6]) to only 10%. This value agrees with the expected statistical dispersion due to the finite number of load bearing contacts, which we can estimate to be of order 50. A time t_{wait} is then waited before reswitching the harmonic shear loading, either as a linear ramp of amplitude, until gross sliding occurs, or as a step with rising time $\leqslant 0.1$ s.

RESULTS

The displacement response $X(t)$ of the slider to a ramp $\gamma_{ac}(t)$ is illustrated in Fig. 1(a). Also shown is the average displacement X_{dc} measured by filtering $X(t)$ through a low-pass filter of cutoff frequency 8 Hz. In region (I), the slider oscillates about a constant average position, no irreversible slip occurs: the MCI responds elastically. Region (III) corresponds to accelerated sliding. In region (II) between these two regimes, the average displacement X_{dc}, i.e., the slipped distance, increases continuously. We use this ramp test to define a threshold $\gamma_s=(F_{dc}+F_{ac})/N$ such that the average sliding velocity $dX_{dc}/dt=100$ μm s^{-1}. We thus obtain, for $t_{wait}=600$ s and $\dot{\gamma}_{ac}=0.1$ s^{-1}, $\gamma_s=0.59\pm 0.03$. The scattering, of order 10%, is consistent with that of the stiffness.

One can see, in Fig. 1(a), that the intermediate creep regime (II) corresponds to a narrow range of $\gamma_{max}=\gamma_{dc}+\gamma_{ac}$. Slow creep is studied by choosing a value of γ_{max} in this range, setting, at $t=t_{wait}$, the amplitude stepwise to γ_{ac}, and recording $X_{dc}(t)$.

The creep curves displayed in Fig. 1(b) all correspond to $t_{wait}=300$ s and $\gamma_{max}=0.54$. The large dispersion between X_{dc} for various runs must, therefore, result from the statistical dispersion of the MCI initial state. After slipping by a finite amount, of order 10–100 nm, over the rising time (0.1 s) of γ_{ac}, the slider performs a slowly self-decelerating creep. After, typically, 10^4 s, the slip velocity has decreased to nonmeasurable values, indicating a saturating, jamming dynamics. We attribute the large dispersion of the creep curves to the expected above-mentioned exponential sensitivity of the dynamics to $\gamma_s-\gamma_{max}$. A direct confirmation of this is obtained from the experiment presented in Fig. 1(c): it shows that a 3% step of γ_{max} turns quasijamming into accelerated sliding.

These ideas can be checked in a more quantitative way as follows: as long as the age of the MCI has not been appreciably modified by the creeping dynamics itself, we expect the characteristic time for creep, t_c, to be that for thermally activated depinning of a typical nm^3 pinned unit within the adhesive layer, $\ln(t_c)\sim\Gamma+\Delta E/kT$, where ΔE is the energy barrier to be jumped by an element under reduced load γ_{max}, and Γ is a stress-independent constant. Close to the

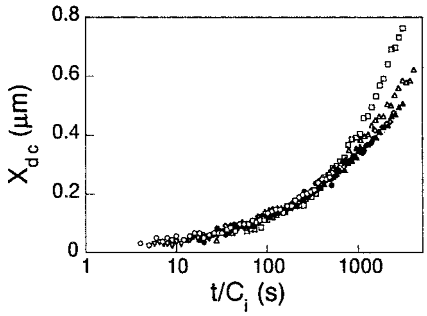

FIG. 2. Scaled plot of seven creep curves [same nominal conditions as for Fig. 1(b)]. The reference run ($C=1$) corresponds to (○) symbols.

depinning threshold [8] $\Delta E/kT \sim (\gamma_s - \gamma_{max})/A$. The RR rate parameter $A = \alpha\sigma_{s0}/\bar{p}$, where $\bar{p}$ is the average pressure on the microcontacts, α and σ_{s0} are defined by expression (1). A has been measured, for PMMA-PMMA, to be 0.013 [9]. Hence, we expect all the creep curves $X_{dc}^{(i)}(t)$, corresponding to various runs (i), to collapse on a single curve, provided the time is properly scaled according to $X_{dc}^{(i)}(t) = \tilde{X}(t/C^{(i)})$, where $\ln(C^{(i)}) \sim (\gamma_s^{(i)} - \gamma_{max})/A$. Figure 2 shows the set of creep curves resulting from such a scaling. Indeed, the collapse onto a master curve is very good in the short time range. Moreover, we find the maximum spread of the scaling factors $\max_{i,j}|\ln(C^{(i)}/C^{(j)})| \approx 4.4$, in excellent agreement with $\max|\Delta(\gamma_s^{(i)} - \gamma_{max})|/A \approx 4.6$.

DISCUSSION

We now analyze our results within the framework of the Rice-Ruina phenomenology [5], which has proved to account very well for the stick-slip frictional dynamics of MCIs [2]. It models the above described rejuvenation-aging process and the velocity strengthening interface rheology as follows.

(i) The friction coefficient reads

$$\mu = F/N = \mu_0 + A \ln\left(\frac{\dot{x}}{V_0}\right) + B \ln\left(\frac{\Phi V_0}{D_0}\right), \tag{2}$$

where Φ is the interface age, μ_0 the friction coefficient at reference velocity V_0 and D_0 is the Dieterich memory length [5]. The instantaneous interfacial sliding velocity $\dot{x}$ is related to the center of mass position by $\dot{x} = d(X - F/\kappa)/dt$, with κ the interfacial elastic stiffness [9].

(ii) The age Φ evolves according to

$$\dot{\Phi} = 1 - \frac{\dot{x}\Phi}{D_0}. \tag{3}$$

On the right-hand side of Eq. (3), the first and second terms correspond, respectively, to time aging and slip rejuvenation.

We have performed numerical integrations of this set of differential equations to calculate the slipped distance $X_{dc}(t)$ with, in Eq. (2), $F/N = \gamma_{dc} + \gamma_{ac}\cos(\omega t)$, and initial conditions for slip and age $X_{dc}(0) = 0$, $\Phi(0) = t_{wait} = 300$ s. We have used for the memory length D_0 and the dimensionless parameters A and B the values $D_0 = 0.42$ μm, $A = 0.013$, $B = 0.026$, obtained from previous measurements on PMMA [9]. As already stated, we choose $V_0 = 1$ $\mu\text{m s}^{-1}$. Due to the exponential amplification by the creep dynamics of the small variations of the absolute friction level between various runs, μ_0 must be left free. This unique fitting parameter is tuned so as to adjust the calculated and measured values of X_{dc} at the end of the run. A typical example of such fits is shown in Fig. 3. It yields $\mu_0 = 0.428\,65$ [10], fully compatible with previous data [2].

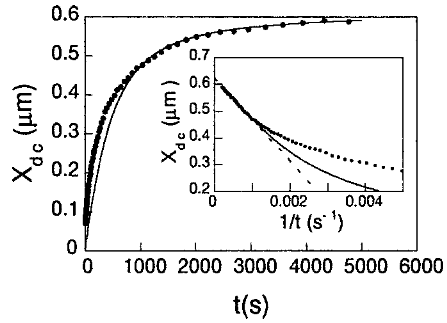

FIG. 3. An experimental creep curve (●) and its fit according to RR model (line). With $\gamma_{dc} = 0.36$, $\gamma_{ac} = 0.18$, and $t_{wait} = 300$ s. Inset: the same plotted versus $1/t$, the dashed line indicates the quasi-jamming asymptotics (see text).

These fits appear to be very good at long times $t \gtrsim 1000$ s, that is in the quasijammed regime where static aging becomes dominant. The corresponding asymptotic dynamics can be analyzed directly. From Eq. (2):

$$\frac{\dot{x}}{V_0} = \left(\frac{D_0}{V_0\Phi}\right)^{\beta} \exp\left[\frac{\gamma_{max} - \mu_0}{A}\right] \exp\left[\frac{\gamma_{ac}(\cos(\omega t) - 1)}{A}\right] \tag{4}$$

with $\beta = B/A$.

Let us consider the oscillation period centered at t_1, with $\gamma(t_1) = \gamma_{max}$. The velocity $\dot{x}$ only takes on significant values for $\gamma \approx \gamma_{max}$, i.e., for $|\tau| = |t - t_1| \ll T$. So, in Eq. (4), $\cos(\omega t) - 1 \approx -\omega^2\tau^2/2$, and

$$\frac{\dot{x}}{V_0} \approx \left(\frac{\Phi_c}{\Phi}\right)^{\beta} \exp\left[-\frac{\tau^2}{\tau_c^2}\right], \tag{5}$$

with the constant $\Phi_c^{\beta} = (D_0/V_0)^{\beta} \exp[(\gamma_{max} - \mu_0)/A]$ and $\omega\tau_c = (2A/\gamma_{ac})^{1/2}$.

To lowest order, the slip-induced Φ variation can be neglected, and Eq. (3) yields

$$\Phi \approx t + \Theta, \tag{6}$$

where the integration constant Θ is the age at some "initial" time within the quasijammed regime.

From Eqs. (5) and (6), the increment of slip over this period,

$$\Delta x \approx \int_{-\infty}^{+\infty} \frac{\Phi_c^\beta V_0}{(t_1+\tau+\Theta)^\beta} \exp\left[-\frac{\tau^2}{\tau_c^2}\right] d\tau, \tag{7}$$

where the integration can be extended to infinity due to the Gaussian decay of $\dot{x}$. Then, for $t_1 \gg \Theta$,

$$\Delta x \approx \frac{V_0 \Phi_c^\beta \sqrt{\pi}\tau_c}{t_1^\beta} + O\left(\frac{1}{t_1^{\beta+1}}\right). \tag{8}$$

From this, the sliding velocity $\dot{X}_{dc}$, coarse grained over the period T,

$$\dot{X}_{dc}(t) \approx \frac{\Delta x}{T} \approx V_0 \sqrt{\frac{A}{2\pi\gamma_{ac}}} \frac{\Phi_c^\beta}{t^\beta}, \tag{9}$$

and we obtain for the slipped distance

$$X_{dc}(t) \approx Cst - \frac{V_0}{\beta-1} \sqrt{\frac{A}{2\pi\gamma_{ac}}} \frac{\Phi_c^\beta}{t^{\beta-1}}. \tag{10}$$

Since, for our system, $\beta = B/A = 2.0$, we thus expect the creeped distance to approach its saturation level as $1/t$.

Our experimental data are seen in the inset of Fig. 3 to fit the jamming asymptotics predicted by the RR model with excellent accuracy.

However, for all the experimental runs, we find (see Fig. 3) that, although the overall shape of $X_{dc}(t)$ is reasonably well described by the RR fits, the agreement is clearly not quantitative at short times ($t \lesssim 1000$ s). In this time bracket, the RR model systematically underestimates $X_{dc}(t)$, hence the rejuvenation efficiency of slip. In particular, it by no means accounts for the fast increase of X_{dc}, which amounts typically to $\sim 10\%$ of the total slip, occurring over the stepping time.

This strongly hints at the fact that the RR model, while it very well describes established sliding, misses some important feature of incipient sliding. We suspect that this missing feature might be slip-induced rejuvenation, i.e., dynamical weakening of σ_s, within the nanometer-thick adhesive junctions themselves. Indeed, these certainly have an amorphous solid structure when pinned, and they flow beyond a stress threshold. As such, they can reasonably be expected to behave as soft glassy materials, whose rheology is now interpreted [3] in terms of structural aging-rejuvenation competition. If this turns out to be the case, two such mechanisms would be at work in the MCI solid friction, on the two scales of, respectively, the micrometric asperities and the nanometric pinning units.

This issue is, in particular, of primary relevance to the modeling of the dynamics of interfacial shear fracture [11,12]. This can be investigated by studying the frictional dynamics of rough PMMA sliding over smooth hard glass. Since, with such a system, the microcontact population is unaffected by motion, rejuvenation, if observed, has to originate from the adhesive junctions. Preliminary results of such an investigation, which is presently under way, clearly indicate the existence of such an aging-rejuvenation process.

[1] P. Berthoud and T. Baumberger, Proc. R. Soc. London, Ser. A **454**, 1615 (1998).

[2] P. Berthoud, T. Baumberger, C. G'Sell, and J.-M. Hiver, Phys. Rev. B **59**, 14 313 (1999); T. Baumberger, P. Berthoud, and C. Caroli, *ibid.* **60**, 3928 (1999), and references therein.

[3] S. M. Fielding, P. Sollich, and M. E. Cates, J. Rheol. **44**, 323 (2000), and references therein.

[4] A. J. Liu and S. R. Nagel, Nature (London) **396**, 21 (1998).

[5] J. R. Rice and A. L. Ruina, J. Appl. Mech. **50**, 343 (1983).

[6] T. Baumberger, L. Bureau, M. Busson, E. Falcon, and B. Perrin, Rev. Sci. Instrum. **69**, 2416 (1998).

[7] C. Carolli and Ph. Nozières, Eur. Phys. J. B **4**, 233 (1998).

[8] B. N. J. Persson, *Sliding Friction: Physical Principles and Applications*, Nanosciences and Technology (Springer-Verlag, Berlin, 1998), Chap. 11.

[9] L. Bureau, T. Baumberger, and C. Caroli, Phys. Rev. E **62**, 6810 (2000).

[10] The five decimal places are necessary to adjust the final X_{dc} to 1%.

[11] A. Cochard and J. R. Rice, J. Geophys. Res. **105**, 25 891 (2000).

[12] C. Caroli, Phys. Rev. E **62**, 1729 (2000).