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Effects of loading angles on stick–slip dynamics of soft sliders

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ABSTRACT

When soft gels move across a hard surface, stick–slip frictional sliding is mediated by propagation of adhesion and detachment fronts. Here we experimentally investigate the sliding dynamics of an extended frictional interface between soft Silicone gel and hard PMMA and identify three distinct sliding regimes. We directly visualize the interface and show that a minute manipulation of the initial loading angle results in a sharp bifurcation between the different sliding states. The phase diagram as well as universal scaling relations governing the dynamics is presented.

1. Introduction

Sliding friction of soft elastic solids has recently been attracting increasing attention for their unique dynamical behavior. Typical examples are found in various natural and man made systems, such as, automobile tires in braking [1], articular cartilages during walking [2–5], and limbless animals in locomotion [6]. While some systems are composed of the same or similar materials in terms of elasticity, many other systems are combinations between dissimilar materials. When such dissimilar bodies are sheared, the contrast in material rigidity induces a systematic variation in normal stress that can result in total separation of the interface [7–9]. Thus, slip may not occur while keeping intimate contact as in similar materials but accompanies detachment and the formation of self-healing cracks, known as Schallamach waves [10–14]. Additionally, it has long been known that even for both similar and different sliding pairs, the dynamics of frictional sliding do not follow the simple Coulomb-like description of two coefficients of friction, static and dynamic [15–18]. In most realistic systems, spatio-temporal factors and their sensitivities to external parameters must be considered in order to account for the complexities of frictional sliding [19–26]. Ben-David et al. [27] and Maegawa et al., [28] introduced non-uniform normal stress fields by adjusting the angle between two identical blocks and observed a systematic change in frictional behavior. One of the authors reported complex stick–slip cycles of a compliant gel sliding against a hard block and had revealed that the sliding speed greatly affects the stick–slip behavior [29]. In this letter, we show that a slight change in the loading angle of the soft and hard pair results in bifurcations of the slip magnitude and the complexity of sliding in stick–slip cycles. Additionally we report that large slip events are characterized with universal scaling relations.

2. Experiment

2.1. Setup

Our experimental system is depicted schematically in Fig. 1(a). An optically flat PMMA (polymethyl methacrylate) slider is connected to a load cell at a given inclination angle θ_0 and slides over a soft Silicone gel base. The dimensions of the PMMA block, W_p, L_p, H_p, are 100, 40, 20 mm in x, y, z directions respectively. The bottom plate is composed of a Silicone (poly-dimethyl siloxane) gel which is cast on a flat glass plate. The dimensions of the gel plate are W_g, L_g, H_g = 200, 200, 20 mm respectively. In order to set an initial condition leading to reproducible results, the top PMMA block is aligned carefully with a small inclination angle θ_0 and is contacted with the bottom gel as slowly as possible without any tangential forces. A constant normal load, F_N (= 5, 10, 15 N), is imposed on the interface through the top block, and the bottom glass plate is driven at a constant velocity V = 10 μm/s for 5000 s. For each trial, the lateral friction force F acting on the interface is recorded at a rate of 1 kHz.

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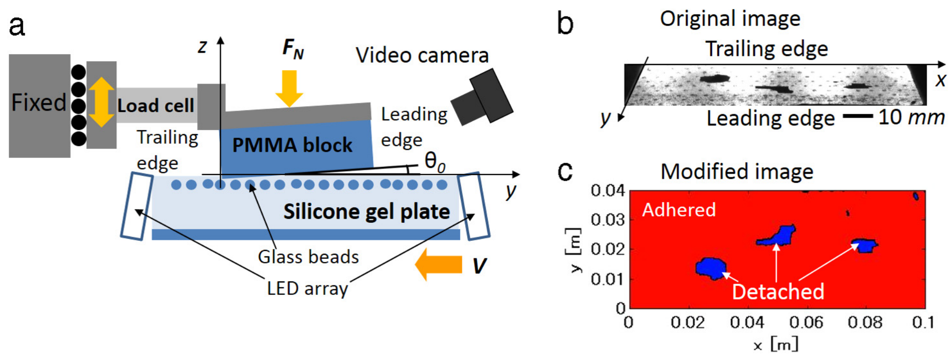

Fig. 1. (a) Schematic of the experimental setup. Silicone gel plate is pressed against PMMA block with initial inclination angle θ_0 and normal load F_N, and is driven at a constant velocity V. (b) Example of side view. y (x) axis is taken parallel (perpendicular) to the sliding direction. Detached (adhered) regions can be visualized as dark (bright) areas. (c) Modified image obtained by binarization of an original image (b). The threshold is set at gray scale value = 50 so that only detached regions are shown as blue (originally dark) areas.

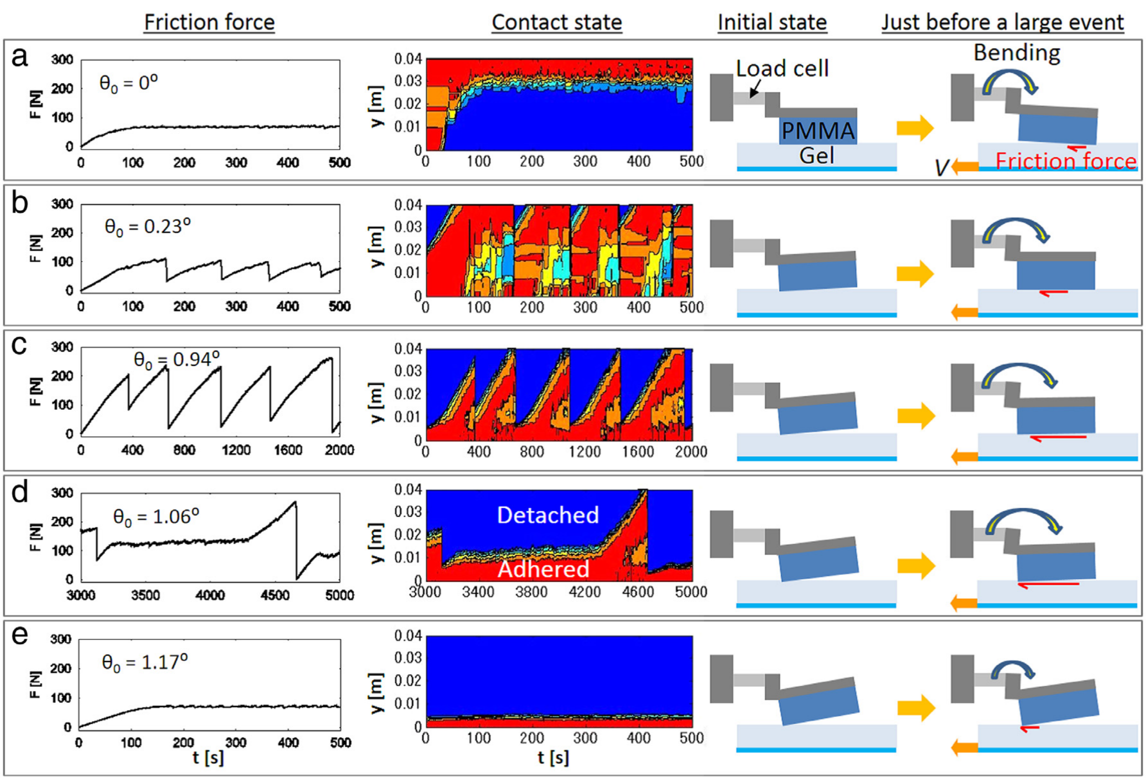

Fig. 2. Time variations of the friction forces $F(t)$ (left), the spatio-temporal maps of the contact state $C(y, t)$ (middle), and corresponding schematic pictures for the initial state and the state just before a large slip event (right). The initial inclination angle is (a) $\theta_0 = 0°$, (b) 0.23°, (c) 0.94°, (d) 1.06° and (e) 1.17°. The applied normal load F_N is 10 N in these experiments.

2.2. Sample

The Silicone gel is a mixture of four components: SILPOT 184 polymer: SILPOT 184 curing agent (Toray Dow Corning): CY52-276 A: CY52-276 B (Toray Dow Corning) = 10: 1: 2: 8 (by weight). The former and latter two components are originally provided to yield viscoelastic elastomer and gel respectively. Here we mix these four and successfully create compliant Silicone gels with small viscous damping, as confirmed by viscoelastic properties. The prepolymer is stirred by an agitator and then degassed by a vacuum pump to remove air bubbles, after which it is poured onto a flat glass plate, and cured at 120 °C for 3 h to prepare a 19 mm thick gel block on a glass plate. Glass beads tracer particles ($d \approx 100$ μm) are then scattered on the fresh gel surface. Then, an additional 1 mm thick layer of prepolymer is added and cured in the same manner. This process results in a 20 mm thick gel block with tracer particles embedded 1 mm below the sliding surface. Such hard particles inside soft gel matrix are expected to affect contact condition, interfacial stress state and dynamic rupture behavior. In order to evaluate the effects of the tracer particles on stick–slip, we conducted preliminary friction experiments using gel samples with and without tracer particles and compared the maximum friction force, the maximum force drop and also the event size distributions. As a result, no significant difference was recognized. In this study, however, any further investigations nor experiments using the tracer particles, i.e., measurement of displacement fields and estimation of stress fields were not performed. The analysis results will be reported elsewhere in a separate paper. The mechanical properties of the Silicone gel were characterized with a rheometer (MCR301, Anton Paar). The storage modulus G' was measured to be 118 ± 3 kPa for frequency ranges from 0.1 to 100 rad/s, while their loss modulus G'' varied from 0.919 (0.1 rad/s) to 2.26 kPa (100 rad/s).

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