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Analytical and experimental analysis on frictional dynamics of a single elastomeric pillar

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ABSTRACT

The frictional dynamics of a single elastomeric pillar is studied analytically and experimentally in meso-scale. An energy equilibrium of a single pillar is established to analyze the static and kinetic friction regimes. The kinematics of the system as well as the components of the total energy of the system is identified. In the experimental section, frictional dynamics of the system is analyzed using the friction loops. The experimental results are compared with the analytical ones in terms of the mean value of the sliding friction force for different diameter and height values of the pillars. It is shown that the analytical and experimental friction force values agreement is up to 10% at high preload values.

1. Introduction

Texturing of a surface starts to become an important tool for the adhesion and friction tuning of a surface without changing any surface chemistry of the interfaces. The textured surfaces are generally obtained by applying a combination of lithography and soft molding techniques where the surface is covered by many independent features standing on a backing layer of a thin film [1–5]. In this way, the tribological characteristics of the surfaces are altered due to the mechanical decoupling of each feature. Therefore, it is possible to play with the degree of adhesion or state of the friction from stick–slip to true sliding or vice versa [6–9].

The shape of the textured surface is generally cylindrical with some degree of aspect ratio to mimic the adhesion and friction properties of gecko. The unexceptional climbing ability of geckos is attributed due to their dense fine and hierarchical structures called setae (foot hairs) on their foot fingers. The unusual fibrillar structure of their foot allows them to move on almost any surfaces, whether hydrophilic or hydrophobic, rough or smooth. During the contact, fibrillar hairs adapt and allow a large real contact area even in rough surfaces which yield high attachment force in the vertical direction. In contrary, low detachment force is observed when the fibrillar hairs are peeled from the surface [10–13]. As nature reveals, tuning interfacial properties of contacting bodies promises enormous application potential [14,15]. As a consequence, there is a significant effort to mimic the structural patterns of the gecko which involve producing the synthetic pillar arrays that are usually made-up of elastomeric materials [1,16–18].

In the initial stage of the development of the gecko-like synthetic adhesives, it is profoundly concentrated on the enhancement of the adhesion of pillars to the surfaces. Afterward, it is recognized that during climbing of a gecko on to a vertical wall, the friction force that balances the gravity force of the gecko's body has an important influence of their attachment capability [19]. Autumn et al. showed that geckos' fibrillar structure shows a different behavior when the setaes are pulled along or against their natural curvature. Either they behave according to Amonton's friction law or violate the law that yields a frictional adhesion model in which gecko adhesion depends directly on the friction force in the gripping direction [20]. The frictional adhesion phenomenon allows gecko to control the adhesion strength through the shear force. Shear force is necessary to initiate adhesion [20] and attention to the shear displacement and force has been given lately [21–24], shear velocity is a decisive factor on friction force. Generally, the friction force between two solids decreases at the sliding condition as velocity becomes higher as discussed in [25]. However, gecko setae and gecko-like synthetic adhesives typically do not behave according to this condition. Friction force increases at the sliding and continue to increase as velocity becomes higher [22,23]. While inducing the velocity, the friction force of the synthetic adhesives has three different phases which are the frictional dynamics, the transition of static to kinetic friction force and lastly the sliding motion. Sometimes special motion which is called stick–slip motion can occur [9,26] where stick–slip motion can be

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thought of an unstable motion. Considering the possible application areas of the dry adhesives such as mobile robots in climbing [27], the transition of static to kinetic friction force and resulting kinetic friction force need to be pointed out. Contribution of the dimension of the pillar structures to the frictional dynamics and the transition to the sliding motion have to be investigated.

The overall adhesion and friction properties of the patterned surfaces heavily depend on the lateral stiffness and damping of a single feature. Therefore, a fundamental understanding of a single pillar's tribological characteristics is necessary. In this paper, kinetic friction force of a single pillar is investigated in meso-scale. The principal mechanism of a single pillar friction is discussed using the friction loop where the shape of the loop is considered to be an important tool to observe the state of the friction. The kinetic friction force is examined within different drag velocities in two drag directions under an initial indentation depth which corresponds to a preload. Sliding motion phase of the friction is analyzed using the energy balance equation and compared with the experimental results. Contribution of preload, drag velocity and dimensions of pillars to the kinetic friction force are investigated and discussed with the shade of the theoretical study. The paper goes in Section 2 with the analytical background. In Section 3, experimental details are given. Results and discussion are detailed in Section 4. Finally, the conclusion and future work are given in Section 5.

2. Energy balance of a single pillar

In this section, a theoretical analysis of the frictional properties of a single pillar that is rubbed on a smooth surface is presented using an energy equilibrium approach. The procedure of the method is such that: (1) a single pillar with a spherical tip in fixed-free boundary conditions is moved along the $+x$ direction where the x-axis coincides with the pillar's principal (neutral) axis as illustrated in Fig. 1(a); (2) the movement of the pillar takes place in the $+x$ direction until a prescribed distance that corresponds to a desired preload (P); (3) after a static contact of the pillar tip with the substrate is ensured, substrate is dragged horizontally along the $+y$ and $-y$ directions with a constant speed of v where the normal (P) and friction (F_{fr}) forces can be measured at the same time as seen in Fig. 1(b).

2.1. Where does the bond rupture?

The complete sliding motion of the pillar in the kinetic friction regime is achieved whenever the friction force exceeds the static friction force. At the beginning of the kinetic friction phase, the interfacial bond between the pillar and the substrate ruptures that results into either a special motion called stick–slip as seen in Fig. 1(c) or a pure sliding motion as seen in Fig. 1(d). In the stick–slip motion, structure leaves its stick phase after some critical energy and begins to slip and then sticks to the surface with some periodicity. In contrary, slipping condition is considered when a pure sliding motion occurs for the pillar on the substrate which is the true-sliding frictional mechanism. In the analytical analysis, true-sliding frictional mechanism is taken into consideration rather than the other mechanism due to the effect properties of the testing condition (i.e., velocity, preload value and radius of curvature of the pillar) which will be elaborated further in the Experimental Results section.

In this section, occurrence position of rupture of the bond between the pillar and surface is investigated by using an energy equilibrium for the pillar contacting with a substrate. In the elastomer friction, it is accepted that the transition of the static to kinetic friction involves peeling (normal separation), no-slip, partial slip and total sliding (true-sliding) periods [28]. In this study, the rupture point corresponds to the transition of static to kinetic friction phase of the pillar. The total energy of the system consists of kinetic and potential (stored elastic energy) energy of the pillar, the potential energy of the preload (mechanical energy) and surface energy at the onset of peeling of pillar from the surface. Note that, there might be a rolling motion due to spherical tip geometry of the pillar before the true sliding happens, which is neglected in this work.

While the pillar is dragged with a constant velocity of v, the energy balance of the pillar on contact surface can be written as $T+V+V_p+S+U_f=0$, where T, V, V_p, S and U_f are kinetic energy, potential energy, mechanical energy, surface energy and dissipative energy, respectively. Dissipative energy might take place in the form of either frictional or damping energy or both. The energies are described, neglecting rotational motion for the pillar along its neutral axis, as follows [29,30]:

$$T=\frac{1}{2}\int_0^L \frac{m}{L}\left(\frac{\partial u(x,t)}{\partial t}\right)^2 dx, \quad (1)$$

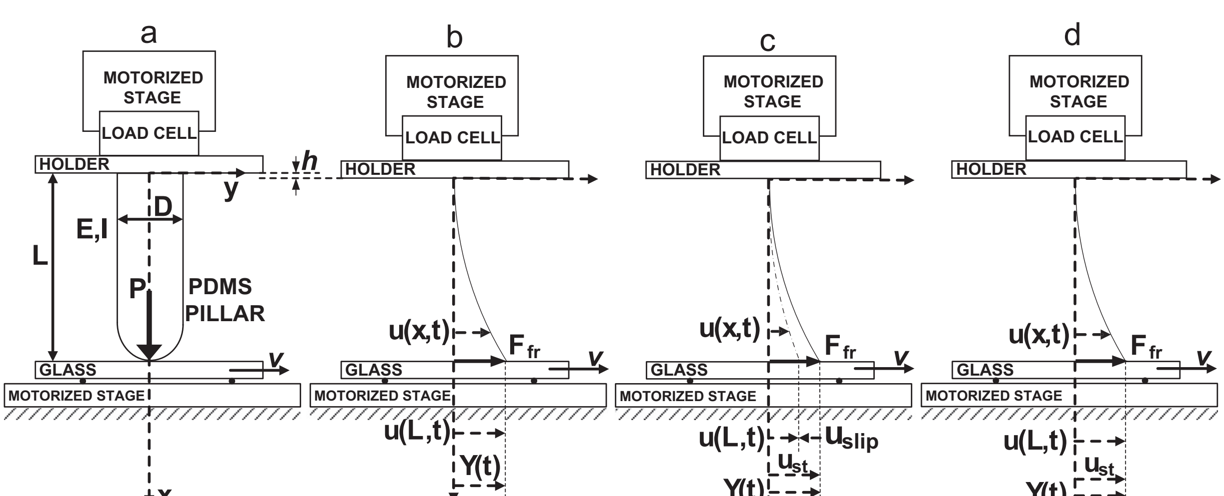

Fig. 1. Motion of the pillar (a) before the vertical motion to achieve a static contact under a preload of P with an indentation depth h, (b) vertical motion of the pillar along the $+y$-axis in stick phase until the slip motion occurs at the position of u_{st} where the tip of the pillar has a deflection of $u(L,t)$, (c) stick–slip motion of the pillar after slipping with a relative movement of u_{slip}, (d) pure sliding motion of the pillar and resulting kinetic friction force of F_{fr}.