Static Friction Coefficient Is Not a Material Constant

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Recommended with a commentary by Robert W. Carpick, University of Pennsylvania, Philadelphia, PA

Friction is a both an extremely common phenomenon (one which we experience, take advantage of, and struggle against every day) and is yet uncommonly difficult to measure. Accessing the details of forces, displacements, and bonds at a buried interface is an intrinsically difficult task. Better understanding of friction can have tremendous impact, including improving earthquake prediction, reducing wasted energy and wear in mechanical systems, and enabling the function of small-scale devices such as micro- and nano-electromechanical systems, which currently are crippled by friction and wear when sliding surfaces are involved in their function.

Finebergs group has been one of the leaders in trying to gain access to this buried interface using clever experimental techniques. They use optically transparent samples (PMMA) that, when coupled with a total-internal reflectance method, allows identification of regions of contact at the interface. This is a critical aspect to understanding friction in any macroscopic or even microscopic interface: even a small amount of surface roughness will ensure that the applied load (normal force) is supported across a small number of contact points or asperities. The true area of intimate contact is typically a minute fraction of the apparent or nominal area. The behavior of these often highly-stressed contact points are crucial to understanding friction. It is relatively well-established that the non-linear relationship between area and load for a single contact point results in a nearly linear relation between total contact area and load for all asperities due to the statistically-random distribution of asperities: adding load not only increases the area of contact for existing asperities, but brings new asperities into contact, leading to a nearly linear relationship between true contact area and normal load. Thus, with friction being nearly proportional to true contact area, the famous result of Amontons and later Coulomb, of the friction force being proportional to normal force, is produced.

Resolving the strain at the interface is crucial too, since there will be an inhomogeneous distribution of strain due to the random assortment of asperity contacts. In Finebergs experiments, strains are locally resolved by embedding strain sensors in the PMMA close to (2 mm above) the interface (the blocks are 100 and 30 mm tall respectively, and the nominal area of contact is 200 mm x 6 mm). These are spaced apart across the interface by separations of the order of several tenths of mm.

This system is in a regime where it exhibits stick-slip instabilities, thus rapid slip events are seen to occur. Both the contact area and applied normal and shear forces are resolved dynamically in time, and normal and shear stress profiles (presumably obtained by converting strain to stress through Hookes Law) were determined prior to each slip event.

One limitation of the optical method Fineberg uses is that the lateral spatial resolution is subject to the far-field diffraction limit, meaning contact areas much smaller than one micrometer across are difficult to discern; two contact regions separated by a distance of 100 nm, for example, cannot be distinguished from a single contact region that includes both. Thus, measurements of contact area can be in error. Obviously, the mm-level spacing of the strain gauges restricts spatial resolution of strains to even larger length scales.

Despite these limitations, the details revealed by these spatially-resolved measurements are intriguing. The color maps in Fig. 2 give us a rare glimpse at the (approximate) regions of contact vs. full separtion upon sliding. Furthermore, important new physical behavior can be uncovered by these techniques. The key question Ben-David and Fineberg address in this paper is whether one can define a true friction coefficient, a proportionality between the normal load and the lateral force at which slip occurs. They find that the value observed depends not only on the load, but also on the application of slight tilt angles to the upper block, which is a way of varying the stress profile at the interface. For a given tilt angle, the friction coefficient and the relative drop in friction when slip occurs are both found to vary, but both scale closely with the ratio of the length l_T to the normal load. The quantity l_T is the length of a pre-existing slipped region that slipped due to a slowly propagating crack. This length will also affect the stress profile at the interface.

Their primary conclusion is that the friction coefficient, be it global (Fs/Fn) or local (shear stress/normal stress in a region) is not constant, but rather is affected by the pre-slip stress profiles and thus to the rupture dynamics. This appears to be highly consistent with the manner in which fracture occurs in solids. Brittle fracture in solids occurs when the strain energy release rate (the rate at which strain energy is relieved as a crack propagates) exceeds a critical value, namely, the energy penalty for creating free surfaces. Ben-David and Fineberg do not discuss it, but this can be quantified in a more versatile manner by comparing the stress intensity factor with the fracture toughness of the material (or in this case, of the interface). This may be worth discussing further in subsequent comments.

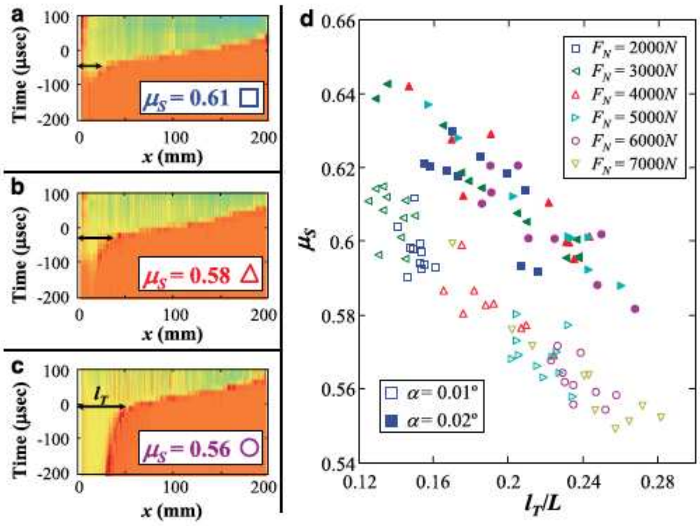

FIG. 2 (color online). (a)–(c) Measurements at 20 μs intervals of the changes in the real contact area $A(x, t)$ for representative events with $\alpha = 0.01°$ and (top to bottom) $F_N = 2000$, 4000, and 6000 N. Hotter (colder) colors indicate increased (decreased) A. $A(x, t)$ was normalized by its value 1 ms before rupture initiation. Each rupture consists of a slow front [6,7] initiating near $x = 0$ which sharply transitions at $x \equiv l_T$ to rapid propagation. Transitions to front velocities $V = 2000$, 1800, and 1500 m/s occur at $l_T = 27$, 38, and 52 mm for (a)–(c). μ_S decreases with increasing l_T. (d) μ_S vs l_T normalized by the interface length $L = 200$ mm, for 113 events with $\alpha = 0.01°$ (open symbols) and $\alpha = 0.02°$ (filled symbols) for $F_N = 2000$–7000 N. For each α, all points collapse to distinct well-defined curves, each offset in μ_S. Whereas for $\alpha = 0.01°$, values of μ_S roughly cluster for each F_N, data for both $F_N = 7000$ N ($\alpha = 0.01°$), and $\alpha = 0.02°$, span most of the collapse.

Figure 1:

In either case, the condition for crack propagation will depend on the precise loading; a small applied moment instead of pure tension, for example, can lead to significantly different critical forces for propagating the crack.

The key point here is that the critical aspect for slip is not force balance, but energy balance between strain energy and surface energy. This is not a new concept. What is potentially new is to apply this to a frictional interface where the dissipation is occurring not just at the crack tip, but across the sliding cracked interface. In other words, the crack faces are not stress-free. The authors mention that no theory that fully accounts for this effect exists. However, there are prior investigations of shear-mode fracture where interfacial friction across the crack faces is taken into account, e.g. [1]. I have not reviewed this body of work in detail. It is likely that, due to the uncertain nature of friction at the slipped interface, many questions remain about this type of fracture. Such prior work likely merits further attention by the authors, although the authors are the first to locally resolve interfacial contact area and stresses, which are important and substantial steps forward.

I disagree with the title and other statements in the paper that the friction coefficient is a material parameter. Tribologists have been well aware for decades that even if one selects two well-defined materials, the velocity, atmosphere, surface roughness, presence of adsorbates, sliding speed, temperature, and static contact time can all affect the friction coefficient. These factors can account for a great deal of the variations in friction coefficients that are typically reported in literature.

However, the Ben-David and Finebergs main point remains valid: given that they are using the same conditions and only varying the normal load and the interfacial stress profile alone, one would not have known what friction coefficient to expect. This study sheds light on the governing interfacial mechanisms that are at play. To understand this further, a comprehensive approach in the framework of fracture mechanics may be warranted. However, it will also need to take into account the frictional dissipation that is taking place at the sliding interface in the wake of the rupture. In other words, we have a conundrum; understanding and modeling static friction seems to require understanding dynamic friction too. Or perhaps the reverse is true: the fluctuations in static friction seen may contain important information on the dynamic friction that occurs at the slipping portions of the interface. Static friction may thus be a sensitive probe of dynamic friction.

[1] On the effect of crack face contact and friction due to fracture surface roughness in edge cracks subjected to external shear, Gross & Mendelsohn, Engineering Fracture Mechanics, v 31, 405-20, 1988.

References

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