



UvA-DARE (Digital Academic Repository)

Decrease of Static Friction Coefficient with Interface Growth from Single to Multiasperity Contact

Peng, Liang; Roch, Thibault; Bonn, Daniel; Weber, Bart

DOI

[10.1103/PhysRevLett.134.176202](https://doi.org/10.1103/PhysRevLett.134.176202)

Publication date

2025

Document Version

Final published version

Published in

Physical Review Letters

License

Article 25fa Dutch Copyright Act (<https://www.openaccess.nl/en/policies/open-access-in-dutch-copyright-law-taverne-amendment>)

[Link to publication](#)

Citation for published version (APA):

Peng, L., Roch, T., Bonn, D., & Weber, B. (2025). Decrease of Static Friction Coefficient with Interface Growth from Single to Multiasperity Contact. *Physical Review Letters*, 134(17), Article 176202. <https://doi.org/10.1103/PhysRevLett.134.176202>

General rights

It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

Disclaimer/Complaints regulations

If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: <https://uba.uva.nl/en/contact>, or a letter to: Library of the University of Amsterdam, Secretariat, P.O. Box 19185, 1000 GD Amsterdam, The Netherlands. You will be contacted as soon as possible.

UvA-DARE is a service provided by the library of the University of Amsterdam (<https://dare.uva.nl>)

Decrease of Static Friction Coefficient with Interface Growth from Single to Multiasperity Contact

Liang Peng^{1,*}, Thibault Roch^{1,*}, Daniel Bonn¹, and Bart Weber^{1,2}

¹*Van der Waals-Zeeman Institute, Institute of Physics, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, The Netherlands*

²*Advanced Research Center for Nanolithography (ARCNL), Science Park 106, 1098 XG Amsterdam, The Netherlands*



(Received 6 September 2024; revised 27 January 2025; accepted 28 March 2025; published 29 April 2025)

The key parameter for describing frictional strength at the onset of sliding is the static friction coefficient. Yet, how the static friction coefficient emerges at the macroscale from contacting asperities at the microscale is still an open problem. Here, we present friction experiments in which the normal load was varied over more than 3 orders of magnitude, so that a transition from a single asperity contact at low loads to multiasperity contacts at high loads was achieved. We find a remarkable reduction in the friction drop (the ratio of the static friction force to the dynamic friction force) with increasing normal load. Using a simple stick-slip transition model we identify the presence of presliding and subcritical contact points as the cause of smaller static friction coefficient at increased normal loads. Our measurements and model bridge the gap between friction behavior commonly observed in atomic force microscopy experiments at microscopic forces, and industrially relevant multiasperity contact interfaces loaded with macroscopic forces.

DOI: [10.1103/PhysRevLett.134.176202](https://doi.org/10.1103/PhysRevLett.134.176202)

The onset of sliding is of critical importance to various natural and industrial interfaces. For example, stick-slip friction behavior leads to catastrophic energy release in earthquakes [1–4] and can hamper the functioning of microelectromechanical systems (MEMS) [5–7]. When slip is initiated, the static friction force generically reduces to a (lower) dynamic friction force [8–10]. This transition from static to dynamic friction, also known as friction drop, can be effectively described by the empirical rate and state friction laws across various contact length scales [11–14]. However, the underlying physical mechanisms remain elusive.

Atomic force microscopy (AFM) friction experiments [15–18] and theoretical models [19–22] have shown that at silicon/silicon contacts, the dynamics of the formation and rupture of interfacial bond networks control the evolution of friction during the onset of slip. While recent experiments suggest that similar bonding phenomena also occur at larger multicontact interfaces [23], additional complexity may emerge as contacts grow [11]. Examples of such complexity include wear [24], multiscale roughness [25], the widening of interfacial pressure distribution [26], non-concurrent slip across the interface [27–29], and interactions between neighboring contact asperities [24,30]. Systematic studies into how such complexity emerges as contacts grow are challenging because rough macroscopic contact interfaces consist of a myriad of contact asperities that are hidden from view by the bulk contacting bodies [28,31,32].

In this Letter, we experimentally demonstrate that the friction drop (the ratio of static to dynamic friction coefficient) decreases as the interface grows from single contact to multiasperity contact by increasing the normal load applied to a silicon-on-silicon contact. The observed decreasing trend of friction drop with increasing normal load can be captured by a simple stick-slip transition model, analogous to a fiber bundle model, based on the local normal contact stress map obtained from boundary integral contact calculations without adjustable parameters. We find that three types of contact points can be identified when the interface is subjected to the maximal tangential force it can withstand. We describe these three types of contact elements as “critical,” “presliding,” and “subcritical.” While single-asperity interfaces are always critical at the onset of slip, we show that the emergence of presliding and subcritical contact asperities at multiasperity interfaces causes the friction drop to decrease.

We study silicon-on-silicon friction using a rheometer (DSR 502, Anton Paar) in combination with an analytical balance (Quintix, Sartorius) inside a humidity-controlled chamber; see Fig. 1(a). To prepare highly hydroxylated silicon surfaces [15,16], the silicon balls and the silicon cantilevers were treated by oxygen plasma cleaning inside a reactor (Zepto One, Diener Electronic) [23]. In the friction experiments, the normal loads were precisely varied from 0.1 to 100 mN by using silicon cantilevers of different normal stiffness (see more details in the Supplemental Material, Sec. A [33]). The imposed sliding speed was fixed at 0.3 $\mu\text{m/s}$ for all the measurements. To reset contact aging [16,17,35], a slide-hold-slide (SHS) measurement

*These authors contributed equally to this work.

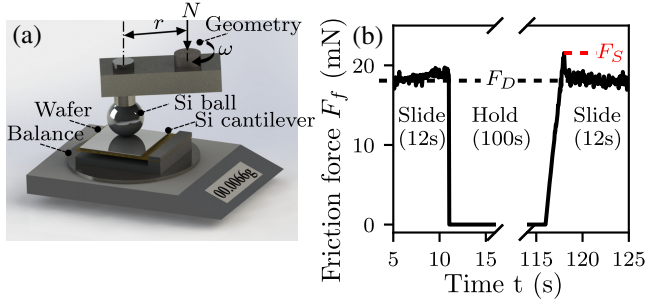


FIG. 1. Experimental system. (a) A 3 mm-diameter silicon ball is clamped to the geometry of a rheometer and brought into contact with a homemade Si cantilever. By rotating the geometry at a constant angular velocity, ω , a sliding speed of ωr ($r = 10$ mm) is imposed at the Si-on-Si contact interface. The corresponding friction force (F_f) and the normal force (N) can be simultaneously measured by the rheometer and the balance. The ratio of friction force and normal load gives the coefficient of friction, $\mu = F_f/N$. (b) An example of the slide-hold-slide experiment protocol with a normal load of 24 mN and a hold time of 100 s. F_S and F_D represent the maximum static friction force and the average dynamic friction force after the sliding is reinitiated, respectively.

procedure was employed [see Fig. 1(b)]: we used the rheometer to impose a stationary state with zero torque (or zero friction) after the initial sliding to avoid impacting the aging process with shear force [4,17,36], followed by reinitiating the sliding in the same direction. The static friction force F_S and dynamic friction force F_D when sliding was restarted, were recorded to calculate the corresponding static friction coefficient, μ_S , the dynamic friction coefficient, μ_D , and the friction drop, μ_S/μ_D , which equals to F_S/F_D . All sliding strokes were measured on previously untouched areas of the silicon wafer and kept short at 10 μm to minimize the influence of wear (Fig. S2).

Both the static and the dynamic friction coefficients, defined as the ratio of friction force to normal force, are widely assumed to be independent of the normal load [9,37,38]. Surprisingly, we observe that the friction drop gradually decreases with increasing normal load as shown with black data points in Fig. 2. Notably, the nanoscale single-asperity friction drop (leftmost black circle in Fig. 2), reproduced from previous AFM experiments (inset of Fig. 2) [15], aligns well with our observed qualitative decreasing trend of friction drop with increasing normal load.

To provide insight into the normal load dependence of the friction drop, we propose a simple stick-slip transition model. In the model, we discretize the interface with square elements (pixels) such that the macroscopic friction force is the sum of all the microscopic interfacial shear forces generated by these elements. We also assume that the element-scale frictional behavior is characterized by an instant drop in friction upon slip, the magnitude of which matches that observed in the AFM friction experiments

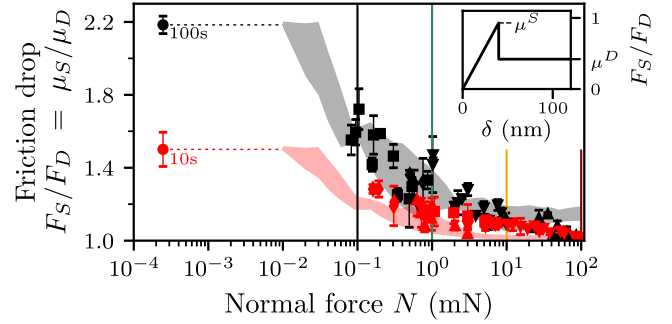


FIG. 2. The friction drop as a function of normal load, measured from experiments (data points) and predicted by our model (shaded area), with black and red corresponding to a hold time of 100 s and 10 s, respectively (the static and dynamic friction coefficients are reported in Fig. S1). Each symbol stands for a different Si cantilever with varying normal stiffness, and each data point represents the average of three measurements. The leftmost red and black solid circle data points, measured from AFM experiments, are extracted from Fig. S5 in Ref. [15], with the evolution of the nanoscale friction coefficient being reproduced in the inset. The vertical lines indicate the normal load corresponding to the normal stress distribution shown in Fig. 3.

shown in the inset of Fig. 2. In other words, the local ratio of shear stress to normal stress (local stress ratio) drops at the onset of local slip, in accordance with the static and dynamic friction coefficient (μ^S and μ^D , respectively) observed in the AFM experiments. The interface is a collection of microscopic contact patches of varying size (see Fig. S4). In our model, the shear force applied to an individual contact patch scales linearly with the number of elements involved in that patch. This means that the applied shear force is distributed homogeneously over the real contact area before any element starts to slip. The excess shear force generated when an element enters slip is uniformly redistributed over the interfacial contact area (elements) that has not undergone slip yet. We also assume that there is no evolution of the area and geometry of the contact patches during sliding, as the substrate wafer is much smoother than the silicon ball [23].

To estimate the local normal stress at the interface, we conduct elastic contact calculations using an open-source implementation of the boundary integral method (BIM) [39]. In the contact calculation, the elastically stored energy of the contact system is minimized under the constraint that the resulting mean contact pressure balances the applied average pressure over the area of the input topography [33] (see more details in Sec. B). Our use of elastic contact is reasonable here, since there is mainly elastic deformation at the contact interface (see Fig. 3) [23,30,40]. Using the calculated local normal stress distribution and the assumed relations between local shear stress and local normal stress described above, the model predicts how the total tangential force, which is externally imposed, is distributed over the contact area and how this

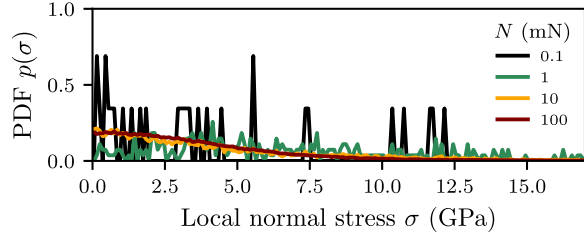


FIG. 3. The probability density function, $p(\sigma)$, of the local normal stress σ under various normal loads.

distribution of local shear stress evolves as the applied tangential force is increased. In our model, at the level of a single element, the maximal (critical) ratio of shear stress to normal stress is constant, in line with the load-controlled friction framework [41–43]. It is the normal stress distribution that completely determines the macroscopic frictional behavior. This enables us to predict the frictional response of the same interface at various normal loads, from which we can compute the macroscopic static friction coefficient and friction drop.

In other words, our model is analogous to a fiber bundle model with equal load sharing [44], where the failure of a bundle of fibers corresponds to the failure of contact elements, with their strength governed by the local normal stress. While sliding heterogeneity can originate from elastic interaction among contact patches [11], we assume that these interactions during the onset of the sliding process are negligible in our system. Indeed, the nanometer-scale contact deformation (~ 5 nm at a normal load of 10 mN based on BIM contact calculation as mentioned above) is considerably smaller than the micrometer-scale distance between contact patches. Therefore, it is reasonable to ignore the role of asperity interactions in the distribution of the shear forces. However, this assumption may break down at increasing normal loads when the distances between contact patches shrink (see Fig. S4).

To quantify ball-to-ball topography variations, we use three different topographies measured on silicon balls that were used in the experiments (see Fig. S3). For each topography and normal load, the model predicts the friction drop. The gray shaded area in Fig. 2 corresponds to the range of predicted friction drop values based on the three topographies, and the nanoscale static and dynamic friction coefficients measured at a hold time of 100 s in AFM experiments. The stick-slip transition model qualitatively reproduces the decrease of the friction drop with increasing normal load and quantitatively matches the experiments without any fitting parameter.

To evaluate the robustness of our model against variations in the system characteristics, we conduct additional experiments with a hold time of 10 s instead of 100 s, and report the corresponding friction drop with red data points in Fig. 2. A decrease of the friction drop with increasing

normal load is observed, similar to the experiments for a hold time of 100 s. Furthermore, it is noteworthy that the measured friction drop for a hold time of 100 s is larger than that for a hold time of 10 s under the same normal force. The larger static friction coefficient, corresponding to a greater friction drop, is expected: a longer hold time during the SHS procedure can enhance the contact strength by forming more interfacial siloxane bonds [15,23], which results in a higher static friction coefficient. Moreover, our stick-slip transition model (red-shaded area in Fig. 2) with the nanoscale static and dynamic friction coefficients measured at a hold time of 10 s from previous AFM experiments [15] (leftmost red circle in Fig. 2, see also Fig. S5), still captures successfully the evolution of friction drop with the normal force for the experiments with 10 s hold time. One should note that there is still a gap between the minimum normal load used in the simulation and AFM experiments in Fig. 2 (marked by black and red horizontal dot lines), which will be discussed later.

To further elucidate the relation between the normal load, the local normal stress distribution, and the macroscopic frictional response, we plot the probability density function, $p(\sigma)$, of the normal stress at the interface, obtained from elastic contact calculations with various normal loads in Fig. 3. With increasing normal load, the probability density function of the local normal stress evolves from being discrete (the black curve, 0.1 mN) to continuous (the yellow curve, 10 mN). This directly relates to the transition from single to multiasperity contact interfaces (see Fig. S4). At lowest normal loads, only a few contact patches are formed, and the macroscopic behavior may be dominated by those patches. At larger normal loads, however, there is a more continuous distribution of normal (and thus shear) stresses at the interface. The normal loads corresponding to the distribution shown in Fig. 3 are indicated with vertical lines of the same color in Fig. 2.

To better understand how the differences in normal stress distribution impact the onset of sliding, we focus on the critical state of the interface, where the peak macroscopic friction force is reached under an imposed tangential lateral displacement of δ_{peak} [see a typical simulated friction-displacement curve in Fig. 4(a)]. We plot the distribution of local stress ratios across all the contact elements at the critical state of the interface in Figs. 4(b)–4(e). For an idealized single element contact [Fig. 4(b)], the element will reach the maximum local stress ratio, μ^S , resulting in an interfacial friction coefficient equal to the local stress ratio ($\mu = \mu^S$). In this limiting case of a single asperity contact, one recovers the frictional behavior as measured from AFM. In our model, this means that below a normal load for which the real contact area is of the scale of the input AFM topography resolution (21 nm), the macroscopic friction coefficient is not dependent on the normal load. Such an extreme case is marked by black and red horizontal dot lines in Fig. 2.

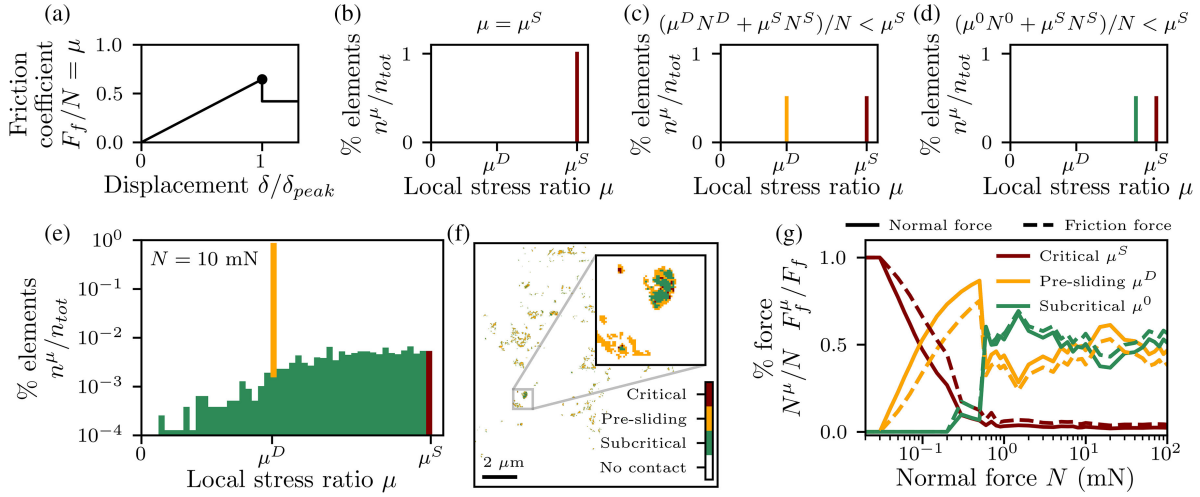


FIG. 4. Local stick-slip transition at the critical state of the interface from numerical computation. (a) Macroscopic friction coefficient versus displacement curve at a normal load of 0.1 mN. The black circle corresponds to the critical interfacial state where no more additional tangential load can be added. (b)–(e) Distribution of local stress ratio for a single-element interface (b), two-element interface (c)(d), and multielement interface under a normal load of 10 mN (e), respectively. The brown, yellow, and green correspond to critical, pre-sliding, and subcritical elements with local stress ratios of μ^D , μ^S , and μ^0 , respectively. μ^0 is smaller than μ^S . n^μ and n^{tot} represent the number of elements under a local stress ratio of μ ($\mu = \mu^S$, μ^D , or μ^0) and the total number of elements, respectively. Movies of the evolution of the distribution of local stress ratios with increasing imposed displacement are available in the Supplemental Material, Sec. C [33]. (f) The state of the contacting elements at the critical interfacial state for a normal load of 10 mN. (g) The fraction of the total normal force (solid lines) and the total friction force (dashed lines) generated by different types of contact elements in the interfaces under various normal loads. N^μ and N represent the shared normal load on those contact elements under a local stress ratio of μ ($\mu = \mu^S$, μ^D , or μ^0) and the total applied normal load, respectively. F_f^μ and F_f represent the same quantity but for the shear load.

The situation becomes more complex when considering multiasperity contact interfaces, as each element potentially experiences different local normal stresses (and thus different local stress ratios at the critical interfacial state). We stress that, within our model, any distribution of local stress ratios (between 0 and μ^S) at a multicontact interface can only result in a decrease in the friction drop as compared to the friction drop at single-asperity level. Hereafter we investigate the details of the critical interfacial state for multiasperity interfaces and its influence on the friction drop, starting with the idealized case of two contacting elements.

For an interface composed of two contacting elements, each carrying a different normal stress, two distinct scenarios arise at the critical interfacial state corresponding to maximal (global) static friction force. In the first scenario, the normal stress carried by each element varies significantly (Fig. 4(c)) such that the weaker element, carrying a smaller normal stress, has already slipped and experiences the local stress ratio μ^D , while the stronger element with the higher normal stress remains stuck with a local stress ratio of μ^S . We can calculate the interfacial friction coefficient as $\mu = (\mu^D N^D + \mu^S N^S)/N$, with N^D and N^S the normal forces carried by the two elements: $N = N^D + N^S$. In the second scenario, the difference in the normal stresses carried by the two elements is smaller [Fig. 4(d)]. This results in both contact elements being stuck at the critical

state of the interface. Now, the failure of the weaker element will trigger the slip of the stronger element due to its excess friction force redistribution. This is reminiscent of the asperity model in geophysics [45], in which the failure of one asperity may cause an avalanche of asperity failure. The element with lower normal stress has reached a local stress ratio of μ^S , while the contact element with higher normal stress experiences a local stress ratio of μ^0 that is smaller than μ^S . Contrarily to μ^D and μ^S , μ^0 is not a fixed value related to the nanoscale friction experiment: it is the instantaneous local stress ratio experienced by a stuck element that is loaded subcritically. The collective friction coefficient is then $\mu = (\mu^0 N^0 + \mu^S N^S)/N$, where N^0 and N^S represent the normal force on the two elements, satisfying $N = N^0 + N^S$ and $N^0 > N^S$. In both scenarios the friction drop is lowered by the addition of a second element, either because an element has already entered slip when the overall friction force is maximal (scenario 1) or because the stronger element is “subcritical”; its slip is activated by failure of the weaker element (scenario 2).

We can therefore define three types of contact elements at the critical state of multiasperity interfaces: critical contact elements, experiencing the maximal local stress ratio μ^S ; pre-sliding contact elements, that have already slipped and therefore show the dynamic stress ratio μ^D ; and subcritical contact elements, with a local stress ratio of μ^0 smaller than μ^S . For a realistic multiasperity interface,

many elements might correspond to each of the three element types. An example is shown in Fig. 4(e), with the distribution of local stress ratios for an interface at the critical state under a normal load of 10 mN. The three types of elements (critical, presliding, and subcritical) are respectively represented in green, yellow, and brown. The corresponding contact map from the BIM computation is shown in Fig. 4(f), with the contact being colored following the same scheme.

The slip of the subcritical elements is activated by the redistribution of excess friction force released when critical elements slip. This instability in our model defines the critical interface state with maximal applied tangential load. Since both μ^D and μ^0 are smaller than μ^S , the collective friction coefficient at the critical interfacial state will, as expected, be smaller as compared to that in a single element interface ($\mu < \mu^S$). Consequently, it is the presliding and subcritical contact elements that dominate the reduction of the collective static friction coefficient at the multiasperity interfaces with respect to its value for a single element interface, leading to a smaller friction drop with increasing normal load. To quantify the relative contribution of critical, presliding, and subcritical contact elements to the overall static friction coefficient, we plot the fraction of the total normal load (respectively friction force) supported by different types of contact elements under various total normal loads in solid (respectively dashed) lines in Fig. 4(g). As the total normal load increases, more contact elements form at the contact interface. The fraction of presliding and subcritical contact elements gradually increases from 0 at single element contact interfaces to an approximately constant value at multiasperity contact interfaces, which suggests that the friction drop decreases with increasing normal force. In contrast, the fraction of critical contact elements decreases from 1 to an almost negligible level. This decreasing fraction of critical contact elements with increasing normal load indicates a smaller contribution of critical contact elements to the static friction coefficient, which matches well with the observed friction drop in Fig. 2. In the low normal load limit, the evolution of friction drop is given by the intrinsic, nanoscale friction drop which can for example be controlled by interfacial bonding dynamics [24]. At low normal loads, the critical asperities govern the static friction coefficient, which is analogous to the dominant role of nucleation regions as identified in previous Letter [46,47]. The specific normal load range over which the friction drop decreases, is controlled by the elastic properties and surface roughness in our model, with the relation between friction drop and normal load shifting to higher normal loads for higher roughness or stiffer materials as long as the contact mechanics remains elastic. For example, MEMS devices typically involve lower roughness and lower normal force compared to our experimental conditions, and may therefore display similar friction drop behavior. At larger

interfaces, however, additional complexity may arise [27,48]. The assumption of independent contact elements in our model may break down at larger loads, where large contact patches lead to increased interfacial stiffness and shear loading [49], resulting in an even more heterogeneous distribution of shear stress, which could further reduce the predicted friction drop.

In conclusion, we have investigated how the macroscopic frictional response of a Si-on-Si system evolves from a single to a multiasperity contact interface, and show how the macroscopic static friction coefficient decreases with increasing normal load across a broad range of loads. We propose a stick-slip model, analogous to a fiber bundle model, based on elastic contact calculations to capture the decrease in macroscopic static friction coefficient and friction drop with increasing normal load. This decrease is found to be dominated by the relative fraction of critical contact elements at the interface that collectively fail when the maximal static friction force is reached. With increasing normal load, we observe the growing populations of presliding elements, i.e., contact elements that slip before the maximal tangential force is applied to the interface, and subcritical elements, i.e., contact elements whose slip is activated by redistribution of the excess friction from critical elements. Both the presliding and subcritical populations of elements observed at the critical interface state grow with increasing normal load, causing the friction drop to decrease with increasing normal force. By changing the hold time in our hold-slide-hold experiments, we demonstrated that these results remain valid when considering a different reference nanoscale friction behavior. All in all, our findings shed new light on the complexity that emerges when contact interfaces scale up from single asperity to multiasperity—a central question in tribology and an important challenge in precision positioning.

Acknowledgments—We thank R. Carpick, B. Mcclimon, J. Dijkstra, and K. Farain for valuable discussions. T. R. acknowledges support of the Swiss National Science Foundation through Fellowship No. P500PT/222342. L. P. acknowledges funding from the China Scholarship Council and is thankful for the invaluable support from Min Li.

-
- [1] A. Ruina, Slip instability and state variable friction laws, *J. Geophys. Res.* **88**, 10359 (1983).
 - [2] C. H. Scholz, Earthquakes and friction laws, *Nature (London)* **391**, 37 (1998).
 - [3] M. J. Ikari, C. Marone, D. M. Saffer, and A. J. Kopf, Slip weakening as a mechanism for slow earthquakes, *Nat. Geosci.* **6**, 468 (2013).
 - [4] K. Farain and D. Bonn, Perturbation-induced granular fluidization as a model for remote earthquake triggering, *Sci. Adv.* **10**, 1 (2024).

- [5] A. Corwin and M. De Boer, Effect of adhesion on dynamic and static friction in surface micromachining, *Appl. Phys. Lett.* **84**, 2451 (2004).
- [6] B. Weber, J. Scheibert, M. De Boer, and A. Dhinojwala, Experimental insights into adhesion and friction between nominally dry rough surfaces, *MRS Bull.* **47**, 1 (2022).
- [7] S. S. Shroff, N. Ansari, W. Robert Ashurst, and M. P. de Boer, Rate-state friction in microelectromechanical systems interfaces: Experiment and theory, *J. Appl. Phys.* **116**, 244902 (2014).
- [8] B. Weber, T. Suhina, A. Brouwer, and D. Bonn, Frictional weakening of slip interfaces, *Sci. Adv.* **5**, 1 (2019).
- [9] T. Baumberger and C. Caroli, Solid friction from stick–slip down to pinning and aging, *Adv. Phys.* **55**, 279 (2006).
- [10] C. Mate and R. Carpick, *Tribology on the Small Scale: A Modern Textbook on Friction, Lubrication, and Wear* (Oxford University Press, New York, 2019).
- [11] S. Li, S. Zhang, Z. Chen, X. Q. Feng, and Q. Li, Length scale effect in frictional aging of silica contacts, *Phys. Rev. Lett.* **125**, 215502 (2020).
- [12] K. Tian, Z. Li, N. Gosvami, D. Goldsby, I. Szlufarska, and R. Carpick, Memory distance for interfacial chemical bond-induced friction at the nanoscale, *ACS Nano* **13**, 7425 (2019).
- [13] L. Frérot, A. Crespo, J. El-Awady, M. Robbins, J. Cayer-Barrioz, and D. Mazuyer, From molecular to multi-asperity contacts: How roughness bridges the friction scale gap, *ACS Nano* **17**, 2205 (2021).
- [14] R. Sahli, G. Pallares, C. Ducottet, I. Ben Ali, S. Al Akhrass, M. Guibert *et al.*, Evolution of real contact area under shear and the value of static friction of soft materials, *Proc. Natl. Acad. Sci. U.S.A.* **115**, 471 (2018).
- [15] Q. Li, T. Tullis, D. Goldsby, and R. Carpick, Frictional ageing from interfacial bonding and the origins of rate and state friction, *Nature (London)* **480**, 233 (2011).
- [16] K. Tian, N. Gosvami, D. Goldsby, Y. Liu, I. Szlufarska, and R. Carpick, Load and time dependence of interfacial chemical bond-induced friction at the nanoscale, *Phys. Rev. Lett.* **118**, 076103 (2017).
- [17] M. Vorholzer, J. Vilhena, R. Perez, E. Gnecco, D. Dietzel, and A. Schirmeisen, Temperature activates contact aging in silica nanocontacts, *Phys. Rev. X* **9**, 041045 (2019).
- [18] N. Z. Badt, D. L. Goldsby, G. M. Pharr, and C. C. Walker, Frictional aging of single-asperity nanoindentation contacts in quartz and calcite, *Geophys. Res. Lett.* **51**, e2023GL105471 (2024).
- [19] W. Ouyang, S. N. Ramakrishna, A. Rossi, M. Urbakh, N. D. Spencer, and A. Arcifa, Load and velocity dependence of friction mediated by dynamics of interfacial contacts, *Phys. Rev. Lett.* **123**, 116102 (2019).
- [20] Y. Liu and I. Szlufarska, Chemical origins of frictional aging, *Phys. Rev. Lett.* **109**, 186102 (2012).
- [21] A. Filippov, J. Klafter, and M. Urbakh, Friction through dynamical formation and rupture of molecular bonds, *Phys. Rev. Lett.* **92**, 135503 (2004).
- [22] Z. Li and I. Szlufarska, Chemical creep and its effect on contact aging, *ACS Mater. Lett.* **4**, 1368 (2022).
- [23] L. Peng, C. C. Hsu, C. Xiao, D. Bonn, and B. Weber, Controlling macroscopic friction through interfacial siloxane bonding, *Phys. Rev. Lett.* **131**, 226201 (2023).
- [24] C. Leriche, C. Xiao, S. Franklin, and B. Weber, From atomic attrition to mild wear at multi-asperity interfaces: The wear of hard Si₃N₄ repeatedly contacted against soft Si, *Wear* **528–529**, 204975 (2023).
- [25] T. H. Goebel, E. E. Brodsky, and G. Dresen, Fault roughness promotes earthquake-like aftershock clustering in the lab, *Geophys. Res. Lett.* **50**, e2022GL101241 (2023).
- [26] C. Hsu, F. Hsia, B. Weber, M. De Rooij, D. Bonn, and A. Brouwer, Local shearing force measurement during frictional sliding using fluorogenic mechanophores, *J. Phys. Chem. Lett.* **13**, 8840 (2022).
- [27] S. M. Rubinstein, G. Cohen, and J. Fineberg, Detachment fronts and the onset of dynamic friction, *Nature (London)* **430**, 1005 (2004).
- [28] O. Ben-David, S. M. Rubinstein, and J. Fineberg, Slip-stick and the evolution of frictional strength, *Nature (London)* **463**, 76 (2010).
- [29] D. S. Kammer, V. A. Yastrebov, P. Spijker, and J.-F. Molinari, On the propagation of slip fronts at frictional interfaces, *Tribol. Lett.*, **48**, 27 (2012).
- [30] Z. Li, L. Pastewka, and I. Szlufarska, Chemical aging of large-scale randomly rough frictional contacts, *Phys. Rev. E* **98**, 023001 (2018).
- [31] B. Weber, T. Suhina, T. Junge, L. Pastewka, A. Brouwer, and D. Bonn, Molecular probes reveal deviations from amontons’ law in multi-asperity frictional contacts, *Nat. Commun.* **9**, 1 (2018).
- [32] V. Romero, E. Wandersman, G. Debrégeas, and A. Prevost, Probing locally the onset of slippage at a model multicontact interface, *Phys. Rev. Lett.* **112**, 094301 (2014).
- [33] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/PhysRevLett.134.176202>, which includes Ref. [34]. The Supplementary Materials comprise three sections and six additional figures. The three sections detail the experimental methods, the computational methodology used for contact simulations and movies of the evolution of the distribution of local stress ratios, respectively. The six figures present: (1) the static and dynamic friction coefficients as functions of normal load at a hold time of 100 s, (2) wear-induced minimal topography changes, (3) atomic force microscopy (AFM) topography data used as simulation inputs, (4) contact maps under varying normal loads, (5) nanoscale friction coefficient–displacement curves used as simulation inputs, and (6) snapshots demonstrating the evolution of the distribution of shear-to-normal stress ratio under applied normal loads of 0.1, 1, and 10 mN.
- [34] A. Socoliuc, E. Gnecco, S. Maier, O. Pfeiffer, A. Baratoff, R. Bennewitz, and E. Meyer, Atomic-scale control of friction by actuation of nanometer-sized contacts, *Science* **313**, 207 (2006).
- [35] S. M. Rubinstein, G. Cohen, and J. Fineberg, Contact area measurements reveal loading-history dependence of static friction, *Phys. Rev. Lett.* **96**, 256103 (2006).
- [36] S. Dillavou and S. M. Rubinstein, Shear controls frictional aging by erasing memory, *Phys. Rev. Lett.* **124**, 085502 (2020).
- [37] P. Berthoud, T. Baumberger, C. G’Sell, and J.-M. Hiver, Physical analysis of the state-and rate-dependent friction law: Static friction, *Phys. Rev. B* **59**, 14313 (1999).

- [38] R. Capozza and M. Urbakh, Static friction and the dynamics of interfacial rupture, *Phys. Rev. B* **86**, 085430 (2012).
- [39] L. Frérot, G. Anciaux, V. Rey, S. Pham-Ba, and J.-F. Molinari, Tamaas: A library for elastic-plastic contact of periodic rough surfaces, *J. Open Source Software* **5**, 2121 (2020).
- [40] F.-C. Hsia, C.-C. Hsu, L. Peng, F. M. Elam, C. Xiao, S. Franklin, D. Bonn, and B. Weber, Contribution of capillary adhesion to friction at macroscopic solid–solid interfaces, *Phys. Rev. Appl.* **17**, 034034 (2022).
- [41] A. Berman, C. Drummond, and J. Israelachvili, Amontons’ law at the molecular level, *Tribol. Lett.* **4**, 95 (1998).
- [42] J. Gao, W. Luedtke, D. Gourdon, M. Ruths, J. Israelachvili, and U. Landman, Frictional forces and amontons’ law: From the molecular to the macroscopic scale, *J. Phys. Chem. B* **108**, 3410 (2004).
- [43] F.-C. Hsia, S. Franklin, P. Audebert, A. M. Brouwer, D. Bonn, and B. Weber, Rougher is more slippery: How adhesive friction decreases with increasing surface roughness due to the suppression of capillary adhesion, *Phys. Rev. Res.* **3**, 043204 (2021).
- [44] S. Pradhan, A. Hansen, and B. K. Chakrabarti, Failure processes in elastic fiber bundles, *Rev. Mod. Phys.* **82**, 499 (2010).
- [45] L. R. Johnson and R. M. Nadeau, Asperity model of an earthquake: Static problem, *Bull. Seismol. Soc. Am.* **92**, 672 (2002).
- [46] S. Dillavou and S. M. Rubinstein, Nonmonotonic aging and memory in a frictional interface, *Phys. Rev. Lett.* **120**, 224101 (2018).
- [47] S. M. Rubinstein, G. Cohen, and J. Fineberg, Dynamics of precursors to frictional sliding, *Phys. Rev. Lett.* **98**, 226103 (2007).
- [48] T. H. Goebel, G. Kwiatek, T. W. Becker, E. E. Brodsky, and G. Dresen, What allows seismic events to grow big?: Insights from b-value and fault roughness analysis in laboratory stick-slip experiments, *Geology* **45**, 815 (2017).
- [49] R. D. Mindlin, Compliance of elastic bodies in contact, *J. Appl. Mech.* **16**, 259 (1949).