Velocity Dependence of Atomic Friction

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Sliding friction between the tip of a friction force microscope and NaCl(100) was studied to deduce the velocity dependence of friction forces on the atomic scale. A logarithmic dependence of the mean friction force is revealed at low velocities. The experimental data are interpreted in terms of a modified Tomlinson model which is based on reaction rate theory.

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The fundamental laws of friction were stated a few centuries ago by da Vinci, Amonton, and Coulomb, who found that (i) friction is independent of the apparent area of contact, (ii) friction is proportional to the applied load, and (iii) kinetic friction is independent of the velocity [1]. These laws, commonly verified on the macroscopic scale, result from the collective behavior of many microscopic asperities which continuously stick and detach during sliding [2].

With the introduction of the friction force microscope (FFM) in 1987 [3] it became possible to produce a single asperity contact and study friction on the atomic scale. In a FFM, a flat surface is scanned by a sharp tip at a constant normal force or height; the lateral (or friction) force is detected by optical techniques which measure the torsional bending of the cantilever which the tip is mounted on. By FFM measurements it was revealed that friction laws for a single asperity are different from macroscopic friction laws. The main result, confirmed by several experiments [3–5], is that the friction force on the nanometer scale exhibits a sawtooth behavior, commonly known as atomic stick slip. This phenomenon can be theoretically reproduced within classical mechanical models [6–8].

Very little is known about the velocity dependence of friction on such scales. Recently, FFM experiments performed in controlled atmosphere on a 1×1 μm^2 scale have been reported. Zwörner *et al.* found that the friction forces between silicon tips and different carbon compounds are constant over a wide range of velocities [9]. Bouhacina *et al.* [10] report a logarithmic increase in friction with velocity between a tip and polymers grafted on silica surfaces. Mechanical models which do not consider the role of finite temperature reveal no significant dependence on velocity [11]. To explain the latter result, Bouhacina *et al.* related the average friction force on the μm scale to a thermally activated stick-slip behavior on the atomic scale.

In this Letter, we present the first measurements of the velocity dependence of atomic-scale friction. The experiments were performed with a silicon tip on a NaCl(100) surface, using a homebuilt UHV-FFM [12] of beam deflection type [13]. The microscope was operated in a UHV chamber, where a pressure below 10^{-10} mbar was maintained during the experiment. The samples were cleaved *in situ* and heated to 120 °C for two hours to remove charging produced in the cleavage process. Friction measurements were performed at room temperature.

The normal and lateral forces acting on the tip, F_N and F_L, were deduced from measurements of the deflections of rectangular silicon cantilevers. The normal and torsional spring constants of each cantilever, c_n and c_t, were calculated from its geometry, permitting a calibration of the forces F_N and F_L [1]. The length and the width of each cantilever was evaluated using scanning electron microscopy (SEM) micrographs; the height of the tip was also determined by SEM, and the thickness of the cantilever was obtained from its resonance frequency [14].

The measurements presented here were performed using a cantilever with low spring constants, $c_n = 0.12$ N/m and $c_t = 66.7$ N/m. We also performed measurements using cantilevers with larger spring constants, but in this case no atomic features were observed. During the scanning process, the external load F_N was kept constant at $F_N = 0.44$ nN or $F_N = 0.65$ nN using a feedback loop. The integral and the proportional gain of the feedback loop were set to low values, as it is known that high values can have a dramatic influence on the measured lateral force [15]. Zero normal force is defined as the position where the cantilever is not bent.

Friction measurements were performed on the same region of the sample with different scanning velocities v between 5 nm/s and 1 μm/s. No changes in topography were revealed after several scans. In Fig. 1(a) a lateral force map of a 5×5 nm^2 area, acquired by scanning at $v = 25$ nm/s, is shown. The lateral stiffness of the contact, k_c, was determined to be $k_c = 0.86$ N/m from the slope of the sticking part of the friction loop [Fig. 1(b)] [1]. The diameter of the contact between the tip and the sample was estimated from k_c to be on the order of one ionic radius [16,17]. This small contact diameter suggests that this method, based on continuum mechanics, is at the limit of its validity. However, the value indicates that the contact consists of only a few atoms, possibly only one atom.

The lateral force, F_L, was computed from the mean absolute value of the lateral force maps, $\langle F_L \rangle$, and from

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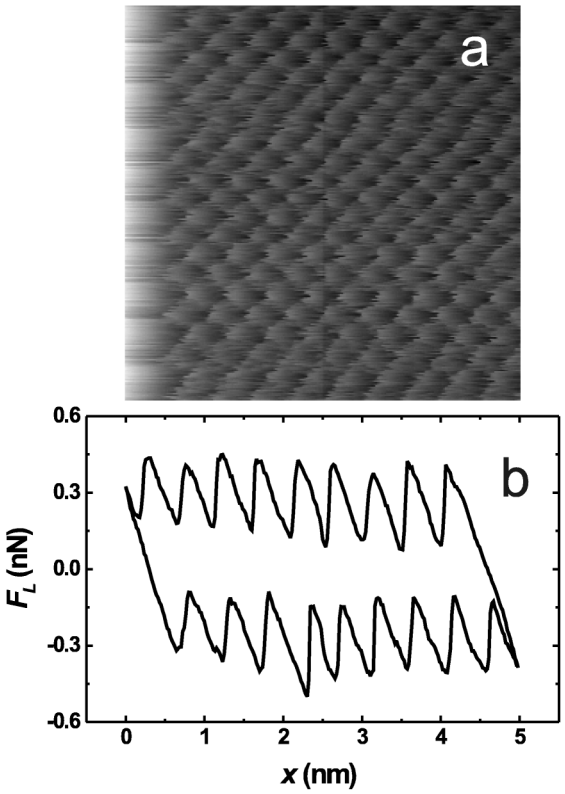

FIG. 1. (a) Lateral force map of NaCl(100) at $F_N = 0.65$ nN and $v = 25$ nm/s. (b) Friction loop formed by two scan lines measured forward and backward, respectively.

the mean absolute value of the peaks in the friction loops, $\langle F_{L,\max}\rangle$. In both cases, it was found that the lateral force, F_L, depends logarithmically on the velocity v (Fig. 2):

$$F_L = F_{L0} + F_{L1} \ln \frac{v}{v_1}, \tag{1}$$

where v_1 is taken to be 1 nm/s for simplicity. The values of F_{L1} calculated from $\langle F_L\rangle$ and $\langle F_{L,\max}\rangle$ nearly coincide for each load; thus $\langle F_{L,\max}\rangle$ has the same dependence on velocity as $\langle F_L\rangle$. This finding is confirmed by the fact that the effective lateral spring constant k_{eff}, given by the slope of the sawtooth in the friction loop, does not change significantly with velocity.

The results can be interpreted within a modified Tomlinson model [6,18,19], taking into account the effects of thermal activation. The friction force microscope can be described by the potential

$$V_{\text{tot}} = V(x_T) + \frac{k_{\text{eff}}}{2}(x_T - x_S)^2, \tag{2}$$

where x_T and x_S are the position of the tip and the support of the microscope, respectively. The first term describes the potential acting on the tip due to the interaction with the sample; the second term describes the elastic energy stored in the cantilever. The adiabatic potential of the tip for a

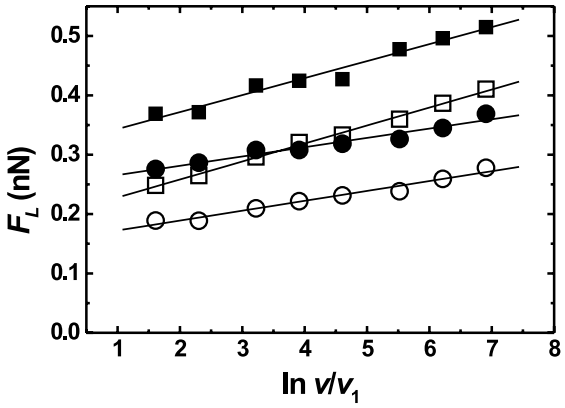

FIG. 2. Friction as a function of the scanning velocity at $F_N = 0.44$ nN (circles) and $F_N = 0.65$ nN (squares) loads. Open and solid symbols refer to $\langle F_L\rangle$ and $\langle F_{L,\max}\rangle$, respectively. The following parameters (see text) have been extracted from the data: $F_{L0} = 0.156$ nN, $F_{L1} = 0.017$ nN (open circle); $F_{L0} = 0.250$ nN, $F_{L1} = 0.016$ nN (solid circle); $F_{L0} = 0.198$ nN, $F_{L1} = 0.030$ nN (open square); $F_{L0} = 0.315$ nN, $F_{L1} = 0.029$ nN (solid square).

fixed support position x_S consists of a multiwell potential as reproduced in Fig. 3. For this figure $V(x_T)$ was assumed to be a cosine function with periodicity $a = 0.4$ nm and a peak-to-peak amplitude E_0 reflecting the energy barrier between two adjacent atomic positions.

At zero temperature an irreversible jump of the tip occurs when the equilibrium of the tip becomes unstable. This takes place if the potential barrier ΔE^+ vanishes. The corresponding support position x_S is referred to as the critical point. The lateral force needed to induce a jump at $T = 0$ will be denoted F_L^*. We study the case of temperatures, where the energy barrier becomes comparable to $k_B T$ only for support positions near the critical point. In this case we can restrict ourselves to a potential containing only two minima, named A and B, the energy minimum B

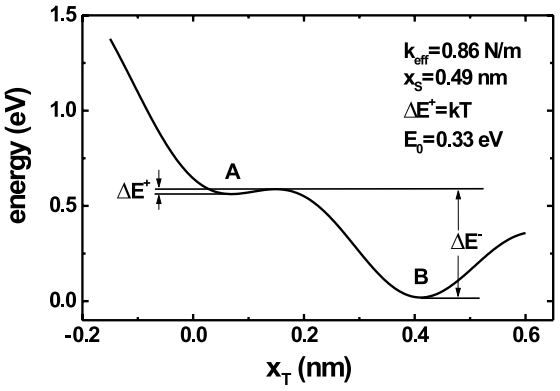

FIG. 3. Potential V_{tot} used for the Tomlinson model including thermal activation. The parameters have been chosen to illustrate a situation with a high probability for a jump from A to B. The values for k_{eff} and x_S are taken from the experimental results presented in Fig. 1. The tip-sample interaction $V(x_T)$ was modeled by a cosine function with periodicity $a = 0.4$ nm and a peak-to-peak amplitude of $E_0 = 0.33$ eV.

being significantly lower than A. The probability to find the tip in valley A or B is given by the probability p and $1 - p$, respectively.

The change of probability is given by the reaction rates describing the flow of probability from A to B and vice versa. We assume that initially the tip is located in valley A. As valley B is much lower than A and the energy barrier ΔE^- is much larger than ΔE^+, we can neglect flow from B to A. The master equation takes the simple form

$$\frac{dp(t)}{dt} = -f_0 \exp\left(-\frac{\Delta E^+(t)}{k_B T}\right) p(t), \tag{3}$$

where $\Delta E^+(t)$ is the activation energy as a function of time and f_0 is the characteristic frequency of the double well system. As we are interested in the lateral force corresponding to the maximum jump probability, we make a change of variable replacing time by the corresponding lateral force. The master equation becomes

$$\frac{dp(F_L)}{dF_L} = -f_0 \exp\left(-\frac{\Delta E^+(F_L)}{k_B T}\right)\left(\frac{dF_L}{dt}\right)^{-1} p(F_L). \tag{4}$$

At this point two assumptions can be made. As a first approximation, we assume that

$$\frac{dF_L}{dt} = \frac{dF_L}{dx}\frac{dx}{dt} = k_{\text{eff}} v. \tag{5}$$

Note that x does not describe the tip position but the support position, recorded during the measurements. This assumption is justified by the linear shape of the sticking part of the lateral force scans.

As a second assumption we assume that the energy barrier vanishes linearly near the critical points with the increasing lateral force F_L [20]. We thus obtain the relation

$$\Delta E^+(F_L) = \lambda(F_L^* - F_L). \tag{6}$$

We will see that the parameter λ determines the velocity dependence of lateral force. For $F_L = 0$ the potential barrier ΔE^+ is equal to the energy barrier E_0 and, therefore, λ should be of the order of $E_0/\langle F_{L,\max}\rangle$.

After substituting (5) and (6) into (4), the maximum probability transition condition

$$\frac{d^2 p(F_L)}{dF_L^2} = 0 \tag{7}$$

yields

$$F_L(v) = F_L^* + \frac{k_B T}{\lambda} \ln \frac{v k_{\text{eff}} \lambda}{f_0 k_B T} = F_{L0} + \frac{k_B T}{\lambda} \ln \frac{v}{v_1}. \tag{8}$$

Thus, at a fixed temperature, the lateral force depends logarithmically on the sliding velocity, as experimentally observed. This also holds true for mean lateral force since both are separated by a constant difference $k_{\text{eff}} a/2$. The parameter λ is given by

$$\lambda = \frac{k_B T}{F_{L1}}. \tag{9}$$

From the experimental data, we obtain $\lambda = 1.56$ eV/nN for $F_N = 0.44$ nN and $\lambda = 0.88$ eV/nN for $F_N = 0.65$ nN. In Fig. 3, the potential at a moment of high probability for a slip event is depicted, i.e., when $\Delta E^+ = k_B T$. The corresponding data for x_S and k_{eff} are taken from the experimental results plotted in Fig. 1. By assuming a simple cosine potential for $V(x_T)$ a barrier height of $E_0 = 0.33$ eV between two adjacent atomic positions can be estimated. Thus, the above criterion for the magnitude of λ is satisfied. The energy barrier seems reasonable for a contact consisting of very few atoms. For the experiment at $F_N = 0.44$ nN the reduced contact stiffness of $k_{\text{eff}} = 0.55$ N/m and the lower mean lateral force result in a barrier height of $E_0 = 0.25$ eV. The lowering of the barrier height emphasizes the role of the tip load for the dynamics of the atoms in contact. The parameter λ, and with it the velocity dependence of atomic friction, shows a stronger dependence on the load than k_{eff} or E_0. Rembering that λ describes how fast the energy barrier to the next slip event vanishes with increasing lateral force, we conclude that λ depends on the shape of the potential $V(x_T)$ which itself may change significantly with load and, of course, with the structure of the contact.

In conclusion, we showed that atomic friction increases logarithmically with the sliding speed. The velocity dependence is due to thermal activation of the irreversible jumps leading to the well known hysteretic behavior of lateral forces. We described the atomic friction mechanism within a one-dimensional Tomlinson model, using reaction rate theory.

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