Surface defects and temperature on atomic friction

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Abstract
We present a theoretical study of the effect of surface defects on atomic friction in the stick–slip dynamical regime of a minimalistic model. We focus on how the presence of defects and temperature change the average properties of the system. We have identified two main mechanisms which modify the mean friction force of the system when defects are considered. As expected, defects change the potential profile locally and thus affect the friction force. But the presence of defects also changes the probability distribution function of the tip slip length and thus the mean friction force. We corroborated both effects for different values of temperature, external load, dragging velocity and damping. We also show a comparison of the effects of surface defects and surface disorder on the dynamics of the system.

1. Introduction

Understanding friction is an actual scientific and technological problem [1–3]. Friction is a complex phenomenon of fundamental interest in many scientific areas that occurs at all length scales [4–7]. Its comprehension at the nanoscale is fundamental for instance for the manipulation of nanoparticles and the miniaturization of moving devices as nano-electromechanical systems (NEMs). With the development of experimental techniques such as the force friction microscope (FFM) and the surface force apparatus (SFA), experimental and theoretical studies of friction at the atomic scale have received increasing interest in recent years. Furthermore, as the frictional interface between two surfaces involves complex interactions among many asperities, the atomic force microscope is an exceptional tool to better understand friction at the nanoscale level, since it can be described essentially as a single asperity dragged along a surface [4, 5, 8].

So far, most theoretical studies describing force friction microscopy (FFM) experiments have focused on the behavior of defect-free and perfect periodic surfaces with or without the inclusion of thermal effects [9–12]. However, the study of the effect of substrate disorder or defects on atomic friction is particularly important since atomically flat surfaces represent ideal models, and defects of different kinds are always present. A recent study in a one-dimensional model indicated that small uncertainties in the interaction effective potential between the FFM tip and the surface can produce strong changes in the frictional behavior of the tip [13]. Other results have shown that other kinds of imperfections in the substrate potential also modify the frictional behavior at the atomic scale [14–16]. Reguzzoni et al studied friction in the sliding of a xenon monolayer on a copper substrate [16]. They found that the onset of slip of the monolayer is strongly affected by the presence of vacancy-type defects within the monolayer. Hölscher et al analyzed the load dependence of atomic friction at atomic-scale surface steps [17].

In order to better characterize atomic-scale friction under realistic surface potentials we present results here for the effect of surface defects on atomic friction and its interplay with thermal effects. By surface defects we refer to absorbed molecules, vacancies or inclusion of attractive or repulsive atoms into the perfect lattice. We will use a minimalistic model which focuses on a small number of the most relevant degrees of freedom and emphasizes the nonlinear nature of frictional dynamics. We consider the one-dimensional case and focus on the stick–slip region of the friction force versus dragging velocity curve. The same problem has been studied previously by Tshiprut et al [14]. We present results for the mean value of the friction force and the slip length, and
for the slip length probability distribution functions (PDFs) for a range of values of the corrugation potential amplitude, density of defects, temperature, and damping. We present results for four different types of defect. Our results indicate that the presence of defects may strongly modify the frictional behavior at the atomic scale. The observed changes in the friction force result from local changes of the potential profile, which in many cases produce also significant changes in the PDFs of the slip lengths. We have compared our results with the defect-free case and evaluated how the inclusion of defects locally modifies the slip length that the tip performs. To finish we make a detailed comparison of the results obtained for surface disorder and surface defects. We also observe that the effect of surface disorder on averaged quantities is screened at enough strong thermal fluctuations. On the contrary, for the surface defects problem we found significant effects even at high temperatures.

2. Model

We study a generalized Prandtl–Tomlinson model which includes the thermal effects [11]

\[
\frac{d^2 x}{dt^2} + \frac{dy}{dt} + \frac{\partial U(R, x)}{\partial x} = \xi(t), \quad U(R, x) = \frac{1}{2}[R(t) - x]^2 + V(x).
\]  

Here the tip is modeled as a single particle dragged by an elastic spring over a one-dimensional substrate potential. \(U(R, x)\) accounts for the tip effective potential and it includes the elastic coupling of the tip with a support which moves at constant velocity \(v_s\) \(R(t) = R_0 + v_st\), and the tip–surface interaction \(V(x)\). \(M \) and \(x\) are the effective mass and the lateral position of the tip and \(k\) is an effective spring constant. \(\xi(t)\) is the random noise term which satisfies the fluctuation-dissipation relation \(\langle \xi(t)\xi(t') \rangle = 2M\gamma k_B T\delta(t - t')\), with \(\gamma\) the microscopic friction coefficient and \(k_B\) the Boltzmann constant.

We model surface defects by including Gaussian terms in the standard tip–surface interaction potential

\[
V(x) = -U_0 \left[ 1.0 + \cos \left( \frac{2\pi}{\alpha} x \right) \right] + \sum_j A_j e^{-\frac{(x-x_j)^2}{2\sigma^2}}. \tag{2}
\]

\(A_0\) gives the amplitude of the defect potential and \(\sigma\) its range. \(\alpha\) and \(U_0\) are the lattice spacing and the amplitude of the defect-free surface potential, respectively. In theory, this amplitude can be changed by varying the normal load [12, 18].

We will show results below for the four kinds of defects shown in figures 1(b)–(e). Panel (a) shows the potential profile for a perfect lattice. As in [14] we model the inclusion of atoms of different natures by introducing a random series of Gaussian terms located in the minima \((x_j = na)\) of the otherwise perfect lattice (see figure 1(b) where \(A_0 = -0.71U_0\) and \(\sigma = 0.2a\)). The absence of atoms in the substrate is modeled by introducing Gaussian terms located randomly in the maxima \([x_j = (2n + 1)a/2]\) of the lattice (see figure 1(c))

where \(A_0 = -2.0U_0\) and \(\sigma = 0.2a\). Figure 1(d) is for defects located in the minima with \(A_0 = +2.0U_0\) and \(\sigma = 0.2a\) and figure 1(e) is for defects in the maxima with \(A_0 = +0.71U_0\) and \(\sigma = 0.2a\). For the first two kinds of defects, figures 1(b)–(c), \(A_0 < 0\) and we will refer to them as type I defects. For the last two cases, figures 1(d)–(e), \(A_0 > 0\) and we will refer to them as type II defects.

To obtain dimensionless equations, energy can be measured in units of the corrugation potential amplitude \(U_0\), space in units of the lattice spacing \((\tilde{x} = 2\pi x/a)\) and time in units of the natural frequency for oscillations of the tip in the surface potential \(\omega = \omega_0\sqrt{2M/a}\). Then \(\tilde{\gamma} = \gamma/\omega_0\), \(\tilde{k} = k/\omega_0^2\) and \(\tilde{v}_s = v_s\sqrt{M/U_0}\) are dimensionless damping, spring constant and velocity respectively. Some of our results will be shown as a function of \(U_0\). From the above relations we see that a change in \(U_0\) produces a change in both the dimensionless damping and the velocity of the system.

We have performed detailed numerical simulations of the dynamics of the system at different parameter values. We will present results for the mean friction force \(F(t)\), with \(F(t) = k[R(t) - x(t)]\), mean slip length \(L\) and slip length PDFs. Following the work by Tshiprut et al [14], we have used \(M = 5.0 \times 10^{-11}\) kg, \(a = 0.45\) nm, \(k = 1.5\) N m\(^{-1}\), \(\gamma = 10^5\) s\(^{-1}\) (except in section 5 where we change the damping) and \(U_0\) in the 0.2–1.2 eV range (then \(\tilde{\gamma}\) goes from 0.3 to 0.1 and \(\tilde{\Theta}\) from 4 to 25). For \(v_s\) we have used 10 nm s\(^{-1}\). Our simulations were performed using a stochastic Runge–Kutta method with dimensionless time step 0.01. Averages were
There, the friction force has been computed in the low driving lattice [4, 5, 8–14] is presented in figure 2 (solid circles). A function of the potential amplitude for the defect-free curve. The well-known behavior of the friction force as the stick–slip region of the force versus velocity characteristic T deterministic dynamics of the system, Here we consider the effect of surface defects in the 3. Surface defects without temperature average quantities with reliable statistics. We will also show the probability distribution function of the slip lengths. An evolution of this length allows one to obtain results of the density of defects is d = 30%. computed after a sliding distance of 2000 lattice constants. An evolution of this length allows one to obtain results of the average quantities with reliable statistics. We will also show the probability distribution function of the slip lengths.

3. Surface defects without temperature

Here we consider the effect of surface defects in the deterministic dynamics of the system, T = 0 K. We focus on the stick–slip region of the force versus velocity characteristic curve. The well-known behavior of the friction force as a function of the potential amplitude for the defect-free lattice [4, 5, 8–14] is presented in figure 2 (solid circles). There, the friction force has been computed in the low driving velocity region (v_S = 10 nm s⁻¹) with U_0 ranging from 0.25 to 1.2 eV. A series of discontinuities can be seen. They mark transitions between different dynamical states characterized by a well defined mean value of the length of the slip events [9, 12, 13, 19]. The regions numbered as 1, 2, 3 and 4 in the figure correspond, respectively, to regions characterized approximately by one-, two-, three- and four-lattice constant jumps. The values of the normalized parameter Θ in the first four regions are 1.0 < Θ_1 < 6.66 < Θ_2 < 11.45 < Θ_3 < 16.03 < Θ_4 < 20.61. For values of Θ < 1, the tip slides smoothly and stick–slip events do not appear.

Figure 2 also presents the result for surface defects with density d = 30%. As expected, in general the presence of type I defects in the potential minima or type II defects in the potential maxima increases the friction. On the contrary the suppression of potential maxima, type II defects in potential minima or type I defects in potential maxima decreases the friction. Thus, a system with both types of defect will experience a certain balance of both effects. However, the dynamics of the system is much more complex and this is not always the case. For type I in minima defects, for instance, it is easy to see the presence of two competing effects: a deep potential causes a longer stick and then high friction, but it can also cause longer slips, which reduce friction. Depending on the parameter values the first or the second mechanism is the more important one. Furthermore, close to the transition points surface defect effects are difficult to predict. In addition, significant changes are observed for large values of the potential U_0. There, the effective damping is smaller² and the dynamics is more sensitive to small changes in the substrate potential.

Figures 3(a)–(c) show the effect of the surface defects on the instantaneous position of the tip (top) and friction force (bottom). Figure 3(a) stands for the perfect sinusoidal potential. This case is characterized by a regular tip dynamics with a characteristic slip length and a periodic friction force. The inclusion of type I defects in potential minima, figure 3(b), produces a significant change in the slip lengths and friction forces. Finally, type I defects-in-maxima, figure 3(c), produce a strong reduction of the slip length and a reduction of the stick phase. We have checked that, as expected, such reduction is complete if we totally remove the potential maximum.

Figures 2 and 3 were computed for a density of 30% of defects. In figure 4 we study the values of the mean friction force and mean slip length as a function of the density of defects (solid lines are for type I defects and dashed lines for type II ones) for three values of the potential amplitude: U_0 = 0.27, 0.38 and 0.58 eV (marked in figure 2). We observe a significant modification of the friction force. As can be seen in the figure, this change is sometimes associated with an important change of the mean slip length, and other times is due to the modification of the potential profile without change of (L). Figure 4 also shows that the friction force and the slip length change linearly with the density of defects. For computational reasons, in what follows we will show results for a density of defects d = 30%.

² A change in U_0 also changes the effective damping of the system since \( \gamma = \gamma_0 p \) and \( c_{op} = 2 \pi \sqrt{U_0/M a^2} \). Thus a high load implies a smaller effective damping and it allows longer slip events.

\[
\begin{align*}
\text{Figure 2. Average friction force versus corrugation potential amplitude } U_0 \text{ in the low driving velocity region } (v_S = 10 \text{ nm s}^{-1}). \quad & T = 0 \text{ and } \gamma = 10^5 \text{ s}^{-1}. \quad (a) \text{ Results for the defect-free (solid circles), type I defects-in-maxima (solid squares), and type I defects-in-minima (open squares) lattices. (b) Results for the defect-free (solid circles), type II defects-in-maxima (open squares), and type II defects-in-minima (solid squares) lattices. The density of defects is } d = 30\%. \\
\text{Figure 3. (a)–(c) The local effects of the inclusion of defects on the instantaneous position and friction force of the tip for } U_0 = 0.27 \text{ eV. The density of defects is } d = 30\%, T = 0 \text{ and } \gamma = 10^5 \text{ s}^{-1}. \quad (a) \text{ The perfect lattice, (b) type I in minima and (c) type I in maxima.}
\end{align*}
\]
In order to obtain a better insight into the findings shown in figure 4, we have computed slip length PDFs at different values of $U_0$ in figure 5 for $d = 30\%$. We show results for the defect-free and type I defect-in-minima cases, other types of defects can be understood in a similar way. For $U_0 = 0.27$ eV (figure 4(a)), for the defect-free case a single peak with $\langle L \rangle$ close to one is found (black dashed line in figure 5(a)). For the lattice with defects the slip length PDF (blue line) presents significant modifications. Now we see a second peak in the distribution, located near $L/a = 1.65$, and a decrease of the original one, located at $L/a = 0.73$. Thus the average slip length is increased and the friction force reduced. Larger densities produce an additional increase of the second peak and reduction of the first one.

For $U_0 = 0.38$ eV the mean slip length $L/a \simeq 1.65$ for all the defect densities studied, figure 4(b). The corresponding PDFs are also slightly modified as seen in figure 5(b). However, we observe an important increase of the friction force which in this case is ascribed to the increase in the potential barriers associated with the defects.

In the third case, $U_0 = 0.58$ eV, figure 4(c), we observe both effects: an important modification of the slip length PDF with an increase of the slip length mean value and also an increase of the friction force.

Finally, the last case, shown in figure 5(d), corresponds to a small normalized damping and there the dynamics of the tip is different. At low values of the normalized damping tip oscillations exist between the accessible wells. This effect introduces additional changes in the friction force and the slip length. These two combined effects, defects and low normalized damping, produce a slightly modified slip length but a significant change in friction force.

4. Surface defects with temperature

In this section we will present results on the combined effect of surface defects and temperature on the friction force of the system. Theoretical and experimental results have shown that thermal effects are fundamental to understanding friction at this scale [10, 11, 14, 20–22, 13]. Previous studies have shown that the main temperature effect is a reduction of the friction force in the stick–slip region. This reduction, which has been observed at high temperatures, is explained in terms of thermally activated jumps of the tip [10, 11]. Recently, it has also been observed that, at low temperatures, thermal fluctuation can increase the friction force, which reaches a maximum and then decreases [13, 14, 21]. This effect is understood in terms of a reduction of the mean length of the slip events which dominates at low temperatures.

Due to the important role played by temperature it is natural to consider now the combined effect of thermal fluctuations and surface defects in the response of the system. Figures 6–9 summarize the main results. In figure 6(a) we
Figure 6. Average friction force versus corrugation potential amplitude $U_0$ at $T = 0, 50$ and $300$ K. (a) Type I defect-in-minima and (b) type I defect-in-maxima case. The open symbols are for the defect-free lattice and the solid symbols for the surface defect one. In all the cases $v_s = 10$ nm s$^{-1}$.

Figure 7. Average values of the friction force and the slip length versus temperature for different potential corrugation amplitudes $U_0$ for the defect-in-minima, defect-in-maxima and perfect (continuous black line) cases. Type I defect-in-minima (solid circles), type I defect-in-maxima (solid squares), type II defect-in-minima (open circles) and type II defect-in-maxima (open squares). $U_0 = 0.27, 0.38, 0.58$ and $0.88$ eV; panels (a)--(d) respectively. As usual, $v_s = 10$ nm s$^{-1}$.

The inclusion of surface defects does not modify the two main competing thermal effects already reported in the literature. The low $U_0$ and high temperature regimes are dominated by a monotonic decrease in friction due to thermal activation without modification of the mean slip length. At low temperatures and high $U_0$ values, friction increases due to the reduction of the mean slip length [13]. However, we observe that at a given temperature the friction force for the type I defect-in-minima case is larger than for the defect-free one which in turn is also larger than for the type I defect-in-maxima lattice.

In figure 8 we show the change in the probability distribution functions by the combined effect of defects and temperature. We present results for the type I defect-in-minima case. The figure shows the results for the same $U_0$ values used in figure 5 but now at four different temperature values. In the first case ($U_0 = 0.27$ eV), figure 8(a), the temperature suppresses the second peak of the PDF. In this case the temperature affects more importantly the defect-free case and moves apart the locations of the peaks. For $U_0 = 0.38$ eV, figure 8(b), the temperature activates a second peak close to $\langle L \rangle = 1$. As the temperature increases the original one decreases and disappears for the defect-free lattice case. For $U_0 = 0.58$ eV, figure 8(c), at zero temperature the main peak is
observed close to \( \langle L \rangle = 3 \). At higher temperatures we observe first the appearance of a second peak close to \( \langle L \rangle = 2 \), which will become the more important one, and later a third one close to \( \langle L \rangle = 1 \). At \( U_0 = 0.88 \) eV, figure 8(d), the normalized damping is smaller and the dynamics is more complex and oscillations between adjacent wells are possible.

An important consequence of figures 7 and 8 is that although the PDFs for the lattices with and without defects can be quite similar (especially at low \( T \)) the mean friction force is very different due to reduction of the effective barrier of the system.

Finally, we have studied again the dependence of the friction force and mean slip length as a function of the density of defects in the surface. In figure 4 we showed the results for the zero temperature case. Now, in figure 9 we plot similar results for \( T = 100 \) and 300 K. As we can see from the figures at all the temperatures, both the mean friction force and the mean slip length depend almost linearly on the density of defects for the studied range.

5. Damping effect

The effect of coupling of the system to many other degrees of freedom is modeled by assuming the existence of a heat bath at a given temperature and satisfying the fluctuation-dissipation relation. The dissipation associated with this coupling is controlled by the damping parameter, with temperature being a well-controlled parameter. However, determination of the correct value of the effective damping for the tip is a much more complex and difficult question. Thus, it is important to study the dynamics of the system for different values of the damping in order to check the robustness of the results against changes of this important parameter of the dynamics of the system.

A critical damping value is usually defined above which the tip oscillations disappear (overdamped dynamics). In this case all the deterministic slips have lengths close to one lattice constant. However, there is experimental evidence which indicates that the damping of the system is below this critical value. In this case the dynamics is more complex and richer [23, 24]. We have studied first in the regular case the effect of the damping parameter on the friction force for values of \( \tilde{\gamma} \) crossing the critical value. Then we analyze how this behavior is affected when surface defects are included.

In figure 10(a) we observe a series of steps in the friction force versus damping curve (open symbols). Close to the discontinuities a small change in the damping can produce a large change in the friction force. Every step in the figure corresponds to a slip of close to one or two lattice sites respectively. In the overdamped limit only the first available minimum (site 1) is reached. When smaller values of the damping are achieved the tip can reach a further minimum (site 2). If damping is reduced again the tip can move through 1 to 2 and then oscillate back to 1 where it is trapped. At small damping the tip oscillates back and forth between the
Figure 9. Average friction force and average length slip versus density of defects centered in minima (gray) or in maxima (black). Type I defects are shown by continuous lines and type II defects by dashed ones. We show results for $U_0 = 0.27, 0.38, 0.58$ eV at $v_s = 10$ nm s$^{-1}$ and $T = 100$ K (left) and 300 K (right).

6. Discussion and conclusions

We have studied the effect of the presence of four different types of surface defect on atomic friction. Our results show that significant changes can be observed even at high temperature. As expected, the differences are more important for $U_0$ values close to deterministic dynamical transition points of the system.

As we have seen, for surface defects, the change in the mean friction force cannot be understood in terms of the change in the mean slip length. In order to understand our numerical results we have made a study of the probability distribution function of the slip length. A rich scenario where jumps of very different lengths may coexist is found.

We have identified two main different mechanisms which modify the mean friction force of the system when defects are considered. First, defects modify the potential profile locally in a way that changes importantly the instantaneous friction force that the tip experiences when it crosses one defect. Second, the presence of defects also changes the slip length probability distribution which also changes the mean friction force.

With respect to the density of defects in the system, our results show an almost linear dependence on this parameter. We will discuss now a different point which is related with the amplitude of the defect potential given by $A_0$. We have chosen $A_0 = -0.71U_0$ for type I defect-in-minima, $A_0 = 0.71U_0$ for type II defect-in-maxima, $A_0 = -2U_0$ for type I defect-in-maxima, and $A_0 = 2U_0$ for type II defect-in-minima cases. These values were chosen to get the potential profiles shown in figure 1. However, other values of $A_0$ can be of interest for a particular real situation. Figure 11 shows the results of the mean friction force and mean slip length.

two minima before reaching an equilibrium value. Then, by decreasing the value of the damping more transitions are observed. For other values of the parameters (larger $U_0$), more complex situations are found. In these cases the dynamics results from the interplay between a larger number of minima than that shown in figure 10.

When surface defects are included (full symbols), additional slight modifications are observed. Figure 10(a) shows the change of the friction force and the mean slip length as a function of the damping for a density of defects of 30% and compares to the regular case curve. With inclusion of the thermal effects (diamond symbols, 100 K), the steps are strongly smoothed, see figure 10(b). At higher temperatures the steps are strongly smoothed or even suppressed (square symbols, 300 K).
Figure 10. The mean friction force and mean slip length versus normalized damping at $T = 0$ K for a perfect lattice (open symbols), a defects-in-minima lattice and a defects-in-maxima lattice. (a) Type I defects and (b) type II defects. Combined effect of surface defects and temperature (circles for $T = 0$, diamonds for 100 and squares for 300 K) on the mean friction force and mean slip length as a function of normalized damping for defects-in-minima and defects-in-maxima lattices. (c), (e) For type I and (d), (f) for type II defects. In all cases $U_0 = 0.27$ eV and the density of defects is 30%.

Figure 11. Friction force and mean slip length dependence on the amplitude of the defect potential $A_0$ for the defects-in-minima and defects-in-maxima cases at $T = 0$ (black triangles), 100 (gray circles) and 300 K (red squares). Dependence on the defect amplitude coefficient $A_0$. Type I defects correspond to $A_0 < 0$ values and type II to $A_0 > 0$ values. Results are given for three temperature values (0, 100 and 300 K) and two $U_0$ values (0.27 and 0.38 eV), showing two different physical situations. The figure shows that the friction force also depends importantly on this parameter in a way that is comparable to the effect of temperature or density defects. The figure also shows that, as expected, the results for the defects-in-minima and defects-in-maxima cases with different sign of $A_0$ are very similar. This was also shown in figures 4, 7 and 9 for instance.

To finish, we find it interesting to compare our results for surface defects with the recently studied effect of surface disorder [13]. There, surface disorder was modeled including a small second harmonic term in the standard tip–surface interaction potential,

$$V(x) = -U_0 \left[ 1.0 + \epsilon \sin \left( \frac{2\pi x}{b} \right) \cos \left( \frac{2\pi x}{a} \right) \right]. \quad (3)$$
Thus the surface disorder changes the potential profile, introduces a distribution of barrier heights and moves slightly the positions of the potential maxima and minima.

Figure 12 compares the results obtained for the cases of the perfect lattice, surface disorder and surface defects. It shows the results for \( T = 0 \) and 300 K at different values of \( U_0 \). The figure shows results for type I defects-in-minima and defects-in-maxima. Similar results for other types of defects are found. At low temperature we found that it is not easy to distinguish between the presence of defects and disorder. However, an analysis of instantaneous quantities such as force and tip position allows us to discriminate the two situations. At high enough temperature our results indicate that the role of the surface disorder is screened by the thermal effects but the presence of surface defects modifies the friction force of the system. The mean value of the barrier that the tip experiences is the same in the regular lattice and the lattice with disorder. However, the presence of surface defects increases or decreases, depending on the type of defect, the value of this mean barrier.

Our model accounts for the effect of adsorbed molecules or vacancies in the lattice, but it could be used also to study artificially designed grooves or ridges. Our results show that a significant density of defects in a sample may change the friction force curve at any temperature and thus this presence affects a comparison between numerical and experimental results.

However, it is important to point out that friction is a very general phenomenon which occurs in several problems. Because of this, the study of simple models is important since it allows understanding of basic effects that can be relevant or realized in different kinds of systems. This is the case, for instance, for the motion of a single colloidal particle in a colloidal system. There are new experiments and simulations where a single colloidal particle can be driven through other particles or quenched disorder and the effective friction and drag measured for varied temperature, density, pull rate and so forth [25–28]. Some similar variations in the system can be rapidly realized by driving a single particle over a random, periodic or combination of periodic and random substrates in 1D, 2D and even 3D so that some of the results from the present work could be tested more directly on real systems.

Another system where the results of the present paper could be applied is that of vortices in type II superconductors. Very recent experiments drag individual vortices over random or periodic pinning arrays [29–31]. It would be interesting to make a periodic 1D or 2D pinning potential and drag a single vortex. This experiment could then be repeated adding additional defects that could act like attractive or repulsive sites.

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Figure 12. (a) Mean friction force versus corrugation potential amplitude \( U_0 \) at \( T = 0 \) K. We compare the effects from two representative types of surface defect on the friction force–corrugation-potential curve of the perfect lattice (open circles): type I surface defects-in-maxima (solid triangles up), defects-in-minima (solid triangles down) and the effect of surface disorder (solid diamonds). (b) A similar comparison at \( T = 300 \) K.
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