Friction of colloidal monolayers on periodic and quasiperiodic surfaces

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Friction (the evil of all motion)

- energy losses
- wear
- plastic/elastic deformation
- indentation
- crack propagation

Often one tries to minimize friction ...

\[ \approx 8\% \text{ GNP due to friction} \]

but sometimes it is (more than) welcome..

control friction
Outline

I. Friction: an old problem
II. Driven colloidal monolayers on light-induced substrate potentials as a model system for nanotribology
III. Observation of kinks & antikinks
IV. Friction on quasicrystalline surfaces
V. Directional locking & dynamical ordering
**History of (dry) friction**

Leonardo Da Vinci (1452-1519)

1. Friction force proportional to load
2. Friction independent of the areas in contact
3. Friction independent of velocity

Guillaume Amontons (1663-1705)

\[ F_{\text{friction}} = \mu F_{\text{load}} \]  

(Amontons - Coulomb)
Real contact area

Bowden and Tabor (1950)

\[ A_{\text{apparent}} \gg A_{\text{real}} \]


\[ F_{\text{friction}} = \mu F_{\text{load}} \]
Nanotribology: point contacts

Friction force microscopy

Tomlinson model (1929)

\[ m\ddot{x} + m\gamma \dot{x} = -\frac{dV(x)}{dx} - K(x - vt) + \xi(t) \]

Stick-slip motion

Gnecco et al. PRL 84, 1172 (2000)

Microscopic extended contacts

Frenkel Kontorova model (1938)

\[ a_c/a_s \] strongly determines the frictional properties

\[ a_c/a_s \] irrational:

SUPERLUBRICITY


A \approx 100 \text{ atoms}
Mass Transport within the FK-Model


running kinks provide efficient mass transport
Our approach

- Replace atoms with micron-sized colloidal particles
- Create substrate potentials with optical light fields
Optical potential landscapes

→ adjustable strength, geometry and length scale of substrate potential

Experimental procedure

1. Colloidal suspension
2. Tuning the interaction
3. Adjust particle density
4. Confinement to 2D
5. Substrate potential
6. Lateral driving force
Lateral driving forces

translation of sample cell with velocity $\vec{u}$

$$\vec{F} = 6\pi \eta a \vec{u}$$

influence of wall and other particles: $\gamma_{\text{eff}} = \frac{k_B T}{D_{\text{eff}}}$
Experimental Setup

- Substrate potential 18W, $\lambda = 532$ nm
- Optical Fence: 7W, $\lambda = 488$ nm
- 2D confinement: 1064 nm
- Control of polarization and phases
Friction at commensurate surfaces

\[ a_c = a_s = 5.7 \mu m \]

F = 4 fN

F = 40 fN

depinning trans.

F = 110 fN

totally sliding state

pinned state
Particle Motion

velocities

F = 0 fN  F = 49 fN  F = 82 fN

voronoi cell area

cell area

fast particles @ lattice compressions

Dynamics of compression zones

- **F= 40 fN**
  - move in direction of F
  - no dispersion

- **F= 95 fN**
kinks & antikinks provide mechanism for efficient mass transport at small length scales
**Incommensurate Conditions**

\[ a_c = 5.7\mu m > a_s = 5.2\mu m \]


F = 0 fN  F = 19 fN  F = 82 fN

![Image showing velocities and voronoi cell area](image)

- fast particles @ domain walls
- fast particles @ lattice expansions!
Incommensurate Conditions

\[ a_c = 5.7\mu m > a_s = 5.2\mu m \]


\[ F= 0 \ fN \quad F= 19 \ fN \quad F= 82 \ fN \]

fast particles @ lattice expansions!
Commensurate vs. Incommensurate

Reduced static friction due to enhanced antikink formation (nucleated at domain walls)
Kink motion

kink interaction time with single particle

\[ T = \frac{\text{kink width}}{\text{kink velocity}} = \frac{L \cdot a_s}{v_{\text{kink}}} = \frac{a_s}{v_h} \]

\[ v_{\text{kink}} = v_h \cdot L \]
**kink motion – friction**

1 dim. model

\[
\langle v \rangle = v_h \cdot L \cdot n_{kink} \cdot \frac{1}{N} = v_{kink} \cdot \frac{n_{kink}}{N}
\]

number of mobile particles

only kink properties required!

<table>
<thead>
<tr>
<th>Commensurate (a = s = 5.7 µm)</th>
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<td>(F ,[fN])</td>
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(anti)kinks dominate friction at small length scales
Quasicrystals


Over centuries: all crystals have rotational symmetry = 2,3,4,6

Quasicrystals: other rotational symmetries but sharp diffraction peaks

aperiodic but perfect long-range order

> 100 systems: intermetallic alloys (i-Al-Pd-Mn, d-Al-Ni-Co)

Bulk: unusual electrical, optical, mechanical properties

Surface: catalytic, corrosion resistance, low friction, good wear resistance

also: natural occurrence
Science 324, 1306 (2009)
Quasicrystalline Substrates

size ratio
golden mean $\tau = \frac{1+\sqrt{5}}{2} = 1.618...$

$L+S = \tau L$

$L = \tau S$\(^{36^\circ}\)

centered decagon/10-fold flower

$S/\tau$

Mikhael, Schmiedeberg, Rausch, Bechinger, *PNAS* 107, 7214 (2010).
Friction on QC substrates

Superlubric behavior
Friction on atomic quasicrystals


Role of kinks?
Friction mechanism on QC surfaces?

Local kinks on QC surfaces
High density $\rightarrow$ small friction

Directional Locking

- atom migration on crystalline lattices
- flux flow in type II superconductors

Directional Locking limited to periodic surfaces?
Influence of particle – particle interactions?
**Directional Locking on QC surfaces**

colloidal liquid on QC surface

Bohlein, Bechinger, PRL (in press)

36° Smectic

Dynamical ordering!

Reichhardt et al. PRL 106, 060603 (2011)

20° Disordered

0° Smectic
Force dependence of dynamical order

Application of lateral driving force induce order
interstitials
non-interstitials

F=47 fN
87 fN
291 fN

lines of deep potential wells

Bohlein, Bechinger, PRL (in press)

coupling of interstitial and non-interstitial particles
Summary

Friction mechanism depends on characteristic length scale

For microscopic extended contacts, structural commensurability important

Friction dominated by topological solitons (kinks/antikinks)

Open Questions

- dependence of friction force on contact size/shape
- short vs. long-ranged particle interactions (width & shape of kinks)
- oscillating substrate potentials
- creeping
- dry friction → friction with lubricants
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