Local friction of soft materials on rough surfaces

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Dry friction of multi-contact interfaces

- **Surface geometry, contact mechanics**

- **Frictional energy dissipation mechanisms**

  - Micro-contacts distribution

  - Real contact area ??

  - Viscoelasticity
    - Non linear material response
    - Adhesion
    - ....

  - Persson, Müser, Robbins,...

  - Pinning / depining

  - Schallamach, Chaudhury,..

  - Bulk viscoelastic dissipation

  - Grosch, Persson...

  - Local friction law $\tau(p)$ ??
Displacement field measurements within contacts with rubbers

Glass lens
$R \approx \text{cm}$

PDMS rubber (surface marked)

Imposed - normal load, $P$
- velocity, $v$

Along sliding direction
Perpendicular to sliding direction

Surface displacements during steady state friction

Spatial resolution $\sim 10 \times 10 \, \mu m^2$

D.T. Nguyen et al J. Adhesion (2011)
Contact stresses: inversion of the displacement field

**Inversion???**

Surface displacement ➔ Surface stresses

• Linear elasticity ➔ Green’s tensor

Incompressible materials, ν=0.5

Lateral displacements

\[ u_i = G_{ij} \star \sigma_{jz} \quad i, j = x, y \]

Vertical displacement

\[ u_{zz} = G_{zz} \star \sigma_{zz} \]

• Experimentally: large strains! ➔ Numerical inversion using FEM

D.T. Nguyen, J Adhesion (2011)
Contact stresses: single asperity contact

Smooth Glass/PDMS contact

Contact pressure

Surface shear stress

Pressure independent shear stress
Contact stresses: randomly rough contact interfaces

Contact pressure

Shear stress

Gaussian roughness
r.m.s roughness ~ 1 µm

20µm
Sand blasted glass lens

Increasing normal load

Pressure dependent shear stress
Local friction law

- PDMS / self affine rough glass surface

Non linear local friction law

Normal load from 0.05 N to 17 N
Gaussian vs non-Gaussian surface roughness

Local friction law

Shear stress (MPa) vs Contact pressure (MPa)

Sand blasting
Sand blasting + etching

Height distribution

Asperity Height (µm)

Contact pressure (MPa)

Shear stress (MPa)

20µm

0.1

1

0.61

0.67

20µm

Shear stress (MPa) vs Asperity Height (µm)

$P_h (1/µm)$ vs Asperity Height (µm)
Friction of rubbers with rough surfaces: the role of viscoelastic losses

- Velocity and pressure dependence of the real contact area?
- Viscoelastic losses at micro-asperity scale?

Surface topography, patterning
Viscoelastic properties of the rubber
Local friction of viscoelastic rubbers with randomly rough surfaces

Sand blasted glass surface

Epoxy rubber $T_g = -42°C$

Torsional contacts

Linear sliding

Bulk viscoelastic dissipation at contact scale!

Light transmitted through the interface more efficiently when only one interface is present.

Transmitted light intensity $I(x,y) \propto \text{Proportion of area in contact } A/A_0(x,y)$
Velocity dependence of the shear stress

**Angular velocity**

- Angular velocity (deg s\(^{-1}\))
  - 0.01
  - 0.03
  - 0.1
  - 0.3
  - 1

\[
\Delta = 100 \mu m
\]

**Transmitted light intensity**

- Angular velocity (deg s\(^{-1}\))
  - 0.01
  - 0.03
  - 0.1
  - 0.3
  - 1

Dependence of the shear stress on the actual contact area:

\[
\frac{\tau(p, v)}{I(p, v)}
\]
Pressure and velocity dependence of the frictional shear stress

\[ k(v) = \frac{\tau(p,v)}{I(p,v)} \]

Smooth contact

\[ \tau_{\text{smooth}}(v) \]

Real contact area: density of micro-contacts

Average shear stress within micro-asperity contacts

\[ \tau(p,v) \propto k(v) \frac{A}{A_0(p,v)} \]

\[ k(v) \approx \tau_{\text{smooth}}(v) \rightarrow \text{Interface dissipation predominates over bulk viscoelastic dissipation} \]

Friction of model randomly rough surfaces

With Manoj Chaudhury and Shintaro Yashima

- Lens covered by a random distribution of rigid spherical micro-asperities

\[ F_t = \sum A_i \tau_i \]

\[ \tau_i = \tau_0 \]

\[ F_t \propto F_n \]

Coulomb’s law retrieved as a consequence of surface roughness

\[ F_t = \mu F_n \]

Greenwood & Williamson, 1965

- Experimental analog to the surfaces of the Greenwood and Williamson model

Can we sum asperity contributions to friction ??
With a single value of the interface frictional stress ??

PDMS

Distributed asperity heights and radius of curvature
Fabrication of rigid asperities surfaces

1. Water droplet condensation

2. PDMS Replica

3. Sol gel replica on a glass lens

Surface density
\[ \phi = 0.41 \]

Radius \( R \) (\( \mu \text{m} \))

Height \( h \) (\( \mu \text{m} \))

\[ h = R(1 - \cos \theta) \]

\[ \theta \approx 57^\circ \]
Normal loading: real contact area

- Only tops of micro-asperities make contact with the PDMS substrate
- Non linearity of the $A(P)$ relationship accounted for by lens curvature

\[ \Delta \propto R_i^{5/9} P^{-1/9} \]
Friction

Rough lens with spherical micro-asperities

Smooth lens covered by a smooth sol-gel layer

- Velocity independent friction $0.01 < v < 5 \text{ mm s}^{-1}$

\[
\tau_0^{asp} = 0.49 \text{ MPa} > \tau_0^{s}
\]

\[
\tau_0^{s} = 0.34 \text{ MPa}
\]

\[
Q^r = \sum_i q_i = \tau_0^{asp} \sum_i (\pi a_i^2)
\]

Frictional stresses at macroscopic length scales cannot be simply transposed to microscopic multi-contacts interfaces
Summary/ Outlook

✓ Local friction law from displacement field measurements

✓ Multi-contact interface with rigid randomly rough surfaces

  Non linear local friction law

  dependence on the details of surface roughness

  Contribution of viscoelasticity to friction

✓ Friction of model randomly rough surfaces

  Contact mechanics of multi-contact interfaces

  Contribution to friction of microasperities at various length scales