MODELLING AND MEASURING ADHESION AND FRICTION IN A TRIBOLOGICAL CONTACT

SURFACES, INTERFACES & COATINGS WORKSHOP

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Rough contacts, adhesion and pre-sliding

Van der Waals forces + Meniscus forces

Elastic deformation

Larger $\Delta A$

(Pre) sliding

Relatively smooth
Basic concepts

Adhesive contact

Pre-sliding

Modelling + Experimental validation
Developed Boundary Element Model (BEM) model

- Mechanical and surface properties
- Surface topography
- Loading conditions
- Static coefficient of friction
- Contact area and contact pressure
- Pre-sliding behavior
- Normal indentation, …
Contact at a rough interface

- 10*10 um AFM measurement

Can be calculated fast (minutes) with order $10^6$ datapoints
Also subsurface stresses, coated surfaces etc.
ADHESIVE CONTACT
VAN DER WAALS INTERACTION
The role of van der Waals forces

\[ p_{vdw} = \frac{8\Delta \gamma}{3z_0} \left( \left( \frac{z_0}{g + z_0} \right)^9 - \left( \frac{z_0}{g + z_0} \right)^3 \right) \]

\[ \sigma_0 = \frac{16\Delta \gamma}{9\sqrt{3}z_0} \]

\[ h_0 = \frac{\Delta \gamma}{\sigma_0} \approx 0.97z_0 \]
The role of van der Waals forces

- AFM measurement 10x10 μm, 256x256 points
- Contact between a smooth silicon wafer and glass coated by CrN
- Work of adhesion = 60 mJ/m²
The role of van der Waals forces

Contact area (%) vs. Normal force per burl (mN)

- Non-adhesive contact
- Adhesive contact - LJ
- Adhesive contact - MD

Adhesive force per burl (mN)

- $F_{adh}$ - LJ
- $F_{adh}$ - MD

Lennard-Jones potential

Dugdale approximation

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Adhesion in rough contacts

\[ \mu_T = 3 \]

\[ \mu_T = 2 \]

\[ \text{rm}/z_0 = 50 \]
\[ A_{\text{Adhesive}} = 0.38 \mu \text{m}^2 \]
\[ F_{\text{Adhesive}} = 130 \mu \text{N} \]

\[ \text{rm}/z_0 = 100 \]
\[ A_{\text{Adhesive}} = 0.039 \mu \text{m}^2 \]
\[ F_{\text{Adhesive}} = 13.5 \mu \text{N} \]
ADHESIVE CONTACT
MENISCUS FORCES
Capillary model for a rough contact

\[ \frac{\partial h}{\partial t} + \gamma \frac{\partial}{\partial x} \left( h_w - h_\gamma \right) \left( \frac{\partial^3 h_w}{\partial x^3} + \frac{\partial^3 h_\gamma}{\partial y^3} \right) = 0 \]

Body 1
- non-contacting asperities
- small gap prone to form a meniscus
- contacting asperities

Body 2
- meniscus-wetted asperities

Water
- free surface

Solid body
- \( h_c(x,y,t) \)
- \( h_s(x,y) \)

Combination of roughness
- height

Non-wetted asperities
- below the cross-cut line

Cross-cut area
- at mean meniscus height

Meniscus-wetted area
Long auto-correlation length

(d) Capillary force

(c) $L_{ac}/L = 0.10$

Roughness height (nm)

-15 -10 -5 0 5 10

RH (%)

0 200 400 600 800 1000 1200 1400

force (µN)

$L_{ac}/L = 0.02$

$L_{ac}/L = 0.05$

$L_{ac}/L = 0.1$

RH (%)
Experimental validation on the AFM
Pull-off force measurement on an AFM

- Cantilever with SiO$_2$ colloidal probe
  - Diameter: 5 micron
  - normal stiffness: 20 N/m
SiO2 ball and silicon wafer surface roughness

(a) Roughness height of the silicon wafer (nm)

(b) Topography of the 5um SiO2 colloidal probe (m)
Measured adhesion curves

(a) State 1

(b) State 2

(c) State 3

ambient → vacuum → Vacuum chamber opened
Results

(a) Si - State 1

(b) Si - State 2

(c) Si - State 3

(d) SiO₂ - State 1

(e) SiO₂ - State 2

(f) SiO₂ - State 3

Legend:
- Contact
- non-Contact
- ss-vdW
- Cap & ws-vdW
Calculations versus experiments

Surface has been cleaned
Topography changes
Assuming no water layers
Topography changes

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PARTIAL SLIP
PARTIAL SLIP

\[ u_x \]

\[ R \]

slip

stick

partial / total slip

lateral force \( F_\parallel \)

displacement
Partial slip model

\[ \Delta s_m(x, y, t) = s_m(x, y, t) - s_m(x, y, t - \Delta t), m = x, y \]

\[
\begin{align*}
A_{st} = \left\{ (x, y) \in A_c \mid \sqrt{q_x(x, y)^2 + q_y(x, y)^2} < \mu_f p(x, y), \sqrt{\Delta s_x(x, y)^2 + \Delta s_y(x, y)^2} = 0 \right\} \\
A_{st} = \left\{ (x, y) \in A_c \mid \sqrt{q_x(x, y)^2 + q_y(x, y)^2} = \mu_f p(x, y), \sqrt{\Delta s_x(x, y)^2 + \Delta s_y(x, y)^2} \neq 0 \right\}
\end{align*}
\]
Friction measurements

Measurements and calculations
Ball topography HDPE Ball

Pressure (MPa), $F_n = 75$ mN
Measurements and calculations

\[
\begin{align*}
F_0 &= 75 mN \\
F_0 &= 50 mN \\
F_0 &= 25 mN
\end{align*}
\]
Calculations

\[ F_0 = 25mN \quad F_0 = 50mN \quad F_0 = 75mN \]

\[ A \quad B \quad C \]

\( \frac{F_x}{\mu F_0} \) vs. \( \frac{2\delta_x}{d_s} \)

non-contact \quad stick \quad slip
Measurements and calculations

HDPE ball - wafer
Conclusions

- Pre sliding, adhesion as well as meniscus formation
  - Have been modelled for rough contacts and compared with measurements
  - Small roughness details matter!