ON THE MODELLING OF ADHESIVE CONTACT AND STICKTION FAILURE IN MICRO-SWITCHES

Ling Wu, Ludovic Noels, Jean-Claude Golinval

University of Liege, Belgium

Department of Aerospace and Mechanical Engineering
Chemin des Chevreuils, 1 Bât. B 52
B-4000 Liège (Belgium)
E-mail: JC.Golinval@ulg.ac.be
1. Introduction
2. Micro-scale model
3. Multi-scale model
4. Elasto-plastic adhesive contact
5. Conclusions
Stiction failure in MEMS (major issue for micro-switches)

Reason
Relatively high surface area: volume ratio (1,000:1 to 10,000:1 m⁻¹)

Adhesive forces
Electrostatic force, Van der Waals force, Capillary force, ...

The risk of in-use stiction increases when plasticity is involved during contact.
Introduction

Multi-scale approach

At the micro-scale

Single asperity subject to adhesive-micro contact forces

Contact model between rough surfaces → prediction of the adhesive force

Integration with FEM

At the macro-scale
Outline

1. Introduction

2. Micro-scale model
   • Single asperity adhesive-elastic contact
   • Statistical model for rough surface

3. Multi-scale Model

4. Elasto-plastic adhesive contact

5. Conclusions
Single asperity adhesive-elastic contact (Hertz) theories

• **Johnson, Kendall, and Roberts (JKR)**
  - The surface forces are short ranged and act only inside the contact area
  - **Ideal for compliant materials with high surface energy and large contact curvature surface**

• **Derjaguin, Muller and Toporov (DMT)**
  - Accounts for the long-ranged adhesive forces acting outside the contact area
  - **Well suited for harder, less compliant materials with low surface energy and small asperity tip radius**
**Maugis model**
- for all elastic materials
- provides transition solutions for intermediate cases between the JKR and DMT regimes
- is based on a Dugdale assumption for interaction potential

- Constant traction $\sigma_0$ within a critical value of separation $z_0$
- Zero traction for gap larger than $z_0$

Work of adhesion: $\mathcal{W} = \sigma_0 \cdot z_0$
The Maugis transition parameter $\lambda$ is defined in terms of the surface properties:

$$\lambda = \frac{2 \sigma^{2/3} R^{1/3}}{z_0 (\pi K^2)^{1/3}}$$

- $\sigma$: Work of adhesion
- $R$: Asperity radius
- $K$: Equivalent elastic constant
- $z_0$: Contact depth

$\Rightarrow \sigma \uparrow, R \uparrow, K \downarrow \Rightarrow \lambda \uparrow$ (JKR model (short-ranged))

$\Rightarrow \sigma \downarrow, R \downarrow, K \uparrow \Rightarrow \lambda \downarrow$ (DMT model (long-ranged))
Single asperity adhesive-micro contact

- Maugis transition solution

Calculation of the load in terms of the deflection for different values of the transition parameter $\lambda$
• Maugis transition solution

Calculation of the load in terms of the deflection for different values of the transition parameter $\lambda$
Single asperity adhesive-micro contact

- Maugis transition solution

Calculation of the load in terms of the deflection for different values of the transition parameter $\lambda$

![Diagram showing load-controlled pull-out, non-contacting adhesion, Hertz contact, contacting adhesion, and load-deflection relationships.](image-url)
Micro-scale model

Statistical model for rough surfaces

- The rough surface is described by a collection of spherical asperities with constant tip radius. The heights $h$ have a statistical distribution:

\[
\varphi(h) = \frac{1}{\sigma \sqrt{2\pi}} \exp\left(\frac{-h^2}{2\sigma^2}\right)
\]

- Rough surfaces interaction
  - Reduced number of interacting asperities
  - The distance between the surfaces is defined in terms of distance $d$
The micro adhesive contact forces between rough surfaces may be computed by integration of the Maugis solution using

$$\varphi(h) = \frac{1}{\sigma \sqrt{2\pi}} \exp \left( -\frac{h^2}{2\sigma^2} \right)$$

**Dimensionless contact force**

$$\frac{F_{nT}}{N \pi \sigma R}$$

**Responsible for stiction**

Contact distance

(b) $\lambda = 0.5$
Outline

1. Introduction

2. Micro-scale model

3. Multi-scale Model
   • Design example: cantilever beam (FEM)
   • Polysilicon to polysilicon interaction
   • Validation with experiments

4. Elasto-plastic adhesive contact

5. Conclusions
Multi-scale model

Design example: cantilever beam entering into contact with the substrate

- Finite element model
  - Timoshenko beams
- Use of adhesive contact law at interface
  - Polysilicon-Polysilicon interactions
  - Surfaces properties from
    - AFM
    - Surface energy measured

<table>
<thead>
<tr>
<th>State</th>
<th>Surface Energy (J/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>In vacuum</td>
<td>$\varpi = 2.54$</td>
</tr>
<tr>
<td>In air</td>
<td>$\varpi = 0.167$</td>
</tr>
</tbody>
</table>

- Contact remains elastic
- Validation vs literature experiments*

Design example: cantilever beam

Initial gap $g = 2.0 \, \mu m$

The design limitations avoiding in-use stiction are calculated in terms of the beam’s geometrical properties (thickness and length) for $\sigma = 2.54 \, J/m^2$. 
1. Introduction

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3. Multi-scale Model

4. Elasto-plastic adhesive contact
   - Plastic deformation of a loaded single asperity
   - Adhesive unloading of a single deformed asperity
   - Adhesive unloading of rough surfaces
   - Lifetime of MEMS

5. Conclusions
Elasto-plastic adhesive contact

- Extension of the multiscale model $\rightarrow$ plastic deformations of asperities

- In case of repeated contacts (cycling loading)

  The height distribution and the tip radii $R$ of asperities change until accommodation is reached

  Surface roughness $R_q \downarrow$

  Adhesive forces $\uparrow$

  Stiction may appear after a few cycles

$\rightarrow$ Elasto-plastic adhesive contact model is required!
Basic idea

- Adhesive contact model of the elastic-plastically deformed asperity

1. The elasto–plastic deformation resulting from the contact of a single loaded sphere is first solved without considering adhesive effect.

2. The Maugis’ adhesive contact theory is performed on the equivalent elastic deformed asperity.

- Asperity-based rough surface model based on the statistical distribution of asperities.
Elasto-plastic adhesive contact

Adhesive loading/unloading of a single asperity

- Material: Ru
- Model vs FE*

<table>
<thead>
<tr>
<th></th>
<th>$R$</th>
<th>$E$</th>
<th>$\nu$</th>
<th>$S_Y$</th>
<th>$z_0$</th>
<th>$\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4 nm</td>
<td>410 GPa</td>
<td>0.3</td>
<td>3.42 GPa</td>
<td>0.169 nm</td>
<td>1 J/m$^2$</td>
</tr>
</tbody>
</table>

Elasto-plastic adhesive contact

Adhesive contact forces during unloading

- For different Ru surface samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_q$ (nm)</td>
<td>2.03</td>
<td>3.99</td>
<td>7.81</td>
</tr>
</tbody>
</table>

- Effect of impact energy at pull-in on plastic deformations
**Liftole of MEMS**

- Repeated loading/unloading $\Leftrightarrow$ changes in surfaces profile
- Ru sample

<table>
<thead>
<tr>
<th>Sample</th>
<th>$R_q$ (nm)</th>
<th>$E_1$ (J/m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>7.81</td>
<td>0.5</td>
</tr>
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</table>
• The adhesion between the contact surfaces has a large influence on the design of micro-switches and needs to be considered carefully.

• The adhesive work and the surface roughness are the main factors to take into account.

• The analytical adhesive contact results can be combined with FEM to predict the stiction of more complicated structures.

• Effect of plasticity can be accounted for.

• The other kinds of adhesive forces, such as capillary force, electrostatic force from dielectric charging, are not considered.
3-Scale Stochastic Modeling for MEMS

- 3-scale modeling
  - MEMS
  - Separation of length scale violated
  - Uncertainties should be considered

- Application to robust design (Stiction risk, Q-factor range)
- 3SMVIB MNT.ERA-NET project
  - Open-Engineering, V2i, ULg (Belgium)
  - Polit. Warszawska (Poland)
  - IMT, Univ. Cluj-Napoca (Romania)
Thank you for your attention.