Stiction failure in microswitches due to elasto-plastic adhesive contacts

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  – Multiscale approach developed

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Introduction

• Stiction in MEMS

Stiction failure in a MEMS sensor
( Jeremy A. Walraven Sandia National Laboratories. Albuquerque, NM USA)

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, Hydrogen bridging…
Introduction

• Multiscale approach developed

Single asperity adhesive-micro contact

Adhesive elastic contact model between rough surfaces

Integration with FEM
Single asperity adhesive-micro contact

- **Adhesive-elastic contact (Hertz) theories**
  - **Johnson, Kendall, and Roberts (JKR)**
    - Short ranged surface forces
    - Act only inside the contact area
    - $\begin{cases} \text{Soft, compliant materials with} \\
        \text{high surface energy} \end{cases}$
  - **Derjaguin, Muller and Toporov (DMT)**
    - Long-ranged adhesive forces
    - Outside of the contact area
    - $\begin{cases} \text{Harder, less compliant materials with} \\
        \text{low surface energy and} \\
        \text{small asperity tip radius} \end{cases}$
  - **Maugis transition solution**
    - Intermediate cases between JKR and DMT
    - For all elastic materials
Single asperity adhesive-micro contact

- **Maugis transition solution**
  - 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 $z_0$
  - **Maugis transition parameter $\lambda$**
  - Representation of the surface properties
    - $R$: asperity radius
    - $K$: equivalent elastic constant
    - $\varpi = \sigma_0 z_0$: adhesive work

$$\lambda = \frac{2\varpi^{2/3} R^{1/3}}{z_0 (\pi K^2)^{1/3}} \quad \Rightarrow \quad \varpi \uparrow, R \uparrow, K \downarrow \Rightarrow \lambda \uparrow$$

$$\varpi \downarrow, R \downarrow, K \uparrow \Rightarrow \lambda \downarrow$$

- **Dugdale Model**
- **Lennard-Jones Potential**
- **JKR model** (short ranged)
- **DMT model** (long ranged)

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Single asperity adhesive-micro contact

- Maugis transition solution (2)
  - Adhesive-micro (elastic) contact force during unloading

- In term of Maugis transition parameter
  \[ \lambda = \frac{2\sigma^{2/3} R^{1/3}}{z_0 (\pi K^2)^{1/3}} \]
Adhesive contact between rough surfaces

- **Rough surfaces**
  - Reduced number of interacting asperities
  - In terms of interference $d$

- **Rough surfaces model**
  - Constant asperity tip radius
  - Statistical distribution in height $h$

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

High roughness $\sigma$

Low roughness $\sigma$

Roughness $\sigma=0$
Adhesive contact between rough surfaces

- Micro adhesive contact forces of rough surfaces
  - Integrate Maugis solution using
    \[
    \varphi(h) = \frac{1}{\sigma \sqrt{2\pi}} \exp\left(-\frac{h^2}{2\sigma^2}\right)
    \]

\[\frac{F_{nT}}{N \pi \sigma R}\]

Responsible for stiction
Multiscale Model

- **Design example: cantilevers**
  - Finite element model
    - Timoshenko Beams
    - Interacting with pad
  - Use adhesive micro-contact law at interface
    - Polysilicon-Polysilicon interactions
    - Surfaces properties from
      - AFM
      - Surface energy measured
        - In vacuum: $\varpi = 2.54 \text{ J/m}^2$
        - In air: $\varpi = 0.167 \text{ J/m}^2$
  - Contact remains elastic

- **Validation vs literature experiments**
Multiscale Model

- Design example: cantilevers (2)
  - Initial gap $g = 2.0 \, \mu m$
  - Admissible thickness $t \, (\mu m)$ & length $l \, (\mu m)$ ???
**Literature***:
- Measures of apparent adhesion energy $\Gamma$
- Simplified models of $\Gamma$

**Numerical methods**
- Extract $\Gamma$ from $s$
- Environmental effect

In vacuum $\varpi = 2.54$ J/m$^2$
In air $\varpi = 0.167$ J/m$^2$

**Different samples**
- Surface roughness

<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>1.4</td>
<td>2.67</td>
<td>3.47</td>
</tr>
</tbody>
</table>

• Elasto-Plastic materials
  – Plastic deformations of asperities

• Repeated contact
  Tip radii $R$ of a part of asperities $\uparrow$
  Surface roughness $R_q \downarrow$

Adhesive forces $\uparrow$

Stiction can appear after some cycles

• Elasto-plastic adhesive contact model is needed!
• Basic idea
  – Adhesive contact model of the elastic-plastically deformed asperity
    Numerical results for an elasto–plastic loaded sphere in contact without adhesive forces
    Maugis’ adhesive contact theory is performed on the equivalent elastic deformed asperity
  – Asperity-based rough surface model
Plastic deformations of a loaded single asperity

- **Curve fitting of FE simulations**
  - Effect of maximum interference $\delta_{\text{max}}$ reached during loading
  - Material parameters: yield $S_Y$, yield interference $\delta_{\text{CP}}$

- **Residual interference**

  \[
  \delta_{\text{res}} = \delta_{\text{max}} \left( 1 - \left( \frac{\delta_{\text{CP}}}{\delta_{\text{max}}} \right)^{0.28} \right) \left( 1 - \left( \frac{\delta_{\text{CP}}}{\delta_{\text{max}}} \right)^{0.69} \right)
  \]

- **Residual tip radius**

  \[
  R_{\text{res}} = R \left( 1 + 1.275 \left( \frac{S_y}{E} \right)^{0.216} \left( \frac{\delta_{\text{max}}}{\delta_{\text{CP}}} - 1 \right) \right)
  \]

Elasto-plastic adhesive contact

- Adhesive unloading of a single deformed asperity
  - Define an equivalent elastic asperity
    - Interference \( \delta_{\text{eff}} = \delta - \delta_{\text{res}} \)
    - Asperity tip radius \( R_{\text{eff}} = R_{\text{eff}}(R, \delta, \delta_{\text{max}}) \)
  - Apply Maugis
    - Extract adhesive-micro contact force
      \[
      F_n = F_n(\delta - \delta_{\text{res}}, R_{\text{eff}})
      \]

Elasto-plastic adhesive contact

- Adhesive loading/unloading of a single asperity
  - Material: Ru
    
    | Parameter | Value     |
    |-----------|-----------|
    | \( R \)   | 4 nm      |
    | \( E \)   | 410 GPa   |
    | \( \nu \) | 0.3       |
    | \( S_y \) | 3.42 GPa  |
    | \( z_0 \) | 0.169 nm  |
    | \( \omega \) | 1 J/m² |

- Model vs FE*

Elasto-plastic adhesive contact

- Adhesive unloading of rough surfaces
  - Different Ru samples
  - Effect of impact energy at pull-in on plastic deformations

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<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rq (nm)</td>
<td>2.03</td>
<td>3.99</td>
<td>7.81</td>
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</tbody>
</table>

(a) Sample A
(b) Sample B
(c) Sample C

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Elasto-plastic adhesive contact

- **Time life of MEMS**
  - Repeated loading/unloading changes in surfaces profile
  - Asperity profile can be updated by tracking history $\delta_{\text{max}}(h)$
  - Ru sample

<table>
<thead>
<tr>
<th>Sample</th>
<th>$R_q$ (nm)</th>
<th>$E_1$ (J/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>7.81</td>
<td>0.5</td>
</tr>
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Conclusions

- The adhesion between the contact surfaces has large influence on the design of MEMS switches, and need to be considered carefully.
- The adhesive work and the surface roughness are the main factors of adhesive force.
- 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.
Thank you!