Adhesive wear process

**Assumptions**
- Multi-asperity contact
- Plastic or fracture deformations (governed by hardness)
- Real contact area is proportional to the normal load

\[
\Delta V = k \frac{L \times s}{H_{\text{soft}}}
\]

\(\Delta V\) is the volume loss due to wear
L is the normal load
s is the sliding distance at constant sliding speed
\(H_{\text{soft}}\) is the hardness of the softer material

Holm, R. Reference [3], pp. 242–254.
Archard’s Wear law at the Macroscale

\[ \Delta V_{\text{running-in}} = w_0 \tau_w \left( 1 - \exp \left( - \frac{t}{\tau_w} \right) \right) \]

Barwell’s law:

\[ \Delta V_{\text{running-in}} = \frac{L \times t}{H_{\text{soft}}} \]


In the Archard’s law, the wear rate, \( \frac{\Delta V_{\text{steady-state}}}{s} \), is independent of the sliding speed, if the sliding distance, \( s \), is kept constant.

Classical view of Archard’s law:

\[ \Delta V_{\text{steady-state}} = k \frac{L \times t}{H_{\text{soft}}} \]
Atomistic wear in a single asperity sliding contact

Wear of a Silicon AFM probe on a polymer surface

“Wear occurs through an atom by atom removal process which implies the breaking of individual bonds”

Simulations confirm the scalability of the released elastic energy assumed to be relatively uniform due to the large amounts of stress distribution. The stress distribution near the junction is the junction, a value assumed to be the lesser of the bulk material where 

\[ d^* = \lambda \cdot \frac{\Delta w}{(\sigma_j^2 / G)} \]

NanoWear Experiments with the AFM  

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• **Main advantage:** - Single asperity contact

• **Limitations:**
  - **Non constant and continuous sliding speed**
  - **Low sliding speed** (typically max. 100 μm/s)
  - Scan drift leads to non well defined wear track
# Wear Experiments using the CM-AFM


<table>
<thead>
<tr>
<th><strong>Conventional Mode</strong></th>
<th><strong>CM-AFM</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Solicitation velocity</td>
<td>Low scanning or sliding velocity (typically, ranging from 1 µm/s to 100 µm/s)</td>
</tr>
<tr>
<td>Advantages / Drawbacks</td>
<td><em>High scanner drift; Low wear; high shear force when the scan changes its direction</em></td>
</tr>
</tbody>
</table>
Wear volume computation

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Averaged height of the wear track obtained with a sharp (40 nm of radius) AFM probe.

Topography before wear

Topography after wear

Difference wear image

Height (nm)

Distance from wear track center (nm)
Comparative analysis of Macro and Nano wear of copper based composite

Processing Method: Powder Metallurgy followed by internal oxidation

<table>
<thead>
<tr>
<th>Designation</th>
<th>Average size particles</th>
<th>Sample roughness Rq</th>
<th>Micro Hardness $V_{50}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nano-composite</td>
<td>Less than 100 nm</td>
<td>4.02 nm AFM image</td>
<td>224</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5µm X 5 µm</td>
<td></td>
</tr>
</tbody>
</table>

Friction coefficient with steel is 0.13 in the steady-state and is independent of the sliding speed.

SEM image of wear track after the macro tests (1 N; 8 mm/s)

Mostly adhesive and light abrasive wear

At the macro-scale, wear of the nano-composite follows Archard wear laws.

SEM and EDX images

Amount of nanoparticles 4.7 wt% and 10% in volume
Heterogeneity of Nano-wear

Black spots

White spot
Wear Volume vs. Sliding Distance (or wear duration)

Sliding speed of 0.88 mm/s; Normal load = 3μN; Diamond Probe

$t = 1$ min.  
$t = 2$ min.  
$t = 4$ min.  
$t = 8$ min.  
$t = 16$ min.  
$t = 32$ min.
- SEM images do not evidence wear of the probes (counter body).
- In both cases, we have an asymptotic steady-state
Wear volume vs. Normal Load

70 nN

140 nN

100 nN

200 nN
Experiments performed in the running-in-like regime if we refer to a macroscopic view of wear.

- Archard-like wear law is obtained.
- Wear depends on the nature of the counter-body.
- For Si$_3$N$_4$ there is a critical threshold load (about 60 nN) from which wear loss is significant.
- If we consider a single asperity contact, this latter behavior is governed by the lateral force which is proportional to the normal load. Eder et al., PRL, 115, 025502 (2015)
For a probe radius, $R = 100$ nm, and a normal load, $L = 60$ nN (threshold value for SiN probe), the contact radius (Hertz model), $a$, is:

$$a = 4 \text{ nm}$$

and the contact pressure is $1.20 \text{ GPa} < H$ of sample $2.45 \text{ GPa}$ (Hardness of copper oxide is 4-5 GPa).

According to the Hertz theory, the shear stress is maximum at a depth of $0.78a = 3$ nm. This depth corresponds to the thickness of oxide copper growths in ambient conditions.

Therefore, 60 nN corresponds exactly to the normal load that generates a maximum shear stress at a depth of 3 nm.

The threshold value may correspond to the minimum load to apply to shear the interface of the oxide/metal interface.
- Wear rate is independent of the sliding speed (for a given sliding distance and a given normal load) in the steady-state (from the macroscopic view) regime.
Conclusions and perspectives

• The methodology based on the CM-AFM gives well-defined wear tracks as the drift of the scanner is limited and the wear loss is significant.

• Well defined wear tracks allows measuring quantitative values.

• Nano-wear heterogeneity is revealed.

Nano-wear of nano-composite,

• Archard-like wear laws are revealed at the nanoscale but it does not mean we have the same mechanisms involved as for the macroscale.

• Wear process may be not governed by the hardness but by the lateral force (or shear stress) and by the physico-chemical interactions in the contact (depending on the nature of the counter-body).

• Can we still think in the same way as for the macroscopic view (running-in, steady-state…) ?
Pure copper Wear loss vs. sliding distance