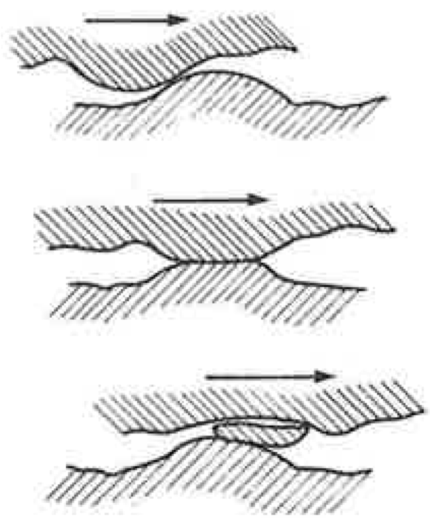
Archard's Wear law at the Macroscale

Adhesive wear process



Assumptions

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

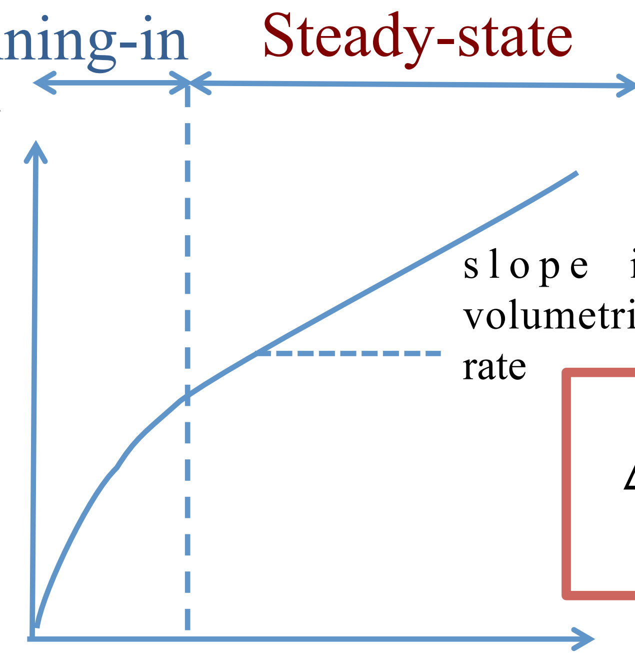
$$\Delta V = k \frac{L \times s}{H_{soft}}$$

ΔV is the volume loss due to wear
L is the normal load
s is the sliding distance at constant sliding speed
H_{soft} is the hardness of the softer material

Archard, J. F., "Contact and Rubbing of Flat Surfaces," *Journal of Applied Physics*, Vol. 24, 1953, pp. 981–988.
Holm, R. Reference [3], pp. 242–254.
Burwell, J. T., and Strang, C. D., "On the Empirical Law of Adhesive Wear," *Journal of Applied Physics*, Vol. 23, 1953, pp. 18–30.

Archard's Wear law at the Macroscale

ΔV is the wear volume



Barwell's law:

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

F. T. Barwell, Wear 1, 317 (1958).

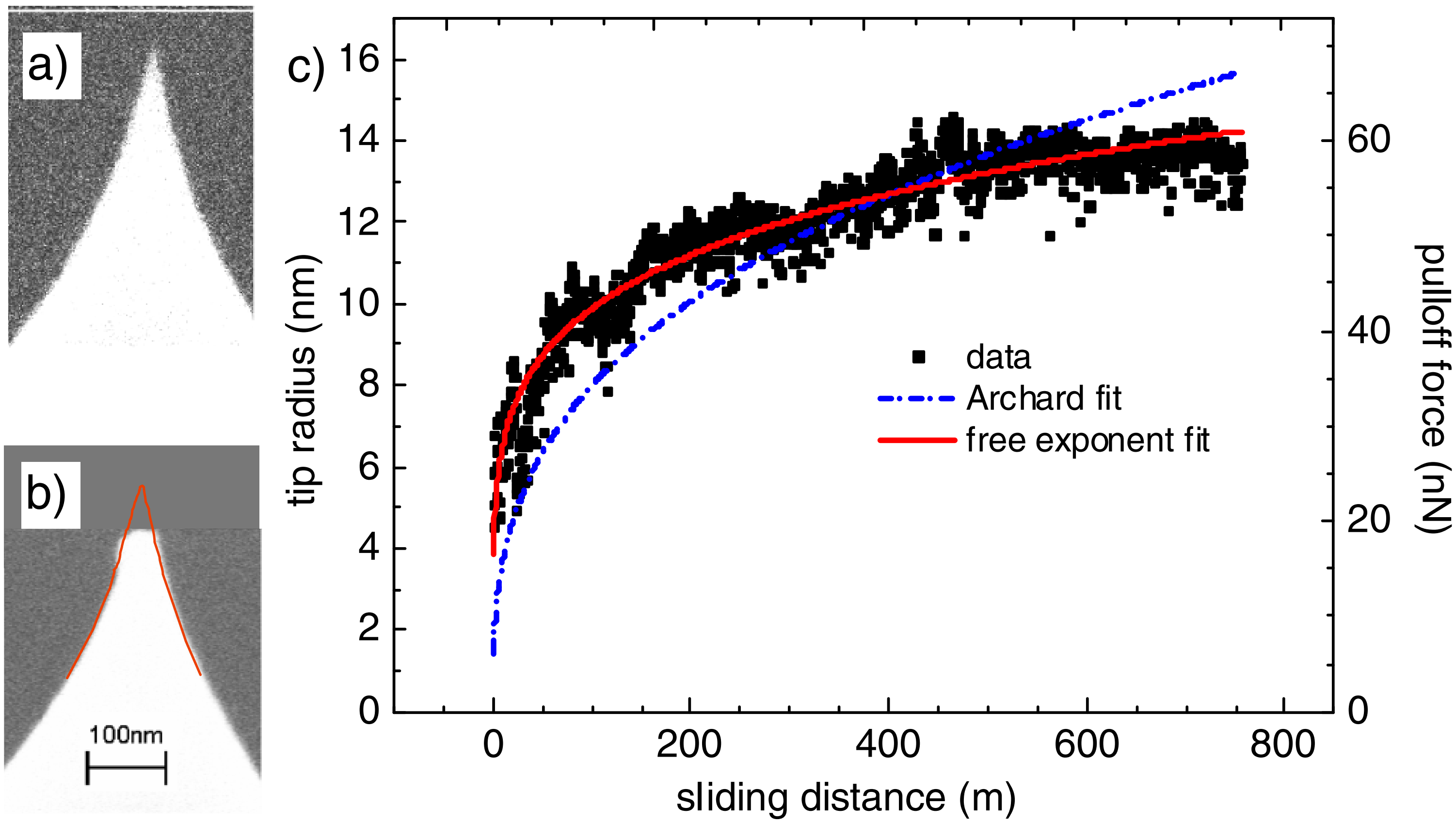
Classical view of Archard's law:

$$\Delta V_{steady-state} = k \frac{L \times t}{H_{soft}}$$

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

Atomistic wear in a single asperity sliding contact

Wear of a Silicon *AFM* probe on a polymer surface

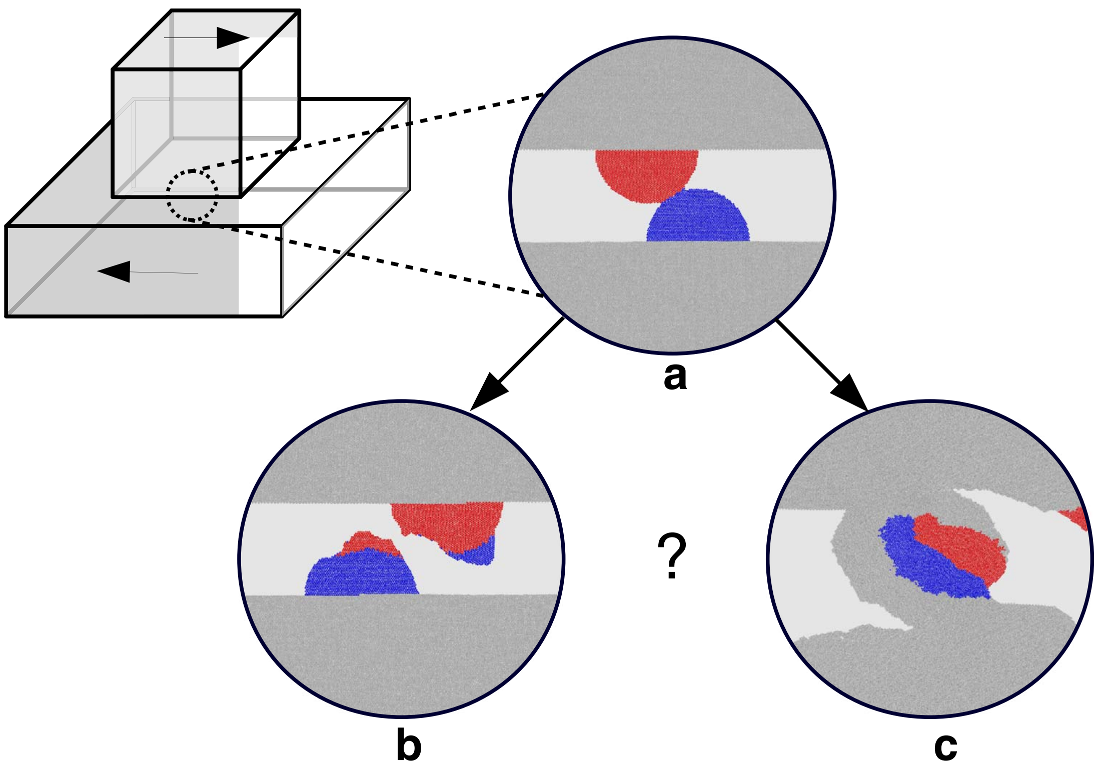


“Wear occurs through an atom by atom removal process which implies the breaking of individual bonds”

B. Gotsmann and M. A. Lantz, *PRL* 101, 125501 (2008)

Atomistic Simulation of NanoWear

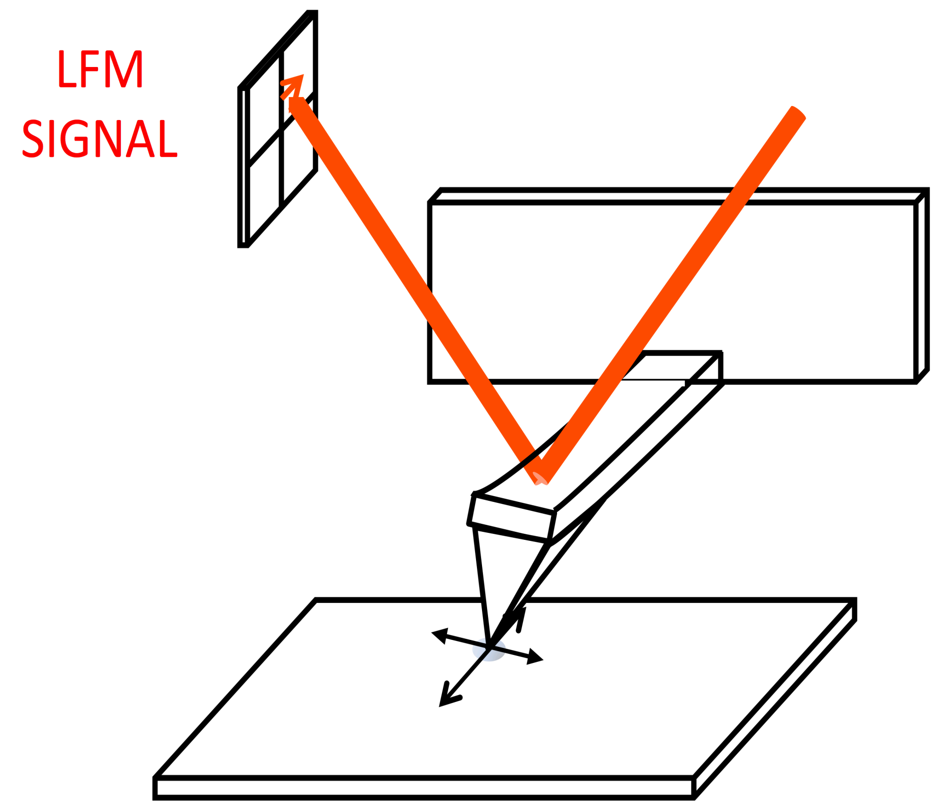
$$d^* = \lambda \cdot \frac{\Delta w}{(\sigma_j^2 / G)}$$



Molinari et al. Nature Communications, 11816, (2016)

NanoWear Experiments with the *AFM*

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



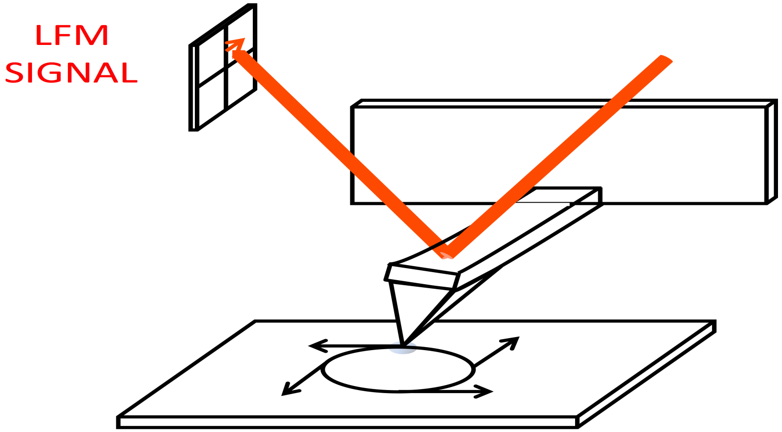
- **Limitations:**

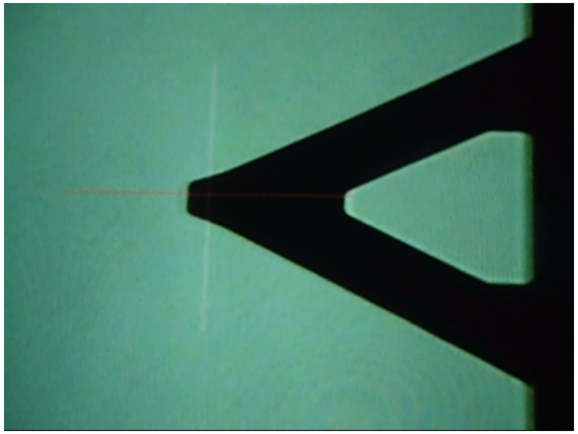
– Non constant and continuous sliding speed

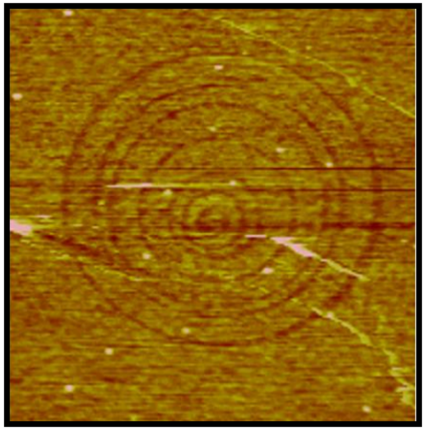
– Low sliding speed (typically max.100 μm/s)

– Scan drift leads to non well defined wear track

Wear Experiments using the CM-AFM



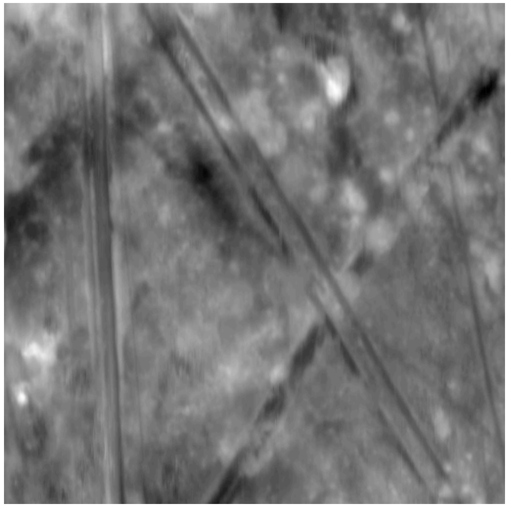




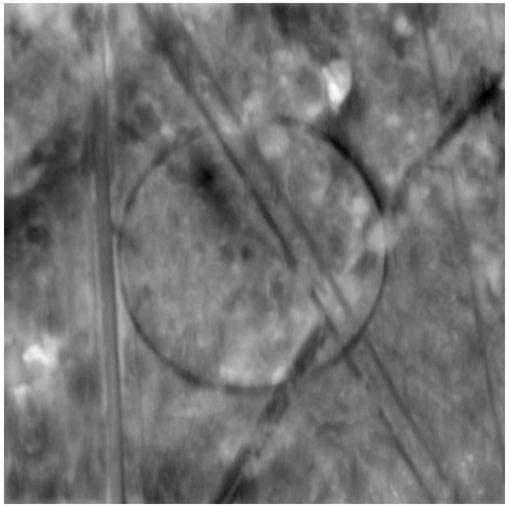
H.Nasrallah, P-E Mazeran, O.Noel. Rev. Sci. Instrum. 2011, 82, 113703.

	Conventional Mode	CM-AFM
Solicitation velocity	Low scanning or sliding velocity (typically, ranging from 1 µm/s to 100 µm/s)	High sliding velocity (> 6 mm/s)
Advantages / *Drawbacks*	*High scanner drift; Low wear; high shear force when the scan changes its direction*	Limiting scanner drift; high wear in a limiting time; well-defined wear track; isotropic wear of the probe if any; anisotropic wear revealed if any; local probing

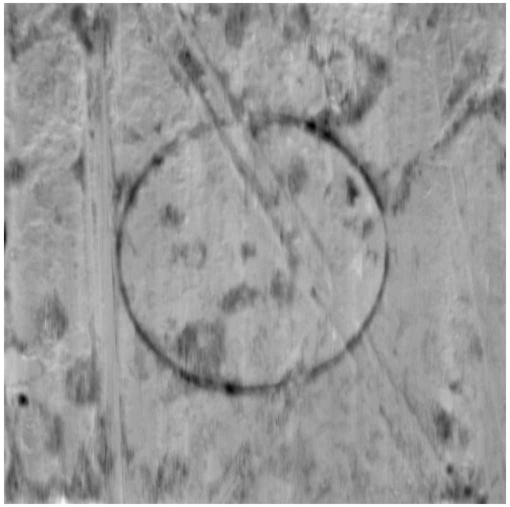
Wear volume computation



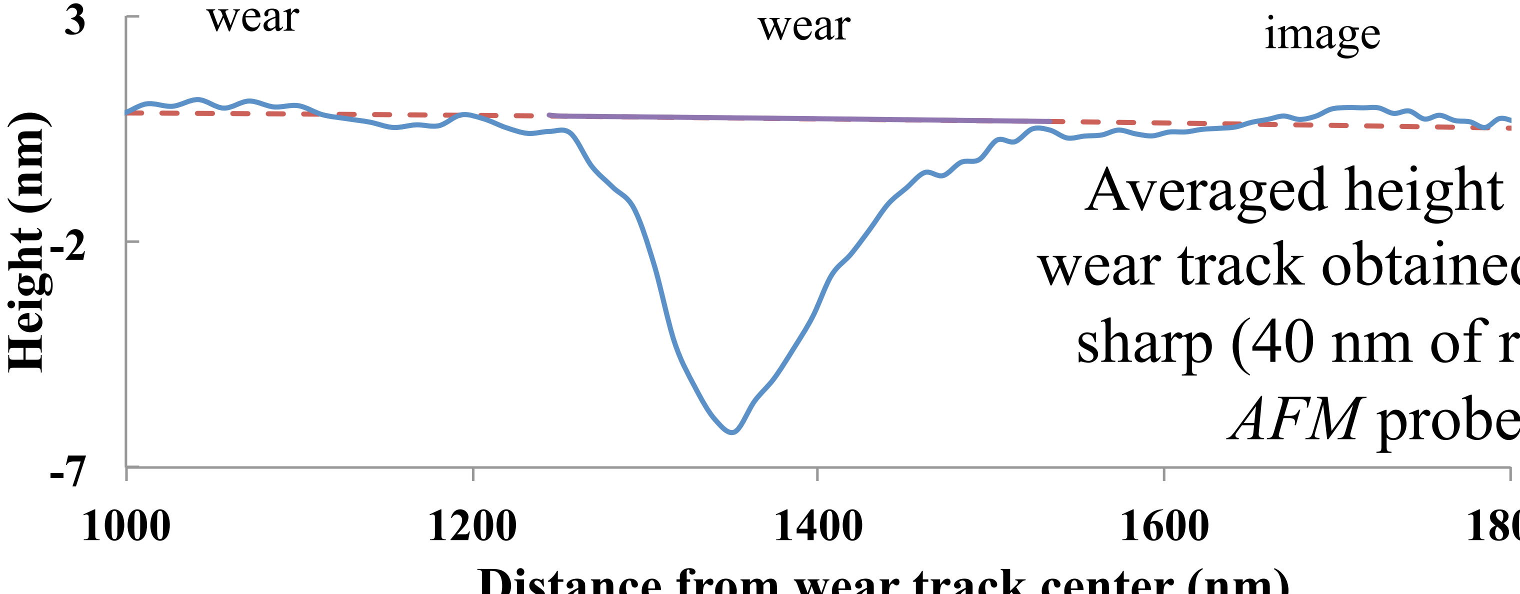
Topography before wear



Topography after wear



Difference wear image



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

Comparative analysis of Macro and Nano wear of copper based composite

Trends in Nanotribology 2017

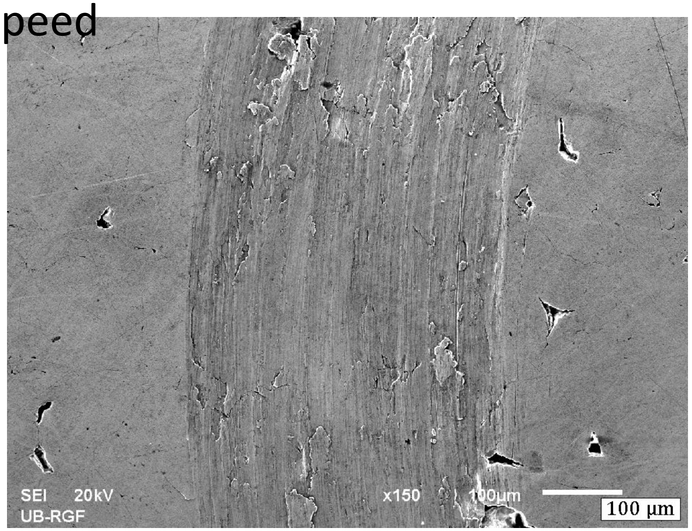
Processing Method: Powder Metallurgy followed by internal oxidation

Designation	Average size particles	Sample roughness Rq	Micro Hardness V_{50}
Nano-composite	Less than 100 nm	4.02 nm *AFM* image 5µm X 5 µm	224

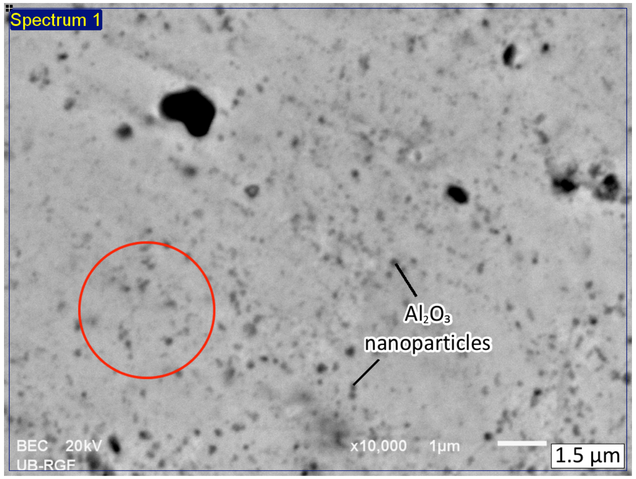
Friction coefficient with steel is 0.13 in the steady-state and is independent of the sliding speed

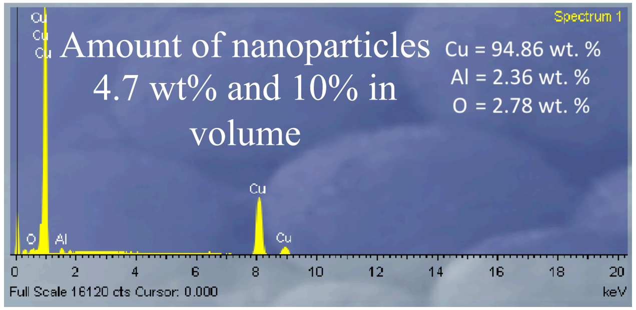
SEM image of wear track after the macro tests (1 N; 8 mm/s)

Mostly adhesive and light abrasive wear



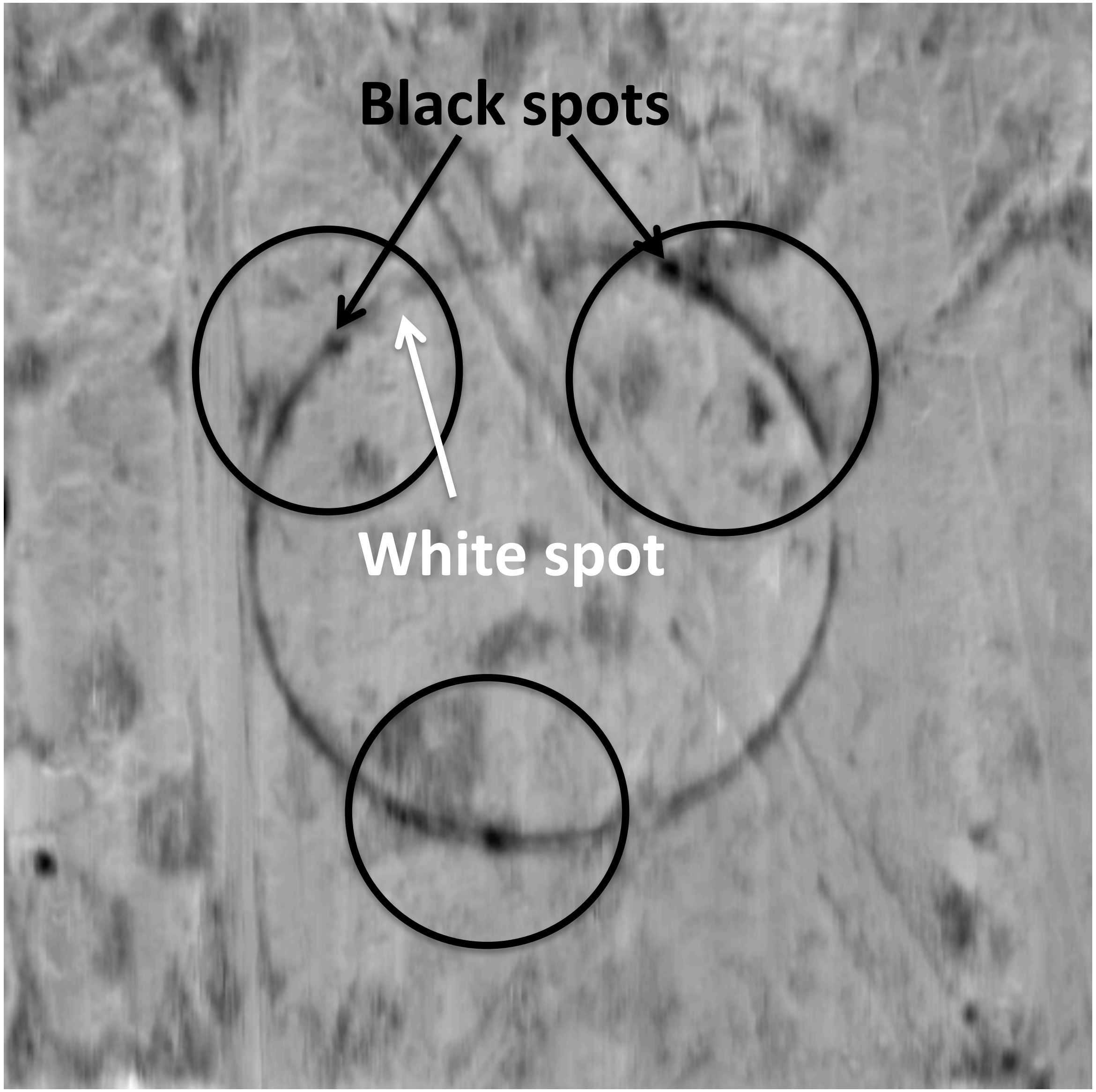
SEM and *EDX* images





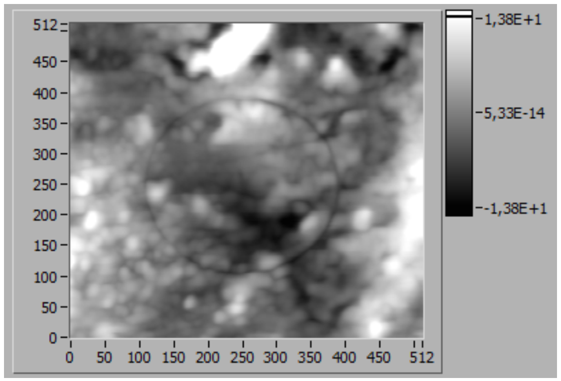
At the macro-scale, wear of the nano-composite follows Archard wear laws

Heterogeneity of Nano-wear

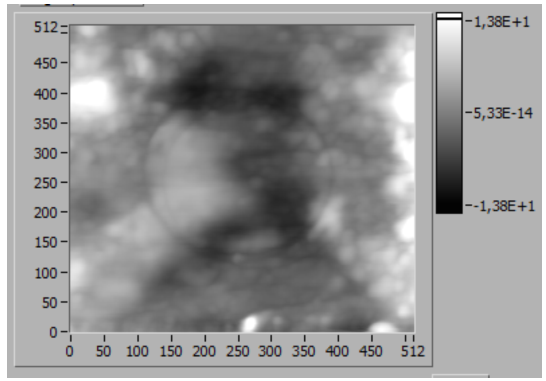


Wear Volume vs. Sliding Distance (or wear duration)

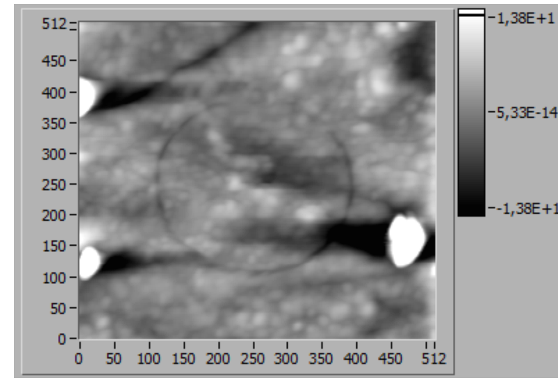
Sliding speed of 0.88 mm/s; Normal load = 3μN; Diamond Probe



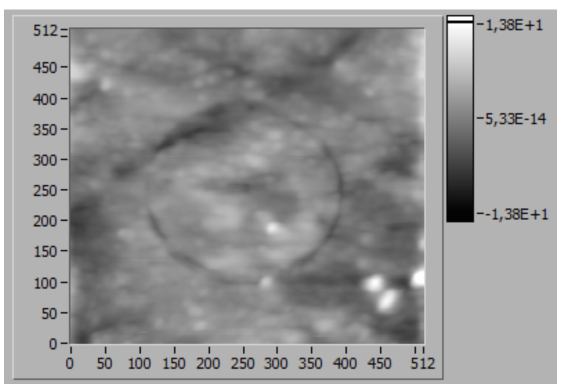
t = 1 min.



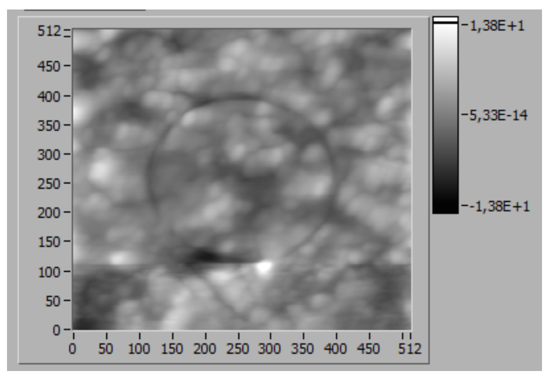
t = 2 min.



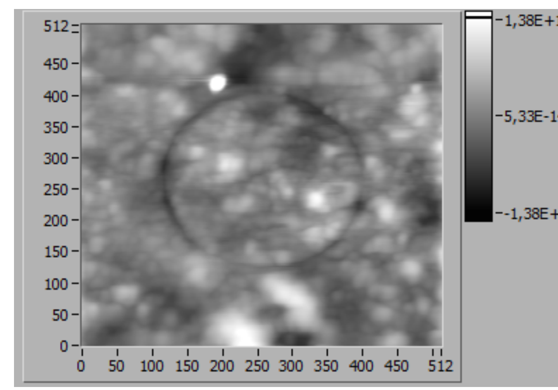
t = 4 min.



t = 8 min.



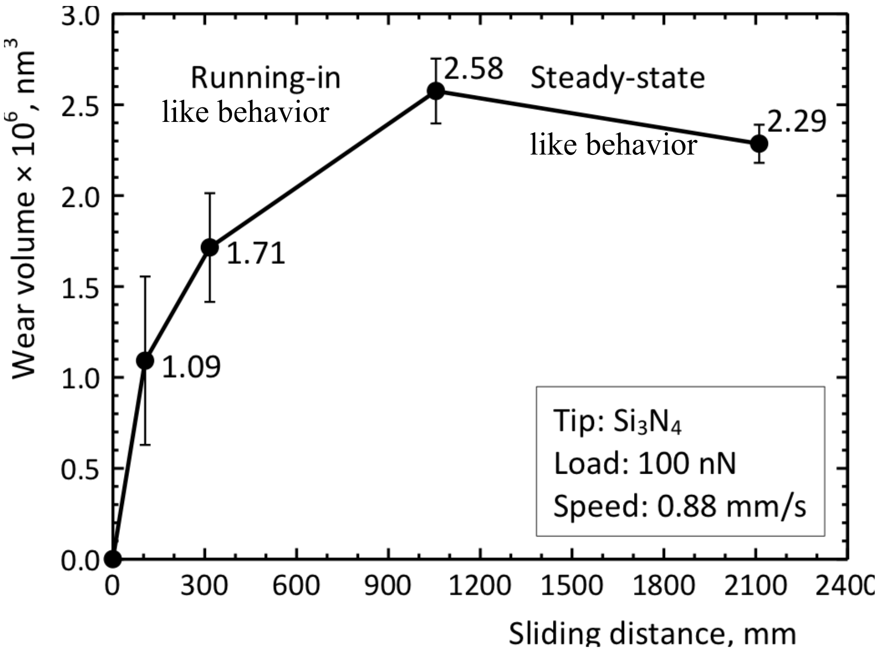
t = 16 min.



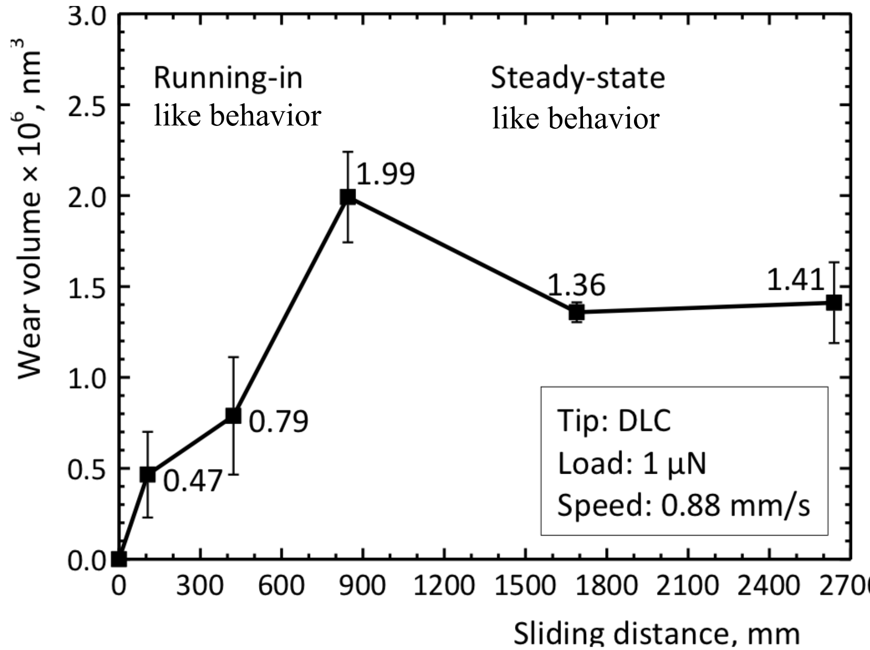
t = 32 min.

Wear Volume vs. Sliding Distance

Si_3N_4 Probe radius: 100 nm



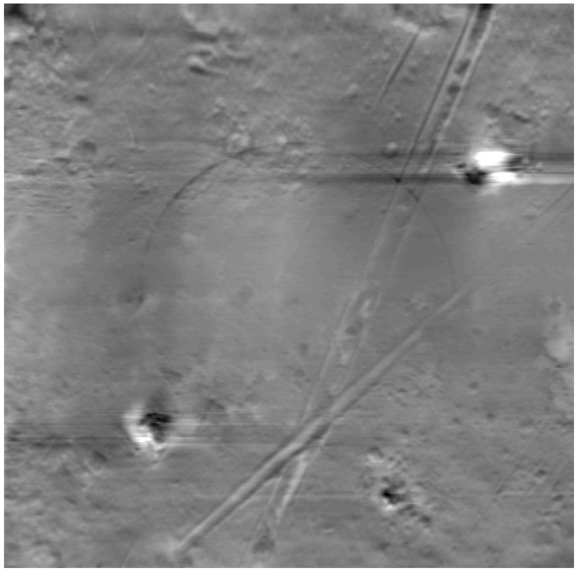
DLC Probe radius: 200 nm



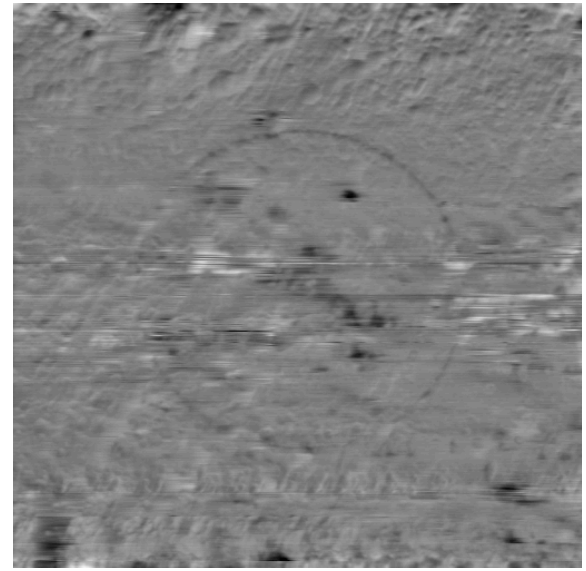
- *SEM* images do not evidence wear of the probes (counter body).
- In both cases, we have an asymptotic steady-state

Wear volume vs. Normal Load

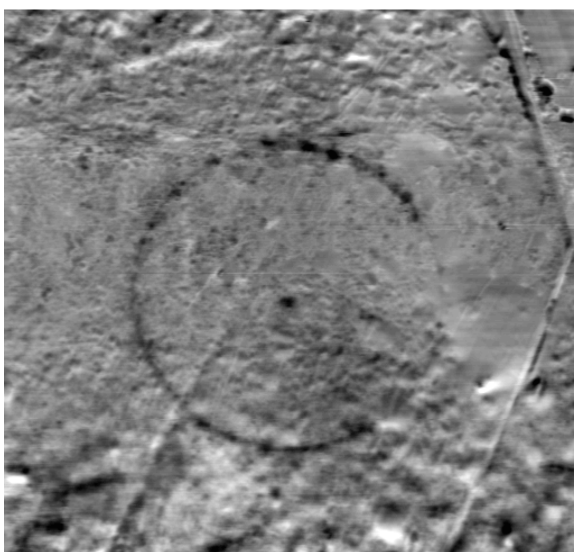
70 nN



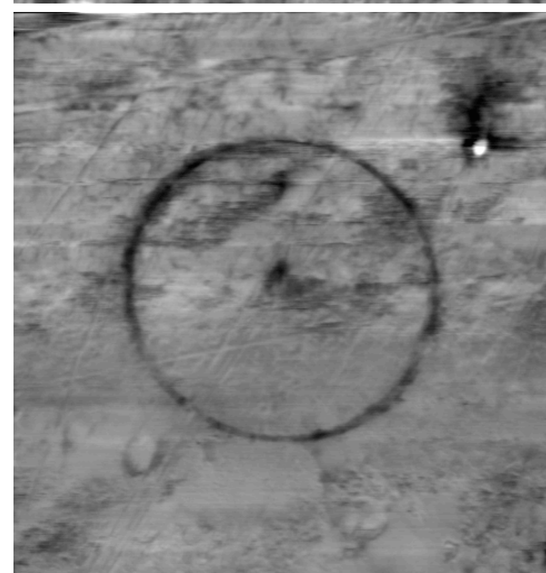
100 nN



140 nN



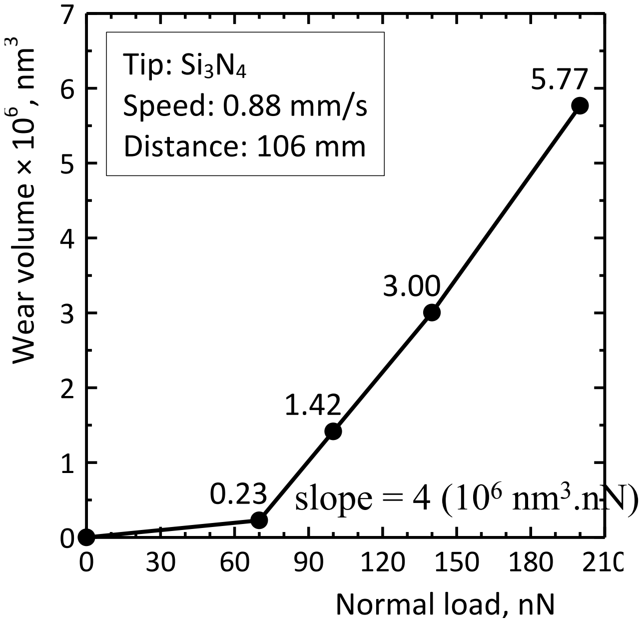
200 nN



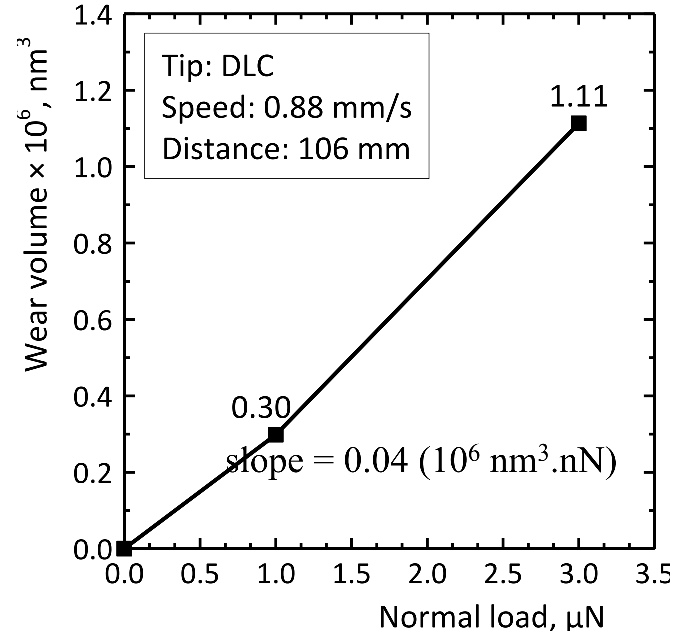
Wear volume vs. Normal Load

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

Si_3N_4 probe radius: 100 nm



DLC probe radius: 200 nm



- Archard-like wear law is obtained.
- Wear depends on the nature of the counter-body.
- For Si_3N_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)

Estimation of the threshold normal load

- 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:

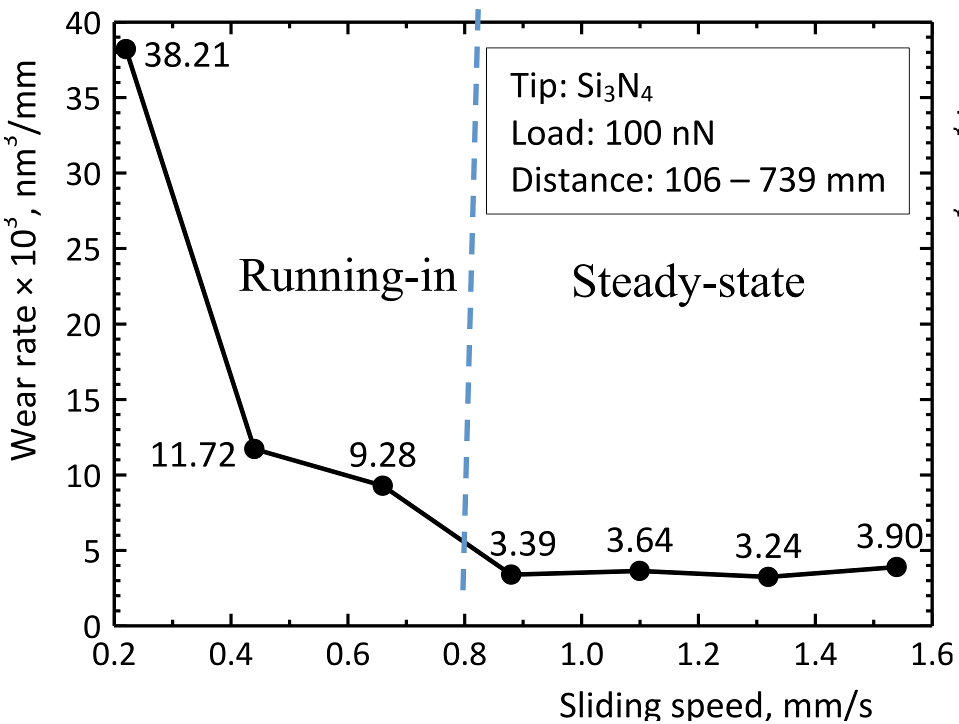
$$a = 4 \text{ nm}$$

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

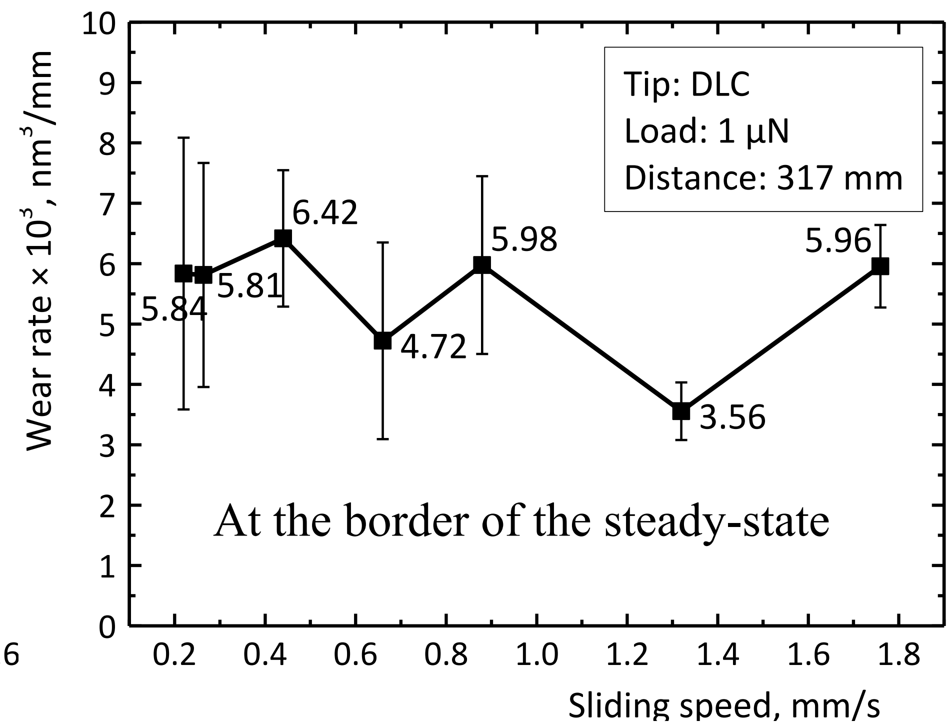
- According to the Hertz theory, the shear stress is maximum at a depth of 0.78 a = 3 nm. This depth corresponds to the thickness of oxide copper growths in ambient conditions.
- Therefore, 60 nN corresponds exactly to the normal load that generates a maximum shear stress at a depth of 3 nm.
- The threshold value may correspond to the minimum load to apply to shear the interface of the oxide/metal interface.

Wear Volume vs. sliding speed

Si_3N_4 Probe radius: 100 nm



DLC Probe radius: 200 nm



- Wear rate is independent of the sliding speed (for a given sliding distance et 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