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Adhesive wear

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TA: Son Pham-Ba

Outline

https://c4science.ch/source/Tribology_Course_nb/

- Lecture 1
  - Introduction of lecturer and laboratory LSMS (lsms.epfl.ch)
  - Introduction to tribology (my vision)
  - From da Vinci to rate and state friction laws

- Exercise 1 (optional HW): Some fundamental solutions in mechanics of solids

- Lecture 2
  - Surface roughness, self-affine roughness
  - Single asperity contact: Hertz contact theory
  - Multiple asperities contact, rough contact mechanics

- Exercise 2 (optional HW)
  - Generation with open-source software Tamaas of rough surfaces
  - Resolution of Hertz contact with Tamaas

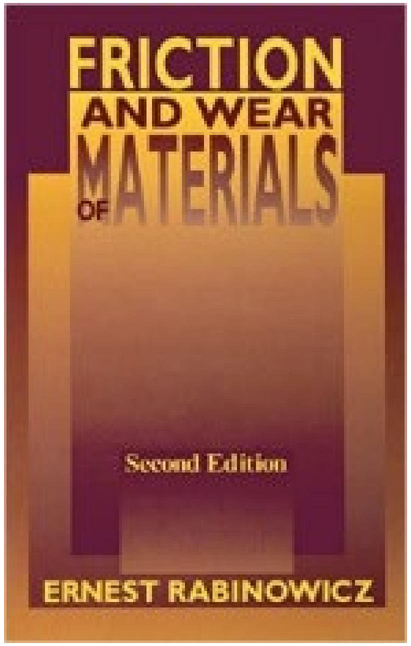
- Lecture 3: From friction to wear

- Exercise 3 (optional HW): Resolution of rough contact mechanics with Tamaas

Wear of materials

Friction is complicated. Wear is even more complicated and messier...

Ernest Rabinowicz:
"Although wear is an important topic,
it has never received the attention it deserves"



Perceived as a "dirty" topic

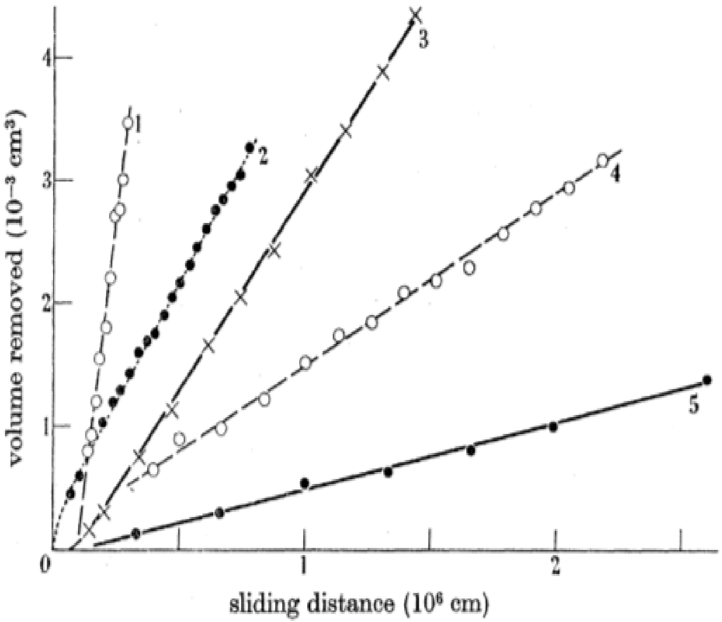
1) Complex physics and chemistry
2) Many forms of wear
    - Adhesive (#1)
    - Abrasive (#2)
    - Surface fatigue, Fretting,
    - Erosive, Corrosion and oxidation…
3) Different stages (history), evolution of roughness, debris (or third bodies)
4) Different regimes (mild wear versus severe wear)

etc…

Meng and Ludema, 1995: 300 equations on friction and wear (1957-1992)

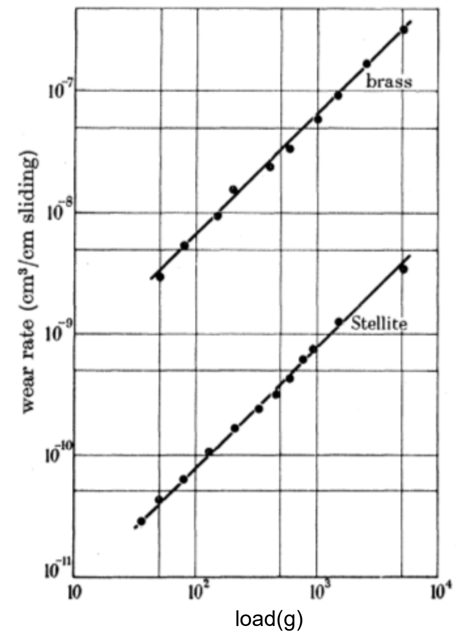
Archard's concept of wear

Very popular engineering model for adhesive wear



Archard, and Hirst, Proceedings of the Royal Society of London A, 1956

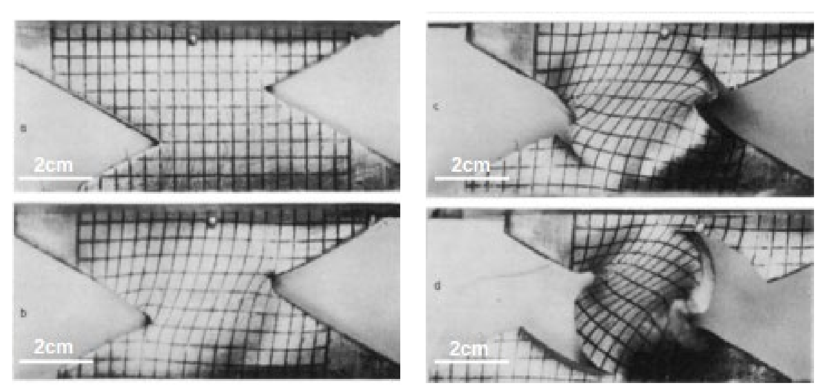
Burwell and Strang, Proceedings of the Royal Society of London A, 1952



$$V = \frac{N\,S}{H_v}$$

K=10^{-8} to 10^{-4}
independent of N (in mild wear regime)

What is K?

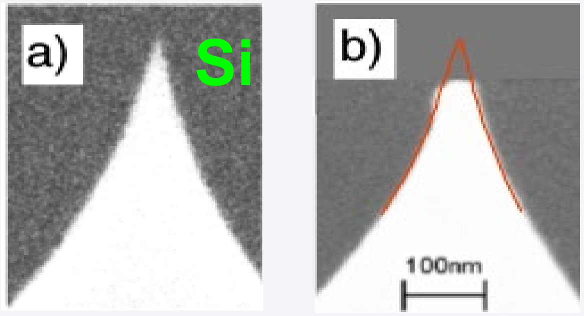


Brockley and Fleming, Wear, 1965

Adhesive wear mechanisms

Two macroscopic interpretations: Holm versus Archard

Small load limit: atom by atom attrition; breakdown of Archard (Jacobs & Carpick, Nat. Nanotech, 2013, …)

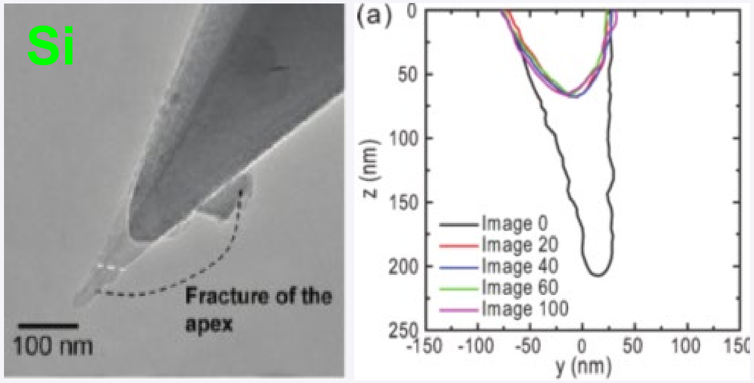


Gotsmann and Lantz, (2008) PRL

Higher loads:
1) Holm (1946): surface asperities worn away by *plasticity* induced *atoms removal*

Plastic flow or brittle fracture?
Holm versus Archard?

2) Burwell and Strang (1953), Archard (1953): surface asperities are worn away by *fracture* induced *debris removal*



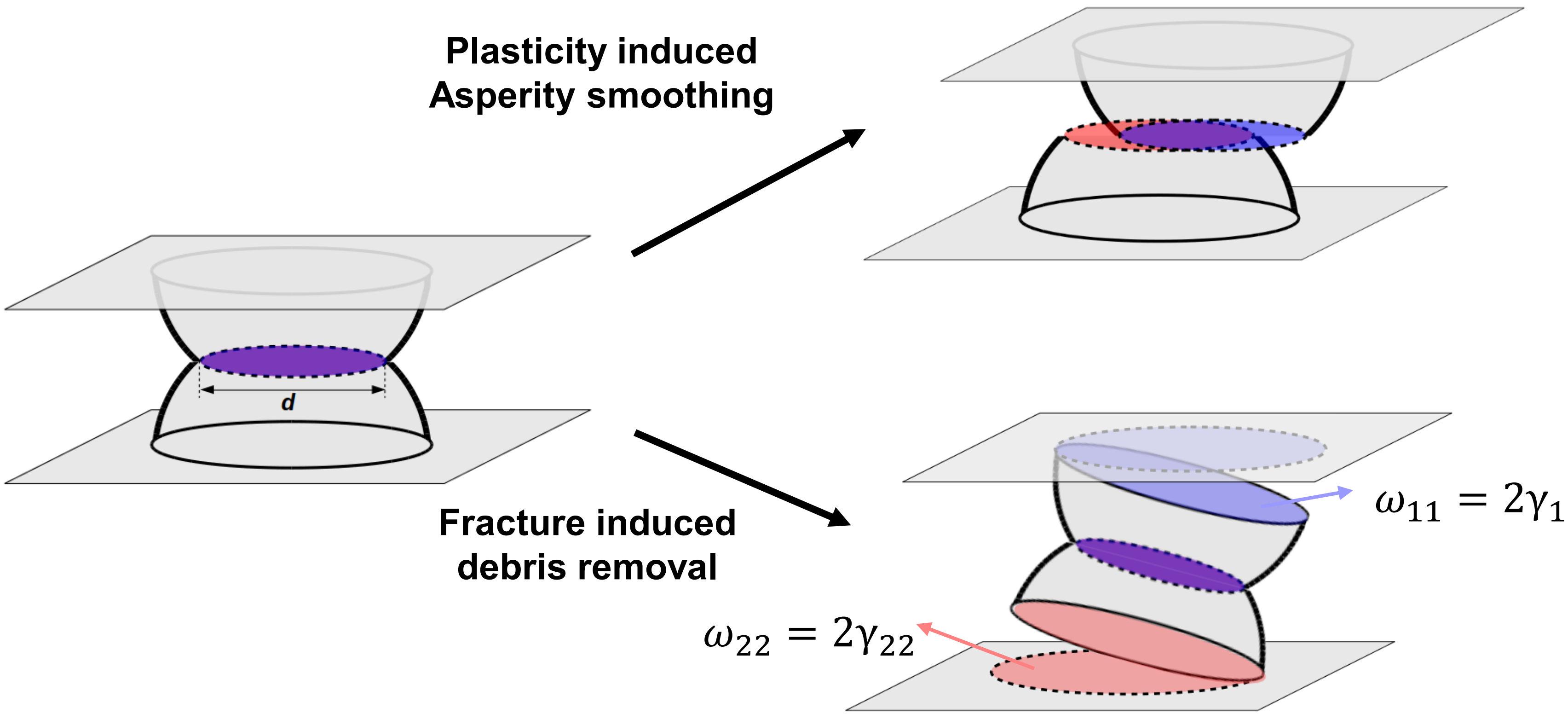
Liu et al., (2010) ACS Nano

Brittle to ductile transition

Simply Griffith; Aghababai Warner Molinari, Nat. Comm. 2016

Holm and Archard are both right !

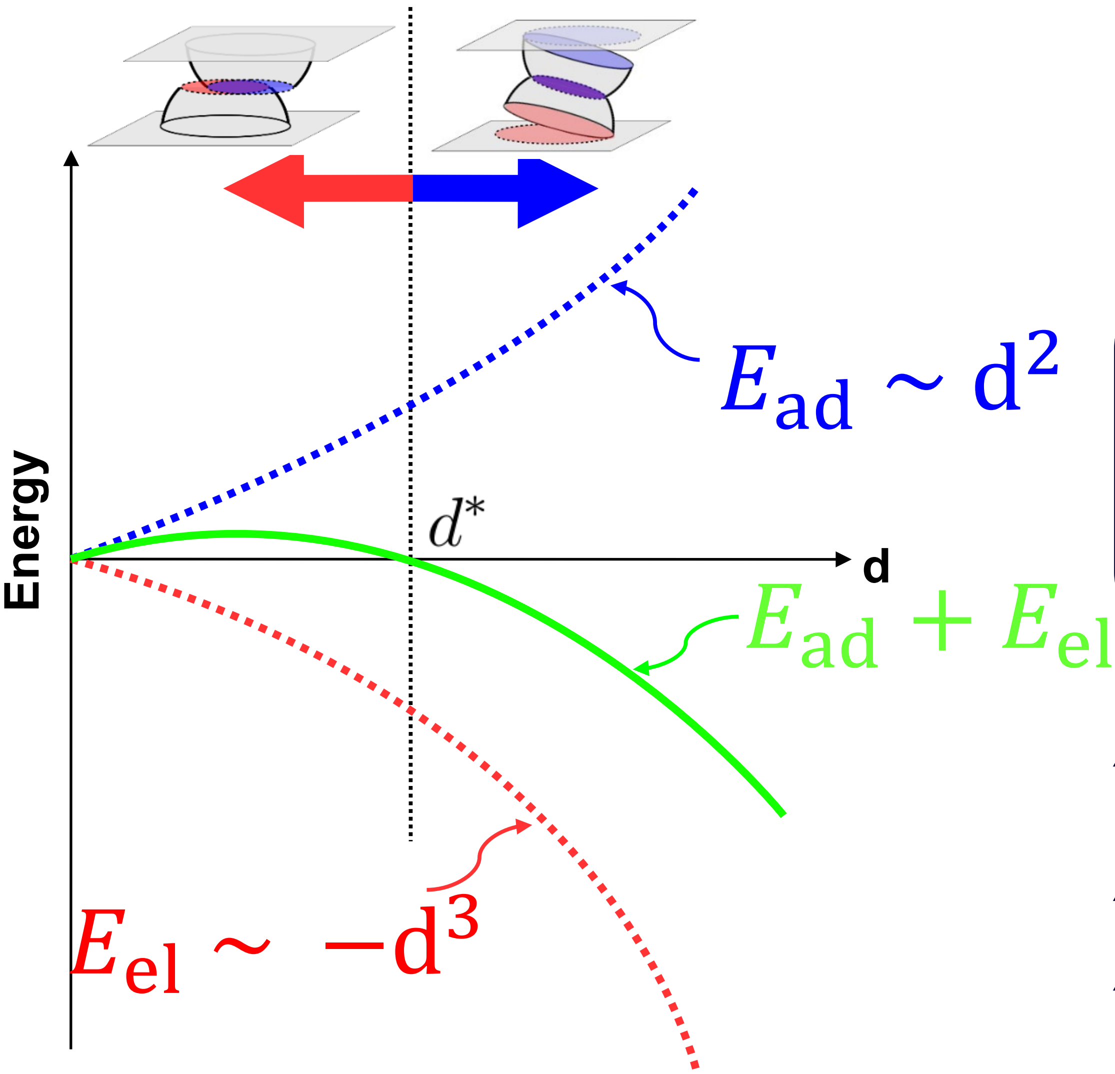
$$E_{el} = \alpha \frac{\sigma_j^2}{2G} \frac{\pi d^3}{6}$$



$$E_{ad} = \beta \underbrace{(\omega_{11} + \omega_{22})}_{\Delta\omega} \frac{\pi d^2}{4}$$

Energy balance

Ductile to Brittle transition explained by Griffith



Wear Transition occurs when:

$$E_{ad} + E_{el} \leq 0$$

Critical Junction size

$$d^* = \lambda \frac{\Delta\omega}{\sigma_j^2/G}$$

Explains discrepant AFM data:

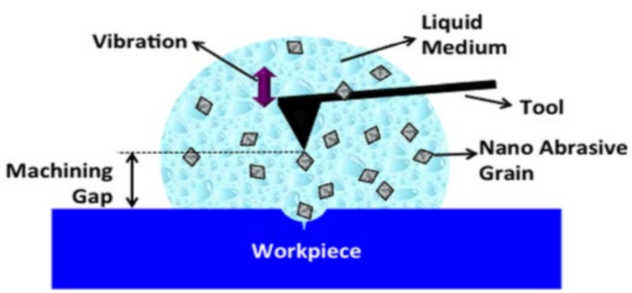
Aghababaei,Warner,Molinari, Nat. Comm., 2016

Brink Molinari, Phys. Rev. Mat, 2019
Aghababaei, Warner, Molinari, PNAS, 2017
Frérot, Aghababaei, Molinari, JMPS, 2018
Aghababaei, Brink, Molinari, PRL, 2018
Molinari et al., Friction, 2018
Milanese et al., Nat. Comm, 2019 …

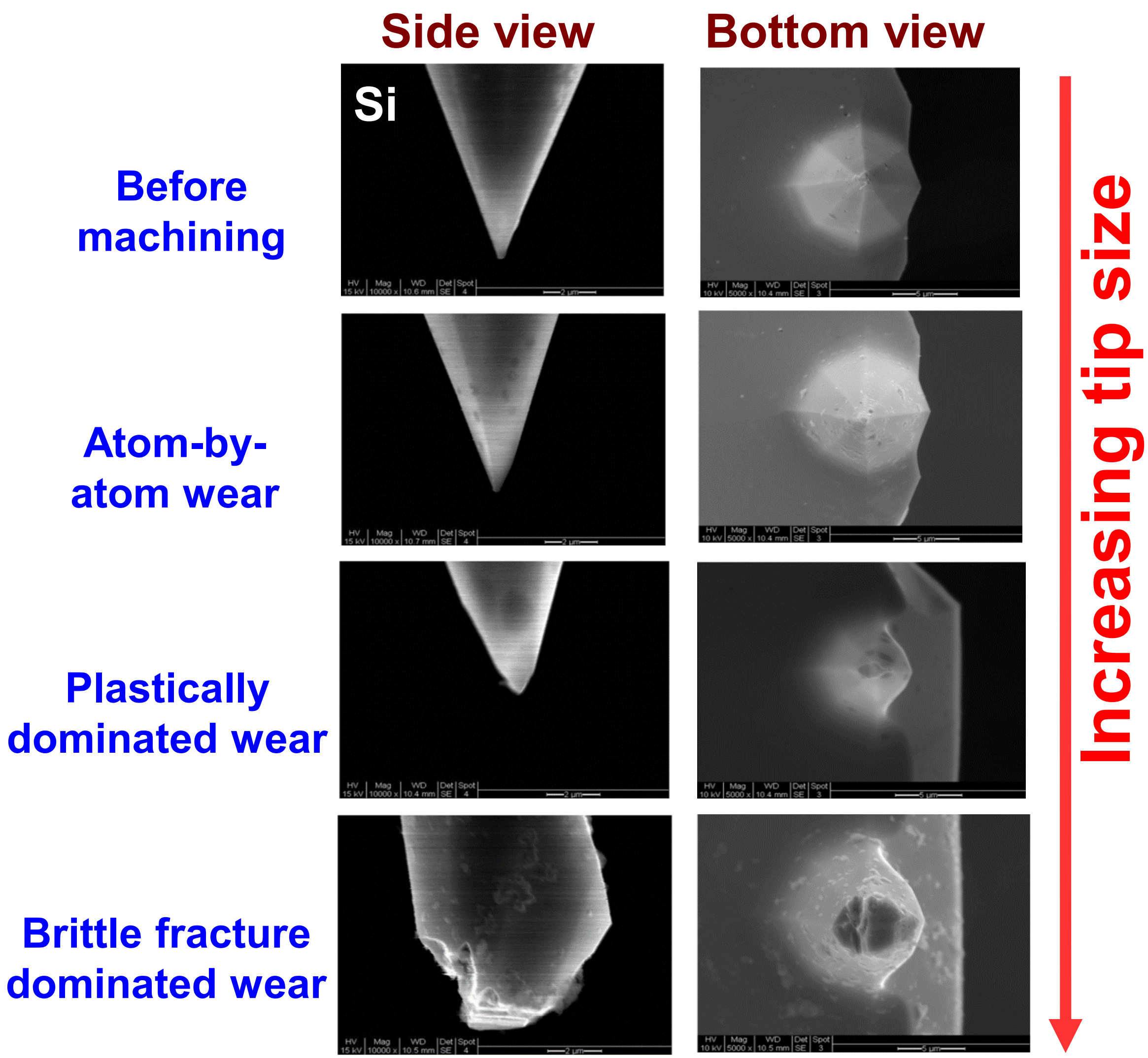
AFM data

Transition to debris formation for increasing AFM tip size

Vibration assisted nano impact-machining by loose abrasives

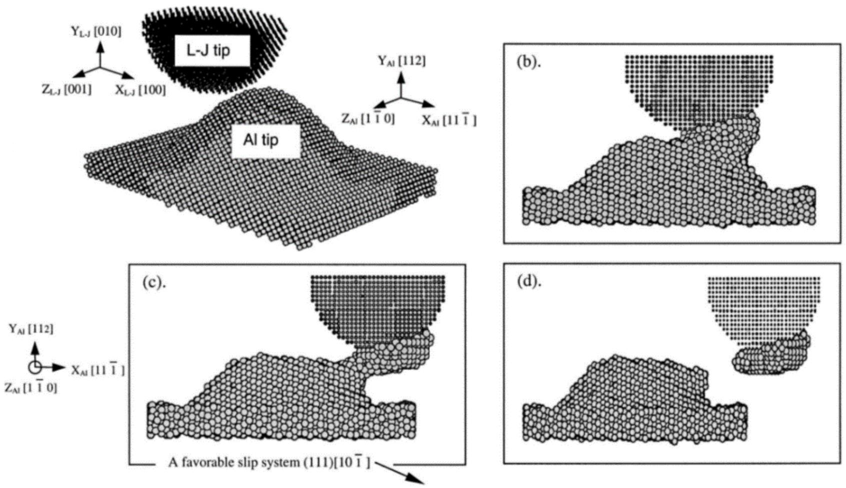


James and Sundaram (2015) J. of Micro-Nano Manuf.

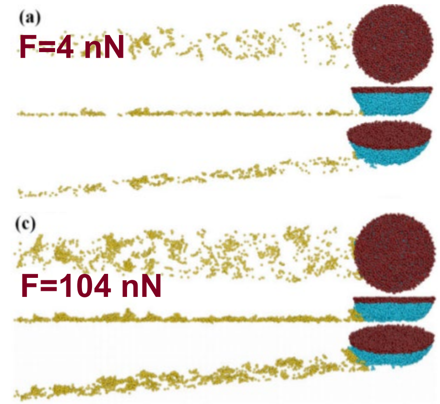


MD simulations

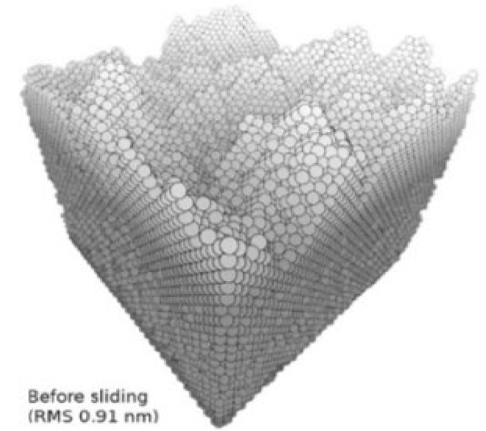
Show asperity smoothing (before 2016)



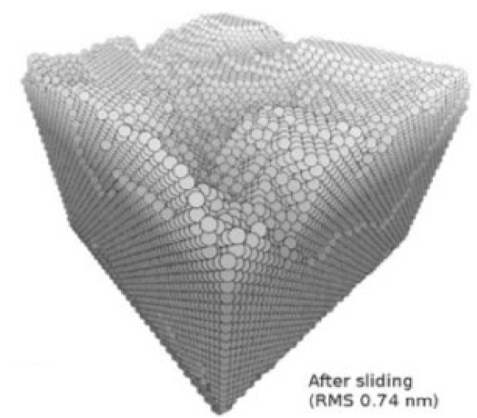
Zhang, J. et al., (2013) J. App. Phys.

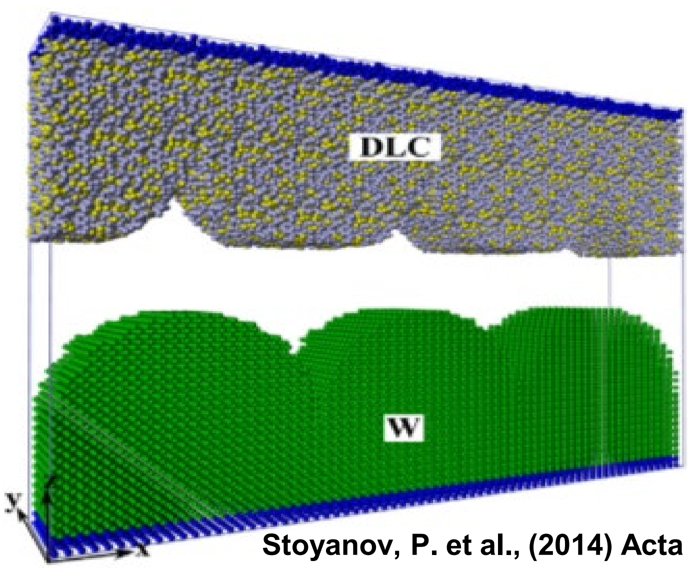


Sha, J. et al., (2013) APL

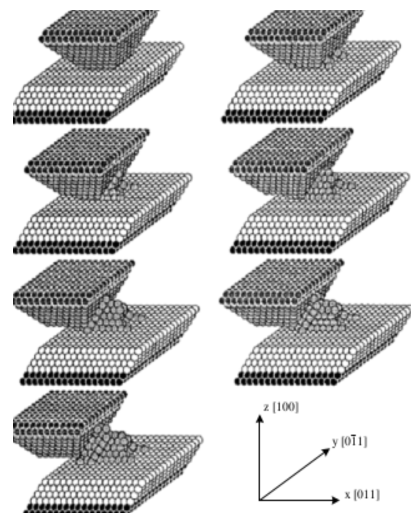


Spijker et al., (2011) Tribology Let.





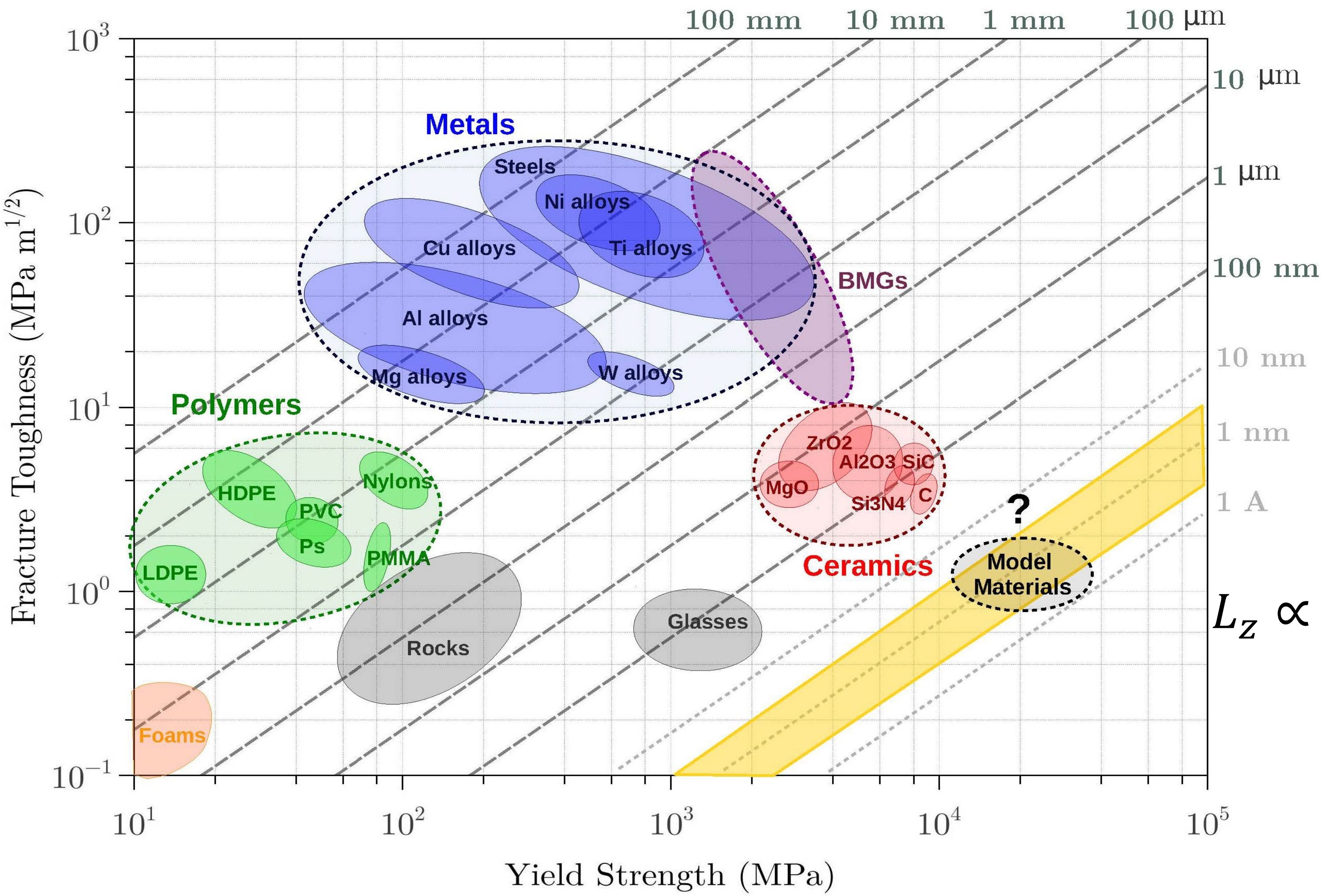
Stoyanov, P. et al., (2014) Acta Mat.



Sorensen et al., (1996) PRB

Ashby map of process zone size

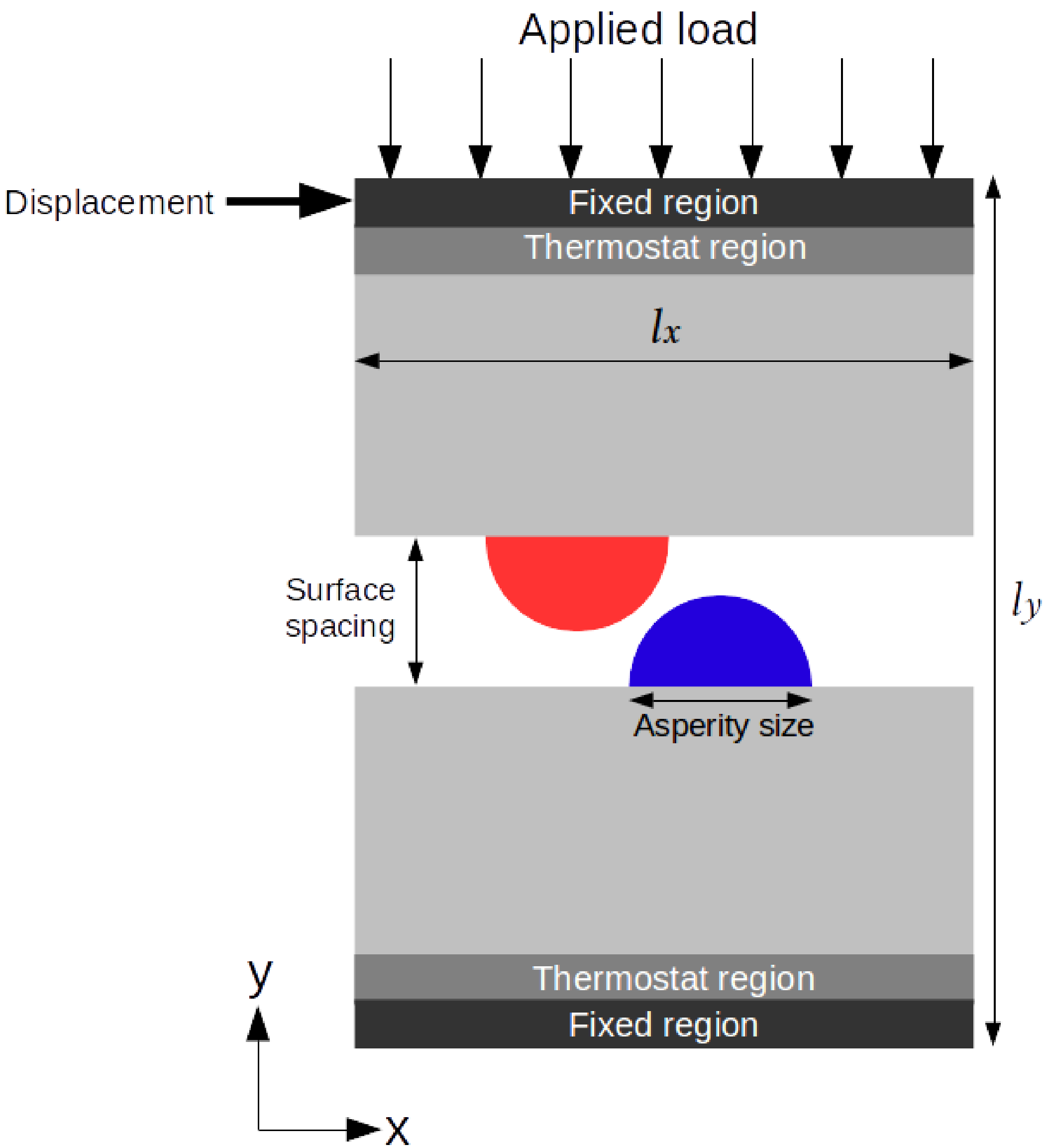
Challenge of scales of MD simulations



$$L_z \propto \left(\frac{K_I}{\sigma_y}\right)^2$$

MD toy model

Aghababaei Warner Molinari, Nat. Comm., 2016



Parameters:

Bulk and interface properties (simple pair potential)

Pressure

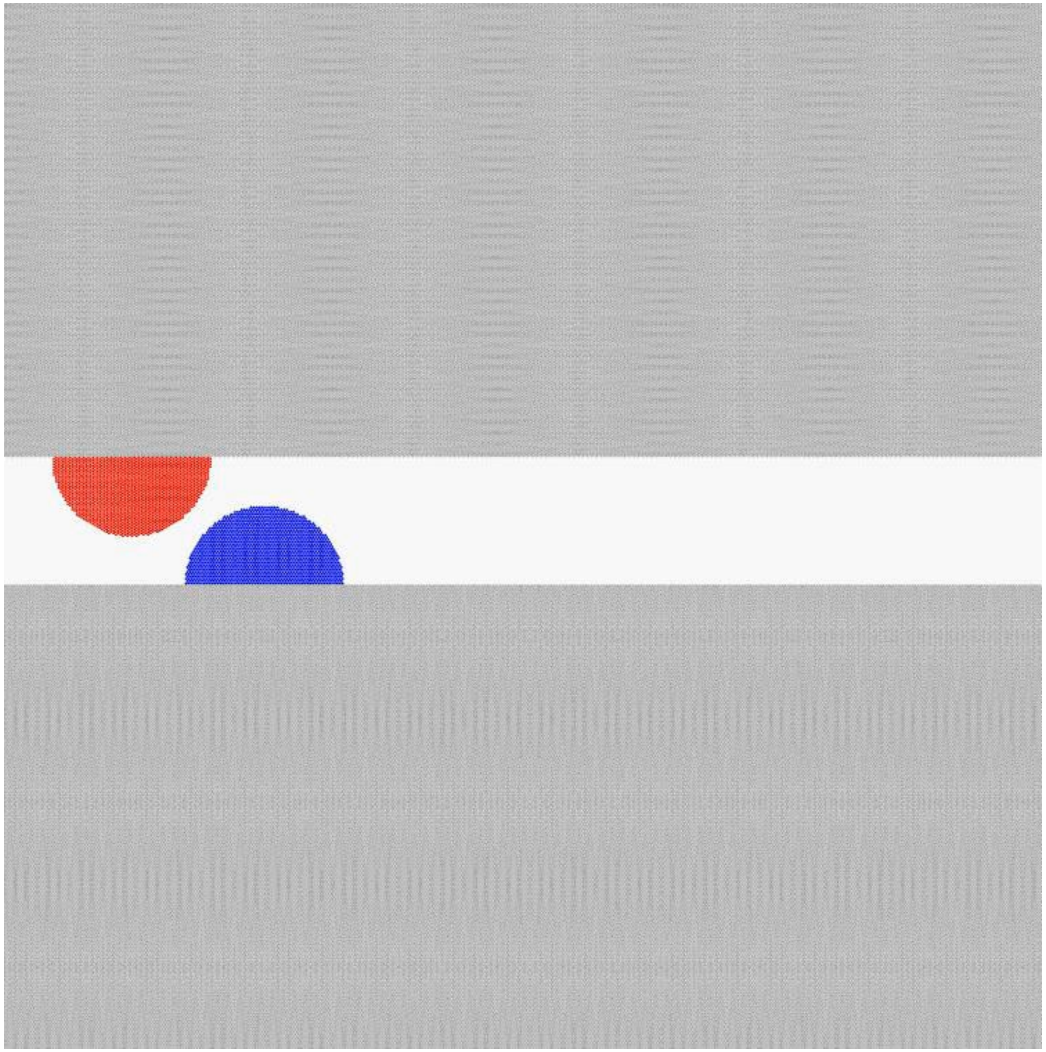
Velocity

Temperature

Geometry
Single, multiple asperities
Asperity size and shape
Interlocking

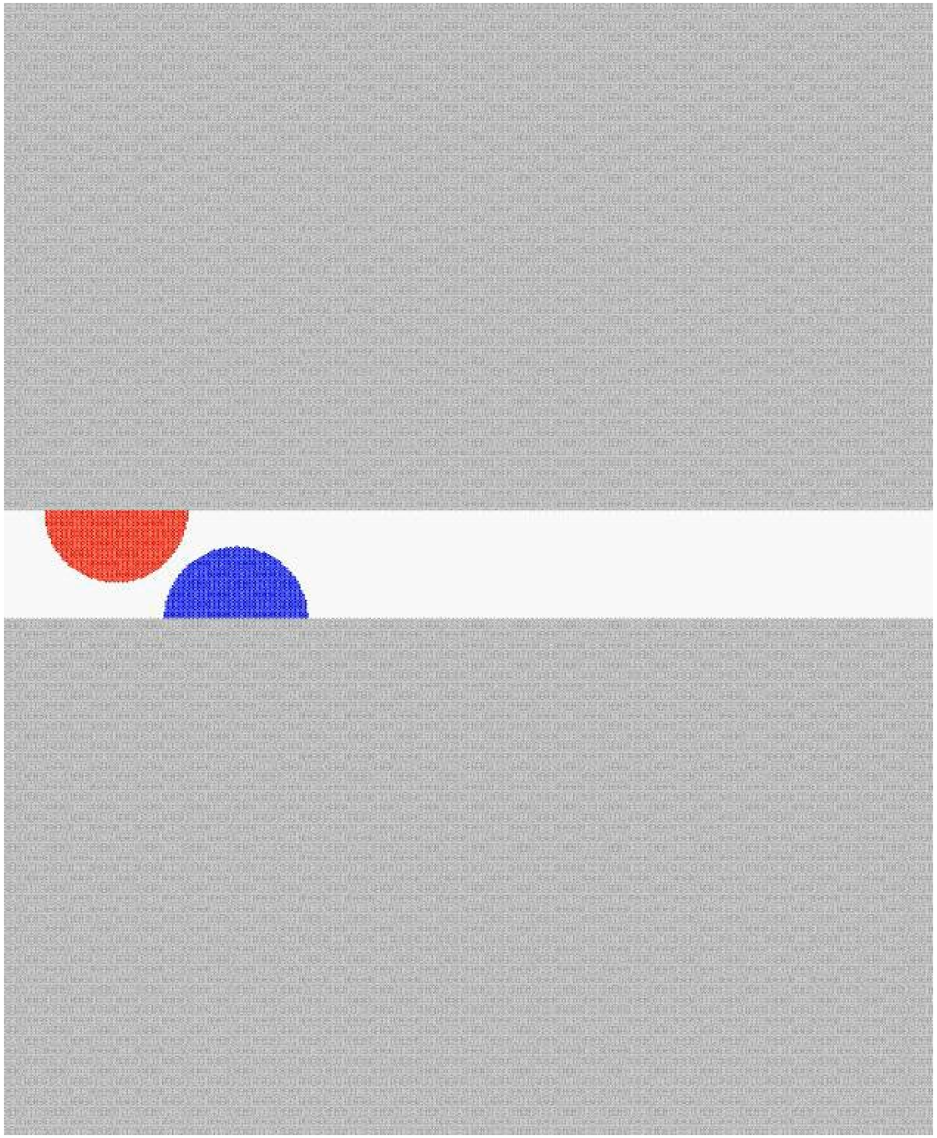
Ductile potential with d<d*

Reveals Holm’s mechanism (plastic smoothening)



Brittle potential with d>d*

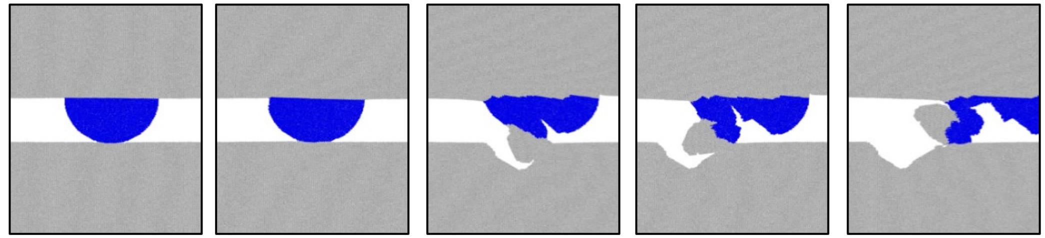
Reveals Archard's mechanism (debris formation)



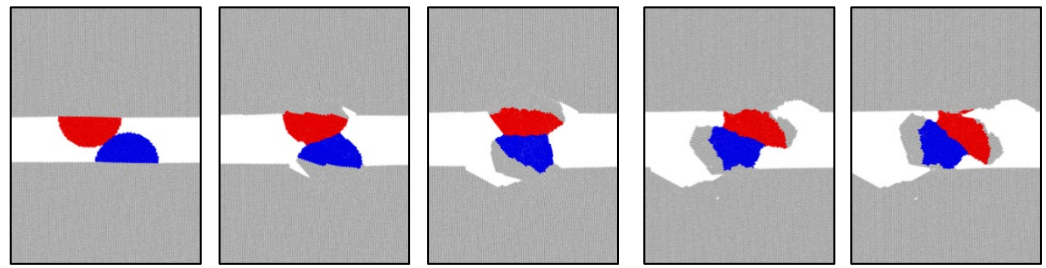
Debris formation

For d > d* for different configurations;

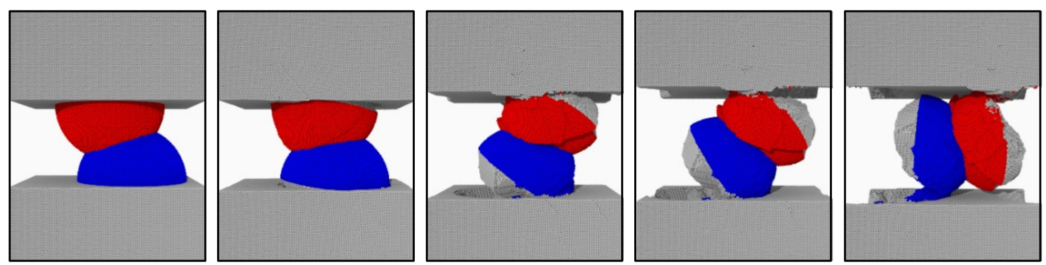
2D single asperity
Model potential



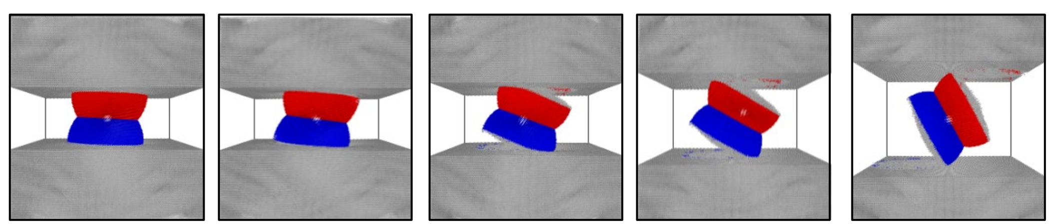
2D asperity/asperity
Model potential



3D asperity/asperity
Model potential



3D asperity/asperity
With diamond potential
(of Pastewka et al., 2013)



Back to Archard’s wear law

What is K? At the asperity level

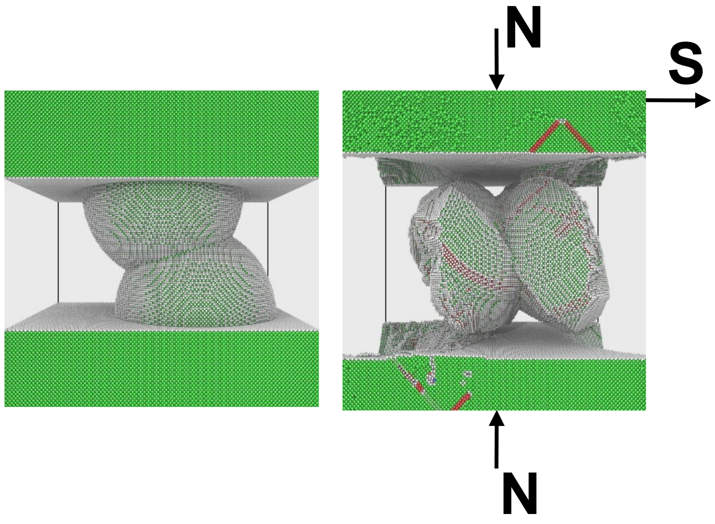
1) At the macroscopic/engineering scale, Archard’s model is essentially probabilistic

$$V = K \frac{N\,S}{H_v}$$

$K=10^{-8}$ to 10^{-4}

K interpreted as probability of asperity/asperity encounter yielding a debris

2) But at the scale of an asperity/asperity junction, our model is fully deterministic



If d > d*, a debris is formed, K=1
Otherwise K=0

How big is this debris?

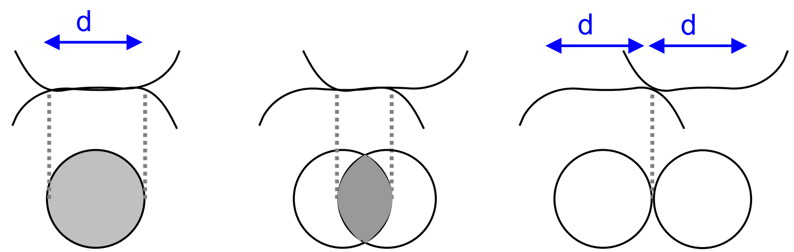
$$V \overset{?}{=} 1\,\frac{N\,S}{H_v}$$

Question: do we recover Archard’s law at the asperity level?

Rationale for Archard's model

At the asperity level

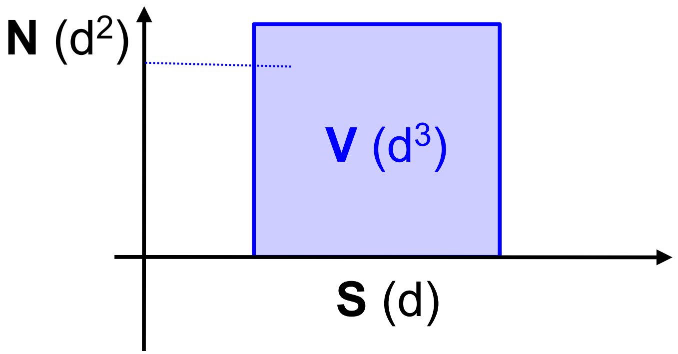
Archard (1953) J. App. Phys.



I. Plastic deformation of asperities

$$\left(N \sim d^2\right)$$

II. Contact duration



III. Shape/Volume of wear debris

$$\left(V \sim d^3\right)$$

The depth, to which the material is worn, is proportional to the junction size.

$$W \sim \frac{V\left(d^3\right)}{S(d)} \sim A\left(d^2\right) \sim \frac{N}{H} \quad \Rightarrow \quad V \sim \frac{N \times S}{H}$$

Recovering Archard ?

Aghababaei Warner Molinari, PNAS, 2017

$$V = \frac{N S}{H_v}$$

Debris volume, V (r_0^3)

But should it be a surprise?

Adhesion: A is not proportional to N

Adhesion?

Plastic shearing?

Asperities collision?

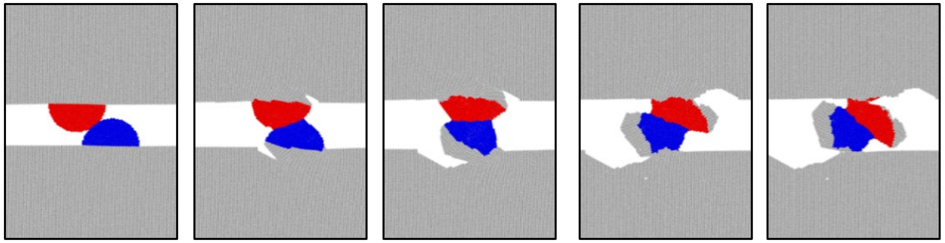
Junction area, A

(N ~A) is influenced by the roughness parameters and adhesion!

Mo and Szlufarska, (2010) *PRB,*   Enachescu, et al., (1998) *PRL*.
Gao, et al., (2004). *J. Phys. Chem. B,*   Pastewka, and Robbins, (2014) *PNAS.*

Accumulated frictional work

Predicts debris size



S=1 r_0 20 r_0 40 r_0 60 r_0 100 r_0

$$\frac{\int F ds}{\sigma_j}$$

$$V = \frac{\int F ds}{\sigma_j}$$

Rediscovering T. Reye:
(1860) Zur theorie der zapfenreibung. J. Der Civilingenieur 4:235–255

Debris volume, V

Minimum particle size?

Set by critical length scale d*

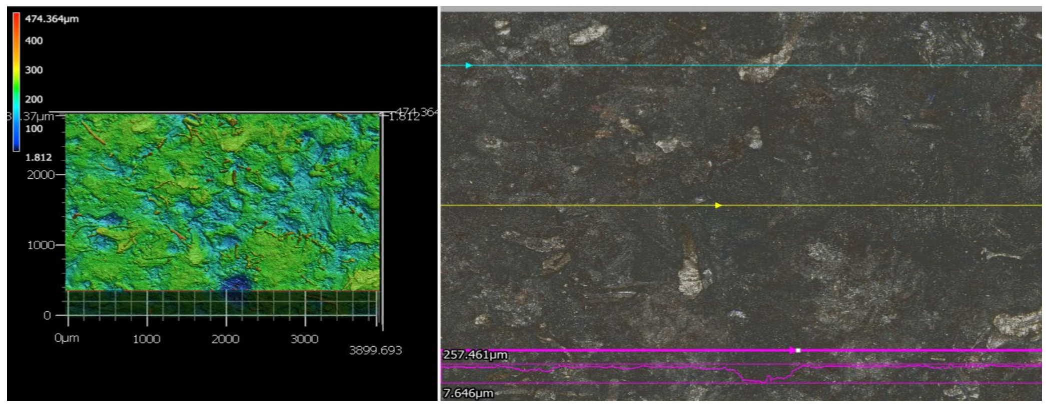
Growing societal concern with regard to air pollution due to ultra fine particles

BBC news, July 2019: «Pollution warning over car tyre and brake dust»
In a world of electric cars, these will dominate air pollution, and there are concerns that they present more health hasards and exhaust particles pollution.

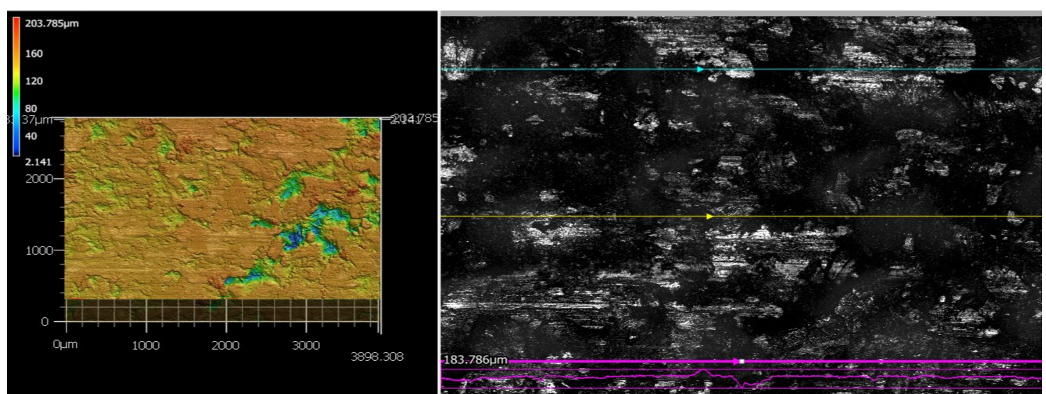
Junction size, d, sets debris size (if d>d*)

$$d^* = \lambda \frac{2Gw}{\tau_j^2}$$

Junction strength (decreases with reduced adhesion)



New brake pa



Worn brake pad

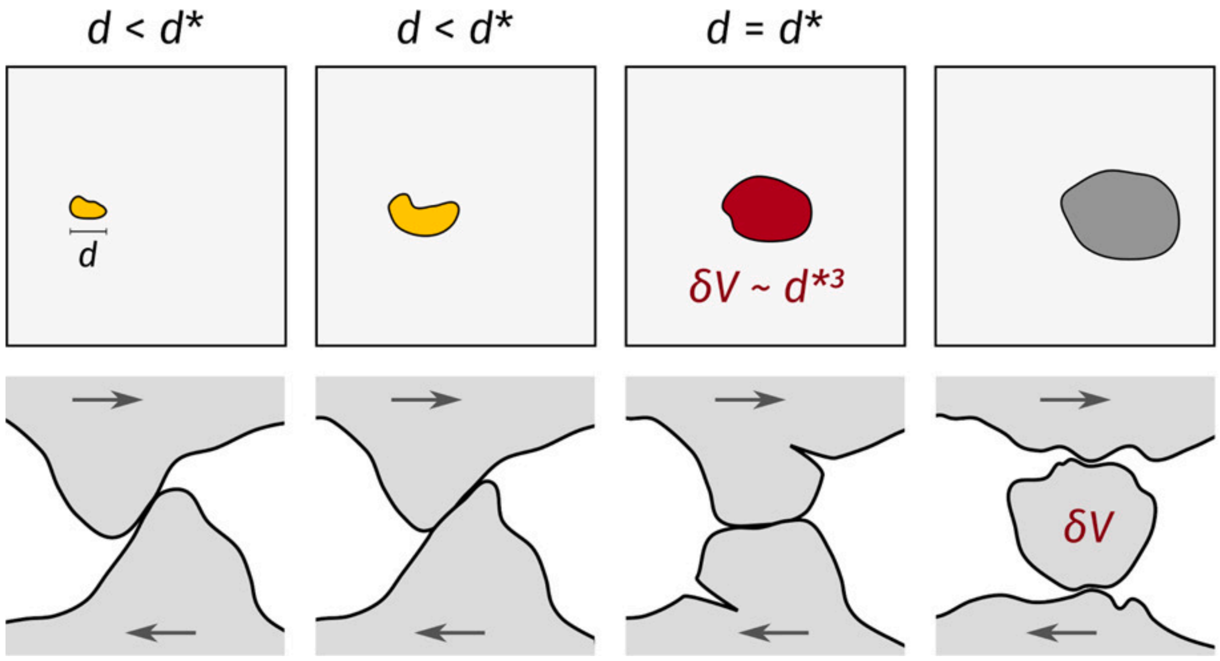
Mesoscale model

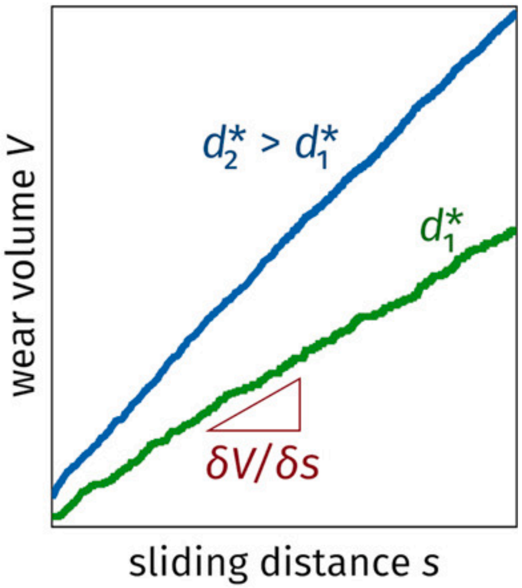
Brink Frérot Molinari, JMPS 2021, A parameter-free mechanistic model

Brittle materials (high hardness) wear less, Archard: $V = K\frac{N\,S}{H_v}$

But d* is smaller when hardness increases: $d^* = \lambda\frac{\Delta\omega}{\sigma_j^2/G}$

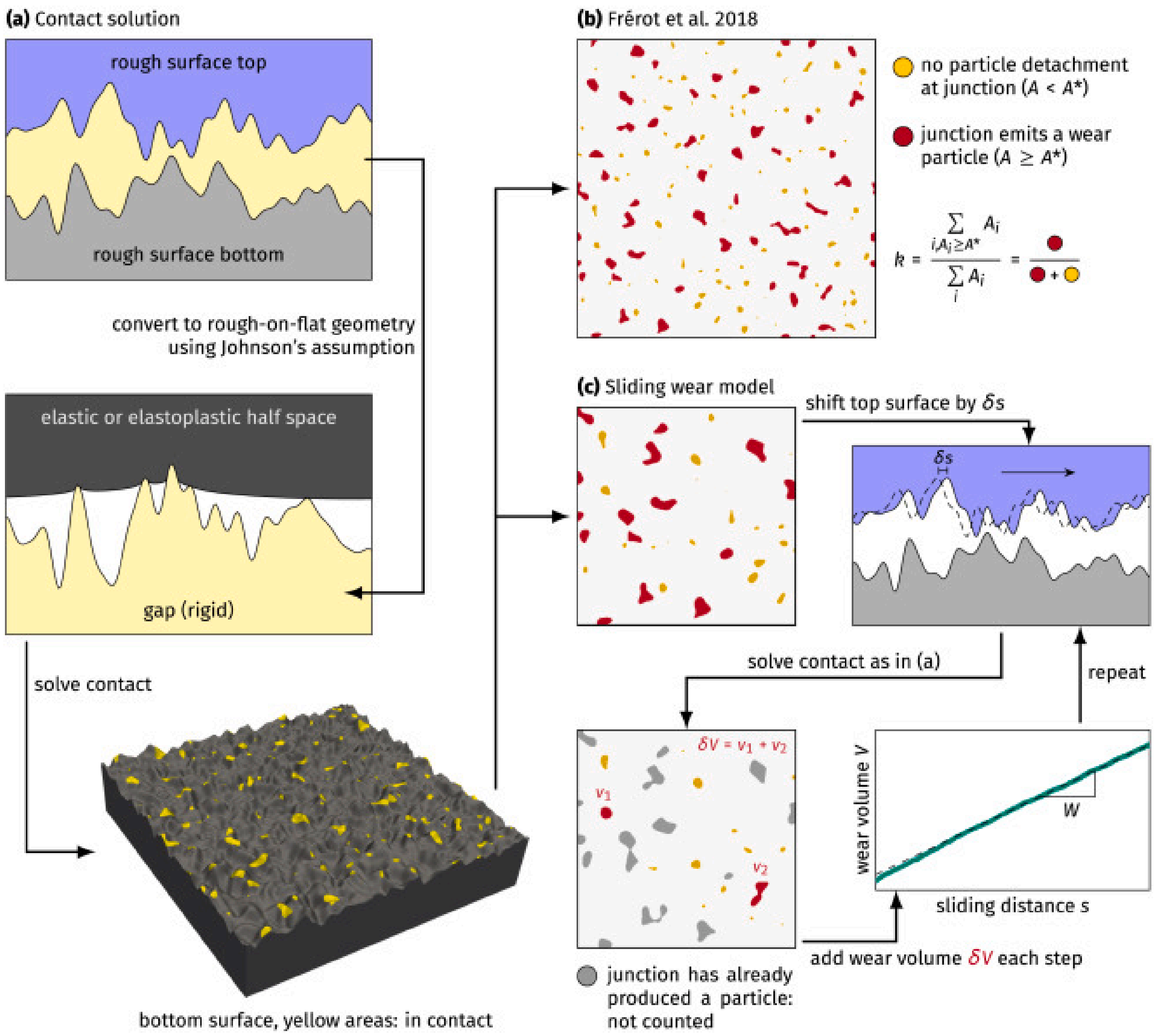
Which results in more debris production. **Contradiction**… solved by sliding history





Rough on rough sliding

Solved with BEM, at each sliding step, TAMAAS software (BEM, FFT), JOSS 2020

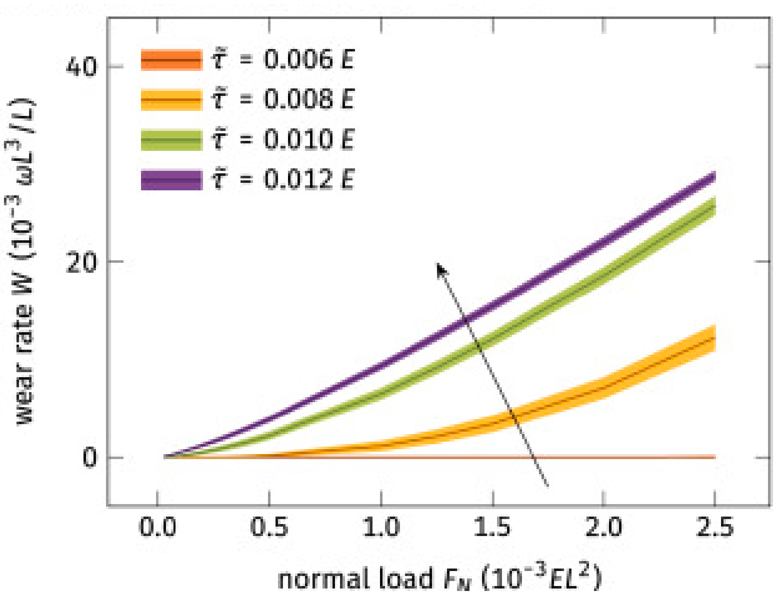


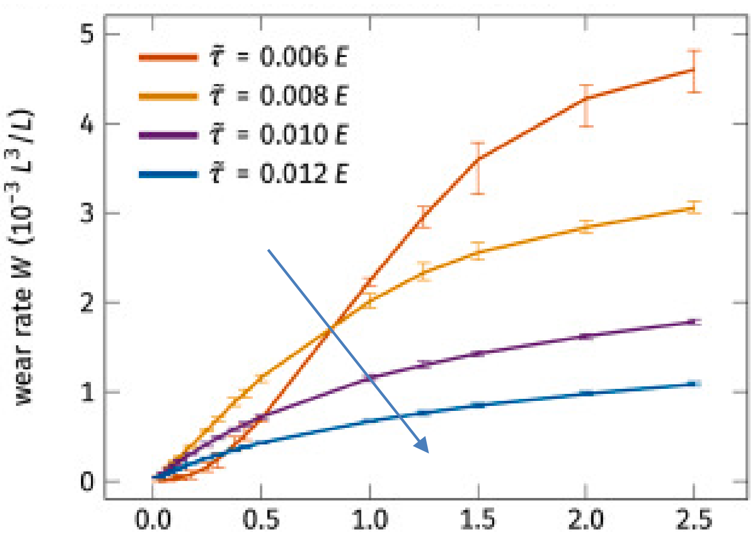
Rough on rough sliding

Solved with BEM, at each sliding step

Importance of sliding history

And disabling debris formation





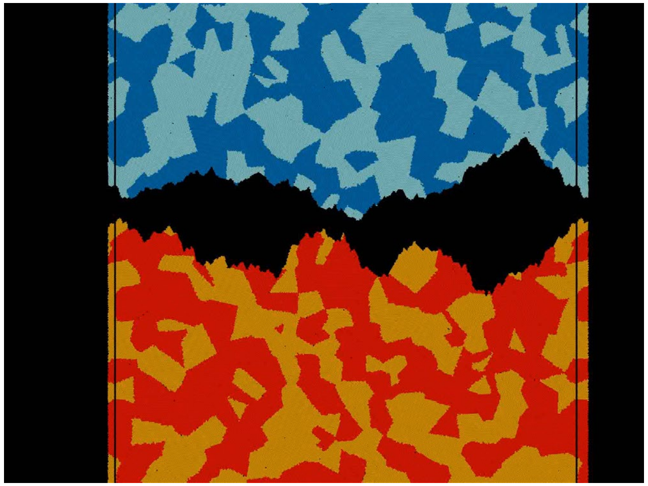
No silding history; wrong qualitative trend
Frérot, Aghababaei, Molinari, JMPS, 2018

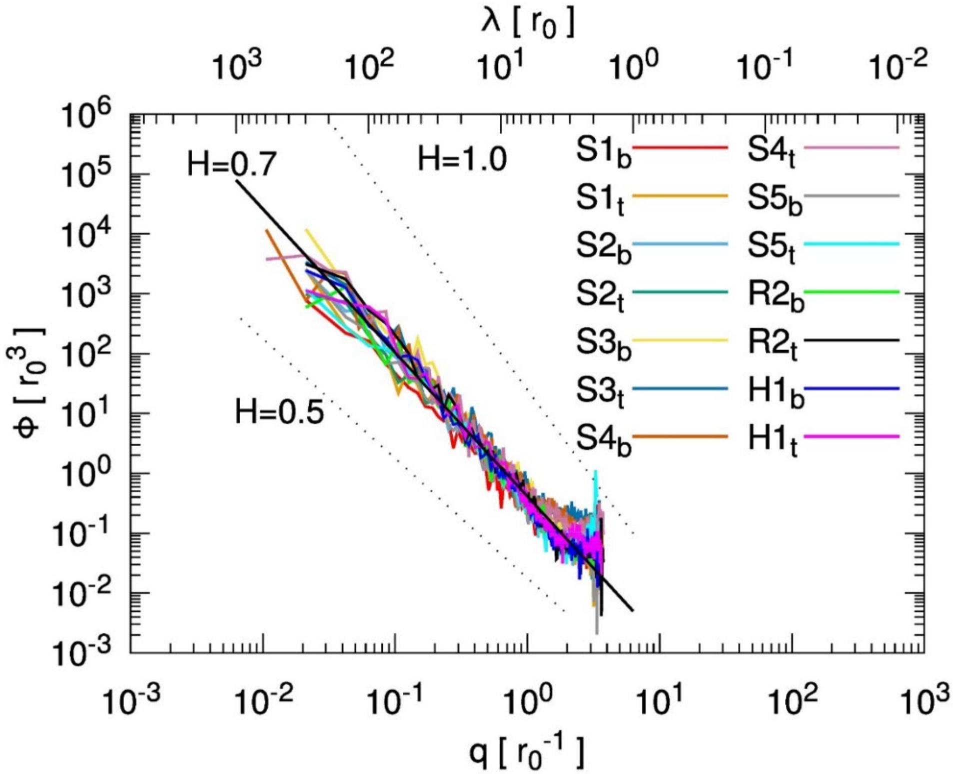
With silding history; correct qualitative trend
Brink, Frérot, Molinari, JMPS, 2021

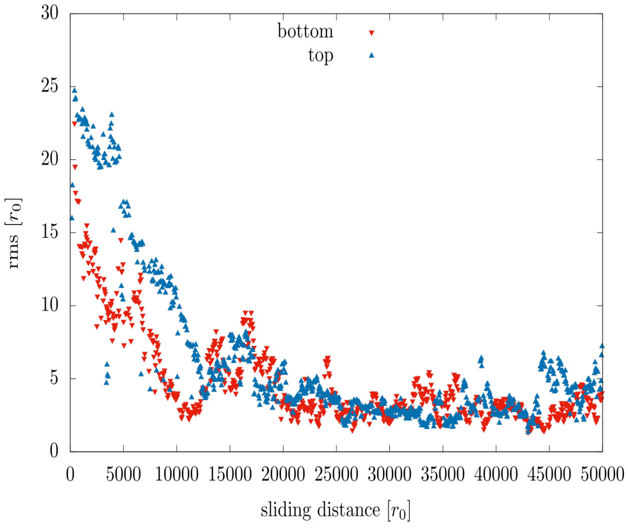
+ Mechanistic model that reproduces qualitative trends
- Quantitatively not predictive (need controlled experiments)
- Missing: roughness evolution, tracking of debris, accumulation of third body

Roughness evolution (2D)

Evolves to a steady state; Enrico Milanese et al., Nat. Comm, 2019







Evolves to Self-affine fractal surface $H \in [0.64, 0.81]$

Requires third bodies (here debris particles)

Two competing mechanisms:

1) Ductile deformation (smoothening, diffusion)

2) Brittle fracture: cracks, roughening

Roughness evolution (3D)

Brink et al., in progress

Piz Daint - Cray XC50, Xeon E5-2690v3 12C 2.6GHz, Aries interconnect , NVIDIA Tesla P100 , Cray Inc., Swiss National Supercomputing Centre (CSCS), Switzerland (Ticino)

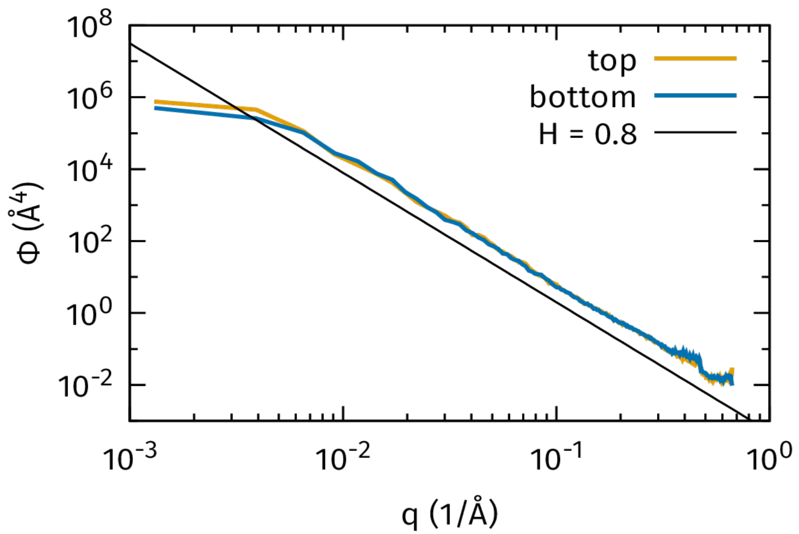
Rmax, 21,230 Tflop/s, 387,872 cores, #6 world, #1 Europe (in 2019, not anymore)

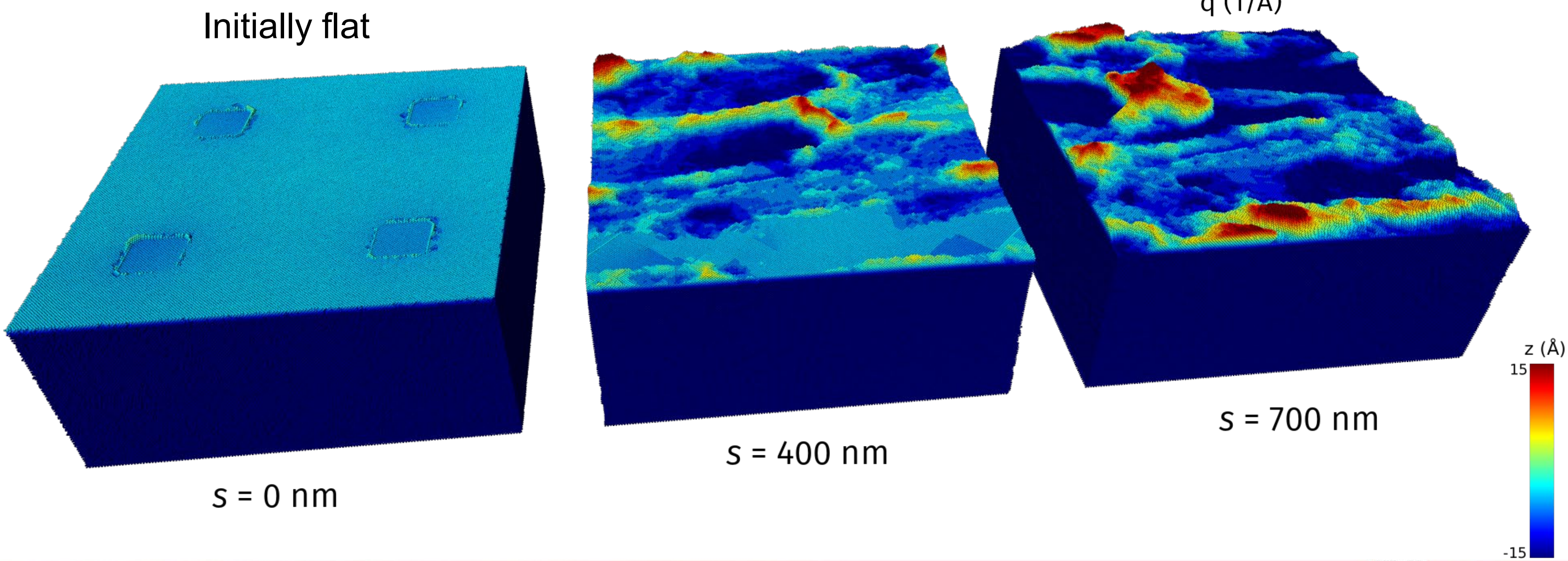
Roughness evolution (3D)

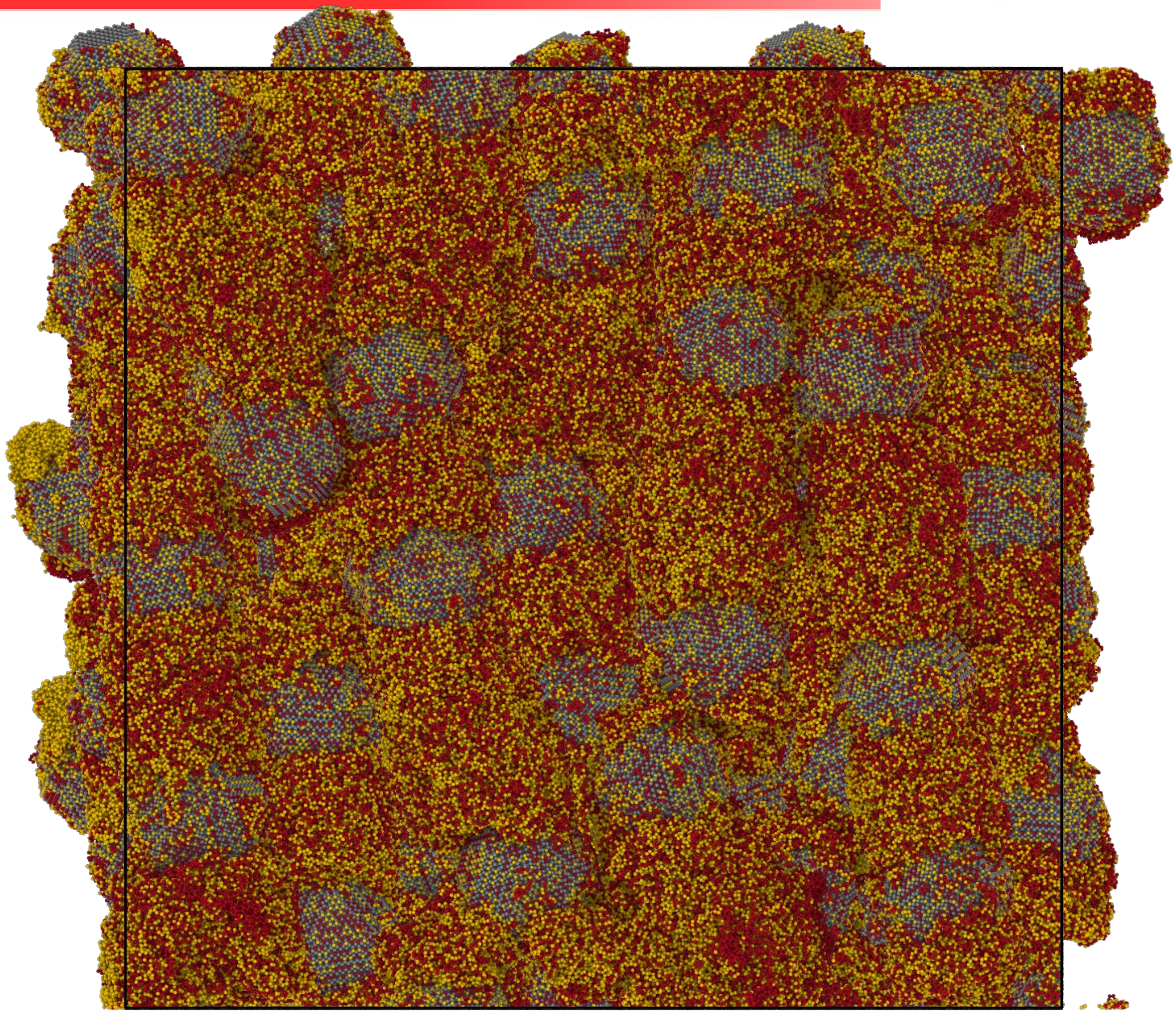
Brink et al., in progress

Abrasive particles on copper

Initially flat surface evolves to around H = 0.7



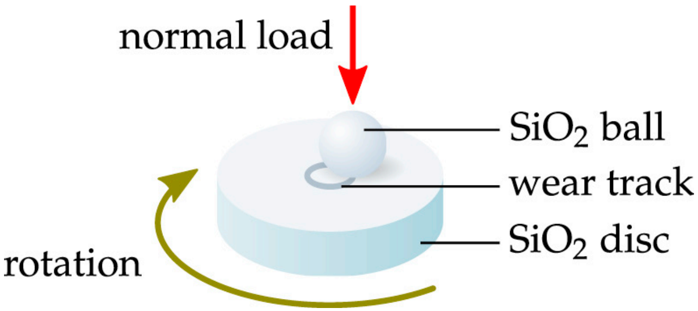


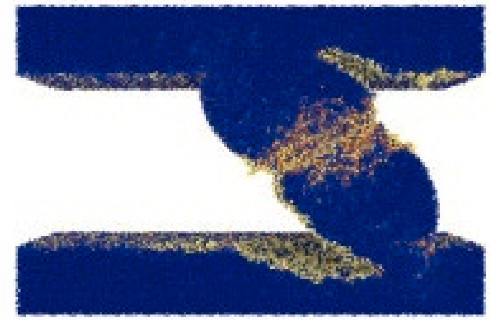


Emergence of wear cylinders in model brittle material, Brink et al., in progress

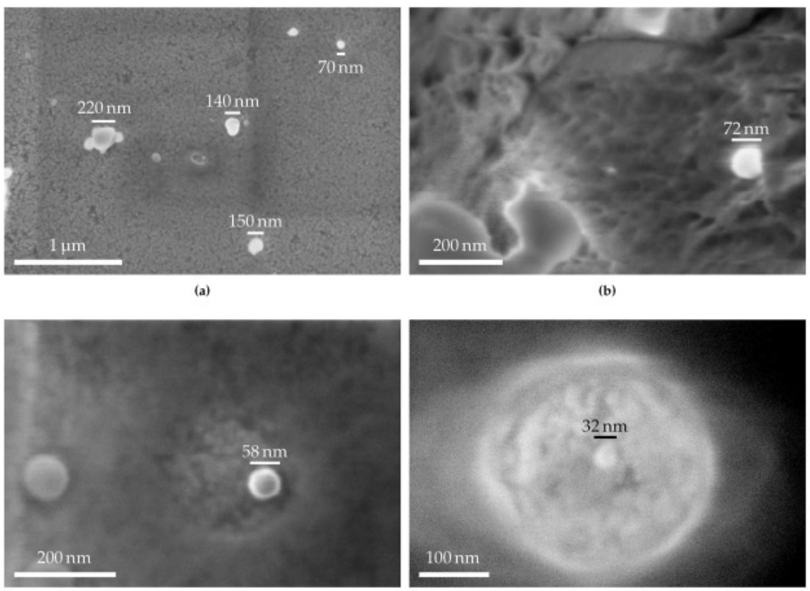
Pin on disc experiments, silica

Pham-Ba Molinari, Wear, 2021; Emergence of cylidindrical rollers

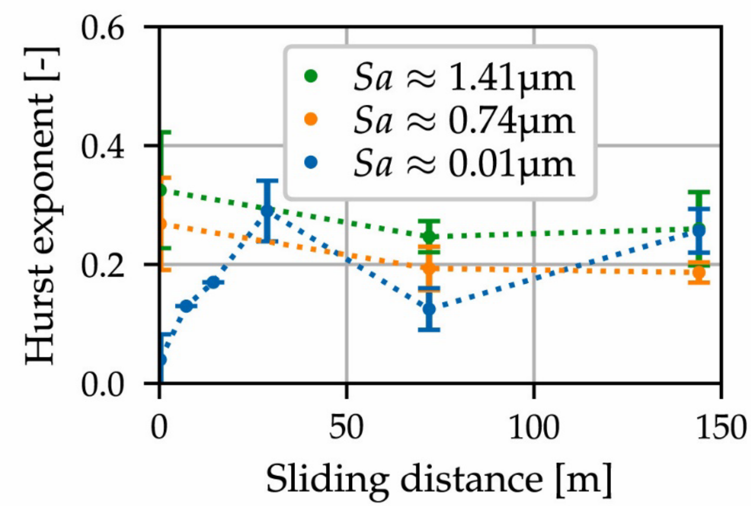




MD simulations with Vashishta potential, d* around 15 nm



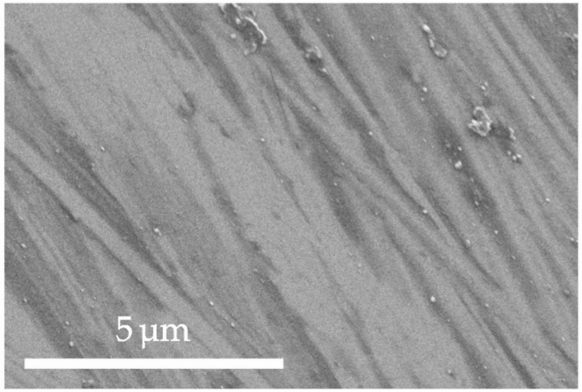
(d) The silica was discriminated from the nickel background using energy-dispersive X-ray (EDX) spectroscopy



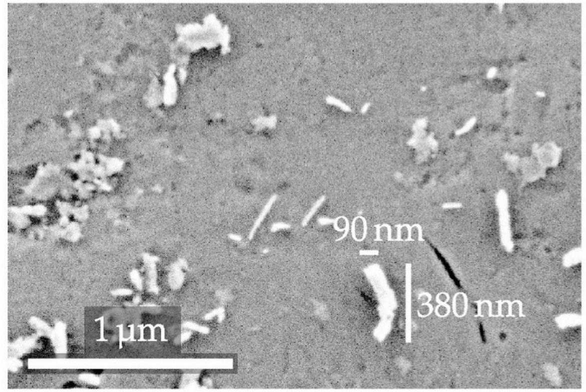
Early stages; few wear particles on track, no sign of particles smaller than d*

Different stages of 3rd body formation

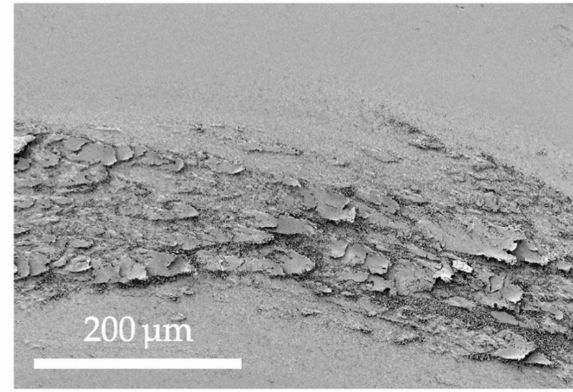
Emergence of cylidindrical rollers, and then assembly in complex structures



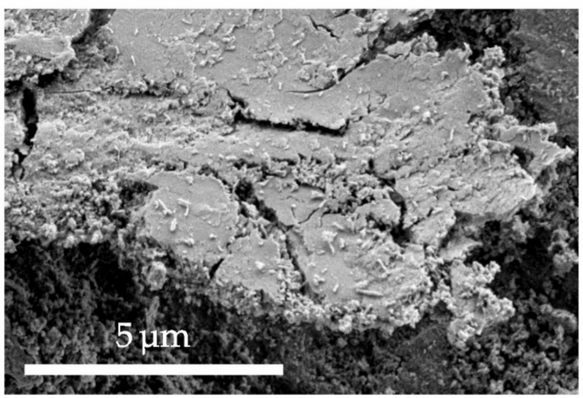
(a) 1 s: formation of first wear particles



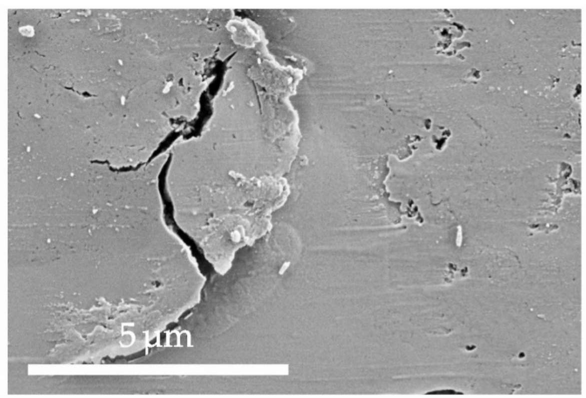
(b) 30 s: cylinders and aggregates



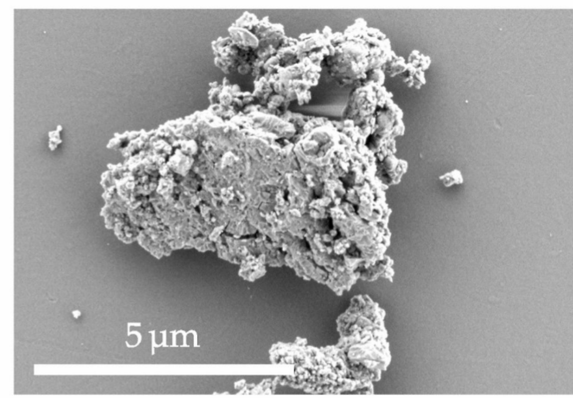
(c) 1 h: large flakes on the disc forming the wear track



(d) 1 h: detail: aggregates forming a large flake



(e) 1 h: detail: cylinders and aggregates on top of a flake



(f) 1 h: detail: aggregated wear particle fallen outside the wear track

Conclusions

1) Critical junction size explains transition in adhesive wear mechanisms (above small load limit):

$$d^* = \lambda \frac{\Delta\omega}{\sigma_j^2/G}$$

2) Tangential (frictional) work predicts initial debris size at the asperity level

3) Opens a path to deterministic wear coefficient K

4) Third bodies and competition between ductile/brittle mechanisms yield self-affine surface roughness

5) Ongoing: experiments on roughness evolution, friction and wear for various materials

6) Interactions between asperities can lead to innovative designs (not discussed today)