2025 Summer School: Tribology and Surfaces Interactions
August 25th-29th, 2025 – Visp, Switzerland

Surfaces & Friction

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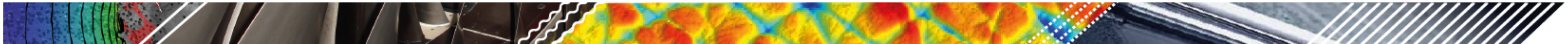


Introduction

- ***Tribology:***

  science of ***contact***, ***friction***, ***wear*** and ***lubrication***

  The key of most ancient techniques of mankind
  (stone tools, fire, wheel…)

  Yet a very recent science: « Tribology » invented in 1966…

- Solids are contacting through their ***surfaces***, forming a ***sliding interface***

- The surfaces' interactions are thus controlling/affecting the ***friction*** (and wear) between solids

Summary

- **Dealing with surfaces…**
  - What is a « surface »? How to describe it?
  - What are the key properties of a surface?
  - How to characterise a surface?

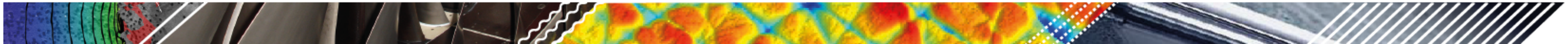
- **Influence of surfaces on friction**
  - What is « Friction »?
  - How can friction be affected by surfaces?
  - How to study surface-related friction phenomena?

- **Case-study**
  - Solid lubrication processes of Diamond-Like Carbon

Surfaces & Friction

Dealing with surfaces…

Part 1



What is a surface?

« God created solids, but the devil made their surfaces »

(Gott schuf das Volumen, der Teufel die Oberfläche)

Wolfgang Pauli

Surface = Interface between two phases
(or between a phase and vacuum)

- Surface = discontinuity of matter!

- We need to describe the solid before considering its surface!
  - How atoms stay together: chemical bonds
  - Strongly dependent on the material considered:
    metal, ceramic, polymer…
  - Key-role of the structure of matter at larger scales (nm → µm)

Cohesion of solids

Cohesion of solid: interactions between atoms or molecules

“Strong” interactions inside molecules or solids,
“Weak” interactions between molecules or solids

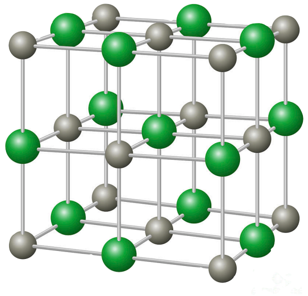
- **Chemical bonds:** electron charge distributions of the atoms (atomic orbitals) is completely changed
- **Physical “bonds”:** atoms/molecules remain distinct entities
- Yet physical binding may be quite strong as well…

Cohesion of solids: chemical bonds

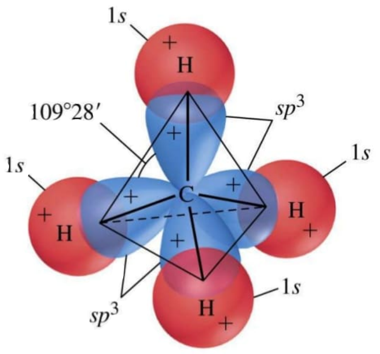
- **Strong chemical bonds:** atomic interactions through electrons (change in shape and occupation of atomic orbitals)

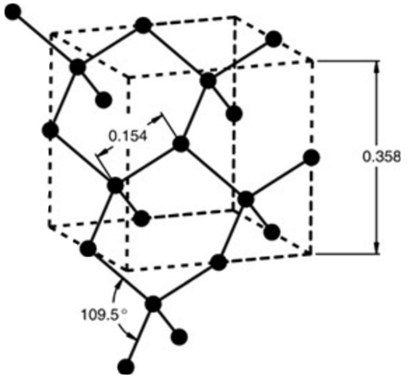
  - **Ionic bond:** exchange of electrons between two atoms
    Example: Sodium Chloride (salt!)

$$Na + Cl \rightarrow Na^{+} + Cl^{-} \rightarrow NaCl$$



  - **Covalent bond:** sharing of electrons between two atoms
    Example: Methane CH_4 *or Diamond*





  - **Metallic bonding:** bonding electrons are delocalised over a lattice of atoms, creating a « gas of electrons »
    The behaviour of this gas and its interactions with the lattice controls the metal properties

Cohesion of solids: intermolecular forces

- **Intermolecular bonding:** involves electrostatic interactions between atoms and/or molecules

  - **Involving charged atoms/molecules:** Charge-charge interactions (*Coulomb forces*) or charge-dipole interactions

  - **Involving polar molecules:** Dipole-dipole, dipole-charge or dipole-induced dipole interactions (*Van der Waals forces*)
    - Polar molecules: distribution of charges within the molecule
    - Dipoles may be inherent to the structure of a molecule, or may be induced by the surrounding environment

- Depending on the type of interactions involved, **different strengths and ranges** will be observed…

The key-role of defects

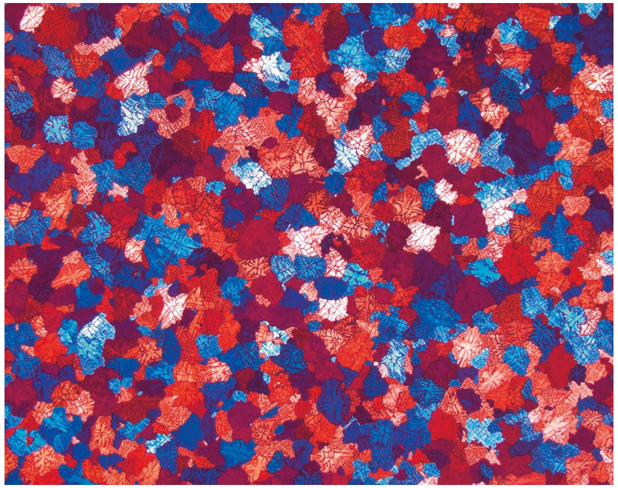
- Solids are the result of a fabrication process - **they can’t be perfect!**

- Several types of defects can be found in crystalline materials:
  - *Point defects (0D):* vacancies or impurities (solid solutions)
  - *Line defects (1D):* dislocations
  - *Planar defects (2D):* grain boundaries
  - *Bulk defects (3D):* voids or precipitates

- All these defects may affect the properties of the solid, especially hardness (while elastic modulus is controlled by interatomic or intermolecular forces)

The key-role of microstructure

- Many engineering materials are alloys
- They consist in an assembly of grains, with different orientations, that might be of different phases
- The nature, size and distribution of these phases control the mechanical behaviour of the material: hardness, toughness…

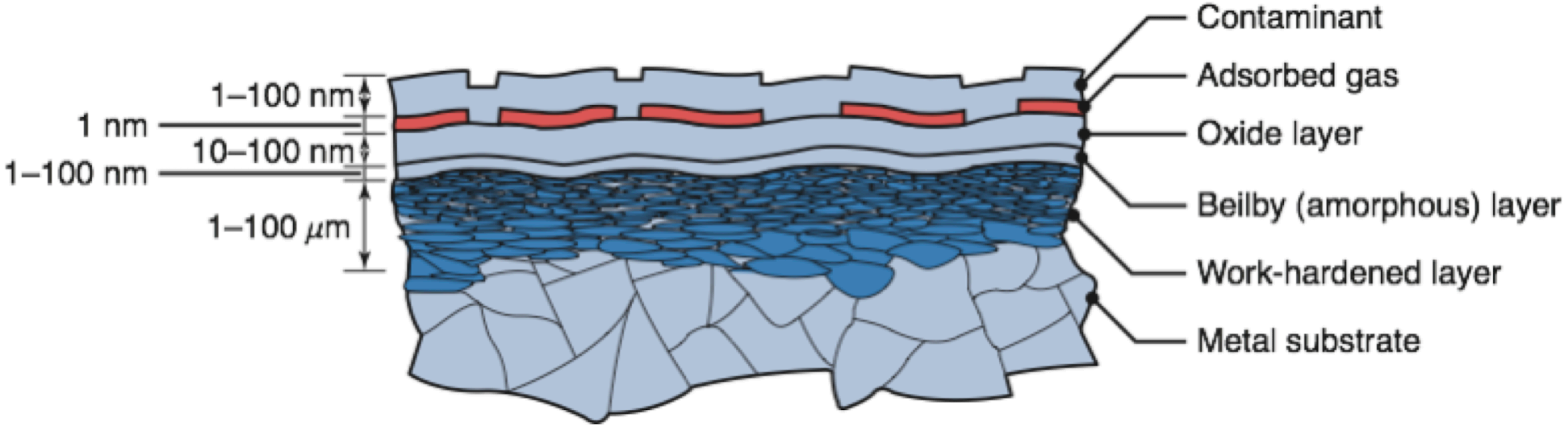


- Study of microstructure:
  - Diffraction (XRD) for cristallography
  - Microscopy on cross-section (optical or electron: SEM), EBSD
  - X-Ray or TEM tomography

Describing a solid surface

- Machining process or fabrication process lead to gradients in the microstructure: *e.g.* change in grain size close to the surface…

- Since the surface is an interface with the environment, chemical reactions may occur at the surface: oxide layers, adventitious carbon…

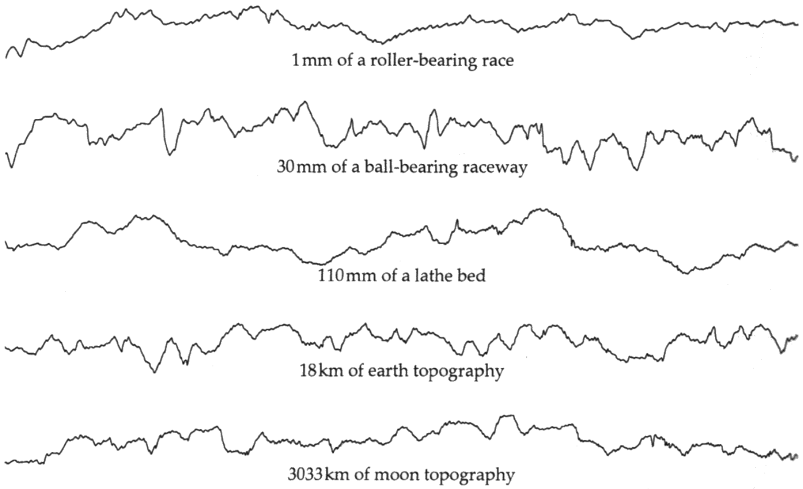


- Even for monocrystalline solids, the edges of a periodic lattice are not favorable: promote “surface reconstruction”

→ there is always some roughness!

Investigating surface topography

- Surfaces always exhibit some roughness…
- Critical role of the considered scale:



- The probe size is thus critical – Many techniques available!
  - Tactile profilometry: from simple stylus to Atomic Force Microscopy (AFM)
  - Laser beam profilometry
  - Optical methods: interferometric microscopy, confocal microscopy…

- Don’t forget to look at surface morphology!
  (e.g. optical or electron microscopy)

Investigating surface topography

- Parameters describing the surface:
  - Height characteristics
    - Arithmetical mean height

$$R_a = \frac{1}{L}\int_0^L |z| \,\mathrm{d}x$$

    - Root mean square roughness

$$R_q = \sqrt{\frac{1}{L}\int_0^L z^2 \,\mathrm{d}x}$$

    - Maximum peak to valley, skewness (asymmetry), kurtosis…
  - Spatial characteristics (lateral)
    - Autocorrelation function, Power spectral density function…
  - Multiscale characterisation
    - Fourier transformation, wavelet transformation…

Investigating surface chemistry

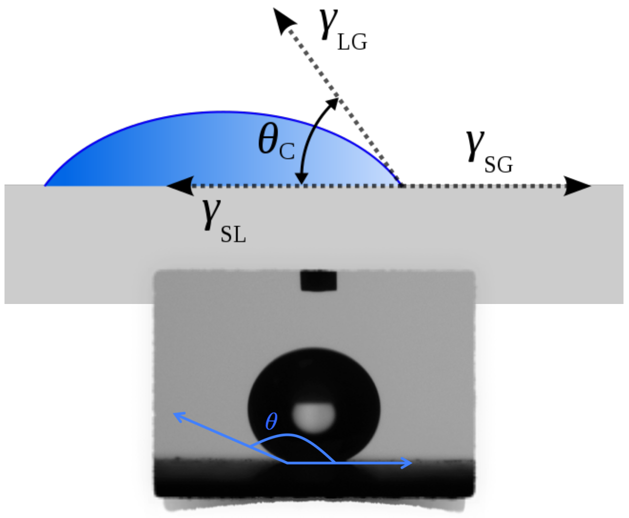
- Knowing the composition and/or chemistry of a surface is critical for understanding its properties

- Many surface characterisation techniques are available:
  - SEM coupled with EDX (Energy Dispersive X-ray spectroscopy)
  - Vibrational spectroscopies: Raman, FTIR…
  - Glow Discharge Optical Emission Spectroscopy (GDOES)
  - Secondary Ion Mass Spectrocopy (SIMS), static (ToF-SIMS) or dynamic
  - X-Ray Photoelectron Spectroscopy (XPS), Auger Electron Spectrocopy (AES)
  - Electron Energy Loss Spectroscopy (EELS) in transmission or reflection
  - …

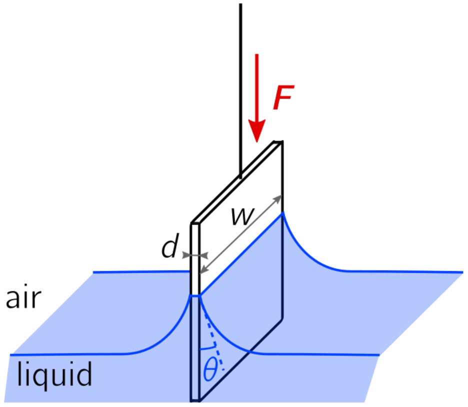
Surface energy

- Surface energy corresponds to the **disruption of interatomic or intermolecular bonds** due to the surface creation
- Equivalence between **surface energy** (J/m²) and **surface tension** (N/m): *Increasing the size of a surface corresponds to the work of a force*

- ***Measuring surface energy:***
  - **Contact angle measurements**
    - Liquid droplet on a surface
    - Young's equation: $\cos\theta_c = \dfrac{\gamma_{SG} - \gamma_{SL}}{\gamma_{LG}}$
    - Work of adhesion: $W_{adh} = \gamma_{LG}\left(1 + \cos\theta_c\right)$



  - **Surface tension measurements** (Wilhelmy plate tensiometer)
    - Immersion of a plate with measurement of undergone force
    - $\gamma = \dfrac{F}{l\cos\theta}$, where l is the perimeter



LTDS
Tribologie et Dynamique des Systèmes

Surfaces & Friction

Influence of surfaces on friction

Part 2

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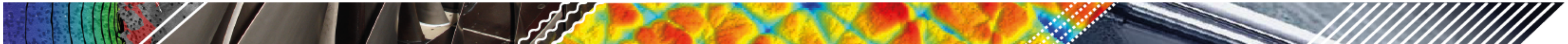
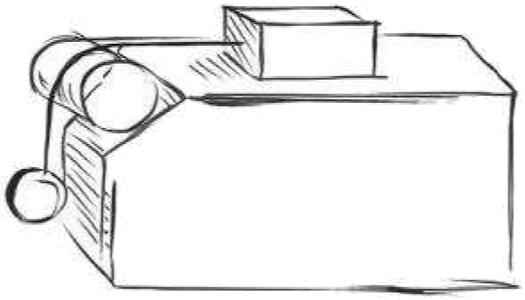
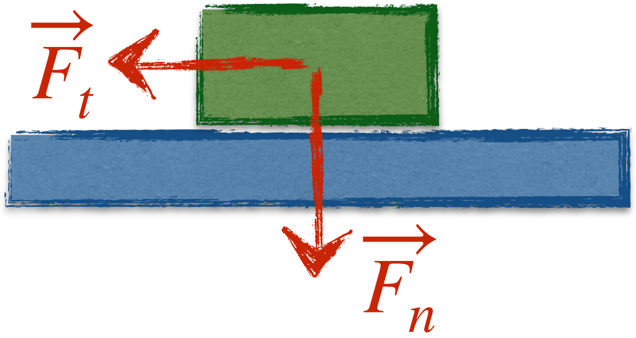


Defining friction…

Friction: the force resisting to relative motion between solids





- **Early laws of dry friction** - Da Vinci, Amonton, Coulomb
  - *Friction force is proportional to load*
  - *Friction force is independent of contact area*
  - *Friction force is independent of sliding velocity*

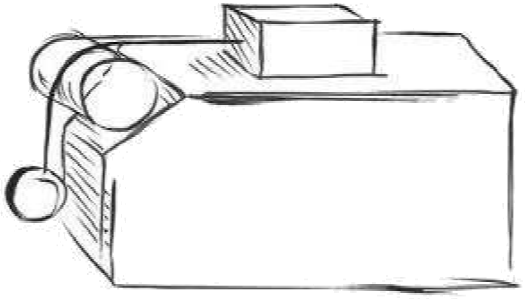
- Definition of the **coefficient of friction** μ

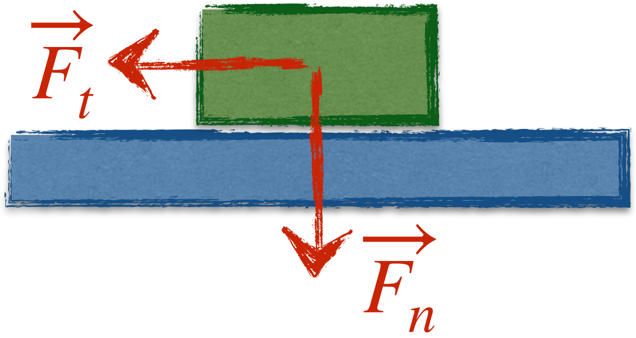
Ratio of the tangential force to the normal force:

$$\mu = \frac{F_t}{F_n}$$

Defining friction…

Friction: the force resisting to relative motion between solids



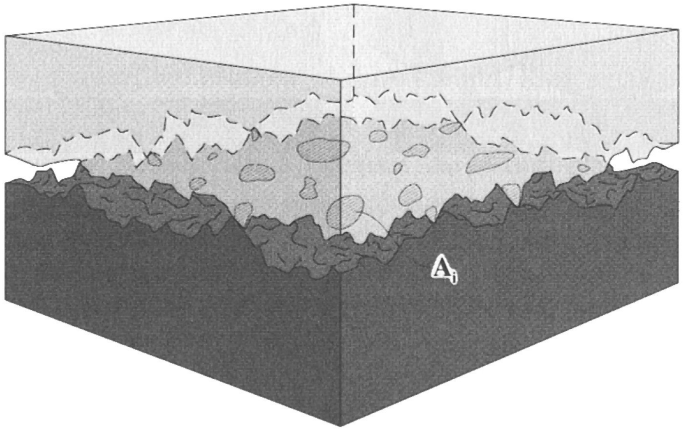


- **Early laws of dry friction** - Da Vinci, Amonton, Coulomb
  - *Friction force is proportional to load*
  - *Friction force is independent of contact area*
  - *Friction force is independent of sliding velocity*

- No effect of **apparent contact area**!

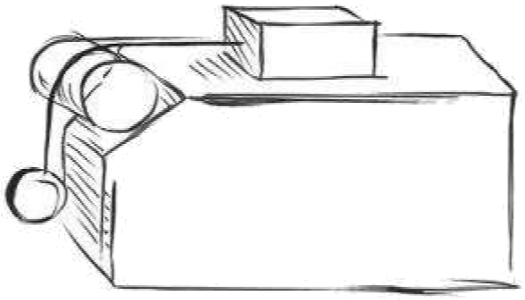
  Due to roughness, only asperities are touching…
  Real vs. apparent contact area

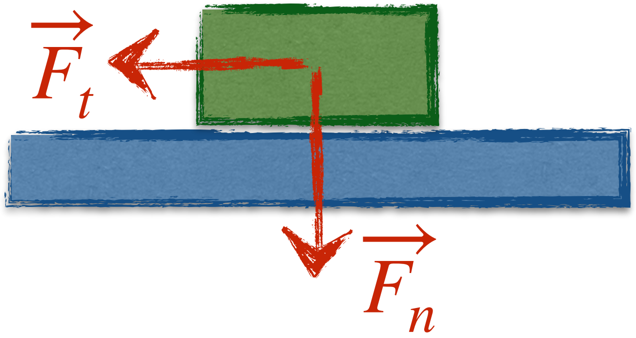
$$A_r \neq A_{app}$$



Defining friction…

Friction: the force resisting to relative motion between solids





- **Early laws of dry friction** - Da Vinci, Amonton, Coulomb
  - *Friction force is proportional to load*
  - *Friction force is independent of contact area*
  - *Friction force is independent of sliding velocity*

- No velocity effect proposed, but:

  Static friction ⩾ Sliding friction (or "kinetic" or "dynamic")
  Static friction: maximum friction force before sliding occurs

The challenge of lubrication: Velocity accommodation

How to accommodate the difference in velocities of the contacting surfaces?

Where is shear occurring?

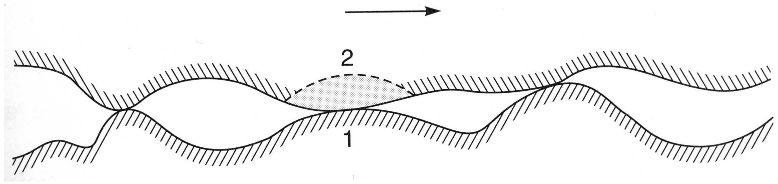
- **Lubrication with oils or liquids:** a fluid film separates the solids, allowing an easy shear of the sliding interface
    - **Hydrodynamic lubrication:** thickness of the fluid film is large compared to the surface roughness
    - **Elasto-hydrodynamic lubrication (EHD or EHL):** elastic deformation of solid surfaces due to high pressure, creating a load-bearing quasi-solid film
    - **Mixed Lubrication:** some asperity contact, but part of the load is carried by the fluid
    - **Boundary lubrication:** most of the load is carried by contacting asperities, which are surrounded by the fluid

- **Solid lubrication:** a material (often a coating) provides an easy shear of the sliding interface

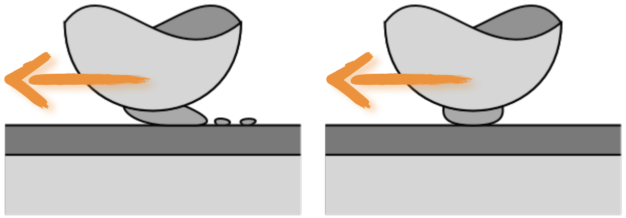
Velocity accommodation in "dry" contacts

- In "dry" or "solid" contacts, when solid asperities interacts, **shear occurs where it's easier**!

- In case of seizure, breaking of **adhesive junctions**
  - at initial interface (1)
  - inside the weakest material (2) (depending on hardness and brittleness)



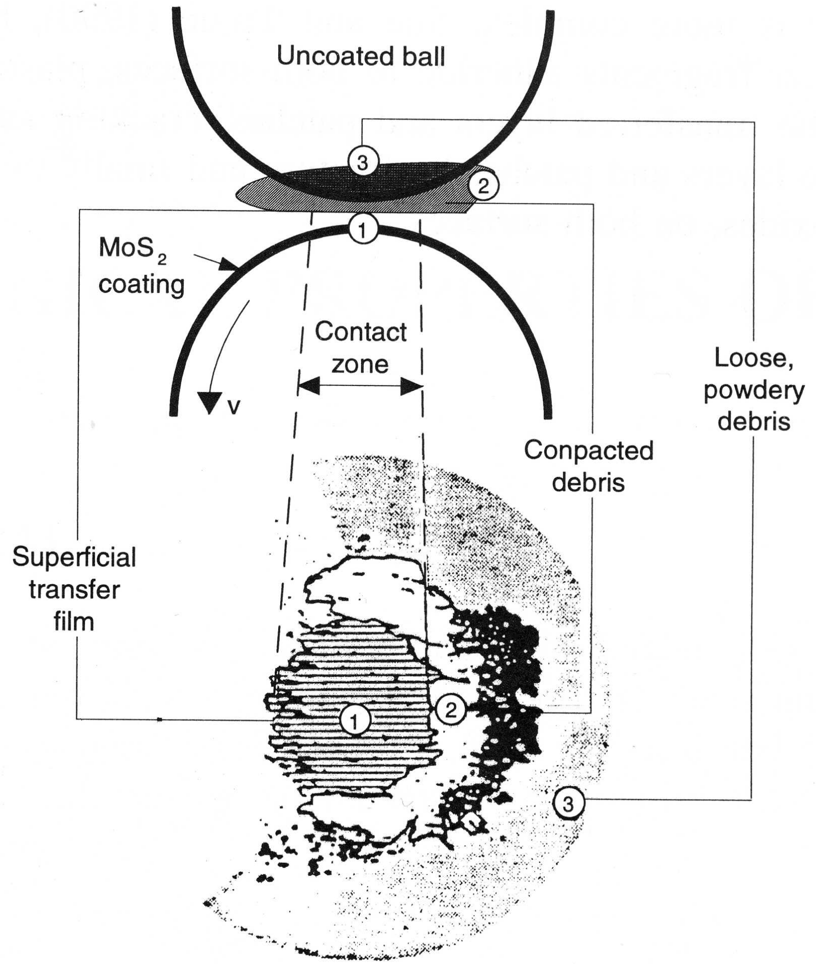
- With solid lubricants, shearing of **interfacial films**:
  - "Intrafilm flow" or "interfilm sliding"



- General case: shearing of debris or trapped particles
  → **Third body concept**

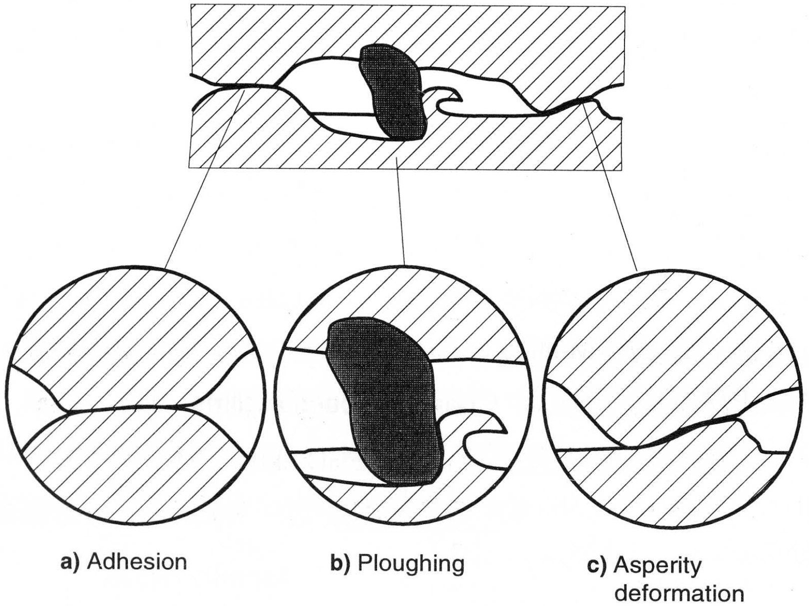
What may be found in a "dry" contact?

- Flow from one solid to the other
- Compaction of wear debris: "third body"
- Build-up of "tribofilms" or "transfer layer"
- Chemical reactions between contacting bodies or with the environment



Origins of friction force

Contributions to the friction force *(Bowden & Tabor)*



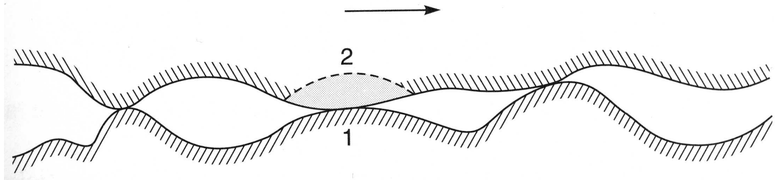
- **Adhesion:** shearing of adhesive junctions (where they were formed)

  $F_{adh} = A_r \cdot \tau$, with A_r: real contact area, τ: interfacial shear strength

- **Plastic deformations:**
  - Macroscopic: ploughing - abrasion of the softer body
  - Microscopic: plastic deformation of contacting asperities

Dry friction of metals: adhesion

Adhesive phenomena between asperities *(Rabinowicz)*



- **Release of adhesive junctions:**
  - Controlled by surface energy → **strength of interface**
  - Controlled by hardness → **strength of asperities**

- Empirical formula based on experimental results:

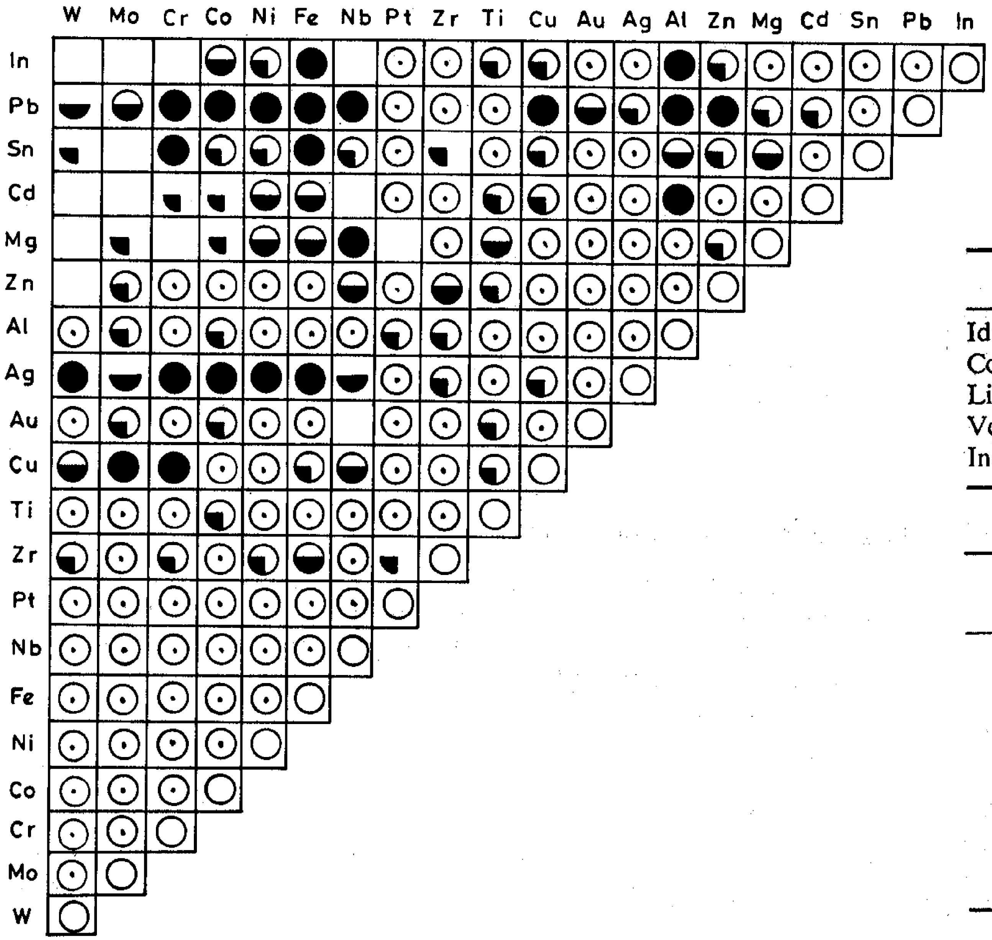
$$\mu \simeq 0.3 + C_1 \frac{W_{12}}{H}, \text{ with } W_{12} = C_2\left(\gamma_1 + \gamma_2\right)$$

$$\mu \simeq 0.3 + C_1 C_2 \frac{\gamma_1 + \gamma_2}{H}$$

W_{12}: work of adhesion – γ_1, γ_2: surface energies
C_1: geometrical constant – C_2: miscibility constant
H: hardness of softer body

Dry friction of metals: adhesion

Adhesive phenomena between asperities *(Rabinowicz)*



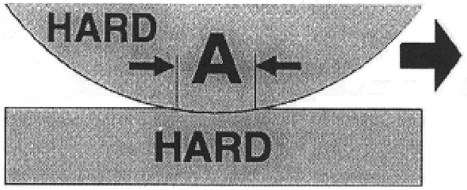
$$\mu \simeq 0.3 + C_1 C_2 \frac{\gamma_1 + \gamma_2}{H}$$

Condition	Symbol	Measured value of C_2
Identical	○	1.00
Compatible	⦿	0.50
Limited compatibility	◔	0.32
Very limited compatibility	◒	0.20
Incompatible	●	0.125

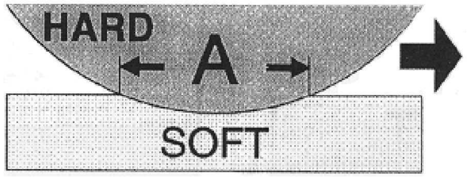
Symbol	Metallurgical solubility	Metallurgical compatibility	Sliding compatibility	Anticipated wear
○	100%	Identical	Very poor	Very high
⦿	Above 1%	Soluble	Poor	High
◔	0.1–1%	Intermediate soluble	Intermediate	Intermediate
◒	Below 0.1%	Intermediate insoluble	Intermediate or good	Intermediate or low
●	Two liquid phases	Insoluble	Very good	Very low

Controlling dry friction: solid lubrication

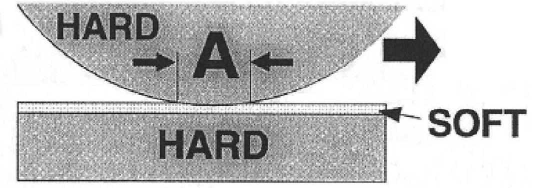
- How to reduce dry friction of metals? *(Bowden & Tabor)*
  - Soft metal film – Playing with A_r & τ in $F_t = A_r \cdot \tau$



τ high
A_r small

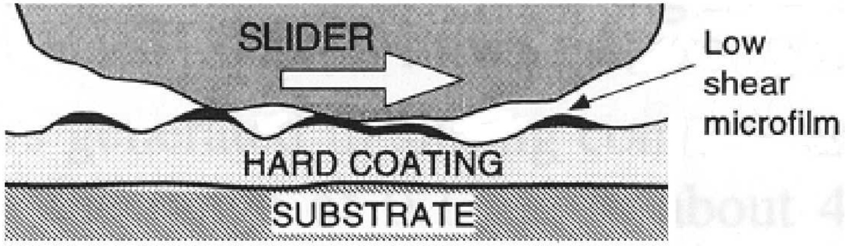


τ small
A_r high



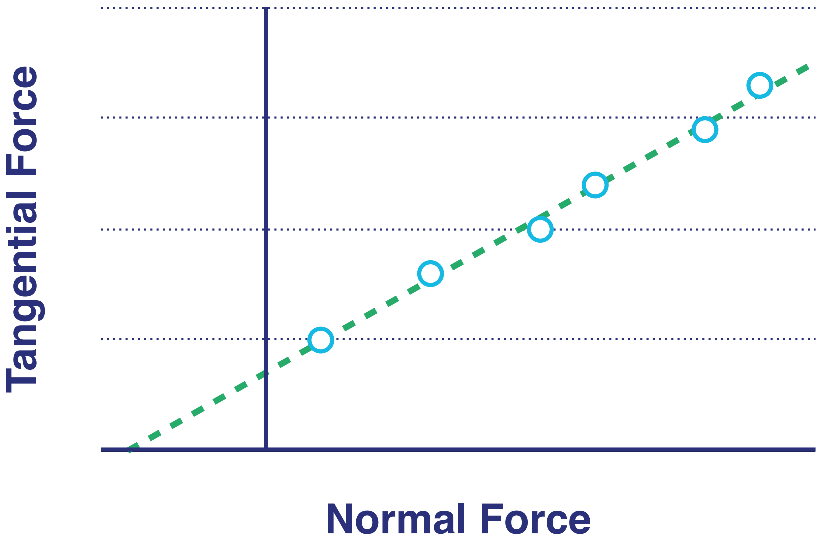
τ small
A_r small

- General case with solid lubricants *(Holmberg & Matthews)*
  - Soft thin coating providing easy shear
  - Hard and stiff substrates (or underlayers)



The limits of Coulomb's law

- Friction force is not always proportional to load: $\mu \neq \frac{F_t}{F_n}$



- Example: affine behaviour
  - $F_t = \mu \cdot F_n + F_{t_0}$: Threshold in interfacial shear strength?
  - $F_t = \mu \left(F_n + F_{n_0} \right)$: Adhesive forces added to normal force?

The limits of Coulomb's law

- Both tangential & normal force are proportional to contact area

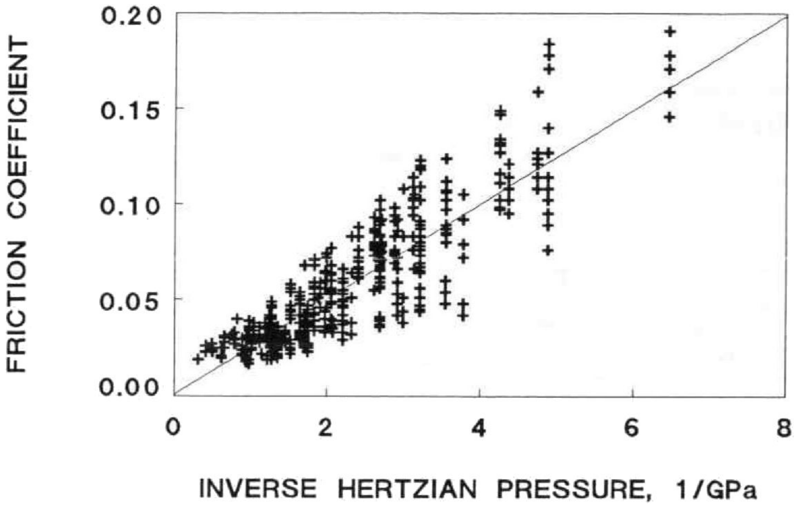
$$F_t = A_r \cdot \tau \text{ and } F_n = A_r \cdot P$$

$$\mu = \frac{F_t}{F_n} = \frac{\tau}{P}$$

- If μ is changing with normal load, or contact pressure P, then it means that τ depends on contact pressure P

Example with MoS2

solid lubricant coatings



e.g. $\tau = \tau_0 + \alpha P$ implies that $\mu = \frac{\tau_0}{P} + \alpha$ *(Singer)*

Key role of interfacial material

- Critical parameters controlling dry friction:
  - ***Shear strength of interface:*** τ

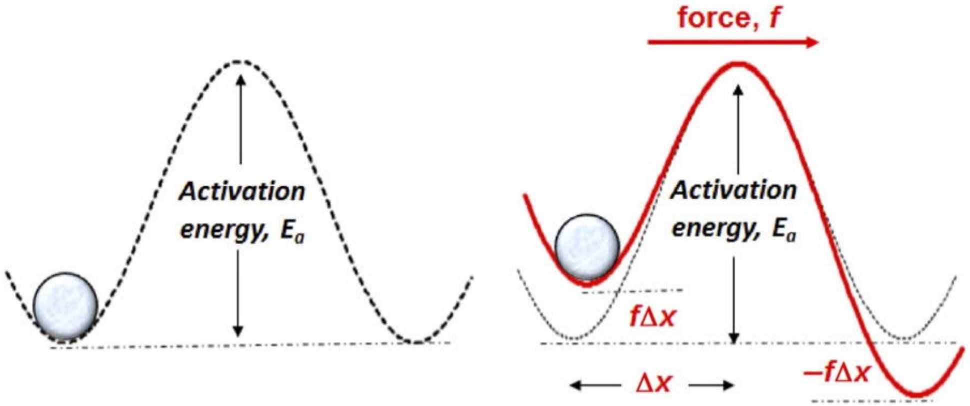
    Depends on the nature of interfacial material
  - ***Load carrying capacity of the substrates:*** P

    Elastic deformation as well as roughness affect the contact pressure

- The nature, composition and properties of the interfacial material are thus critical for understanding friction and its evolution!

Friction-induced chemical changes: Tribochemistry

- Producing new compounds through chemical reactions require energy. Several ways to provide the energy:
  - Photon activation: photochemistry
  - Electrical activation: electrochemistry
  - **Thermal activation: thermochemistry**
  - **Stress-induced activation: mechano-chemistry**

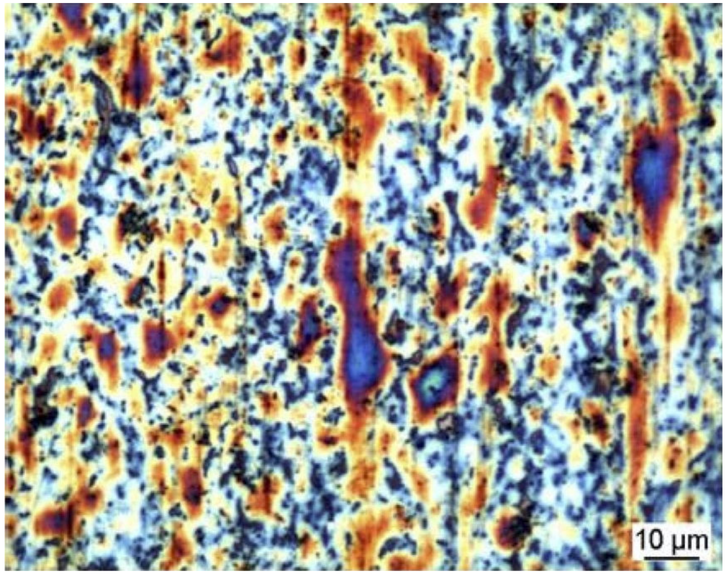


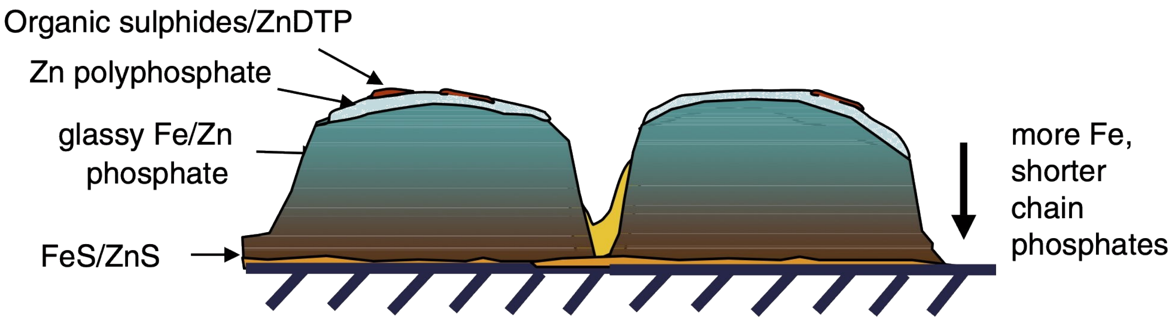
- *Contacts are « chemical reactors » where reactions may take place between the counterfaces and/or with the environment*

Friction-induced chemical changes: Tribochemistry

- Tribochemistry: some specificities though!
  - Reacting species must be “close enough”
  - Stress distribution in a real contact is highly heterogeneous
  - Nature of reaction products will affect tribological response

  ⇒ **Complex structure of “tribofilms” with lateral & vertical gradients**

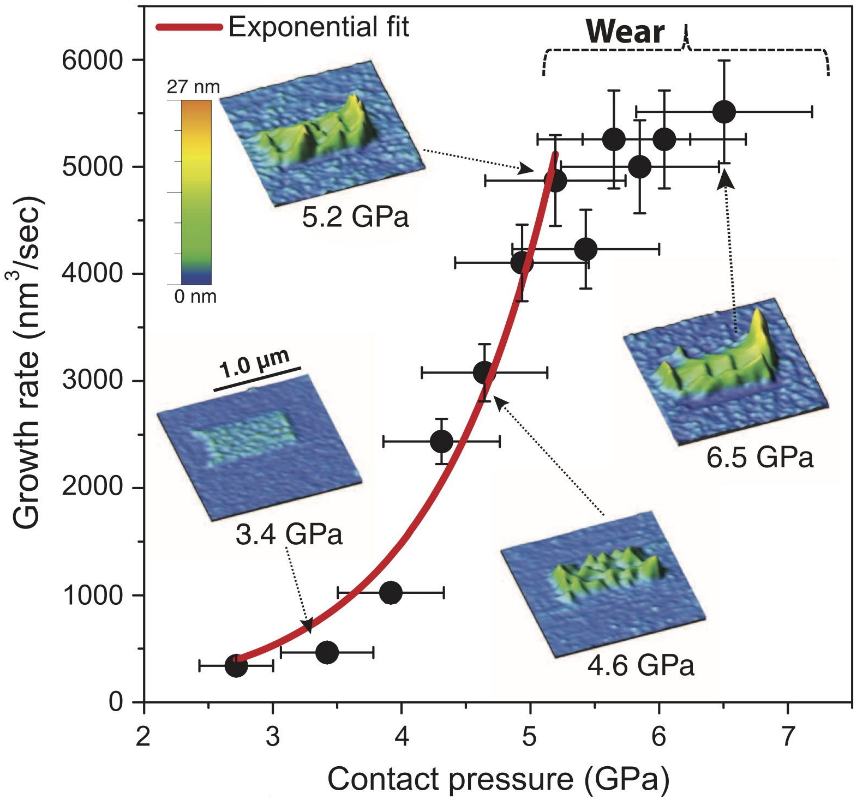


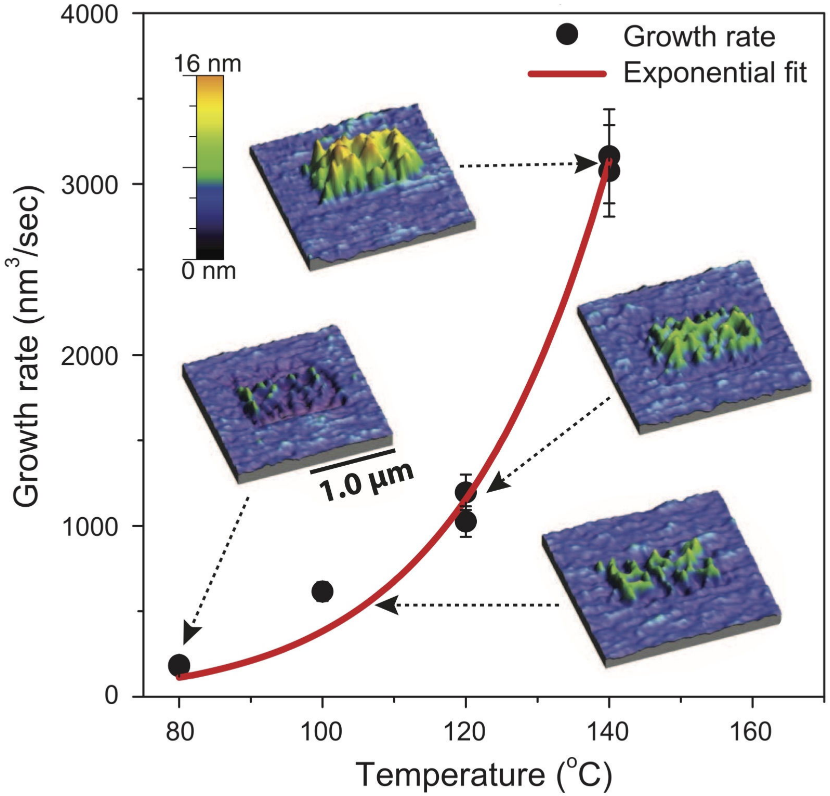


Example of tribofilm growth on steel from an anti-wear lubricant additive, Zinc dialkyl-dithiophosphate (ZDDP or ZnDTP)

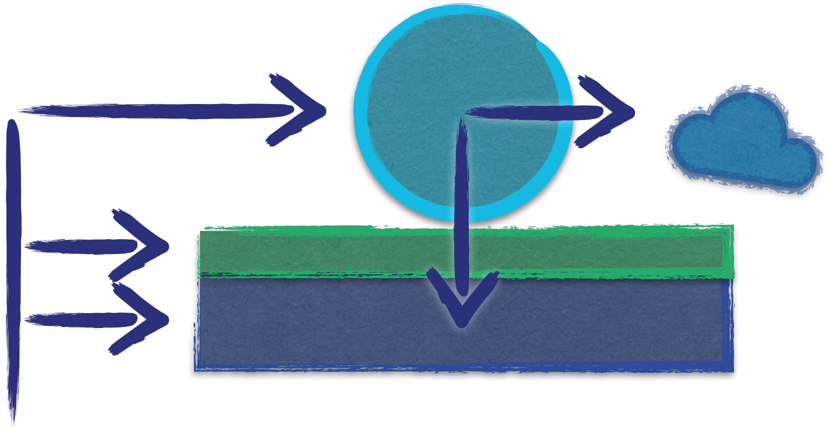
Friction-induced chemical changes: Tribochemistry

- Competition between stress activation and catalysis
  - Due to wear, new surfaces are exposed: “nascent surfaces”
  - Presence of metal or oxides may affect chemical processes
  - Yet experiments with Atomic Force Microscopy (AFM) clearly evidence a stress and temperature activation





Key tribological parameters



Intrinsic parameters: Materials

- **Surfaces & interfaces**
  - Composition & chemistry
  - Roughness
- **Coatings**
  - Composition & chemistry
  - Structure & thickness
  - Adhesion to substrate
  - Mechanical properties
- **Substrates**
  - Composition & chemistry
  - Structure
  - Mechanical properties

Extrinsic parameters: System

- **Contact parameters**
  - Geometry & applied forces
  - Contact pressure
- **Kinematic parameters**
  - Nature of relative motion
  - Speed, length
  - Frequency of exposure
- **Environmental parameters**
  - Nature & pressure of gases or presence of liquid
  - Temperature
  - External solid particles

Adjusting contact severity…

Geometry

- Point contact / Line contact / Surface contact
- Increasing apparent contact area
- Decreasing contact pressure

Applied force

- Affects contact area and pressure
- Contact computations: Hertz, K.L. Johnson…
- Maximum stress beneath the surface

Sliding velocity / contact frequency

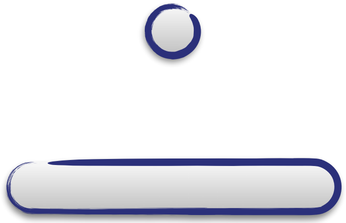
- Contact temperature
- Kinetics of tribochemical reactions

Environment

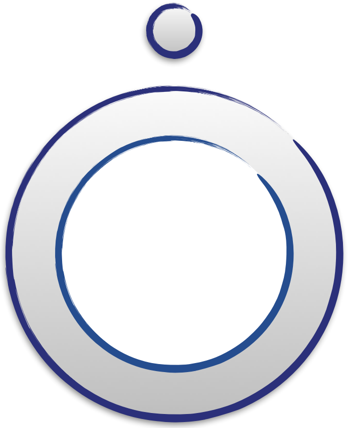
- Nature & reactivity of the environment
- Imposed temperature

Playing with kinematics…

- Different **type of motion**: linear, rotating / continuous or reciprocating
- **Dwell time**: time between passes – may affect chemical reactions with environment
- **Kinematic lengths** of both counterparts: asymmetric nature of most tests!
  - ***Linear ball-on-flat case***



    - Distance traveled by a point on the ball: $L_{ball} = l \cdot N$
    - Distance traveled by a point on the flat: $L_{flat} = 2a \cdot N$
    - With $2a = 100\ \mu m$ & $l = 5\ mm$, ratio: $\dfrac{L_{ball}}{L_{flat}} = \dfrac{l}{2a} \simeq 50$
  - ***Rotating ball-on-disk case***



    - Distance traveled by a point on the ball: $L_{ball} = 2\pi R \cdot N$
    - Distance traveled by a point on the flat: $L_{flat} = 2a \cdot N$
    - With $2a = 100\ \mu m$ & $R = 15\ mm$, ratio: $\dfrac{L_{ball}}{L_{flat}} = \dfrac{2\pi R}{2a} \simeq 1000$

LTDS
Tribologie et Dynamique des Systèmes

Surfaces & Friction

Solid lubrication processes of Diamond-Like Carbon

Part 3

INSTITUT CARNOT
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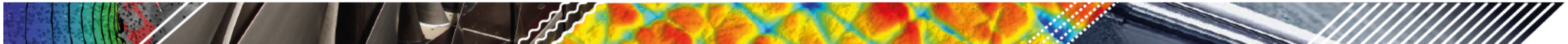
cnrs ÉCOLE CENTRALE LYON CENTRALE LYON ENISE ENTPE membres de UNIVERSITÉ DE LYON



- **Introduction to DLC coatings**
- Role of surface chemistry
- Role of surface topography
- Discussion & summary

Diamond-Like Carbon: Popular tribological coatings…


montre24.com


hefusa.net

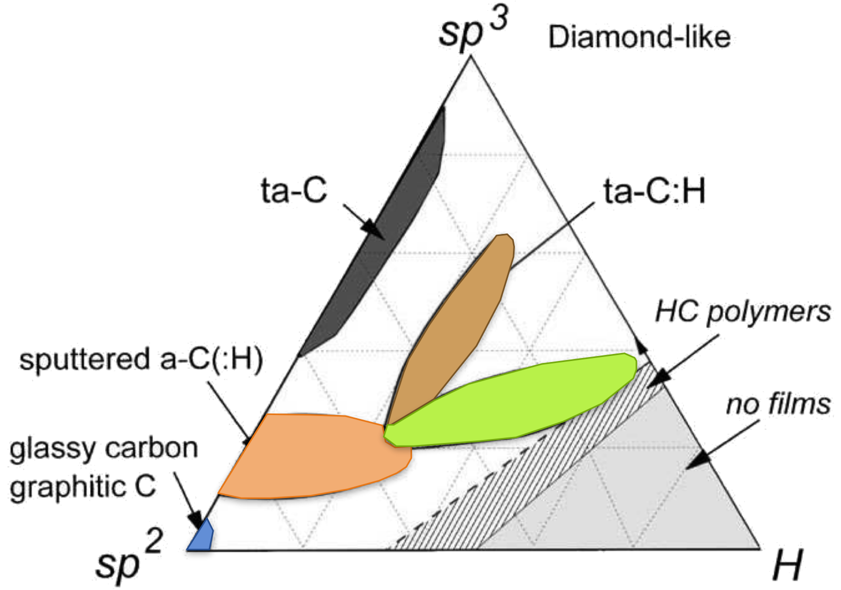

cutcaster.com


Sulzer.com

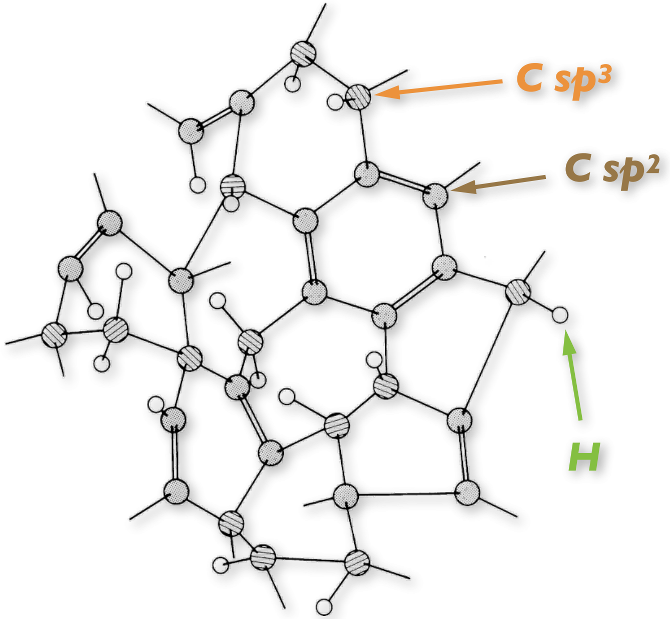

directindustry.com

- DLC: a family of hard amorphous carbon films
- Provide low friction and wear:
  good performances as solid lubricants
- Many industrial applications…

Diamond-Like Carbon:
… An amorphous carbon structure…



Pseudo-ternary phase diagram of bonding in amorphous carbon-hydrogen alloys
Robertson et al. (1997)

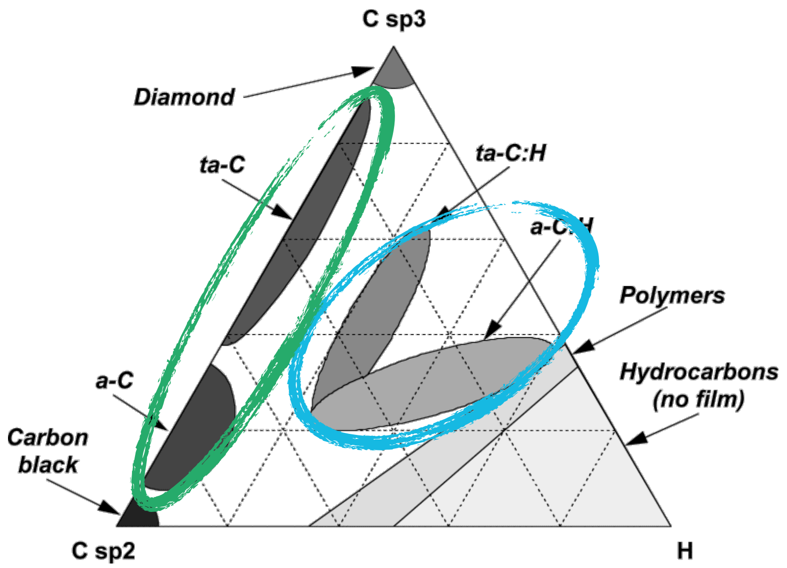


Random covalent network model of hydrogenated amorphous carbon films
Angus et al. (1992)

- Metastable amorphous DLC structure:
  - "Random Covalent Network" of sp^2 C, sp^3 C, H
    … with defects: dangling bonds, entrapped H_2 or CH_4…
  - Clustering of sp^2 C: aromatic rings (6-fold C rings)
    … with defects: 5- or 7- fold rings (non planar clusters…)
  - Graphite is the stable form of carbon,
    but high disorder may hinder long-range ordering

Diamond-Like Carbon:
… With versatile properties…

- **Large variety of DLC coatings:**
  many different structures & compositions depending on deposition process …
  ⇒ wide range of properties
  - ***Physical Vapor Deposition*** (PVD) for hydrogen-free a-C and ta-C
  - ***Chemical Vapor Deposition*** (CVD) for hydrogenated a-C:H and ta-C:H

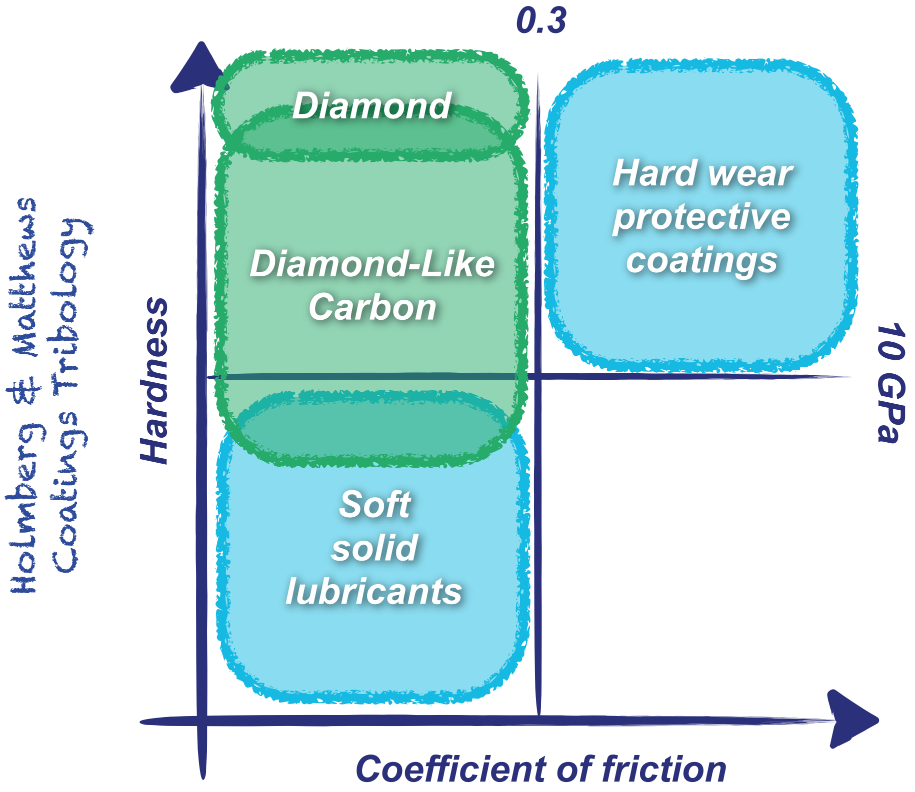


Hydrogen content	< 1 to > 50 at.%
Percentage of sp^3	20 to 90%
Optical gap	0.4 to 4 eV
Compressive stress	up to few GPa
Surface energy	< 20 to > 60 mN.m^{-1}
Thermal stability	up to ~300°C

	a-C	**a-C:H**	**ta-C**	**ta-C:H**
Hardness (GPa)	10 - 20	2 - 30	25 - 70	25 - 60
Elastic modulus (GPa)	150 - 200	50 - 250	200 - 650	150 - 300
H/E ratio	0.08 - 0.1	0.1 - 0.16	0.1 - 0.2	0.16 - 0.2

- As hard or harder than steel or most metallic substrates
- Comparable or lower elastic modulus (except high sp^3 content ta-C)
- Higher H/E ratio (~ strain to failure)

Diamond-Like Carbon:
… But a tribological paradox!



- ***Archard's law***
  The harder the more wear-resistant
  Nitrides, carbides, ceramic coatings

$$V_{worn} = \frac{k}{H} \cdot F_n \cdot L$$

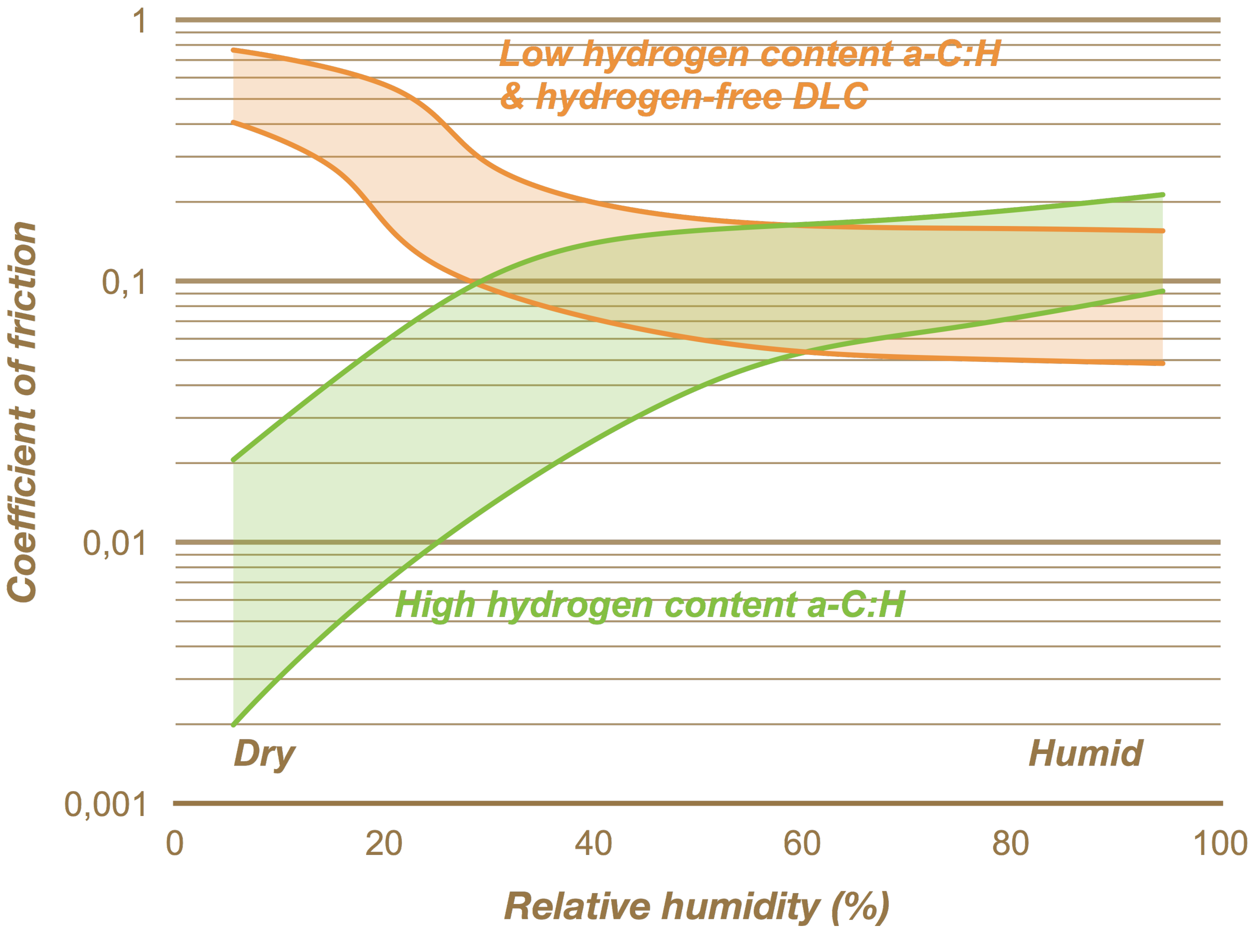
- ***Bowden & Tabor***
  Easy shear thin film trapped between hard and stiff substrates
  Soft metals, lamellar solids…

$$F_t = A_r \cdot \tau$$

How can DLC be both hard and easy to shear?

Yet some limitations!

- Strong sensitivity to environment and coating composition!
- Versatility of the tribological performance…
  …dependence on deposition process parameters

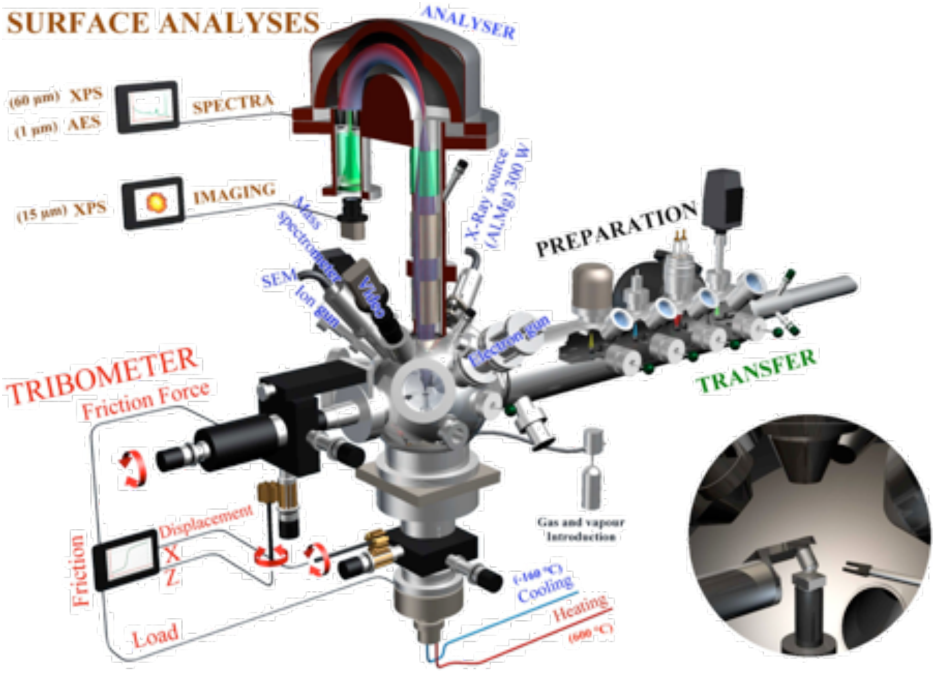


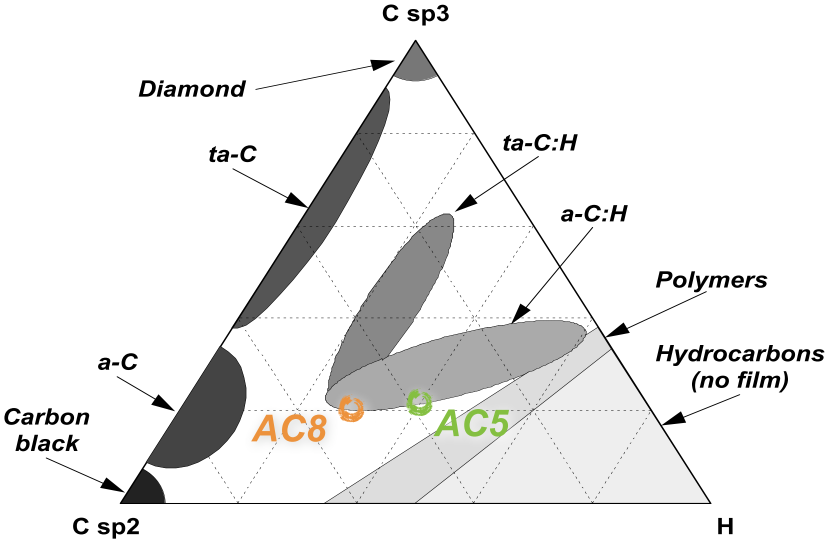
- Introduction to DLC coatings
- **Role of surface chemistry**
- Role of surface topography
- Discussion & summary

Tribological experiments on “model” DLC

Analytical UHV tribometer

Linear reciprocating motion
DLC (1 µm) on Si(100)
Environment: UHV (<10^{-6} Pa) or pure gases
Sliding speed: 0.5 mm/s
Pin material: 52100 bearing steel
Pin radius: 8 mm
Normal force: 3-5 N
Max. Hertz pressure: ~550 MPa
Contact width ~100 µm
Macroscopic contact

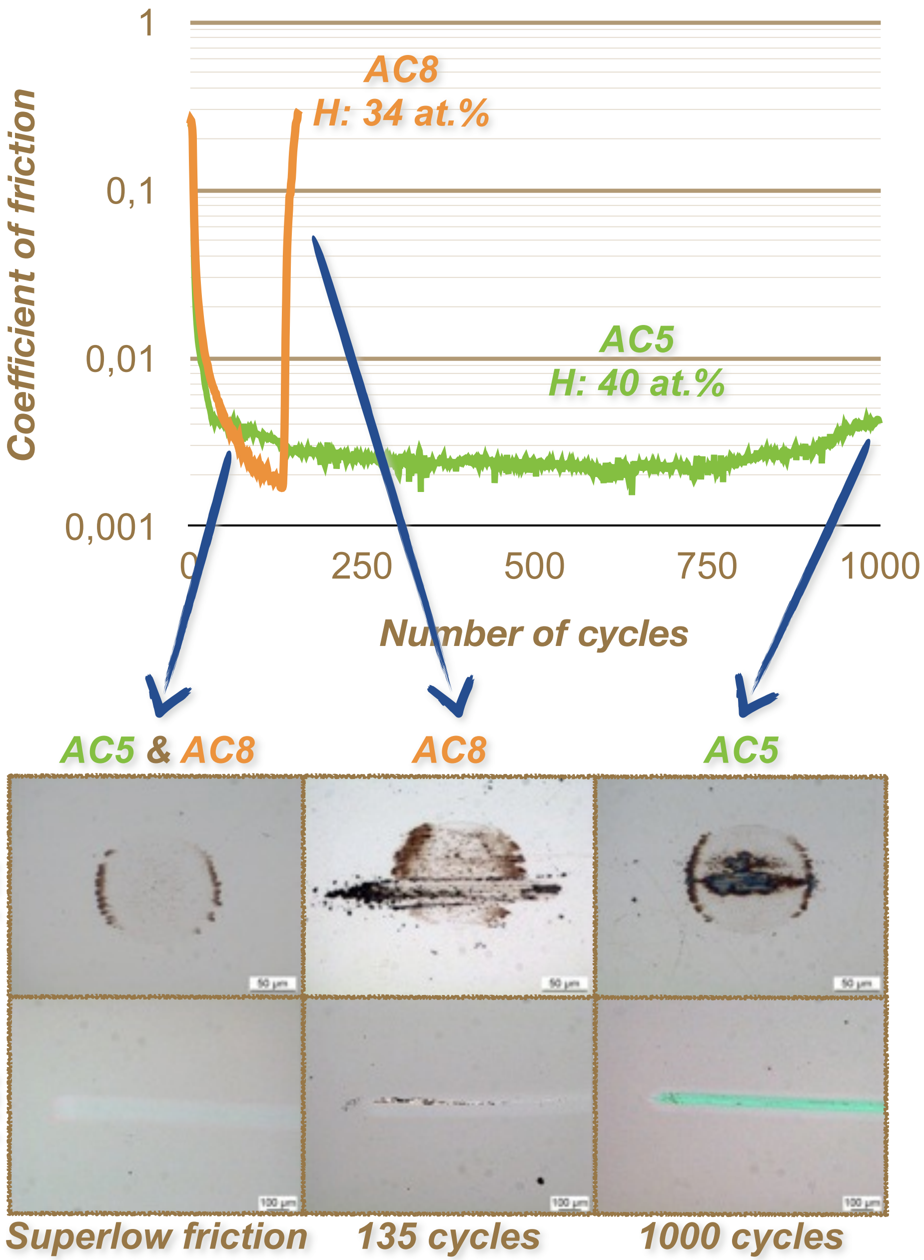




dc-PECVD	**AC8**	**AC5**
Precursor	C_2H_2	C_2H_2
Flow rate	10 sccm	10 sccm
Pressure	100 mTorr	200 mTorr
Bias voltage	-800 V	-500 V
Carbon content	66 at.%	60 at.%
C sp^3	*30%*	*35%*
C sp^2	*70%*	*65%*
Hydrogen content	34 at.%	40 at.%
Free H (FTIR)	*43%*	*27%*
Free H (NMR)	*7%*	*2%*
Hardness	10.5 GPa	7.5 GPa
Elastic modulus	80 GPa	62 GPa

Donnet & Grill, Surf. Coat. Technol. 1997
Donnet et al., J. Appl. Phys. 1999
Bec et al., Phil. Mag. 2006

Friction of a-C:H in UHV



Comparison of these 2 a-C:H films

AC8: 34 at.% of H – ***AC5:*** 40 at.% of H

Superlow friction is achieved
(µ < 0.01)

For ***AC8***, **drastic friction increase** occurs
after few tens of cycles
(> x100)

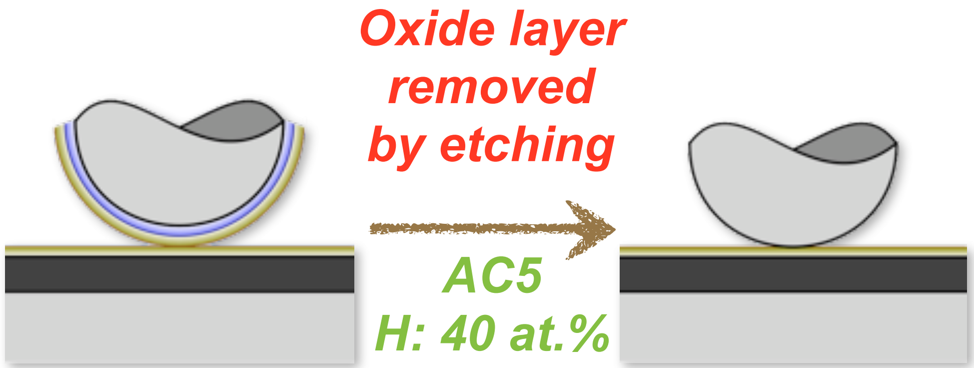
For ***AC5***, **small friction increase** occurs
after few hundreds of cycles
(< x10)

Tribofilm is formed during running-in

Drastic friction increase correlated
with ***removal of tribofilm***

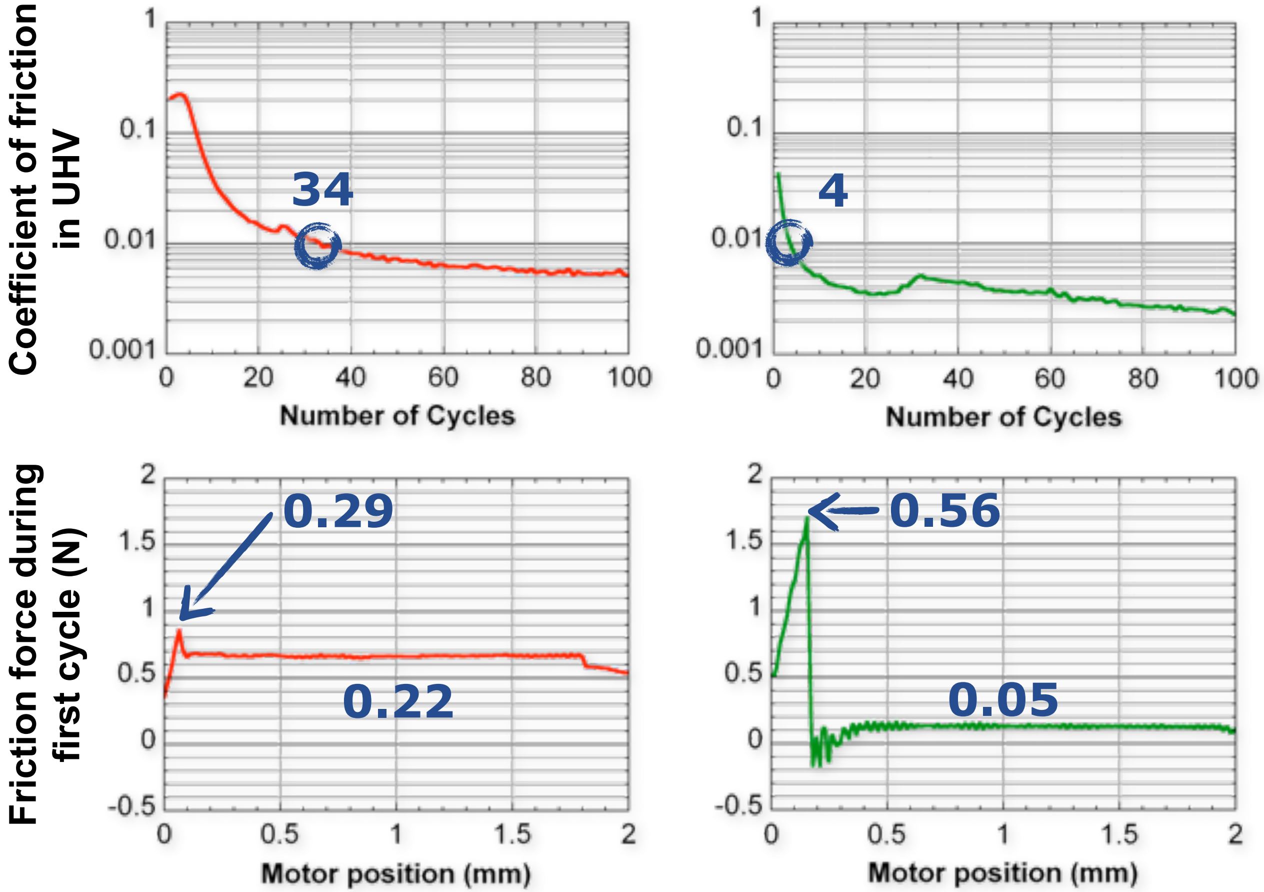
Key-role of hydrogen content?

Surface chemistry & tribofilm build-up



Oxide layer removed by etching

AC5
H: 40 at.%



"Tribofilm"

Interfacial material on counterface could be different from initial a-C:H

≠ "Transfer film"

Removal of iron oxide

↓

Strong adhesion

↓

Faster tribofilm build-up

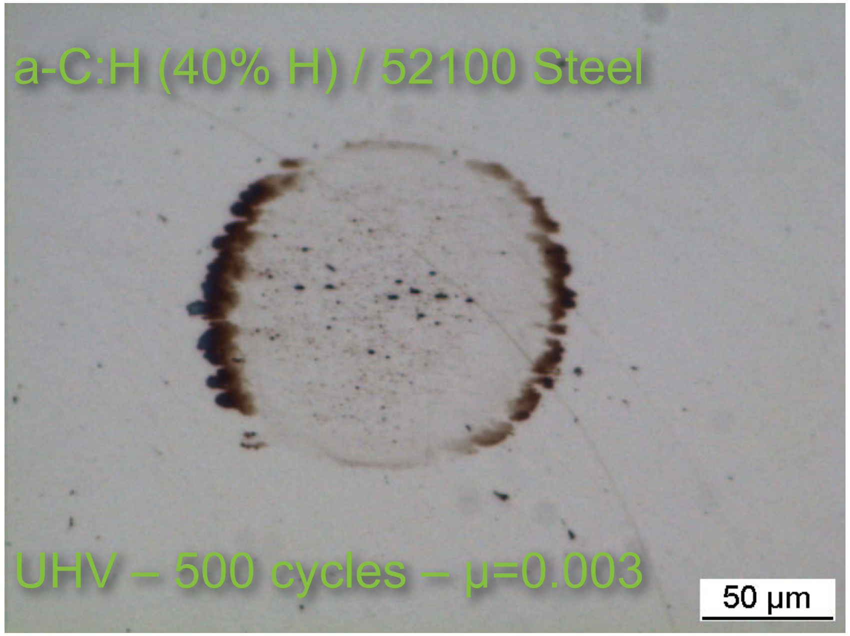
↓

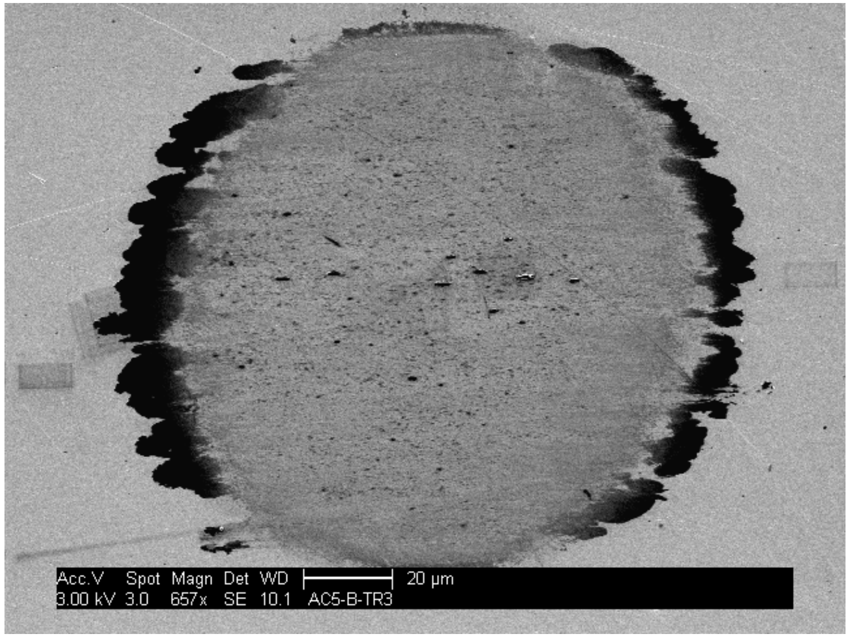
Faster friction decrease

Fontaine et al.
Thin Solid Films 482 (2005) 99.

Key role of tribofilm build-up

- Tribofilm grown on metallic counterface



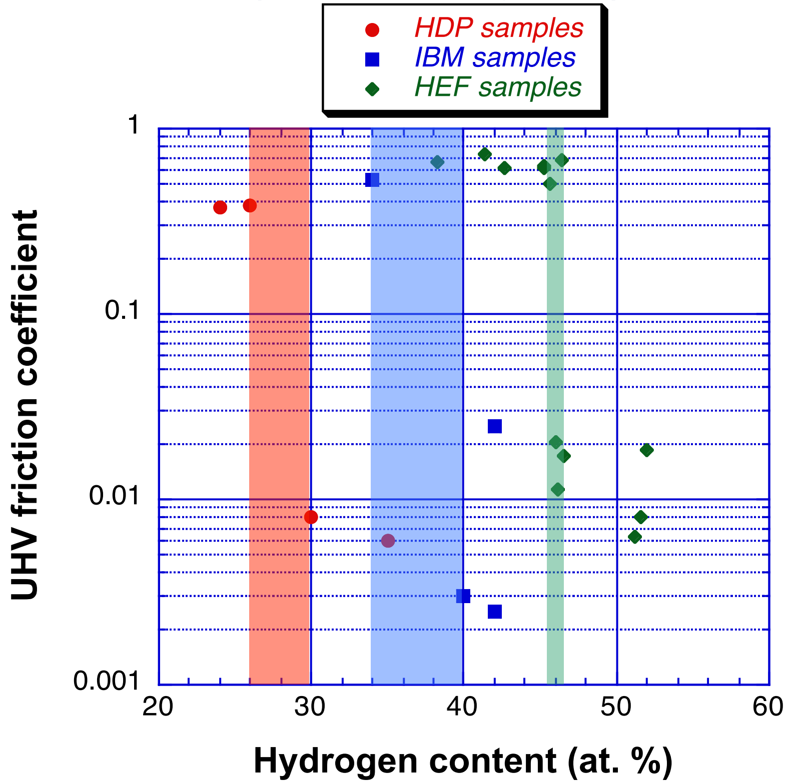


- Weak interactions between carbon-based sliding surfaces
  - Reduced adhesion if enough hydrogen on the surface? (or “passivating” species)
  - Avoiding strong bonds: covalent or metallic

Critical surface coverage by hydrogen?

- ***Surface coverage by Hydrogen*** would explain superlow friction of a-C:H under UHV?

“Stabilized” UHV friction coefficient
(after 500 cycles)



3 different PECVD processes

HDP: *rf-PECVD from C_2H_2 + H_2*

IBM: *dc-PECVD from C_6H_{12} or C_2H_2*

HEF: *dc-PECVD from C_2H_2*

(PVD Ti-based underlayers)

HDP: 26-30 at. %
IBM: 34-40 at. %
HEF: ~ 46 at. %

↓

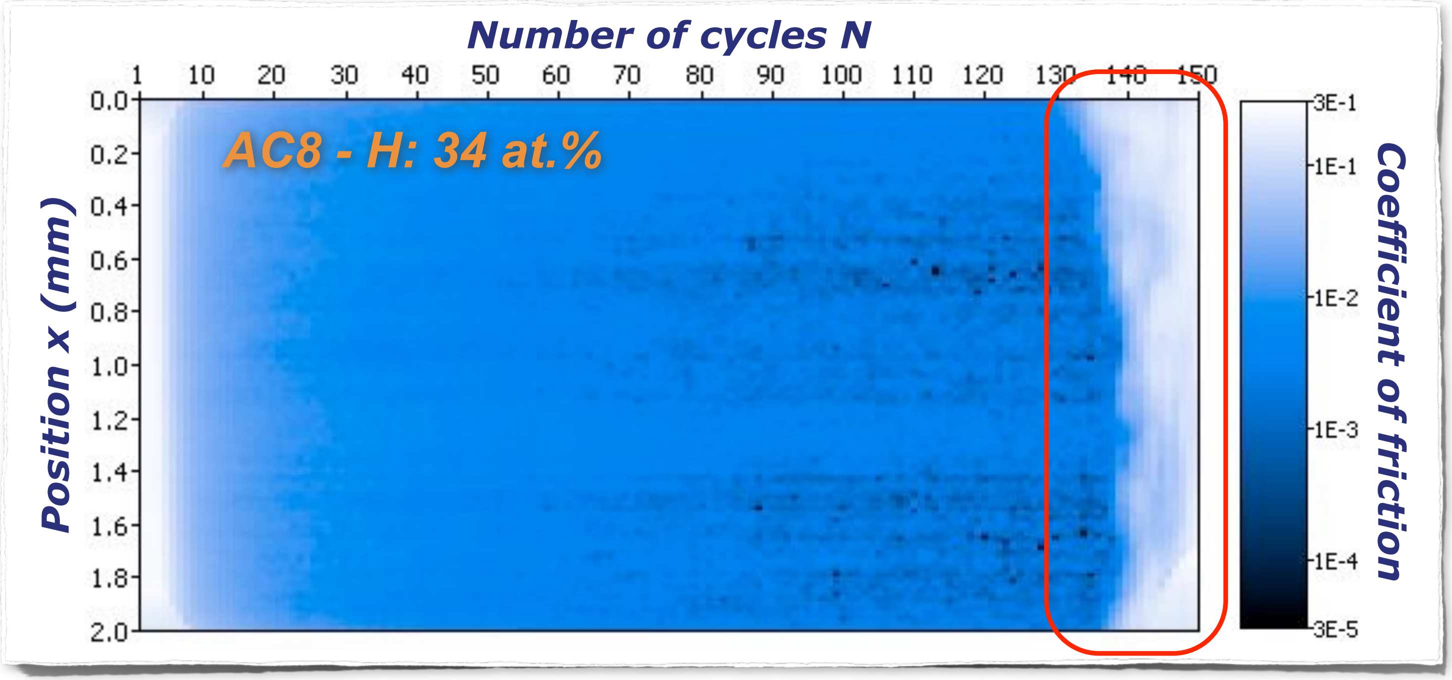
Threshold in hydrogen content depends on deposition process

How could we have similar hydrogen coverage with such different hydrogen contents?

Loss of superlow friction…

- ***How to better understand the loss of the superlow friction regime?***

Triboscopy: "friction maps"
Friction as a function of position and number of cycles



Loss of "superlow" friction:

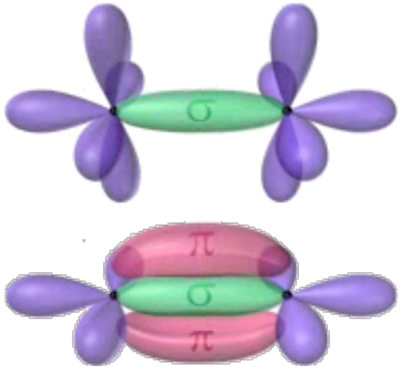
- Start at localized points of the wear track
- Quickly extends to an entire cycle

⇒ ***due to adhesive phenomena***

The key-role of adhesive phenomena

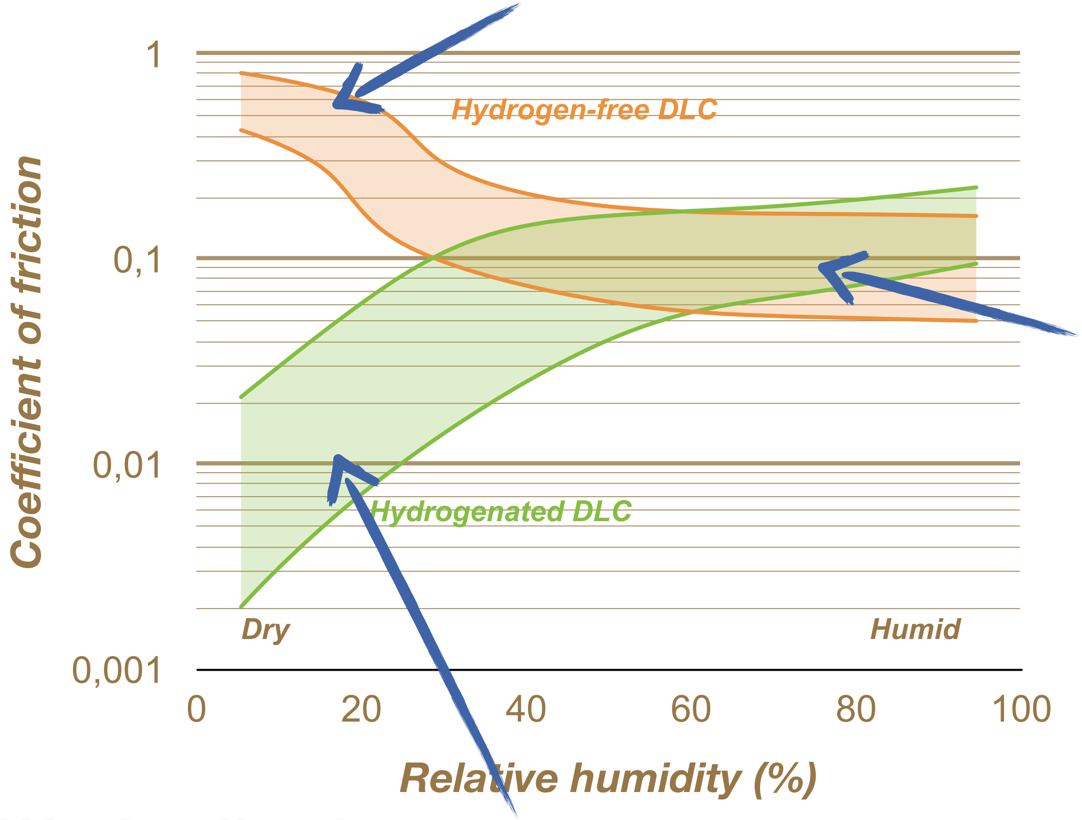
- **Positive role** of adhesive phenomena:
  → promote tribofilm build-up and friction reduction
- **Negative role** of adhesive phenomena:
  → may lead to drastic friction increase
- **Adhesion** seem to control the friction of DLC
  → related to surface chemistry?

Surface chemistry & adhesion



Strong adhesion

- “Dangling” σ bonds
- π orbitals interactions? Metallic bonding?



Intermediate adhesion

Critical role of water vapor

- Hydrogen bonding ?
- Capillarity ?

Weak adhesion

- Hydrogen-terminated surfaces
- Van der Waals interactions

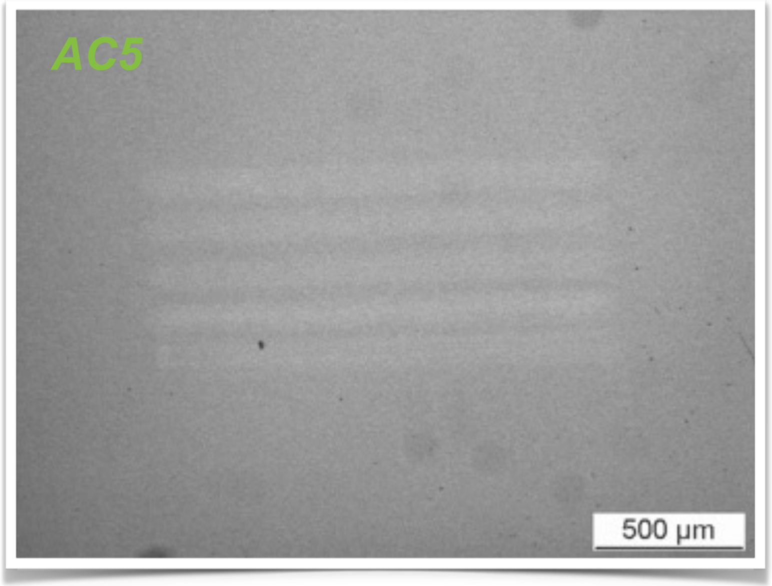
- Introduction to DLC coatings
- Role of surface chemistry
- **Role of surface topography**
- Discussion & summary

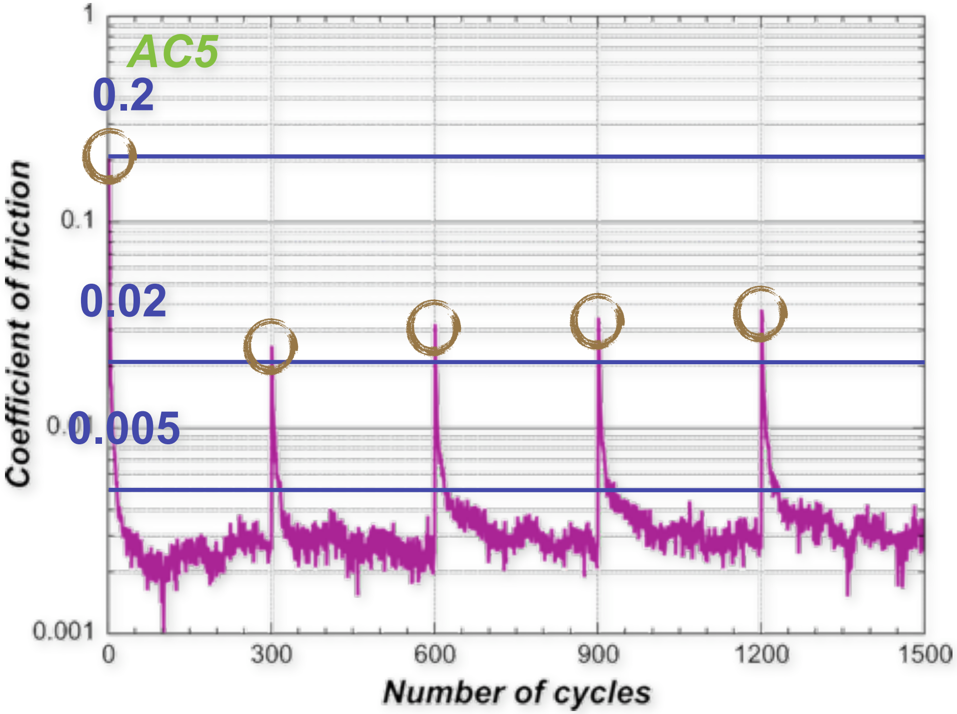
A closer look at running-in…

Running-in: only due to tribofilm build-up?

UHV friction experiments with :

- *5 different positions on the DLC coated flat*
- *Same position on the steel pin*
- *300 cycles at each flat position*





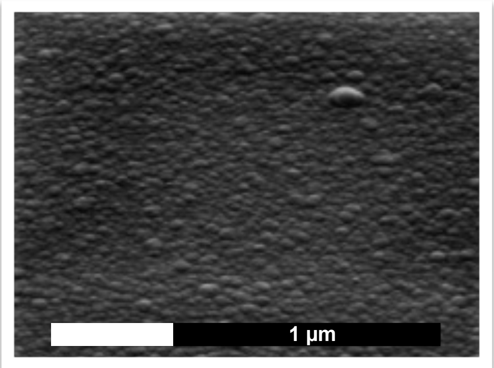
Systematic running-in from > 0.02 during > 15 cycles…

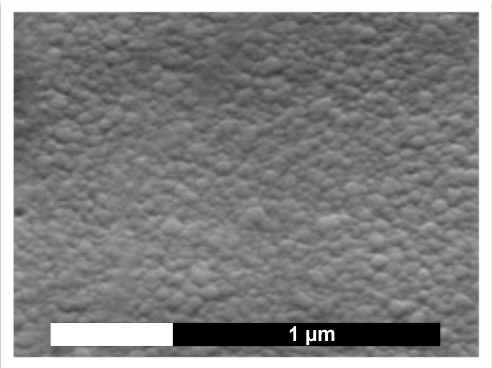
Something has to change on DLC surface!

Investigating surface morphology

AC5
0 cycles

R_a = 2.7 nm
R_q = 3.4 nm





AC5
500 cycles

R_a = 1.4 nm
R_q = 1.9 nm

$\mu \simeq 0.25$

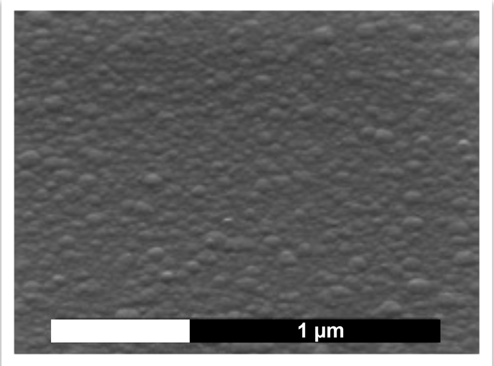
Before friction

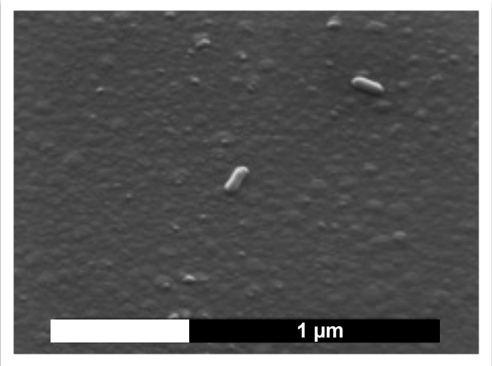
Superlow friction

$\mu \simeq 0.003$

AC8
0 cycles

R_a = 1.8 nm
R_q = 2.4 nm





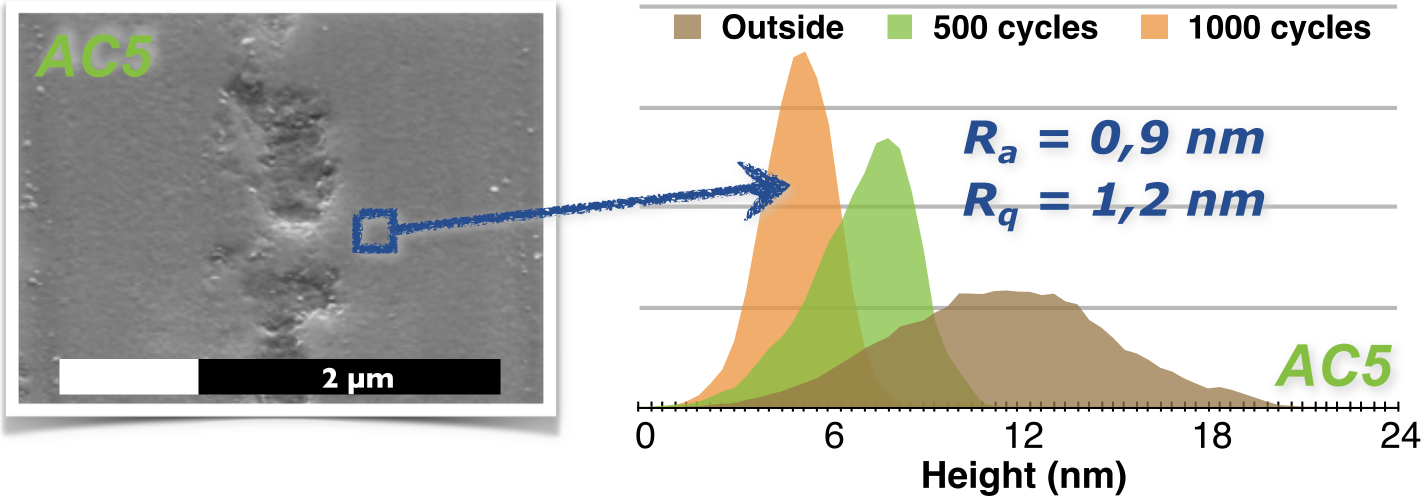
AC8
80 cycles

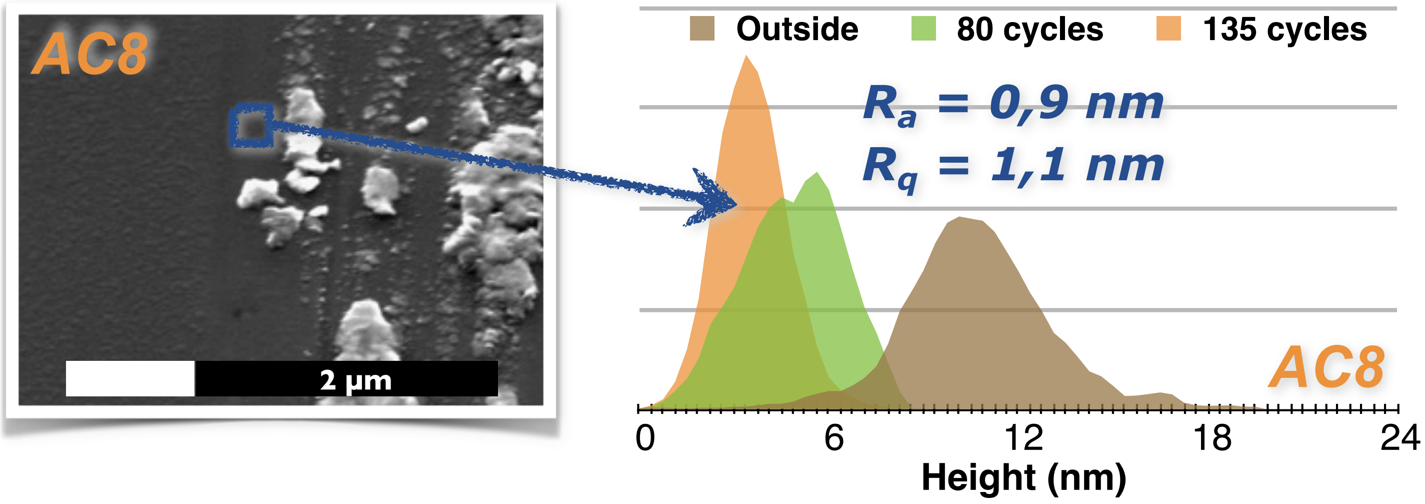
R_a = 1.3 nm
R_q = 1.6 nm

- Topography observed by SEM and measured by AFM
- Both samples exhibit **roughness at nanoscale**
- Partial wear of asperities is necessary to reach superlow friction
- Wear of **AC8** asperities seems faster than **AC5**

Surface smoothening & adhesion

What happens near the high friction areas?





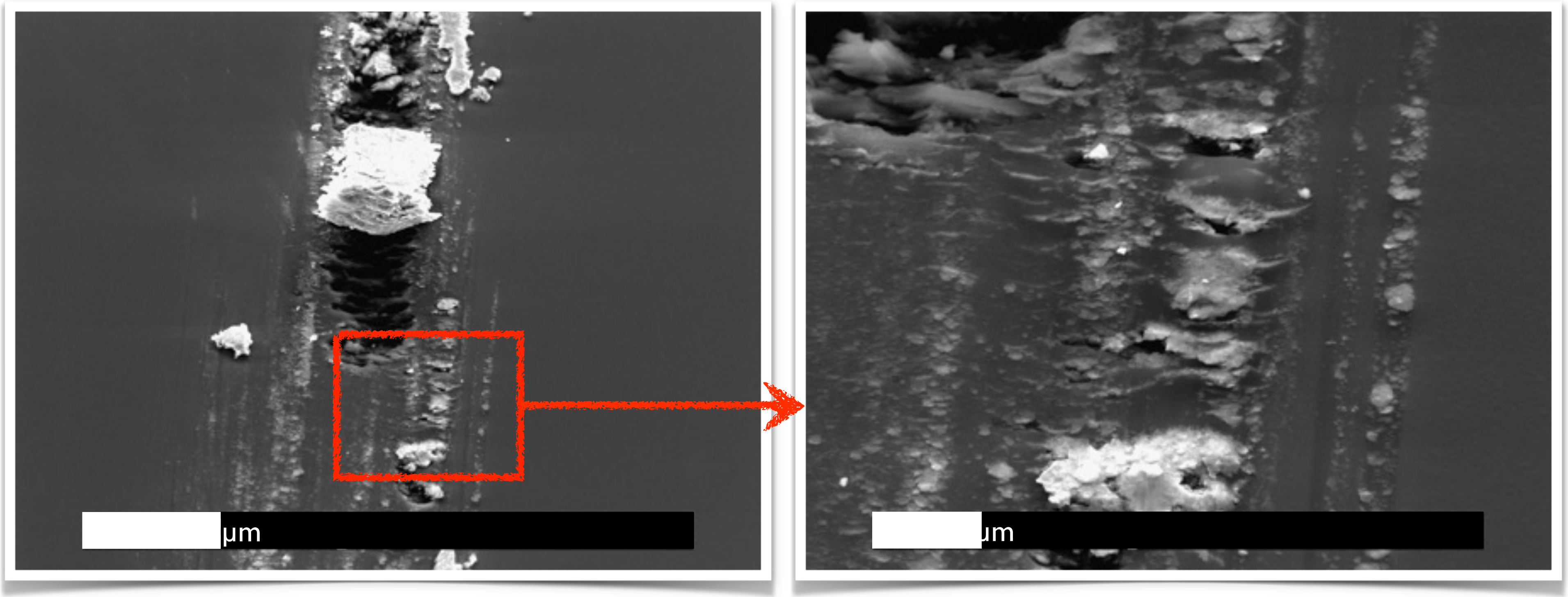
Smoothening of nanoscale roughness leads to ***large adhesive phenomena***

Why such different friction evolution between these two coatings?

Consequences of adhesion

SEM / EDX observations of wear tracks on the AC8 flat:

- *Iron is transferred to the DLC surface (in high friction zones)*
- *Some cracks can be found in the DLC around transferred iron particles*
- *Deep grooves are then formed from these “adhesive junctions”*
- ***Adhesion is clearly controlling the loss of superlow friction for AC8***

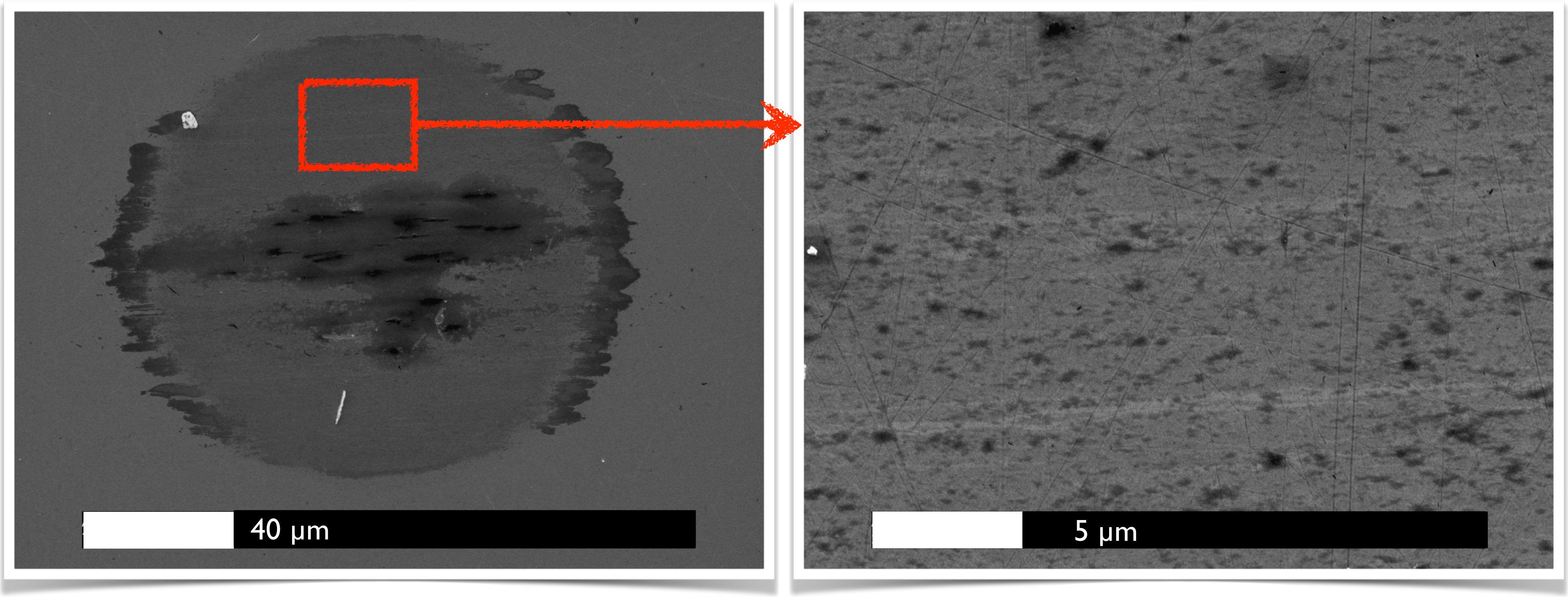


AC8 - 34 at.% H

Consequences of adhesion

SEM / EDX observations of tribofilm on counterface of AC5:

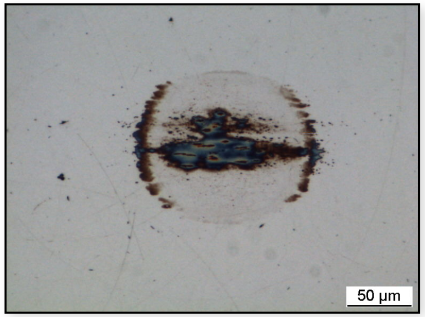
- *Tribofilm doesn't appear to be continuous!*
- *Many "dots" of carbon-based materials are covering the steel surface*
- *Much thicker tribofilm is found in high friction areas*
- ***Growth of tribofilm results from the release of adhesive junctions***



AC5 - 40 at.% H

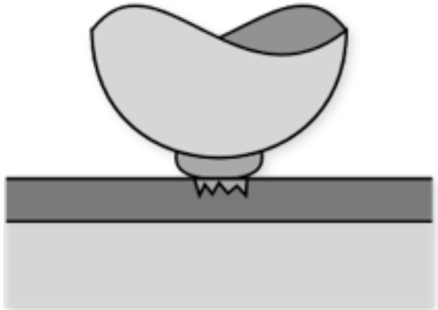
Key-role of mechanical properties

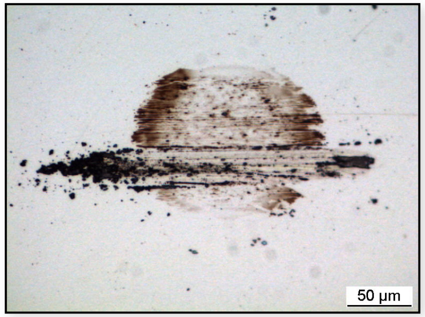
Mechanical properties of DLC control how adhesive junctions will break :



SOFTER AC5 :
H = 7.5 GPa
Viscoplasticity: 6.8 10^{-2}

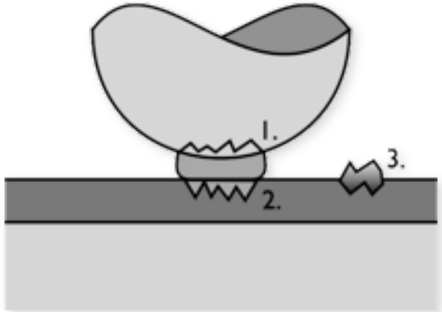
Adhesion
↓
Transfer of DLC to steel pin
thicker tribofilm
↓
Preserving **low friction**



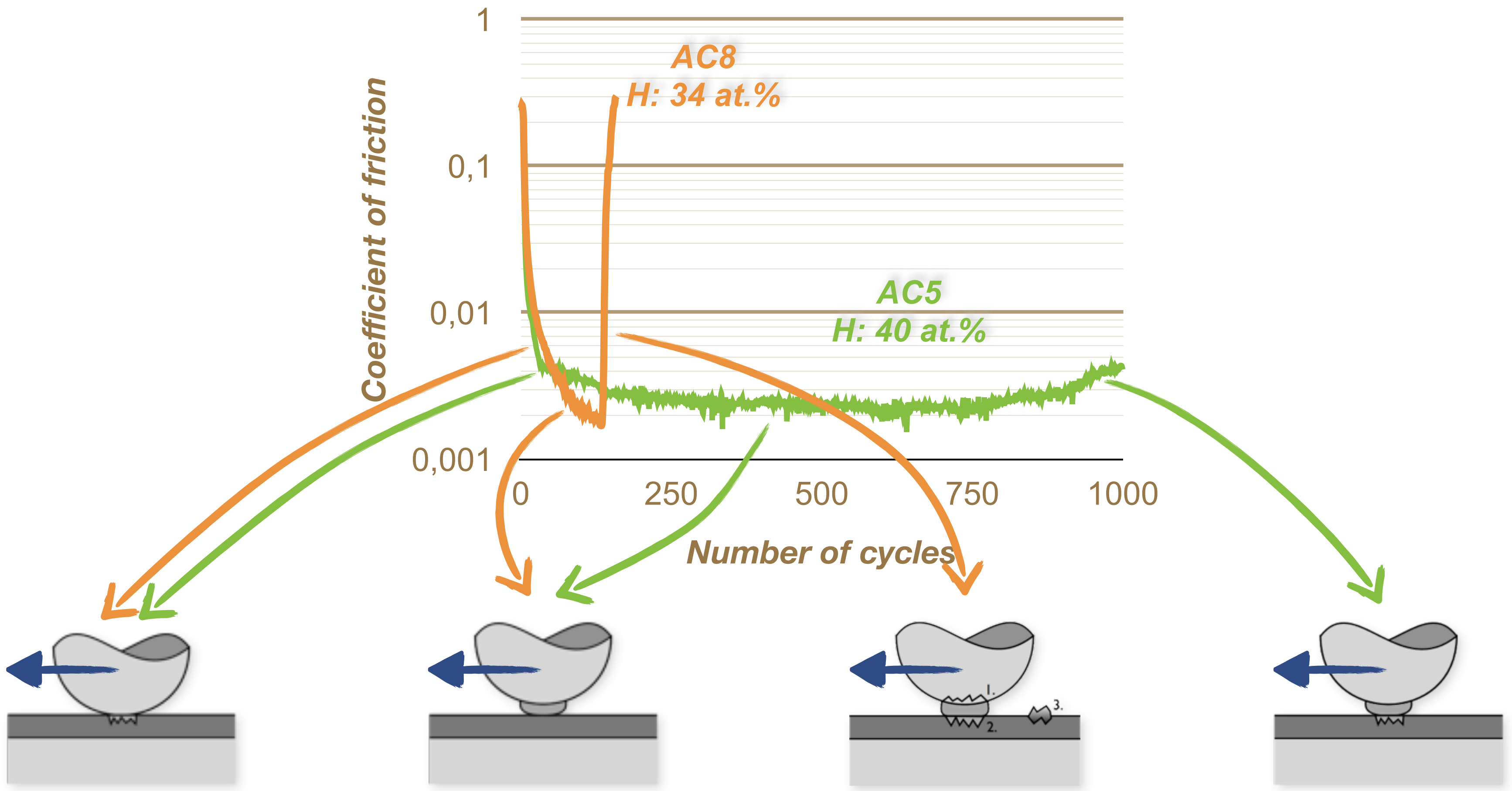


HARDER AC8 :
H = 10.5 GPa
Viscoplasticity: 1.4 10^{-2}

Adhesion
↓
Transfer of steel to DLC flat
Tribofilm removal
↓
Leading to **high friction**



Solid lubrication process of DLC



Small adhesive junctions
⇒
Tribofilm build-up

Surface “passivation”, few small junctions
⇒
Interfilm sliding

Large adhesive junctions
⇒
Tribofilm removal

Large adhesive junctions
⇒
Wear of DLC

- Introduction to DLC coatings
- Role of surface chemistry
- Role of surface topography
- **Discussion & summary**

Tribology of DLC: multi-physical aspects

Solid lubrication processes of DLC coatings seems to be controlled by:

- **Physical interactions**
  - Van der Waals forces (H-terminated surface)
  - Hydrogen bonding (with water vapor)
  - Overlap of π-orbitals (for low H coverage) or even metallic bonding?
  - Physisorption of environmental gases?
  - Contribution of electrostatic interactions?

- **Chemical reactions**
  - Covalent bonding between sliding surfaces
  - “Passivation” of dangling bonds by environmental gases
  - Controls the nature of sliding surfaces…

- **Surface mechanical behavior**
  - Controls the real area of contact
  - Controls the release of adhesive junctions
  - ***Not only hardness*** to be considered: viscoplasticity, fracture toughness…
  - Role of time-dependance of mechanical properties?
  - Importance of ductile/brittle transition?

Tribology of DLC: multi-scale aspects

Solid lubrication processes of DLC coatings involve different scales:

- **At the scale of molecules…**
  - Adhesive phenomena are controlled by physical interactions & chemical reactions

- **At the scale of asperities…**
  - Nanoscale surface topography controls the size of adhesive junctions
  - Mechanical behaviour of asperities controls friction & wear

- **At the scale of the coating…**
  - Mechanical properties control the real area of contact
  - When large adhesive junctions are formed, they also control future evolution of the contact: where are these junctions released?