Dry tribology for space application:

From MoS_2 coating to self lubricating composite

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From Earth to Space…

The 3 lives of a mechanism


Source: Thalès Alenia Space


Source: Ariane Espace


Source: ESA

Phases	Ground	Launch	Space
Operations	Assembling, Tests Storage	Launch	Orbit Transfer, Deployment Functioning
Mechanical Env.	Gravity	High accelerations and vibrations	Low accelerations and vibrations
Gaseous Env.	Dry and humid air Dry N2, Simulated vacua		Heterogeneous vacua Outgassing
Duration	Months to years	Minutes	Years

From Earth to Space, the 3 lives of a mechanism…

		Earth	
Environment	**Altitude (km)**	Sea level	
	Pressure (Pa)	1013×10^2	
	Kinetic Temperature (K)	**Clean rooms:** 295±3	
	Composition	78%N2, 21%O2, 1%Ar	N2, Vac., Cryo.,
	Particles & Radiations	(55±10) %HR	0 %HR
	Gravity	Yes	
Technical operations	**Operation undergone**	Assembly, Tests operation, Storage	
	Time spent	From few months to several years	

** Difference in vacuum pressure outside and inside a satellite after one year of work. Robbins, ESMATS, 1975

From Earth to Space, the 3 lives of a mechanism…

		Earth		Launch	
Environment	**Altitude (km)**	Sea level		30	200
Environment	**Pressure (Pa)**	1013×10^2		10^2	10^{-4}
Environment	**Kinetic Temperature (K)**	**Clean rooms:** 295 ± 3		~173	~1200
Environment	**Composition**	78%N2, 21%O2, 1%Ar	N2, Vac., Cryo.,	N_2, O_2, Ar	N_2, O, O_2, O^+
Environment	**Particles & Radiations**	(55 ± 10) %HR	0 %HR		
Environment	**Gravity**	Yes		Acceleration	
Technical operations	**Operation undergone**	Assembly, Tests operation, Storage		Violent acceleration, noise, vibrations	
Technical operations	**Time spent**	From few months to several years		Several minutes	

** Difference in vacuum pressure outside and inside a satellite after one year of work. Robbins, ESMATS, 1975

From Earth to Space, the 3 lives of a mechanism…

		Earth		Launch		Space					
Environment	**Altitude (km)**	Sea level		30	200	400	800	6500	22000	36000	400000
	Pressure (Pa)	$1013x10^2$		10^2	10^{-4}	10^{-5}	10^{-7}	10^{-11}	$<10^{-11}$	$<10^{-11}$ out 10^{-10} in 10^{-5} **	10^{-13}
	Kinetic Temperature (K)	**Clean rooms:** 295±3		~173	~1200	From 3 to more than 1000 **Temperature cycling [70 ; 370]**					
	Composition	78%N2, 21%O2, 1%Ar	N2, Vac., Cryo.,	N_2, O_2, Ar	N_2, O, O_2, O^+	O, He, O+, H		H+, H, He+, **e-**	85%H+, 15%He2+, **e-**	Mainly H+, **e-**	Mainly H+, **e-**
						+ outgassing and motor emission species (Hydrazine, Nitrogen…)					
	Particles & Radiations	(55±10) %HR	0 %HR			X rays, α rays, γ rays, UV, solar wind, cosmic rays, meteoroids…					
	Gravity	Yes		Acceleration		Microgravity					
Technical operations	**Operation undergone**	Assembly, Tests operation, Storage		Violent acceleration, noise, vibrations		Orbit transfer		Deployment		**Operation (communication, observation…)**	
	Time spent	From few months to several years		Several minutes		Up to several years		Few minutes		Up to 30 years	

** Difference in vacuum pressure outside and inside a satellite after one year of work. Robbins, ESMATS, 1975

From Earth to Space…

The 3 lives of a mechanism

Source: Thalès Alenia Space

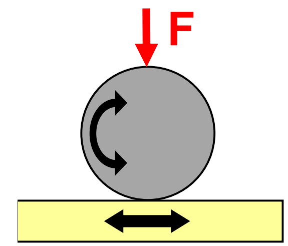
Source: Ariane Espace

Source: ESA

Succession of strongly different mechanical and physicochemical environments in which lubrication must be sustained

Challenge* = *Predicting lubricant behavior

Tribological consequences of **vaccum**



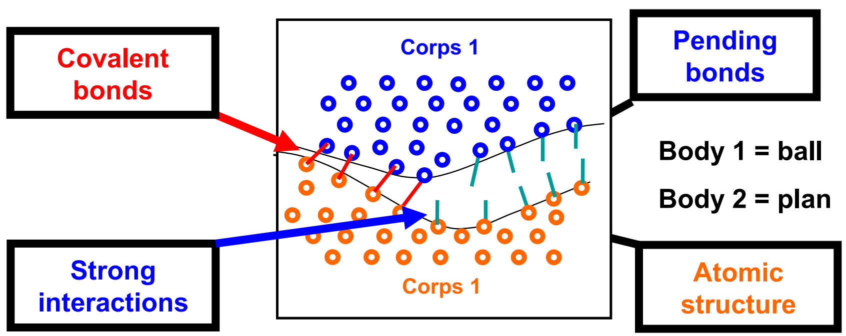
Contact conditions (sliding, rolling…)

↓

Creation of pending bonds

Air → **Chemical reaction with molecules of the surrounding gaz** → **- Weak adhesion**
- Low or high friction coefficient

Vaccum → **Direct interaction between bodies in contact** → **- Strong adhesion : cold welding**
- Blocking of the mechanism



Failure in space:

Mission ***GALILEO***

High Gain Antenna

Mission :

Study Jupiter and its moons

Program duration :

initial : 1989 – 1997

extended to 2003

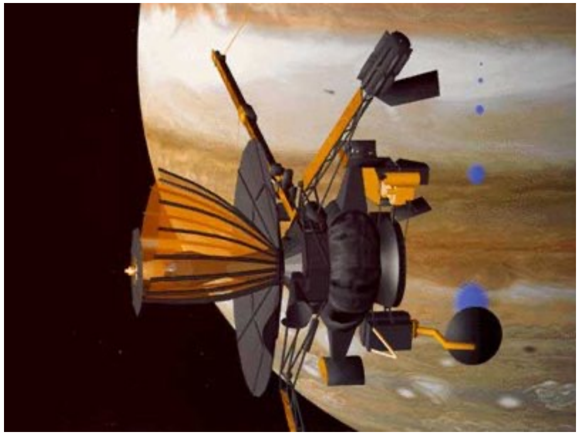
Program cost:

close to 1,39 billion dollars

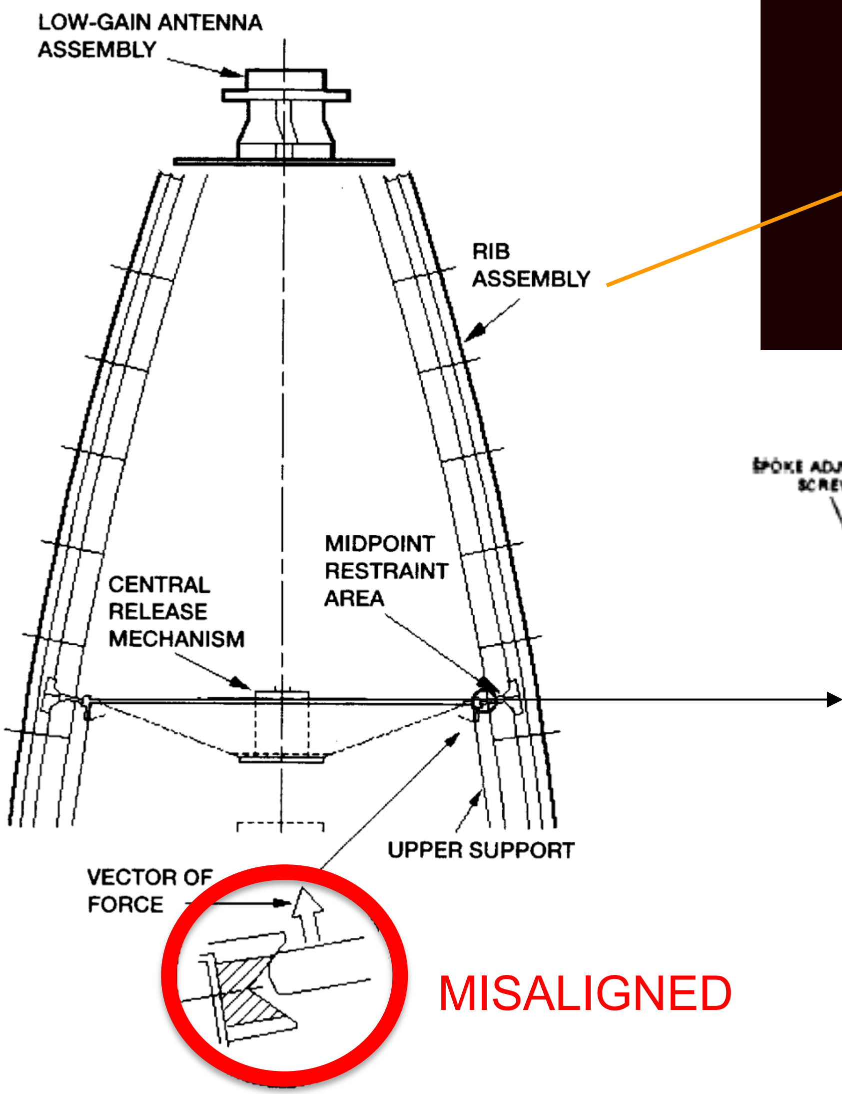
Anomaly :

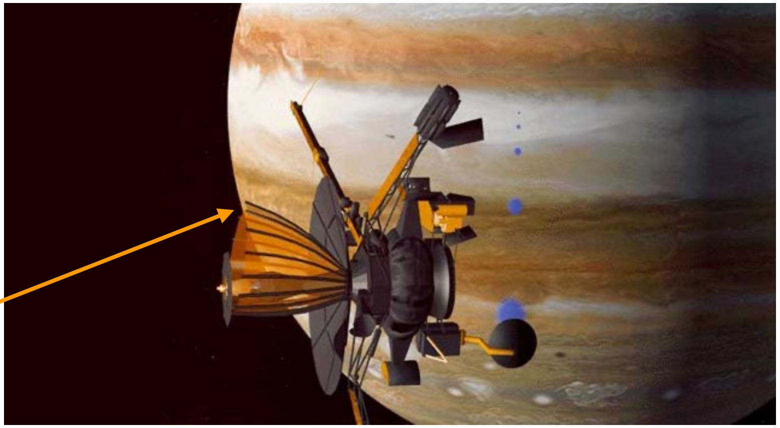
Incomplete deployement of HGA

(partial umbrella deployement)

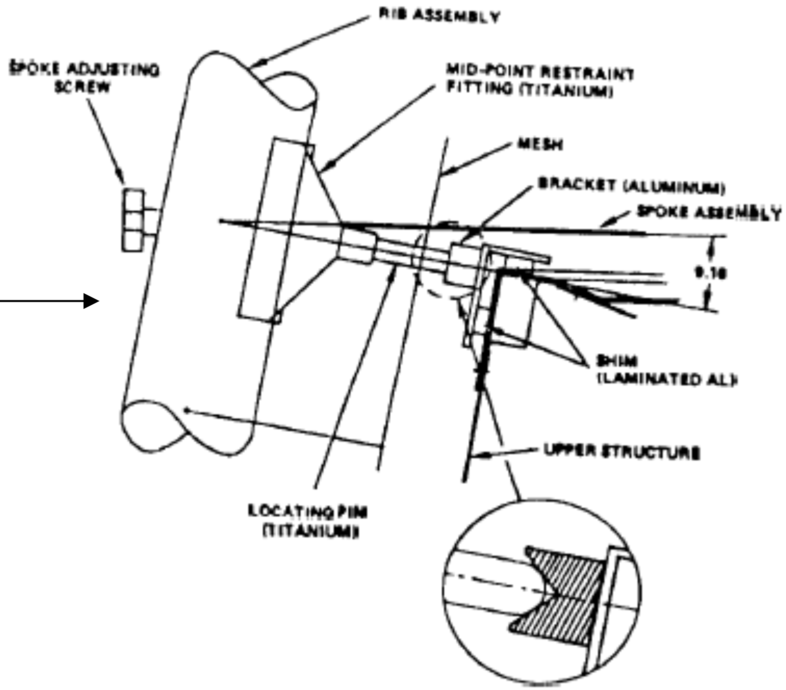


https://www.jpl.nasa.gov/news/galileo-antenna-deployment-problem-under-analysis





MISALIGNED



NOMINAL

THE GALILEO HIGH GAIN ANTENNA DEPLOYMENT ANOMALY

Michael R. Johnson
California Institute of Technology
Jet Propulsion Laboratory
Pasadena, California

CONCLUSIONS

The high contact stresses on the V-groove pin/socket interfaces destroyed the integrity of the lubricant film and started the chain of events that led to the deployment anomaly. The conical sockets and pins were exposed to all of the same environments as the V-groove sockets and pins, but the lubricant surface was not breached. A low enough friction level was maintained such that the conical sets did not inhibit the antenna deployment. The main difference between the cone sockets and V-groove sockets is the contact stress level.

The use of drylube, specifically molybdenum disulfide, on a mechanism that is going to be operated in an atmosphere should be carefully evaluated. The wear rate of the MoS2 in air is so much higher than in a vacuum that any coatings could be worn out by in-air testing and not provide the desired lubrication when needed. The pins and sockets on the HGA that received the greatest amount of relative motion due to the shipping method were the same ones that were exercised most by the vibration testing. These are also the same pins and sockets that are stuck on the spacecraft.

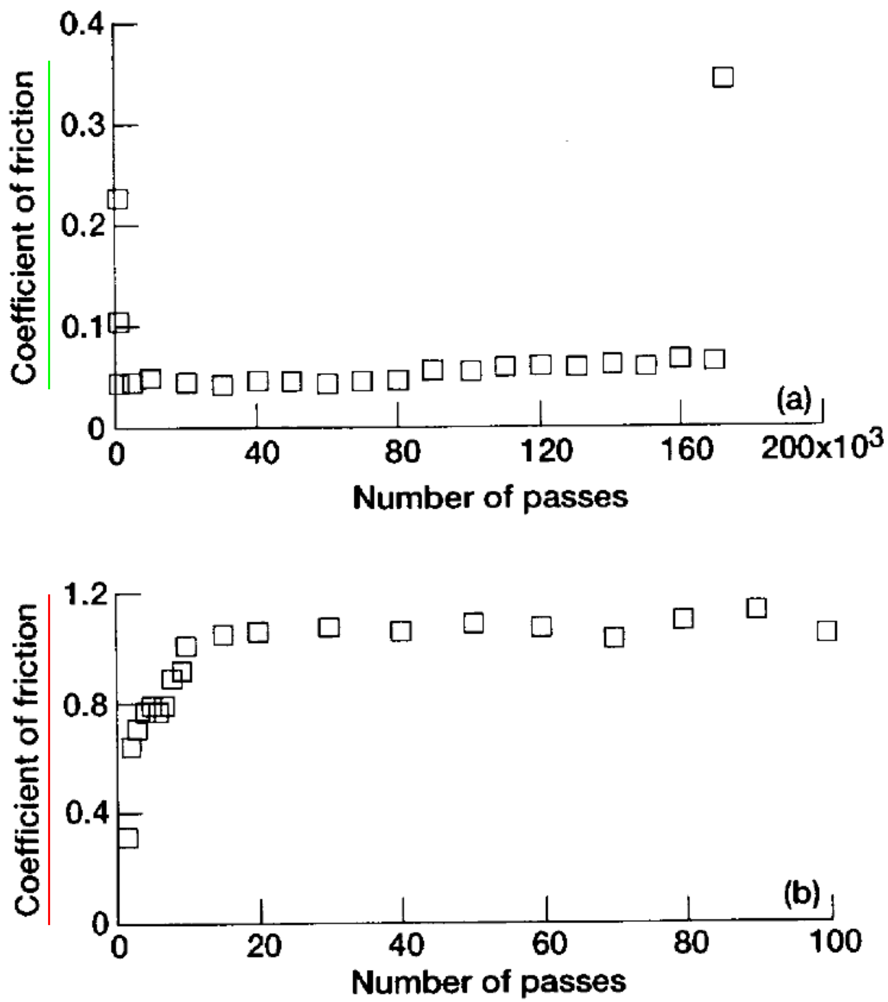


Figure 6.—Coefficients of friction for dry-film-lubricated and unlubricated Ti-6Al-4V pins sliding against high-nickel-content superalloy disks as function of number of passes in vacuum. (a) Dry-film-lubricated pin at 8.5-N load. (b) Unlubricated pin at 4-N load.

Failure in space:

Mission ***GALILEO***

Mission :

Study Jupiter and its moons

Program duration :

initial : 1989 – 1997
extended to 2003

Program cost:

close to 1,39 billion dollars

Anomaly :

Incomplete deployement of HGA
Titanium part deformation
(mout/unmount/sun temperature)
and
loss of solid lubricant (vibrations)

Consequence :

10bit/s instead of > 130 000bit/s

Solution ?

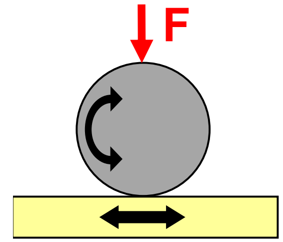
Reprogram to transfert to 2nd antenna

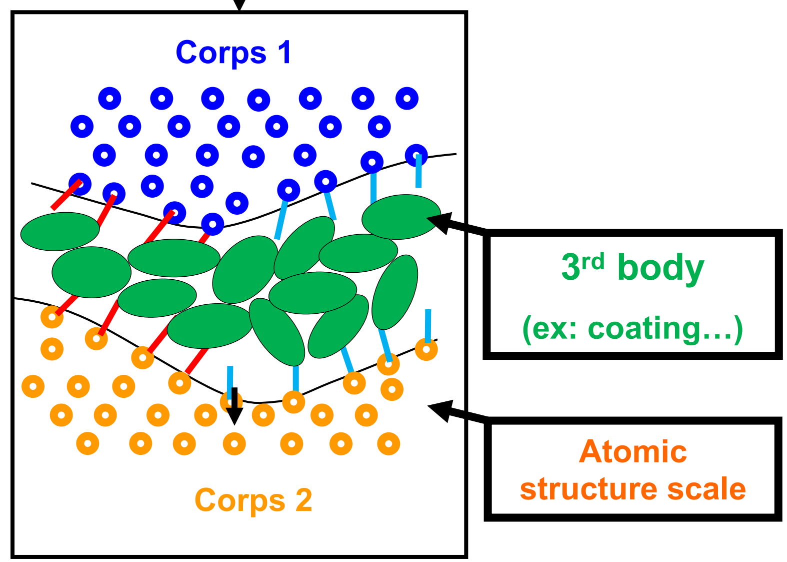
Satelite global efficiency: 70 %

Tribological consequences of **vaccum**

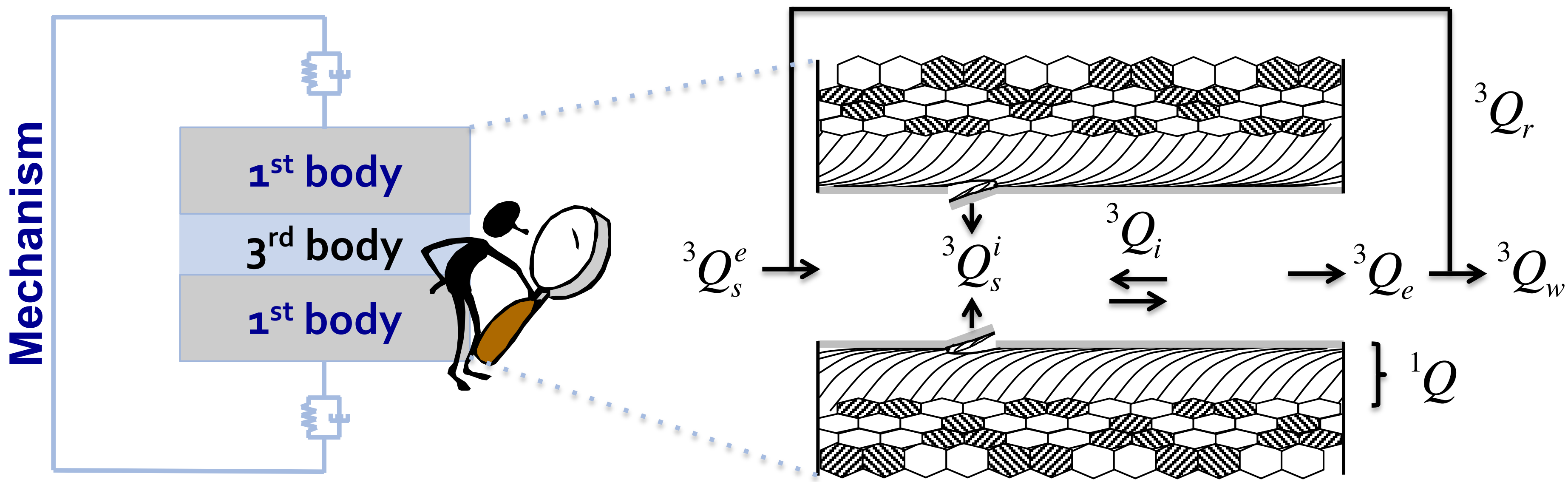
Contact conditions (sliding, rolling…)

Necessity of a 3rd body





Conceptual tools :
Tribological triplets and **circuits**



Tribological triplet
M. Godet - 1984

Tribological circuit
Y. Berthier - 1988

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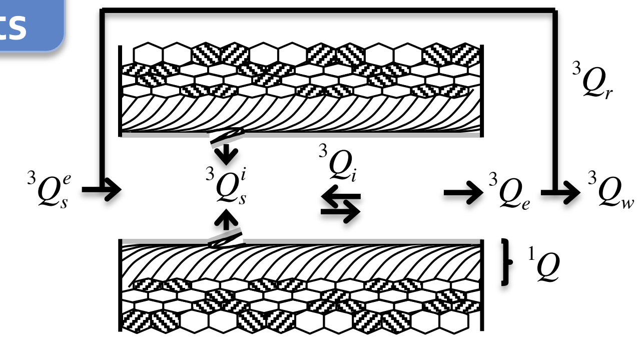
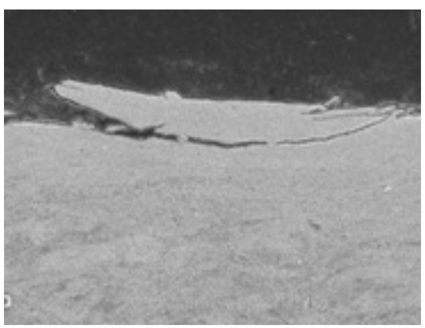
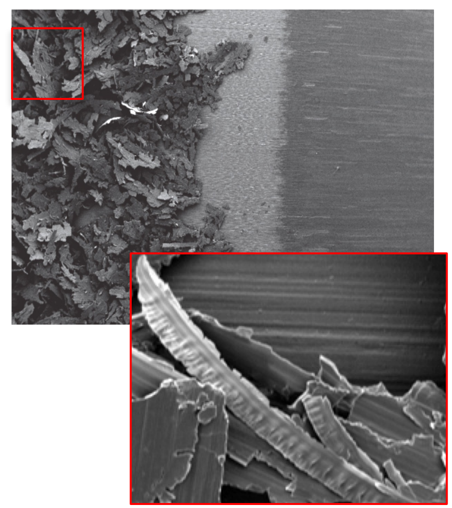
Conceptual tools : **Tribological triplets** and **circuits**

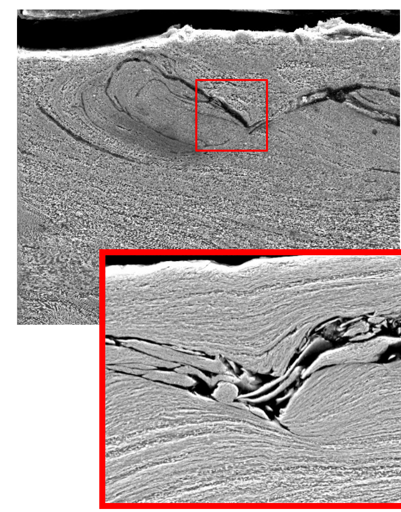


3rd bodies flows

- $^3Q_s^e$ Source flow $^3Q_s^i$
- Internal flow ^3Q_i
- ^3Q_e Ejection / Wear ^3Q_w
- Recirculation ^3Q_r

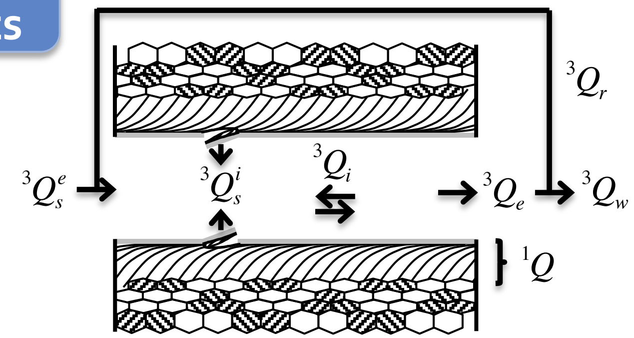






Images courtesy of G. Colas & A. Saulot

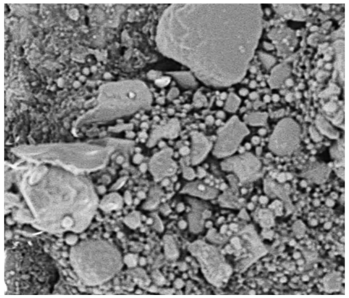
Conceptual tools : **Tribological triplets** and **circuits**



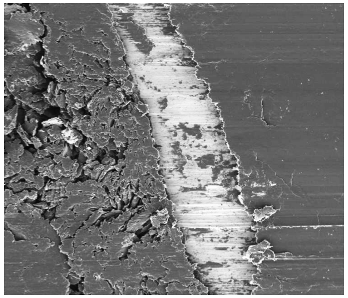
3rd bodies flows + **3rd bodies caracteristics**

- Cohesive / powdery
- Ductile / fragile
- Adhesive / Slippery
- Reactive / no-reactive

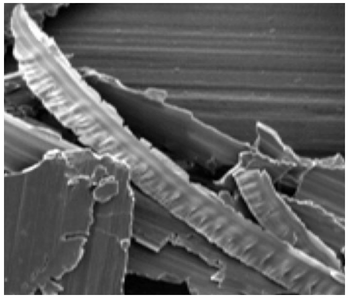
powdery



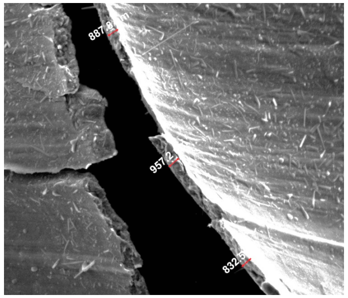
powdery / cohesive



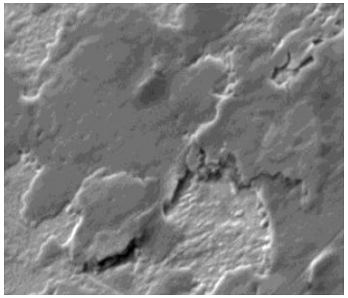
ductile



fragile



adhesive



Images courtesy of R. Charlery & A. Saulot

Source: ESA

Sphere joint

Roller screw

Ball bearing

3rd bodies

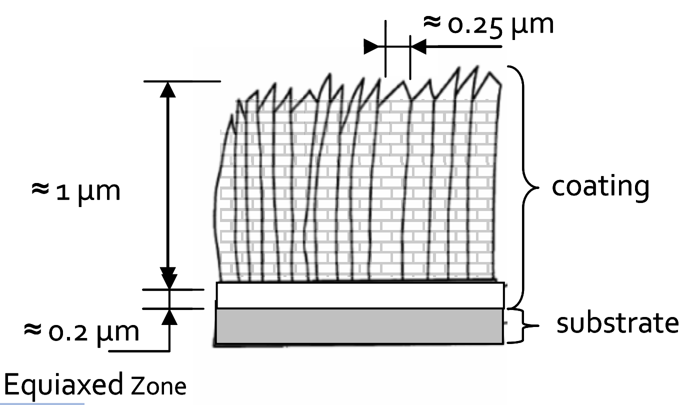
- **From coatings**
- **From self-lubricating composite**

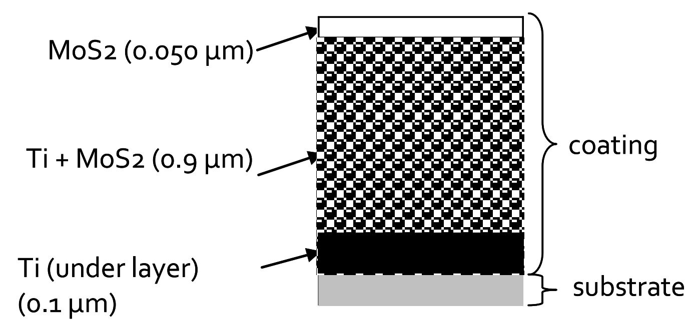
No time this year ! Next summer school

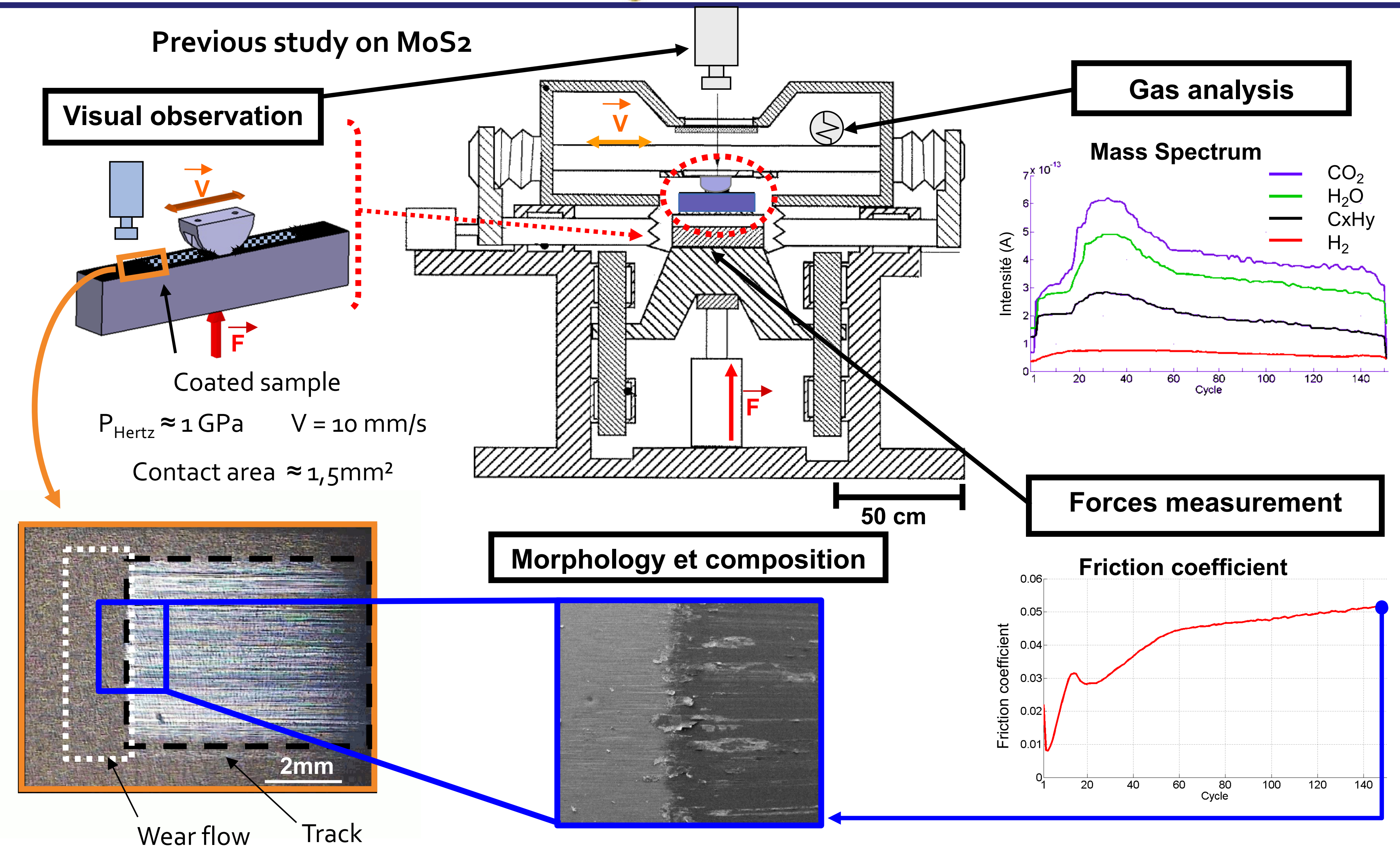
From coatings

Tribologically « ideal » behaviour of a coating

Vaccum		Air
MoS_2 - c	Tribological antoginism	MoS_2+Ti
Microstructure: colomnar and critalline		**Microstructure: amorphous and non colomnar**

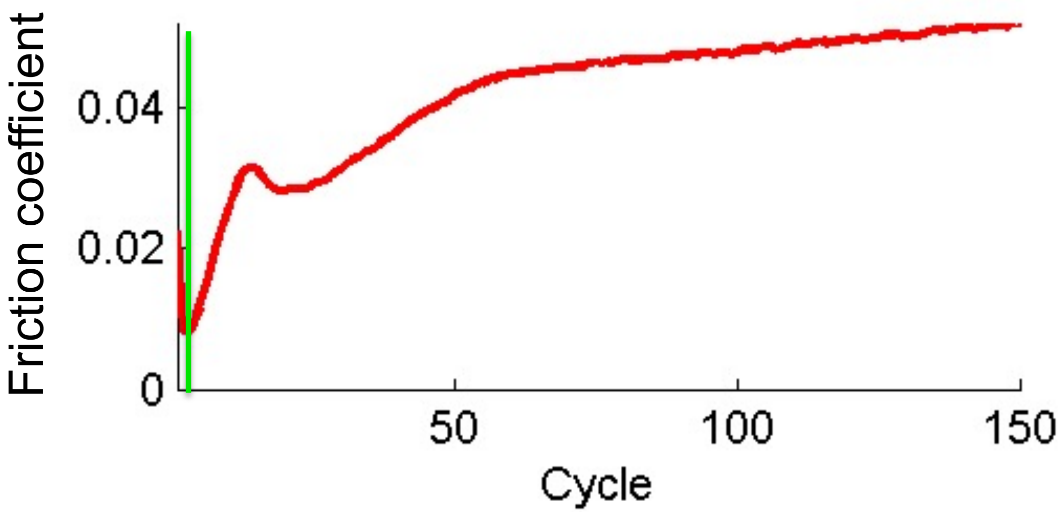


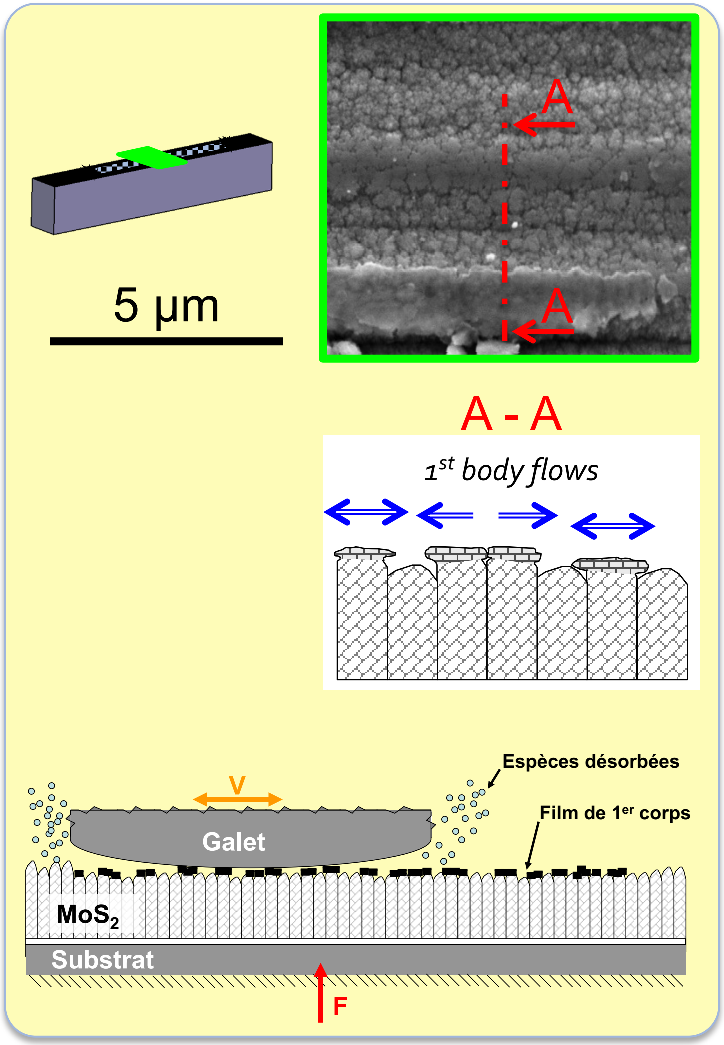



Previous study on MoS2
Visual observation
V
F
Coated sample
$P_{Hertz} \approx 1$ GPa
V = 10 mm/s
Contact area ≈ 1,5mm²
2mm
Wear flow
Track
V
F
50 cm
Gas analysis
Mass Spectrum
x 10^-13
CO_2
H_2O
CxHy
H_2
Intensité (A)
Cycle
Forces measurement
Morphology et composition
Friction coefficient
Friction coefficient
Cycle

Case of MoS_2 – C

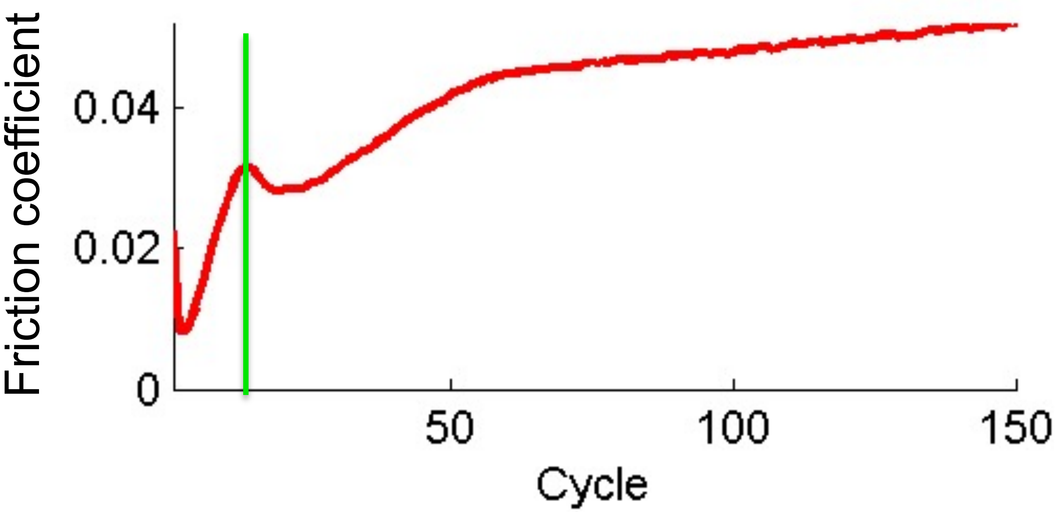
under ultra-high-vaccum

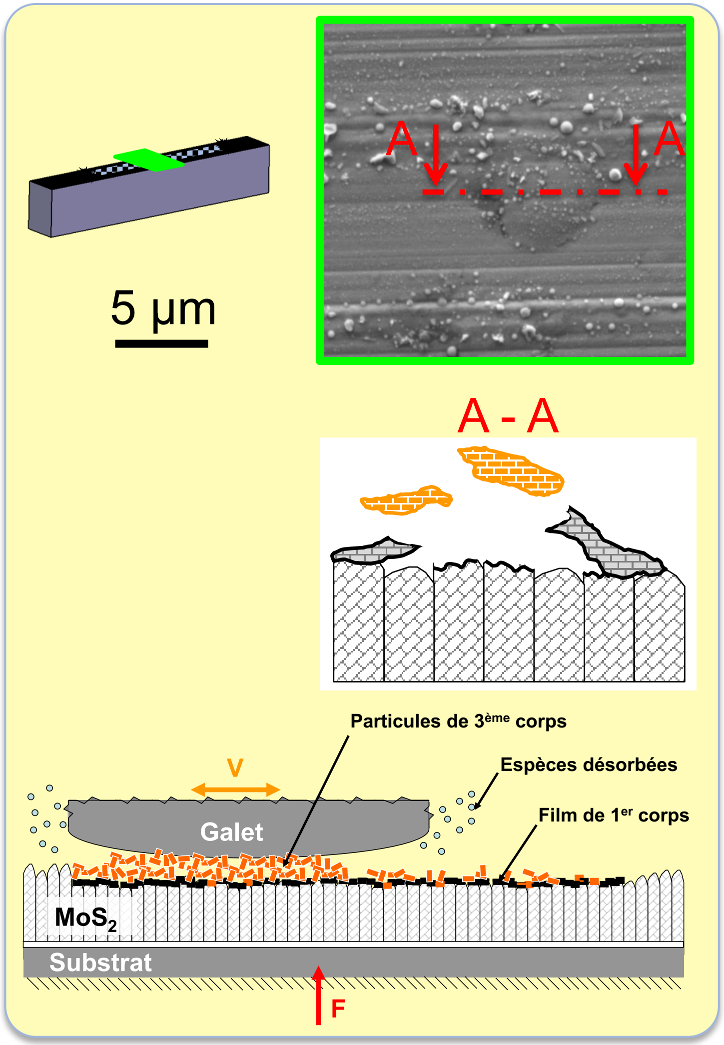




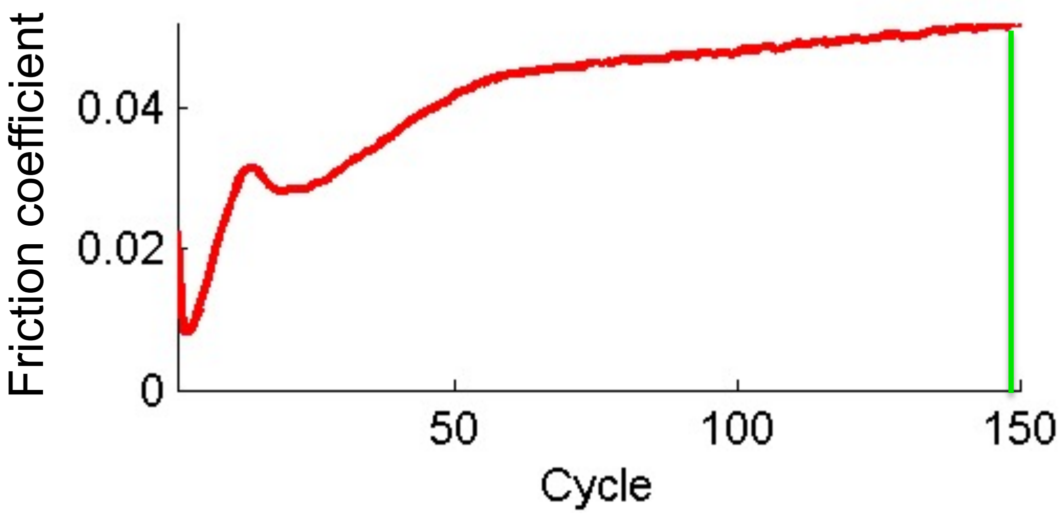
Case of MoS_2 – C

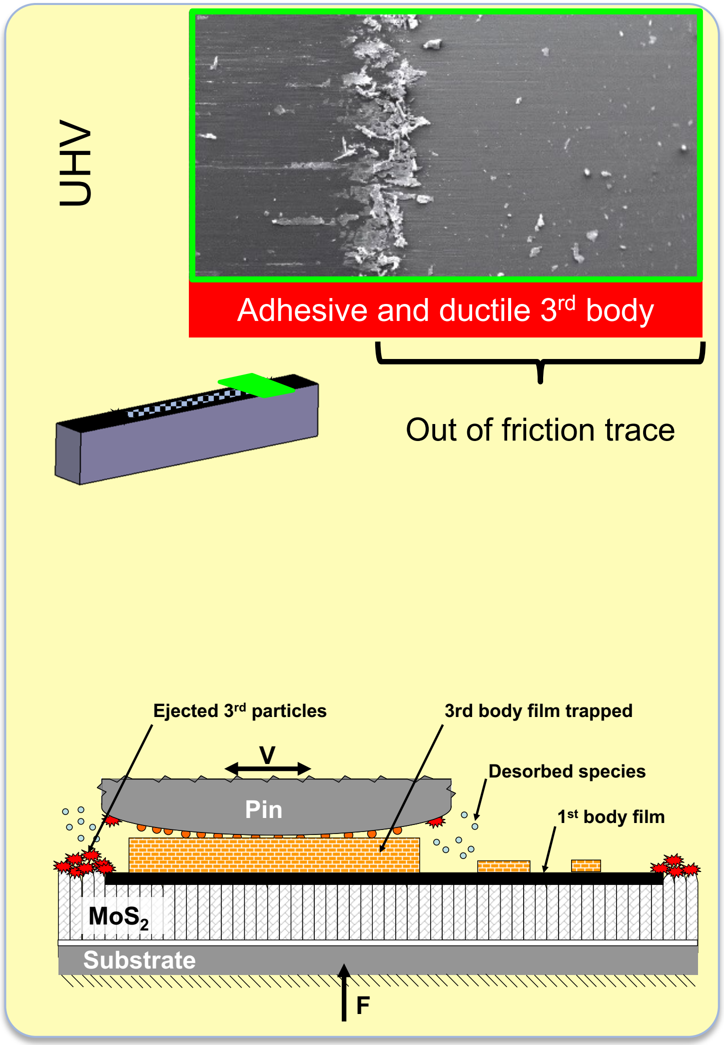
under ultra-high-vaccum





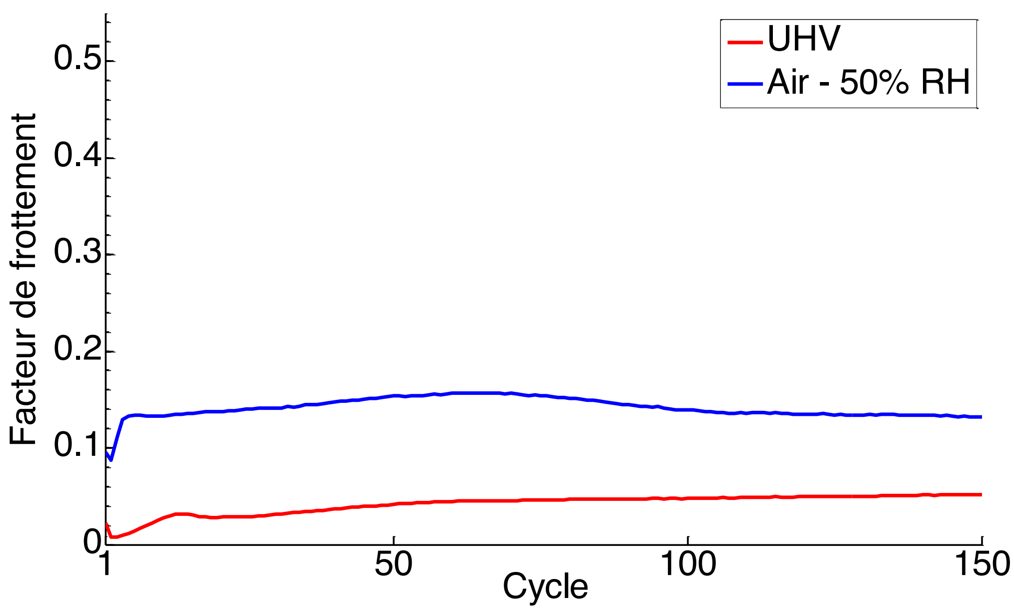
Case of MoS_2 – C under ultra-high-vaccum

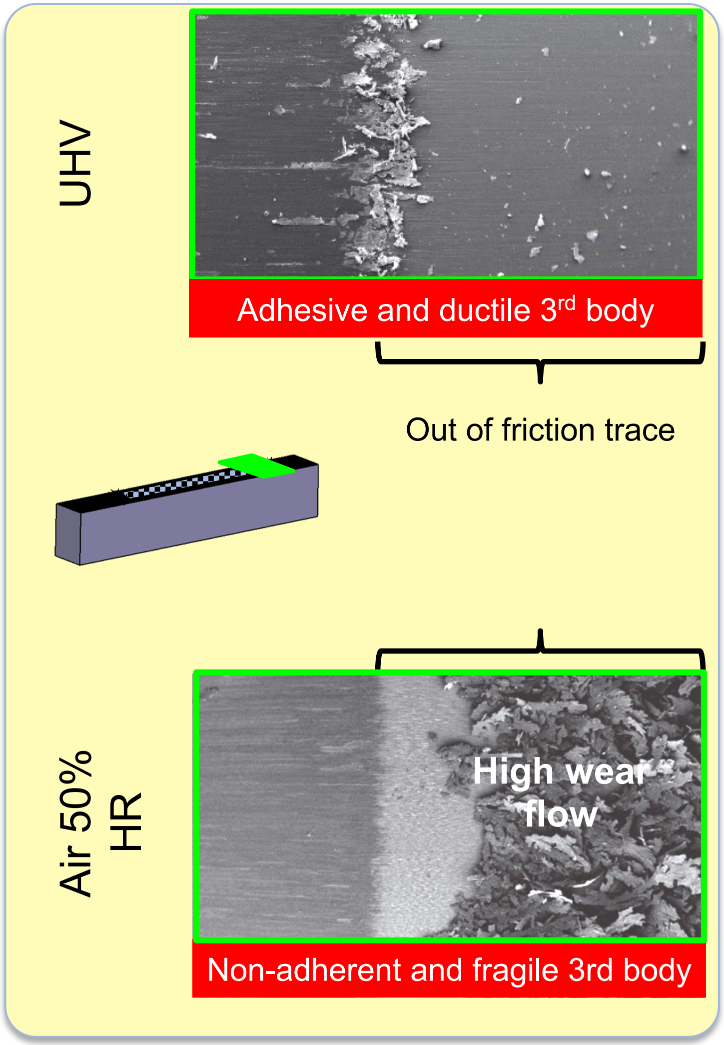




Case of MoS_2 – C

UHV vs. Air 50% RH



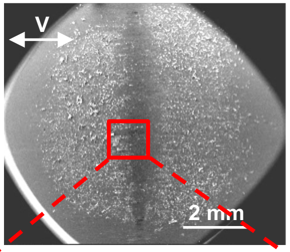


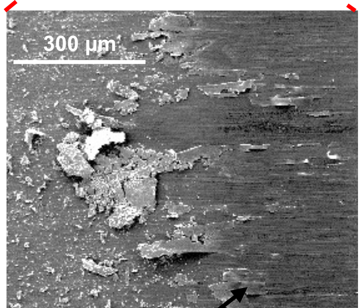
μ is a function of, at least:

- the evolution of the interface…
- the environnement…

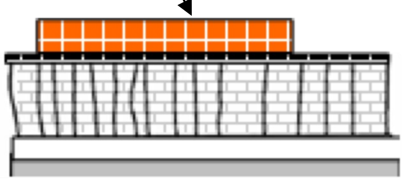
UHV (10^{-6}Pa)

μ = 0,06, W = +++

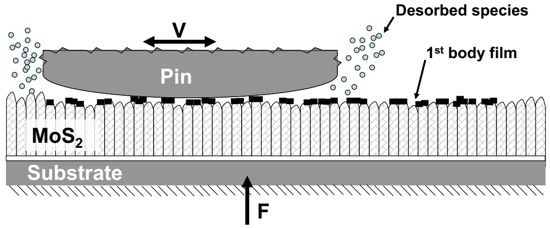




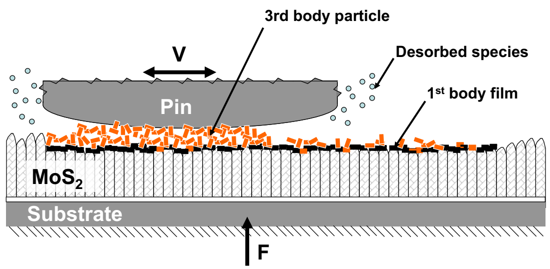
Ductile, ***MoSxOy***



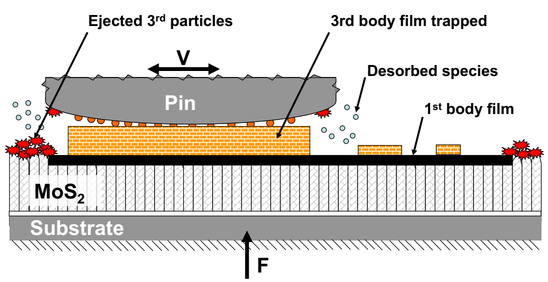
3 Cycles

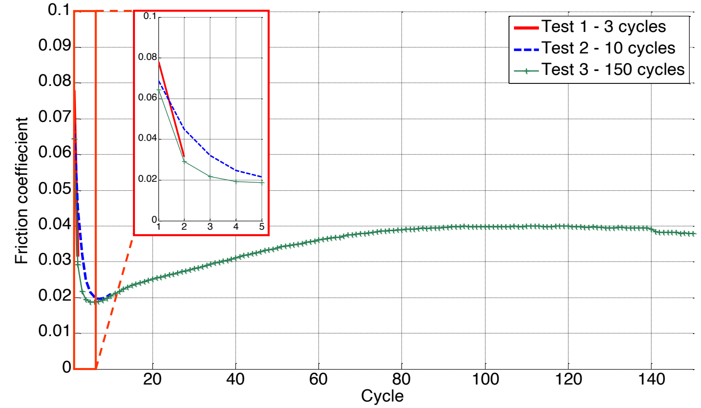


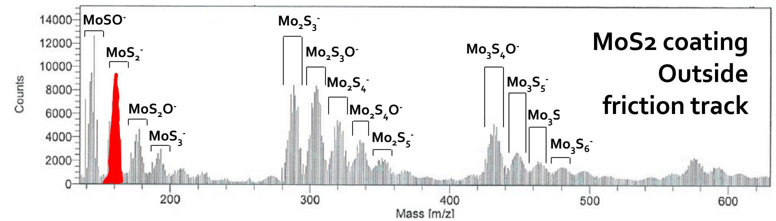
10 Cycles



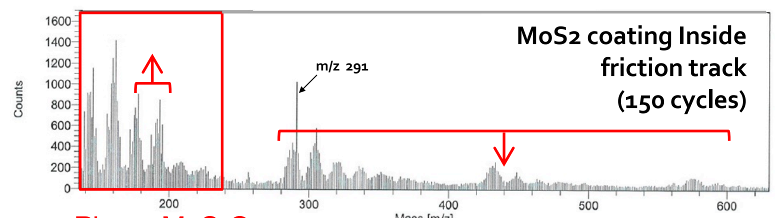
150 Cycles







Evolving chemical re-arrangement

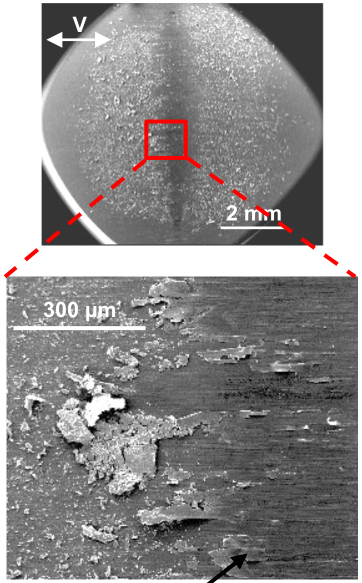


Phase MoS_xO_y

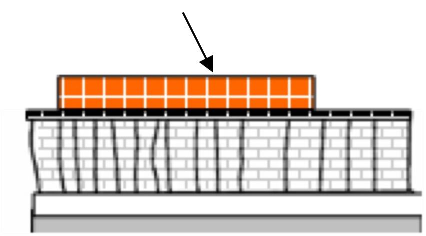
[1] Colas et al, Tribol. Int 65 (2013) *[2] Colas et al, Wear 305 (2013)* *[3] Colas et al, Wear 330 – 331 (2015)* *[4] Colas et al, Thin Solid Films 588 (2015)*

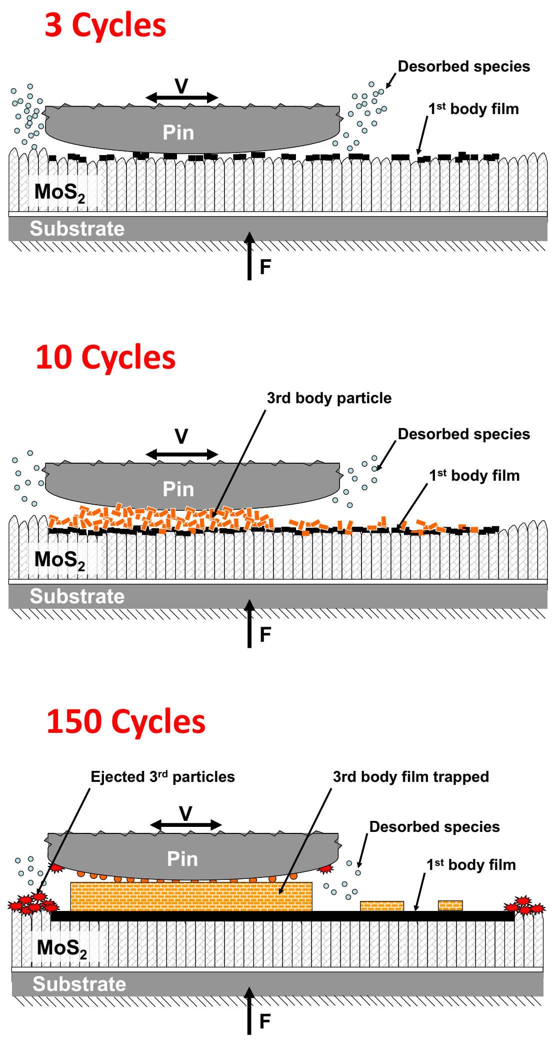
UHV (10^{-6}Pa)

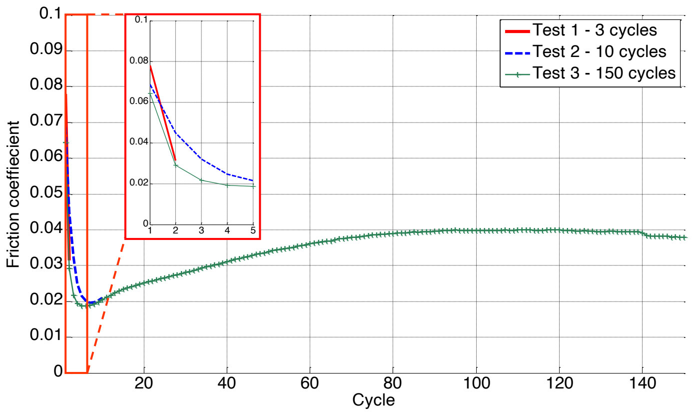
μ = 0,06, W = +++



Ductile, *MoSxOy*







Internal and **external contamination** & **coating structure control rheology** of **3rd bodies** [1-4] and consequently the tribological behaviour of MoS_2

Evolving track and 3rd body **morphologies** and chemical **composition**

[1] Colas et al, *Tribol. Int 65 (2013)* [2] Colas et al, *Wear 305 (2013)* [3] Colas et al, *Wear 330 – 331 (2015)* [4] Colas et al, *Thin Solid Films 588 (2015)*

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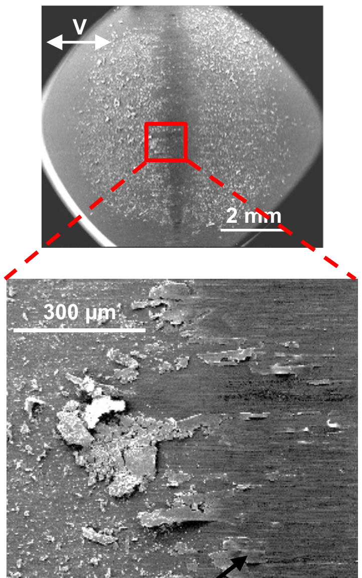
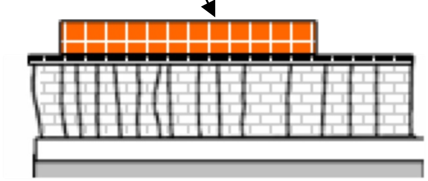


Ductile, ***MoSxOy***

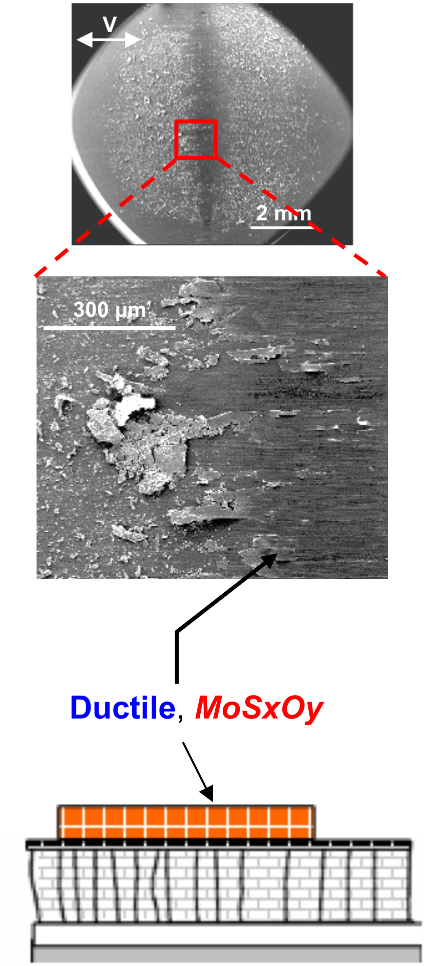


-Reaction with coating ***internal contaminants***

-Plastic flow and sliding

UHV (10^{-6} Pa)

μ = 0,06, W = +++

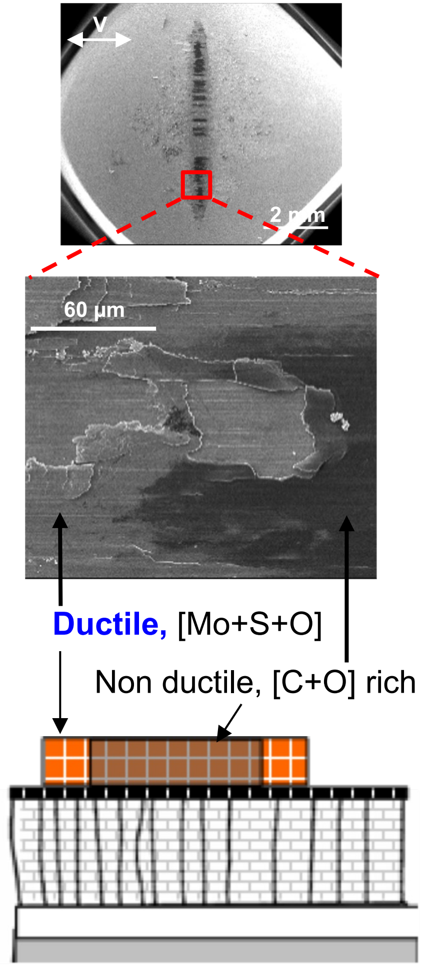


-Reaction with coating *internal contaminants*

-Plastic flow and sliding

HV (10^{-3} Pa)

μ = 0,02, W = +



-**Reaction with** contaminant and **environment**

-Sliding and **Plastic flow**

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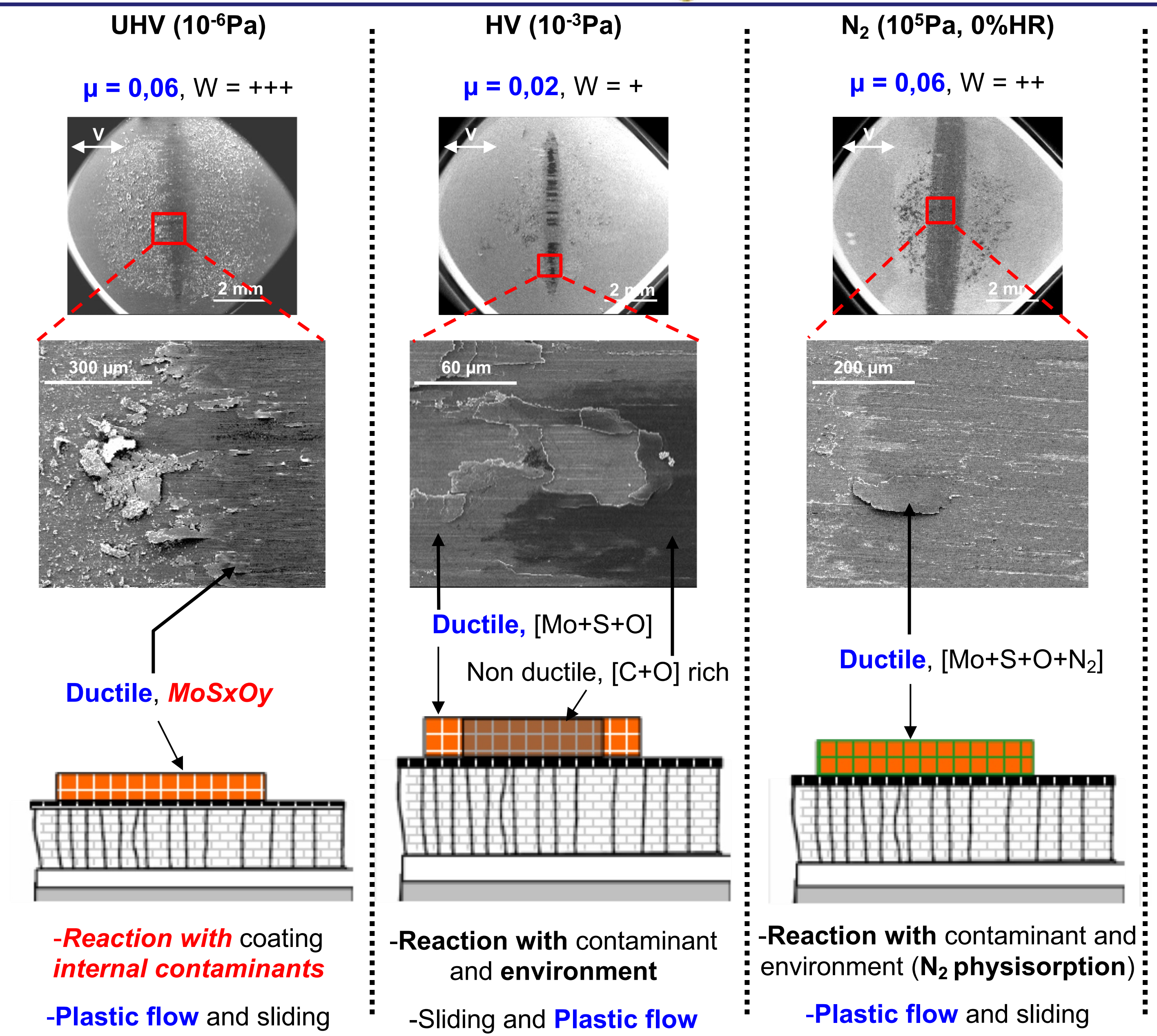
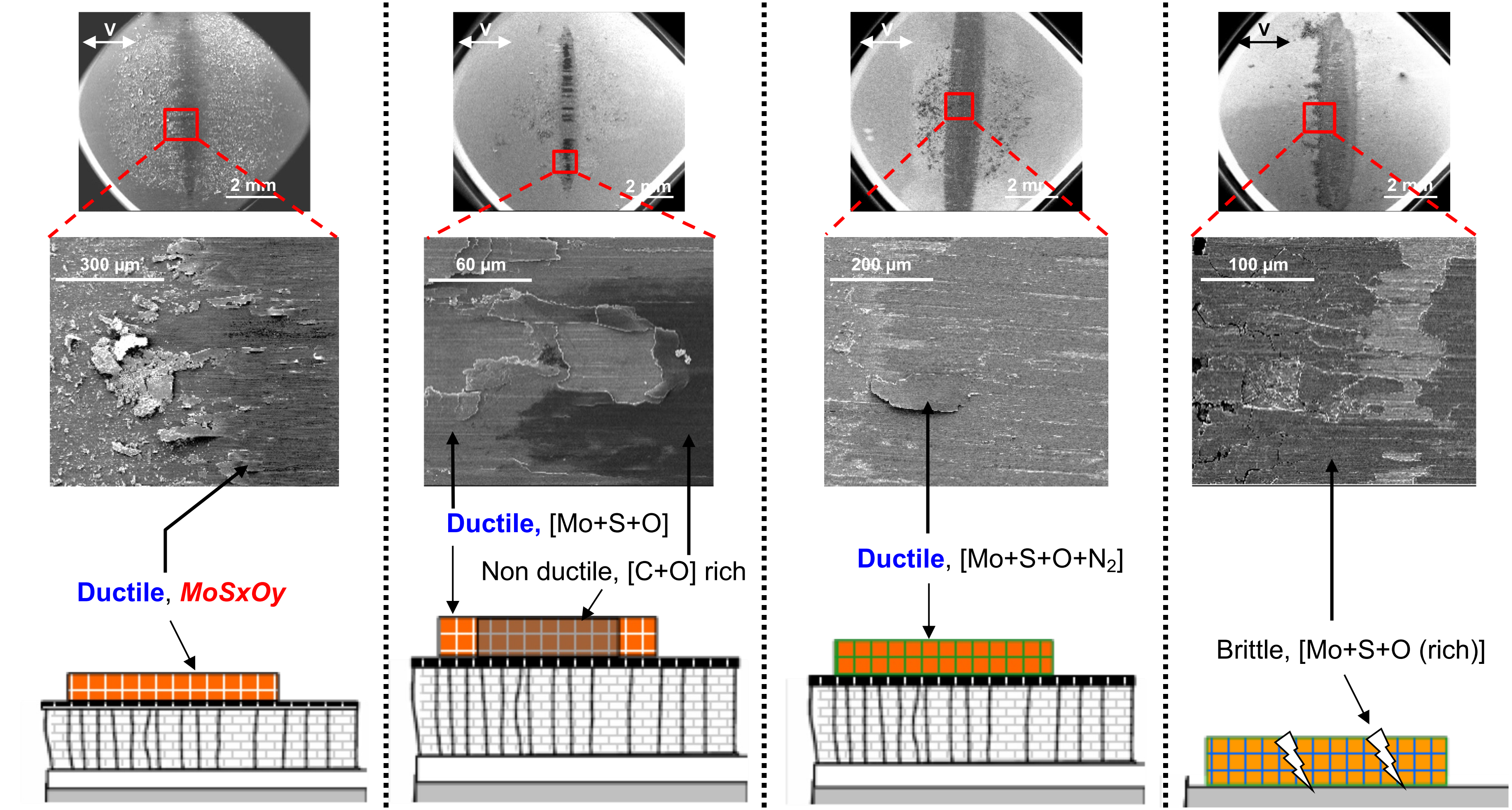
lmgc LABORATOIRE de MÉCANIQUE et GÉNIE CIVIL
AAC aerospace & advanced composites



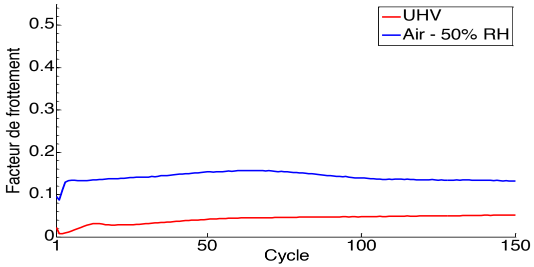
cnes CENTRE NATIONAL D'ÉTUDES SPATIALES | INSTITUT DES SCIENCES ANALYTIQUES | Mateis | femto-st SCIENCES & TECHNOLOGIES | LaMCoS UMR 5259 | UNIVERSITY OF TORONTO | NanoM² | LABORATOIRE de MÉCANIQUE et GÉNIE CIVIL | AAC aerospace & advanced composites

UHV (10^{-6}Pa)	HV (10^{-3}Pa)	N_2 (10^5Pa, 0%HR)	Air (10^5Pa, 50%HR)
μ = 0,06, W = +++	**μ = 0,02**, W = +	**μ = 0,06**, W = ++	μ = 0,13, W = +++++

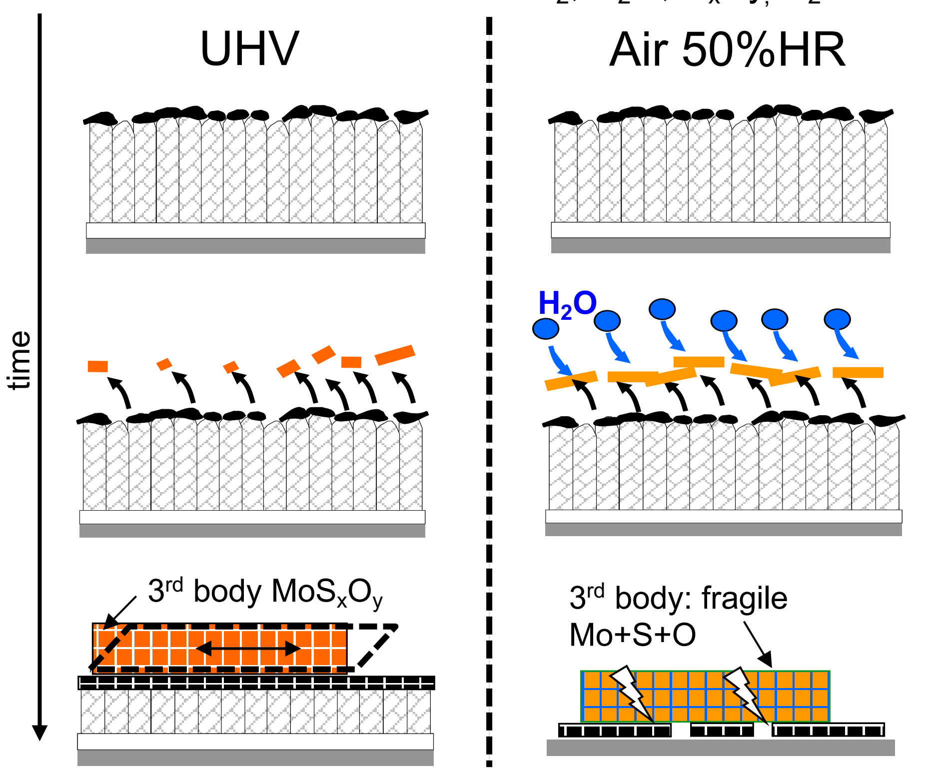


UHV (10^{-6}Pa)	HV (10^{-3}Pa)	N_2 (10^5Pa, 0%HR)	Air (10^5Pa, 50%HR)
-*Reaction with* coating *internal contaminants*	-**Reaction with** contaminant and **environment**	-**Reaction with** contaminant and environment (**N_2 physisorption**)	-**Important Reaction with environment** (H_2O)
-**Plastic flow** and sliding	-Sliding and **Plastic flow**	-**Plastic flow** and sliding	-Sliding

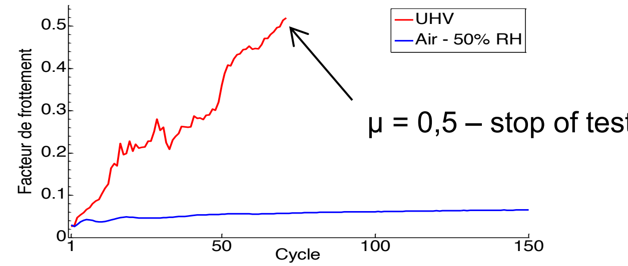
MoS_2 - C



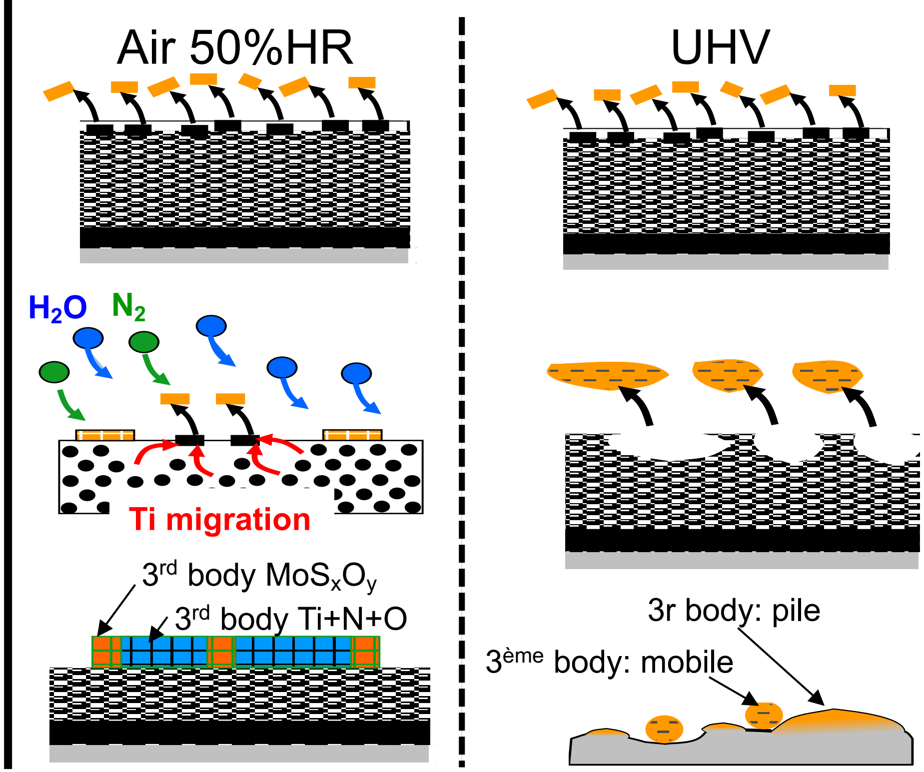
Internal contaminats : CO_2, H_2O, C_xHy, H_2



MoS_2+Ti



Internal contaminants : Ar



MoS2 and MoS2 + Ti are definitively not optimal (in these conditions!)

Does an optimum exist ?

Name	Additional metal	Structure	
MoS2-c	none	Nanocristalline	Classical in space
MoS2 + Ti (MoST)	Ti (about 8%)	Amorphous	Used for low cycle space application
MoS2 + WC	WC (% not given)	WC nanocristalline in amourphous MoS_2	Asked to be validated by agencies
MoS2 + MetalX	Ta (% not given)	Not given	New material

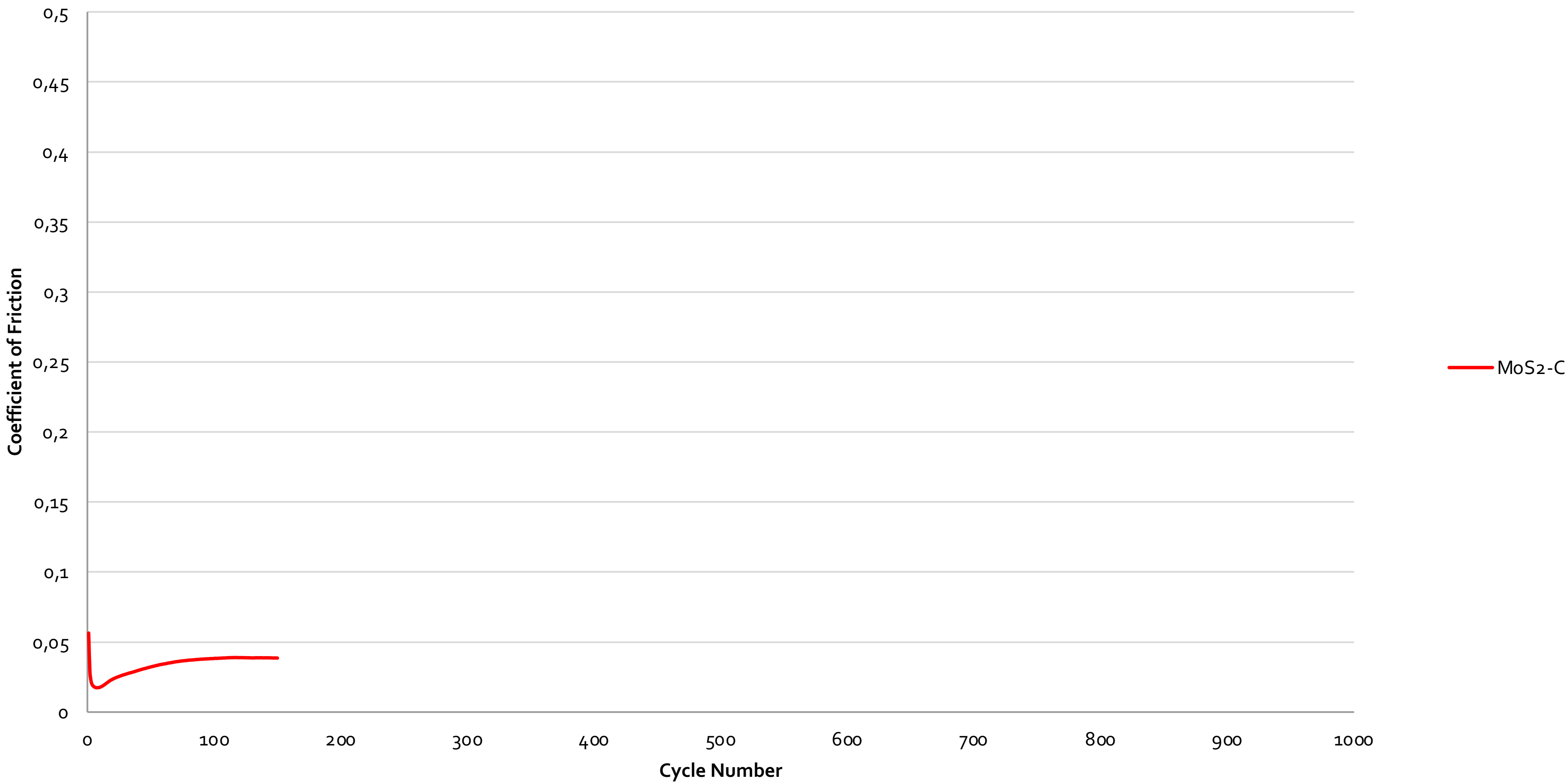
** New world patented material (WO/2022/254130 CNES-INSA-LIST).*

UHV

Humid air

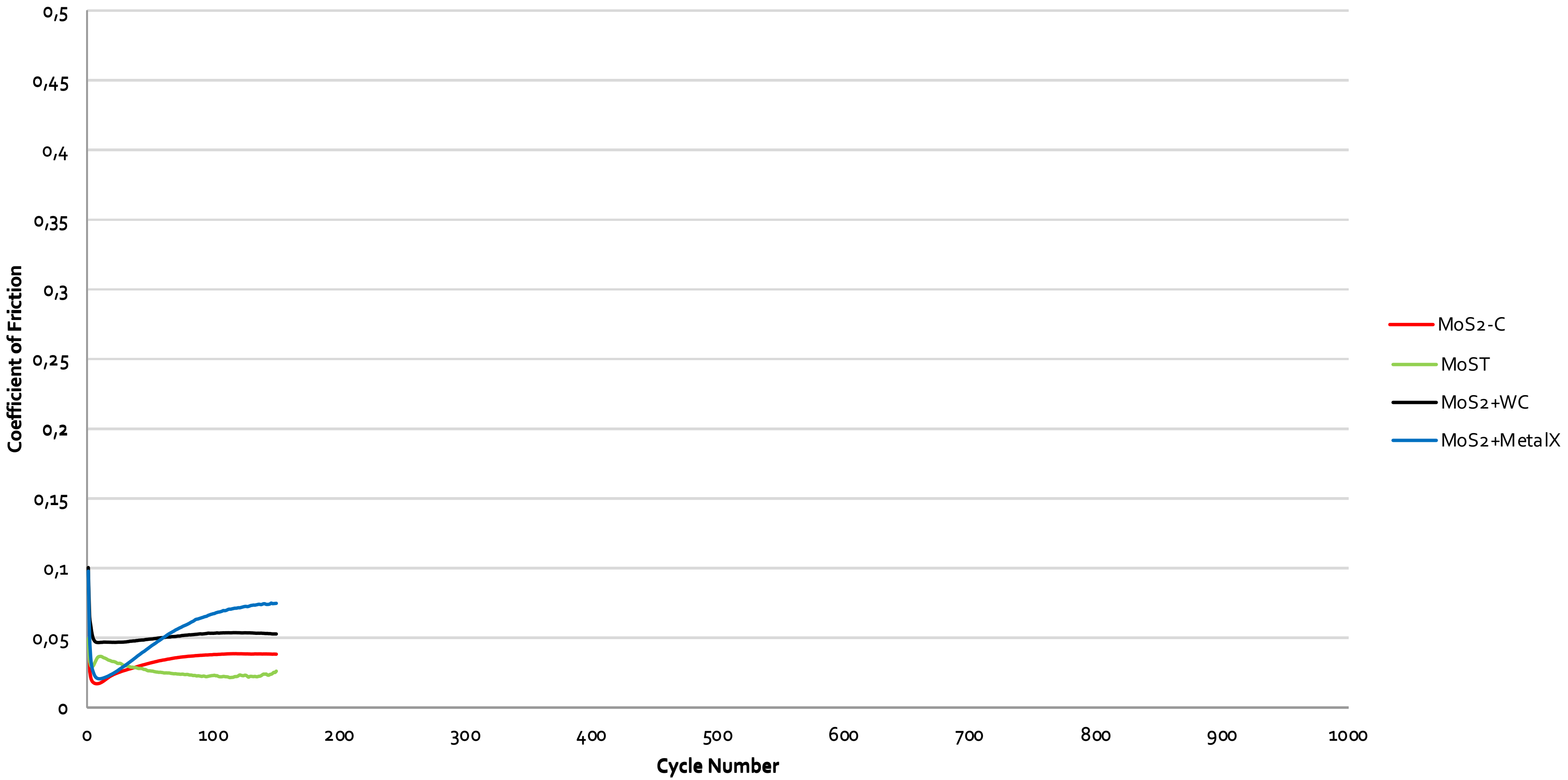
Transition Humid Air - UHV

UHV Friction coefficient after 150 cycles



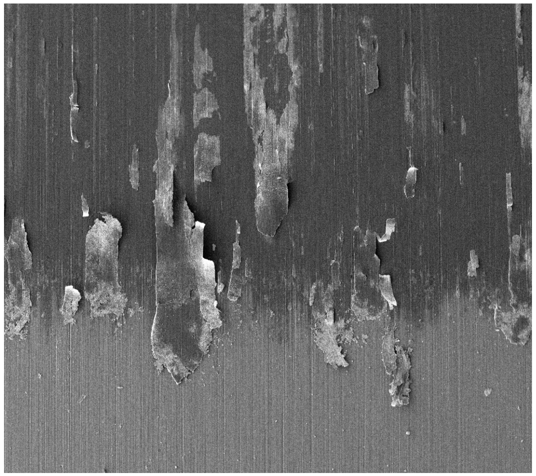
Classical behaviour of « MoS_2-c » Blösch-Vilab under UHV (G. Colas PhD, 2009) : μ ~ 0,04

UHV Friction coefficient after 150 cycles

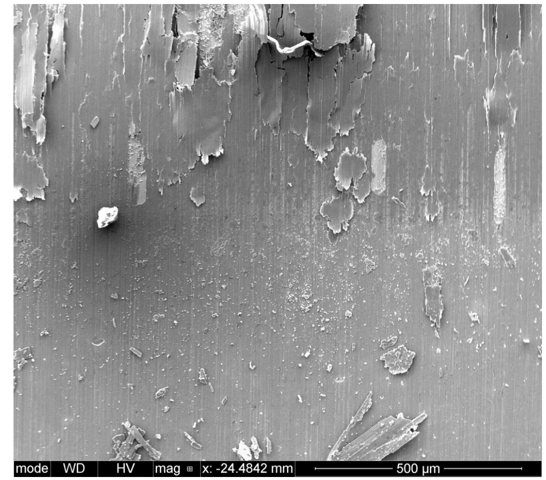


MoS2-c, MoST, MoS2 + WC et MoS2 + Metal X:
Classicaly low friction coefficient in all cases < 0,1

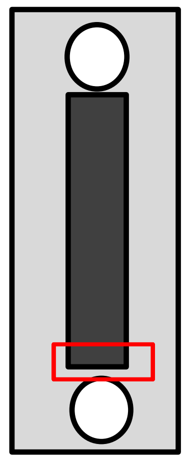
UHV SEM observation after 150 cycles



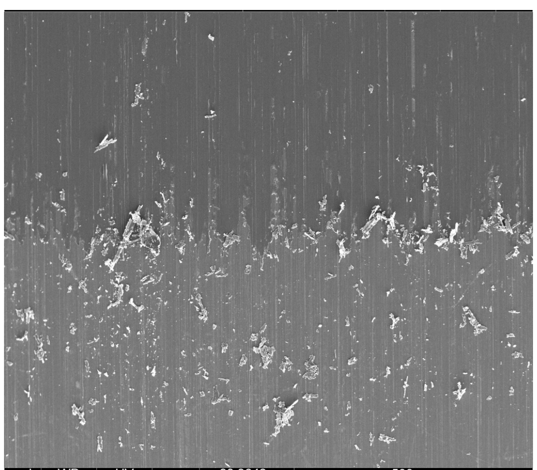
MoS_2 alone



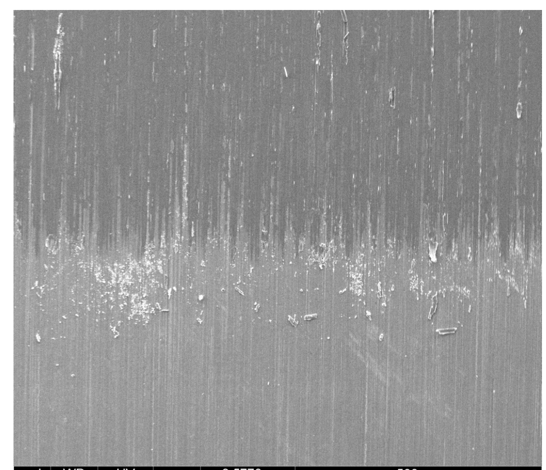
MoS_2 + WC



500 µm

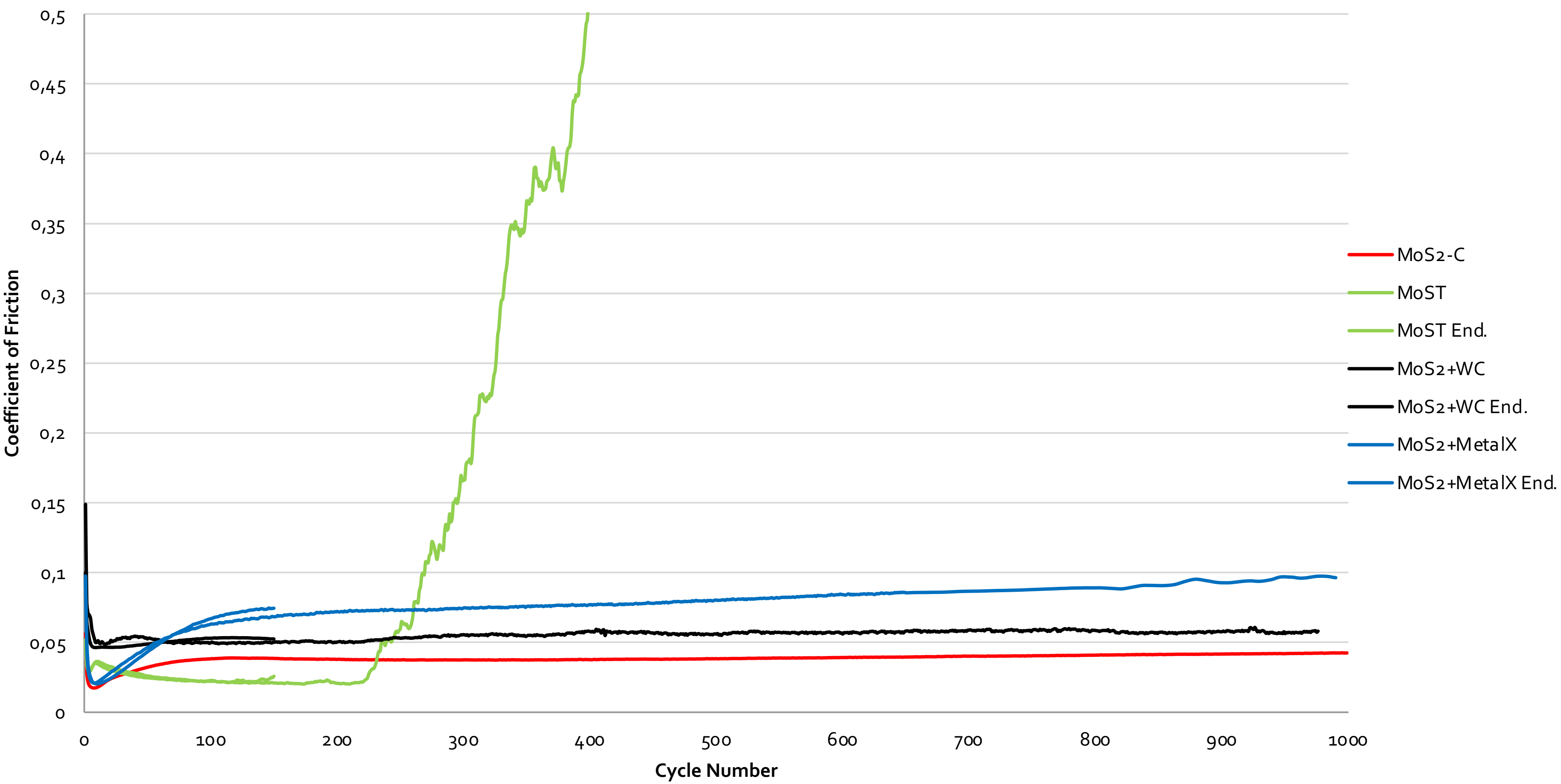


MoS_2 + Ti



MoS_2 + Metal X

UHV Friction coefficient after 150 cycles vs. after 1000 cycles (or less)

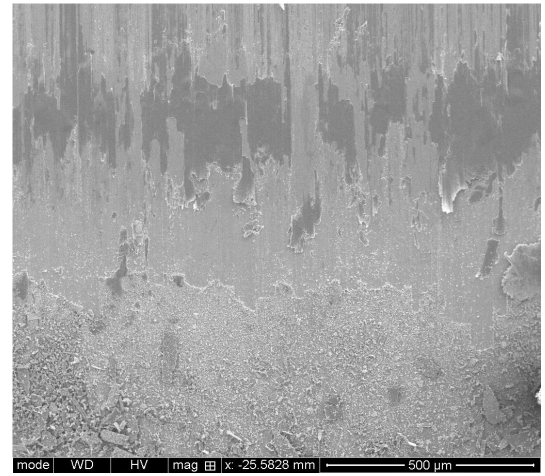


MoST: High increase of μ, test stopped for μ = 0,5

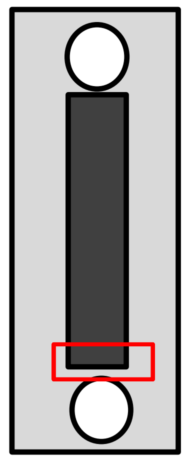
MoS2-C, MoS2 + WC et MoS2 + Metal X: Quite constant μ, < 0.1 for all cases

UHV SEM observation after 1000 cycles (or less)

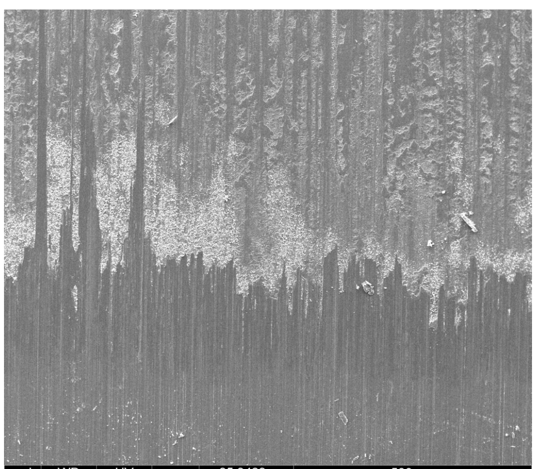
MoS$_2$ alone



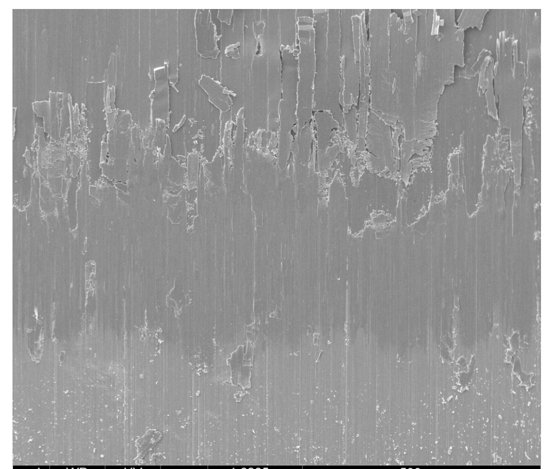
MoS$_2$ + WC



500 µm



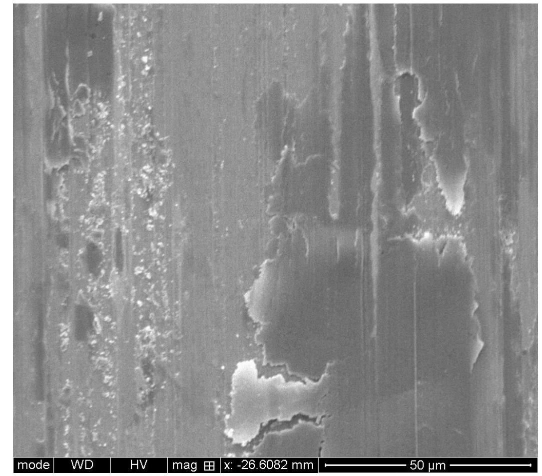
MoS$_2$ + Ti



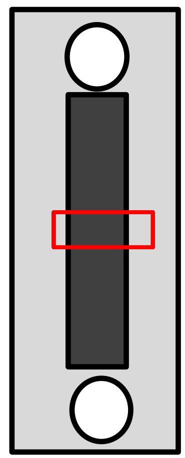
MoS$_2$ + Metal X

UHV SEM observation after 1000 cycles (or less)

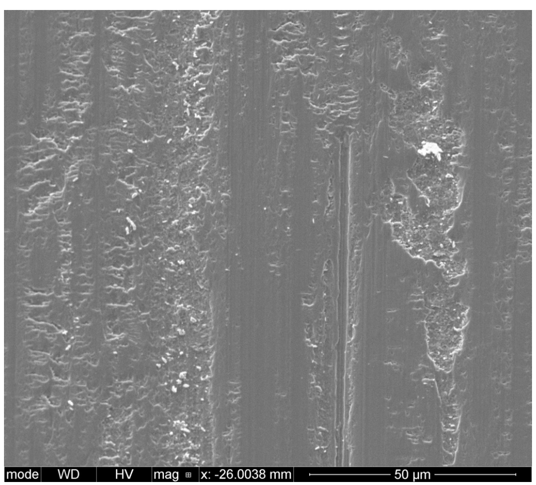
MoS_2 seul



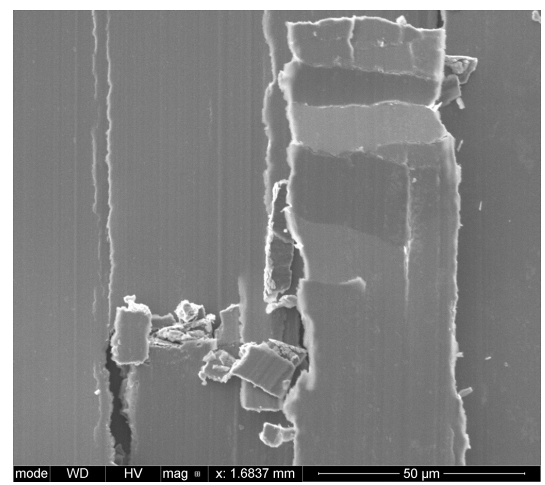
MoS_2 + WC



50 µm

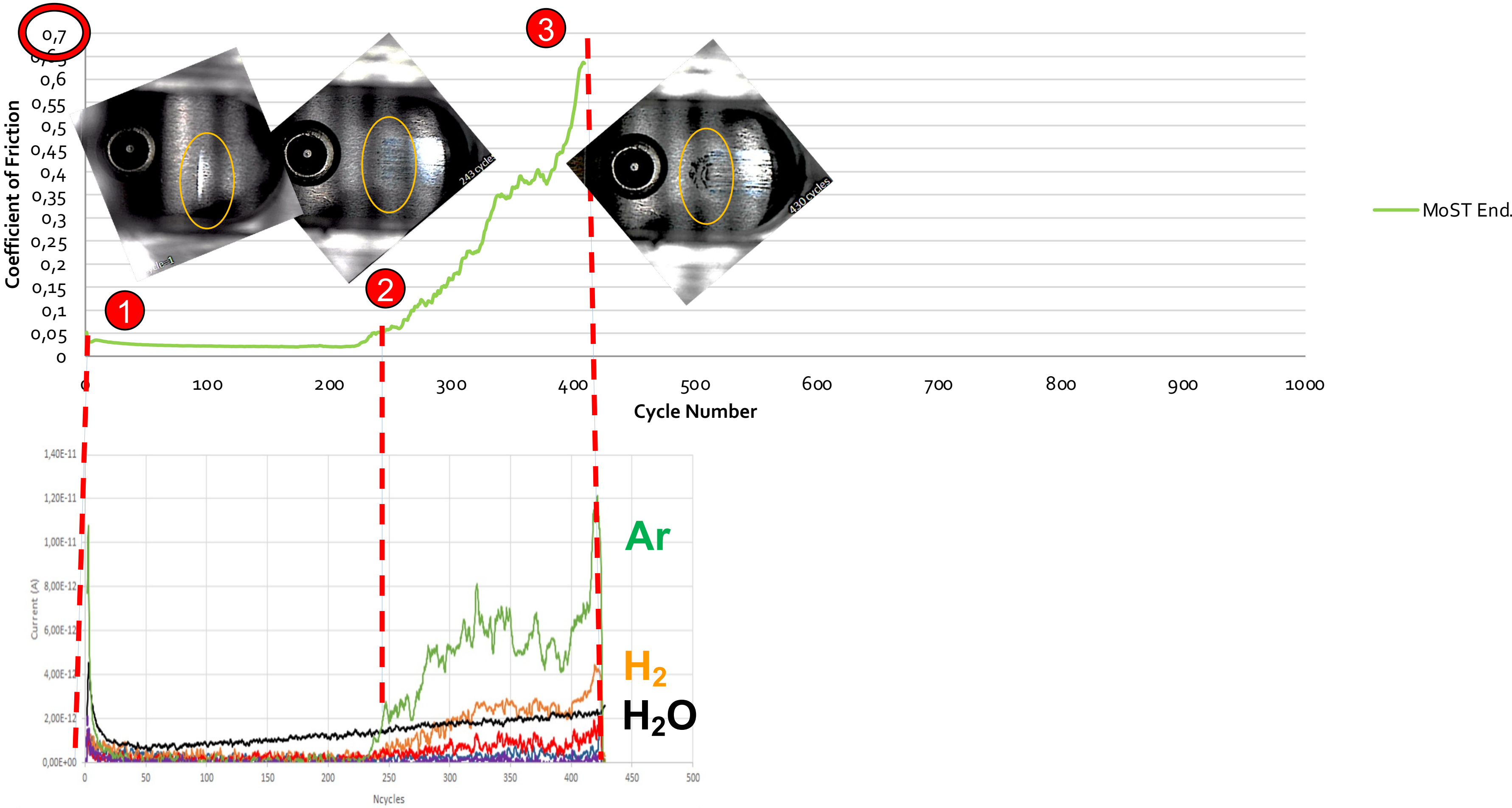


MoS_2 + Ti



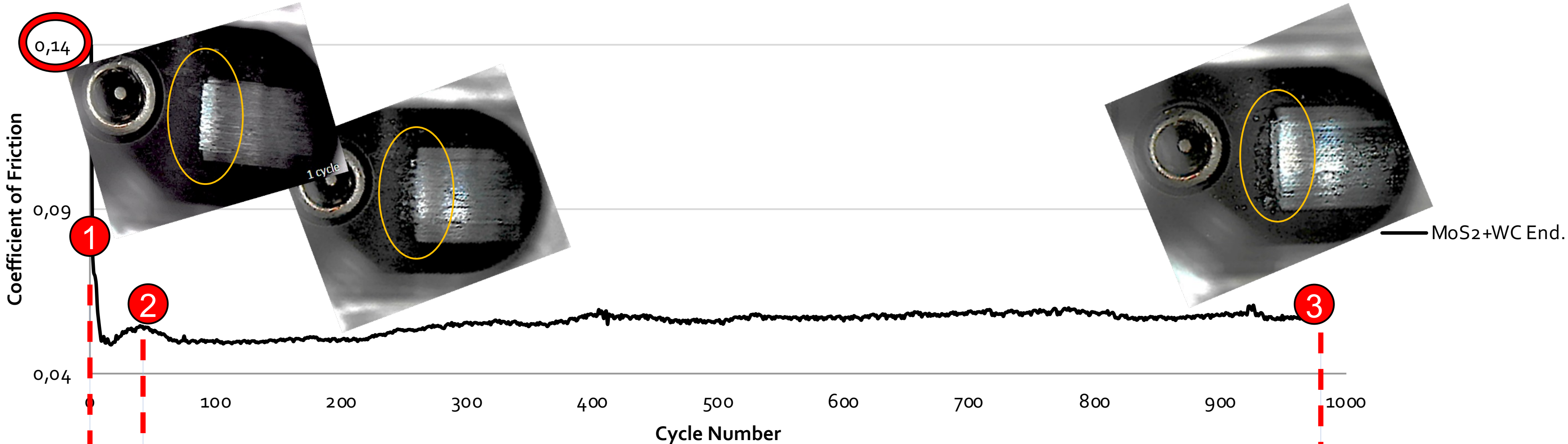
MoS_2 + Metal X

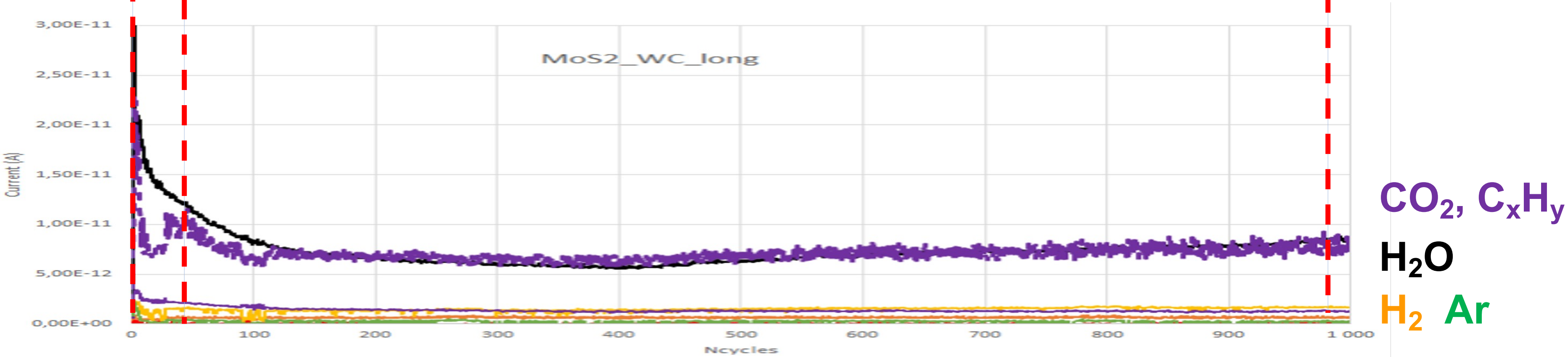
UHV **MoS2 + Ti –** synthesis with mass spectrometry



- **Ar** is linked to deposition process et $\mathbf{H_2}$ is linked to stainless stell fabrication process
- Link between **Ar** outgasing, and both coating wear and μ
- Emission of $\mathbf{H_2}$ linked to AISI440C substrat outgasing (friction between 1st bodies, coating removed)

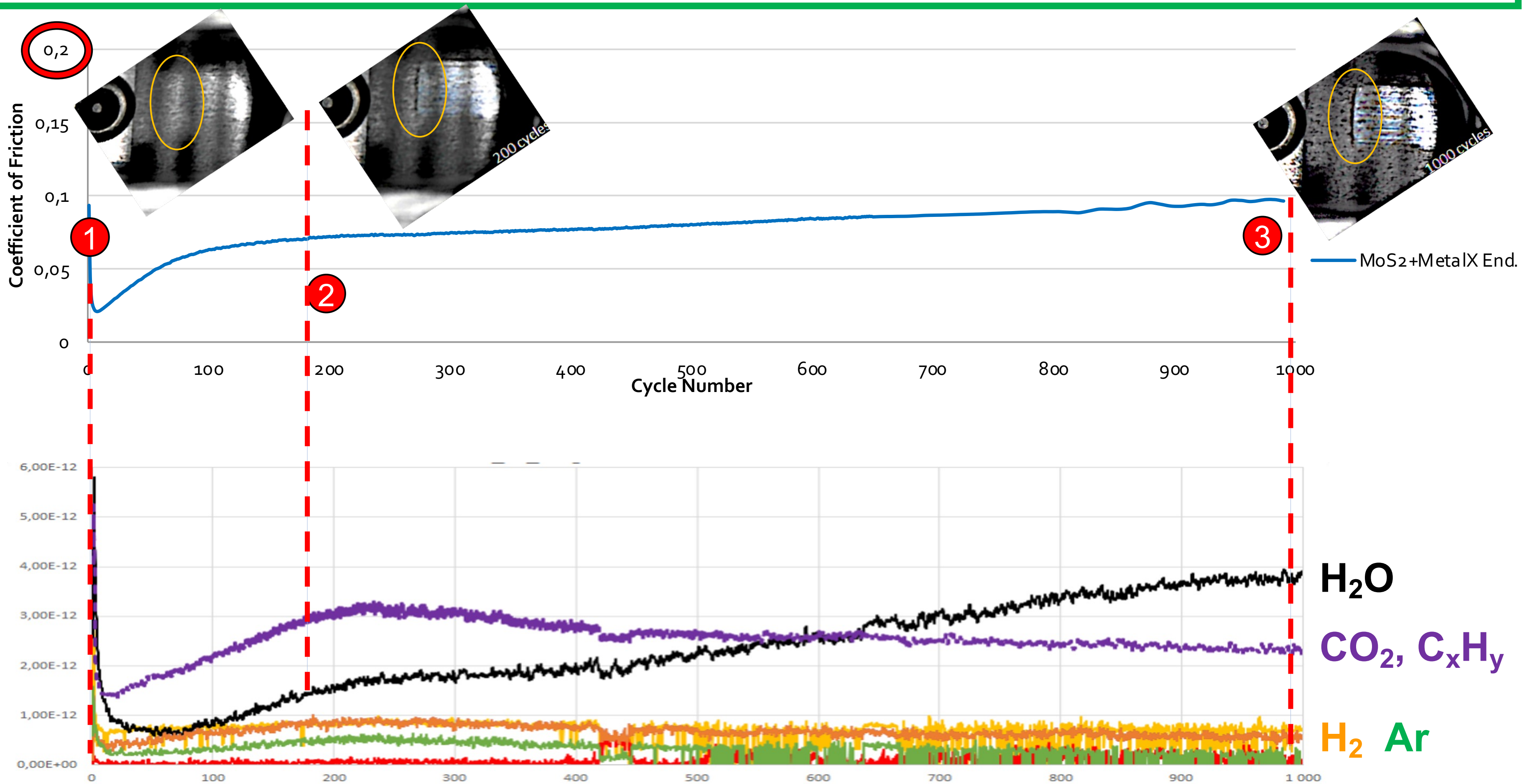
Evaluation sous UHV **MoS2 + WC –** synthesis with mass spectrometry all along 1000 cycles





- Link between **CO_2 / C_xH_y** (after 100 cycles for H_20) outgasing and μ
- Link between **H_2O, CO_2 / C_xH_y** outgasing and 3_r^d body particules ejection (nearly continous)
- No outgasing of **H_2**, the substrat remove untouched

UHV **MoS2 + Metal X -** synthesis with mass spectrometry all along 1000 cycles

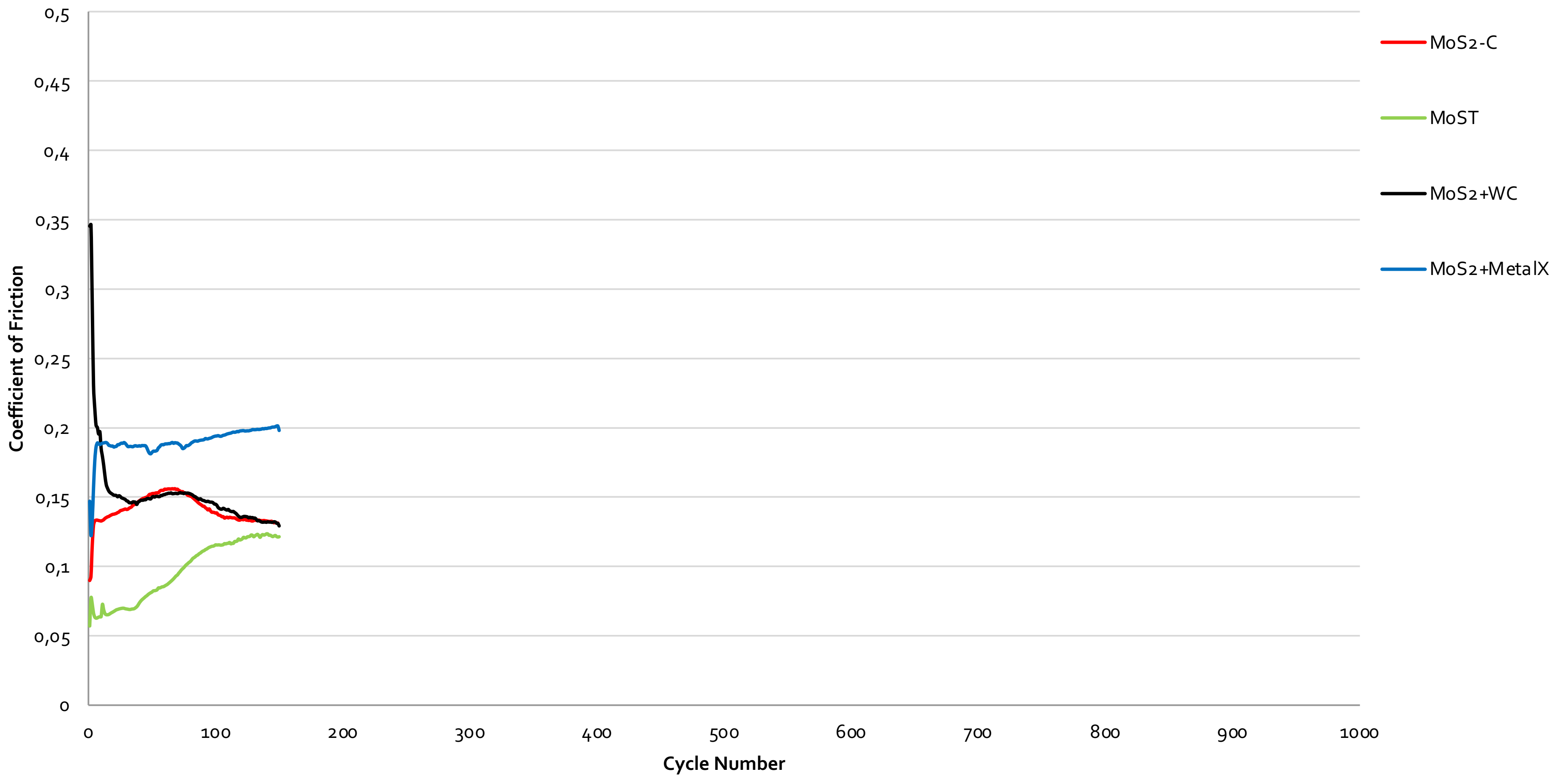


- Link betweek **H_2O** outgasing and μ
- Unclear linked between **H_2O**, **CO_2** ou **C_xH_y** outgasing and 3rd body particules ejection

Synthesis

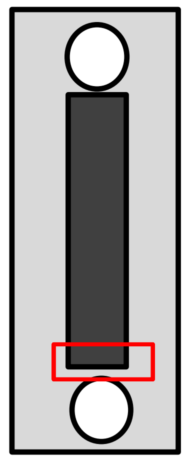
After 1000 cycles	Friction						Wear (not quanti.)		
	Level			Stability			UHV	Hum Air.	Transition
	UHV	Hum. Air	Transition	UHV	Hum. Air	Transition			
MoS2 - c	0,04			Oui			++		
MoS2 + Ti	0,7			Non			++++		
MoS2 + WC	0,06			Oui			++		
MoS2 + Metal X	0,09			Presque			+		

Humid air Friction coefficient after 150 cycles

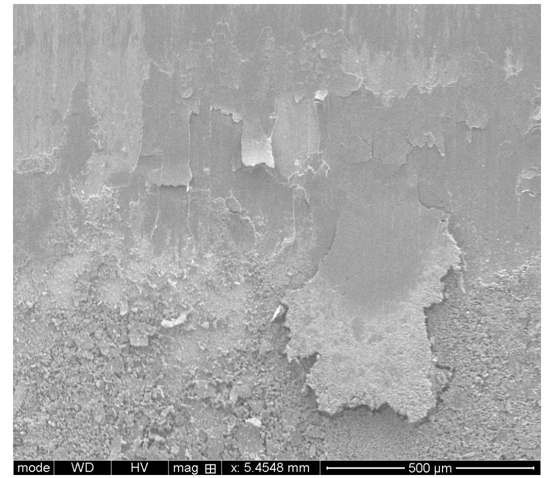


Humid air SEM observation after 150 cycles

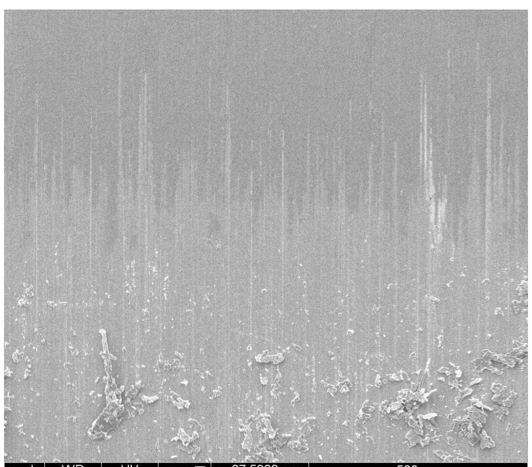
MoS_2 alone



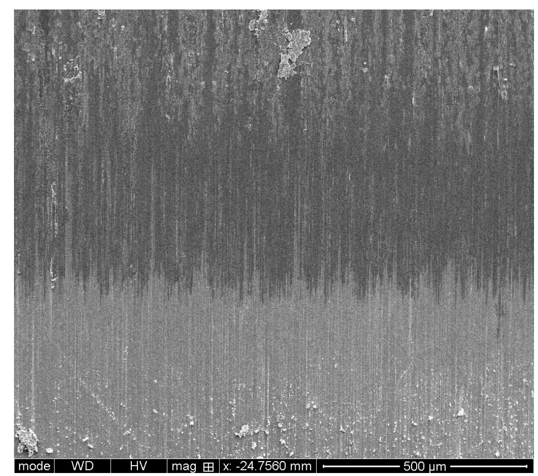
500 µm



MoS_2 + WC

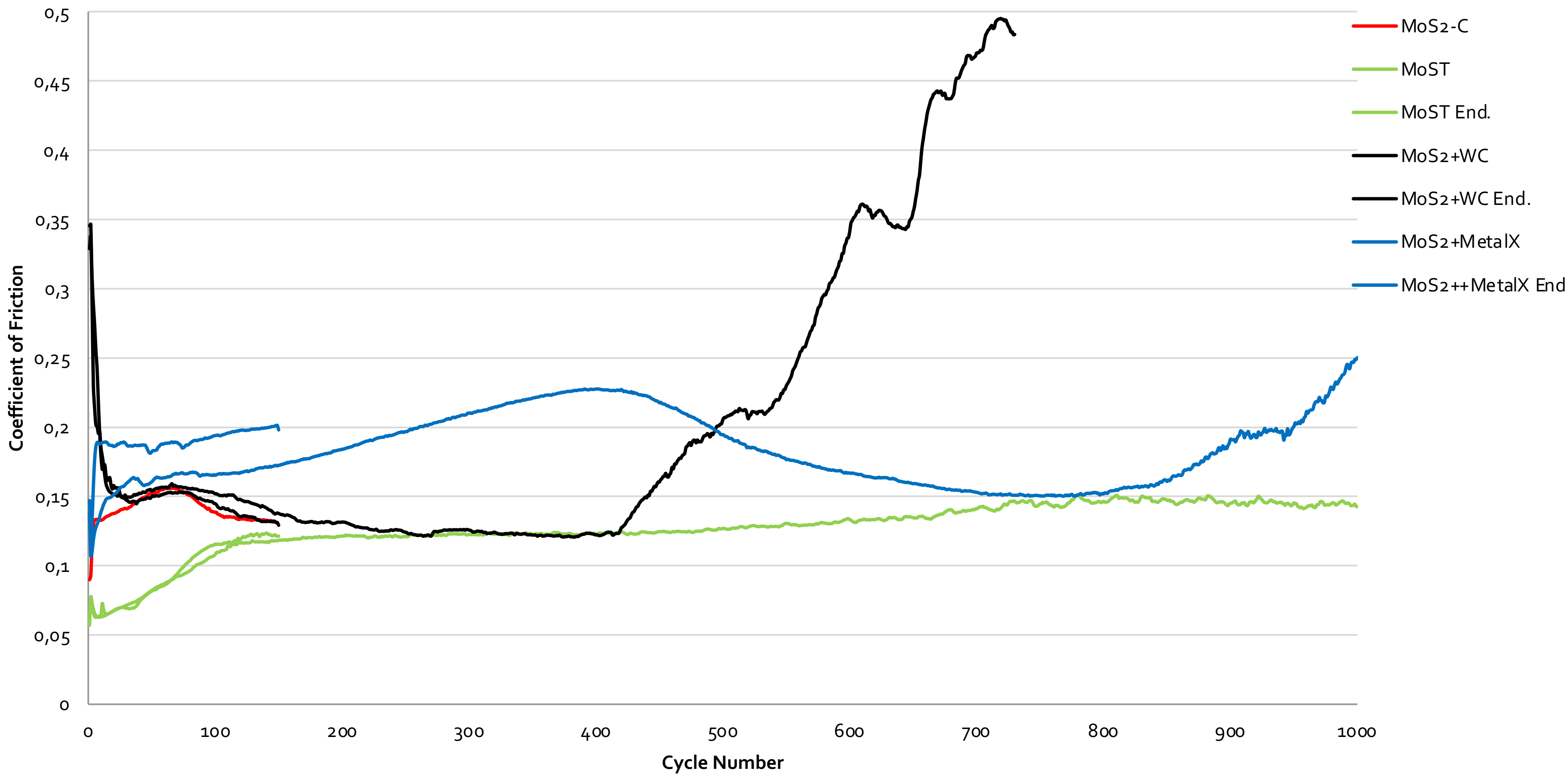


MoS_2 + Ti



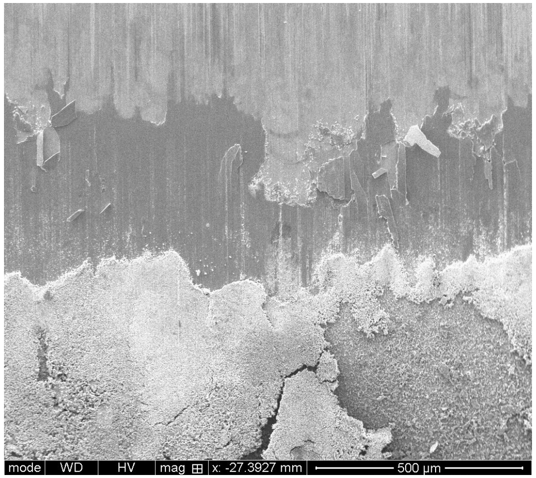
MoS_2 + Metal X

Humid air Friction coefficient after 150 cycles

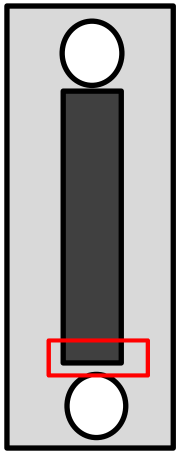


Humid air SEM observation after 1000 cycles (or less)

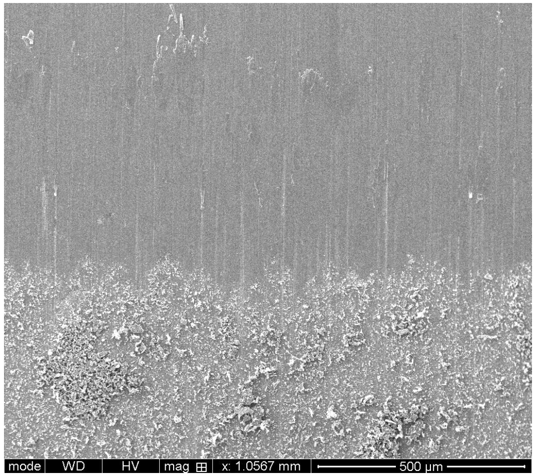
MoS_2 seul



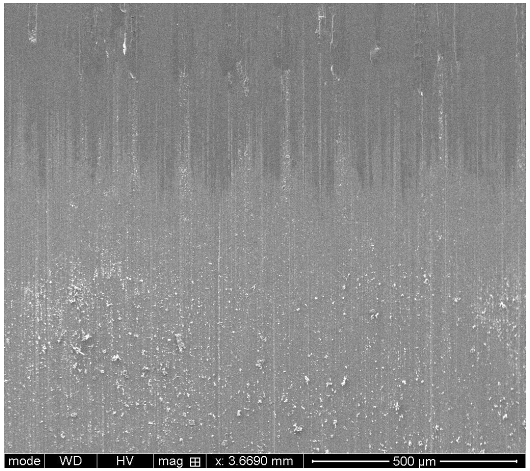
MoS_2 + WC



500 µm



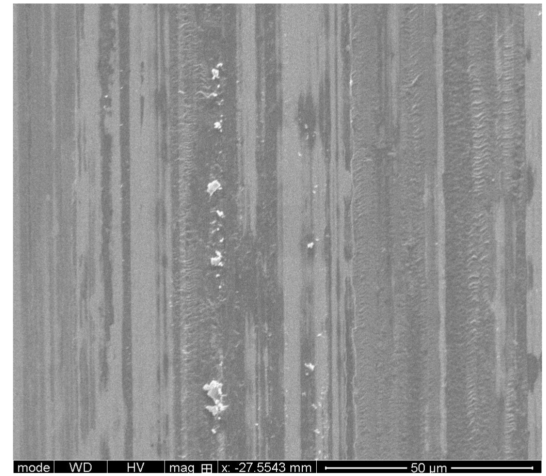
MoS_2 + Ti



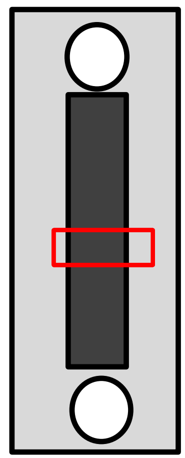
MoS_2 + Metal X

EvalHumid air SEM observation after1000 cycles

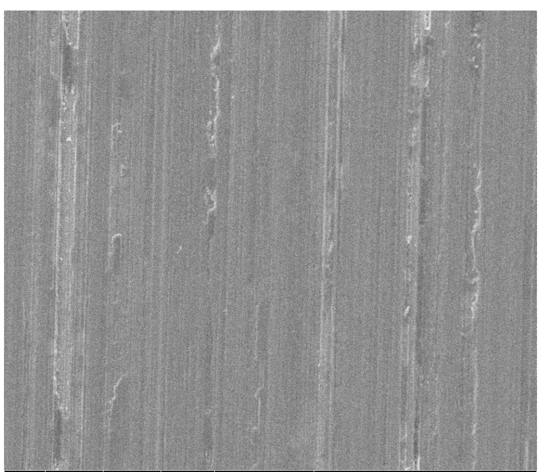
MoS_2 alone



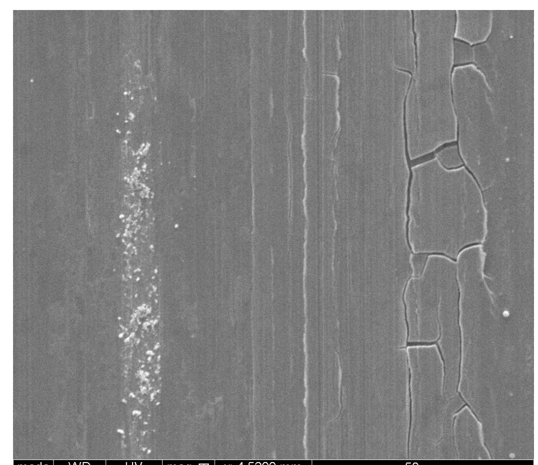
MoS_2 + WC



50 µm



MoS_2 + Ti

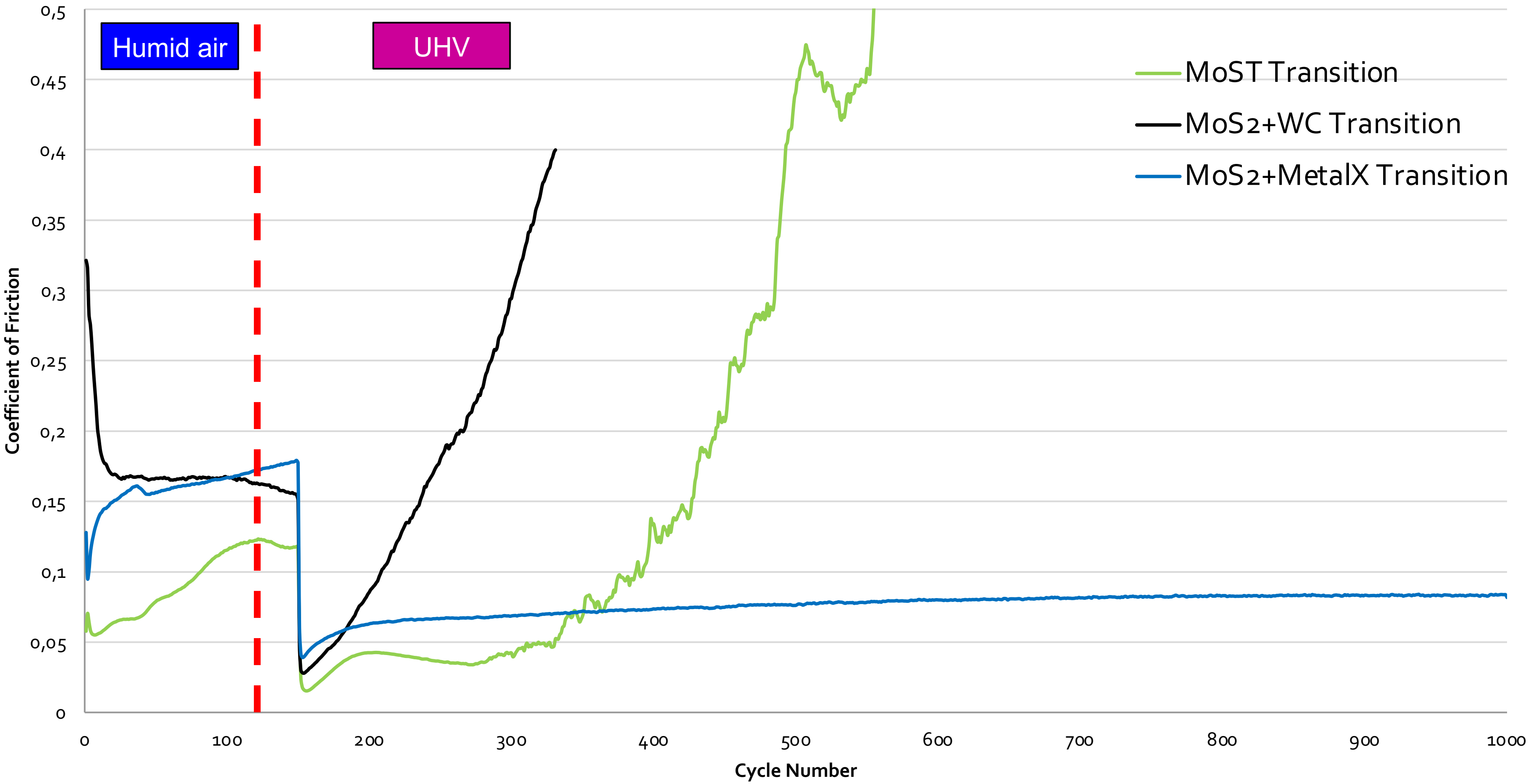


MoS_2 + Metal X

Synthesis

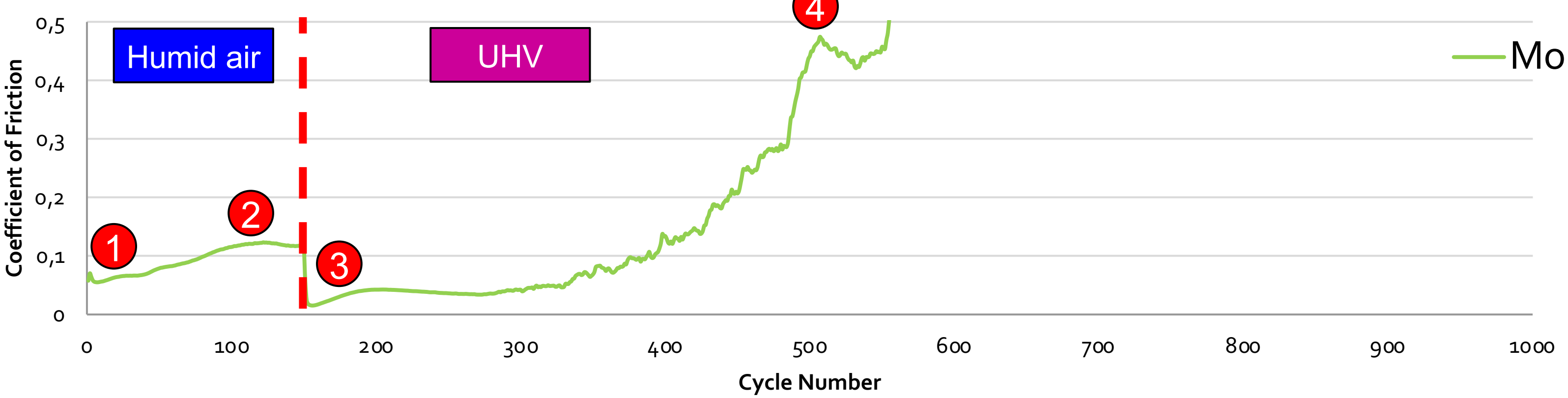
After 1000 cycles	Friction						Wear (not quanti.)		
	Level			Stability			UHV	Hum Air.	Transition
	UHV	Hum. Air	Transition	UHV	Hum. Air	Transition			
MoS2 - c	0,06			Yes			++		
MoS2 + Ti	0,7	0,15		No	nearly		++++	++	
MoS2 + WC	0,06	0,5		Yes	No		++	+++	
MoS2 + Metal X	0,09	0,25		Nearly	Periodic		+	++	

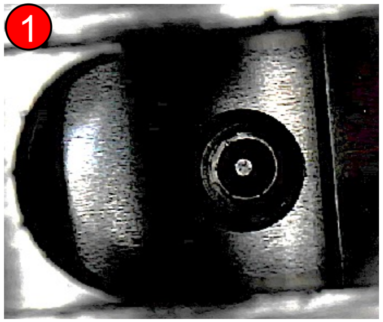
TRANSITION between Humid air and UHV Friction coefficient after 1000 cycles (or less)



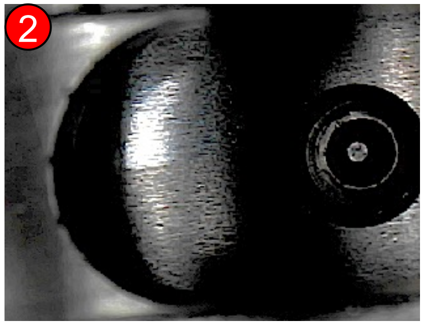
Only the « **MoS_2 + Metal X » do not have a memory effect under UHV after the humid air cycles on μ**

TRANSITION between Humid air and UHV Friction coefficient after 1000 cycles (or less)

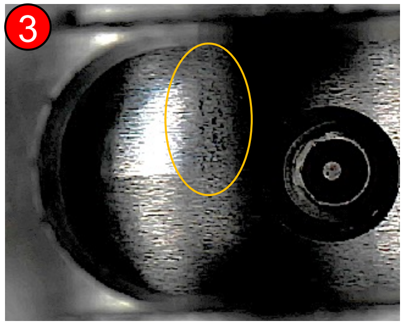




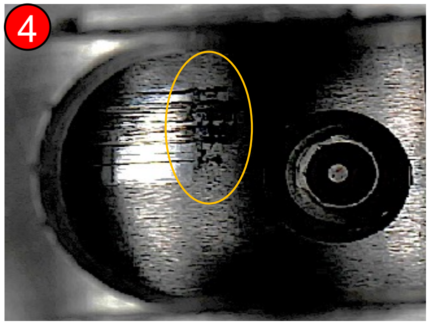
Cycle 3 (μ=0.06)



Cycle 111 (μ=0.12)

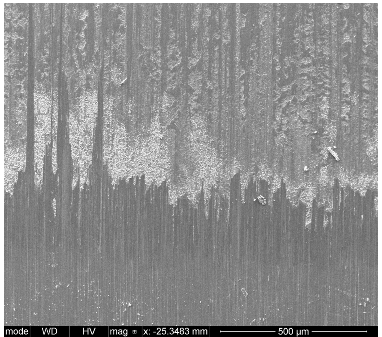


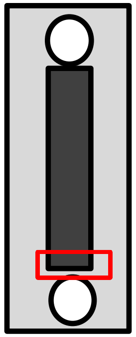
Cycle 184 (μ=0.03)



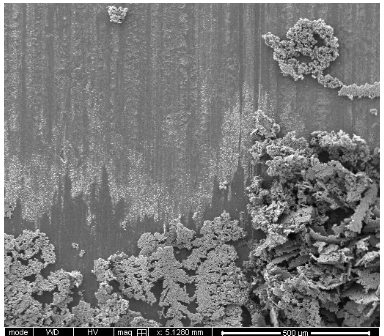
Cycle 508 (μ=0.47)

UHV alone



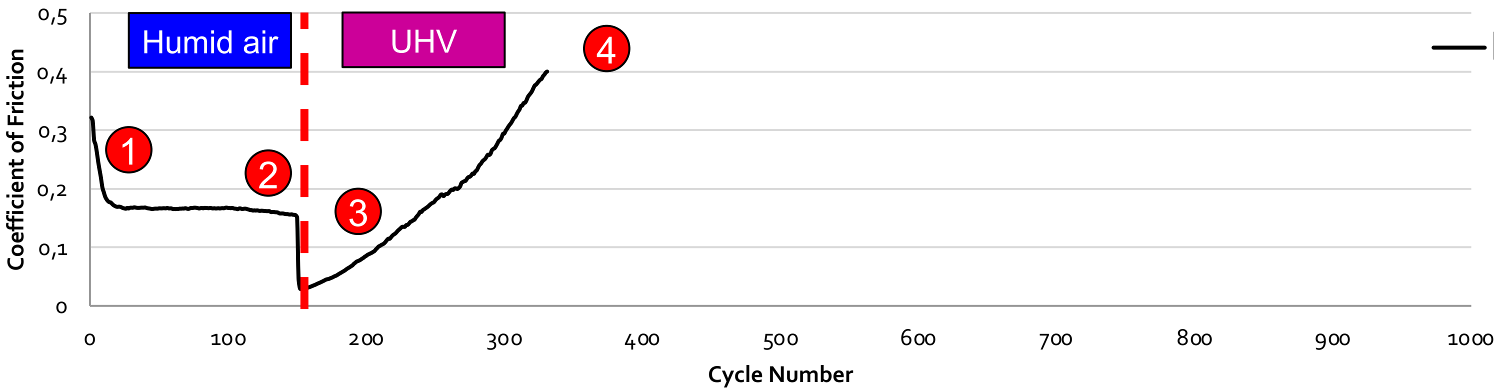


500 μm

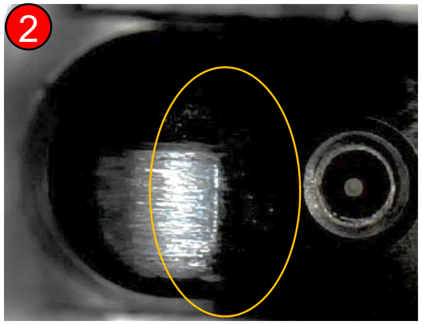


Transition (end)

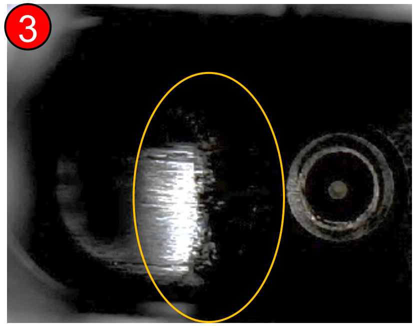
TRANSITION between Humid air and UHV — Friction coefficient after 1000 cycles (or less)



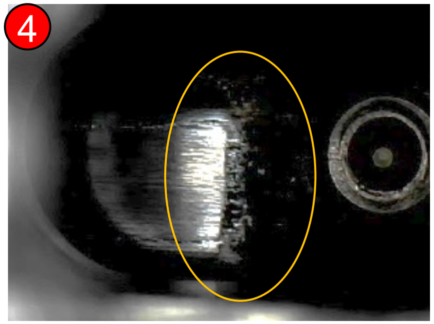
Cycle 3 (μ=0.28)



Cycle 110 (μ=0.16)

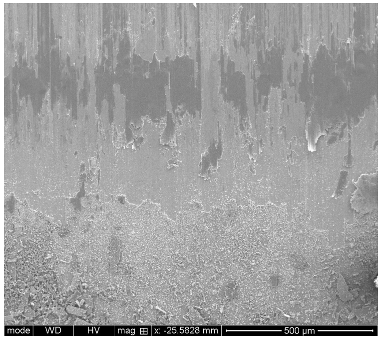


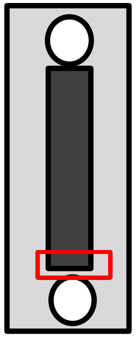
Cycle 172 (μ=0.05)



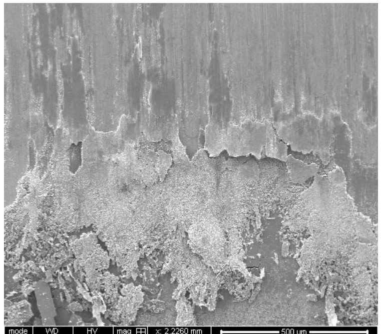
Cycle 331 (μ=0.40)

UHV alone



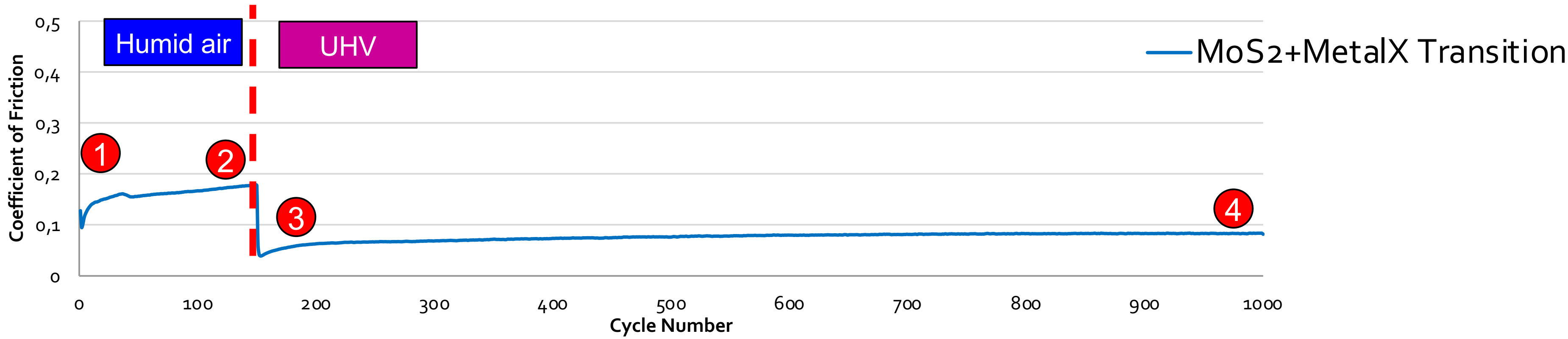


500 μm

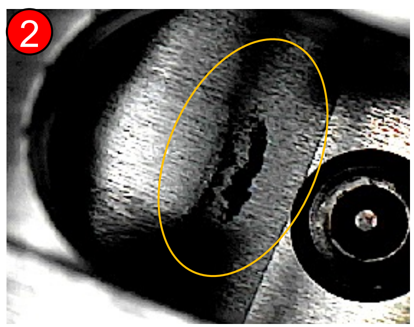


Transition (end)

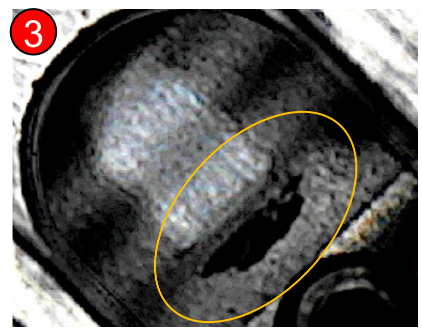
TRANSITION between Humid air and UHV — Friction coefficient after 1000 cycles (or less)



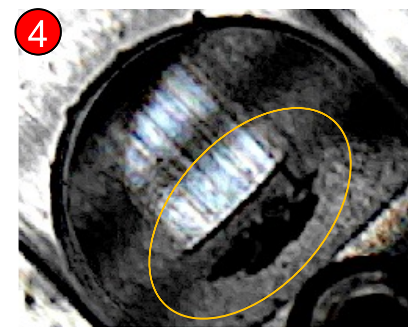
Cycle 9 (μ=0.13)



Cycle 110 (μ=0.17)

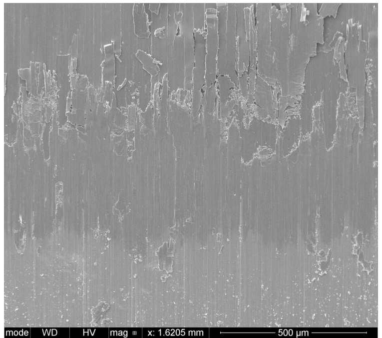


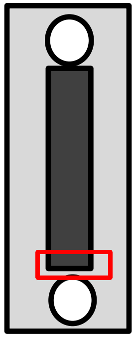
Cycle 191 (μ=0.06)



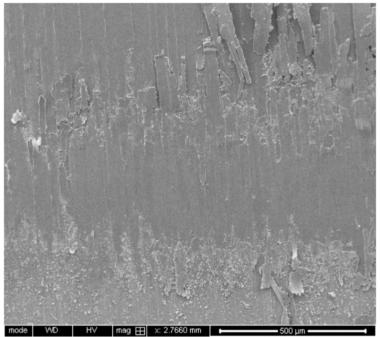
Cycle 978 (μ=0.08)

UHV alone





500 μm



Transition (end)

Synthesis

After 1000 cycles	Friction						Wear (not quanti.)		
	Level			Stability			UHV	Hum Air.	Transition
	UHV	Hum. Air	Transition	UHV	Hum. Air	Transition			
MoS2 - c	0,06			Yes			++		
MoS2 + Ti	0,7	0,15	0,5	No	nearly	No	+++	++	++++
MoS2 + WC	0,06	0,5	0,4	Yes	No	No	++	+++	++++
MoS2 + Metal X	0,09	0,25	0,08	Nearly	Periodic	Nearly	+	++	+

Question: why the MoS2 + Metal X works well ?

Some litterature to read:

P. Serles et al., *High Performance Space Lubrication of MoS_2 with Tantalum*, **Advanced Functional Materials**, 2022, Vol 32 (20), 2110429, https://doi.org/10.1002/adfm.202110429

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(if you want to know more on the two presented topics)

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- P. Serles et al., *High Performance Space Lubrication of MoS_2 with Tantalum*, **Advanced Functional Materials**, 2022, Vol 32 (20), 2110429, https://doi.org/10.1002/adfm.202110429

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- Colas G et al., *Strength measurement and rupture mechanisms of a micron thick nanocrystalline MoS_2 coating using AFM based micro-bending tests*, **Journal of the Mechanics and Physics of Solids**, *2019, Vol. 128, pp. 151-161, https://doi.org/10.1016/j.jmps.2019.04.007*

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Dry tribology for space application:

From MoS_2 coating to self lubricating composite

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