
Wheel-rail contact: a tribological antagonism

Tuesday 14th april 2026

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Railway system in France



Increase of traffic
(+20% in France in 15 years)

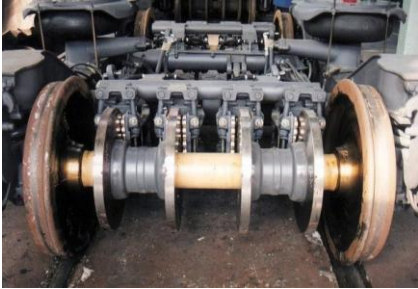
Low CO₂ emission



32 000 km of railway to maintain !
=> 32 000 km of tribological issues!

Railway system & Tribology

Braking



Tribology of the Railway system

Wheel – rail
contact



Contact between
catenary and
pantograph



Railway system & Tribology

Braking



Tribology of the Railway system

Wheel – rail
contact



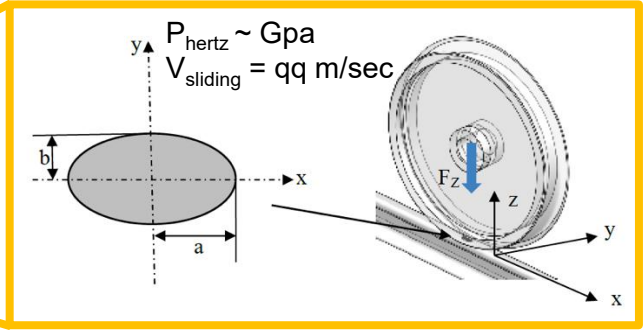
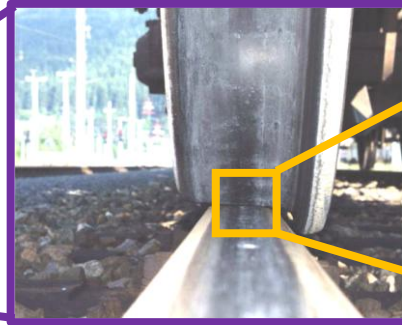
Contact between
catenary and
pantograph



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■ ■ ■

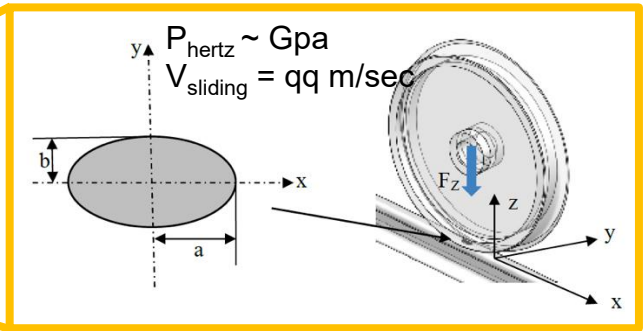
WRC, the only link between train and track



What's the comun link?



WRC, the only link between train and track



What's the comun link?



- 320 km/h
- 400 tonnes
- 52 wheels
- 1.3 cm² contact



Total ~70cm²



How many folding ?

Emergency braking: 3 km

1 584 MJ to dissipate

About **53 kJ / cm²** !
(full sliding – not realistic !)

In reality: less 2% sliding
Consequences ?

Energy dissipated in many brakes, see Pr Massi



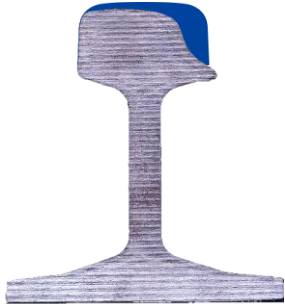
72 brake disks



WRC at the origin of several rail defects

Rail defects (many, classified by UIC)

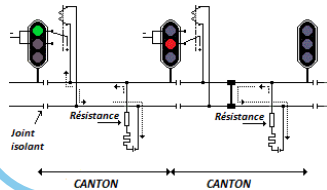
Lubrication
Badly optimized



Pollution
(ex: leaves, ...)



Unshunting



Full sliding



Corrugation wear



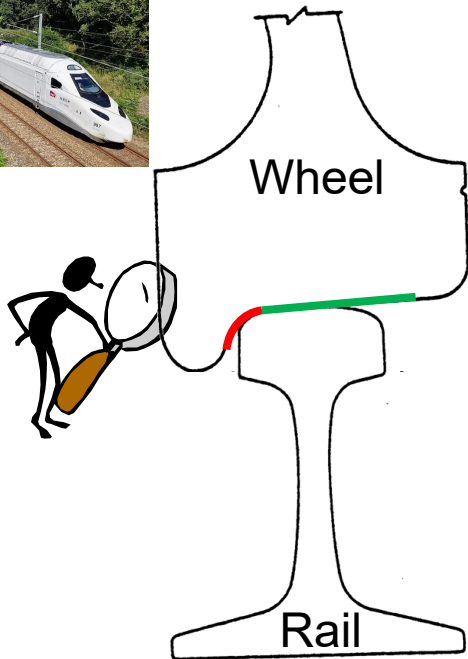
Squat (fatigue)



Need to master the wheel-rail contact **tribological antagonism** !

WRC, a tribological antagonism

What is the WRC tribological antagonism & how is this managed in real life !



Lower possible friction
(improve curving and wear)

Higher possible friction
(improve traction and braking)



On track



On board



WRC life depends on steel-on-steel **friction** and **wear** phenomena

WRC, steel-on-steel friction S ?



Frictional contact



Normal problem
(Contact pressure and area)

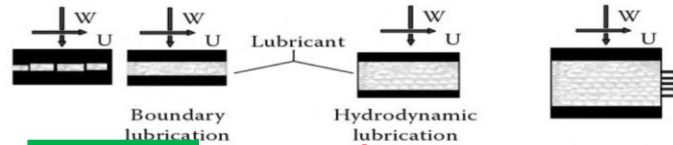
Amonton's law (1699) –
Coulomb's Law (1781)
 $F_t = \mu \times F_n$

Tangent problem
(Tangential stress and velocity field)

Hertz theory
(1880)...

Fluid: Reynolds (1882)...

Dry: Carter (1926),
Kalker (1967)...



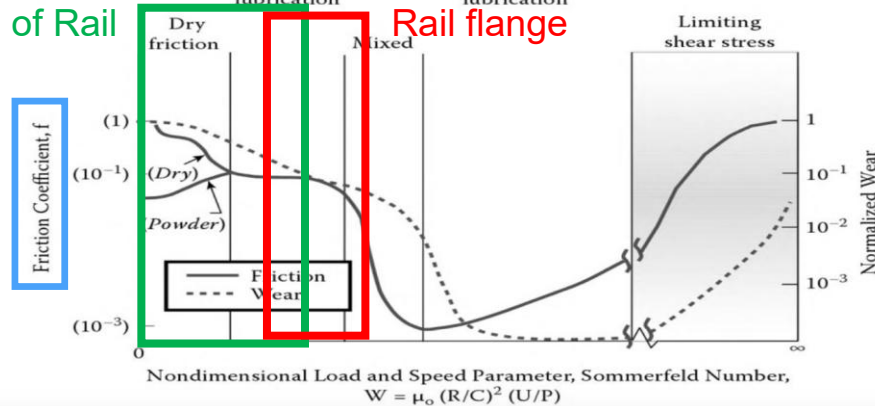
WRC
Mixed dry & Lub

Regimes:

Top of Rail

Rail flange

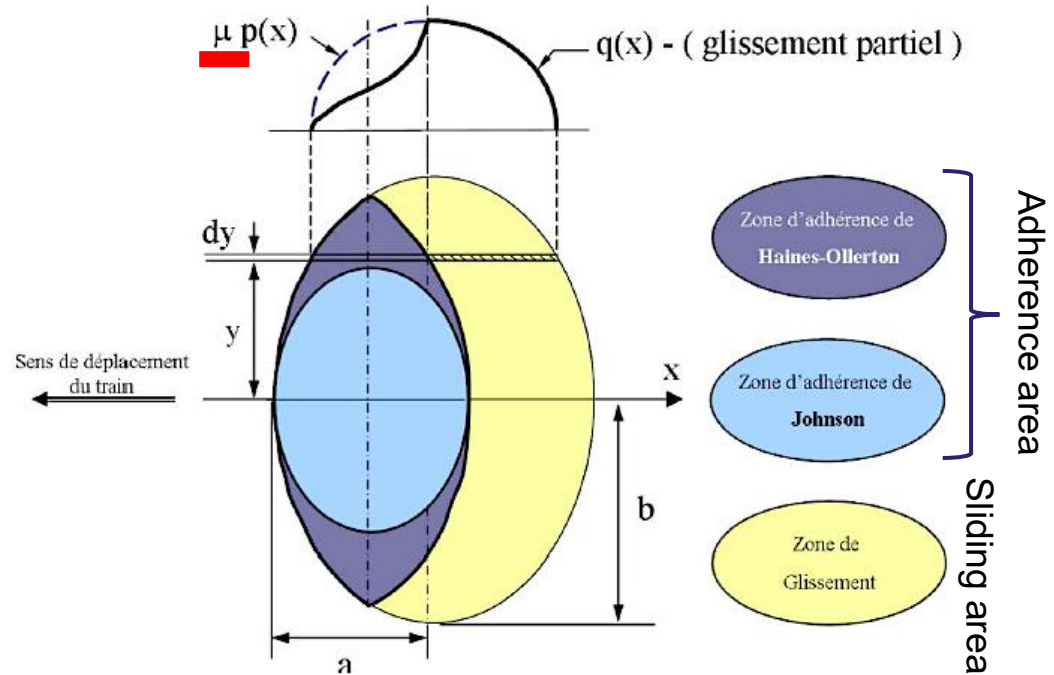
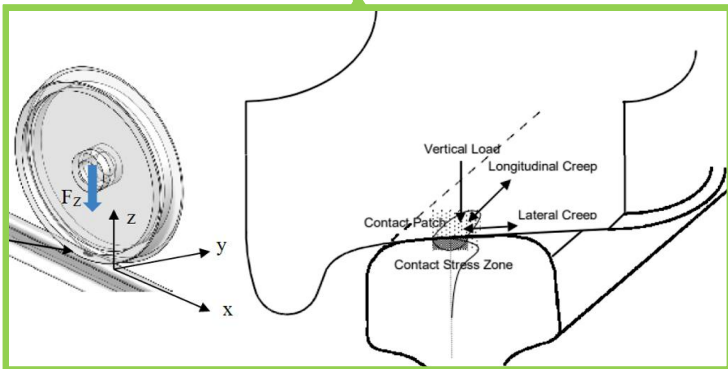
Lubrication regimes
R. Stribeck, 1902



WRC, steel-on-steel dry friction ?

Top of Rail: dry

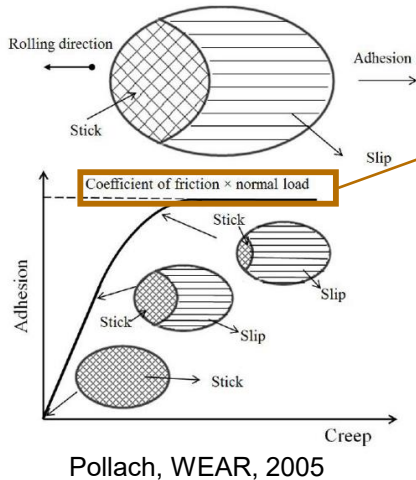
Dry: Carter (1926),
Kalker (1967)...



WRC, steel-on-steel dry friction ?

Top of Rail: dry

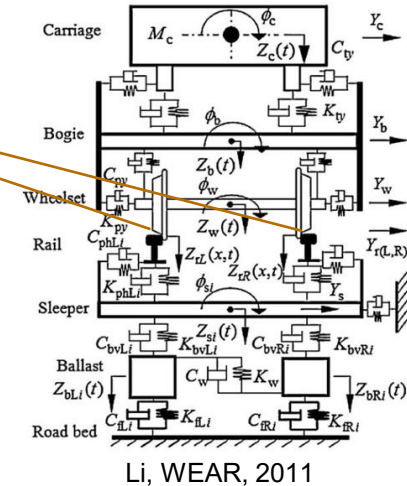
« Steel-on-Steel friction » in WRC
expected equal to +/- 0.3 in « dry conditions »



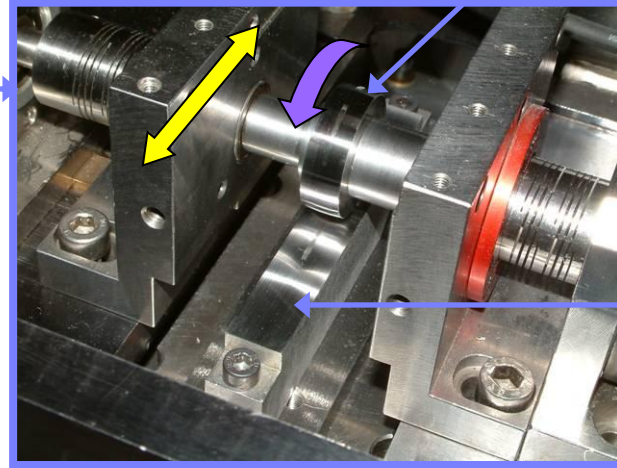
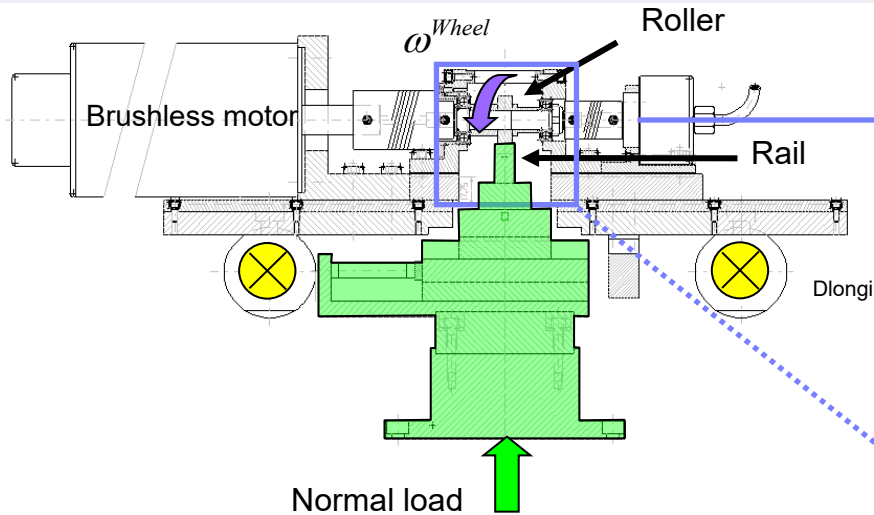
$$\mu_{\text{steel-steel(dry)}} = \pm 0.3$$

Experimental « reality » (?)

Which tribometer?
 Ex: on roller-plate tribometer

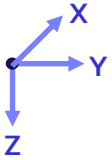


WRC, steel-on-steel dry friction ?



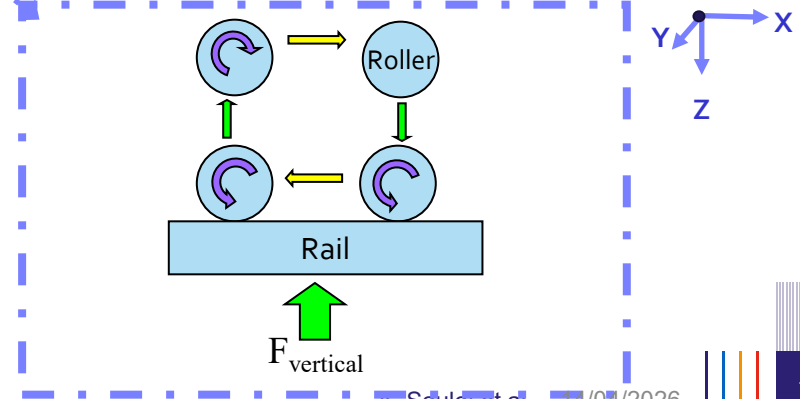
Top of Rail: dry

Roller



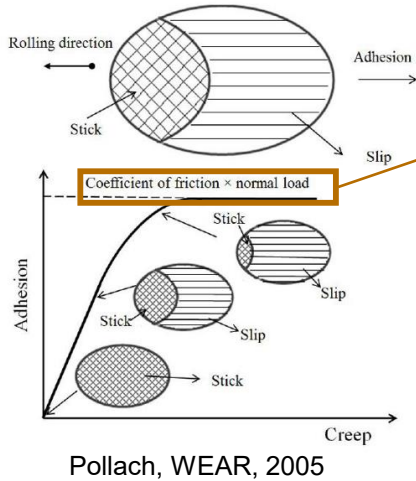
Rail

Wheel/Roller	Radius	16mm
	R_{convex}	40mm
r	Material	R7-T grade Hypereutectic steel grade wheel (NF F 01-133)
Rail/Rail sample	R_{longi}	∞
	R_{convex}	∞



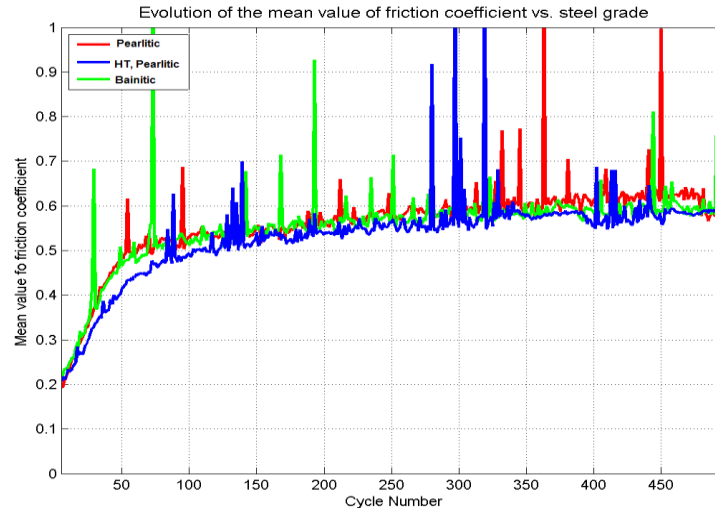
WRC, steel-on-steel dry friction ?

Top of Rail: dry

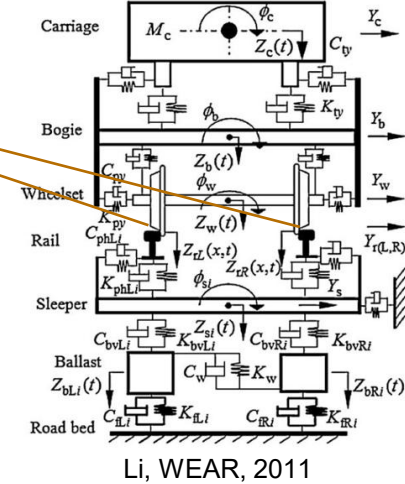


$$\mu_{\text{steel-steel(dry)}} = 0.3$$

Experimental « reality » (?)
on roller-plate tribometer



(Dayot, Trib. Int., 2009)



« Steel-on-Steel friction » in WRC
is NOT equal to +/- 0.3 in « dry conditions »

WRC, steel-on-steel dry friction ?

Top of Rail: dry

« Steel-Steel friction » in WRC
expected equal to +/- 0.3 in « dry conditions »

Valeurs indicatives Nature des matériaux en contact	Adhérence : $\mu_s = \tan \varphi_s$		Frottement $\mu = \tan \varphi$	
	à sec	lubrifié	à sec	lubrifié
Acier sur acier	0.18	0.12	0.15	0.09
Acier sur fonte	0.19	0.1	0.16	0.08 à 0.04
Téflon sur acier	0.04		0.04	
Nylon sur acier			0.35	0.12
Bois sur bois	0.65	0.2	0.4 à 0.2	0.16 à 0.04
Métaux sur bois	0.6 à 0.5	0.1	0.5 à 0.2	0.08 à 0.02
Métal sur glace			0.02	
Pneu de voiture sur route	0.8		0.6	0.3 à 0.1 (sol mouillé)

https://public.iutensigne.net/mecanique/mecanique-du-solide/charbonnieras/mecanique/132_lois_du_frottement_sec_lois_de_coulomb.html

Type de contact	Stat	Dyn
acier-acier sec	0,6	0,4
acier-acier graissé	0,1	0,05
pneu-chaussée sèche	1	0,7
pneu-chaussée humide	0,7	0,3
bois-bois	0,5	0,3
bois-métal	0,6	0,1
téflon-acier	0,04	0,04

https://perso.ens-lyon.fr/marc.lagoin/LP/LP01%20--%20Contact%20entre%20deux%20solides;%20frottements/LP_01_frottements.pdf

Materials	μ_s	μ_k
Steel on steel	0.74	0.57
Aluminum on steel	0.61	0.47
Copper on steel	0.53	0.36
Rubber on concrete (dry)	1.0	0.8
Rubber on concrete (wet)	0.3	0.25
Wood on wood	0.25-0.5	0.2
Glass on glass	0.94	0.4
Teflon on Teflon	0.04	0.04
Teflon on steel	0.04	0.04
Waxed wood on wet snow	0.14	0.1
Waxed wood on dry snow	0.10	0.04
Metal on metal (lubricated)	0.15	0.06
Ice on ice	0.1	0.03
Synovial joints in humans	0.01	0.003
Very rough surfaces		1.5

https://physics.ucf.edu/~saul/01-Spr_2048C/04-Forces/FrictionCoeffs.html

System	Static friction μ_s	Kinetic friction μ_k
Rubber on dry concrete	1.0	0.7
Rubber on wet concrete	0.7	0.5
Wood on wood	0.5	0.3
Waxed wood on wet snow	0.14	0.1
Metal on wood	0.5	0.3
Steel on steel (dry)	0.6	0.3
Steel on steel (oiled)	0.05	0.03
Teflon on steel	0.04	0.04
Bone lubricated by synovial fluid	0.016	0.015
Shoes on wood	0.9	0.7
Shoes on ice	0.1	0.05
Ice on ice	0.1	0.03
Steel on ice	0.4	0.02

<https://physicsteacher.in/2019/10/13/friction-coefficient/>

What chatGPT says about Steel-Steel friction for WRC ?

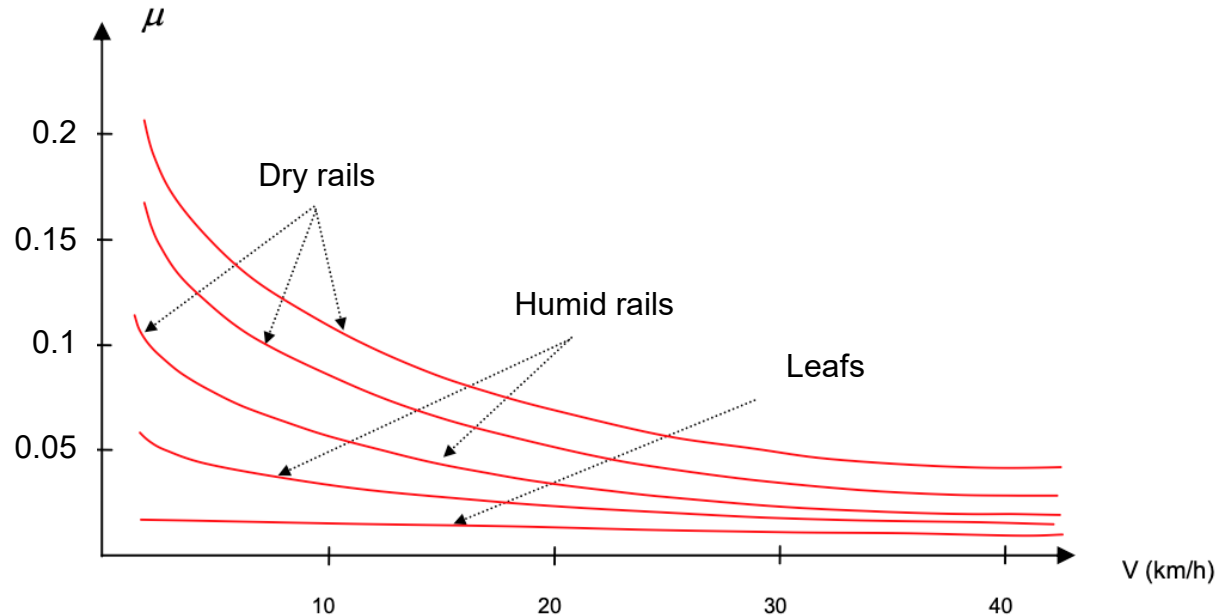
The wheel rail contact operates with the limitations imposed by the friction existing between steel surfaces. When exerting traction a friction coefficient no greater than roughly 0.2 - 0.4 can be assumed and for **safety braking duty demands no more than 0.1!!!!**

<https://www.kth.se/>

$$\begin{aligned} \mu_{\text{steel-steel(dry)}} &= \pm 0.3 \text{ used in most studies} \\ &= (0.2 + 0.4) / 2 \\ &= (0.15 + 0.3 + 0.4 + 0.57) / 4 \\ &= \dots \end{aligned}$$

Railway safety rules:

Maximum « usable adherence » vs. rail tribological status and train velocity (1)



(1) Alacoque J.C., P. Chapas, Technique de l'ingénieur, 2005

Friction and Wear measurement: difficulties...

Except for tribologist, the frictionnal interface is usually **restricted to**:

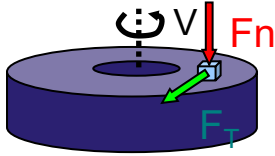
- a “global” friction coefficient
- a “global” wear rate

... both depending only of the **material couple**.

A contact is much more than just a friction coefficient and a wear coefficient,
whose are **complexes to determine realistically. Why ?**

Friction and Wear measurement: difficulties...

Wear map from Lim et Ashby



Dimensionless Pressure = F_n / SH

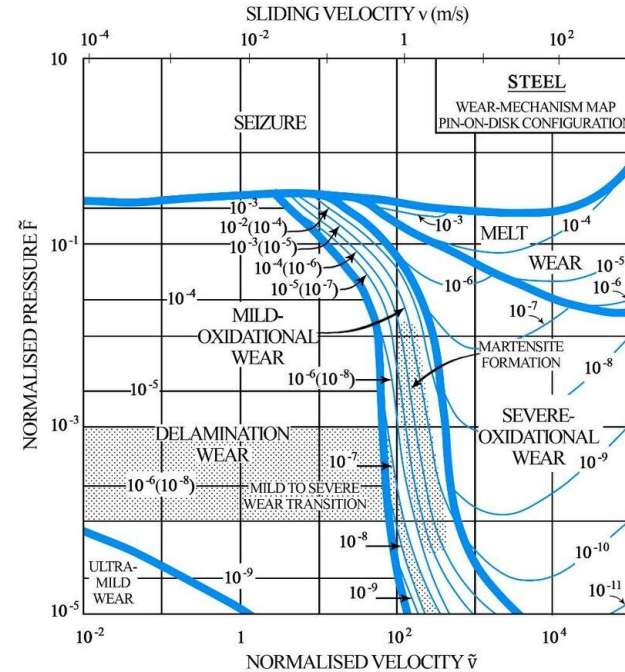
Dimensionless Velocity = $v \cdot r_0 / a$

S , nominal contact area

H , hardness of the softer material

r_0 , radius of the pin

a , thermal diffusivity



Steel-steel contact in dry conditions for pin-on-disk configuration
(Lim & Ashby 1987)

What test condition(s)?

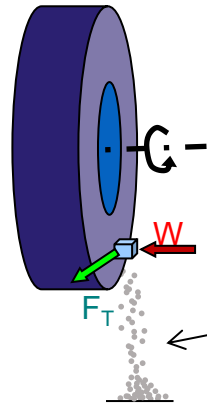
*Environment, tribometer characteristics, sample preparation and manufacturing
... an impossible generalisation?*

Friction and Wear measurement: difficulties...

Difficulty #1: The orientation issue

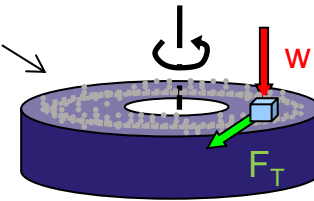
same load, same sliding velocity.... to different orientation of the tribometer

Configuration A



in favour of ejection

Configuration B



in favour of recirculation

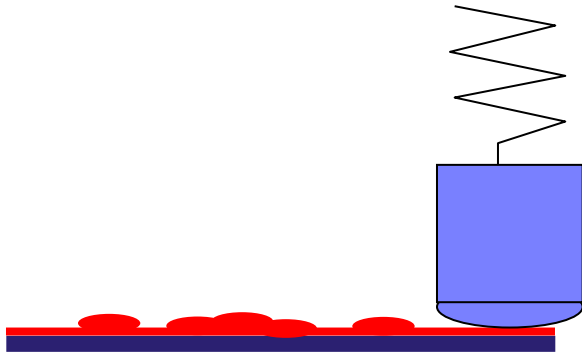
... different wear rate for a same material !

=> Depending also on the properties (morphology, deformability, reactivity, etc.) of the wear particles: **this may or may not be favorable to wear!**

Friction and Wear measurement: difficulties...

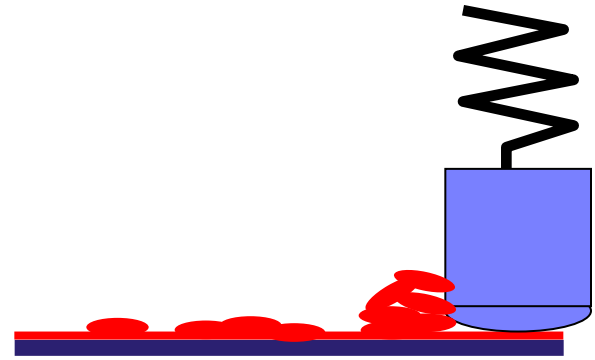
Difficulty #2: The stiffness issue

same load, same sliding velocity, same orientation.... but different stiffnesses



Low stiffness : all particles pass

« Interface accommodation »



High stiffness: few particles may pass

« Mechanism accommodation... »

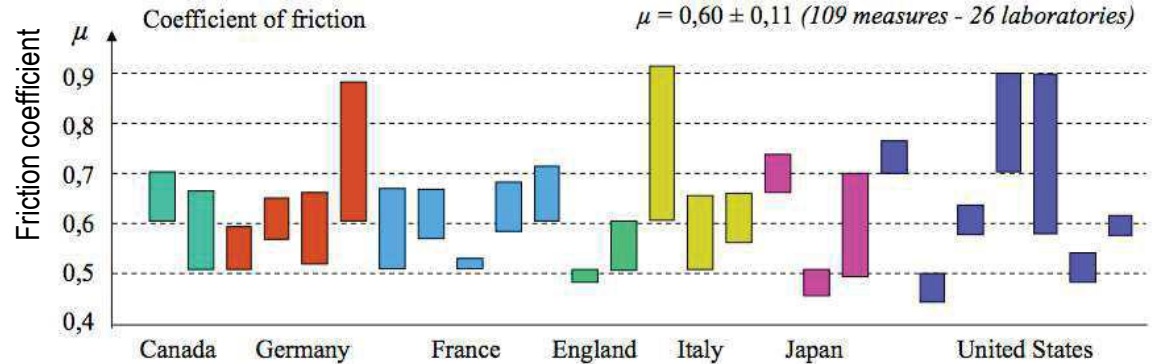
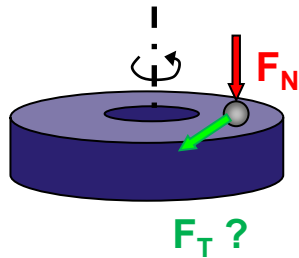
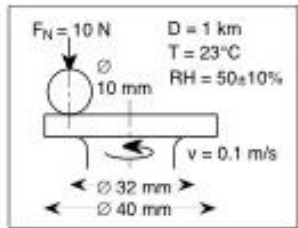
Friction coefficient and wear rate may differ for a same material!

Friction and Wear measurement: difficulties...

Friction – Wear: two simple concepts, but a veil hiding a real complexity!

The well know VAMAS international experiment (1987)

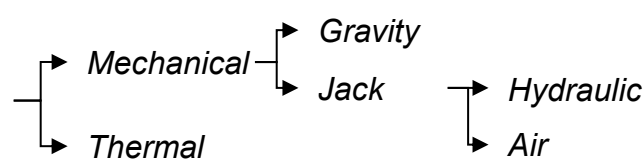
« Laboratories in 7 countries have compared their tribological results for a same test »
 (synthesis paper: Czichos et al., Wear 1987 - [https://doi.org/10.1016/0043-1648\(87\)90020-2](https://doi.org/10.1016/0043-1648(87)90020-2))



Repetability: -inside a laboratory :
 -between laboratories :

friction coefficient ± 13 % & wear ± 14 %
 friction coefficient ± 14 % & wear ± 38 % (!)

Ex: Origin of the dispersion

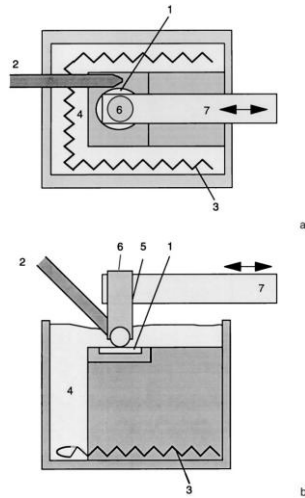


Ex: Different stiffnesses

Friction – Wear: two simple concept, but a veil hiding a real complexity!

Other round robin shows a similar friction coefficient but other divergences occurs ⁽¹⁾
(example of on tribo-electrochemical measurement... thanks to Pr. Mischler in 2001!)

The seven involved laboratories have developed different tribometer designs:



- A – pin-on-disk tribometer with a pin rotating (top) on a flat specimen (bottom). The load is applied through a **hydraulic piston**.
- B – pin-on-disk apparatus characterised by a stationary pin and with an **inertial load application**
- C – Special inverse pin-on-disk; the rotating disk is loaded, using a **compression spring**, on top of a stationary ball.
- D – Reciprocating motion apparatus with a pin rubbing on top of a plate and an **inertial load**.
- E – Rig for microtribocorrosion that includes a rotating alumina tube that is loaded through a **spring** against a stationary plate

(1) S Mischler, P Ponthiaux, *A round robin on combined electrochemical and friction tests on alumina/stainless steel contacts in sulphuric acid*, **Wear**, Volume 248, Issues 1–2, 2001, Pages 211-225, [https://doi.org/10.1016/S0043-1648\(00\)00559-7](https://doi.org/10.1016/S0043-1648(00)00559-7)

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Table 5
Mean values and mean deviations of the parameters extracted from the wear test at the corrosion potential (Experiment 3)

Parameter	Laboratory							
	Laboratory 1	Laboratory 2	Laboratory 3	Laboratory 4	Laboratory 5	Laboratory 6	Laboratory 7	Average
Open circuit potential just before rubbing starts (mV SHE)	-164 ± 19	-212 ± 3	-201 ± 0	-66 ± 27	-244 ± 1	Not reported	-114 ± 10	-169 ± 61
Average open circuit potential during rubbing (mV SHE)	-97 ± 3	-137 ± 7	-156 ± 25	-39 ± 8	-197 ± 5	-88 ± 13	-170 ± 26	-126 ± 44
Open circuit potential just after rubbing stops (mV SHE)	-81 ± 5	-128 ± 9	Not reported	-25 ± 13	-194 ± 7	Not reported	-68 ± 7	-99 ± 49
Average coefficient of friction μ	0.45 ± 0.01	0.29 ± 0.01	0.35 ± 0.00	0.39 ± 0.02	0.34 ± 0.02	0.28 ± 0.08	not reported	0.35 ± 0.05
Width of the wear track (mm)	0.669 ± 0.037	0.48 ± 0.102	0.267 ± 0.004	0.662 ± 0.1	0.335 ± 0.007	0.178 ± 0.011	not reported	0.43 ± 0.17
Surface of the wear track (cm ²) (width × length)	0.336 ± 0.019	0.855 ± 0.022	0.134 ± 0.002	0.995 ± 0.150	0.016 ± 0.000	0.018 ± 0.001	not reported	0.294 ± 0.26
Wear volume (mm ³)	0.128 ± 0.005	0.105 ± 0.065	0.007 ± 0.001	0.491 ± 0.261	0.0072 ± 0.0010	0.00284 ± 0.00031	0.018; 0.001	0.106 ± 0.12
Wear coefficient (mm ³ /Nm)	14.2 × 10 ⁻⁵	3.90 × 10 ⁻⁵	0.78 × 10 ⁻⁵	18.2 × 10 ⁻⁵	5.5 × 10 ⁻⁵	4.5 × 10 ⁻⁵	0.14 × 10 ⁻⁵ ;	6.75 × 10 ⁻⁵
	± 0.6 × 10 ⁻⁵	± 2.41 × 10 ⁻⁵	± 0.15 × 10 ⁻⁵	± 9.67 × 10 ⁻⁵	± 0.59 × 10 ⁻⁵	± 0.49 × 10 ⁻⁵	0.01 × 10 ⁻⁵	± 5.41 × 10 ⁻⁵

Friction coefficient (no dim): 0.35 +/- 0.05



On of the conclusions was logically:

« A good convergence of the measured coefficients of friction was found among the different laboratories. »

Why so good compared to VAMAS experiment?

Is the liquid environment one of the reason ?

Is dry friction more prone to chaotic behaviour ?

Is dry friction more sensitive to little experimental changes ?

...

(1) S Mischler, P Ponthiaux, A round robin on combined electrochemical and friction tests on alumina/stainless steel contacts in sulphuric acid, **Wear**, Volume 248, Issues 1–2, 2001, Pages 211-225, [https://doi.org/10.1016/S0043-1648\(00\)00559-7](https://doi.org/10.1016/S0043-1648(00)00559-7)

Friction and Wear measurement: difficulties...

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Friction coefficient (no dim): 0.35 +/- 0.05



Wear coefficient (mm³/Nm): 6.7 10⁻⁵ +/- 5.41 10⁻⁵



On of the conclusions on wear was logically:

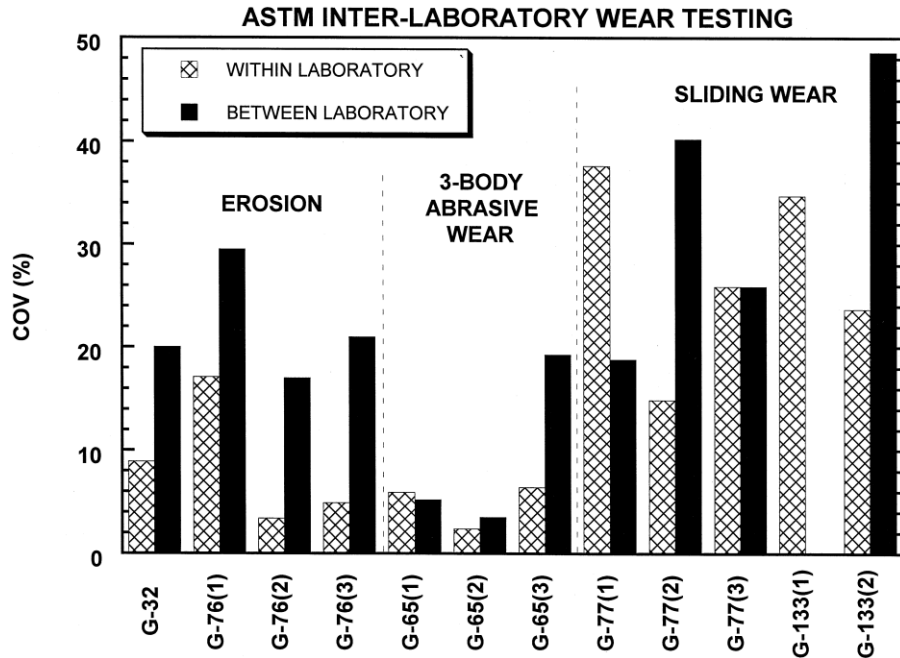
« The scattering of the wear results depends critically on the criterion used. Using the wear track width the scattering is around 50% whilst the wear coefficients scatter over three orders of magnitude. Better defined wear criteria are needed. »

(1) S Mischler, P Ponthiaux, A round robin on combined electrochemical and friction tests on alumina/stainless steel contacts in sulphuric acid, **Wear**, Volume 248, Issues 1–2, 2001, Pages 211–225, [https://doi.org/10.1016/S0043-1648\(00\)00559-7](https://doi.org/10.1016/S0043-1648(00)00559-7)

Friction and Wear measurement: difficulties...

More Recently: still same problem

P. Blau, Wear, 2017, <https://doi.org/10.1016/j.wear.2016.11.012>



Sources of Data Scatter ("Repeatability") in Wear Data

Material Factors

Type of Wear
(erosive, abrasive, impact, rolling contact, sliding, fretting, ...)

Homogeneity of the Materials

Wear Area Size Effect
(wear scar size relative to microstructural constituents)

Consistency in Specimen Preparation and Cleaning
(machining, finishing artifacts, contamination, corrosion,...)

Third Body Effects
(internal debris or external interfacial species)

Tribosystem Factors

Design and Mechanics of the Equipment
(method of producing relative motion, sensor selection, stiffness, natural frequency,...)

Units of Measure Used to Quantify Wear
(length, mass, depth, area, volume, time to wear through, critical load, normalized rates, wear coefficients,...)

Aging/Wear of the Equipment

External Influences
(vibration, heat, contaminants, ...)

Human Factors

Operator Consistency and Judgment
(Set-up and calibration of sensors, loads, flow, velocity,...)

Operator Consistency and Judgment
(training, operation of the equipment, follow procedures exactly each time)

Operator Consistency and Judgment
(Reduction of data, assumptions, approximations, and operation of measuring equipment)

Fig. 1. Coefficient of variation within laboratories and between laboratories for five ASTM wear test methods. Data obtained from the respective standards documents.

Except for tribologist, the frictionnal interface is usually **restricted to**:

- a “global” friction coefficient
- a “global” wear rate

... both depending only of the **material couple**.

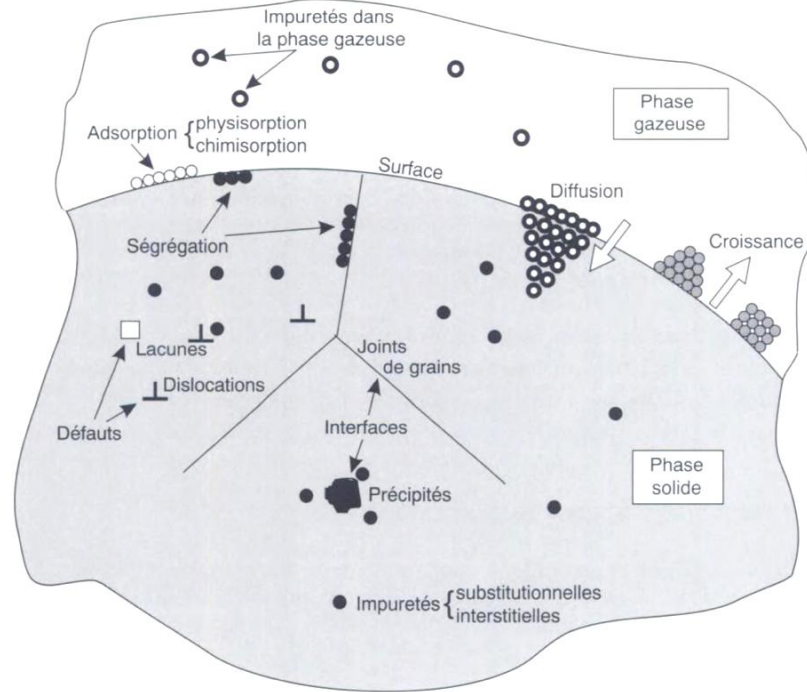
To understand a tribological problem....

... is to understand the interface life!

Surfaces:

From topography to physico-chemistry

The surface « interacts with its environment »

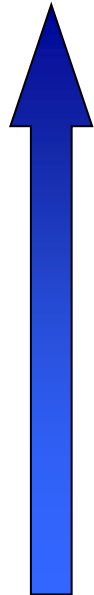


Surfaces:

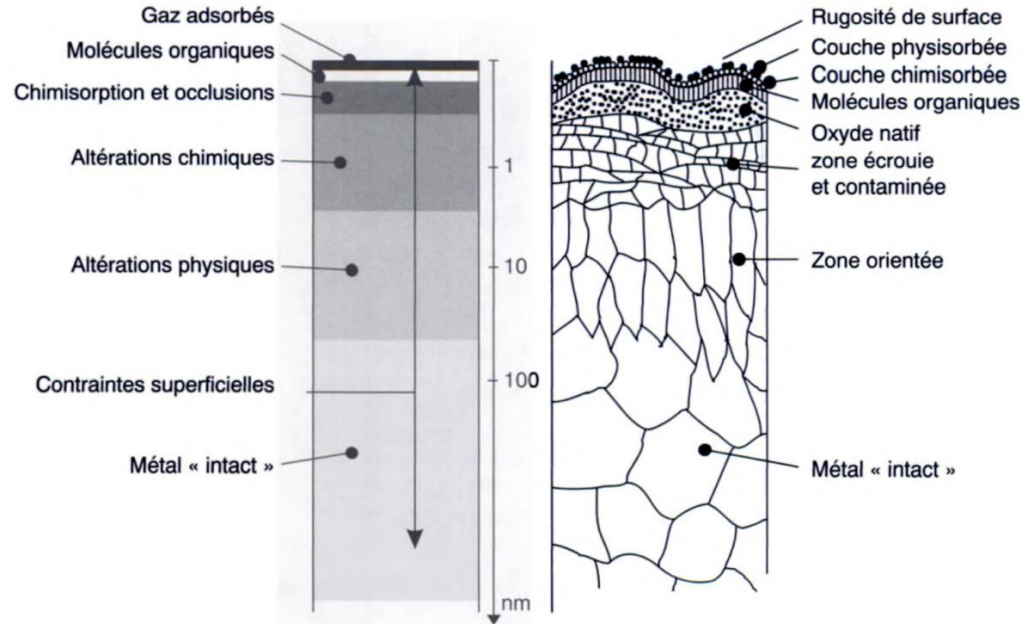
From topography to physico-chemistry

The surface « interacts with its environnement »

Physico-chemistry



Mechanics

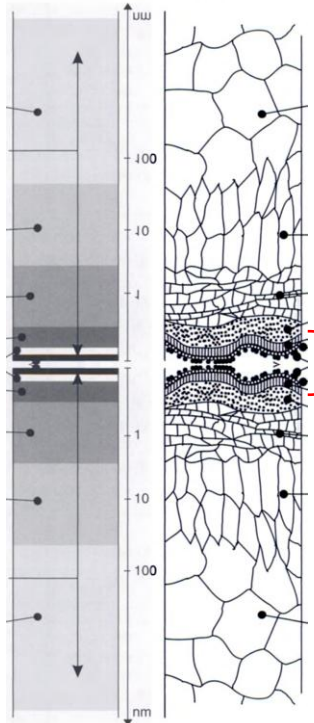


Example: Microscopic structure of a metallic surface after machining

Physique Et Ingénierie Des Surfaces, A. Cornet & JP Deville, EDP Science

Interface

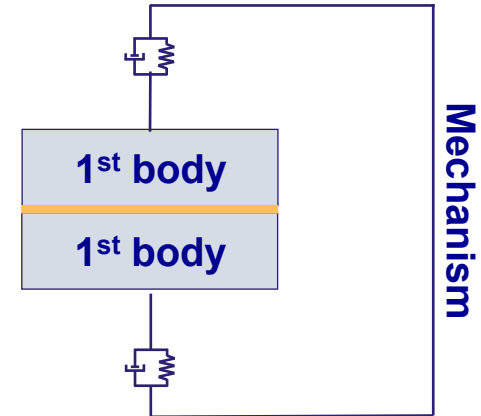
« INTERFACE » - THE place of interactions between surfaces of two solids



INTERFACE

Friction, wear →

Contact between two bodies
« Classical view »



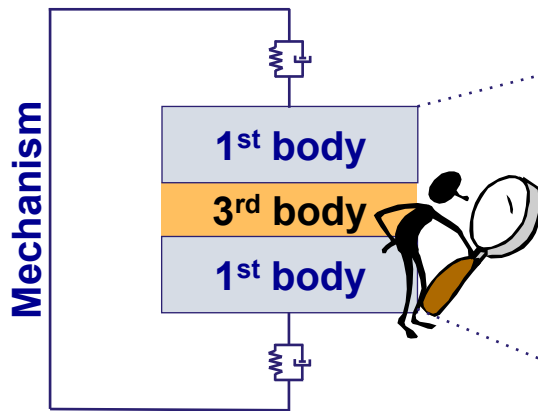
Friction and wear, two hotchpotches that are natural consequences of the interface life!

⇒ Need to **improve interface description** to understand their lives.

Interface: The 3rd body concept

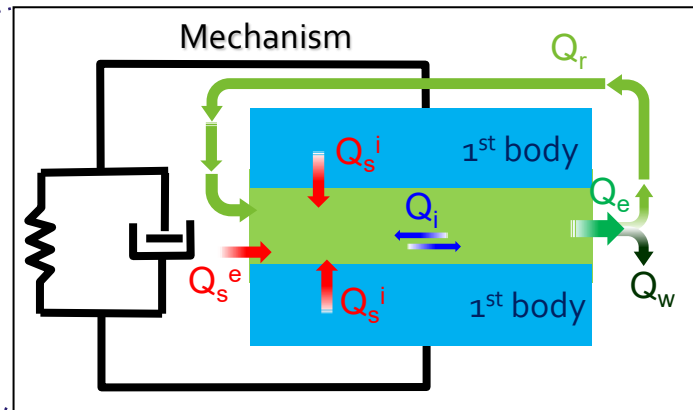
Triplet, tribological circuit and accommodation sites
« Descriptive tools to help understanding the life of interfaces »

«In the last decades, Tribology has moved, **from the Tribology of Volumes**, which attempted to produce friction and wear laws for different material combinations, **through the Tribology of Surfaces**, which rests strongly on surface science, **to the Tribology of Interfaces** which focusses on the role of the interface on friction and wear. [...] » **M. Godet**, *Wear*, 1990



Tribological triplet

M. Godet - 1984



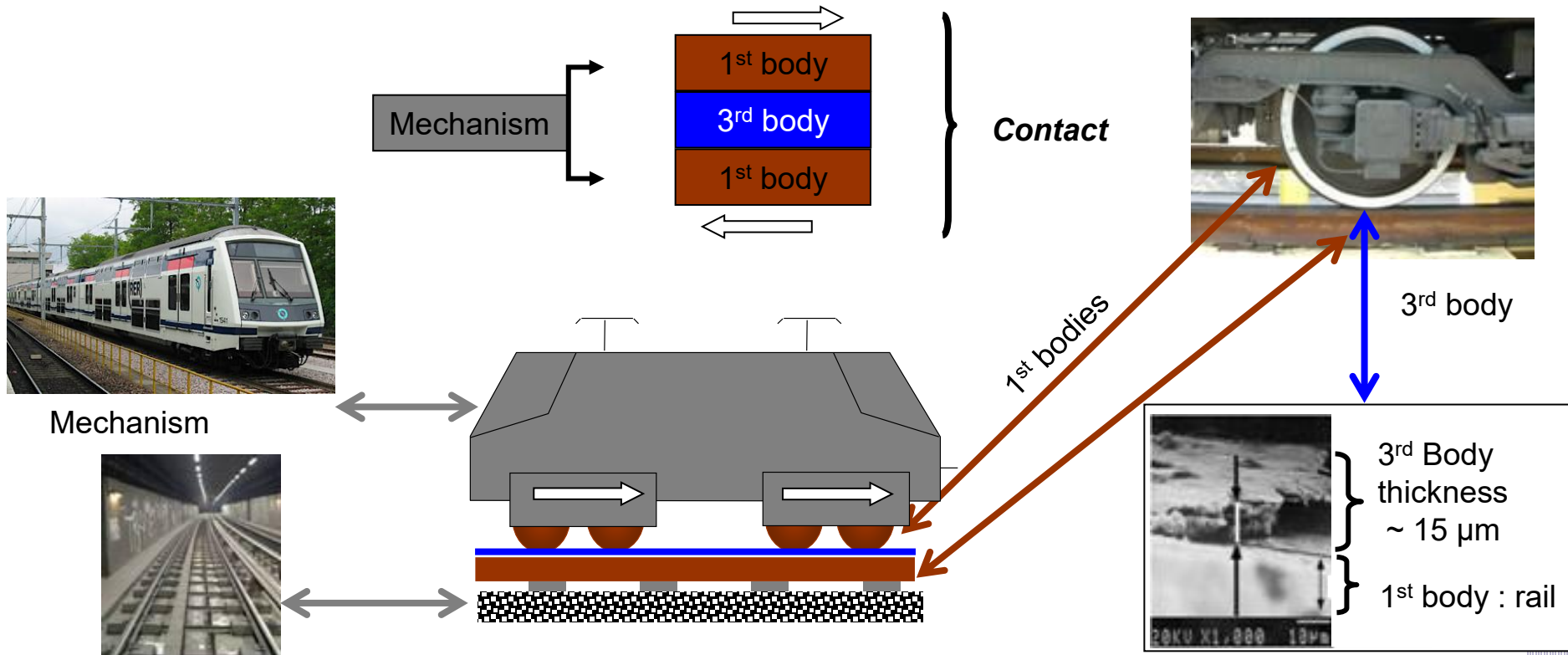
Tribological circuit

Y. Berthier - 1988

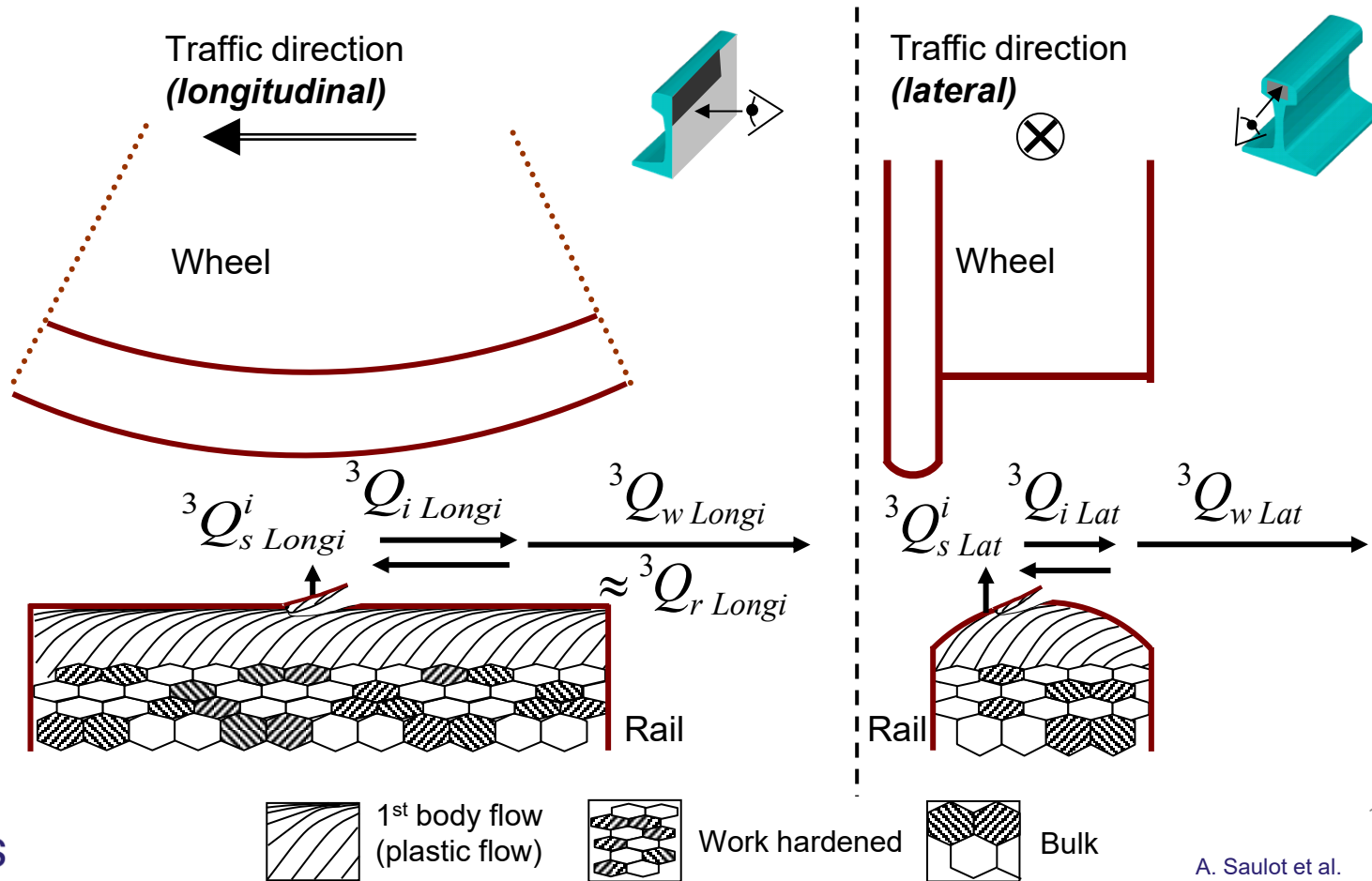


Interface: The 3rd body concept for railways

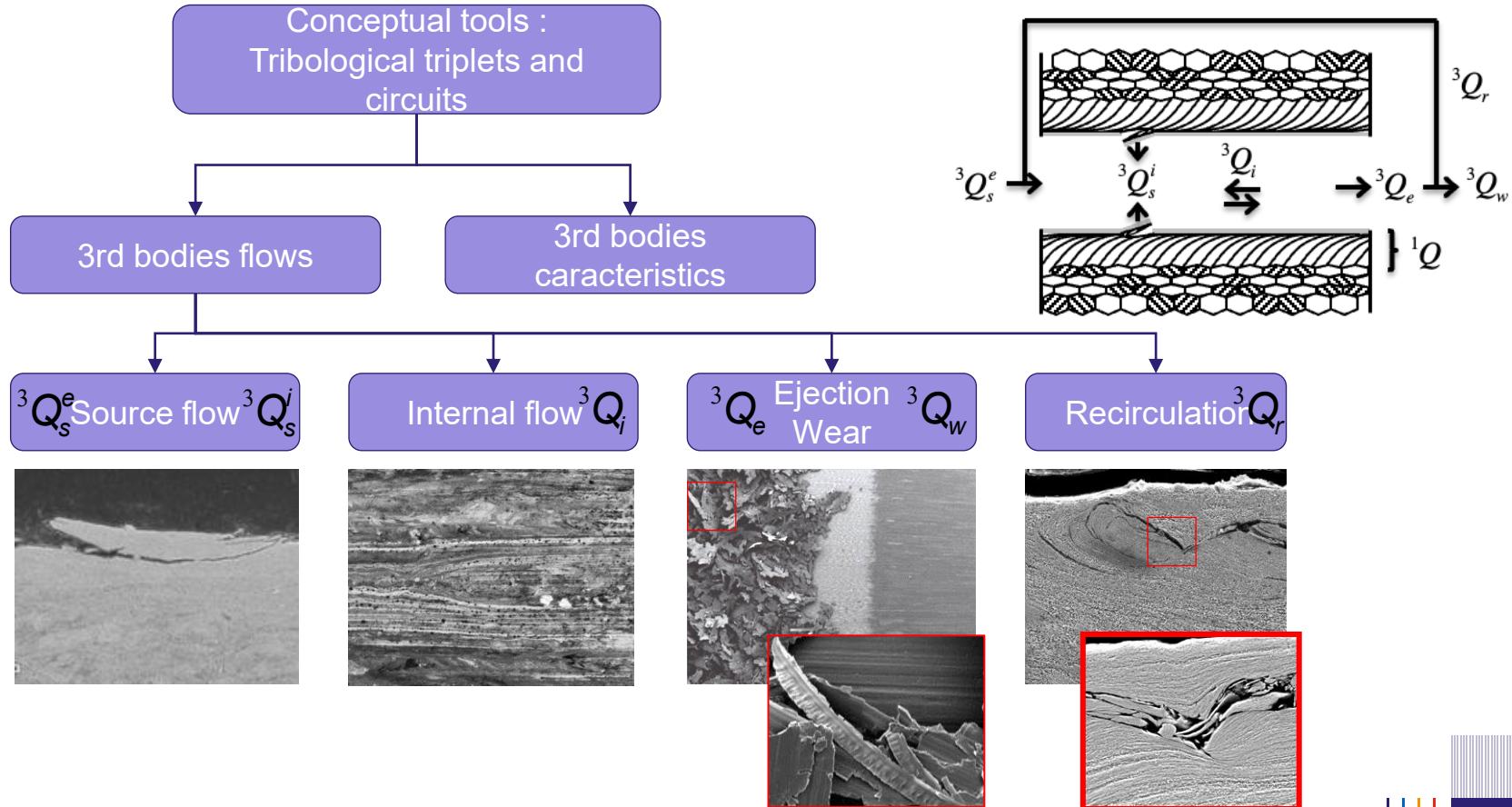
Tribological concepts : the 3rd body concept



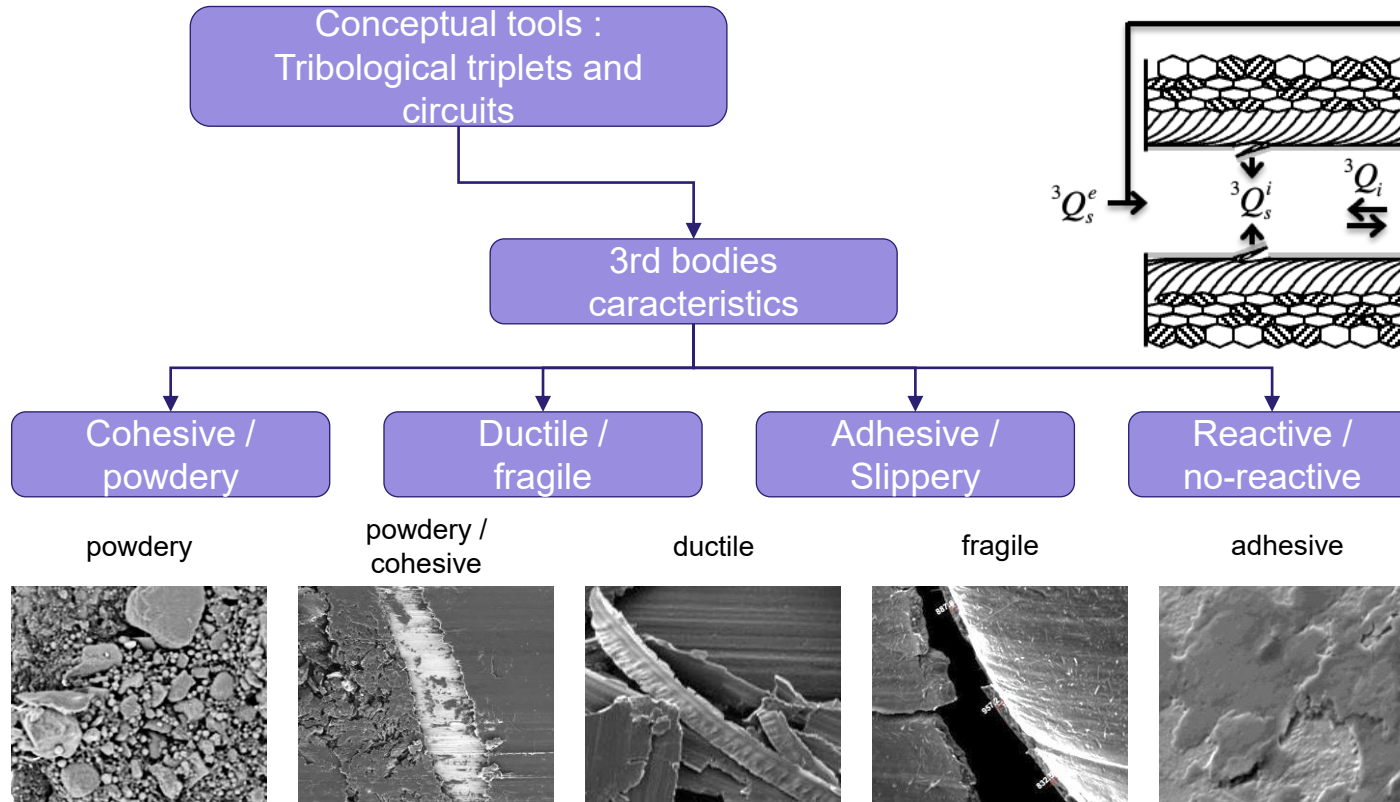
Interface: The 3rd body concept for railways



Example of 3rd body realities



Example of 3rd body realities



Images courtesy of R. Charlery, G. Colas, J. Ho & A. Saulot

From 3rd body to Site and Modes of accommodation

Accomodation mechanisms - SiMj

Local mechanisms which allow the mouvement

Site S_0 : **mechanism accomodation**

- M_0 pure elastic deformation (no energy dissipation)

Sites S_1 et S_2 : **1st body**

- M_1 plastic deformation
- M_2 fracture
- M_3 superficial shear

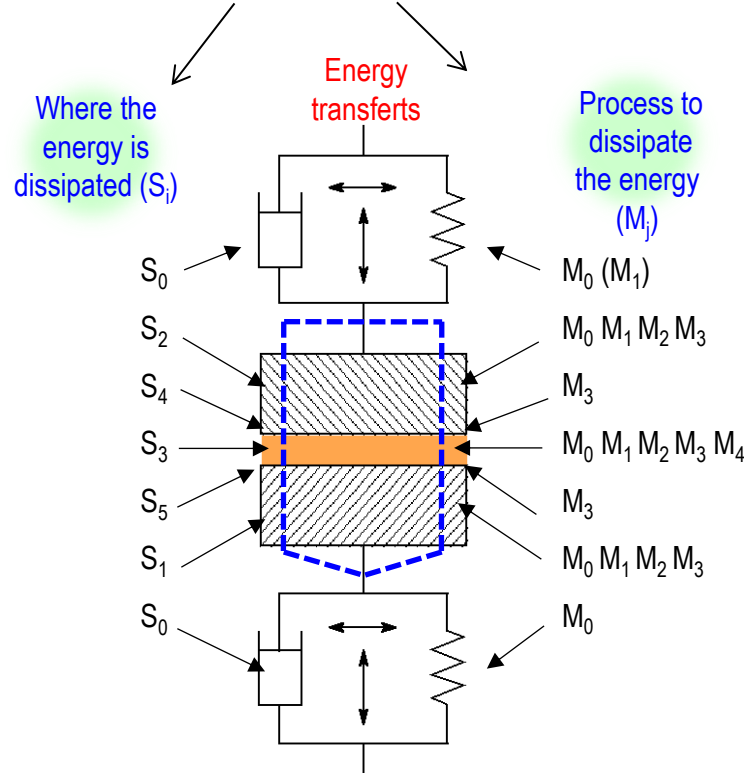
Site S_3 : **3rd body** (detached particles...)

- M_1 plastic deformation
- M_2 fracture
- M_3 shear
- M_4 rolling

Sites S_4 et S_5 : **superficial layers** (screens)

- M_3 wall sliding (shear)

Identification of **sites** and **modes** of accommodation



Séminaire SiMj « Concept de troisième corps et comportement des particules d'usure en frottement sec », J. Denape, Juillet 2018

Basé sur les travaux de Y. BERTHIER, L. VINCENT and M. GODET (1992), Velocity Accommodation Sites and Modes in Tribology Eur. J. Mech. A/solids, vol 11, 1, 35-47.

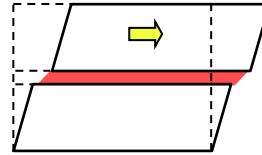
A combination of a site and a mode = a **velocity accomodation mechanism** ($S_i M_j$)

From 3rd body to Site and Modes of accommodation

In practice : 8 main mechanisms (dissipative) of accommodation (symetry of triplet)

Local activation of the most suitable accommodation mechanism to circumvent the blocking imposed by the adhesion of the surfaces

Migration of sites, coexistence and relay of several modes of accommodation in a contact

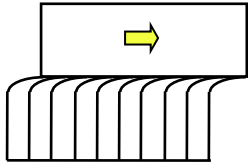


Non dissipative global mechanisms :
Elastic deformation
(S_0, S_1, S_2, S_3) M_0

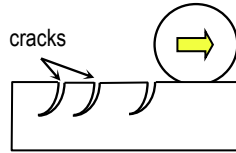
Séminaire SiMj « Concept de troisième corps et comportement des particules d'usure en frottement sec », J. Denape, Juillet 2018

Basé sur les travaux de Y. BERTHIER, L. VINCENT and M. GODET (1992), Velocity Accommodation Sites and Modes in Tribology Eur. J. Mech. A/solids, vol 11, 1, 35-47.

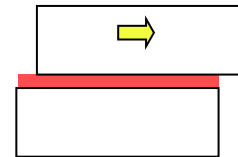
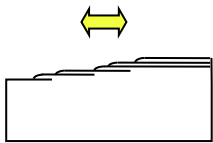
1st body and screens



Plastic deformation
 $S_1 M_1$

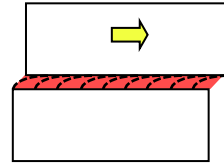


Superficial cracks
 $S_1 M_2$

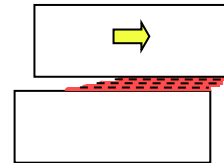


Sliding over screens
 $S_4 M_3$

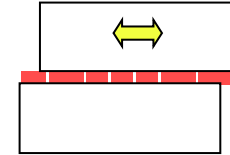
3rd body



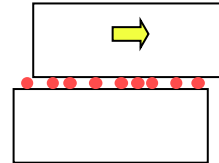
Plastic deformation
 $S_3 M_1$



Shear of 3rd body
 $S_3 M_3$



Fracture of 3rd body
 $S_3 M_2$



From 3rd body to Site and Modes of accommodation

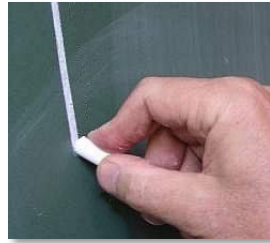
Séminaire SiMj « Concept de troisième corps et comportement des particules d'usure en frottement sec », J. Denape, Juillet 2018

... also be observed in the context of everyday life...

Basé sur les travaux de Y. BERTHIER, L. VINCENT and M. GODET (1992), *Velocity Accommodation Sites and Modes in Tribology Eur. J. Mech. A/solids*, vol 11, 1, 35-47.



Lubricated bearing S_3M_3



School chalk S_1M_3



Eraser S_3M_4



Brush S_1M_0



Your chose for him? S_1M_1 ?

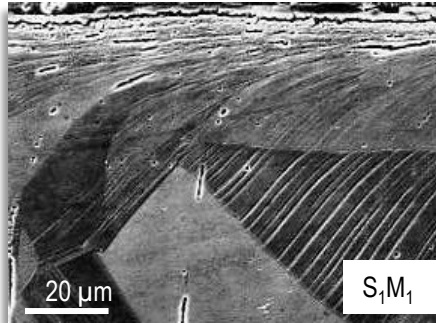
From 3rd body to Site and Modes of accommodation

Séminaire SiMj « Concept de troisième corps et comportement des particules d'usure en frottement sec », J. Denape, Juillet 2018

Basé sur les travaux de Y. BERTHIER, L. VINCENT and M. GODET (1992), *Velocity Accommodation Sites and Modes in Tribology Eur. J. Mech. A/solids*, vol 11, 1, 35-47.

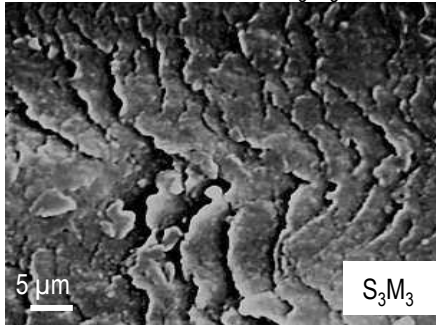
Example of accommodation morphologies... contact reality!

Superficial plastic flow - S_1M_1



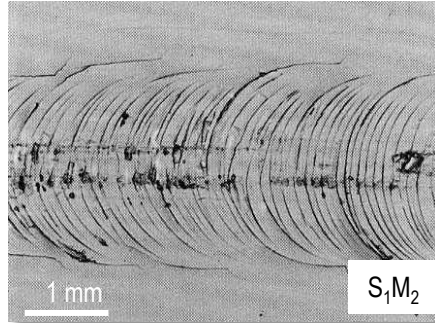
Transversal cut of an austenitic steel after friction against an austenitic steel

Interfacial shear - S_3M_3



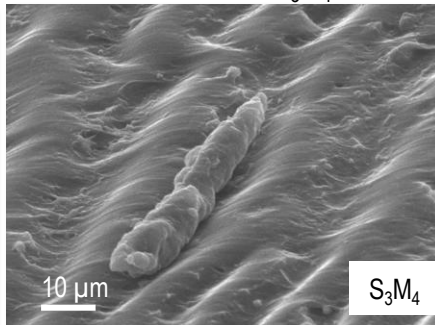
Surface of alumina after friction against alumina (dry)

Superficial cracks - S_1M_2



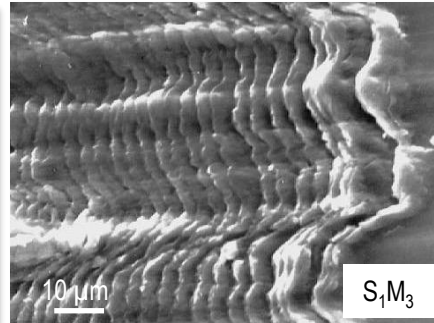
Glass surface after friction against a tungsten carbide ball (dry)

Roller formation - S_3M_4



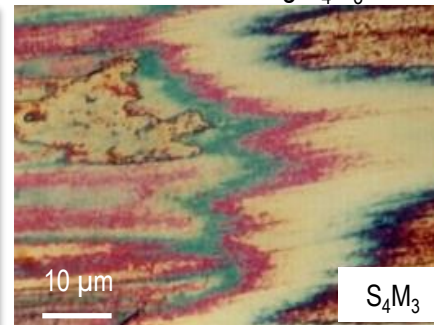
Surface of a thermoplastic after friction against steel (dry)

Superficial shear for 1st body - S_1M_3



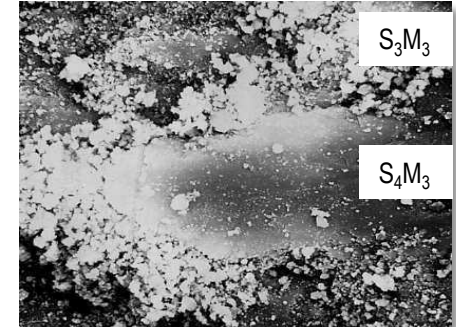
Surface of a contact of Ti6Al4V after friction against Ti6Al4V

Screen shearing S_4M_3



Superficial contamination layer

Coexistence of mechanisms

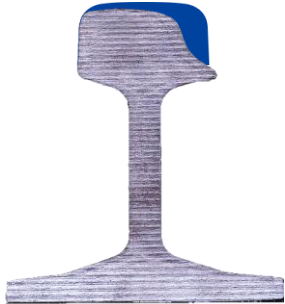


Surface of silicon nitride after friction against steel (dry)

WRC at the origin of several rail defects

Rail defects (many, classified by UIC)

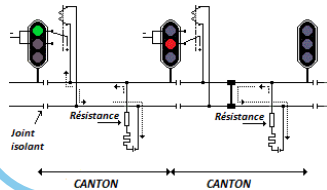
Lubrication
Badly optimized



Pollution
(ex: leaves, ...)



Unshunting



Full sliding



Corrugation wear



Squat (fatigue)



Need to master the wheel-rail contact **tribological antagonism** !

Foot wear mechanism... similar to rail wear ?

S_1M_1 / S_1M_2



Walk

↓
Heel friction

↓
Stratum corneum
(hardened layer to protect the derma)

↓
No Wear

↓
Cracks



Hard on soft



Positive wear
(stratum corneum grinding)



Natural wear (exfoliation)
« magic wear »

↓
No cracks

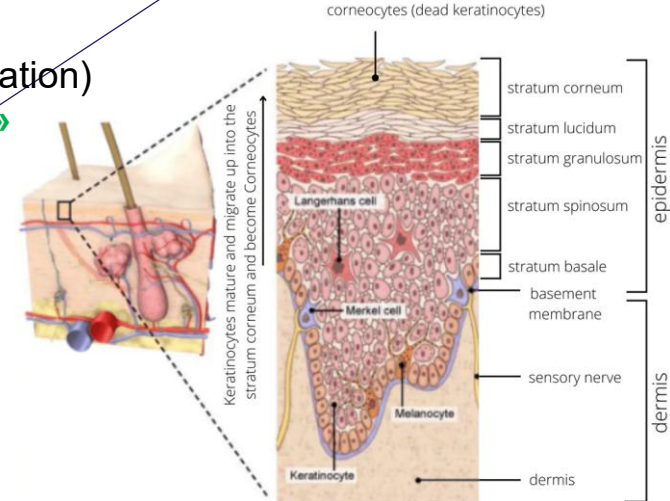


Soft enough on soft

Minimize friction
(minimize stratum corneum layer)



Soften hard layer
(hydration of stratum corneum layer)

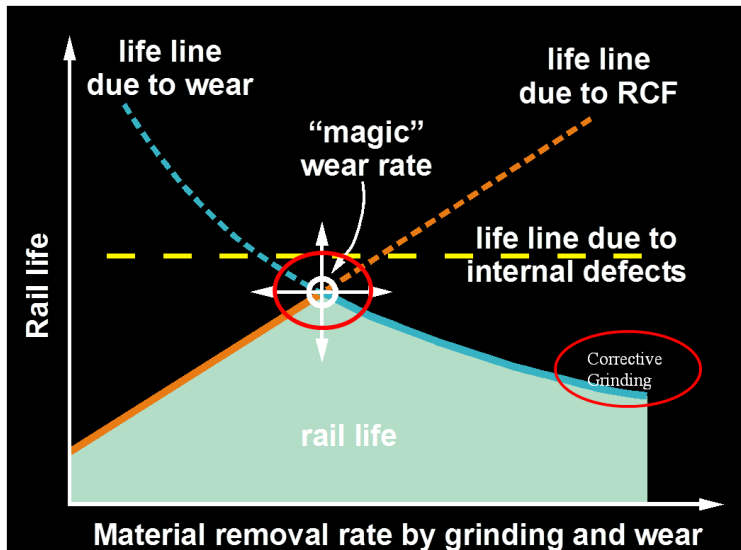


Foot wear mechanism... similar to rail wear ?

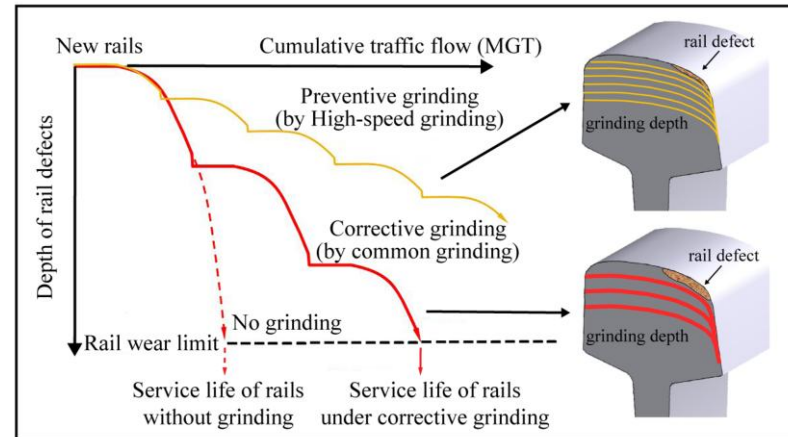
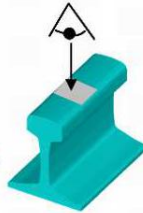
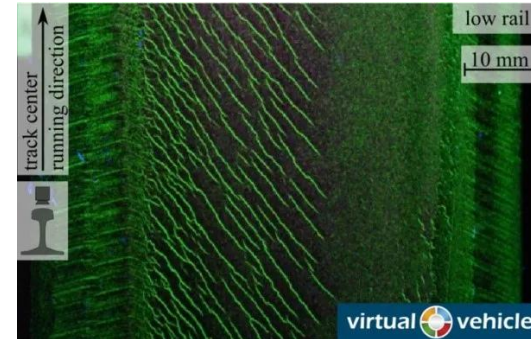
S_1M_1 / S_1M_2

Natural wear (exfoliation) → Valid for feet → also valid for railway !
 « magic wear »

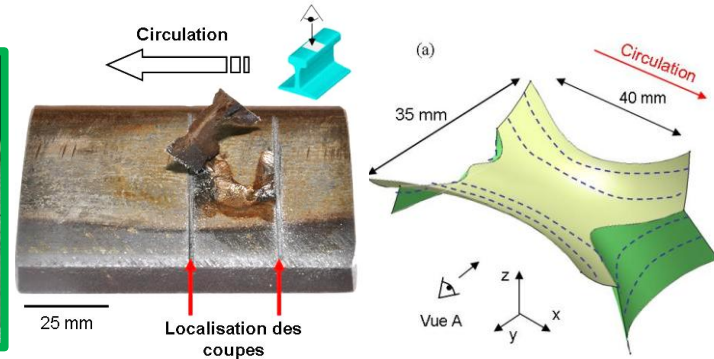
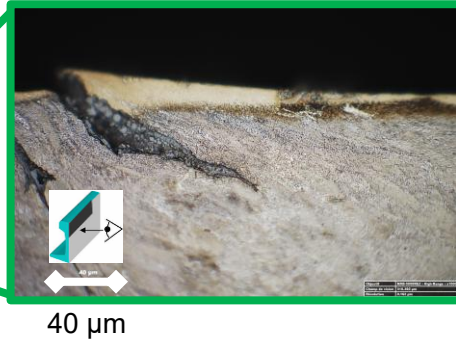
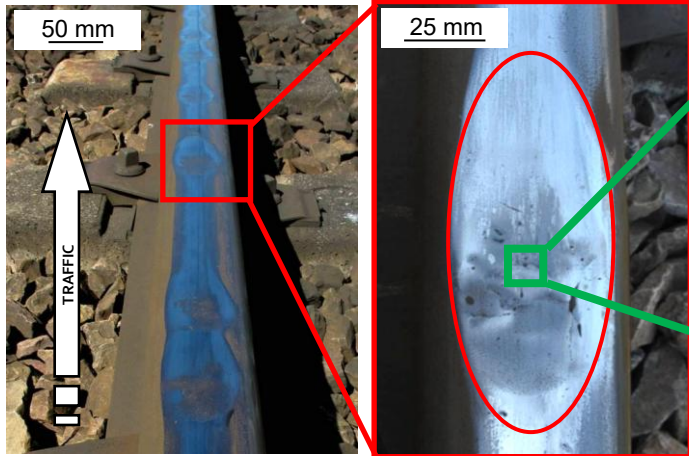
« In theory, and under some laboratory conditions, a proper amount of natural wear exists which is just enough to suppress HC initiation and growth and is called **magic wear rate**. » Zhou et al., Wear, 2014



<https://interfacejournal.com/archives/1229>
 Chasing the magic wear rate, Magel et al, 2014

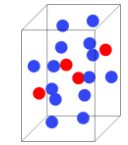
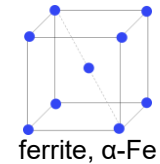
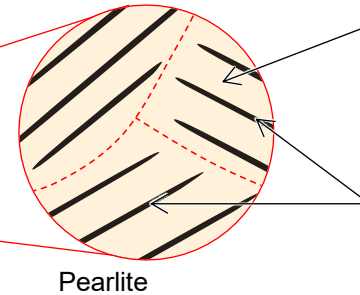
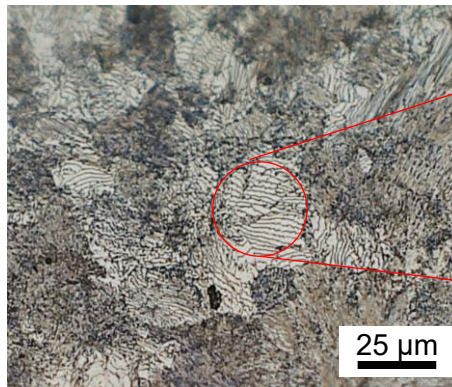


Squat defects



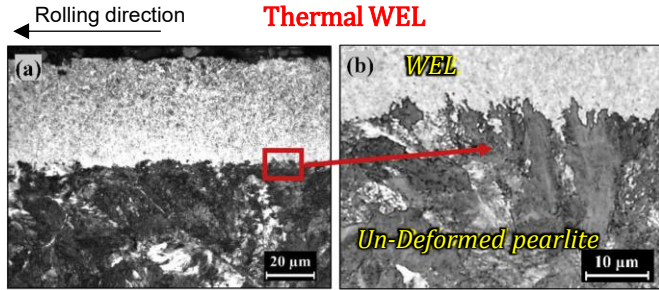
Chemical composition of R260 rail steel grade

	C	Mn	Si
weight%	0.74	1.1	0.3
atomic%	3.35	0.7	0.29

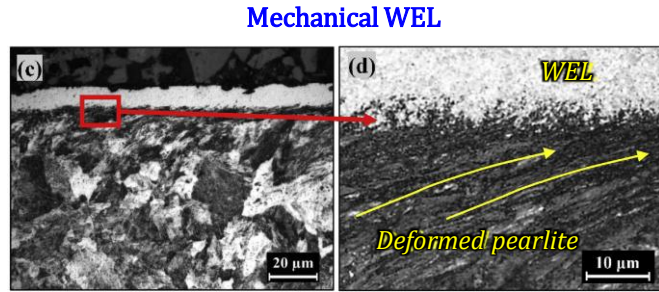


Pearlite

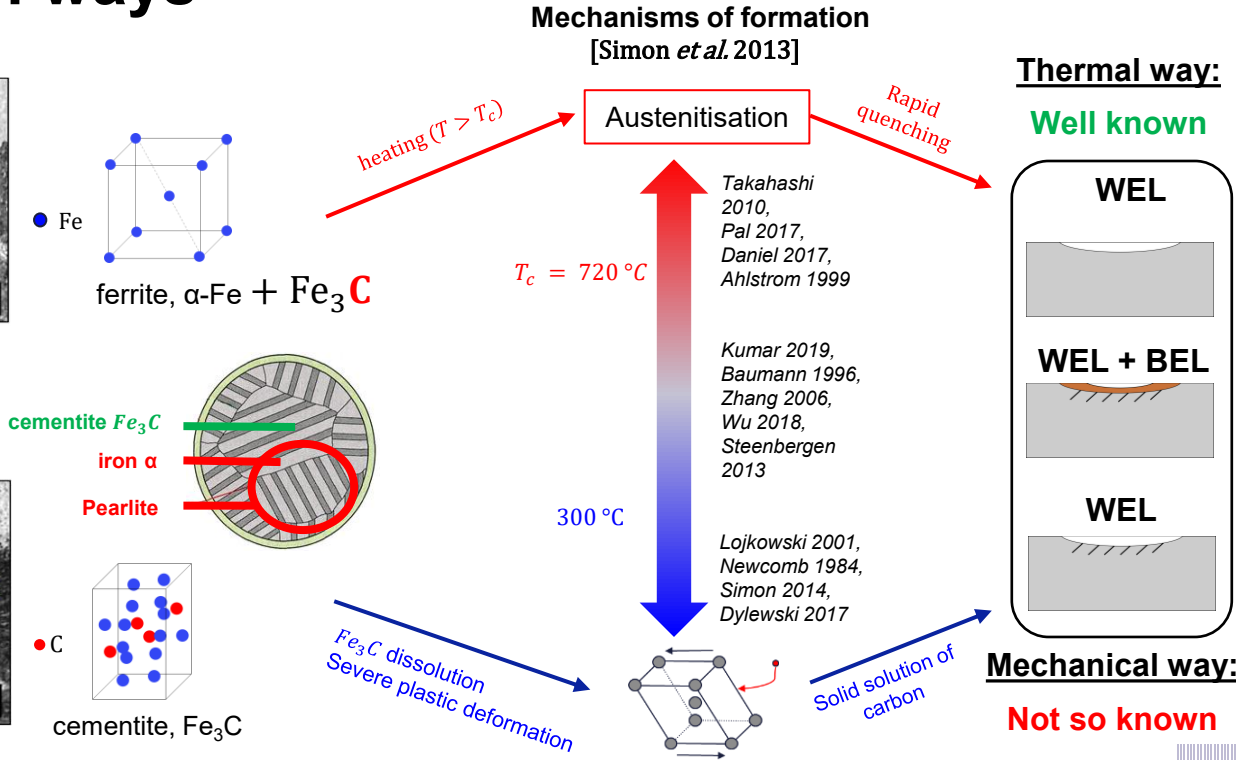
WEL's formation ways



Area : train station entrance and exit (high braking)
 Consequences : temperature rises (important sliding rate)

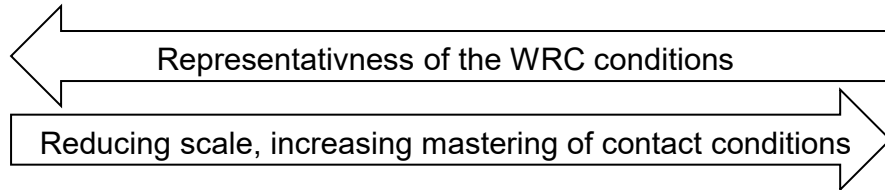


Area : High speed straight line and heavy traffic line
 Consequences : plastic strain accumulation

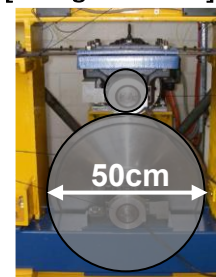


To study WEL formation mechanism
 => need of a **tribometer representative of the WRC reality**

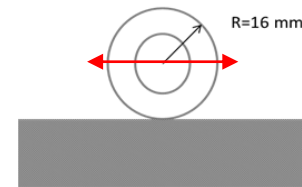
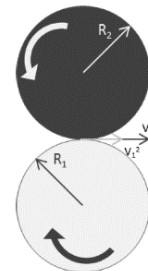
Overview of WRC tribometers



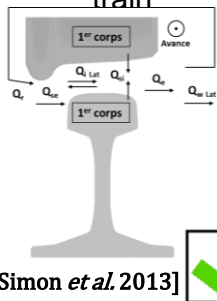
[Vuong *et al.* 2011]



Another way ?



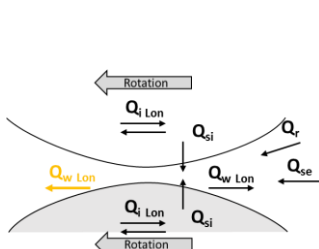
Instrumented train



[Simon *et al.* 2013]

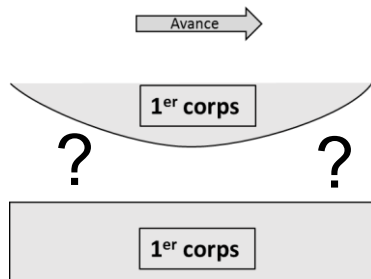


Full scale test 1:1

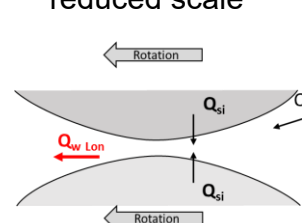


[Ullrich *et al.* 2014]

[Saulot *et al.* 2009]



Bi-disk reduced scale

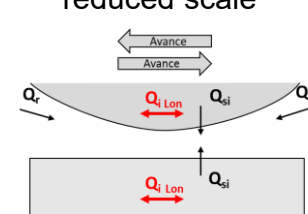


[Lewis *et al.* 2006]

[Vargolici *et al.* 2012]



Linear roller-plate reduced scale



[Niccolini *et al.* 2005]

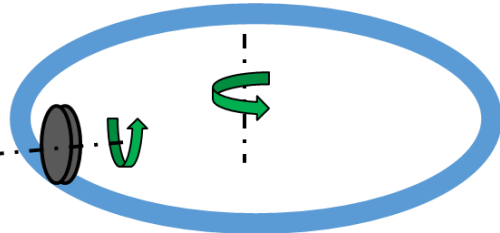
[Saulot *et al.* 2009]



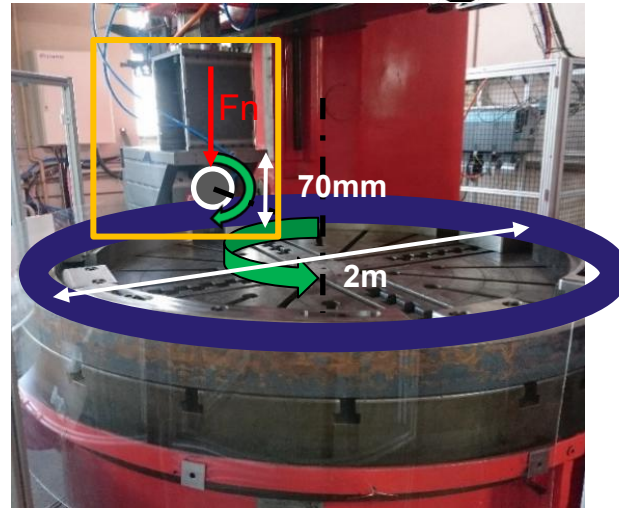
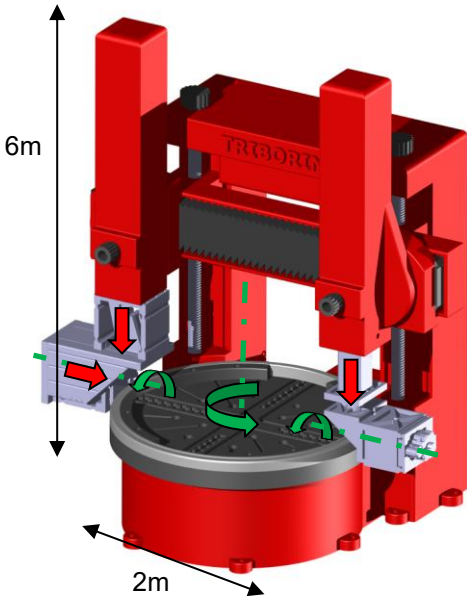
Triboring: WRC tribometer with two heads

[Merino *et al.*, PhD, 2019]
[Merino *et al.*, Wear, 2021]

TriboRing



Roller on ring



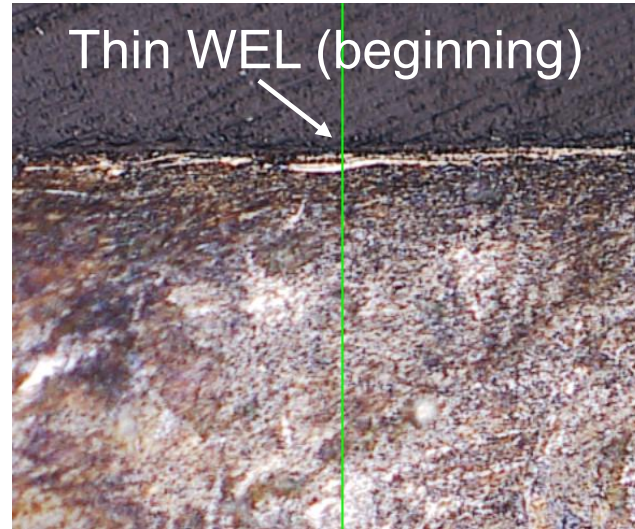
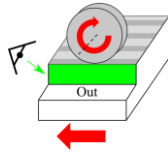
- Type/Scale : 1/15 scale **roller on ring** (based on 45t tool machine)
- Rail: single part ring forged from **real rail material**
- Wheel: machined from real **rail or wheel**
- Velocity: **up to 7 m/sec** (+ mastered rolling to full sliding conditions)
- Vertical load: **up to 10 kN**



Triboring: Mechanical WEL successfully reproduced

S_1M_1 / S_1M_2

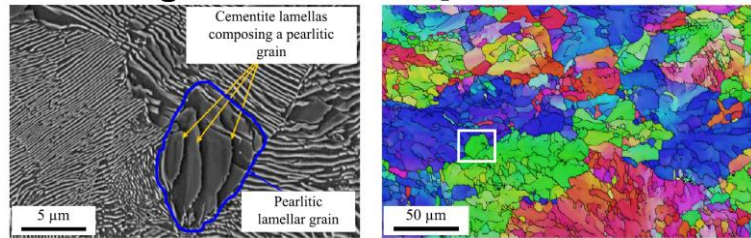
[Merino *et al.*, 2019]



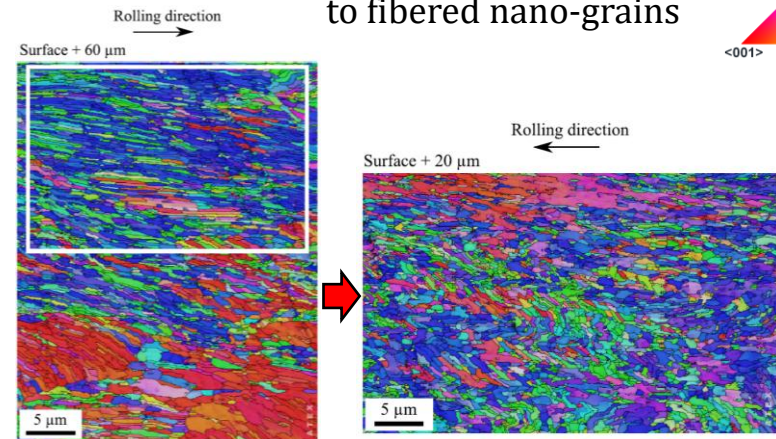
50 μm

Triboring: Mechanical WEL stages identified

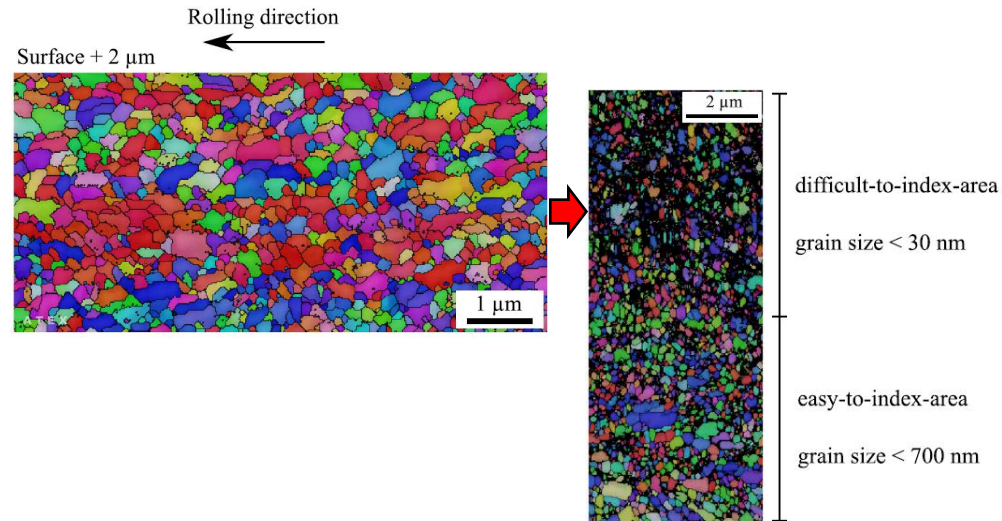
Stage 1 : As received pearlitic state



Stage 2 and 3 : From fibered micro-grains to fibered nano-grains



Stage 4 and 5 : From nano-pearlitic to nano-WEL



S_1M_1 / S_1M_2

[Thiercelin *et al.*, 2022]

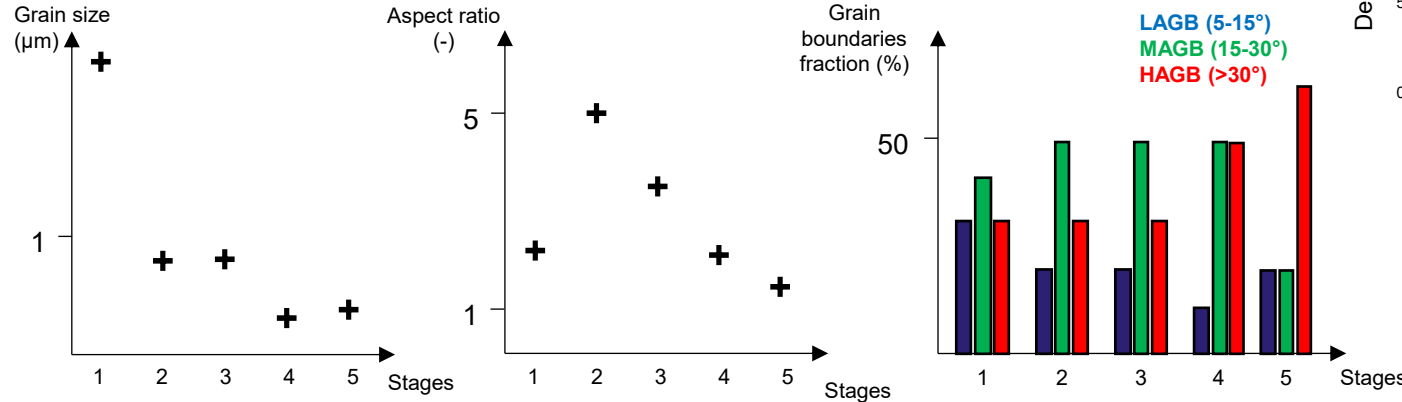
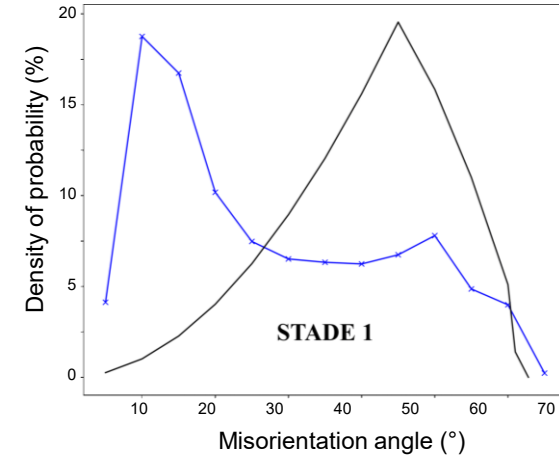
Triboring: Mechanical WEL stages identified

S_1M_1 / S_1M_2

[Thiercelin *et al*, 2022]

Grain state	Z value (-)	Grain size (μm)	Aspect ratio (-)	LAGB - MAGB - HAGB (%)
As-received pearlitic	0	7.1 ± 7.5	2.0 ± 0.83	30 - 41 - 29
Fibered and unfragmented	0.25	0.78 ± 0.28	5.3 ± 3.0	20 - 48 - 32
Fibered and highly fragmented	0.5	0.85 ± 0.42	3.2 ± 1.7	19 - 50 - 31
Unfibered and nanostructured	0.75	0.37 ± 0.06	2.0 ± 0.74	9 - 48 - 43
WEL	1	0.46 ± 0.1	1.8 ± 0.61	20 - 18 - 61

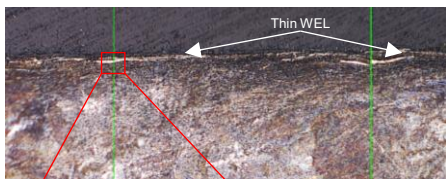
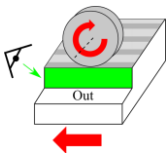
Distribution of grain boundary misorientation angles



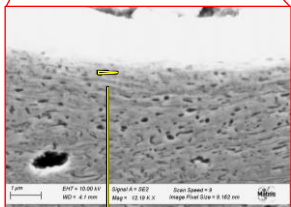
Triboring: Deeper inside stages

[Russo *et al.*, 2025]

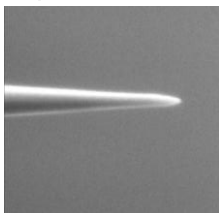
Stage 4 and 5 : From nano-pearlitic to nano-WEL (Atomic Probe Tomography)



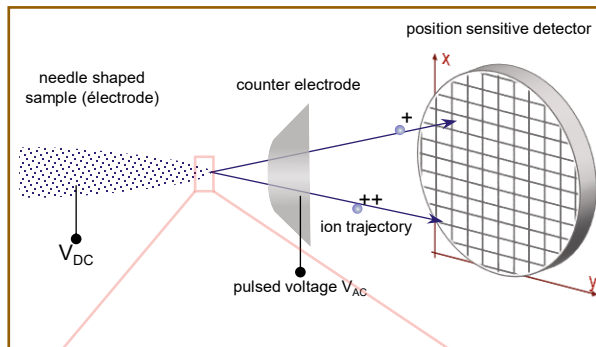
50 μm



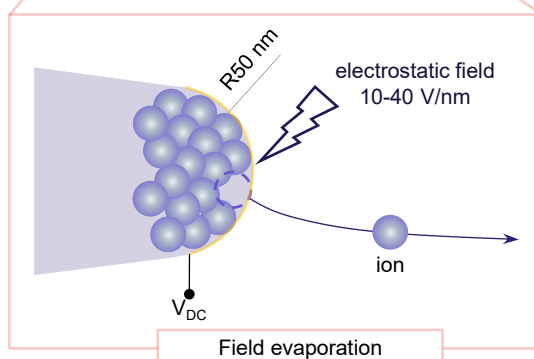
1 μm



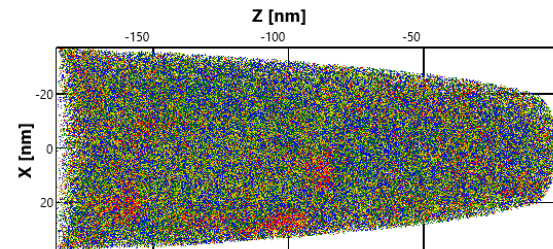
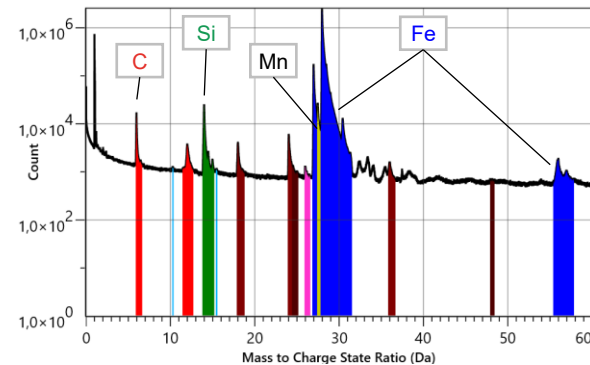
400 nm



Ultra high vacuum cryogenic chamber



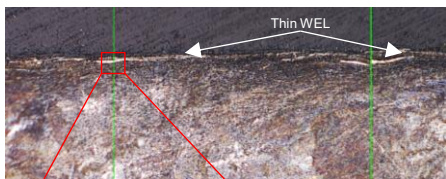
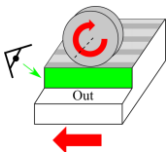
Field evaporation



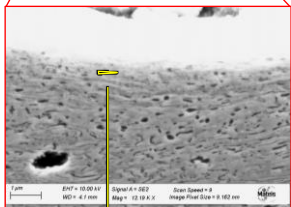
Triboring: Deeper inside stages

[Russo *et al.*, 2025]

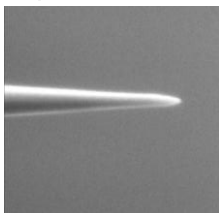
Stage 4 and 5 : From nano-pearlitic to nano-WEL



50 μm

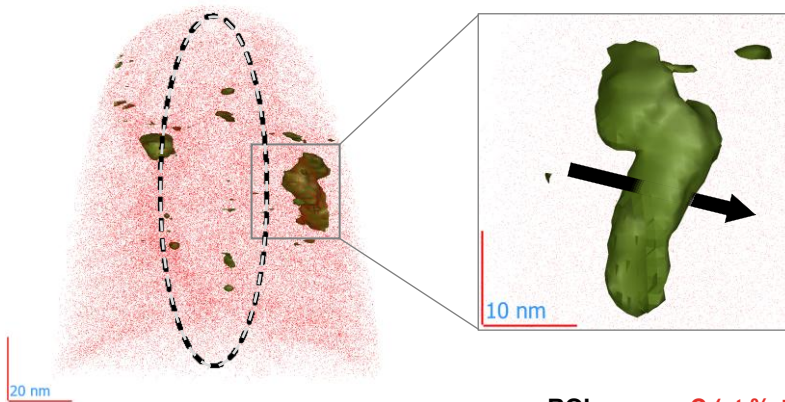


1 μm

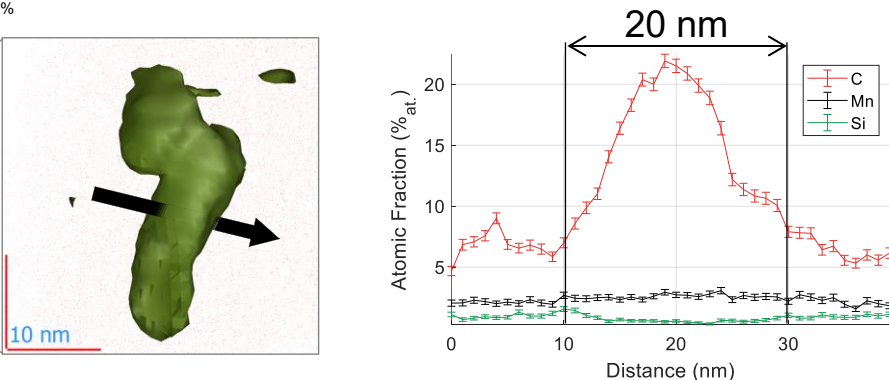


400 nm

(C) iso-composition: 12 at. %

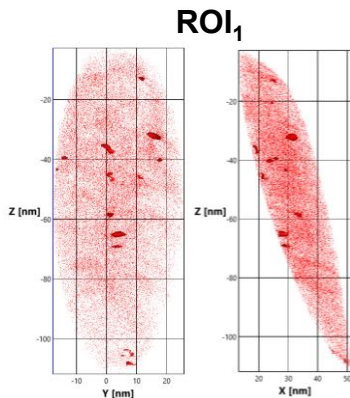


20 nm



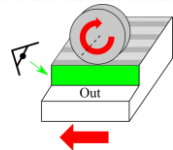
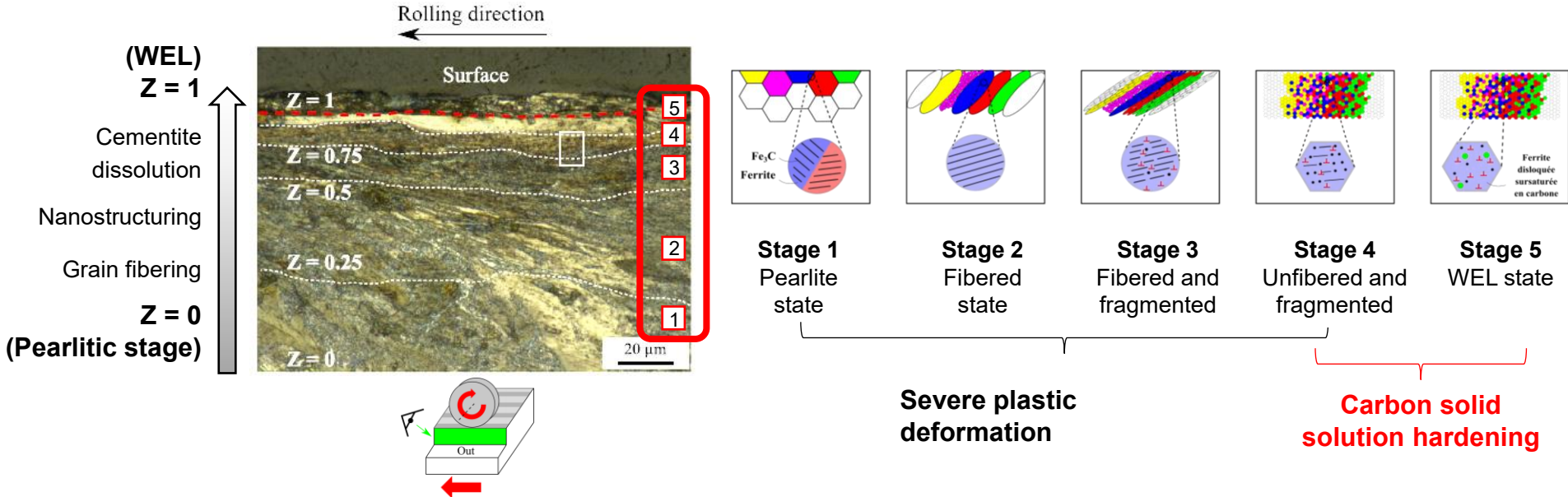
ROI	C (at.% ± 1 SD)	Mn (at.% ± 1 SD)	Si (at.% ± 1 SD)
whole sample	2.84 ± 0.005	0.90 ± 0.002	0.86 ± 0.002
1	2.31 ± 0.01	0.92 ± 0.01	1.04 ± 0.01

- **Proof of cementite dissolution** (nano size, C homogenisation)
- **No residual austenite observed** (not presented)



WEL's ... to be modeled macroscopically

[Thiercelin *et al.*, 2020, 2022]



Tribology

- Thin white etching layers under optical microscope
- Mixed fragmented-lamellar nanostructure
- Cementite dissolution
- Mechanical driving force is the primary factor

Work under progress:

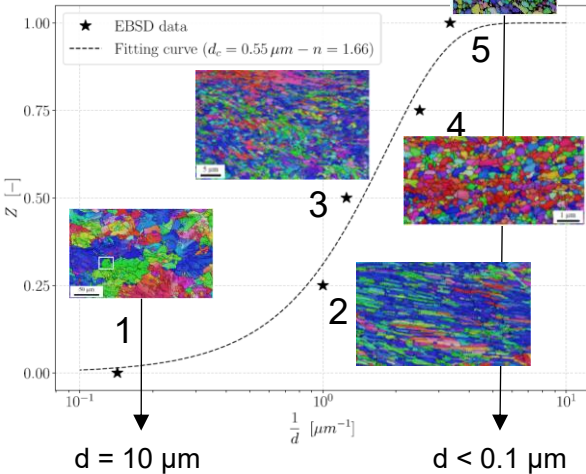
M. Russo (PhD on Pearlitic steels)
A. Vieira (Ph D on Bainitic steels)

WEL's ... to be modeled macroscopically

[Thiercelin *et al.*, 2020, 2022]

Microstructural indicators ...

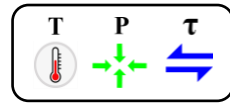
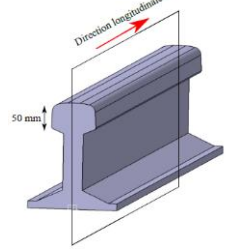
- Grain size
- Aspect ratio
- Grain disorientation



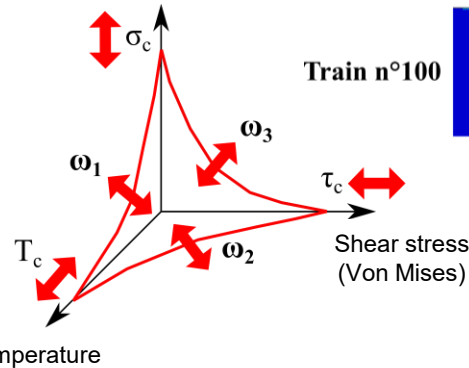
...to a 1st Correlation function...

$$Z = 1 - \exp\left(-\left(\frac{d_c}{d}\right)^n\right)$$

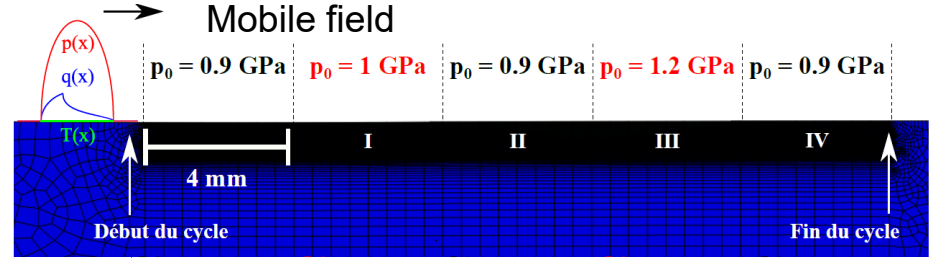
... Implemented in a 2D model



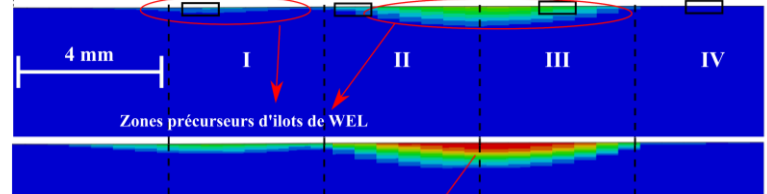
Hydrostatic pressure



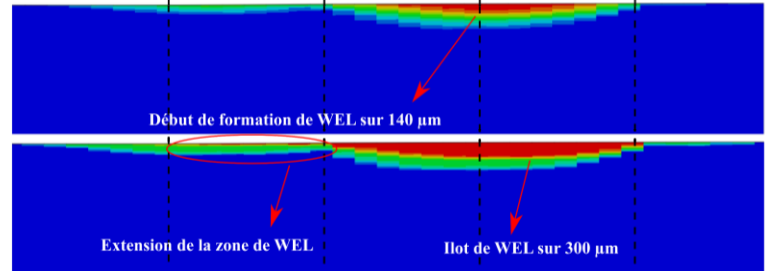
Mobile field



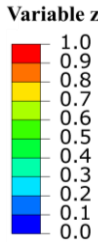
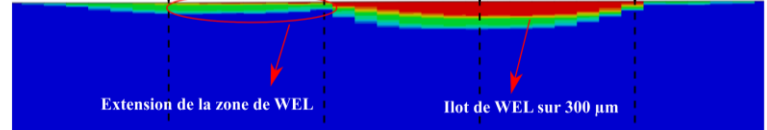
Train n°5



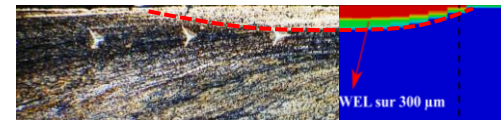
Train n°20



Train n°100



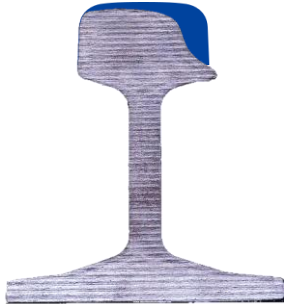
Reproduced mechanical WEL's



WRC at the origin of several rail defects

Rail defects (many, classified by UIC)

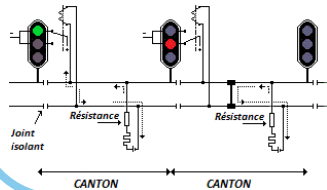
Lubrication
Badly optimized



Pollution
(ex: leaves, ...)



Unshunting



Full sliding



Corrugation wear

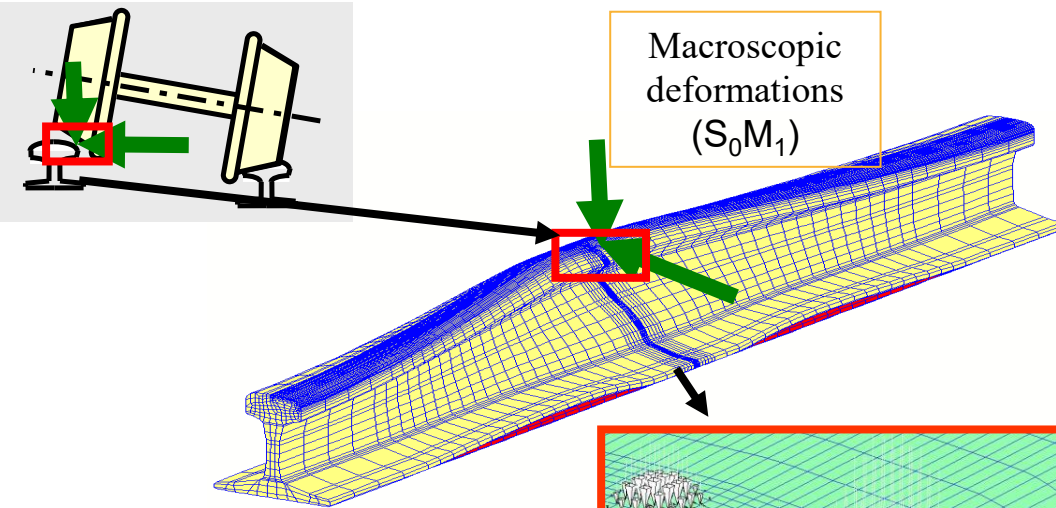


Squat (fatigue)



Need to master the wheel-rail contact **tribological antagonism** !

Flange lubrication for WRC

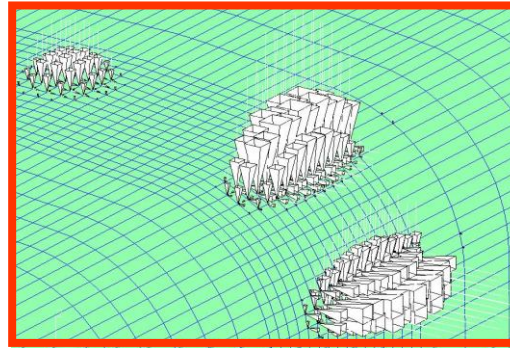


Macroscopic deformations (S₀M₁)

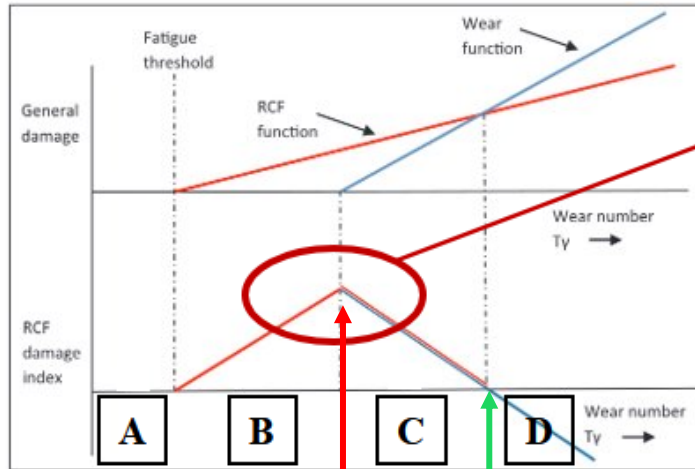


TTS S₁ and 3rd body S₃M₃

Local plastic deformation (S₁M₁)



Flange lubrication for WRC



~ 70 kN
[Chollet]

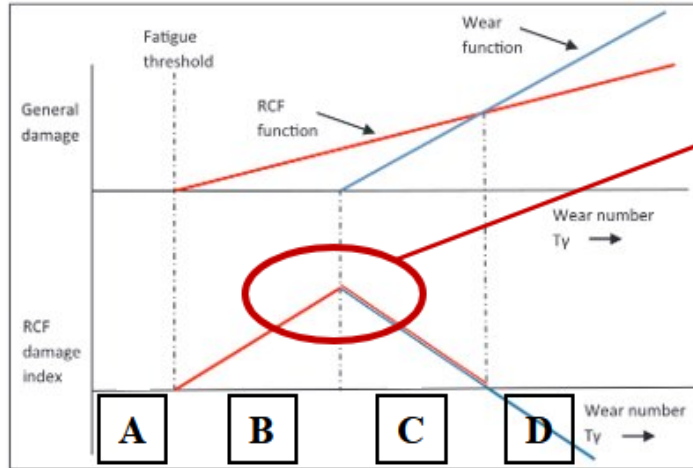
$$T\gamma = F_x \xi_x + F_y \xi_y$$

- **A** : few to no wear/RCF
- **B** : **Mostly RCF**
- **C** : **RCF vs. wear**
- **D** : **Mostly wear**

Maximum RCF

« Magic » wear

Flange lubrication for WRC



$\sim 70 \text{ kN}$
[Chollet]

- **A** : few to no wear/RCF
- **B** : **Mostly RCF**
- **C** : **RCF vs. wear**
- **D** : **Mostly wear**

$T\gamma$ parameter

$$T\gamma = F_x \xi_x + F_y \xi_y$$

$T\gamma = f(\text{lubrication})$

Unlubricated : Mostly wear $\rightarrow T\gamma \gg 70$ (?)

Lubricated :

Excessive lubrication (Flow x2)

$\rightarrow T\gamma ?$

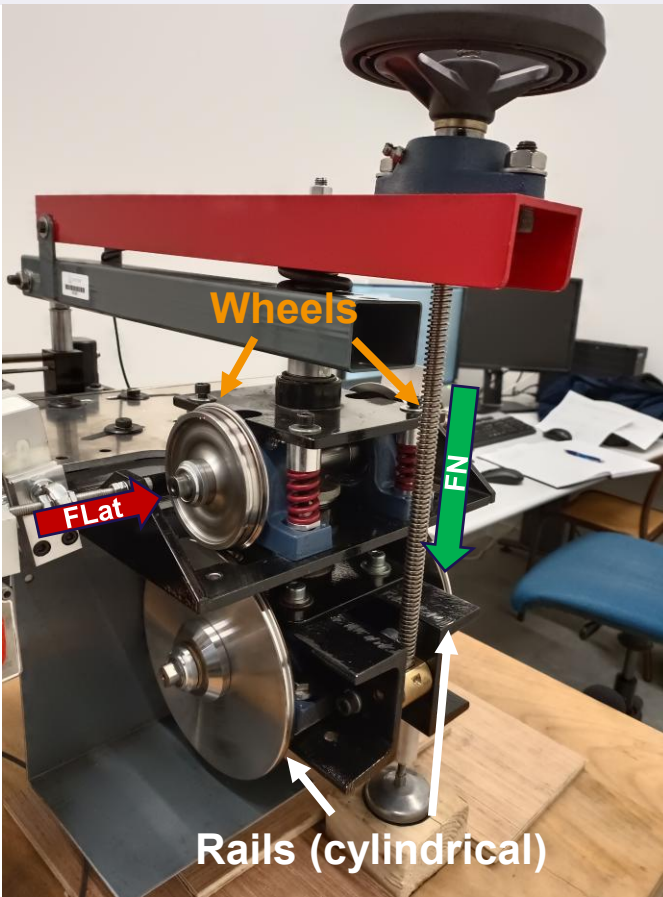
Reference lubrication (Flow equivalent to field)

$\rightarrow T\gamma \leq 70$ (?)

Insufficient lubrication (Flow /2)

$\rightarrow T\gamma ?$

Flange lubrication for WRC



- Close to **twin-disc** test, with more representative geometries
- Actual **wheel shape** and rail surface profile
- **Simulate** (scale 1/10th) leading train wheel in curve
- **Auto-adjustment** of wheelset during test
- Initially designed by **H. Chollet** (*University Gustave Eiffel*)



Objective : **maximal criticality** towards Rolling Contact Fatigue (**RCF**) degradation

- **Imposed** wheel climbing on rail flange
- **No cant**
- **Monotonic solicitation**

Flange lubrication for WRC

Parameter	Value	Scale
Normal force	1 kN	1/100
Lateral force	100 N	1/100
Speed	200 rpm (~ 6 km/h)	1/10
Pressure	1.5 (tread) / 3.7 (flange) GPa	1
Wheel/rail angle	10 mrad	1
	Value	Scale
Initial lubrication	Equivalent to 30s of lubrication	1/100
Lubrication flow	Confidential	Flow /100
Lubrication position	Wheel flange	1

Simulated conditions

Conditions identified to be the **most severe for RCF**

- **Passenger train**
- **Low linear speed (< 100 km/h)**
- **Tight curve**

Lubrication conditions

Lubrication flow **equivalent** to in-field

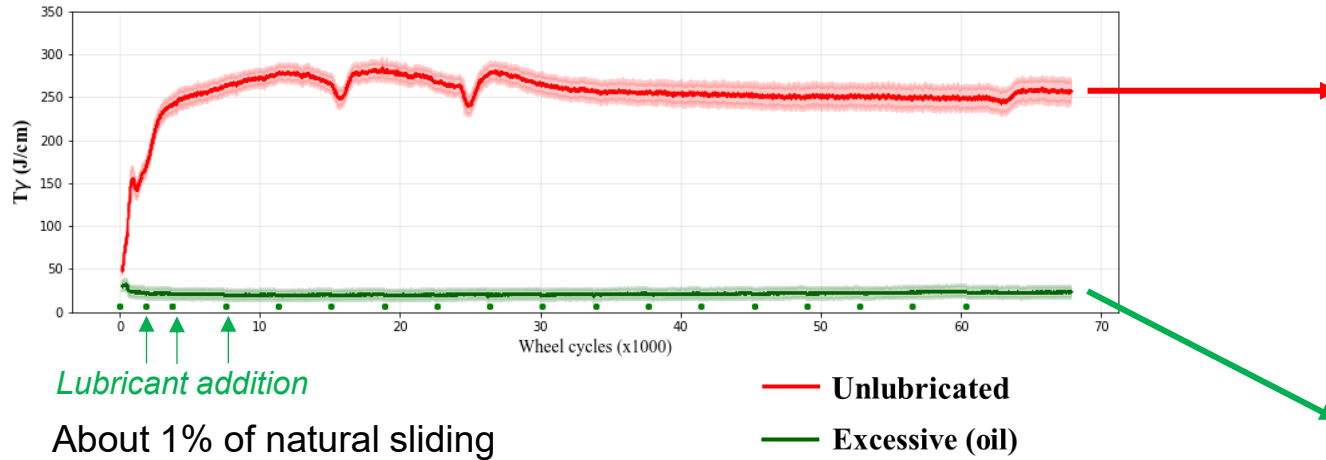
Contact area /100 → lubricant flow /100

Reference lubrication



Flange lubrication for WRC: Ref. Oil Lubricated

[Lesage et al., ESMC 2025]



Lubricant addition

About 1% of natural sliding

— Unlubricated
— Excessive (oil)

No Lub



Ref. Oil

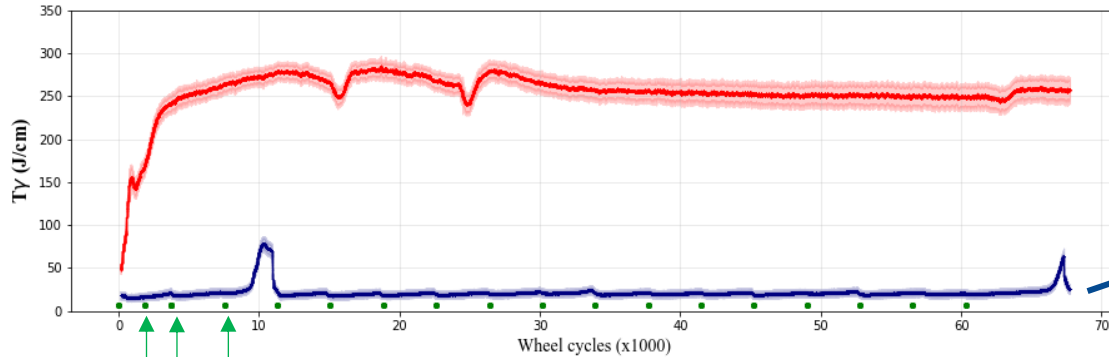


Reference Oil excessive lubrication

- Clear **diminution of Ty** compared to unlubricated test
- $Ty \leq 70$ J/cm; indicating prevalence of **RCF** regime
- **Oil flows** along rail tread (up to opposite flange)

Flange lubrication for WRC: BioGrease Lub.

[Lesage et al., ESMC 2025]



Lubricant addition

About 1% of natural sliding

— Unlubricated
— Excessive (grease)

BioGrease



Ref. Oil

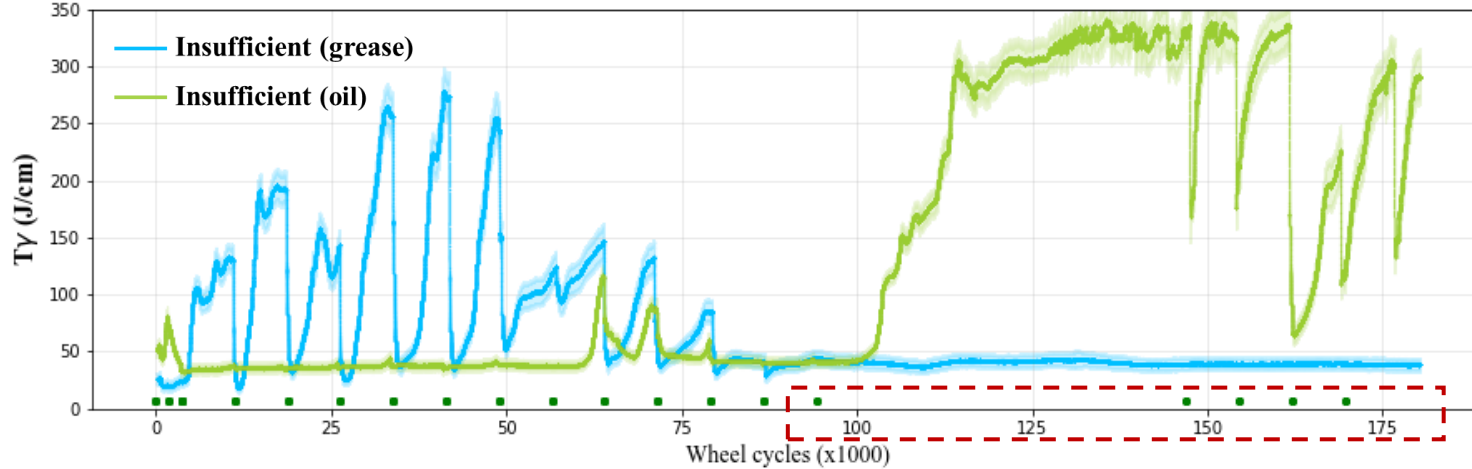


BioGrease excessive lubrication

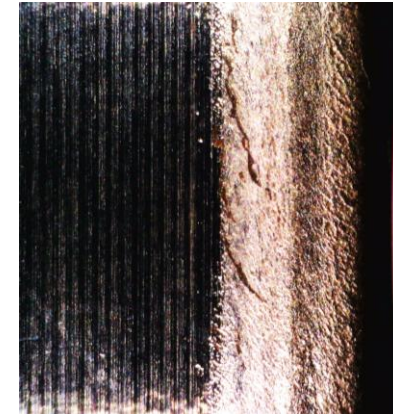
- **Similar behavior** compared as oil-lubrication
- Some accidents observed locally
- **Few lubricant migration** on rail and wheel tread

Flange lubrication for WRC: Long tests !

[Lesage et al., ESMC 2025]



- Effective in lowering T_y as long as it is regularly provided
- **Oil**: Lubrication is **effective immediately** after lubrication and **as long as** lubricant is provided
- **Grease**: An accumulation of lubricant is needed (**full film formation**) to observe adequate lubrication. **Once this film is formed**, lubrication is effective for a long duration

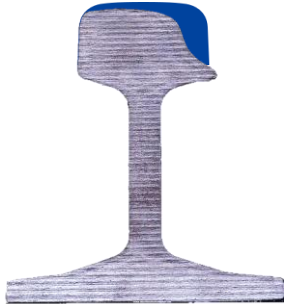


1 mm

WRC at the origin of several rail defects

Rail defects (many, classified by UIC)

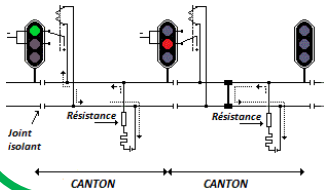
Lubrication
Badly optimized



Pollution
(ex: leafs, ...)



Unshunting



Full sliding



Corrugation wear



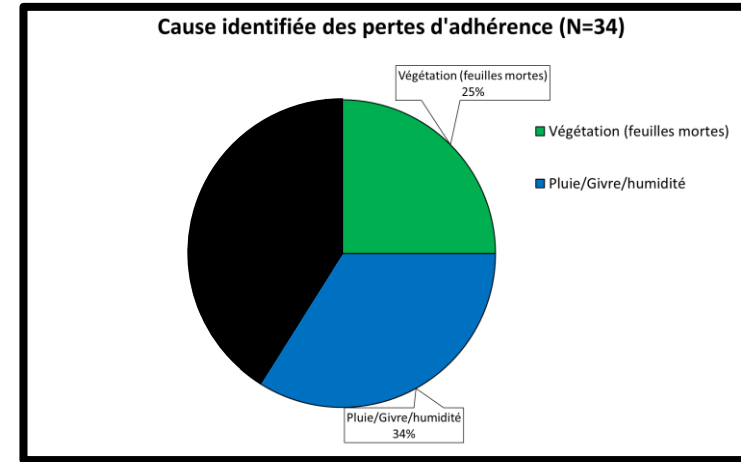
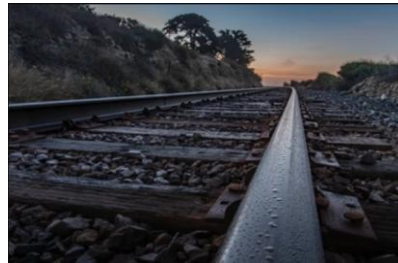
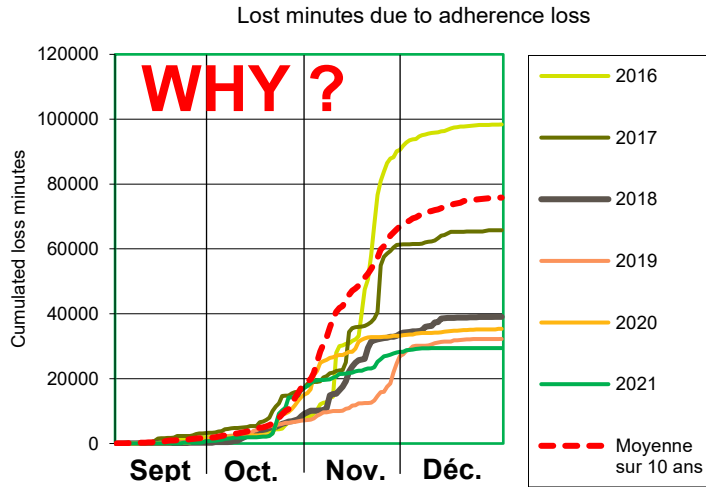
Squat (fatigue)



Need to master the wheel-rail contact **tribological antagonism** !

Loss of adhesion in autumn

[Guidoum et al., 2023]



Two main causes: **leafs** et **hygrometry variations**

Leaf, a specific 3rd body

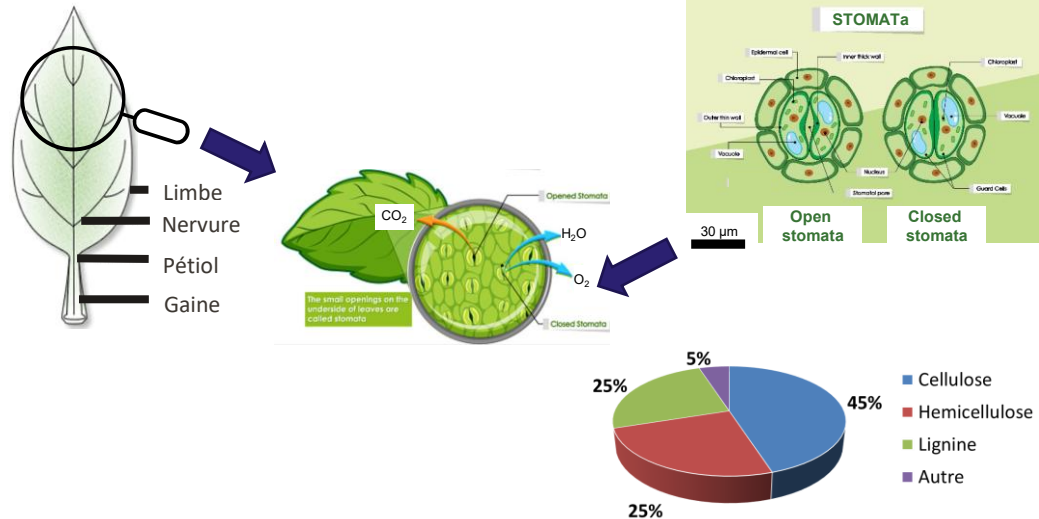
[Guidoum et al., 2023]

Hygrometry variations

	Janvier	Février	Mars	Avril	Mai	Juin	Juillet	Août	Septembre	Octobre	Novembre	Décembre
Température moyenne (°C)	4	4.3	6.7	9.9	13.4	16.4	18.5	18.1	15.5	12.1	7.7	4.7
Humidité(%)	84%	81%	77%	72%	72%	72%	71%	73%	76%	80%	86%	85%

Climate data in Nord-Pas-De-Calais, France (2020)

Leafs

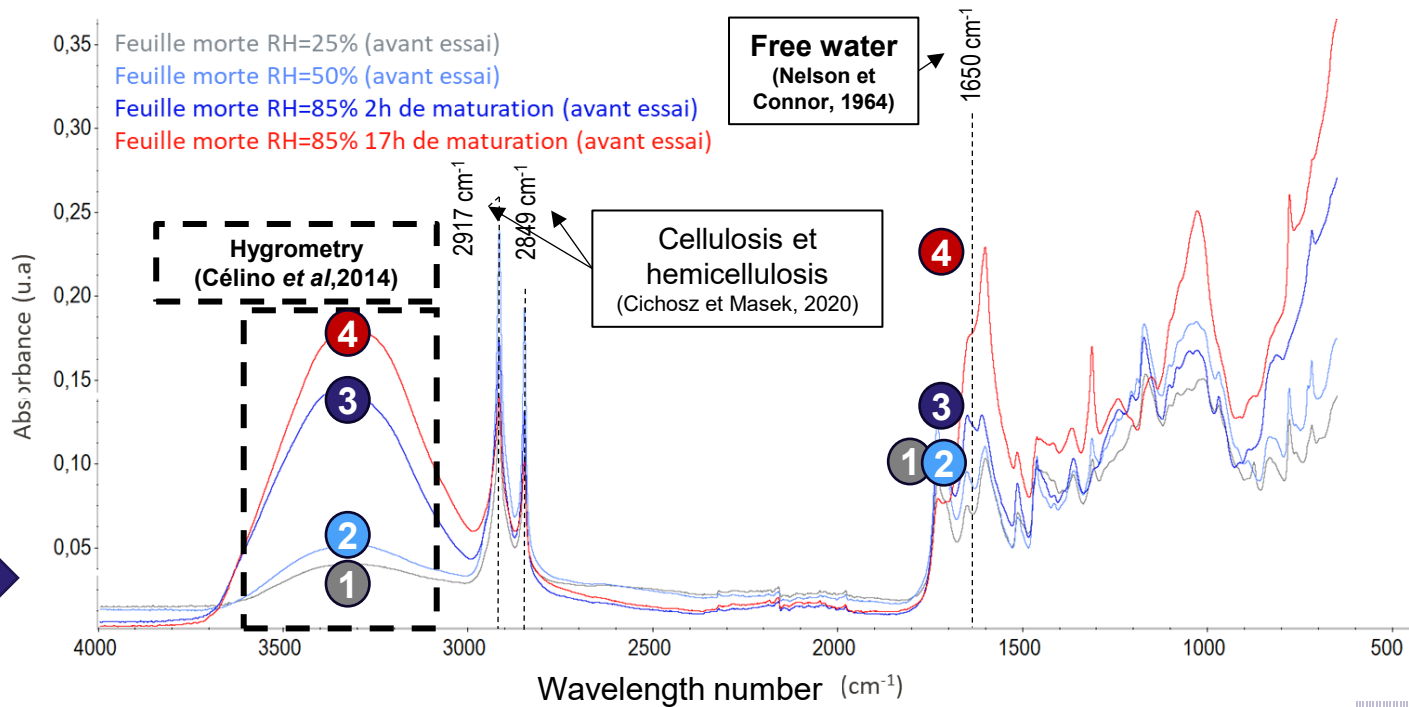
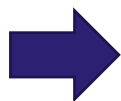
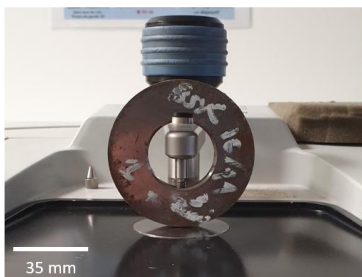
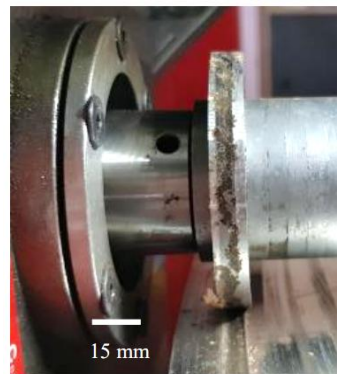


(Wertz, 2010)

Relative hygrometrie (RH%) of 3rd bodies :

- RH ≤ 35% :
Dry 3rd body
(middle of afternoon)
- RH ≈ 50% :
Intermediate 3rd body
(end of morning)
- RH ≥ 85% :
Humid 3rd body
(beginning of morning and/or evening)
→ 2h and 17h of maturation
(physico-chemical changes (Bringel, 2021))

Leaf, a specific 3rd body



Infrared spectroscopy (FTIR)

Leaf, a specific 3rd body: tests on Triboring

[Guidoum et al., 2023]

External 3rd body (dead leaves)



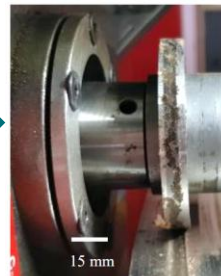
Triboring (1GPa, 1%, 2.5m/sec)



3rd body layer reproduced (S₃M₃)



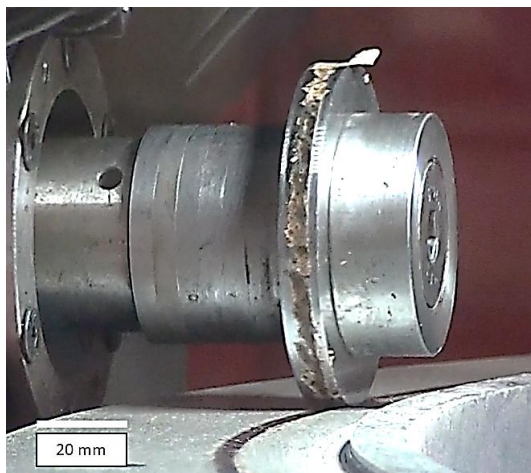
Experiment



Real life

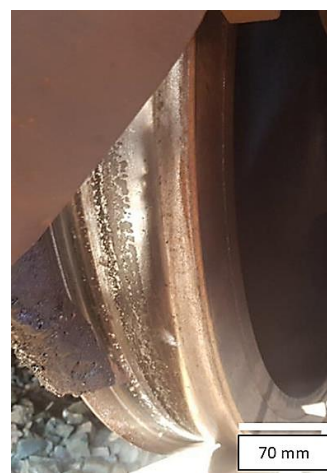


Real wheel

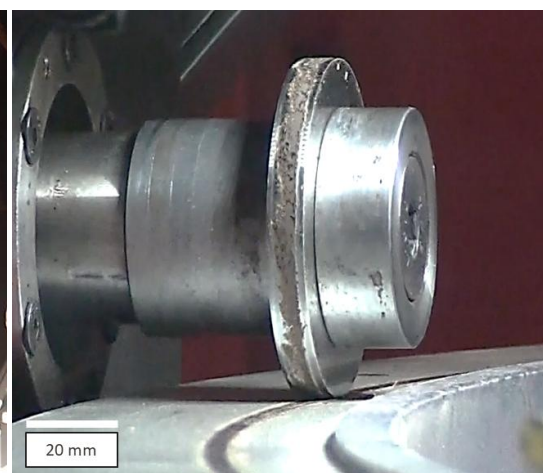


Triboring roller

Cumulative distance: **130m**



Real wheel



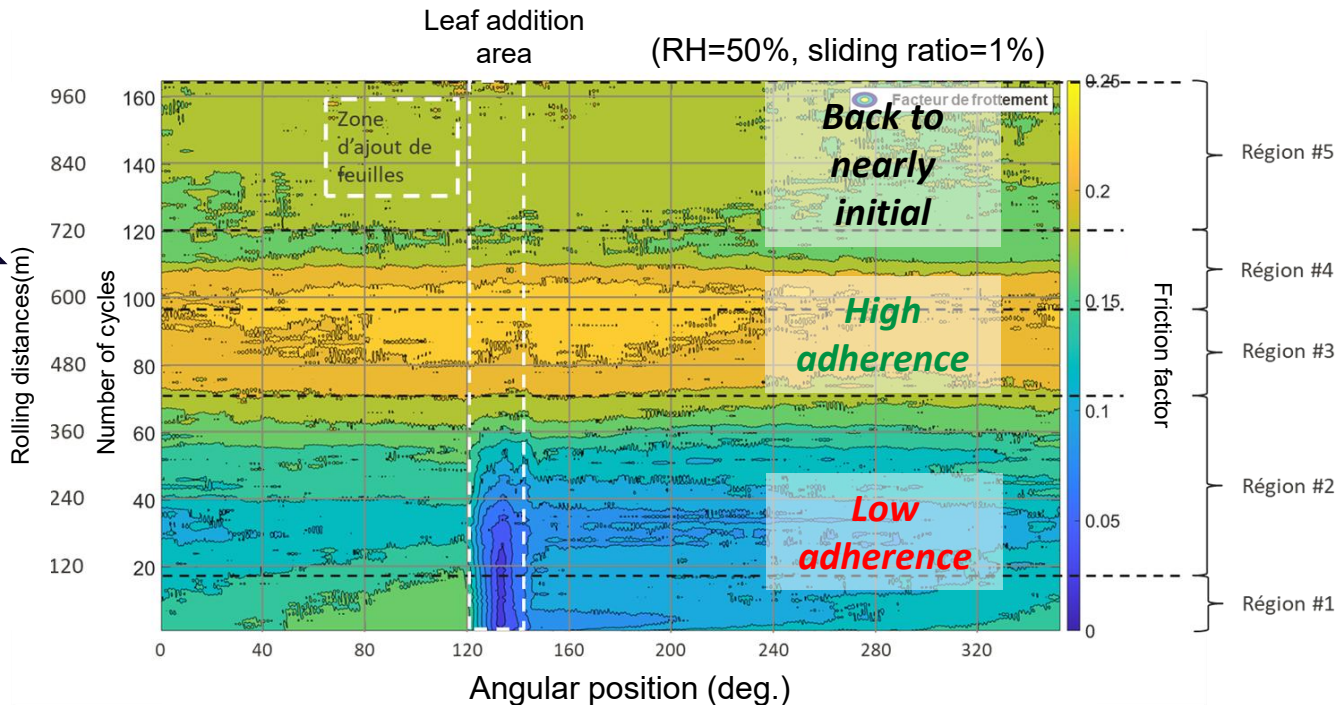
Triboring roller

Cumulative distance: **340m**

Leaf, a specific 3rd body: tests on Triboring



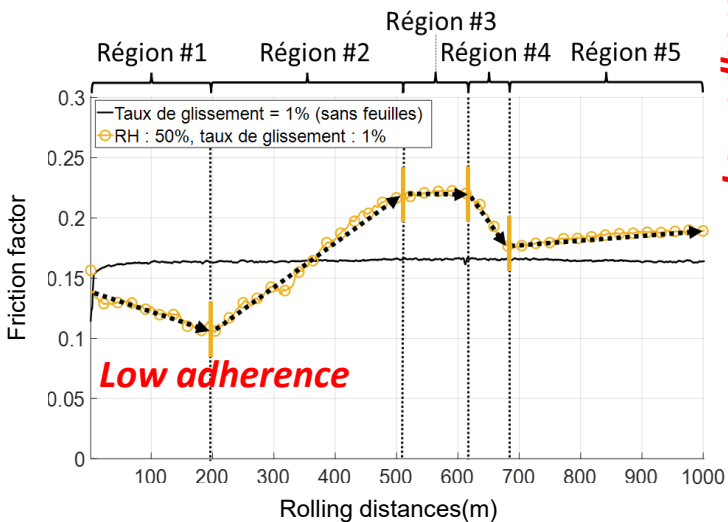
20 mm



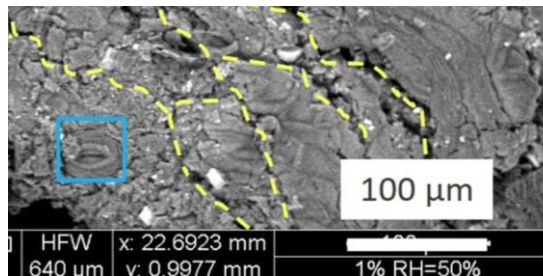
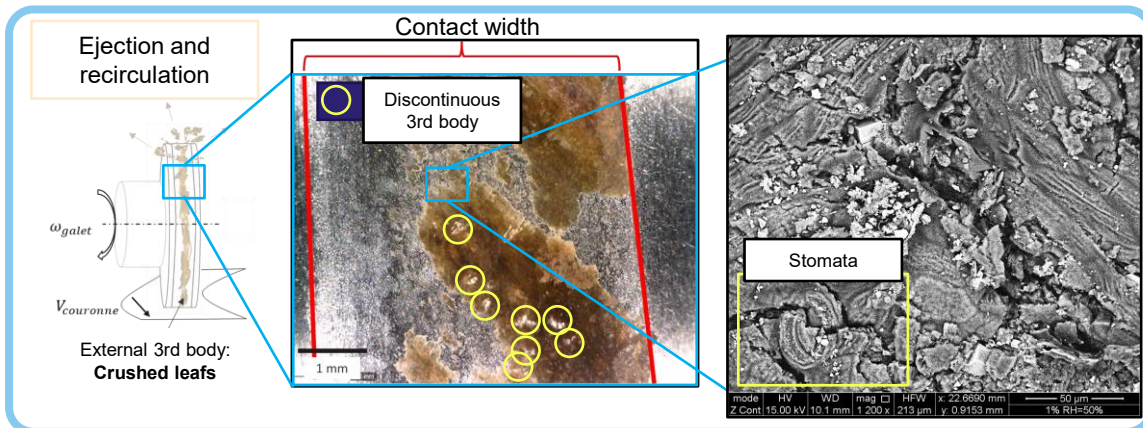
Friction level recovery and some time higher than initial steel-steel thanks to the 3rd body evolution.

Leaf, a specific 3rd body: adherence evolution

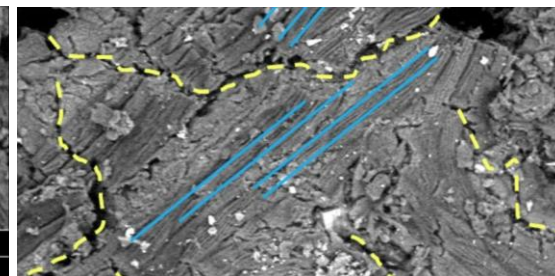
[Guidoum et al., 2023]



Low adherence



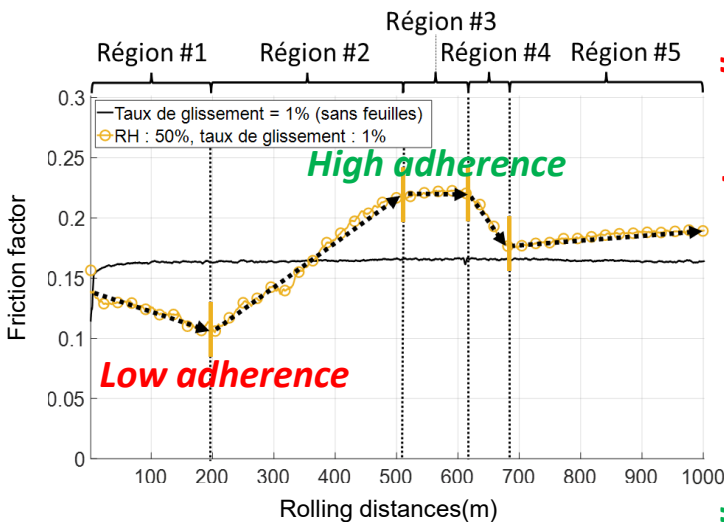
Stomata



Leaf vein

Leaf, a specific 3rd body: adherence evolution

[Guidoum et al., 2023]



Test end



Low adherence

High adherence

Low adherence

Ejection and recirculation

Contact width

Discontinuous 3rd body

Stomata

External 3rd body: Crushed leaves

$\omega_{gale\grave{e}t}$

$V_{couronne}$

1 mm

50 μ m

1% RH=50%

High adherence

3rd body ejection

Ejection orientation

More continuous and homogeneous

NO Stomata NO Vein

$\omega_{gale\grave{e}t}$

$V_{couronne}$

Ejection orientation

1 mm

400 μ m

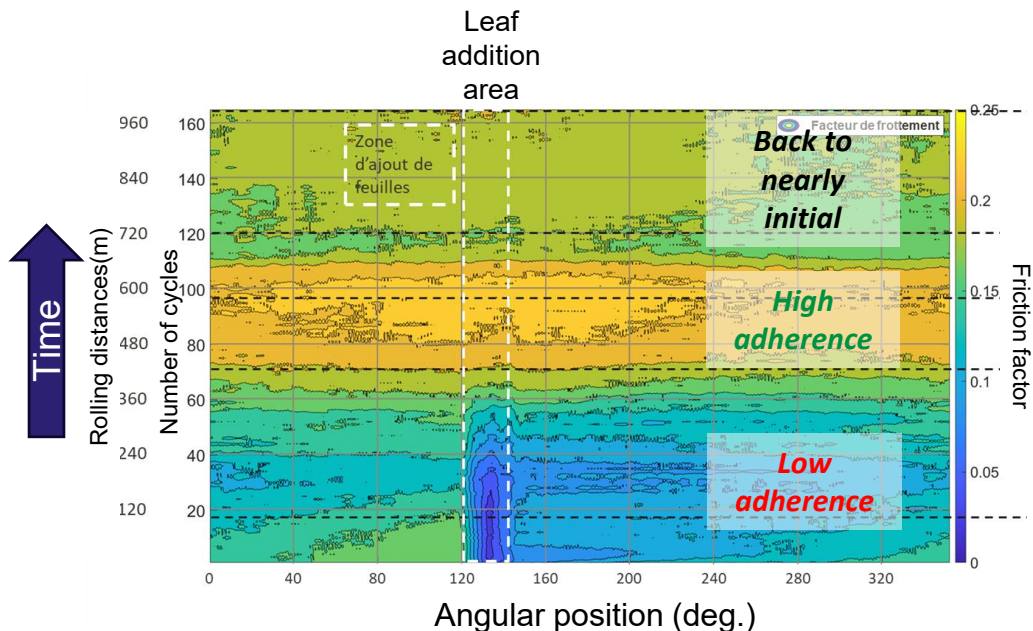
50 μ m

Leaf, a specific 3rd body: adherence vs %RH

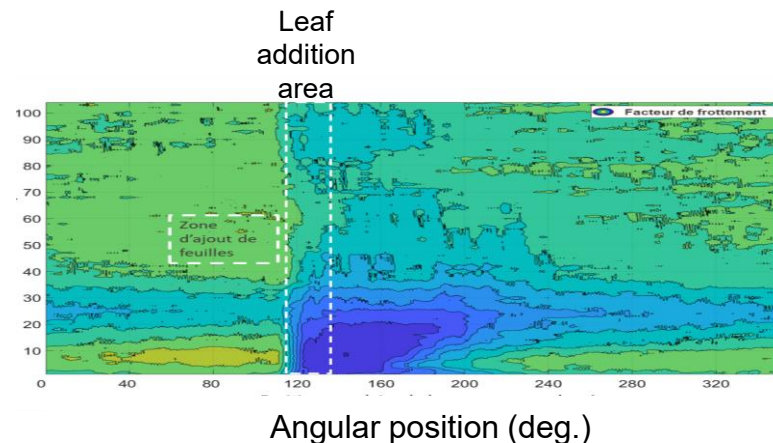
[Guidoum et al., 2023]

(RH=50%, sliding ratio=1%)

(RH=85% 2h maturation, sliding ratio=1%)



After 100 cycles, **no recovery !**
(no change until end of test 160 cycles – no represented)

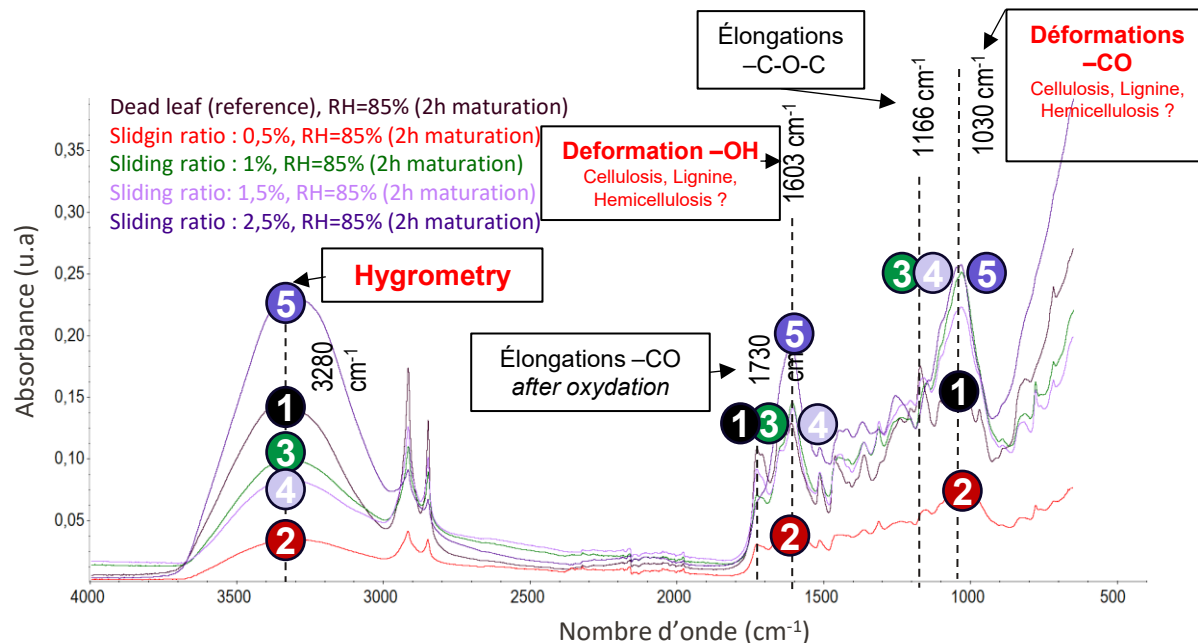
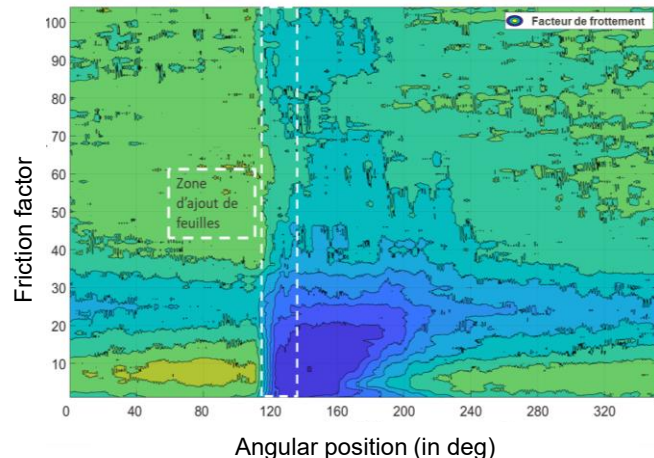


With **higher initial %HR and maturation time:**
No recovery of adherence in the tested conditions (100 wheels ⇔ 4 TGV !)

Leaf, a specific 3rd body: adherence evolution

[Guidoum et al., 2023]

(RH=85% 2h maturation, sliding ratio=1%)

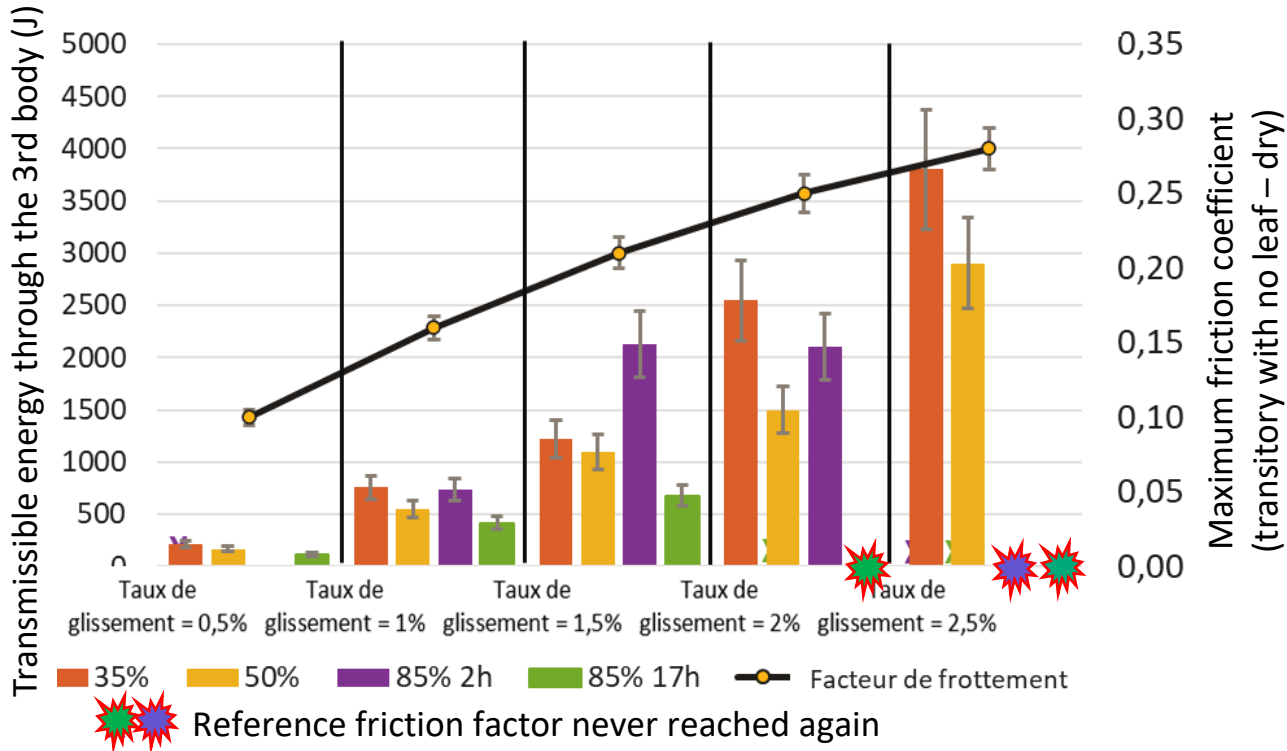


Maturation of 3rd body with high %HR give the worth friction behaviour at high sliding ratio.... due to physicochemical reactions in the 3rd body who modify its rheology ?

.... no strong explanation yet, study to be continued !

Leaf, a specific 3rd body: Friction vs. %RH vs %SR

[Guidoum et al., 2023]



Maturation of 3rd body with high %HR give the worst friction behaviour.....
... may not have the possibility to recover original « no leaf adherence »!

How to recover adherence, actual solutions ...



Washer train !
(1 500 bar pressure)



Grinding

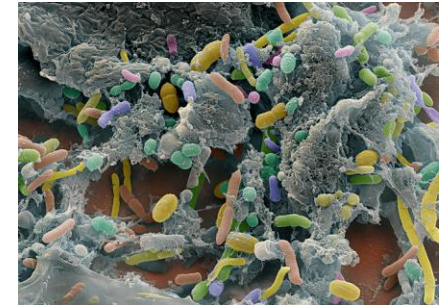
Appropriate tree species ?

Which one will help to create the appropriate 3rd body ?



Sanding

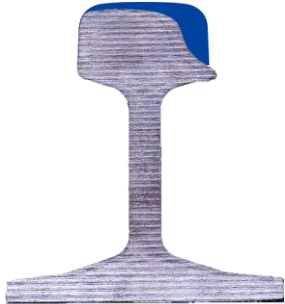
3rd body digestion with bacteria ?



WRC at the origin of several rail defects

Rail defects (many, classified by UIC)

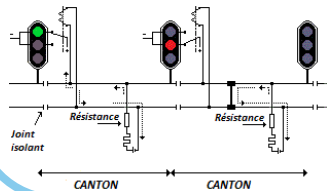
Lubrication
Badly optimized



Pollution
(ex: leaves, ...)



Unshunting



Full sliding



Corrugation wear



Squat (fatigue)



Need to master the wheel-rail contact **tribological antagonism** !

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Plenary Lectures

Call for Abstracts

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Victoria Van Camp

Adjunct professor of machine elements
Luleå University of Technology, Sweden

*Efficiency first! How tribology could reduce global power need
and ease decarbonisation, today.*

Kenneth Holmberg

Retired Research Professor in tribology, condition monitoring and operational reliability
VTT Technical Research Centre, Finland

Impact of Tribology on Global Energy Use and Decarbonisation

<https://leeds-lyon2026.sciencesconf.org/>



Do not forget to
register before :

May 31st, 2026
(earlybird)

Wheel-rail contact: a tribological antagonism

Tuesday 14th april 2026

Pr A. Saulot, Tribology team, LaMCoS

With other colleagues: Y. Berthier, S. Simon, P. Merino, M. Russo, F. Duan, A. Vieira, S. Cazottes, X. Sauvage, M. Veron, E. Feulvarch, L. Thiercelin, F. Lebon, L. Baillet, S. Descartes, L. Lafarge, A. Ferrieux, P. Veuillet, T. Lesage, J. Chalon, S. Guidoum, E. Montero...