



Journées Tribologie et Traitements de surface  
22-23 novembre 2023, CETIM - SENLIS

# Processus d'usure en freinage par friction : quelle clé pour atténuer à la source les émissions de particules ?

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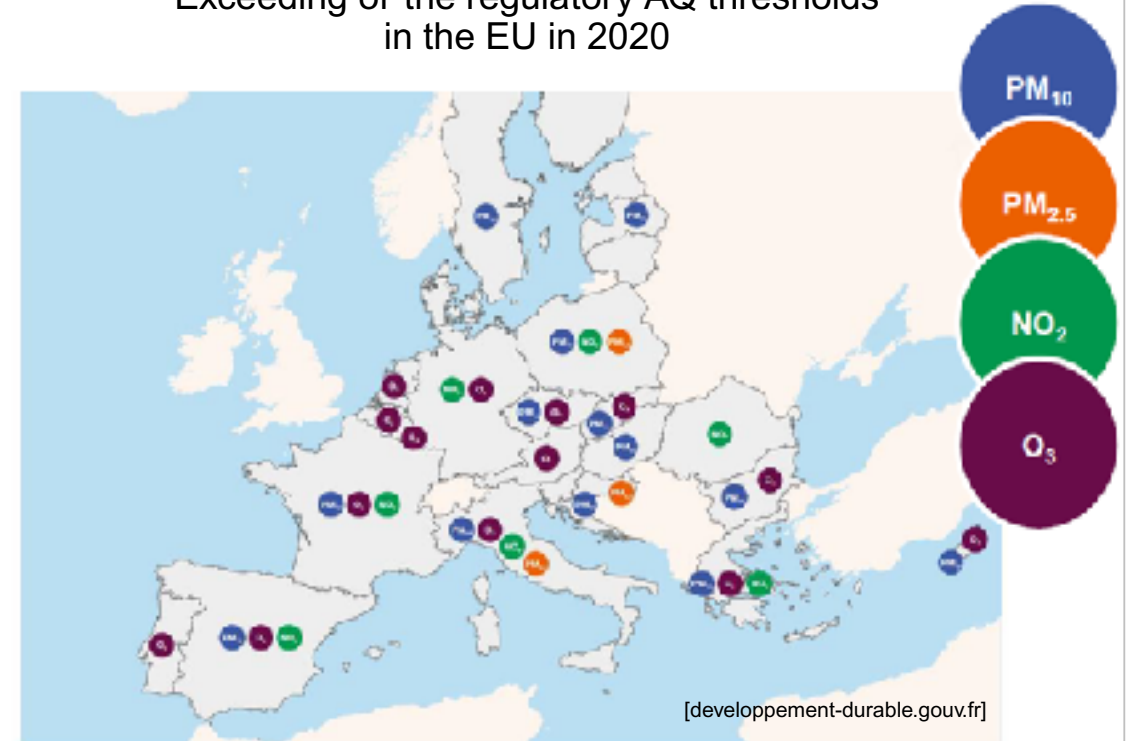


# Context and issues

## Air quality

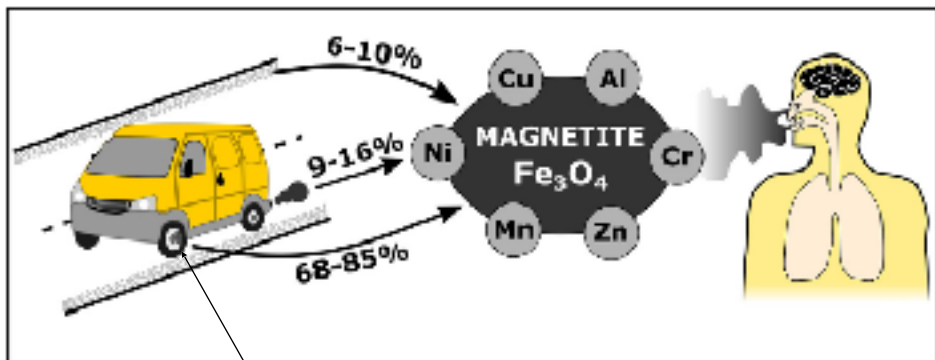
- Air Quality is a major concern in urban/suburban areas and in mobility
- Although improving for over 20 years, it still doesn't meet the WHO recommendations
- Poor Air Quality in urban centers leads to **238,000 premature deaths** (European Environment Agency).

Exceeding of the regulatory AQ thresholds in the EU in 2020



# Context and issues

## Particle emissions - Automotive braking

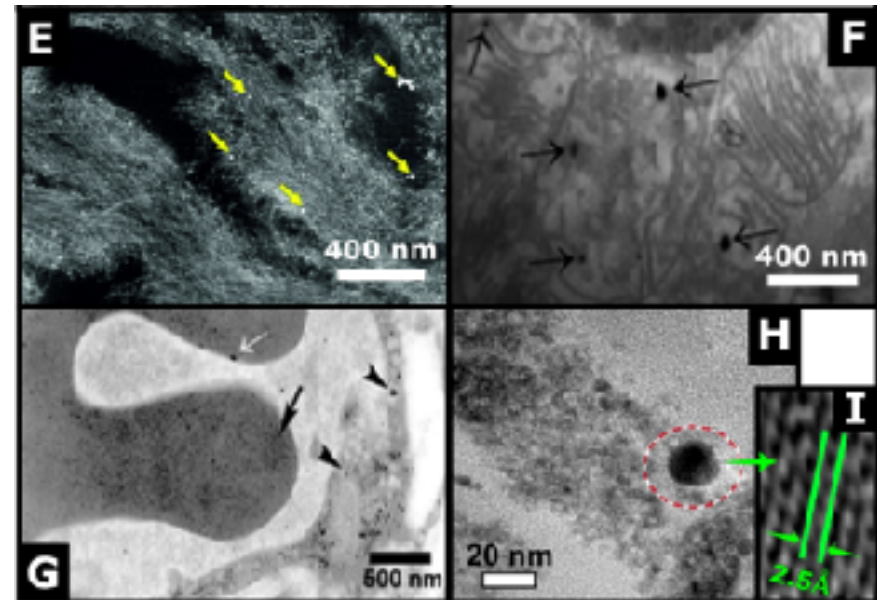


Cast iron brake disc

[Gonet, 2021]

Magnetite in neurons

Magnetite in the heart and red cells



Magnetite in the left ventricle of a human

Magnetite in the heart and red cells

[Gonet, 2021]

- Iron oxides could play a specific role in Alzheimer's disease [Maher, 2019]
- Limitation of particle emission from Euro7 Norm (European Commission) :
  - 7 mg/km until 2035.
  - 3 mg/km after 2035.

# Context and issues

## Particle emissions - Railway braking

- Rail transport contributes to less than 1% of the total atmospheric particle emissions from all sources.
- However, in underground railway enclosures, these emissions lead to concerning particle concentrations.
- The main sources of these particles are largely attributed to railway activities (braking system, wheel-rail contact, ...)

PM: Comparison between outdoor (**Urban Air Ambient**) and indoor (**Underground Rail Enclosures**)

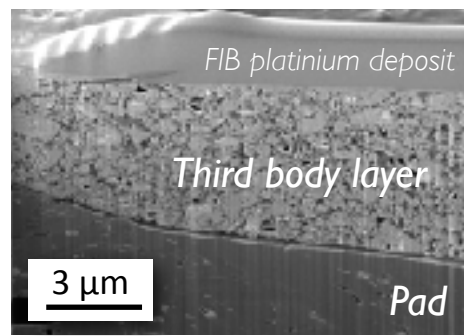
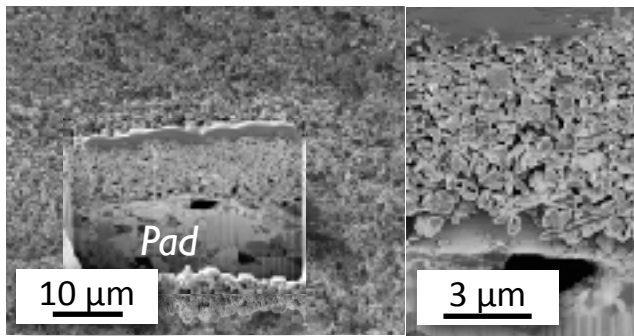
Ville	Année de mise en service	Année de mesure	Espèces mesurées	Niveaux intérieurs ( $\mu\text{g}\cdot\text{m}^{-3}$ )	Niveaux extérieurs ( $\mu\text{g}\cdot\text{m}^{-3}$ )	Référence
Barcelone	1924	2011	PM <sub>10</sub> ; PM <sub>2.5</sub>	346 ; 125	– ; 18	Querol et al. (2012)
	2009	2011	PM <sub>10</sub> ; PM <sub>2.5</sub>	145 ; 46	– ; 18	Querol et al. (2012)
Londres	1863	1995	SPM ; PM <sub>0.5</sub>	669 ; 245	–	Pfeifer et al. (1999)
		1999	PM <sub>2.5</sub>	200	35	Adams et al. (2001)
Los Angeles	2000	2010	PM <sub>10</sub> ; PM <sub>2.5</sub>	78 ; 57	31 ; 20	Kam et al. (2011a)
Paris	1980	2015	PM <sub>10</sub> ; PM <sub>2.5</sub>	207 ; 79	20 ; 12	AEF [2017]
	1999	2015	PM <sub>10</sub> ; PM <sub>2.5</sub>	38 ; 13	20 ; 12	AEF [2018]
Prague	1974	2002	PM <sub>10</sub>	103	85	Irančík (2006)
		2013	PM <sub>10</sub> ; PM <sub>2.5</sub>	205 ; 94	–	Cusack (2015)
New York	1904	1999	PM <sub>2.5</sub>	52	13	Chilrud et al. (2004)
		2004	PM <sub>2.5</sub>	52	–	Grass et al. (2010)
Stockholm	1964	2004	PM <sub>2.5</sub>	52	–	Grass et al. (2010)
Seoul	1974	2005	PM <sub>10</sub> ; PM <sub>2.5</sub>	350 ; 129	155 ; 102	Kim et al. (2008)
	1985	2014	PM <sub>10</sub> ; PM <sub>2.5</sub>	214 ; 78	44 ; 14	Lee et al. (2018)
Shanghai	1993	2008	PM <sub>10</sub> ; PM <sub>2.5</sub>	366 ; 193	–	Ye et al. (2009)
	2010	2012	PM <sub>2.5</sub>	64	66	Lu et al. (2015)
Taipei	1997	2010	PM <sub>10</sub> ; PM <sub>2.5</sub>	58 ; 33	44 ; 30	Cheng et Yan (2011)
Tokyo	1927	1997	SPM	120	–	Furuya et al. (2001)

[Durand,2021]

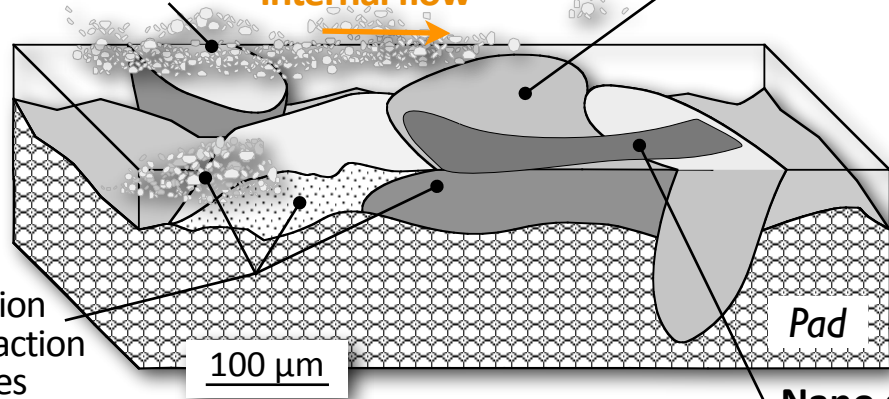


# Context and issues

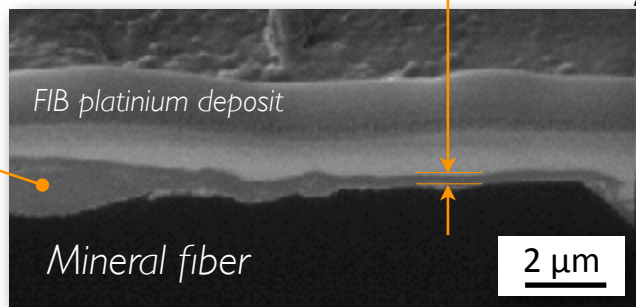
## Tribological circuit and mechanisms involved by braking



Powder beds **Internal flow** compacted plateaus

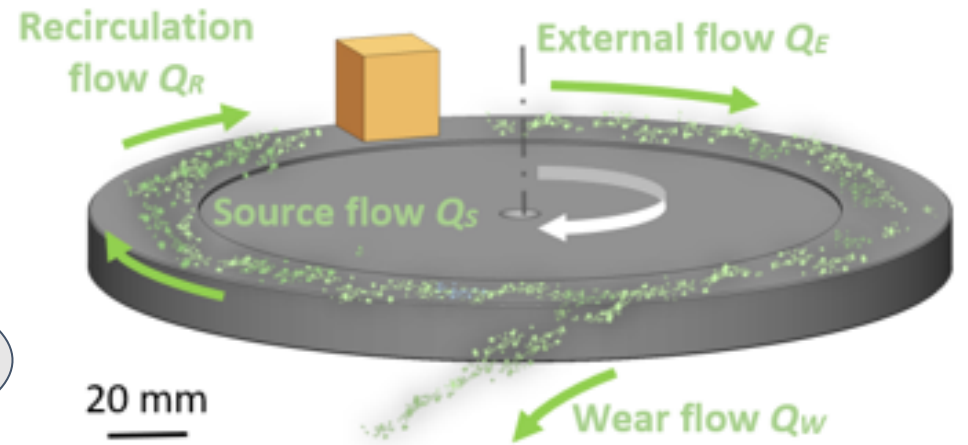


Load bearing capacities  
Sliding velocity accommodation

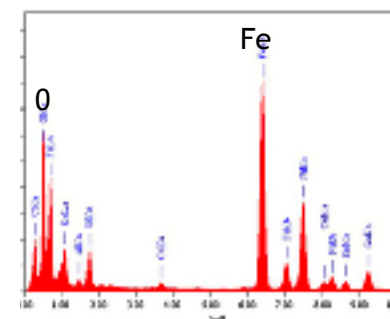


Osterle, wear 2009

### Tribological circuit



Main source of particles:  
tribo-oxidation of the disc

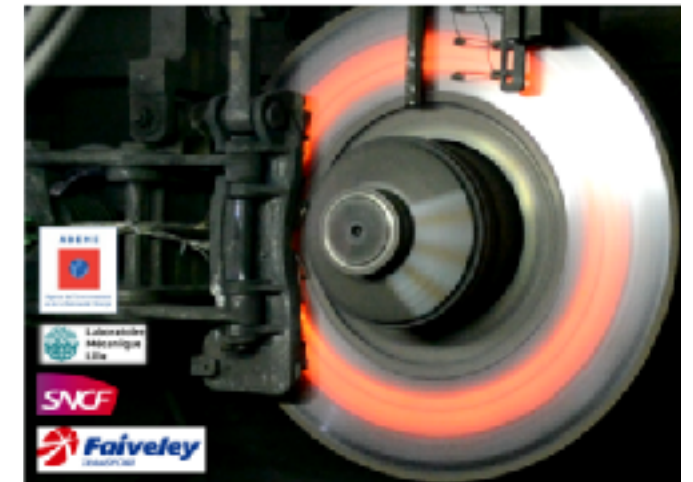
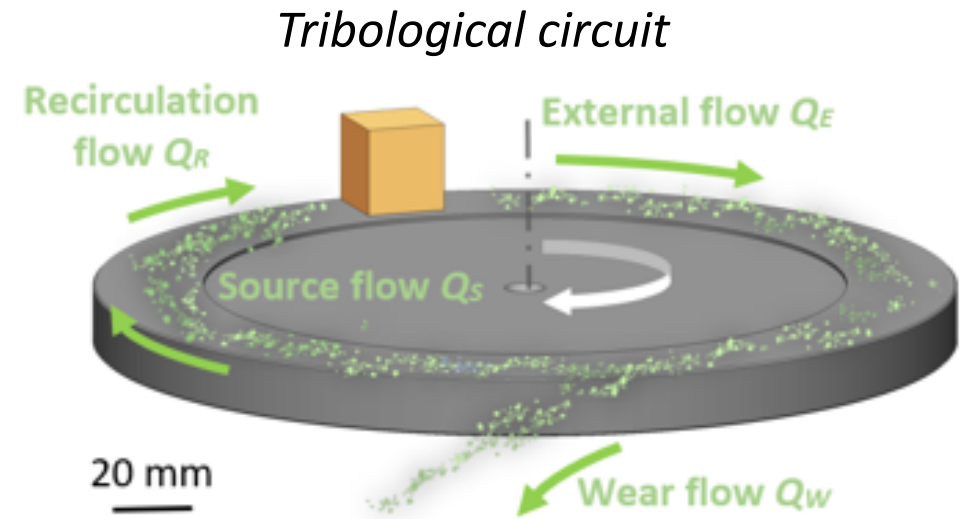
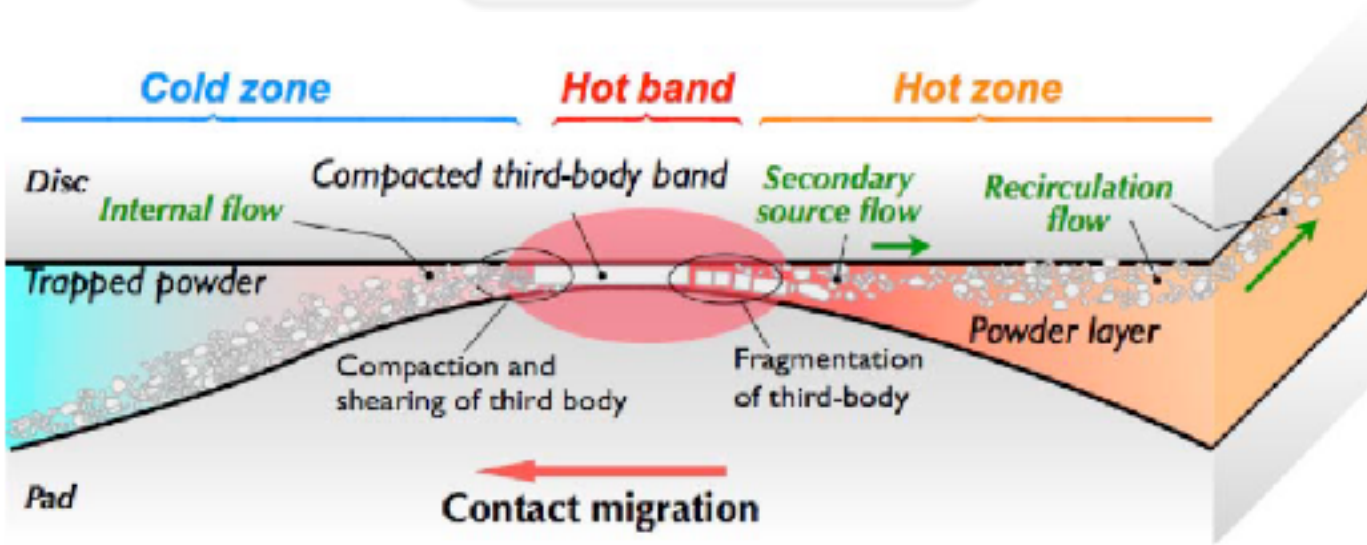


Third-Body EDS spectrum

# Context and issues

## Tribological circuit and mechanisms involved by braking

Hot banding  
Radial localization



Effect of the tribosystem parameters

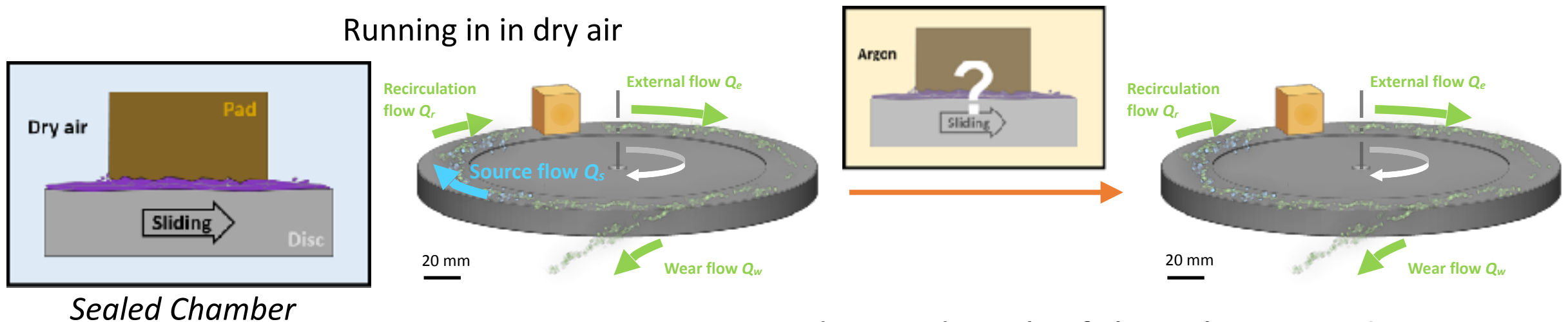
- What is the relation between the third body flows and the particle emission?

# Example 1

## Evidence of third-body source flow

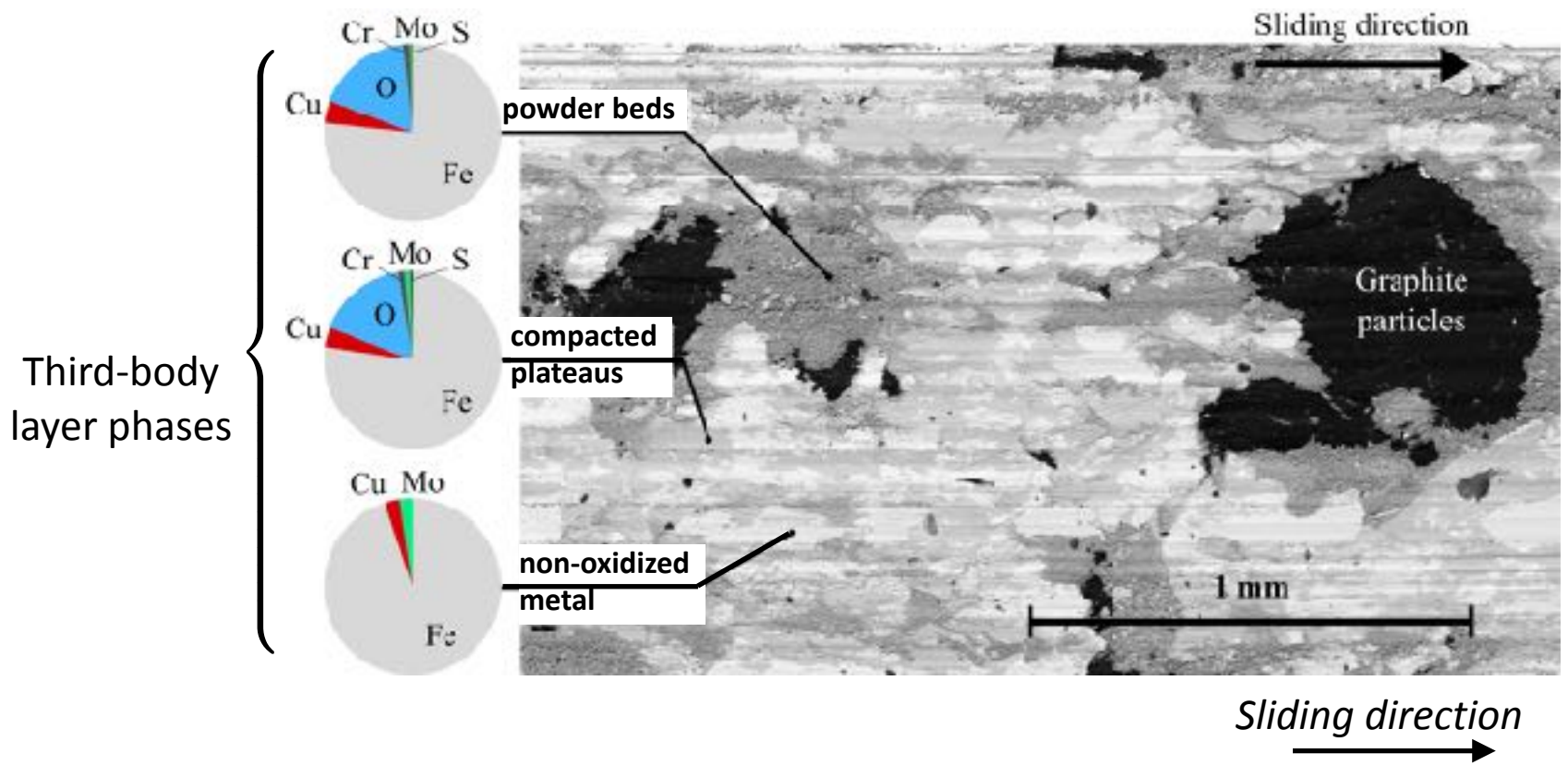
Thèse Edouard DAVIN 2019

- Friction material paire: sintered FeCu-matrix composite pad - 15CrMoV6 steel disc
- Sequences of 20 friction tests (8 m/s, 200 N, contact area 20 x 20 mm)
- First stage: running in in dry air
  - ➔ development of a third-body layer representative of braking situations
- Second stage: running-in in argon
  - ➔ change of the tribological matter balance by removing the oxidative source flow



How does it disturb of the tribosystem?

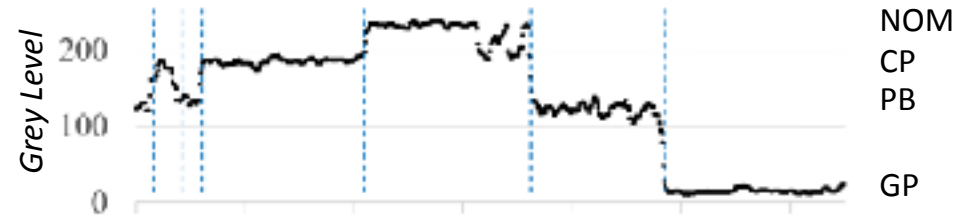
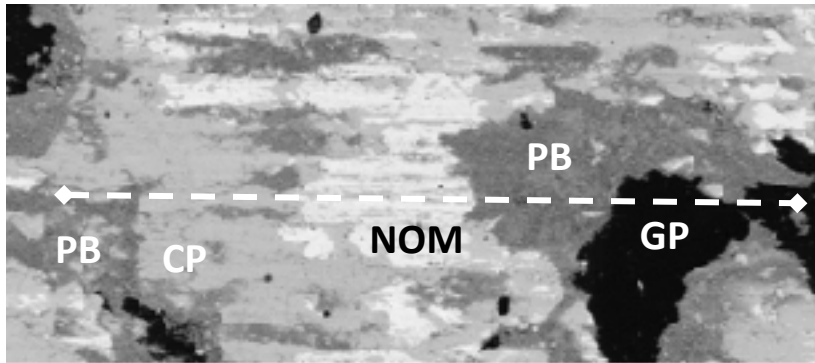
# Third-body layer after running-in in dry air



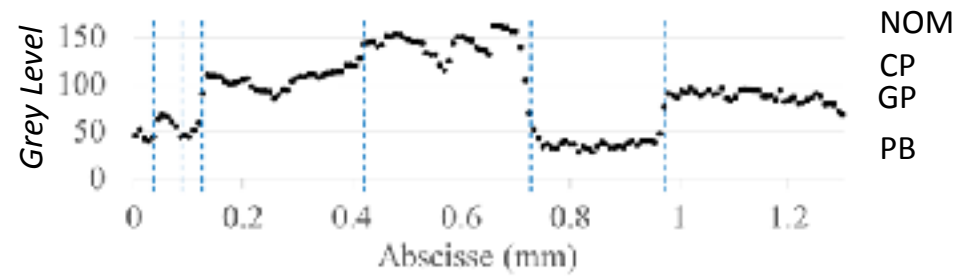
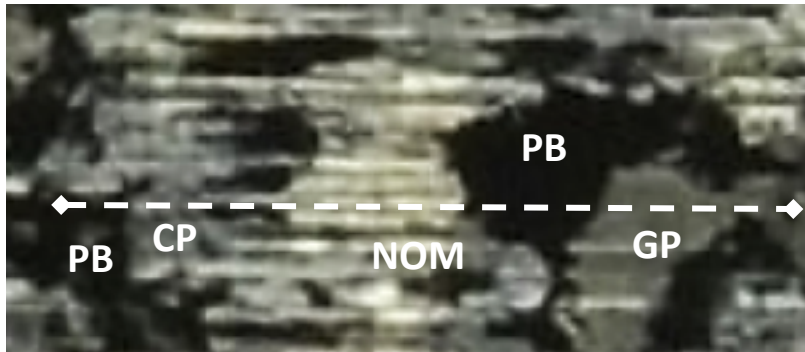
- Powder beds and compacted plateaus: mainly iron oxides mixed with pad and disc elements
- non-oxidized metal: mixture of iron with elements from pad (Cu) and disc (Mo)



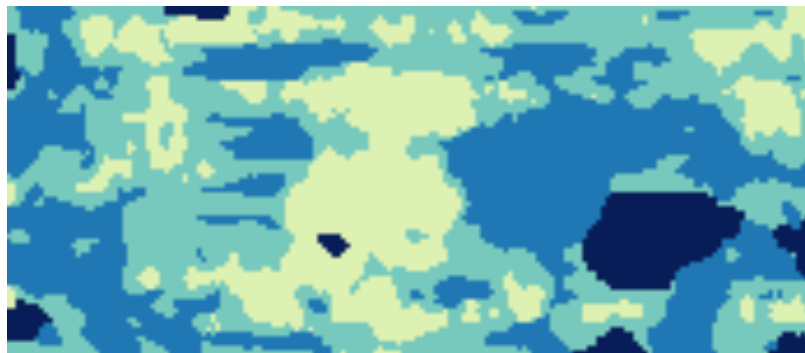
# Mapping of surface composition using image analysis







SEM BSE image



Photograph

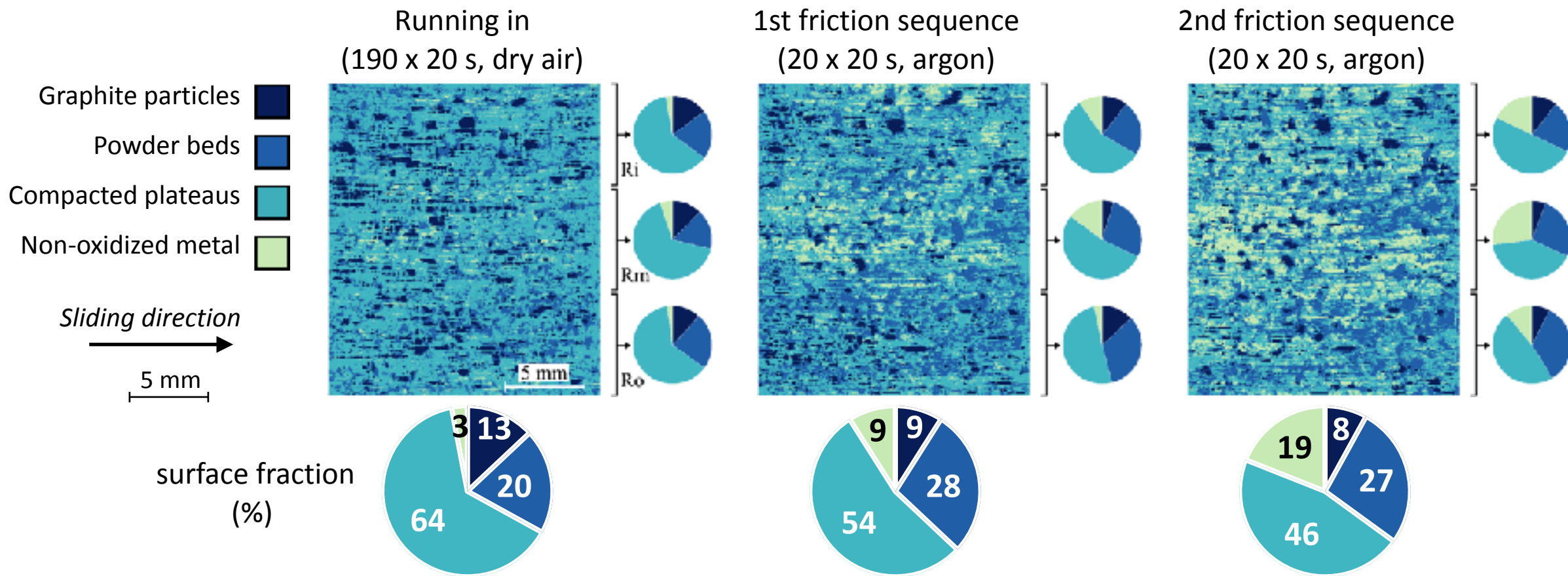


Colored map

-  graphite particles (GP)
-  powder beds (PB)
-  compacted plateaus (CP)
-  non-oxidized metal (NOM)

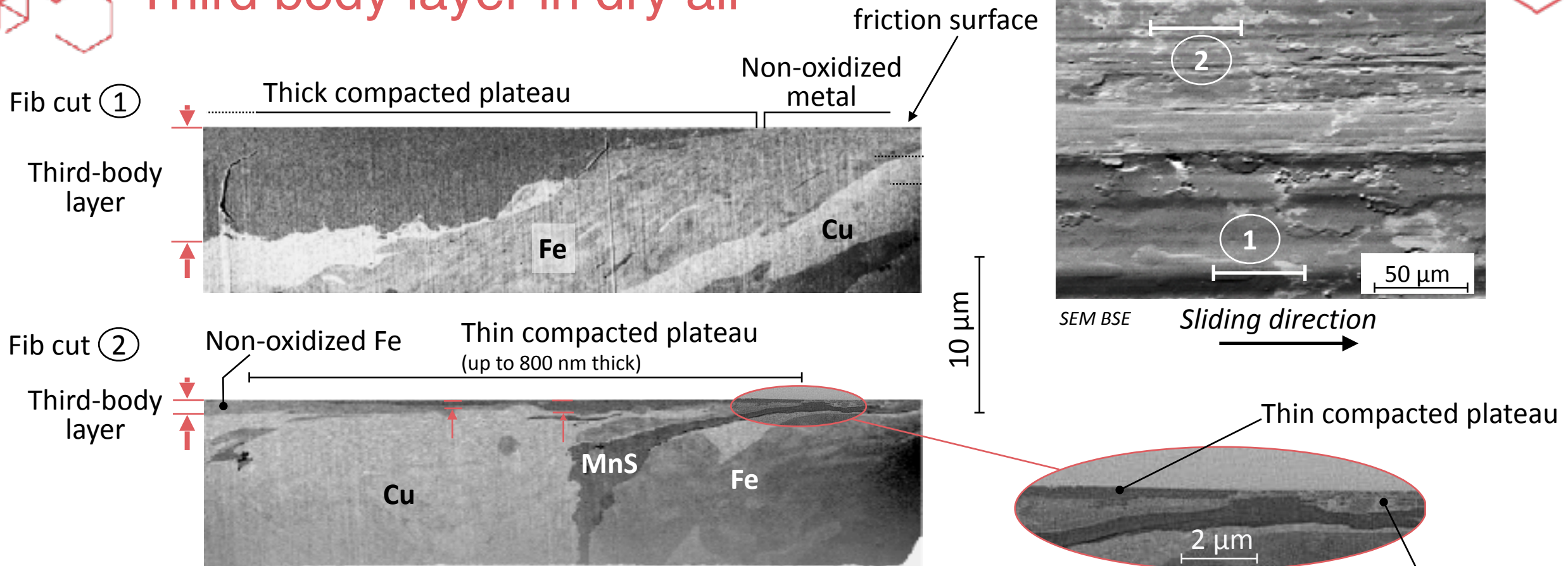


# Evolution of pad friction surface



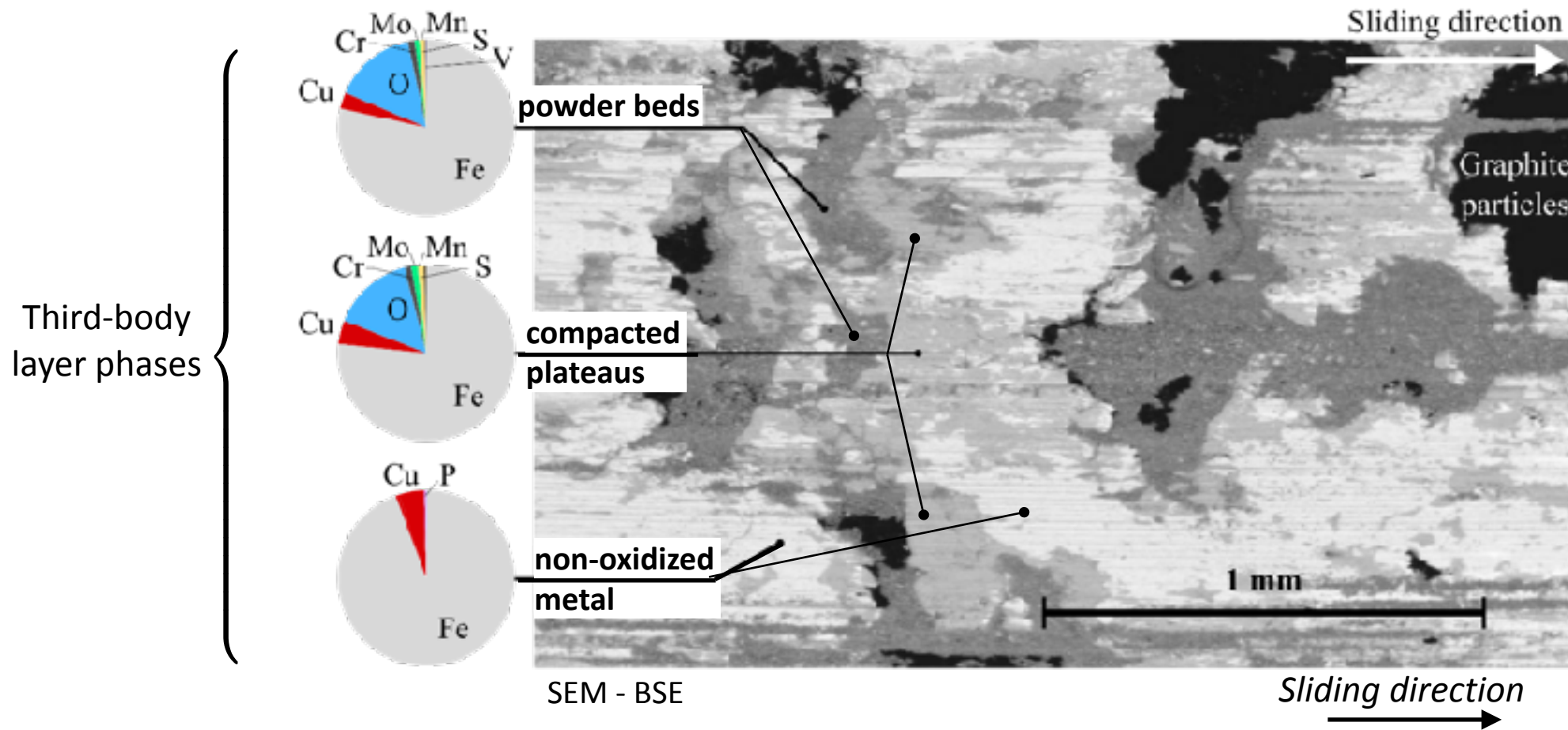
- When oxidative source flow of third body is reduced:
  - areas of compacted plateaus decrease
  - areas of non-oxidized metal increase
  - areas of powder beds and graphite remain rather constant

# Third body layer in dry air



- Compacted oxidized third body consists of:
  - thick plateaus formed in surface porosities where power beds are trapped
  - thin plateaus covering large areas of the friction surface
- Non-oxidized metal layers result of high plastic deformation and mixture of pad-disc particles

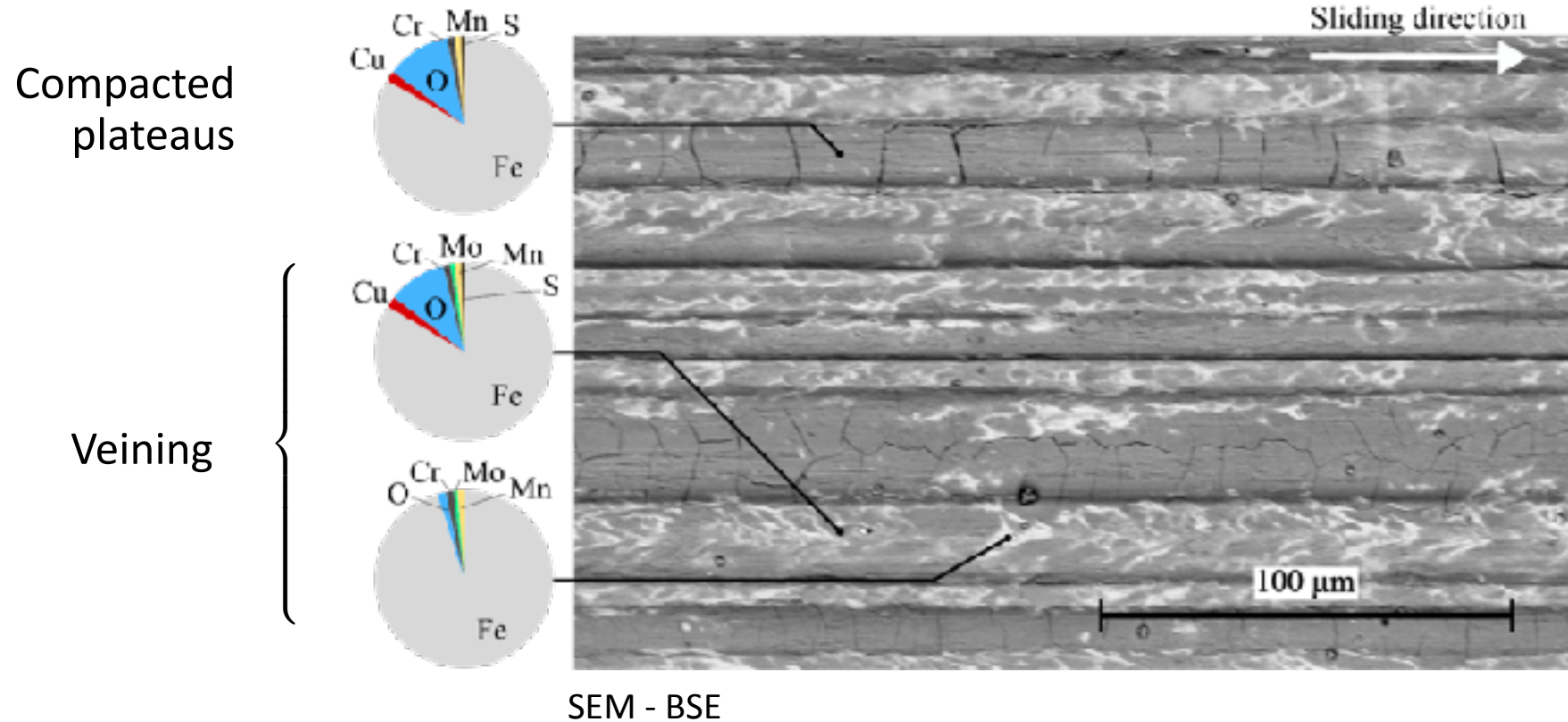
# Third body layer change in argon



- less extent of the compacted plateau layer downstream powder beds
- development of the non-oxidized metal phase downstream compacted plateaus



# Third body layer change in argon - disc surface

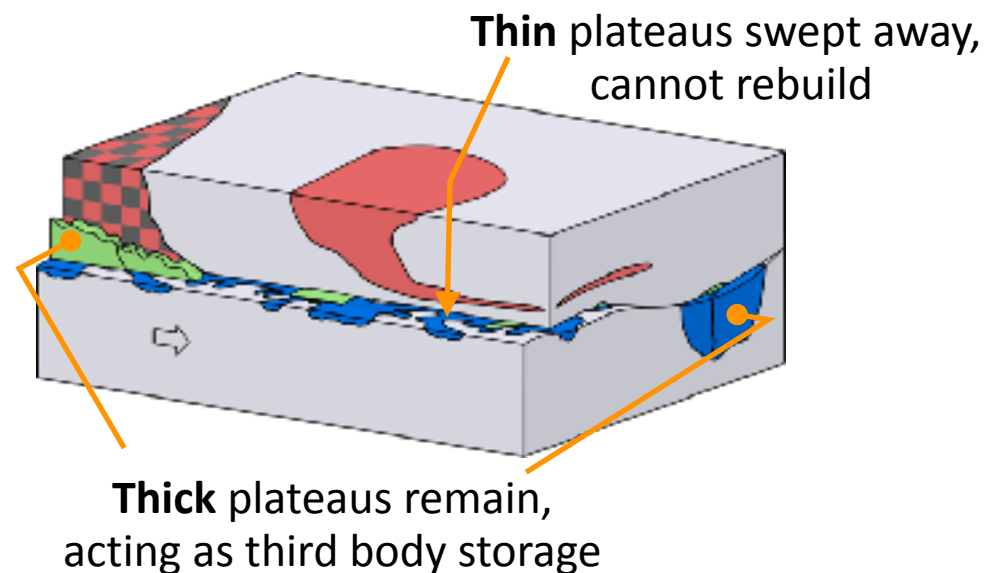
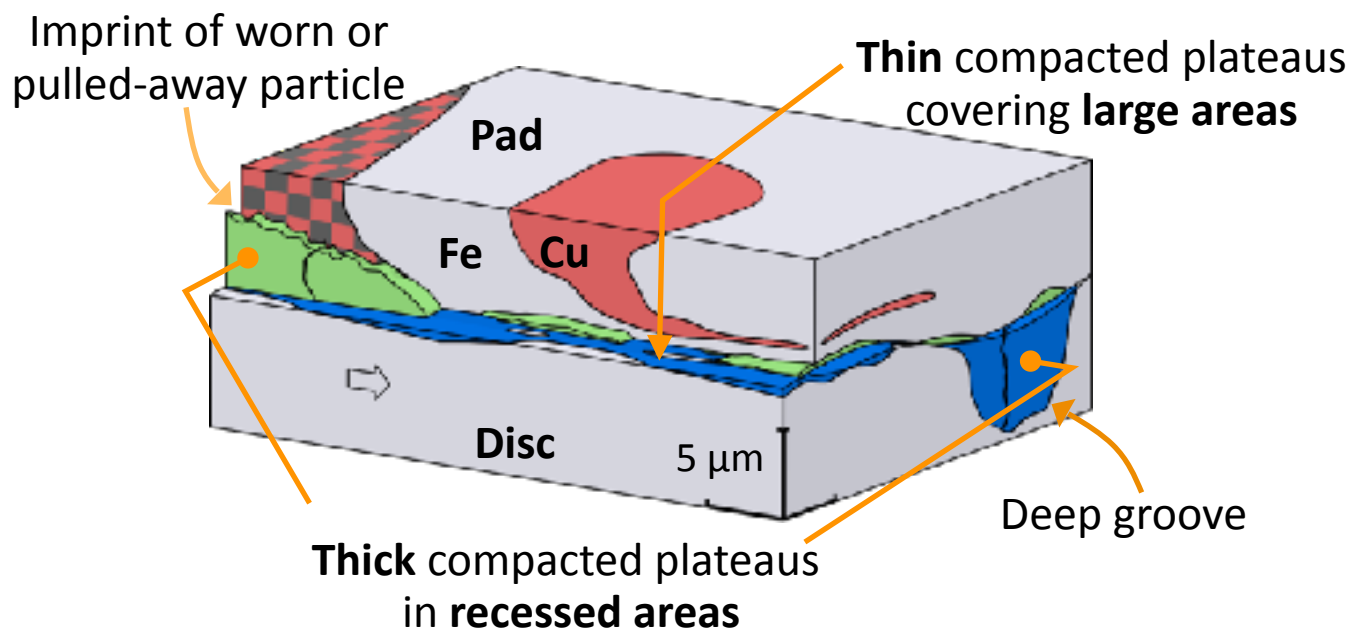


- Thick compacted plateaus remains trapped inside disc grooves
- Veining corresponds to alternance of thin compacted plateaus and non-oxidized metal
- Lack of powder beds

# To conclude

## Schematization of wear mechanisms alteration

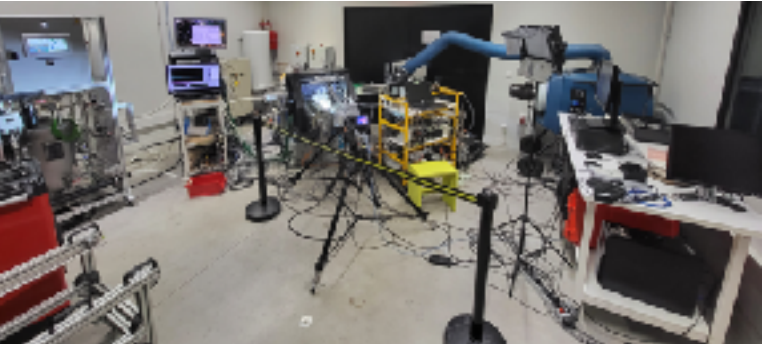
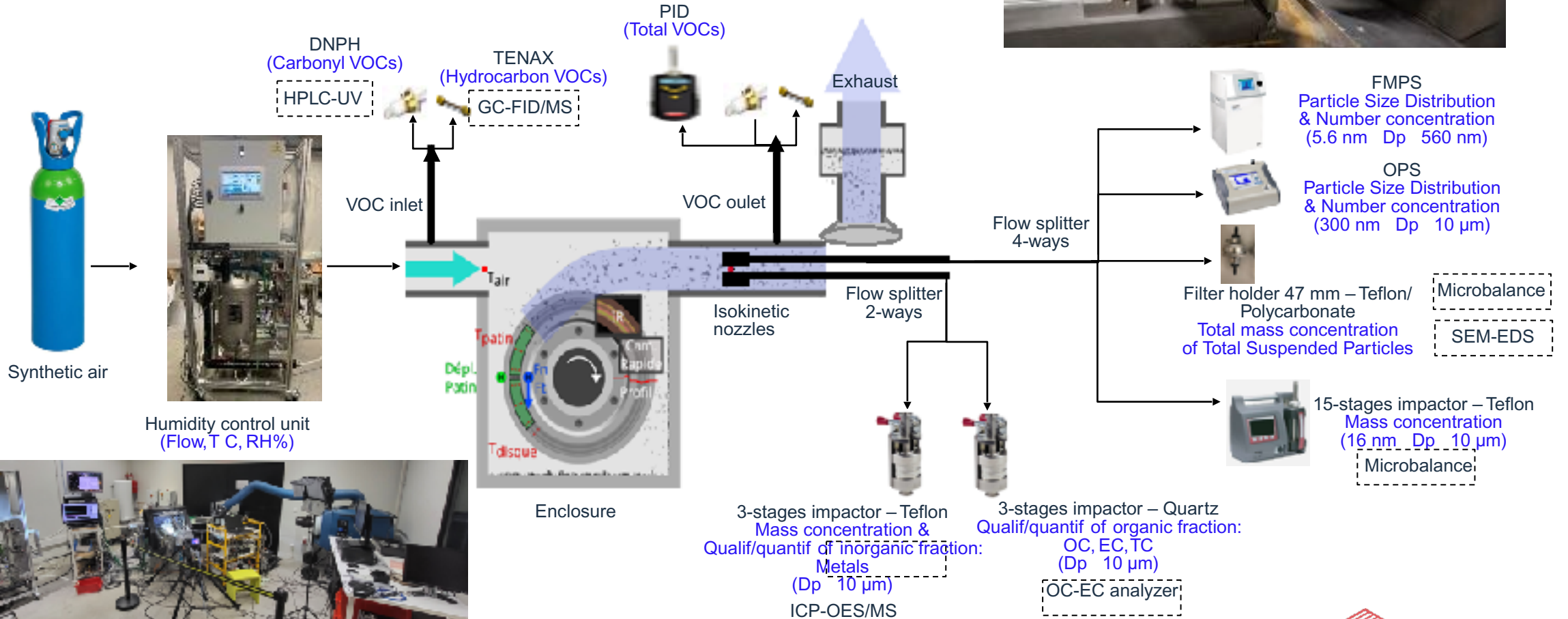
Third-body layer in braking situation  $\xrightarrow[\text{Imbalance between source and wear flows}]{\text{Oxidative source flow reduction}}$  Altered load-bearing capacities



The evolution of third-body flows changes load-bearing capacities in nature and extent, becoming more heterogeneous with a decrease of compacted third-body plateaus.



# Braking emissions Experimental set up

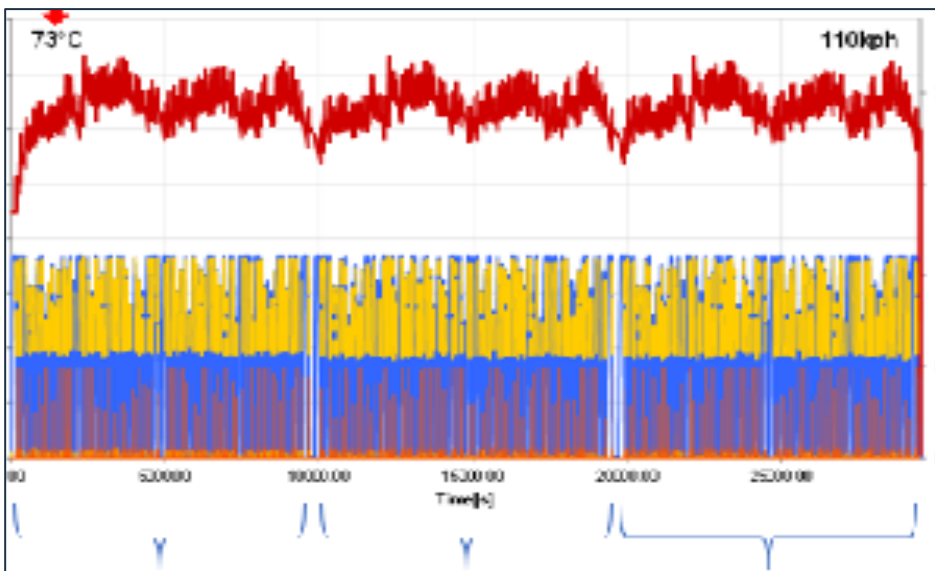


# Exemple 2

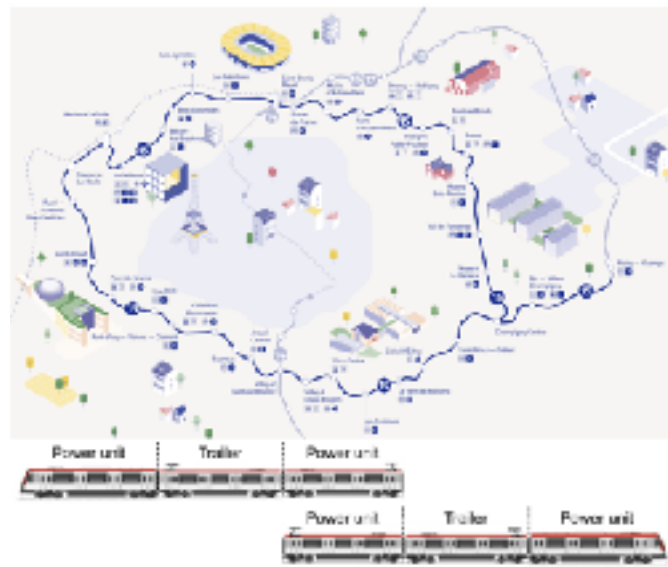
## Simulation d'une journée d'exploitation d'une ligne de métro

Grand Paris Express - Ligne 15

**BREAQ** – **BR**aking Emissions characterization & mitigation for **Air Q**uality improvement



3 allers-retours - 216 arrêts  
9h d'exploitation - 450 km



Study and characterization of brake wear and emissions



Mitigation



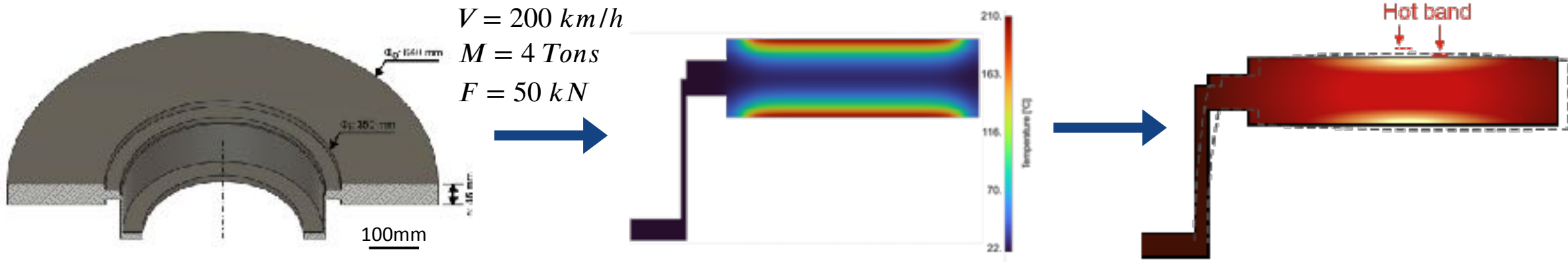
*Thèses en cours* Joseph FRANGHIE  
Raafa AL-KADERI  
Post-Doc Asma GRIRA



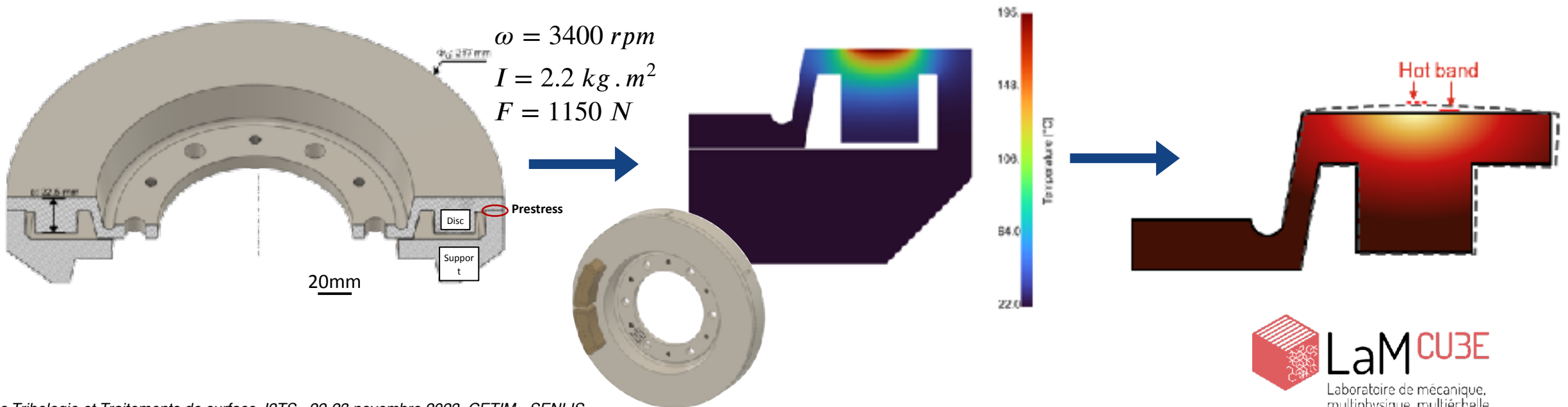
# Réduction d'échelle - approche thermomécanique

## Reproduction de la sollicitation en bande chaude

- Full scale braking



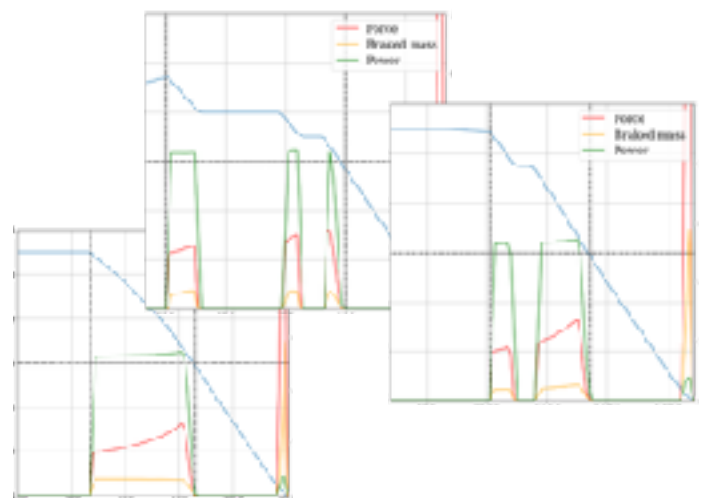
- Pad on disc designed for reduced scale:



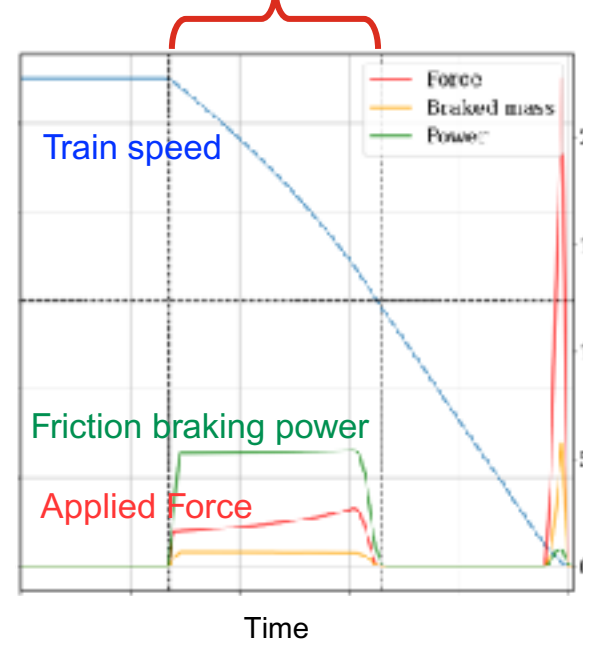
# Procédure d'essai

- Parcours en exploitation Normale PN
  - 3 allers retours
  - 216 arrêts - diversité de freinages
- Parcours Modèle PM
  - 2 allers retours (144 station stops)
  - Reference braking
  - Real inter-braking time extracted from PN
- Reference braking series:
  - 20 x Braking of PM
  - Fixed inter-braking time (set to 60s)

Freinages de service - PN  
 Diversité des arrêts  
 Conjugaison frein électrique



Freinage de référence - PM  
 une seule application du frein



Day 0	Day 1	Day 2	Day 3	Day 4
Weight Profilo.	20 reference brakings	PN – 3 allers-retours 216 arrêts en station 517 applications du frein (344 pour 2 allers-retours)	Weight Profilo.	20 reference brakings
				PM – 2 allers-retours 144 arrêts en station
				Weight Profilo.



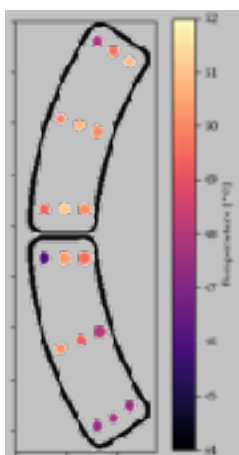
# Evolution de la portance - frottement - usure du patin

« Premiers résultats »

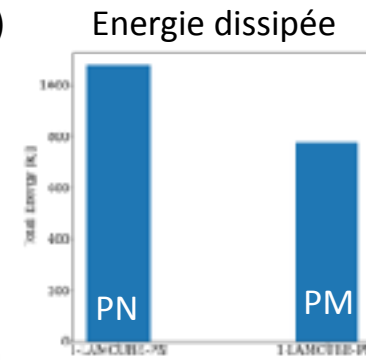
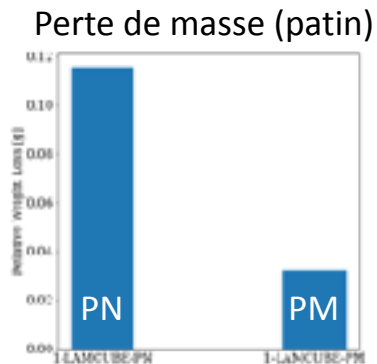
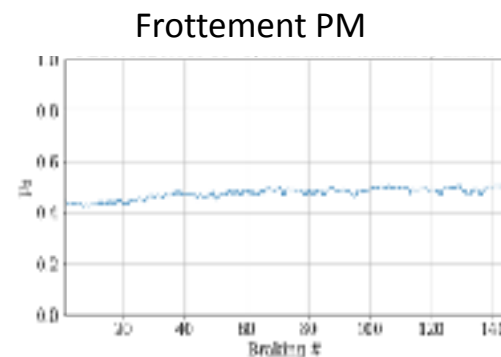
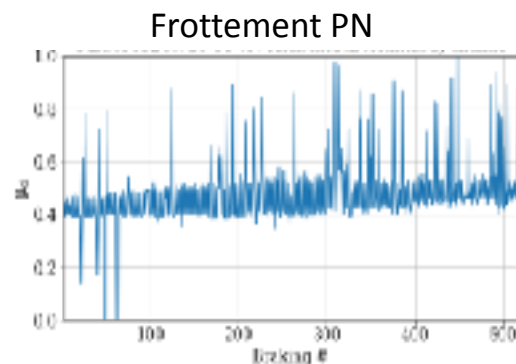
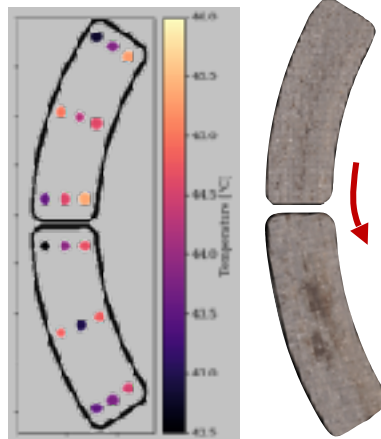
Après rodage portance localisée en sortie de contact



Pendant PN : relocalisation progressive de la portance sur le demi patin d'entrée de contact



Pendant PM : portance installée, localisée sur le demi patin d'entrée de contact



	PN	PM
Total energy [MJ]	1,078	0,78
# braking applications	517 (344 / 2 AR)	144
Pad weight loss [g]	0,115	0,032
Rate [g/MJ]	0,107	0,041
Sliding distance [m]	In Progress	

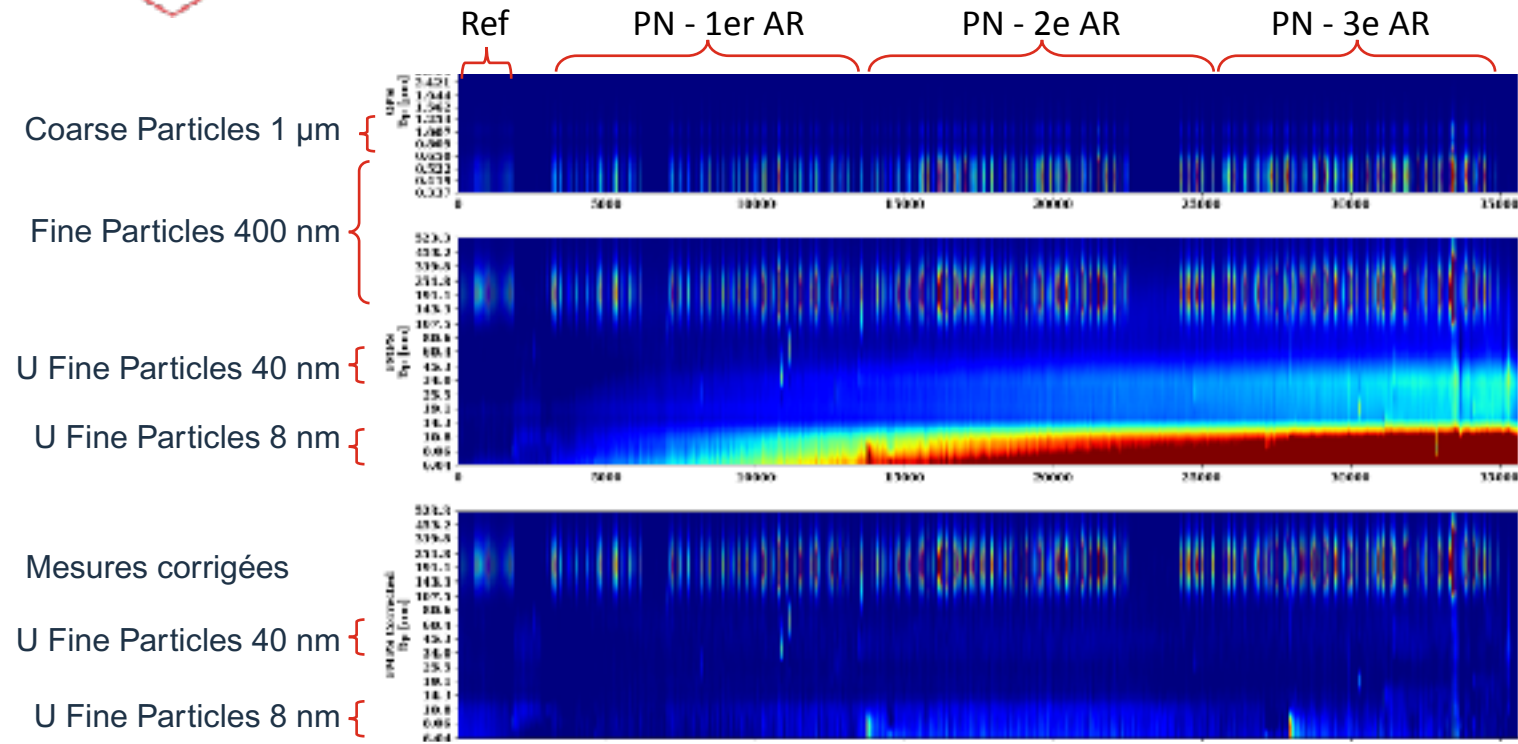
Quels sont les facteurs de perte de masse ?

- circuit tribologique:
  - adaptation de la portance
- usage du frein:
  - diversité des freinages
  - multiplicité des applications du frein
- design du frein:
  - 2 demi patin

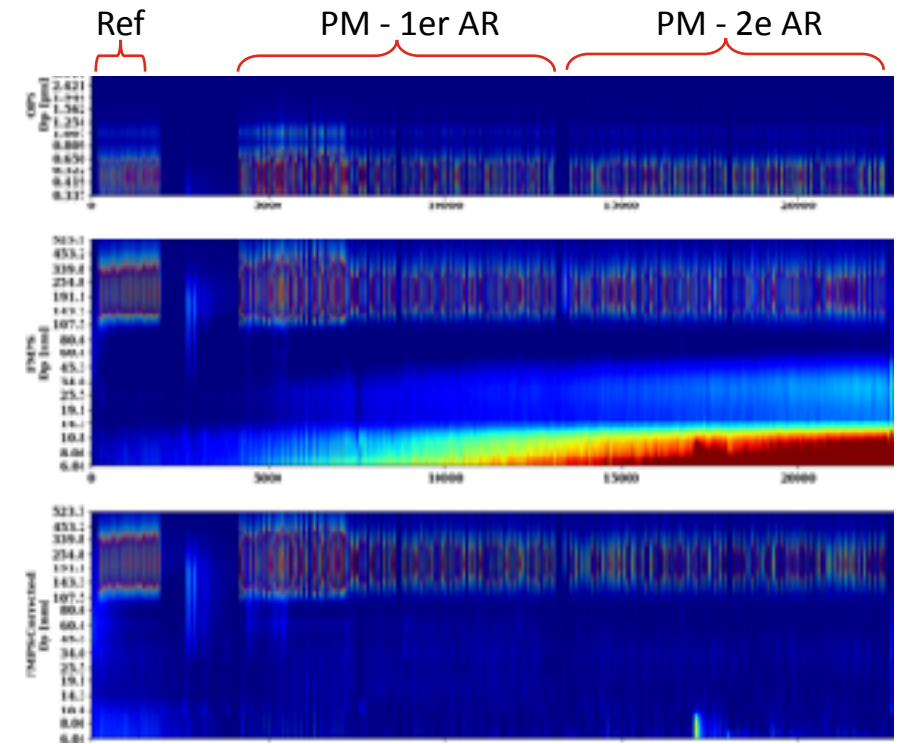


# Evolution des émissions

dN/dLogDp [# / cm<sup>3</sup>]



Durée essai 9h



Durée essai 6h

Quelle relation usure - émissions ?

- circuit tribologique:
  - historique de freinage, cumul troisième corps
  - capacité de stockage du troisième corps
- usage du frein:
  - diversité et multiplicité des applications du frein
  - multiplicité des applications du frein
- design du frein:
  - ouverture - fermeture du contact

# Example 3

## Simulation of repetitive low-energy urban slowdowns (from 50 to 20 kph)

- Experimental set up and testing protocol

### Materials

a single organic pad  
2 disc materials:

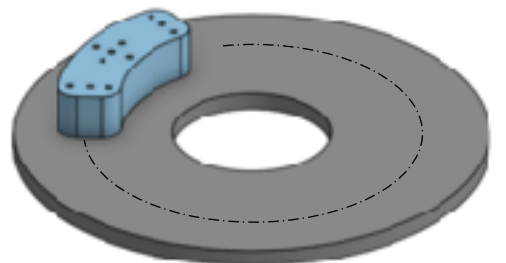
**Cast iron**

**Stainless steel**

### Braking conditions

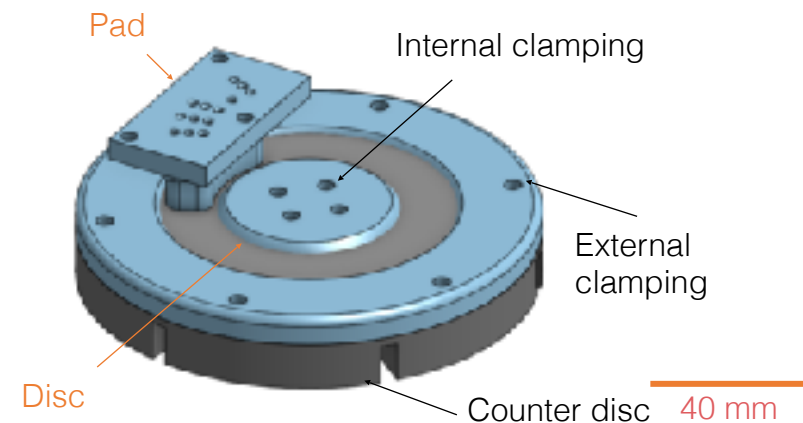
Series of 50 slowdowns  
of 12 s and 13.7 kJ per  
slowdown

Contact geometry

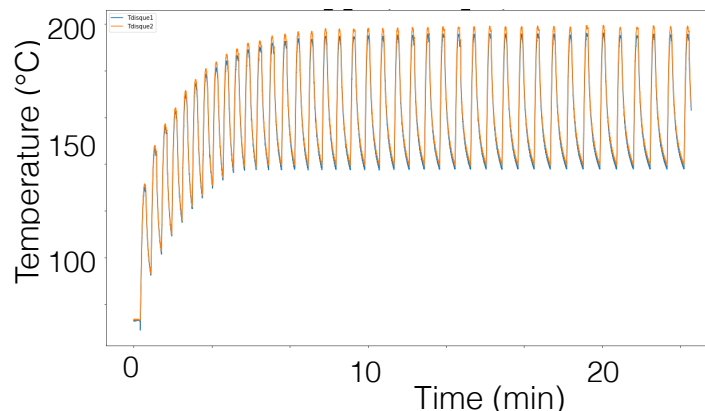
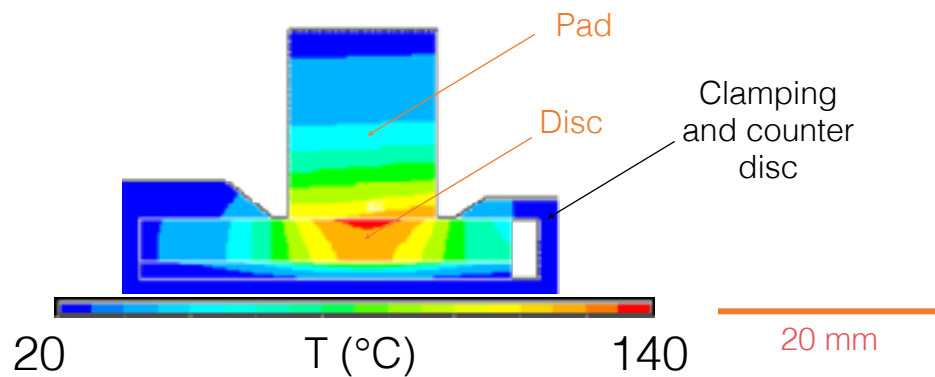


Contact area: 4.4 cm<sup>2</sup>  
Disc thickness: 4.5 mm

Pad - Disc assembly



- Contact loading like real-life automotive braking - hot banding situation

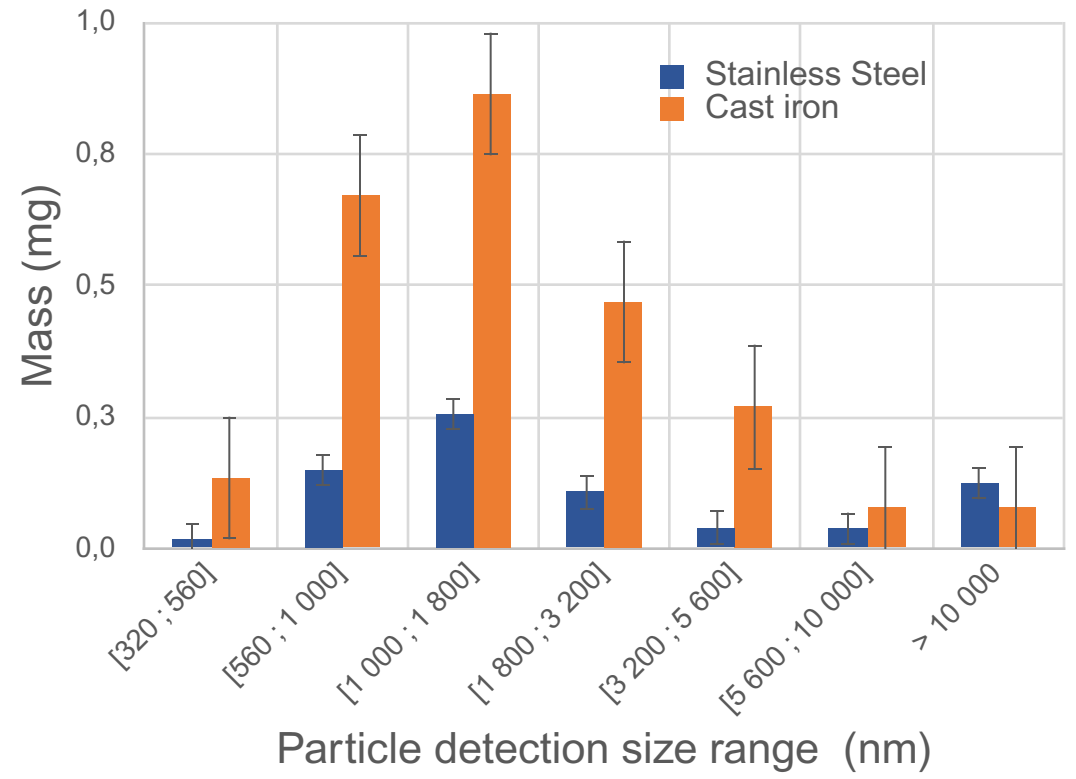


Thèse Mathis BRIATTE en cours

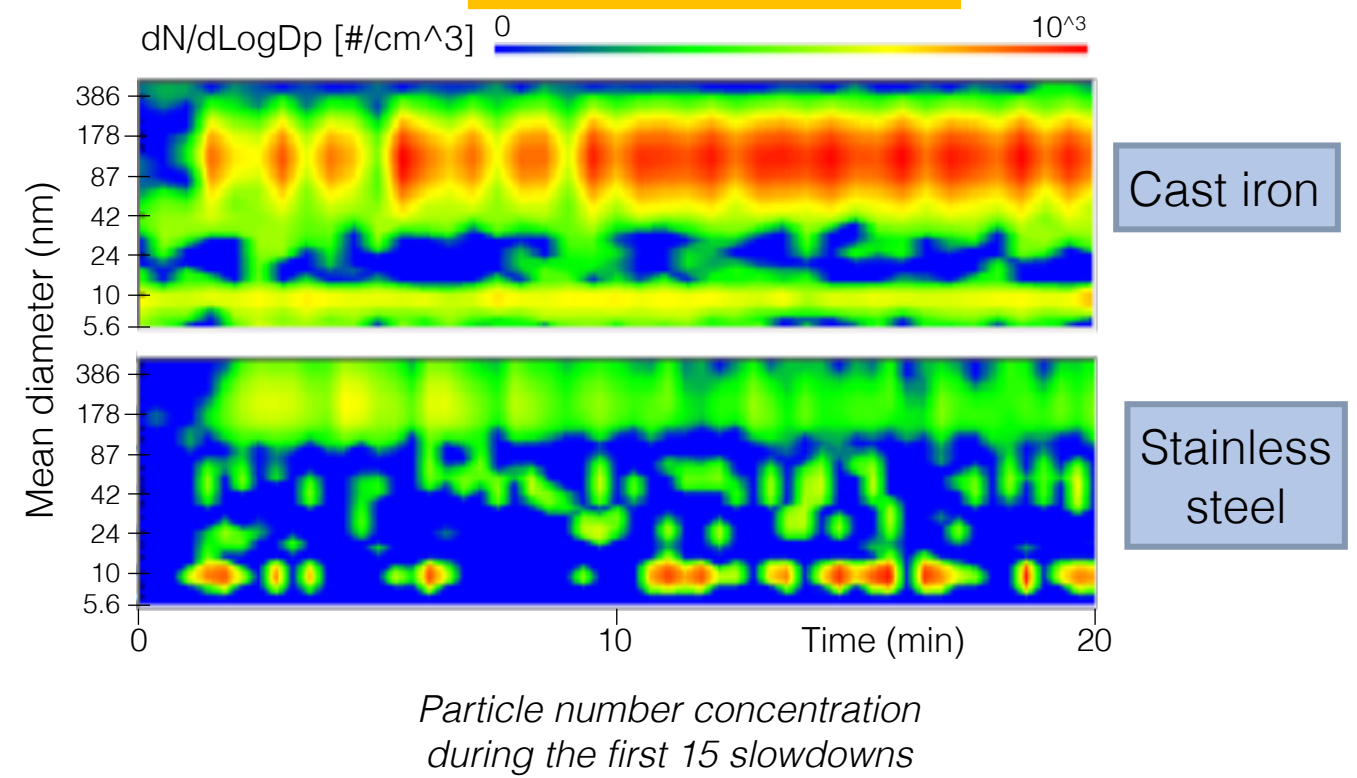


# Particulate emission - comparative study

Mass



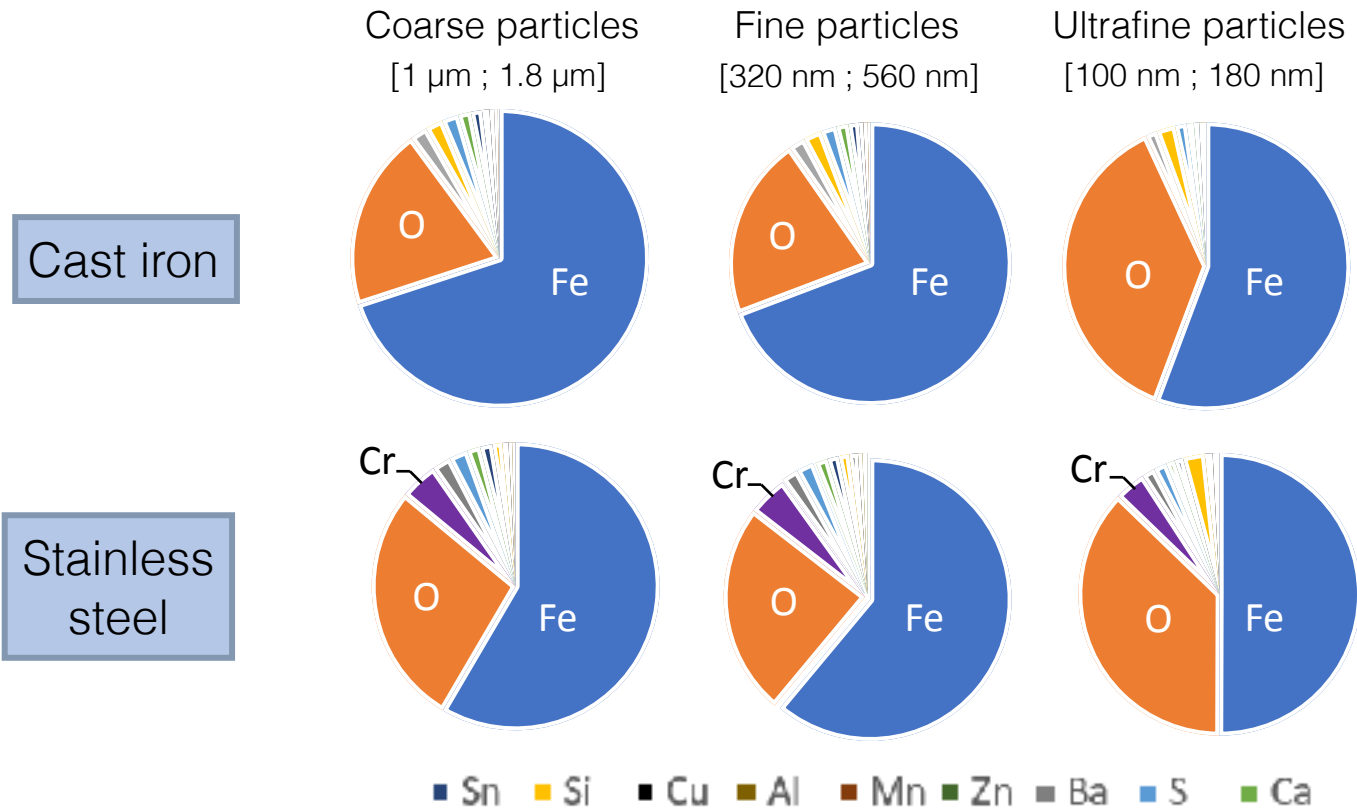
Particle number



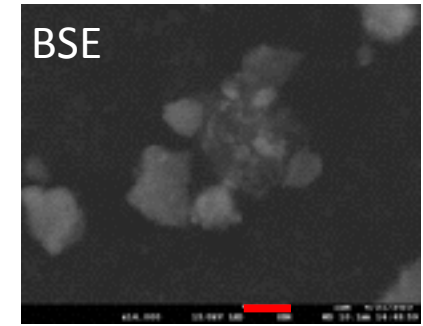
- Particulate emission involves mainly fine and coarse particles.
- Particulate emission is higher for cast-iron discs than for stainless steel discs.

# Particulate emission - comparative study

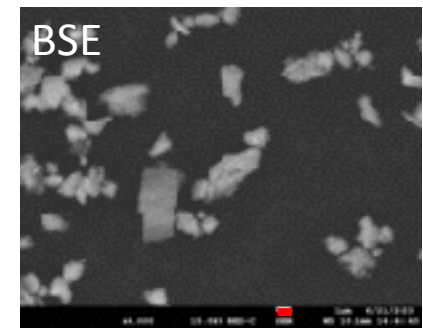
## Composition



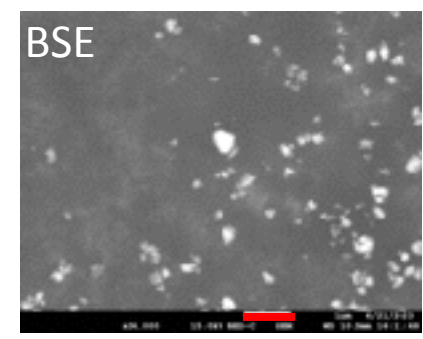
## Morphology



Coarse particles and agglomerate



Fine particles elongated & angular shape



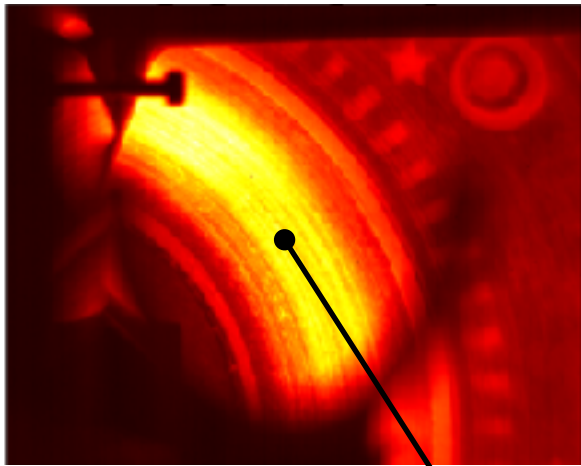
Ultrafine particles spherical shape

How to explain the difference in particle emissions?

# Friction & thermomechanical loading

## Cast iron

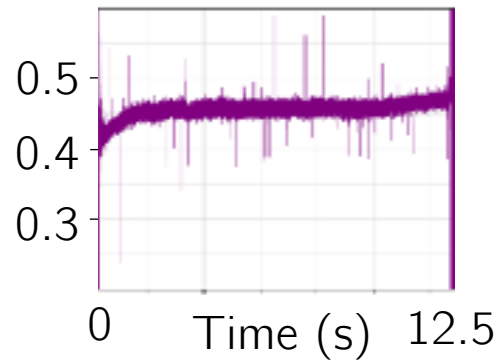
Disc-track IR thermogram



20 mm

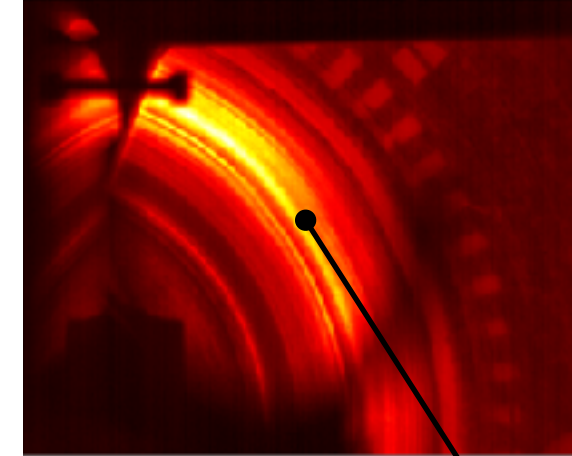
Hot band

Coefficient of friction



## Stainless steel

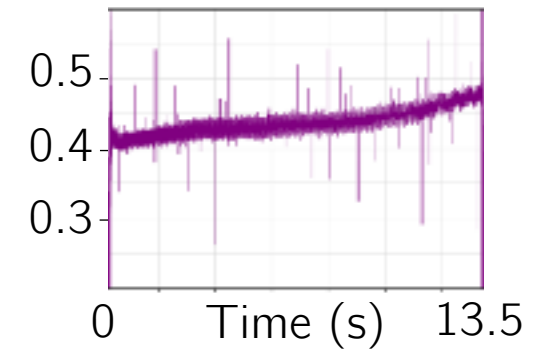
Disc-track IR thermogram



20 mm

Hot band

Coefficient of friction



- Similar hot banding phenomena, located in the center of the disc track.
- Fairly similar friction behaviour.

Friction and contact loading cannot explain the difference in particulate emissions behaviour.



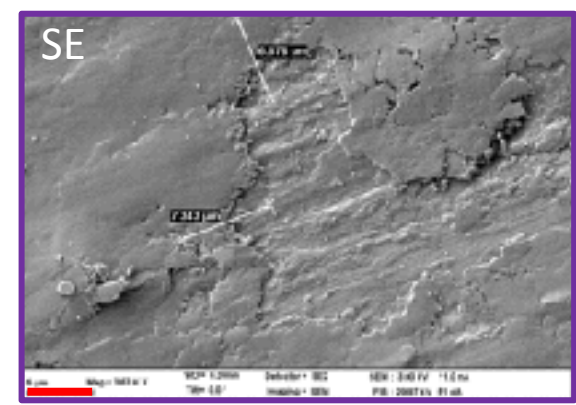
# Tribological circuit

Cast iron

Disc rubbed surface

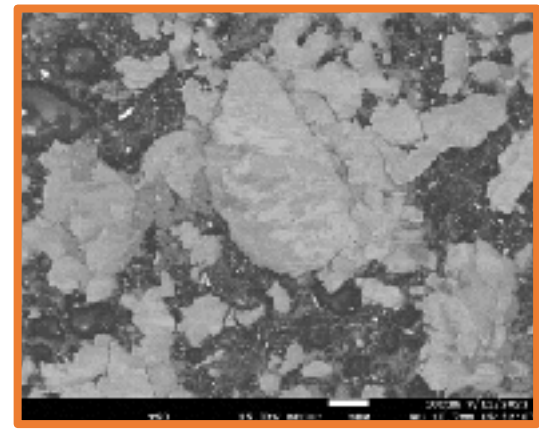


200 μm

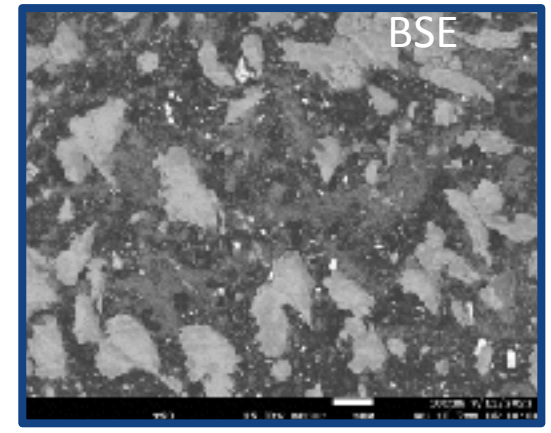


5 μm

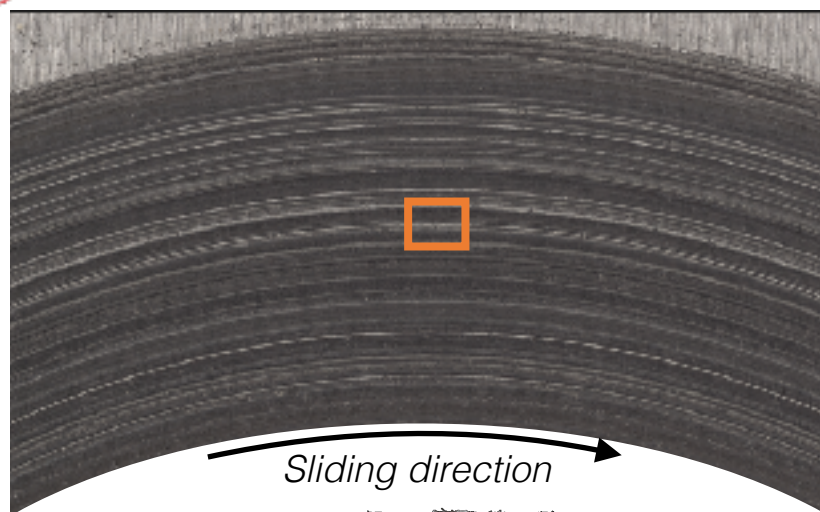
Pad rubbed surface



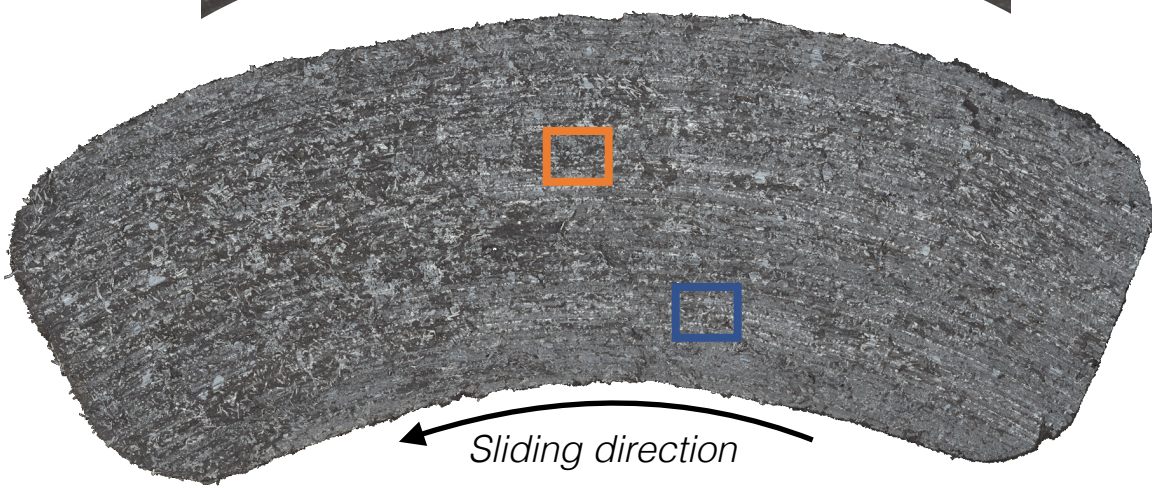
200 μm



200 μm



Sliding direction



Sliding direction

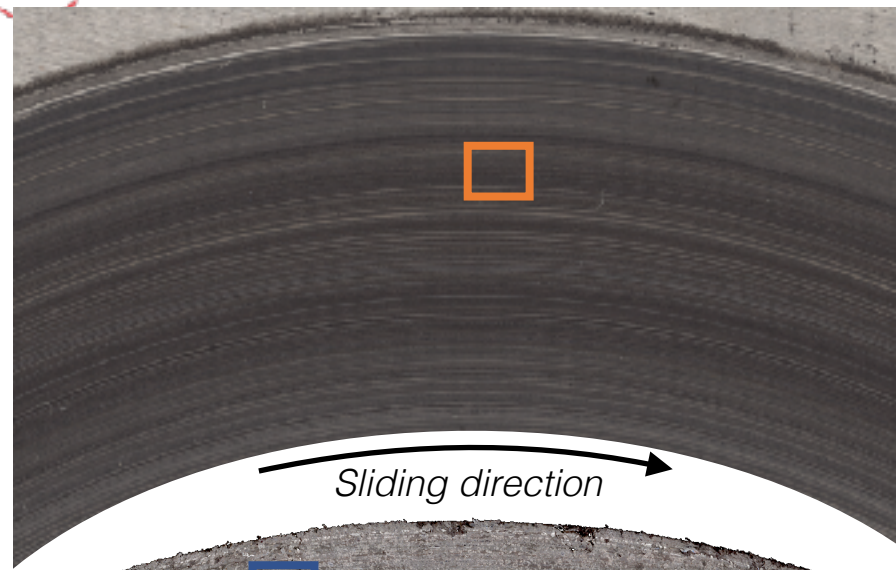
10 mm

High concentration of powdery areas

- Particularly smooth and extended third-body layer
  - Numerous powdery areas (Pad)
- ➔ High third-body flows involved in the tribological circuit

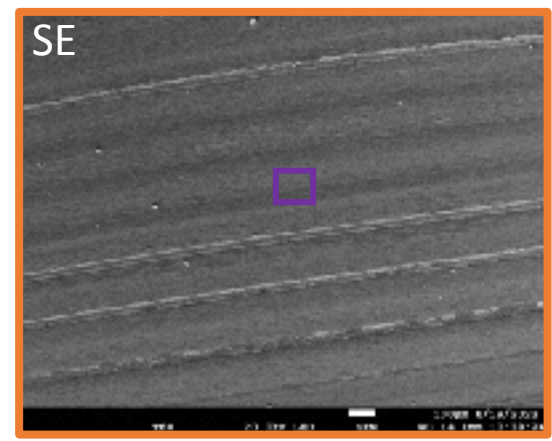


# Tribological circuit

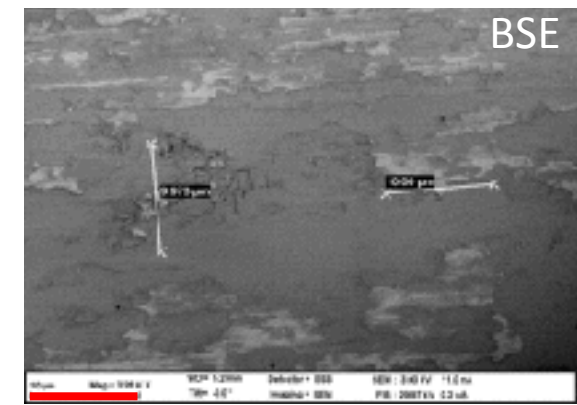


Stainless steel

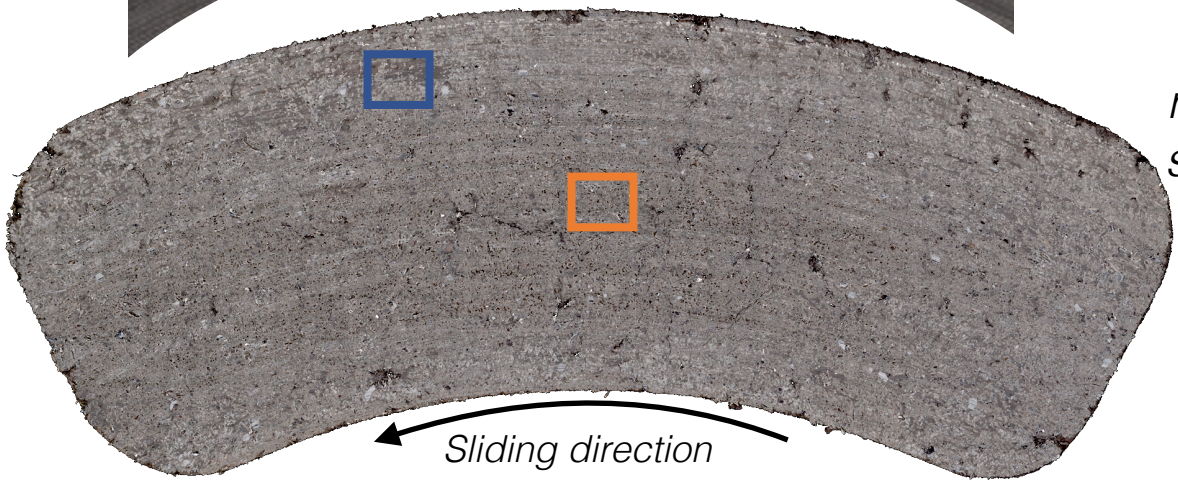
*Disc rubbed surface*



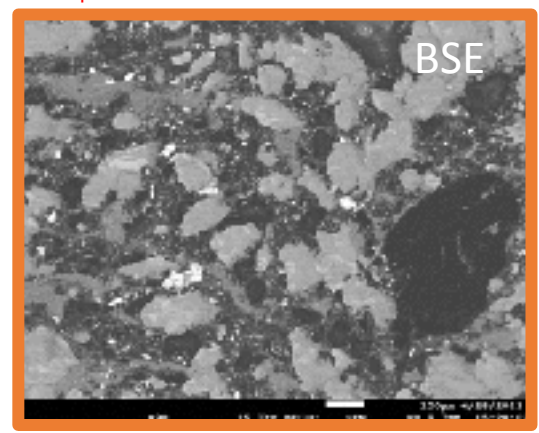
200 μm



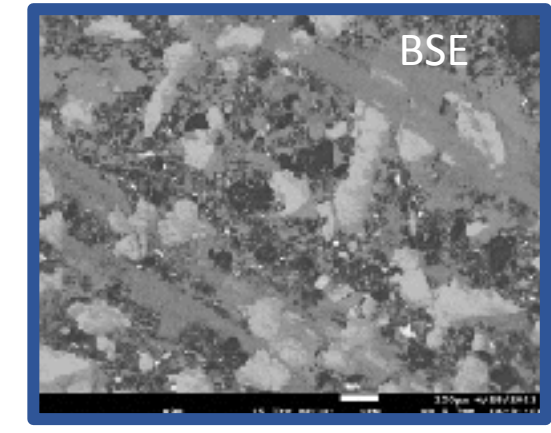
10 μm



*Pad rubbed surface*



200 μm



200 μm

*Low concentration of powdery areas*

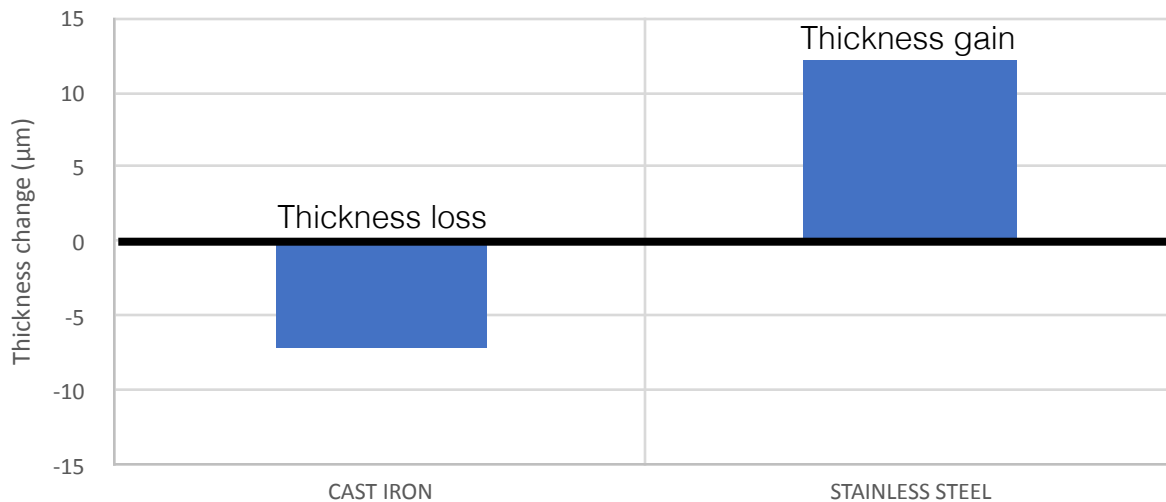
10 mm

- More structured third-body layer
  - Initial disc morphology remains visible: low disc wear rate.
- ➔ low third-body flows involved in the tribological circuit

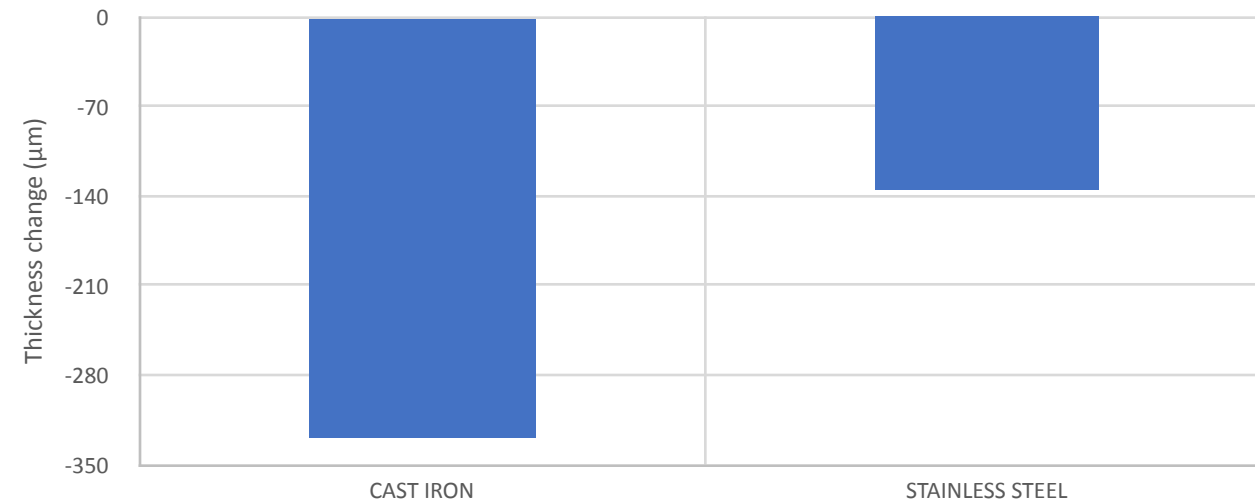
# Tribological circuit

## Wear quantification *(disc and pad - include bedding and slowdown series)*

Disc thickness change (from profilometry)



Pad thickness change (from profilometry)



- The change in thickness correlates with the amount of fine particles expelled from the tribological circuit.

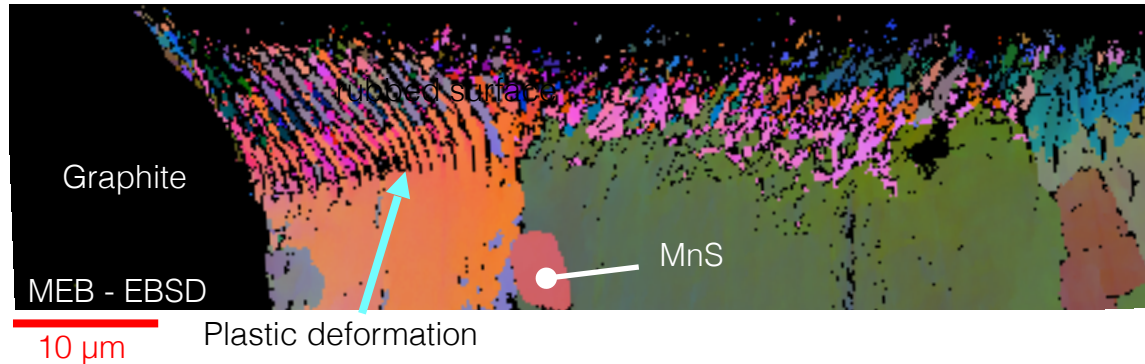
Wear on the pad-disc pair involving a cast-iron disc is much greater than in the case of a steel disc. The high source flow of third body saturates the tribological circuit, which is unable to contain a large quantity of third body, leading to the high level of particle ejection.

# Adaptation des matériaux (disque)

## Transformations tribologiques de surface

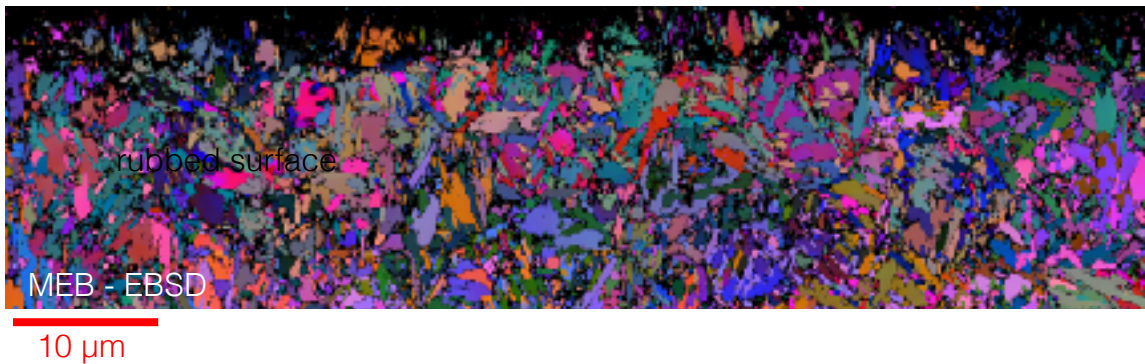
Rubbed sub-surface sections in the hot-band area

Cast iron



- Significant plastic deformation in the vicinity of graphites and solid lubricant (MnS).

Stainless steel



- Reduced grain size very close to the rubbed surface.



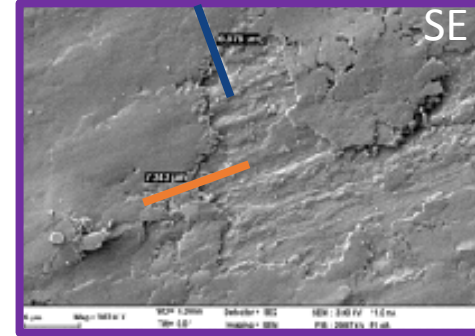
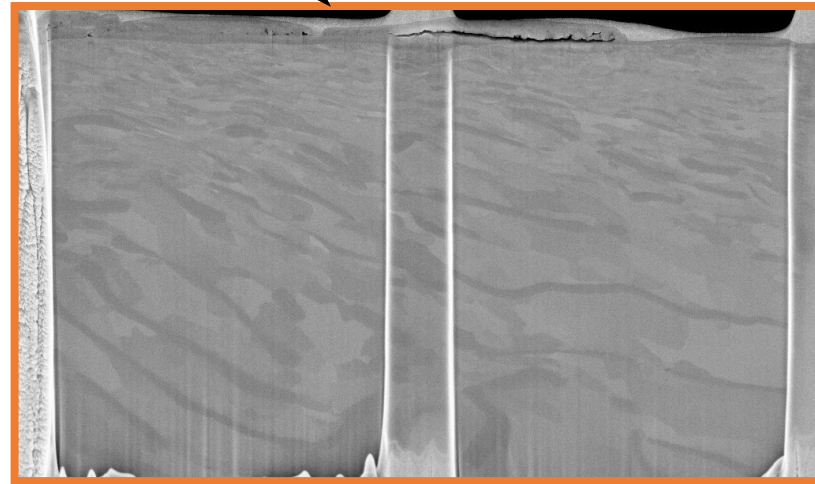
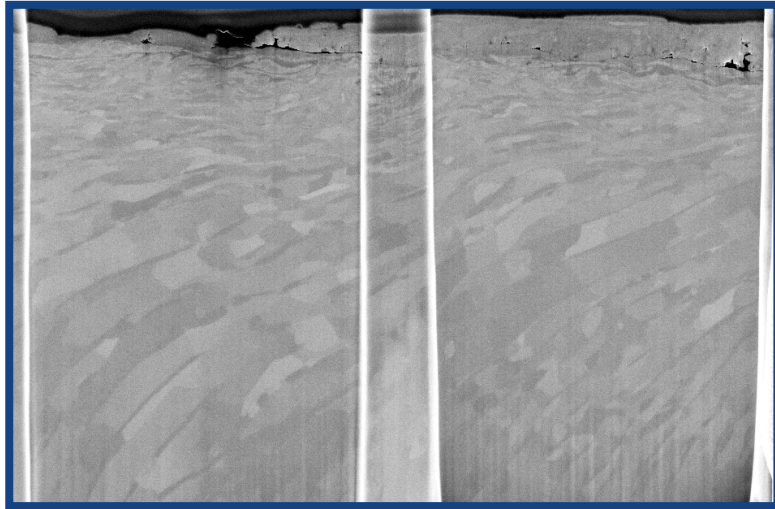
# Adaptation des matériaux (disque) Transformations tribologiques de surface

radial direction

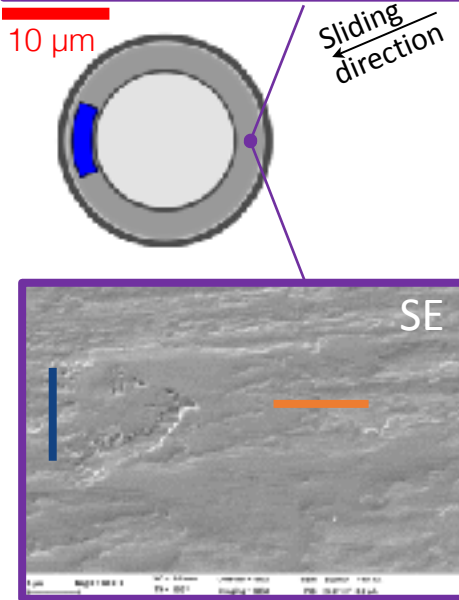
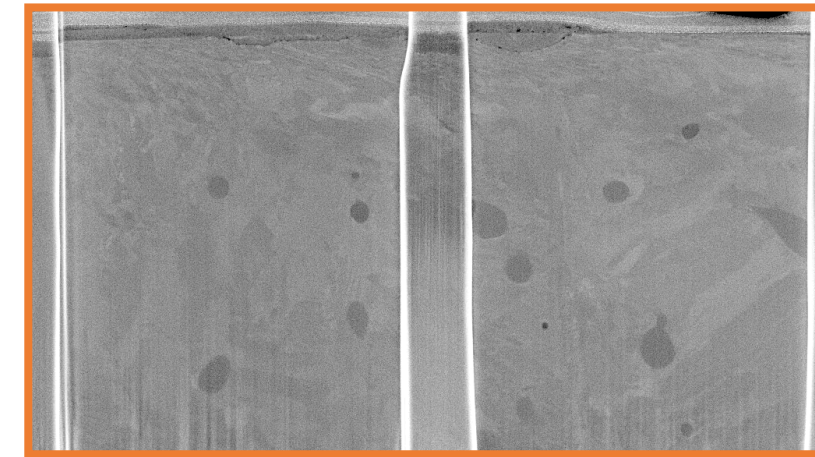
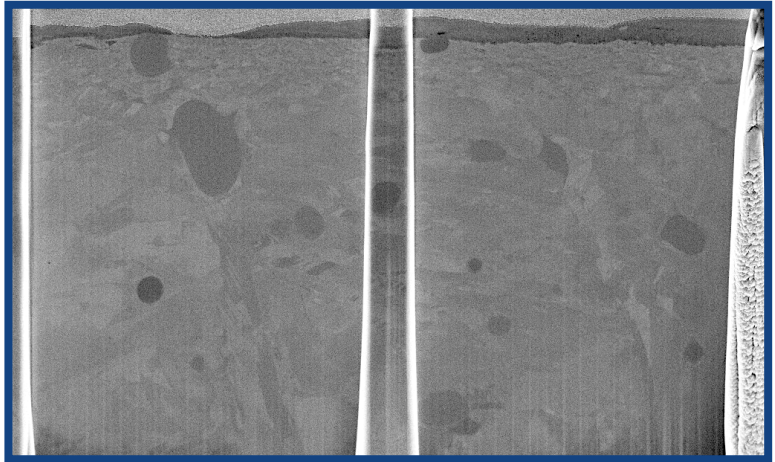
sliding direction

FIB cut location

Cast iron



Stainless steel



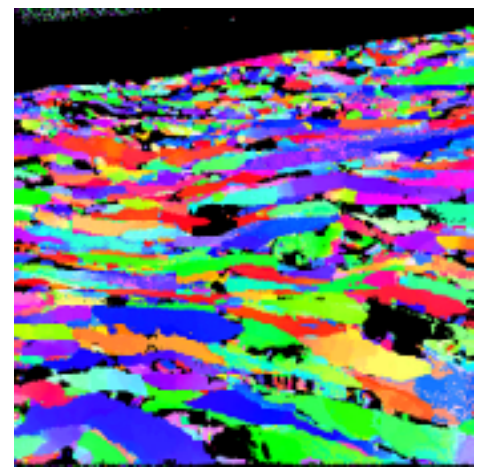
1 µm

10 µm

sliding direction

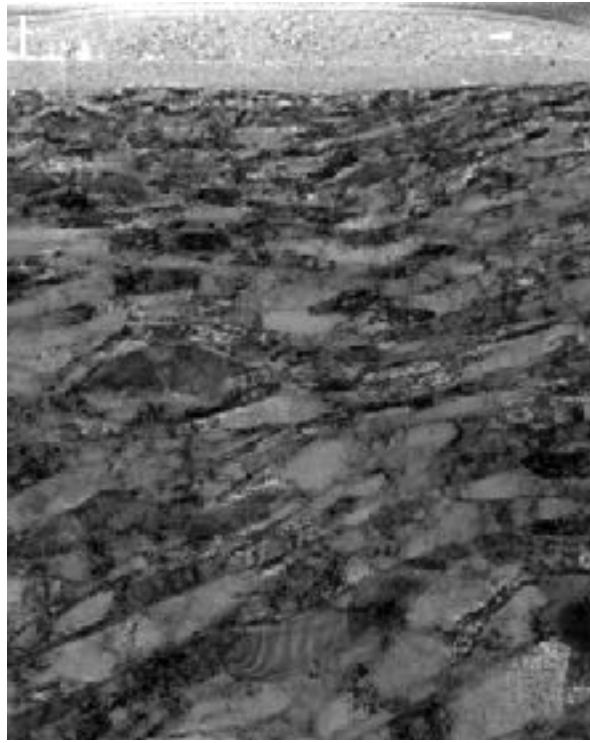
# Adaptation des matériaux (disque) Transformations tribologiques de surface

Sliding direction  
←



500 nm

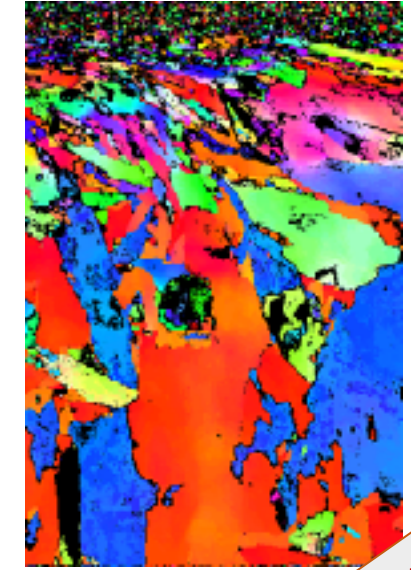
Cast iron



500 nm



500 nm



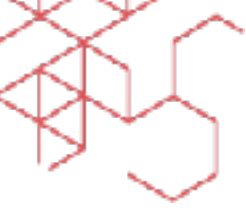
500 nm

Stainless steel

1 μm

- In depth plastic deformation below the rubbed surface.
  - Nanostructured structure close to the rubbed surface.
  - Plastic flows exist in both sliding and radial directions.
  - No significant phase change observed.
- Low thickness of area affected by plastic deformation





## Pour conclure

- Usure et émission en freinage sont interdépendants et dependent de nombreux facteurs, qui demandent à considérer le système tribologique dans son ensemble :
  - environnement : oxydation, humidité, température...
  - matériaux (disque et garniture) : oxydation, plasticité, tts...
  - usage du frein : régularité, diversité, historique, fréquence d'applications
  - design du frein : localisations thermiques, ouverture et fermeture du contact
- L'usage du système tribologique (frein) détermine le fonctionnement du contact (accommodation de la portance et du glissement, dissipation de l'énergie) par la formation du troisième corps et l'adaptation des matériaux et des surfaces.
- Les émissions dépendent de l'activation des débits de troisième au sein du circuit tribologique. Leur réduction à la source reposent sur le dosage de ces débits et la maîtrise de l'équilibre entre ces débits.



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# Merci de votre attention

Acknowledgments:

