



Friction and wear of self-lubricating composites used in transfer lubrication of ball bearing in space applications

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^e AAC GmbH, Wiener Neustadt, Austria



Context

Long life space mechanisms

Dry lubricated ball bearing

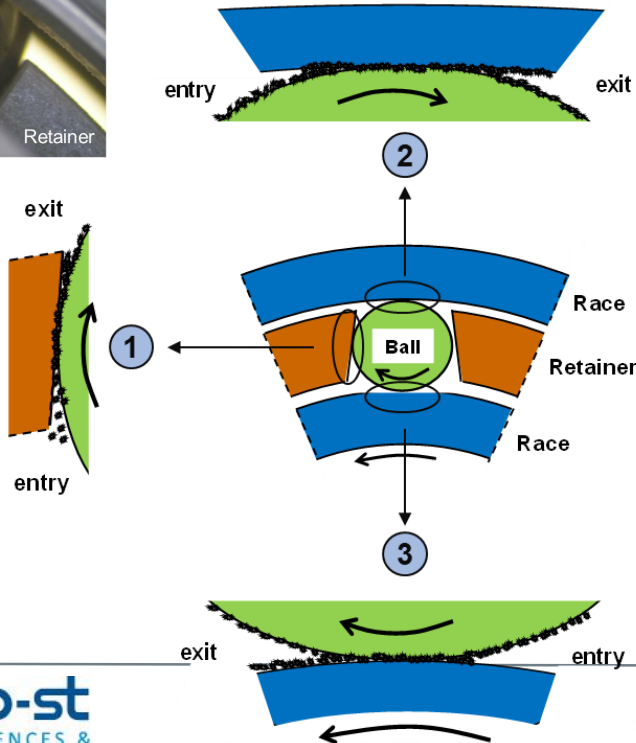
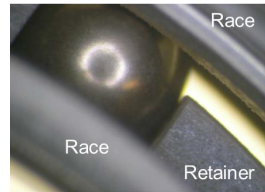
Can perform $> 800.10^6$ rotations @ 60RPM



Source: Thalès Alenia Space

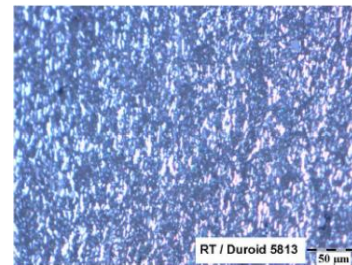


Source: ESA



Double transfer lubrication
Retainer => ball & ball => races

Composites are materials of predilection



Duroïd 5813

PTFE Matrix
 18% MoS₂ size ~ 10µm
 19% Glass fiber Ø 3µm

Reference Material
 Production ceased (90s)

- ▶ Lubrication must be sustained all along the mechanism working life
- ▶ Keep working specifications of mechanisms

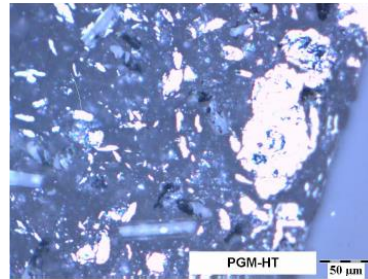
Context

In the quest of a new material

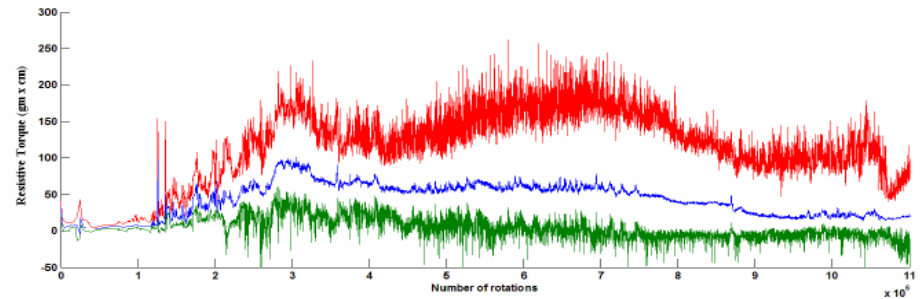
=> Similar composite composition = similar behavior ?

PGM-HT lubricated bearing

PTFE Matrix
10% MoS₂ size ~ 100 μm
24% Glass fiber Ø 20 μm



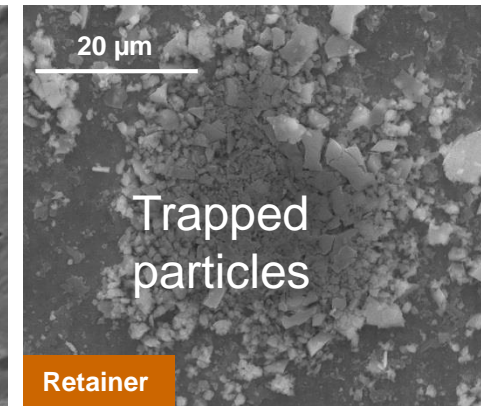
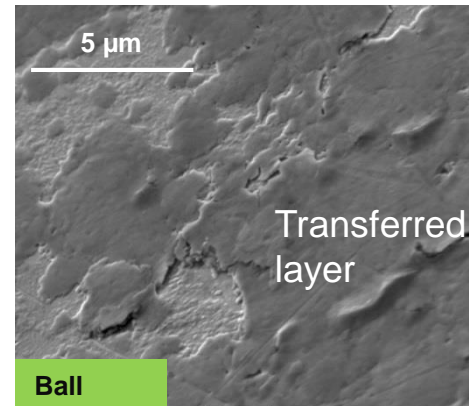
Resistive torque from PGM-HT lubricated bearing



Sicre, ESMATS, 2009

Objective of the study

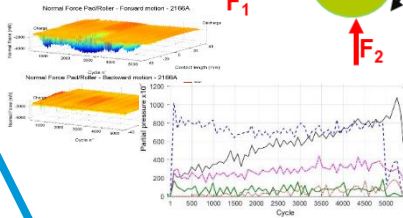
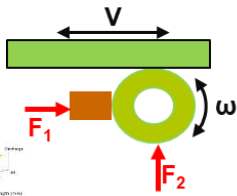
- Study and understand the mechanisms governing the double transfer lubrication
 - Help defining criterion to select and design next generation of self lubricating material



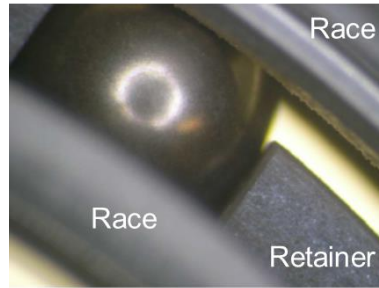
Test plan - 3 phases _ in UHV and air 50% HR

Tribological testing

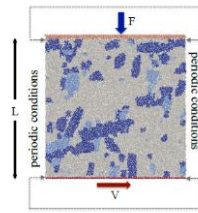
2 env.
UHV & Air



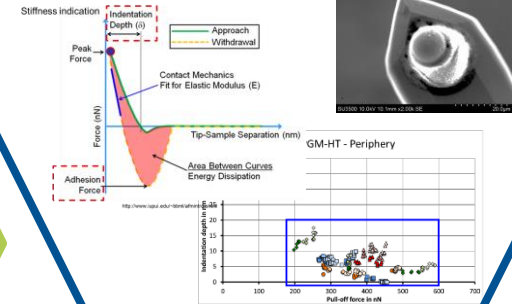
4 composites
Includes 2 prototypes



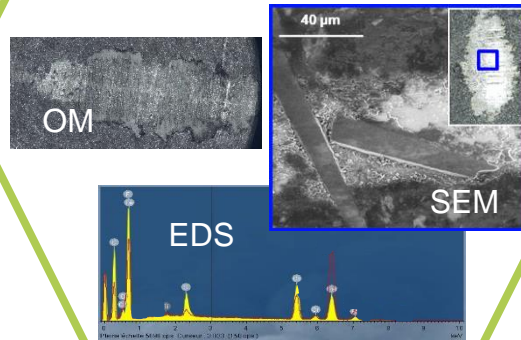
DEM modeling



Pre- and Post tests adhesion



Post tests analysis



Literature survey

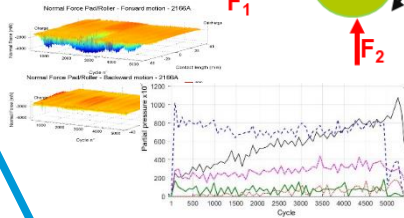
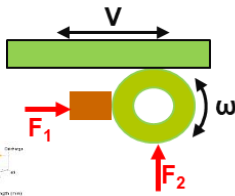
Macromolecules
Ultralow Wear PTFE-based Polymer Composites—The Role of Water and Triboschemistry
Kaveri V. Kanchan¹, Mark A. Schallert², Connor C. Alberry³, Emma F. Babicka⁴,
Charles A. Schallert⁵, Jason J. Brankin⁶, Christopher P. Frank⁷, and Brandon S. Mack^{1*}
¹Department of Materials Science and Engineering, ²Department of Mechanical Engineering and Materials, Loughborough University, Loughborough, Leicestershire, LE11 3TU, UK
³Industrial and Manufacturing Engineering Programme, Masdar University, Abu Dhabi, UAE
⁴UK Space Agency, Cranfield, Bedfordshire, MK43 0AL, UK
⁵Department of Mechanical Engineering, University of Cambridge, Cambridge, UK
⁶Department of Materials Science and Engineering, University of Cambridge, Cambridge, UK
⁷Department of Materials Science and Engineering, University of Cambridge, Cambridge, UK
*Correspondence: b.s.mack@lboro.ac.uk

Experimental Investigation

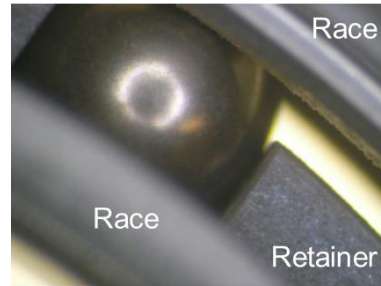


Tribological testing

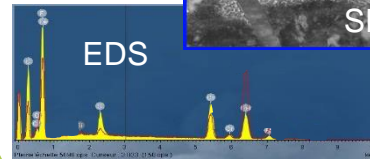
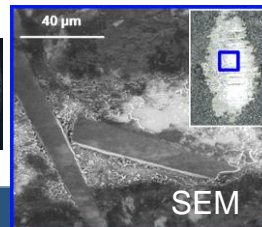
2 env.
UHV & Air



4 composites
Includes 2 prototypes



Post tests analysis



Materials of interest



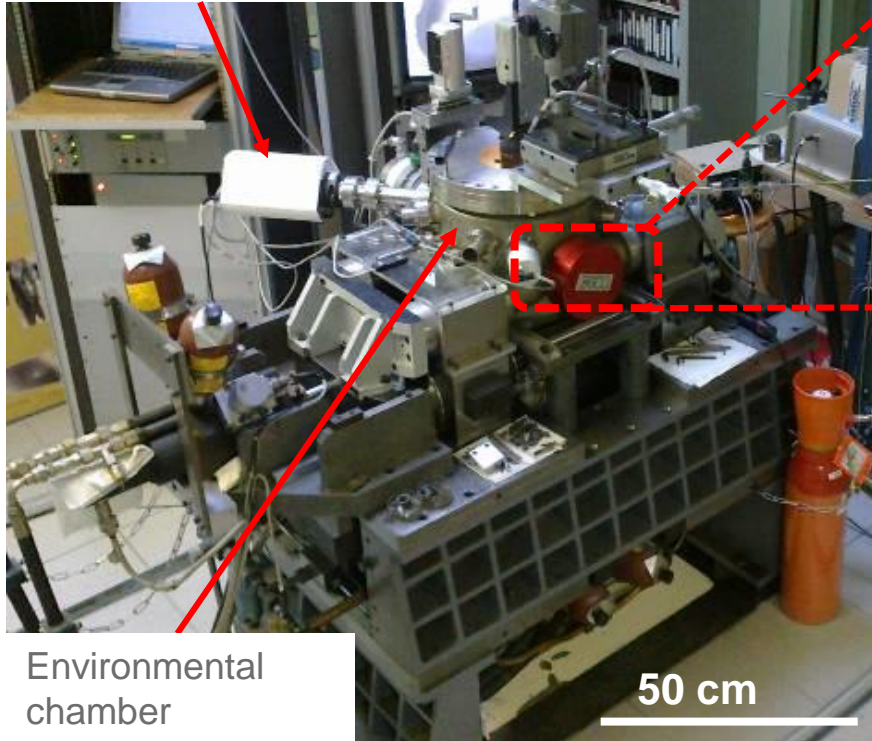
Composite	Supplier	Composition	Manufacturing Process
Duroïd 5813	Rogers Corp. (USA)	PTFE matrix 18% MoS ₂ Ø10 µm * 19% glass fiber Ø3 µm *	Unknown
PGM-HT	JPM Mississippi (USA)	PTFE matrix 10% MoS ₂ Ø100 µm * 24% glass fiber Ø20 µm *	Hot compression molding preconditioned in vacuum
AAC-C1	Formulation by AAC, produced by ENSINGER SINTIMID GmbH	PTFE matrix 10% MoS ₂ particles 25% glass fiber Ø13 µm	Hot compression molding
AAC-C9	Formulation by AAC, produced by ENSINGER SINTIMID GmbH	PTFE 10% MoS ₂ particles 15% mineral fiber Ø3 µm	Hot compression molding

Experimental set-up



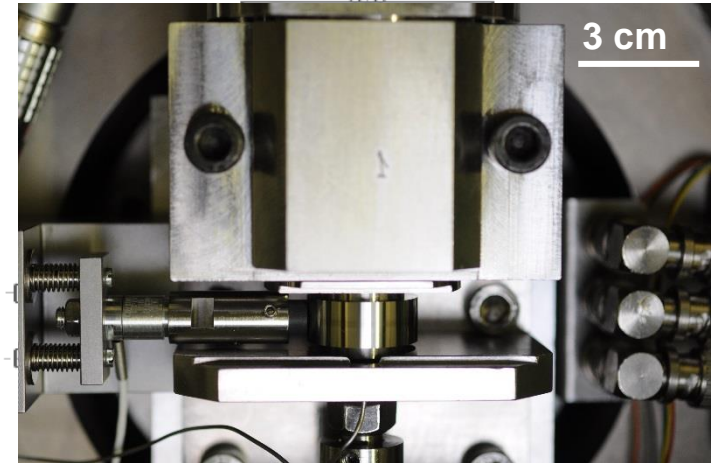
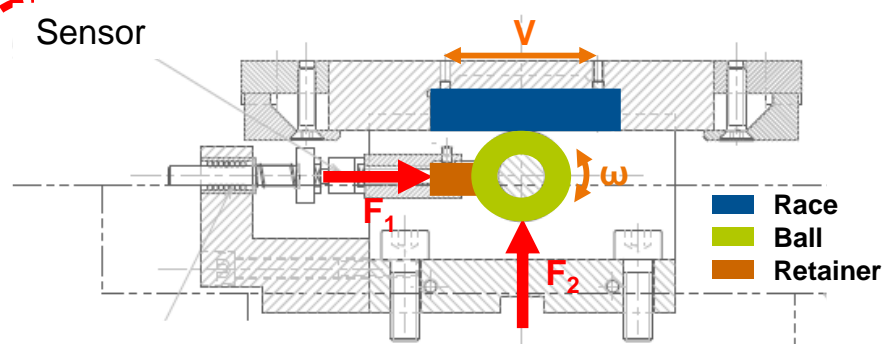
Experimental device

Gas analysis
Mass spectrometer



Environmental chamber

50 cm



3 cm

Test plan - 3 phases _ in UHV and air 50% HR

A – Contact ball/pad 5000 cycles

- Pure sliding, oscillating ($\pm 37,5$ mm)
- Sliding speed : 100 mm/s *
- Normal force ball/pad : 1,5 N (~ 10 Mpa)

** information from real mechanisms*



3 tests per composites
in UHV

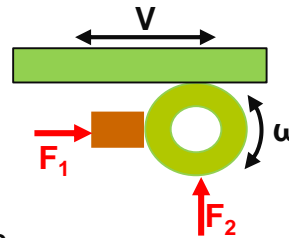
1 with phase A

1 with phase AB

1 with phase ABC

B – Contact ball/pad and ball/plate 5000 cycles

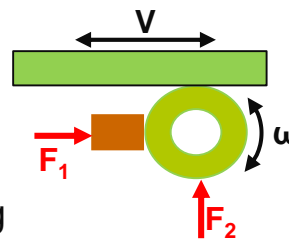
- Contact ball/pad
 - Idem phase A
- Contact ball/plate
 - Rolling **without** sliding, oscillating
 - Contact pressure ball/plate: 0,5 GPa



1 test per composite in
air 50%RH

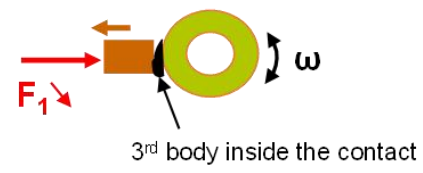
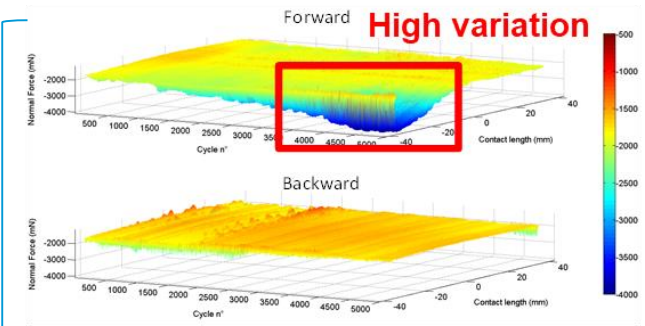
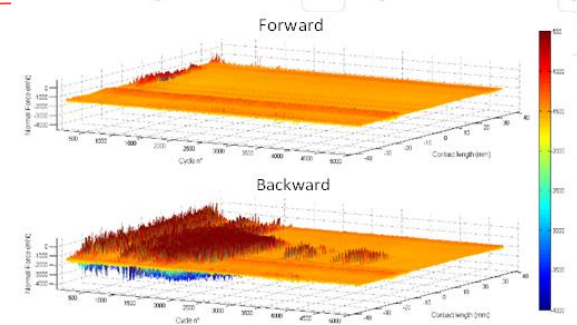
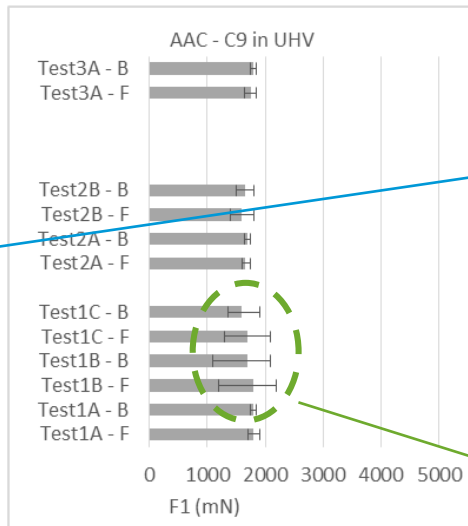
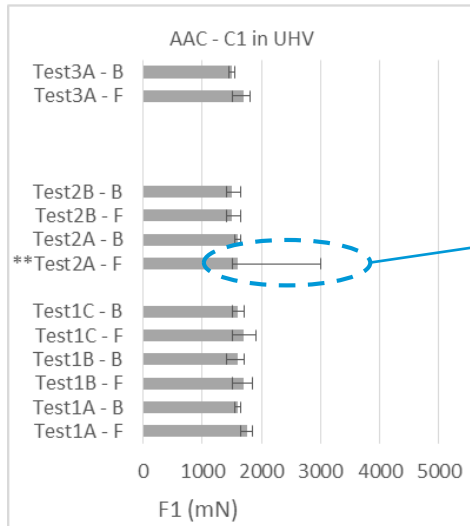
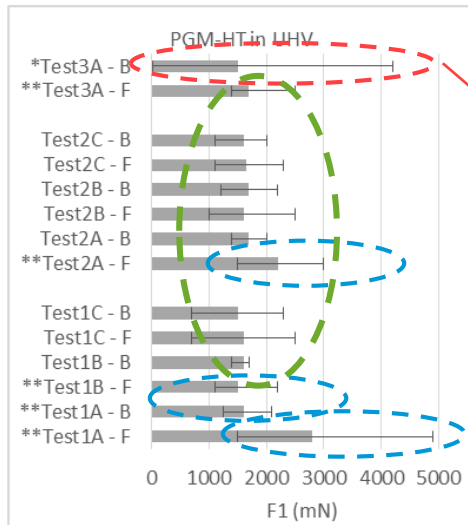
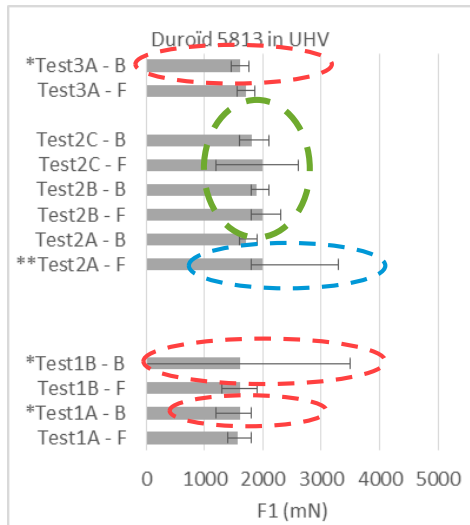
C – Contact ball/pad and ball/plate 5000 cycles

- Contact ball/pad
 - Idem phase A
- Contact ball/plate
 - Rolling **with** 0,5% sliding, oscillating
 - Contact pressure ball/plate: 0,5 GPa



1 with phase ABC

Tribological Tests - UHV



A combination of both ?

Tribological Tests - UHV

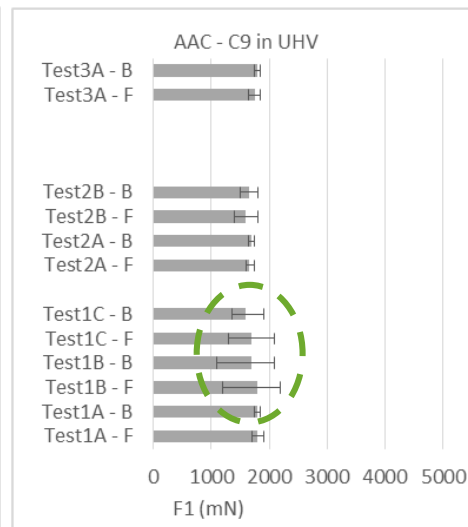
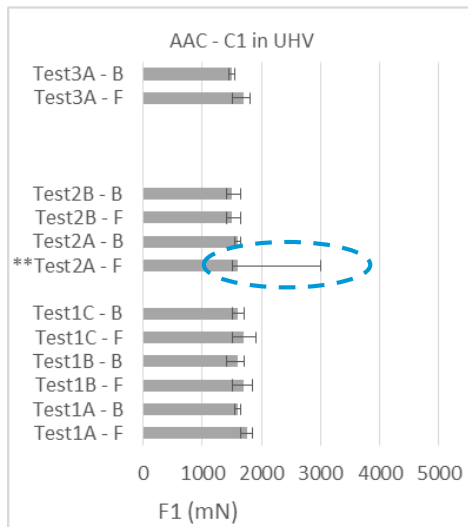
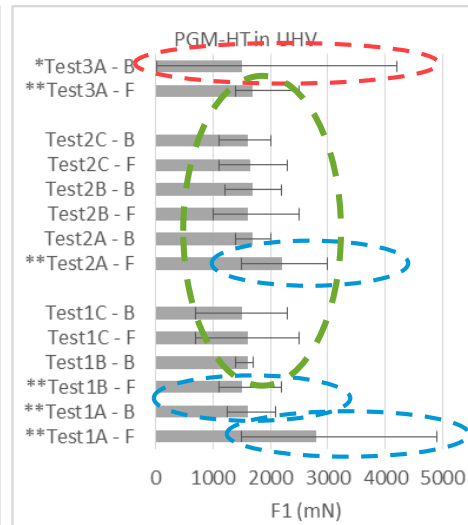
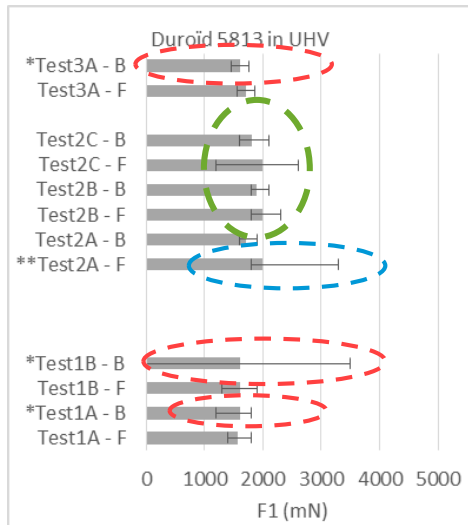


PGM-HT : highest variations ► **big particles** + **instabilities** + **both**

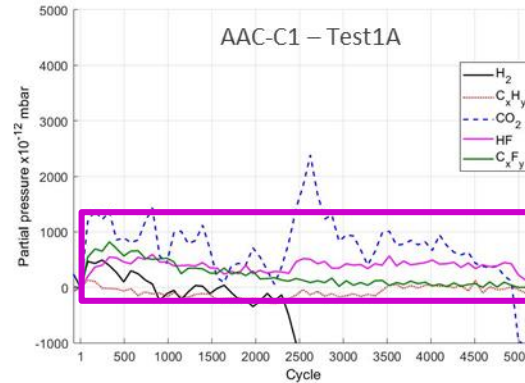
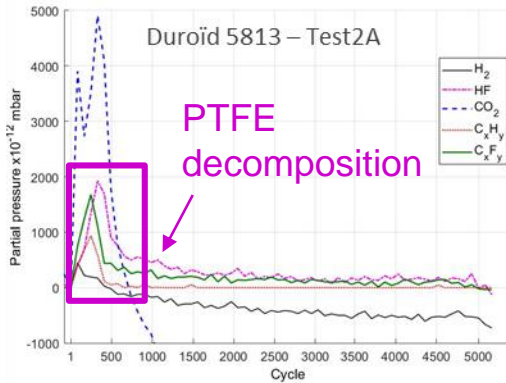
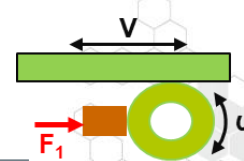
Duroïd : moderate variations ► **instabilities** + **both**

C1: the lowest variations except in one test (phase A) ► **big particles**

C9: low variations but variations are the highest with rolling motion ► **both**

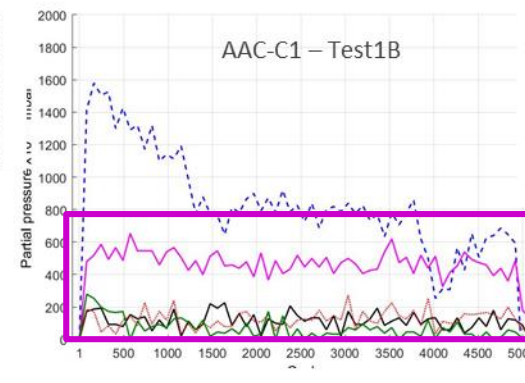
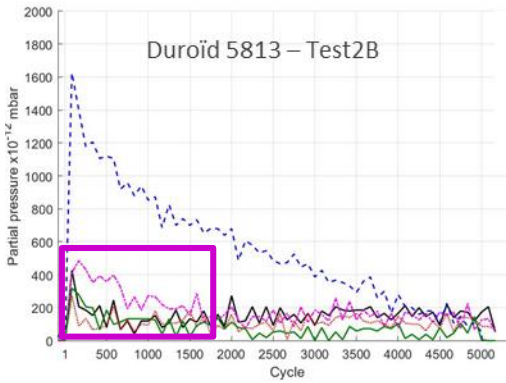
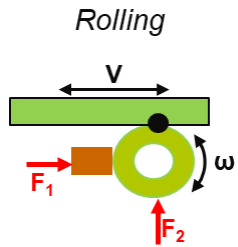


Tribological Tests - UHV



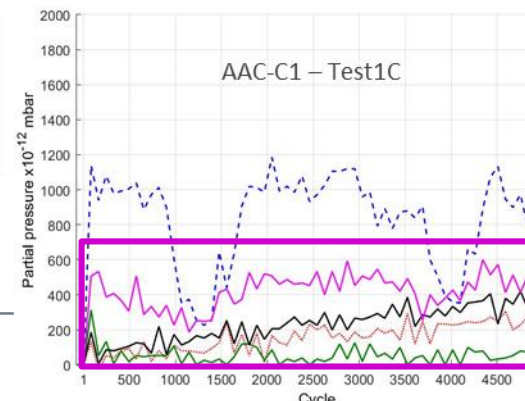
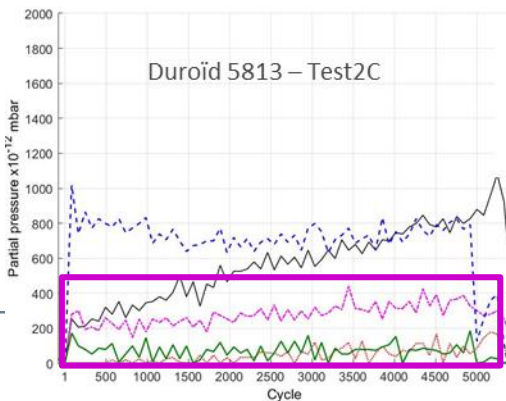
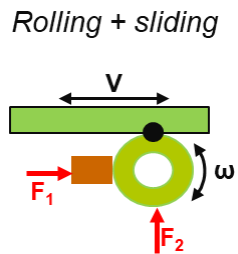
+ *OM and SEM*

Duroïd transfer little during phases A and B but a lot in phase C



► idem for PGM-HT

AAC-C1 continuously transfer during all phases A, B, and C

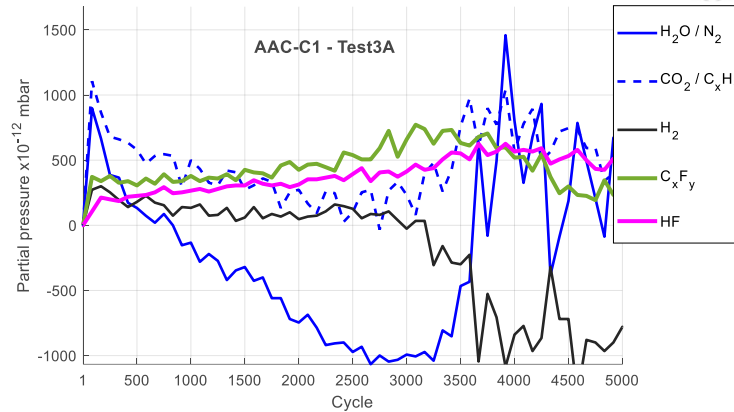


► idem for AAC-C9

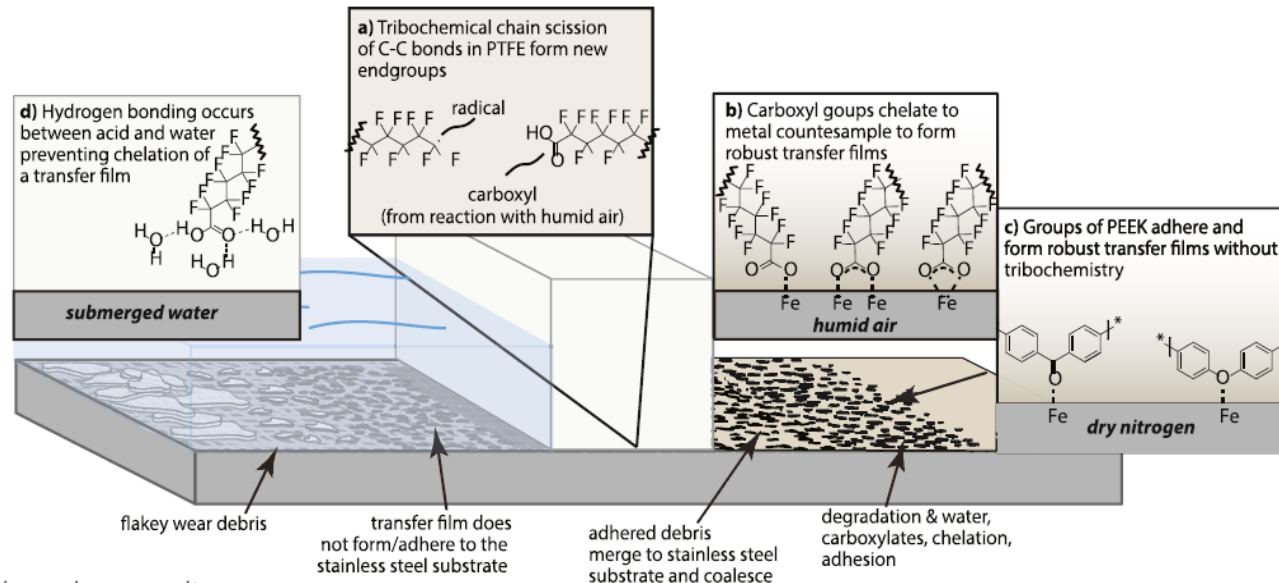
Tribological Tests - UHV



Specificity of AAC-C1
 ► Water adsorption in phase A and in UHV !!!



Campbell, 2019 ► water adsorption during friction may contribute to increase friction stability due to the creation of carboxylate groups on PTFE to anchor the transfer film on steel surface



a, b, d : PTFE based composites

Tribological Tests - UHV

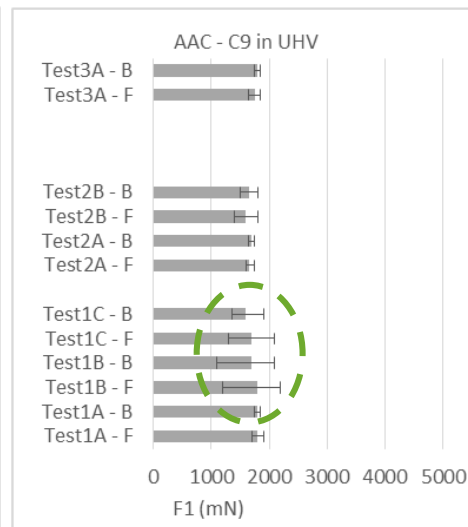
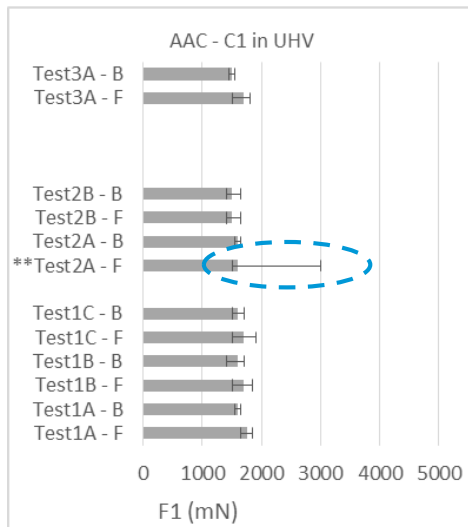
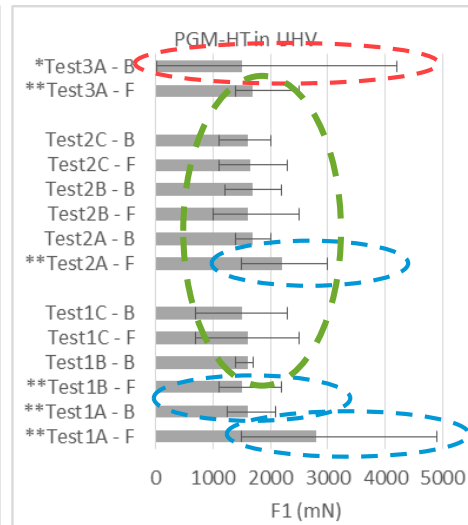
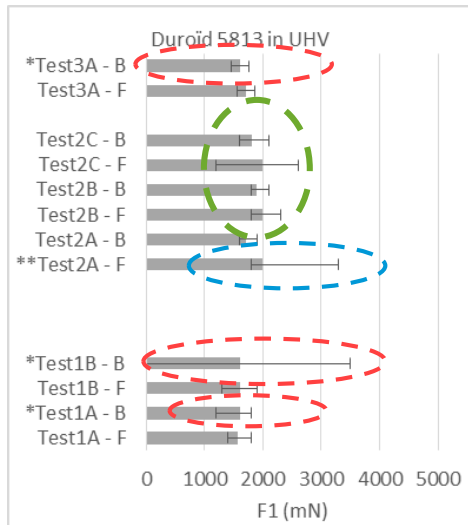


PGM-HT : highest variations ► **big particles** + **instabilities** + **both**

Duroïd : moderate variations ► **instabilities** + **both**

C1: the lowest variations except in one test (phase A) ► **big particles**

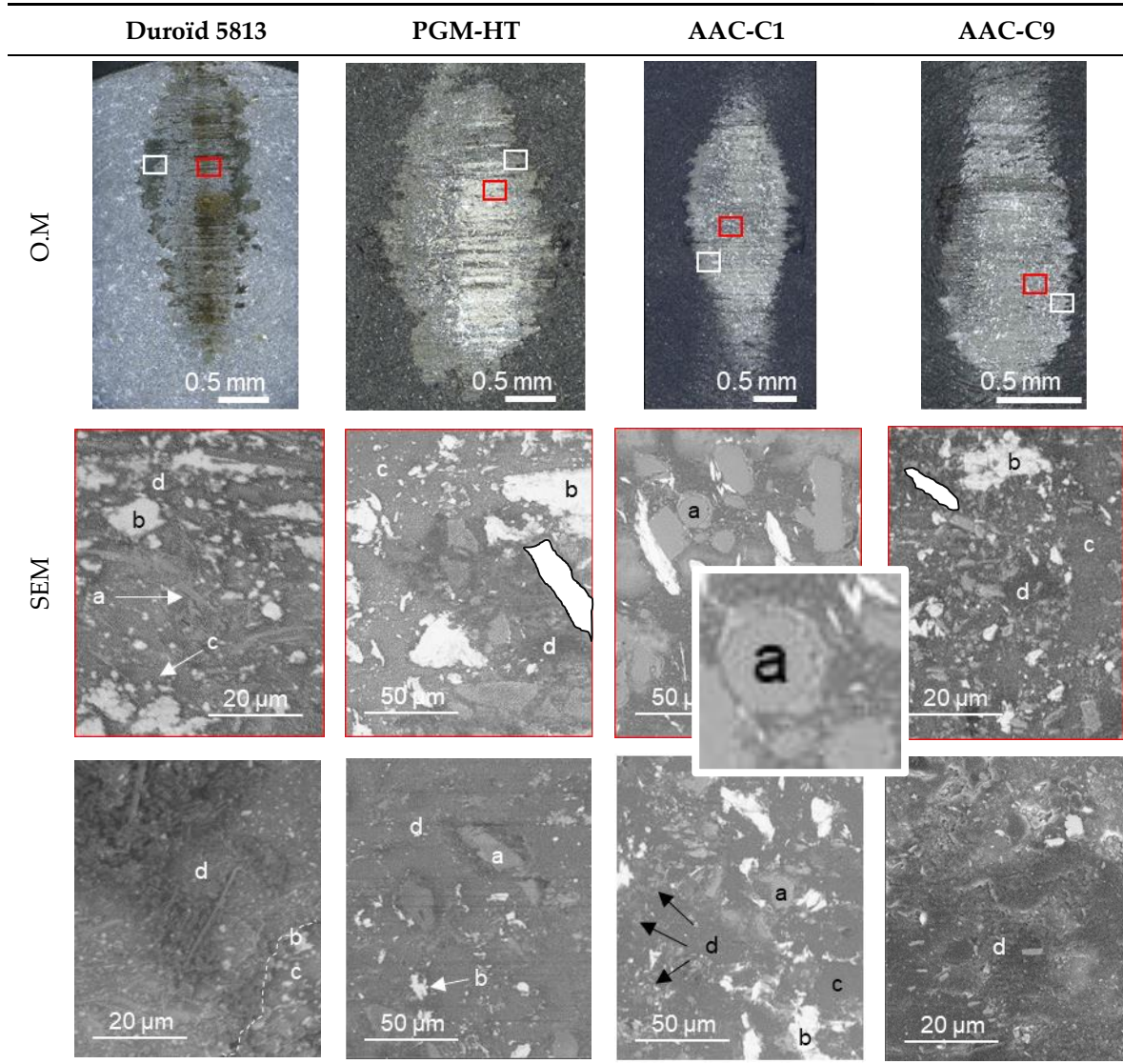
C9: low variations but variations are the highest with rolling motion ► **both**



C1 and C9: smooth erosion/stress of PTFE and good transfer

C1: water adsorption which is good for anchorage of transfer film and friction stability

Tribological Tests – Post test Analysis



Pad ellipse morphology

PGM-HT ⇔ AAC-C9
 Duroïd ⇔ AAC-C1
 Counter intuitive

High magnification SEM

PGM-HT ⇔ AAC-C9

► fiber aligned in the contact plane

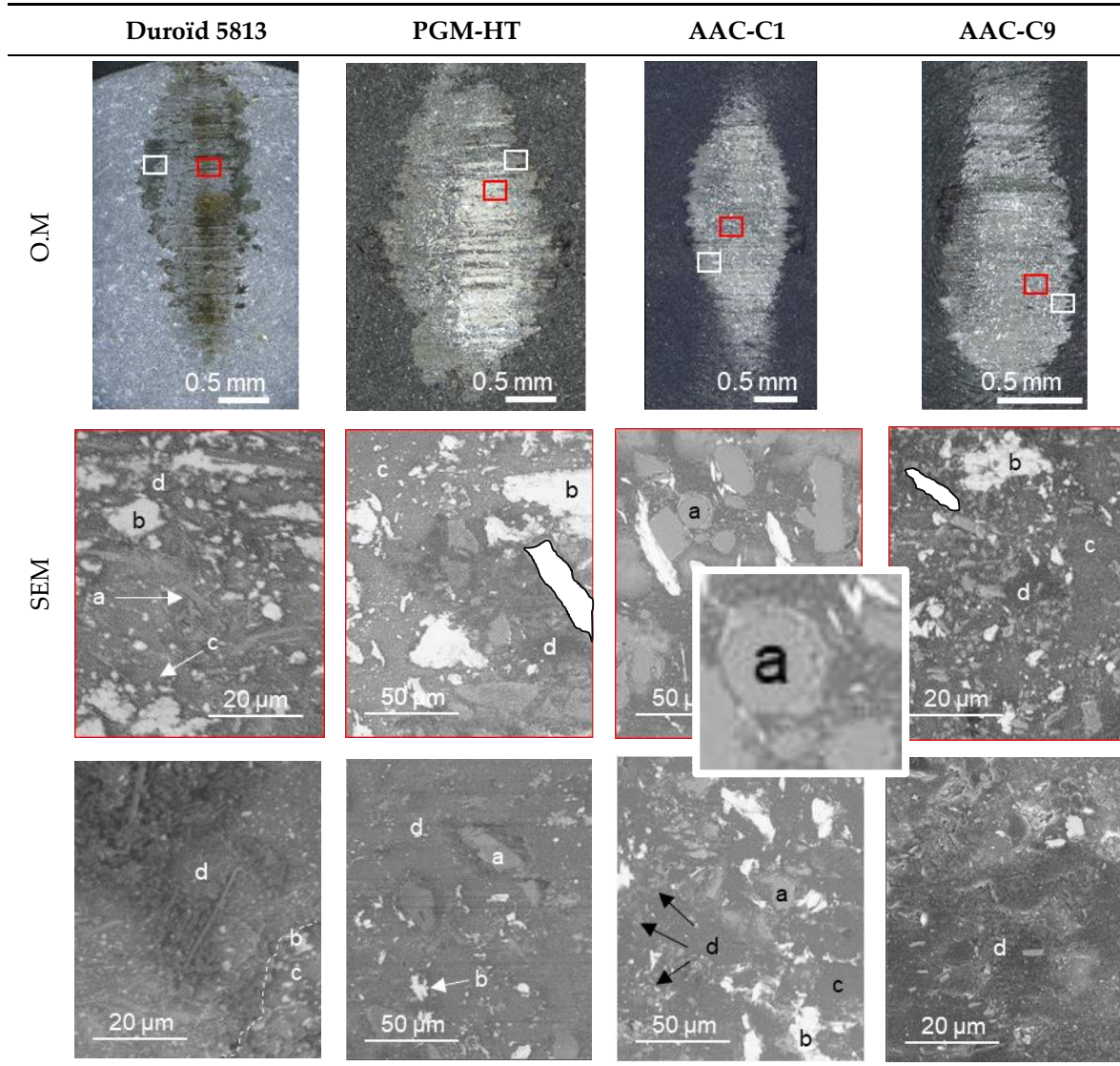
Duroïd ⇔ AAC-C1

► Duroïd: small chunk of fibers dispersed in the contact but aligned in the contact plane

► C1: fibers orthogonal to contact + 3rd body buffer layer around them

a: fiber ; b: MoS2; c: PTFE matrix; d: 3rd body

Tribological Tests – Post test Analysis



Pad ellipse morphology

PGM-HT ⇔ AAC-C9
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High magnification SEM

PGM-HT ⇔ AAC-C9

► fiber aligned in the contact plane

Duroïd ⇔ AAC-C1

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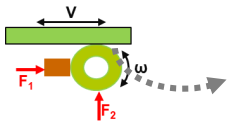
► C1: fibers orthogonal to contact + 3rd body buffer layer around them

Nak-Ho, 1979 => Detrimental + enhanced by decohesion
 Champagne, 2014 => corner edge leading to breakage and big chunk formation

C1: Fiber strongly bonded to PTFE

a: fiber ; b: MoS2; c: PTFE matrix; d: 3rd body

Tribological Tests – Post test Analysis



Transfer film on the plate sample



PGM-HT exhibits the worst capability of transfer

	Duroïd 5813	PGM-HT	AAC-C1	AAC-C9
O.M				
SEM				

Duroïd exhibits smooth, homogeneous, but moderate (thin) transfer

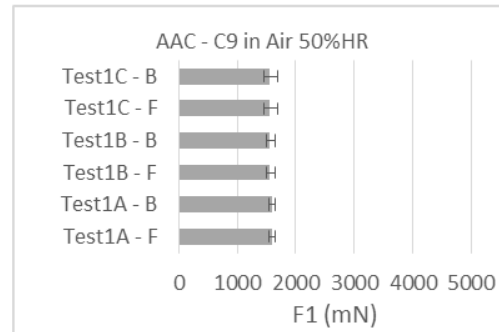
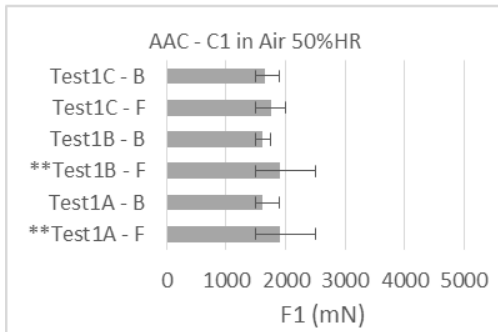
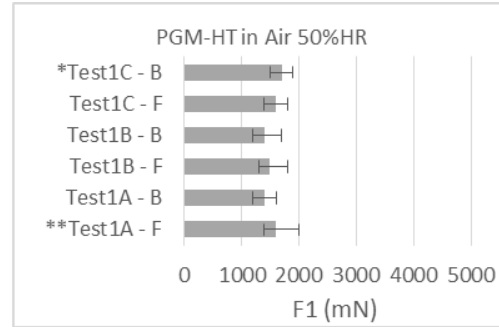
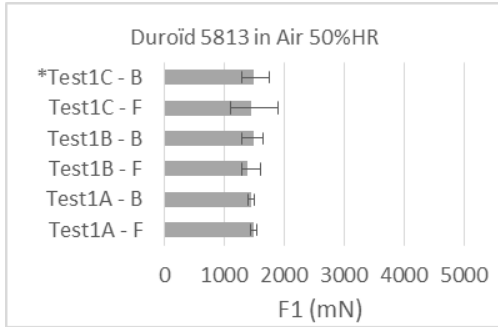
AAC-C1 exhibits smooth, homogeneous, but good transfer

AAC-C9 exhibits smooth, homogeneous, and thick transfer

AAC-C9 ⇔ Duroïd
Transfer film less adhesive to steel than transfer from AAC-C1

AAC-C1 ► best option ?

Tribological Tests - Air



PGM-HT : moderate variations ► **big particles** + **instabilities** + **both**

Duroïd : moderate variations only in phase C ► **instabilities** + **both**

C1 : moderate variations ► **big particles** + **both**

C9 : lowest variations but variations

No significant differences on pad ellipse

Duroïd and PGM-HT: thick, patchy, transfer film

C1 and C9: Smooth and thin transfer film, particularly for C9

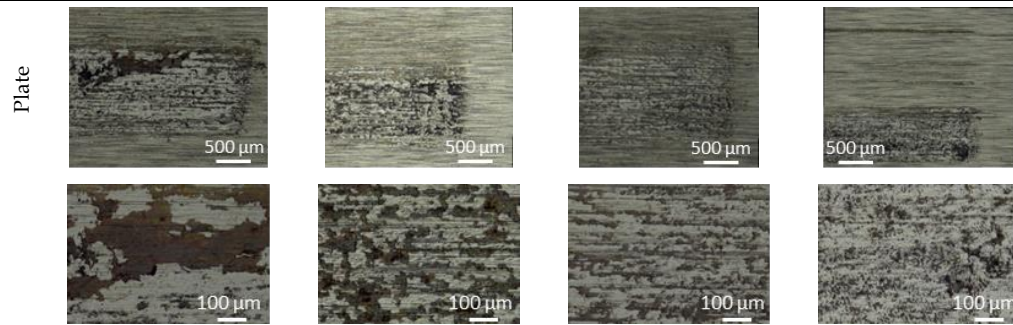
Water adsorption mitigates all detrimental effect of fibers, etc. by promoting PTFE and transfer film anchorage

Duroïd 5813

PGM-HT

AAC-C1

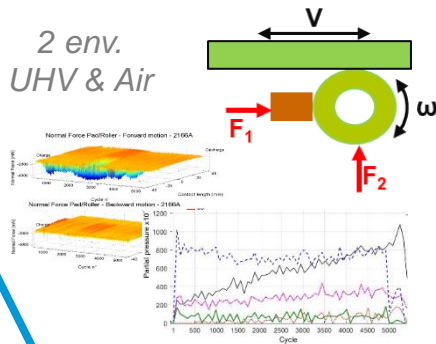
AAC-C9



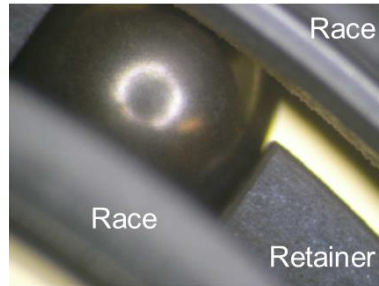
Experimental Investigation_partial conclusion

Tribological testing

2 env.
UHV & Air



4 composites
Includes 2 prototypes



Why ???

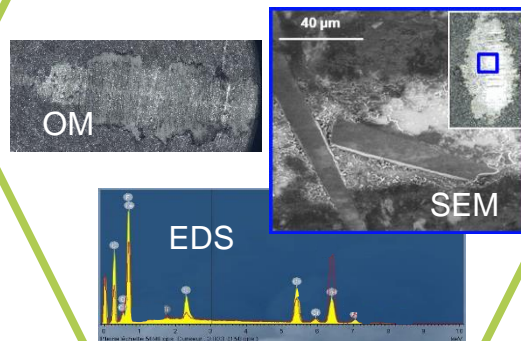
*Significant differences
in behaviour although
similar compositions*

2 EU prototypes perform the best

- ▶ smooth erosion/stress of PTFE and good transfer
- ▶ water adsorption which is good for anchorage of transfer film and friction stability
- ▶ strong Fiber/PTFE bound but buffer 3rd body that sporadically lead to big chunk detachment and circulation

AAC-C1 ▶ best option ?

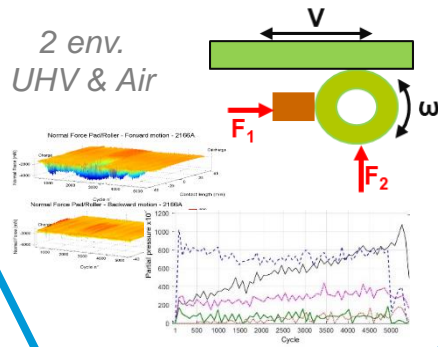
Post tests analysis



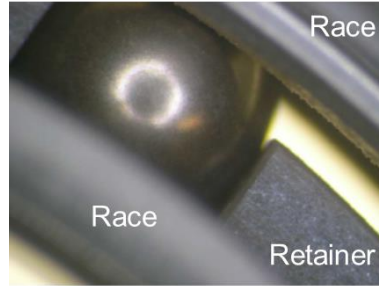
Test plan - 3 phases _ in UHV and air 50% HR

Tribological testing

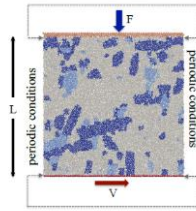
2 env.
UHV & Air



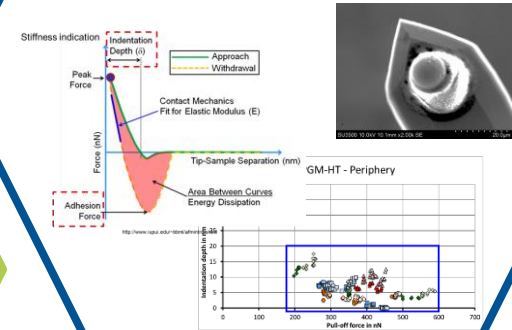
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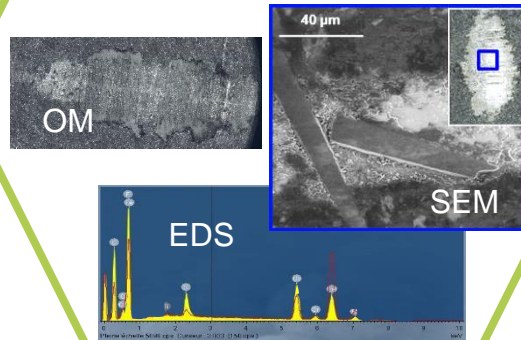
DEM
modeling



Pre- and Post
tests adhesion



Post tests
analysis

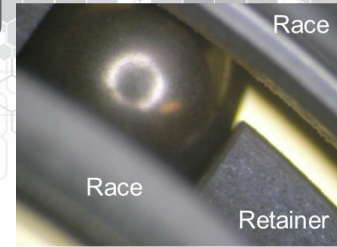


Literature
survey

Macromolecules
Ultra-low Wear PTFE-based Polymer Composites—The Role of Water and Tribosensitivity
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For optimized transfer lubrication of ball bearing

- Low but continuous transfer of material all along the test, without damaging nor wearing too much the composite
 - Random orientation of fiber with high proportion of fiber orthogonal to the contact AND Moderate matrix stiffness AND fiber/matrix strongly bounded
 - Small fragments from hard filler to modulated mechanical properties of transfer film and insure long life
 - High adhesion of MoS₂ towards steel AND high adhesion of fiber towards PTFE
 - Favors lubricant & limits abrasion from fiber sliding over steel and transferred film
 - Equilibrium between internal cohesion of transferred material, and adhesion to counterparts must be satisfied
 - Adsorption of residual water inside the vacuum
 - Gentle running to lead to better transfer and anchorage of the transferred material



High water desorption during 1st year(s) of operation

Significant inside/outside pressure differential

Thanks for your attention



lubricants



Article

Experimental Analysis of Friction and Wear of Self-Lubricating Composites Used for Dry Lubrication of Ball Bearing for Space Applications

Guillaume Colas ^{1,*} , Aurélien Saulot ² , Yann Michel ³, Tobin Filleter ⁴ and Andreas Merstallinger ⁵





Tribological Tests - UHV

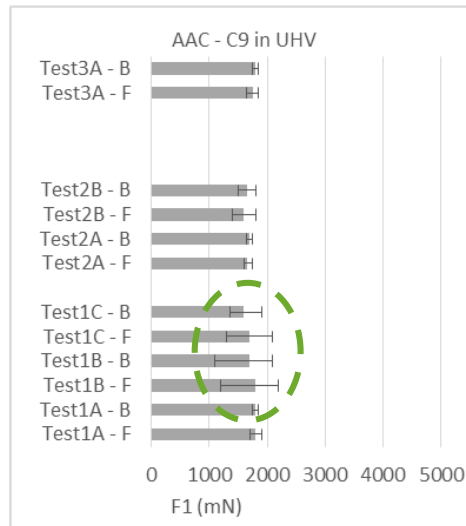
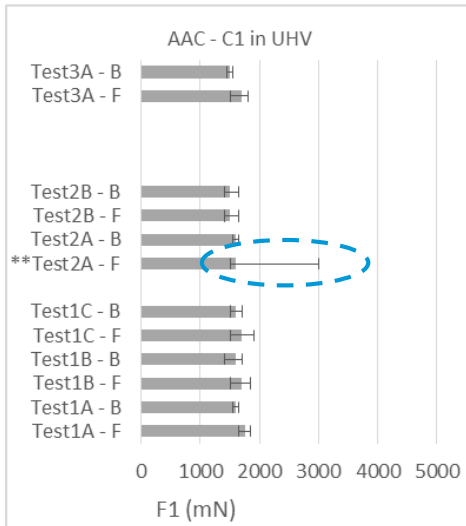
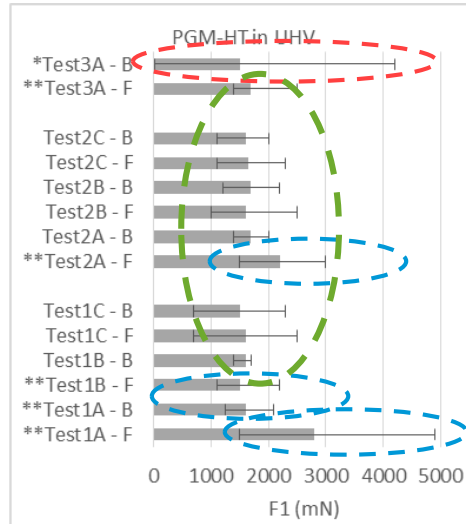
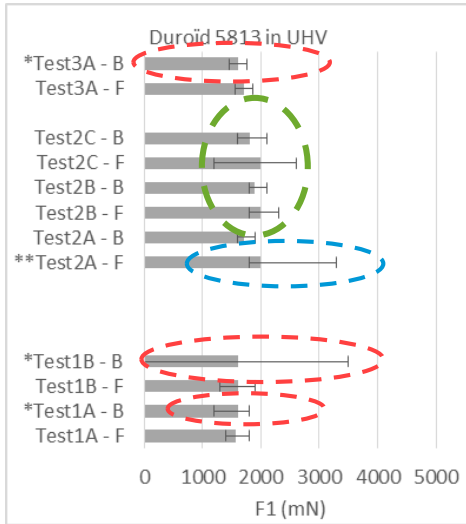


PGM-HT : highest variations ► **big particles** + **instabilities** + **both**

Duroïd : moderate variations ► **instabilities** + **both**

C1: the lowest variations except in one test (phase A) ► **big particles**

C9: low variations but variations are the highest with rolling motion ► **both**

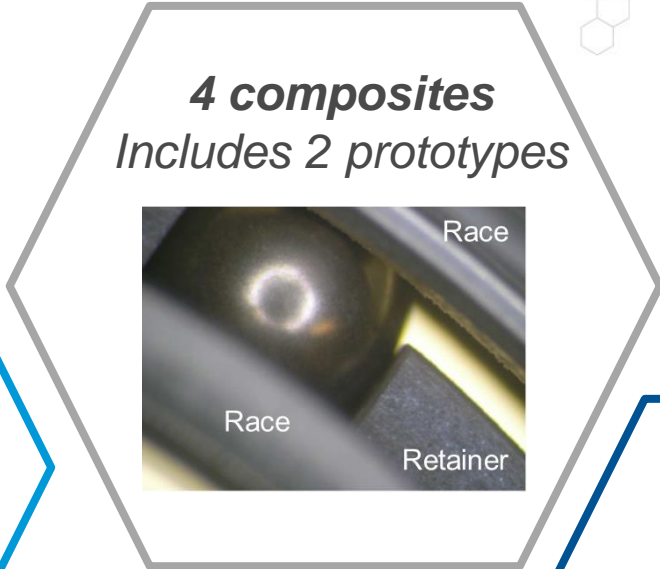
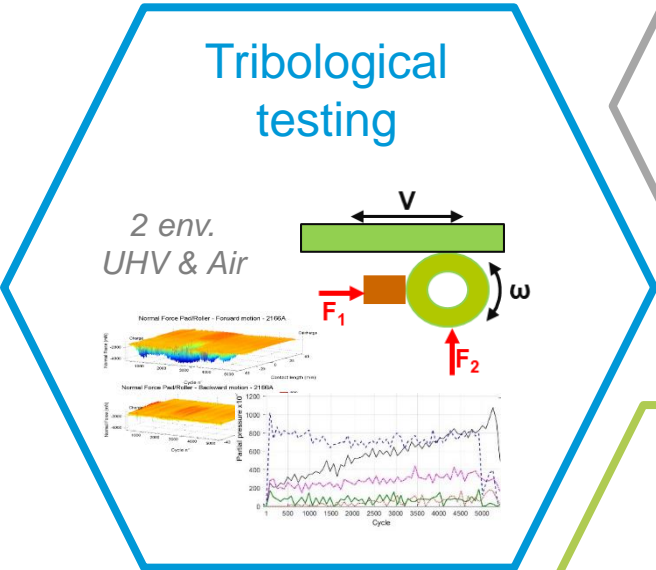


C1 and C9: smooth erosion/stress of PTFE and good transfer

C1: water adsorption which is good for anchorage of transfer film and friction stability

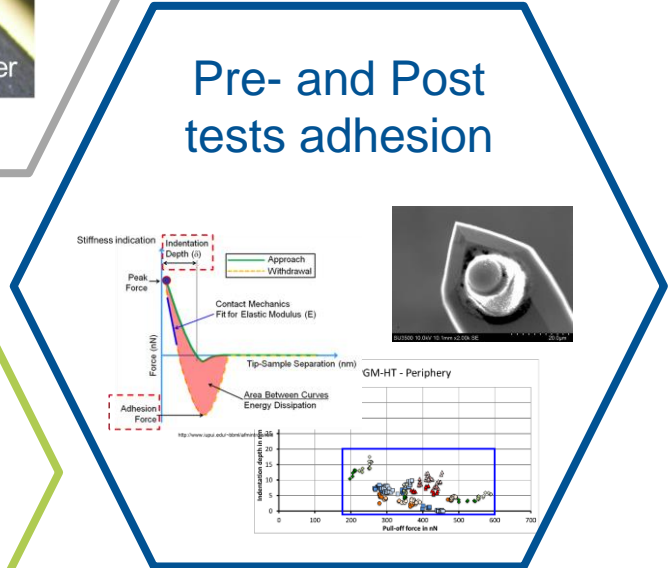
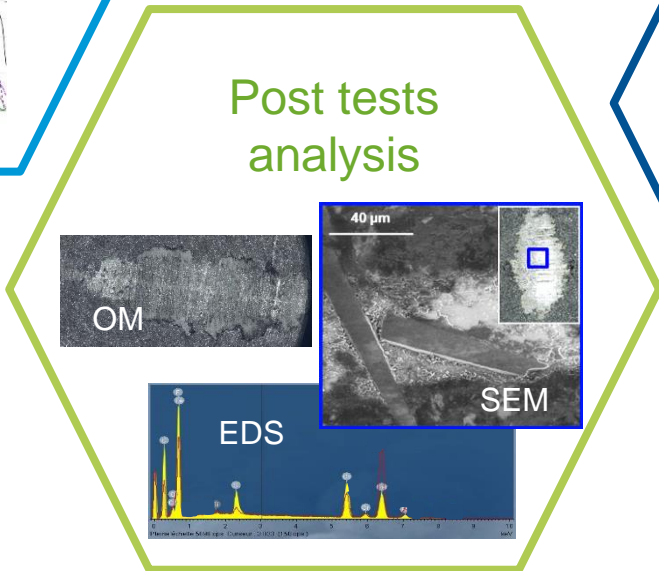
C1: strong Fiber/PTFE bound but buffer 3rd body that sporadically lead to big chunk detachment and circulation

Experimental Investigation



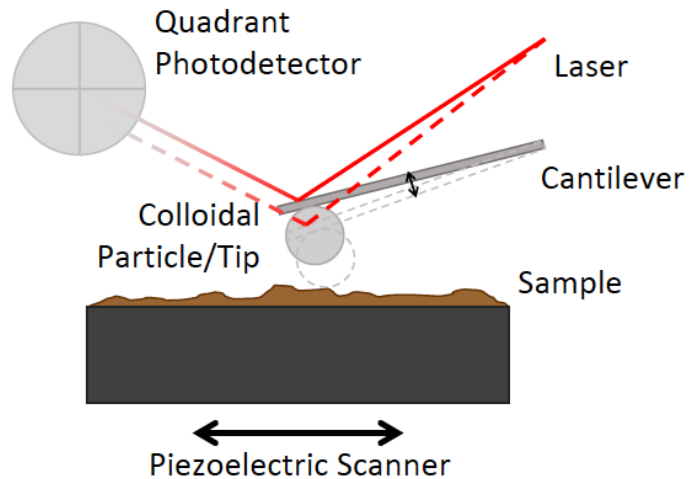
Why ???

Significant differences in behaviour although similar compositions



Pre- and Post-tests adhesion investigations

AFM based adhesion



Commercial Borosilicate glass (BSG)
& In-house made stainless steel
colloidal probes

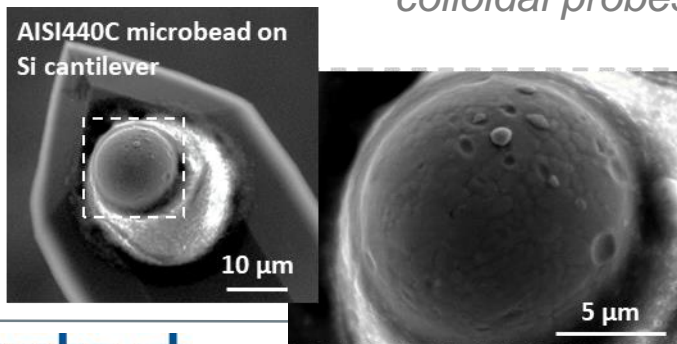
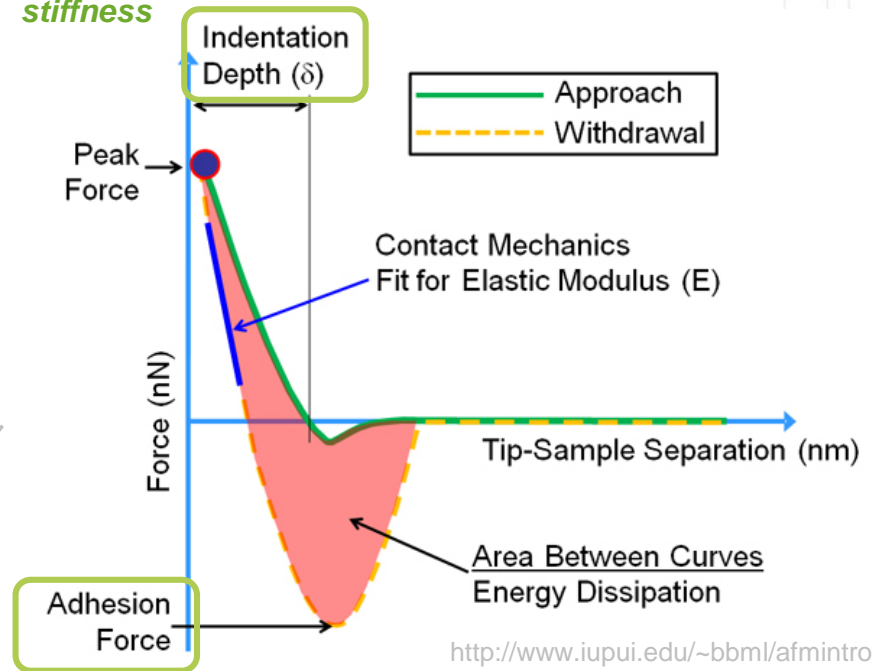


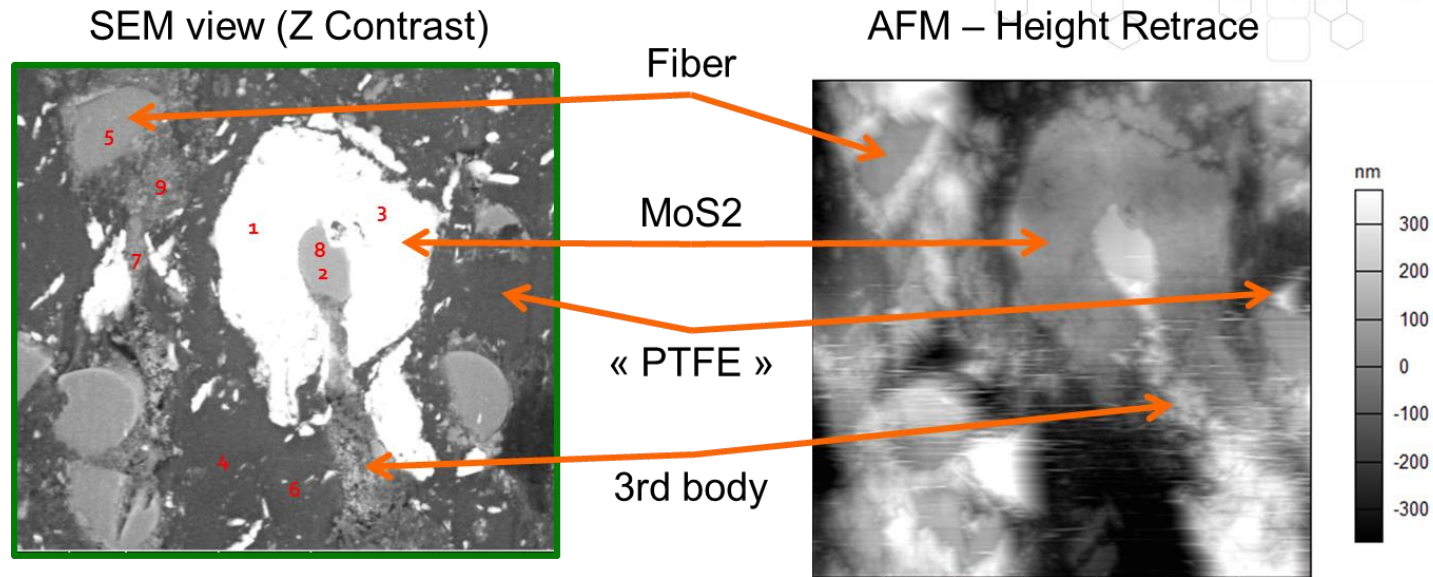
Image of local material stiffness



NB: Here we choose to work in pure elastic regime

- ▶ no energy dissipation due to permanent material deformation
- ▶ focus on adhesion force

Pre- and Post-tests adhesion investigations

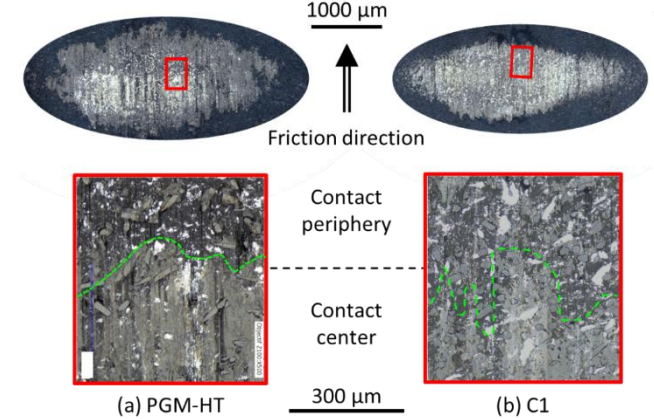
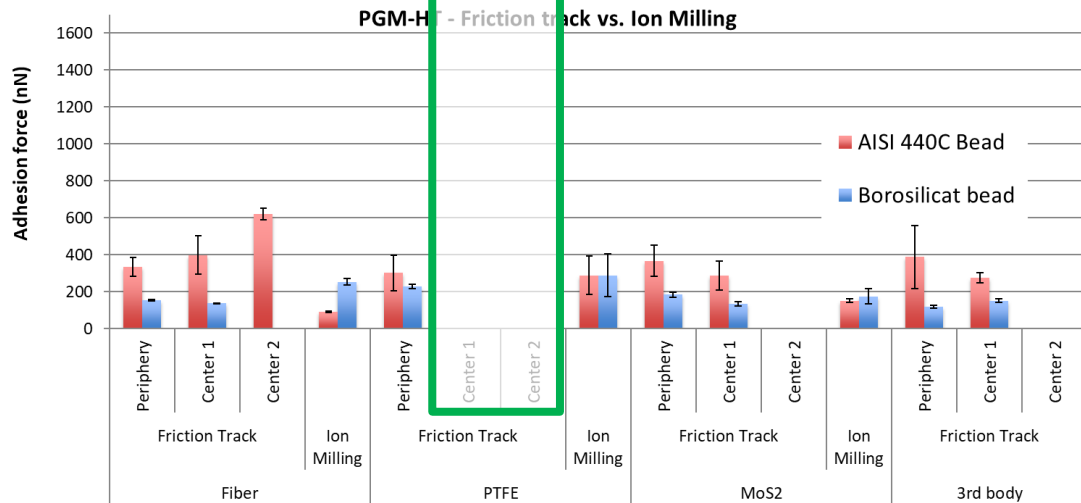
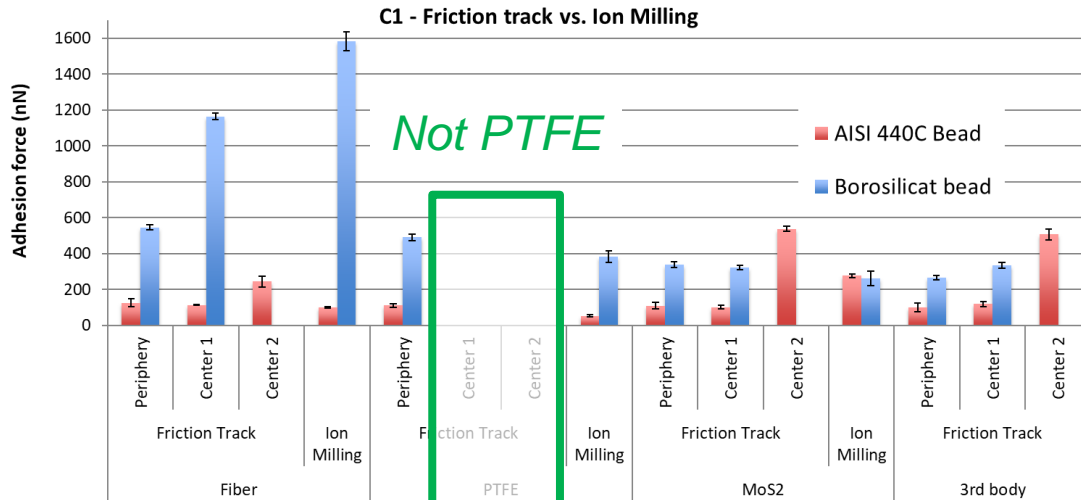


- 1- Identification of a Region of interest
- 2- Scan with the colloidal probes
- 3- Identification of individual material
- 4- Measures in « random » order
- 5- Control of probe contamination:
 - ▶ adhesion @ location #1 measured twice at least (1st and last)

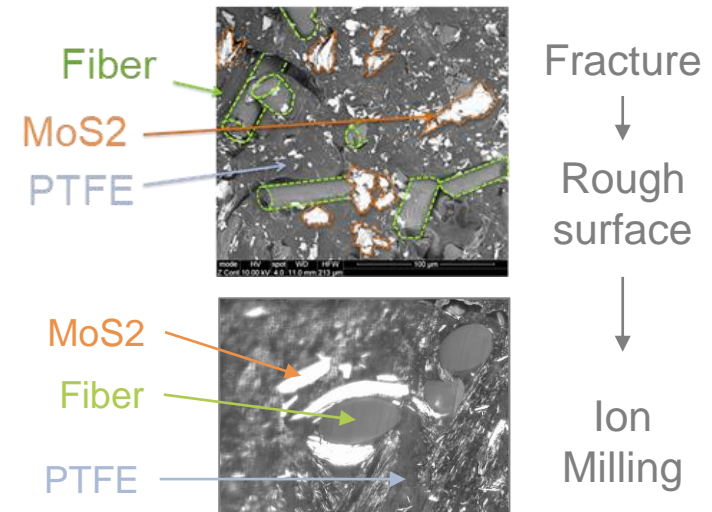
Composite	PTFE	Glass Fiber	MoS2	3 rd body
PTFE	-	☑	-	-
Glass Fiber	☑	☑	☑	☑
MoS2	-	☑	-	-
3 rd body	-	☑	-	-
AISI440C	☑	☑	☑	☑

Loading pattern: 1 μ N ▶ 2 μ N ▶ 3 μ N ▶ 2 μ N ▶ 1 μ N
6 repetition per load

Results of adhesion investigations



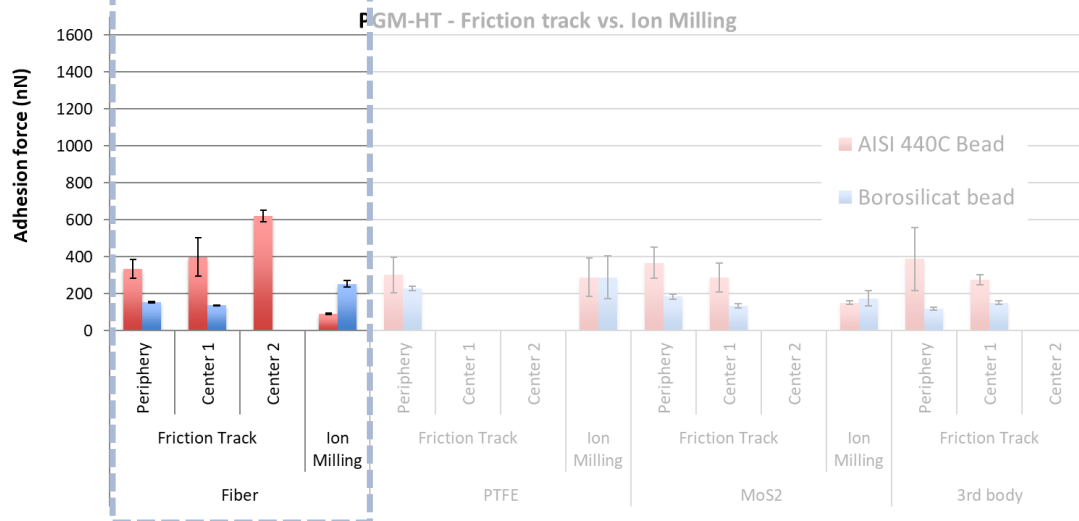
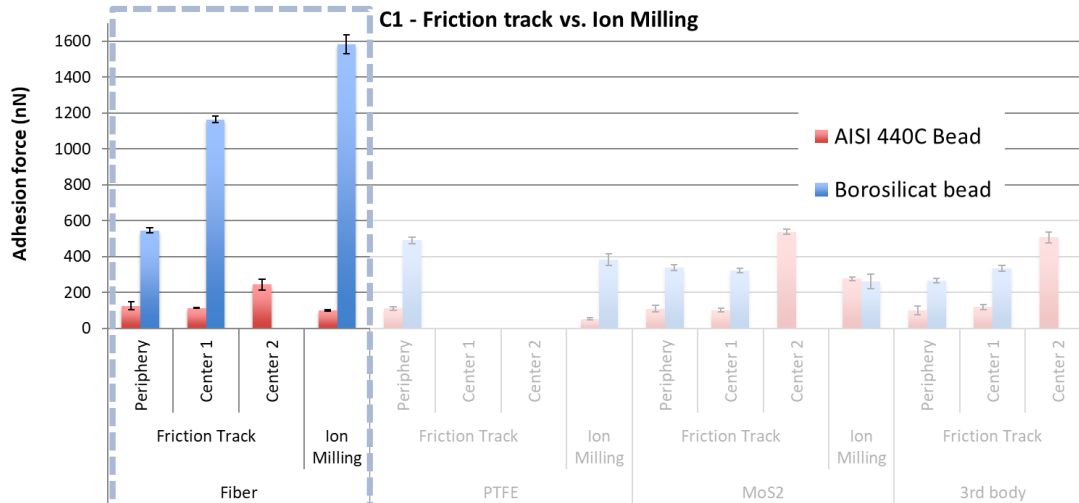
Composite before friction



Results of adhesion investigations



▶ behaves as expected: High adhesion of glass bead on glass fiber



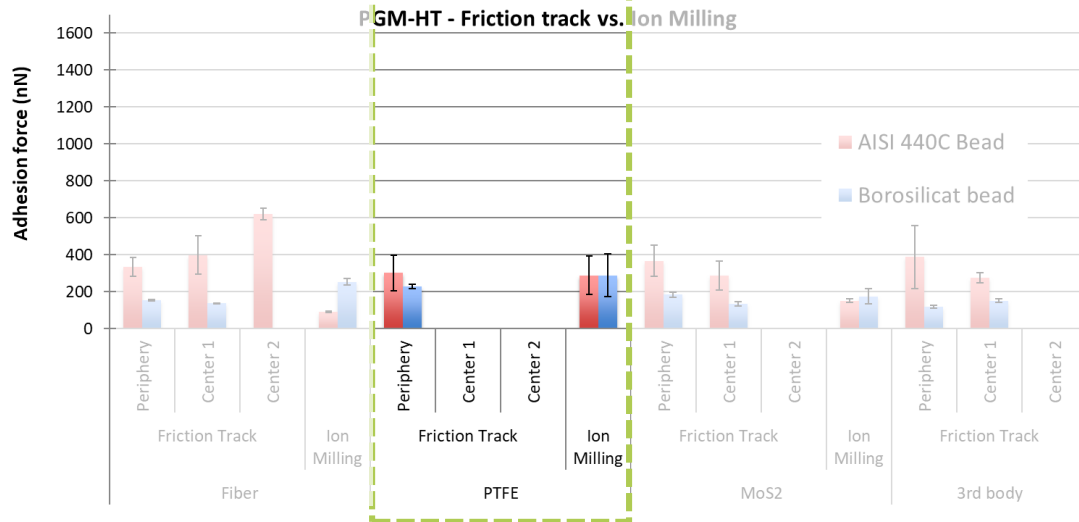
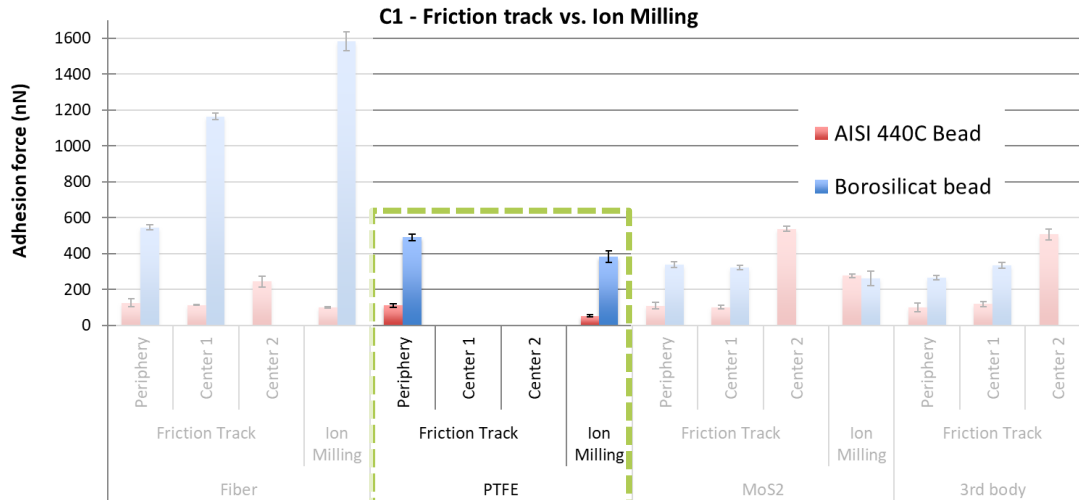
▶ PGM-HT: High adhesion of fiber towards steel

Results of adhesion investigations



► behaves as expected: High adhesion of glass bead on glass fiber

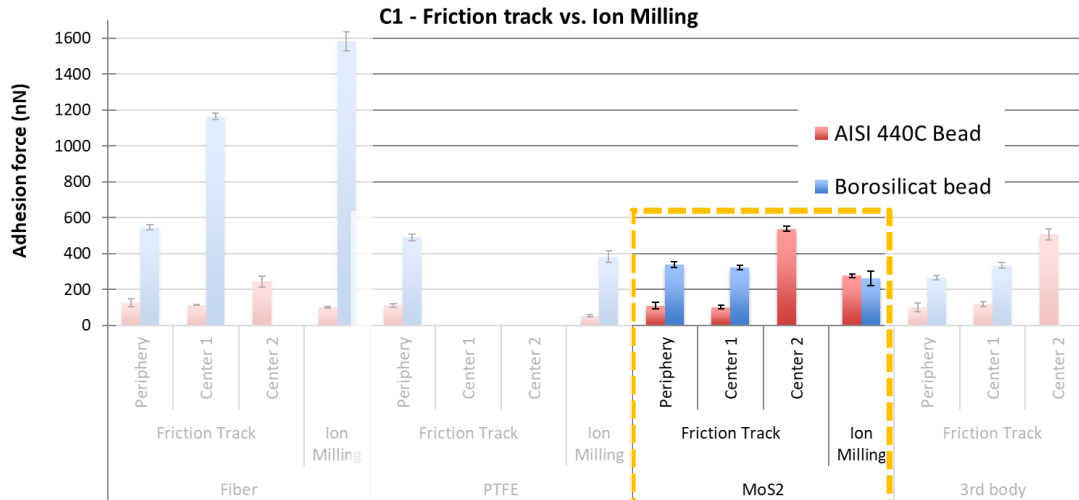
► PTFE adheres more to glass than to steel



► High adhesion of fiber towards steel

► PTFE to glass as much as to steel

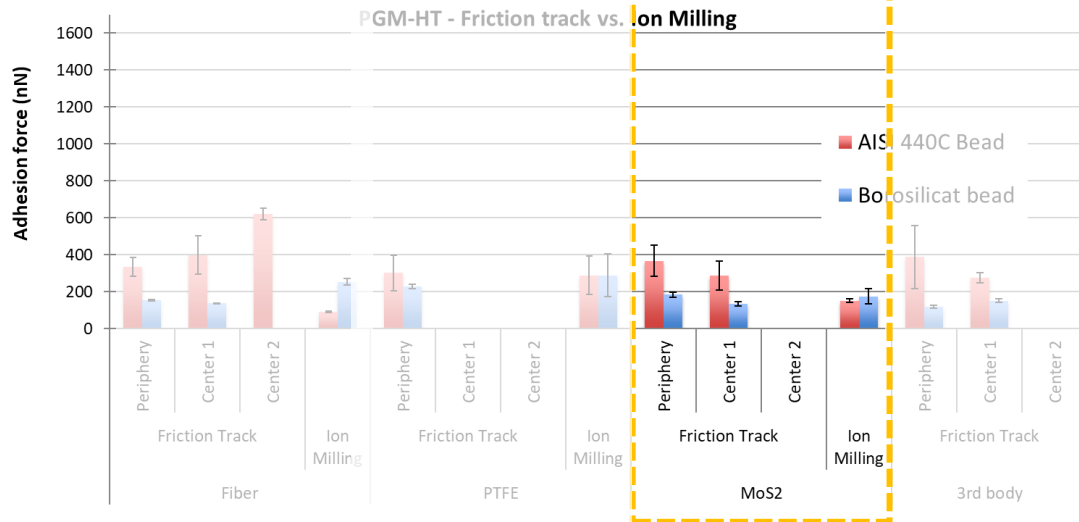
Results of adhesion investigations



▶ behaves as expected: High adhesion of glass bead on glass fiber

▶ PTFE adheres more to glass than to steel

▶ MoS2 adheres more to steel in the most stressed region, otherwise adheres more to PTFE

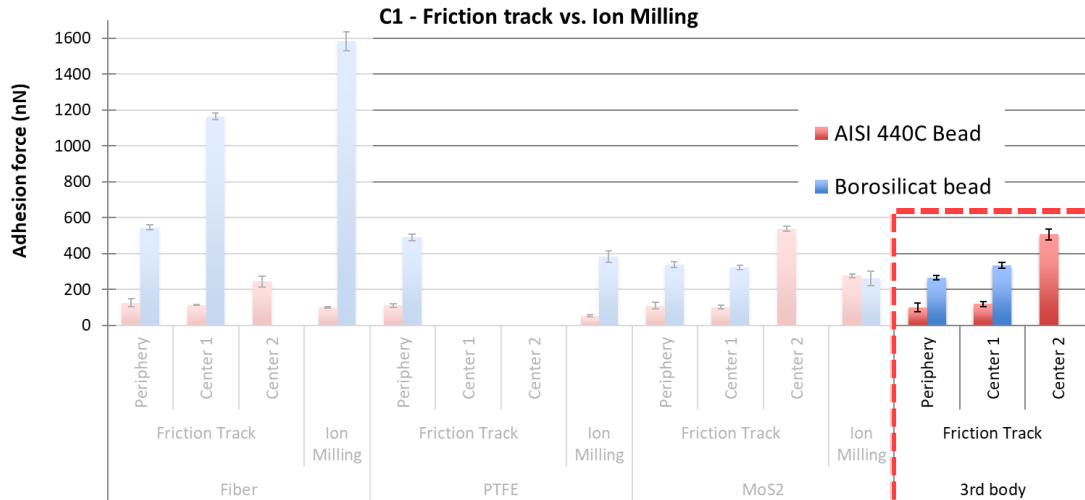


▶ High adhesion of fiber towards steel

▶ PTFE adheres to glass as much as to steel

▶ MoS2 adheres more to steel, *no accessible data in the most stressed region*

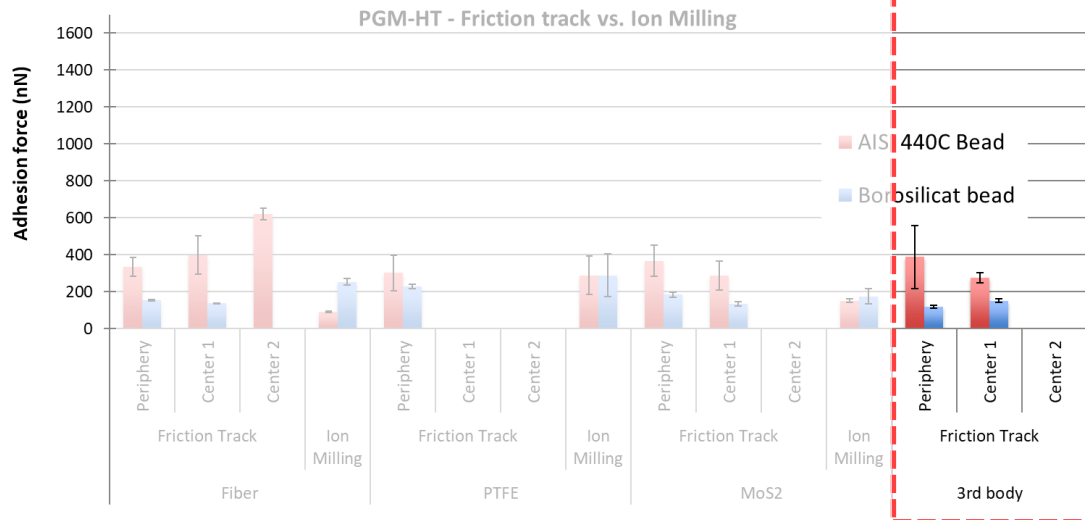
Results of adhesion investigations



▶ behaves as expected: High adhesion of glass bead on glass fiber

▶ PTFE adheres more to glass than to steel

▶ MoS2 and 3rd body adhere more to steel in the most stressed region, otherwise adheres more to PTFE

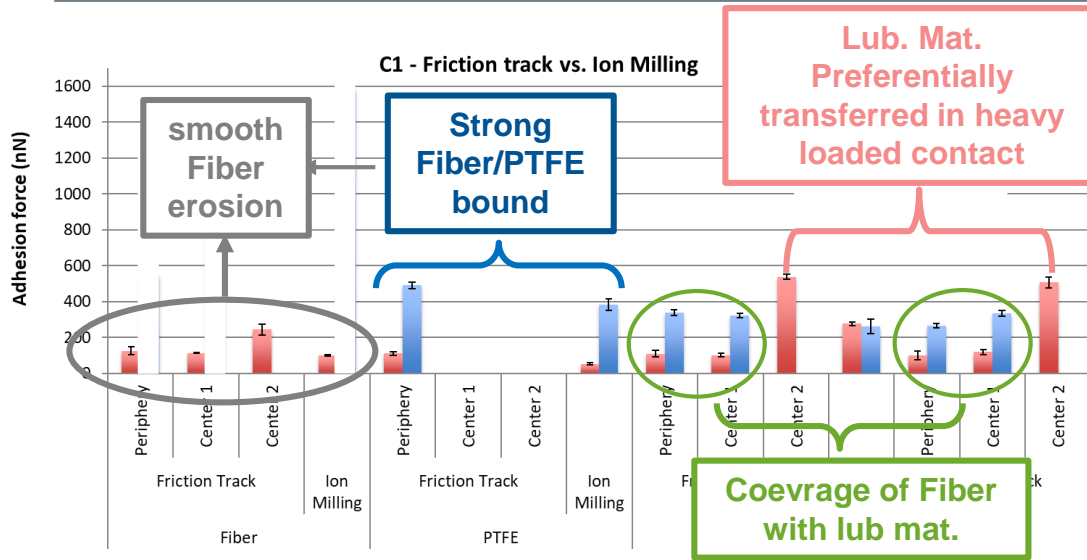


▶ High adhesion of fiber towards steel

▶ PTFE adheres to glass as much as to steel

▶ MoS2 and 3rd body adhere more to steel, *no accessible data in the most stressed region*

Results of adhesion investigations

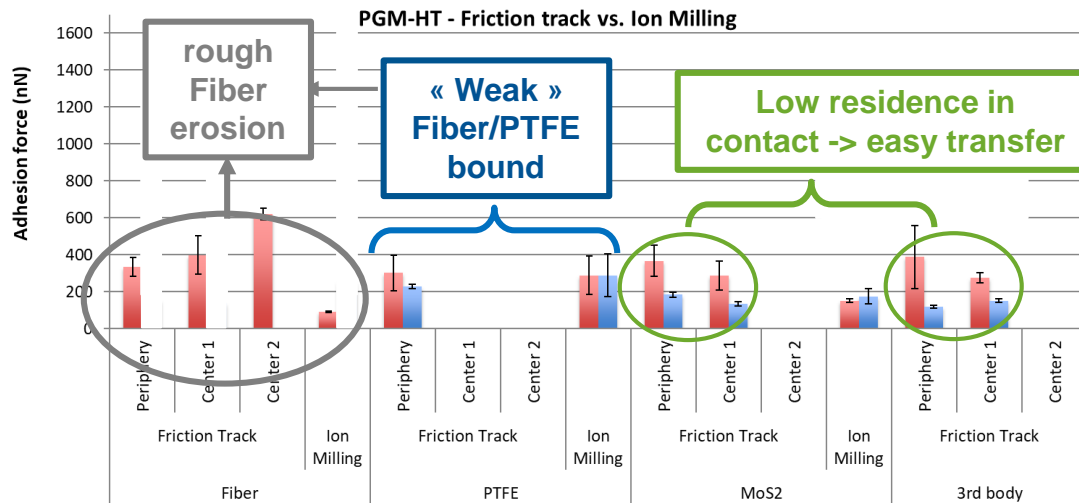


► behaves as expected: High adhesion of glass bead on glass fiber

► PTFE adheres more to glass than to steel

► MoS2 and 3rd body adhere more to steel in the most stressed region, otherwise adheres more to PTFE

Smooth transfer + self protection against large abrasive fiber particle formation by => few large particle & low instabilities



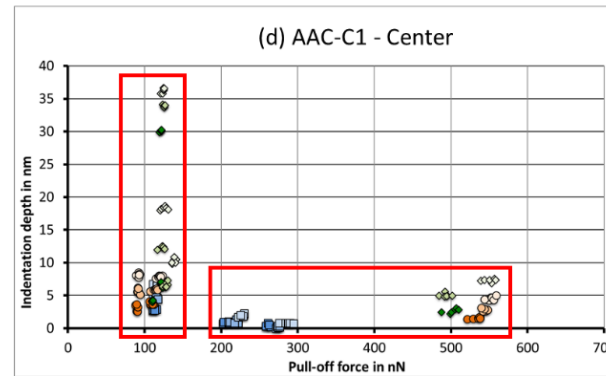
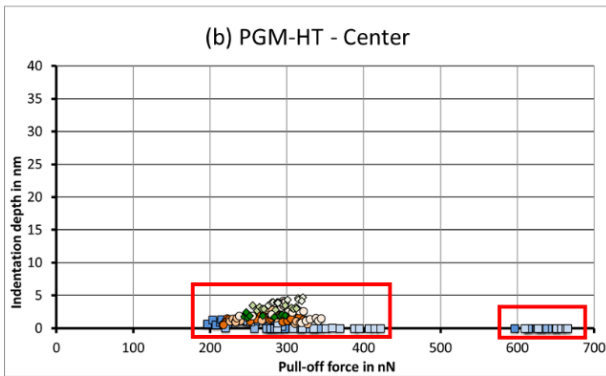
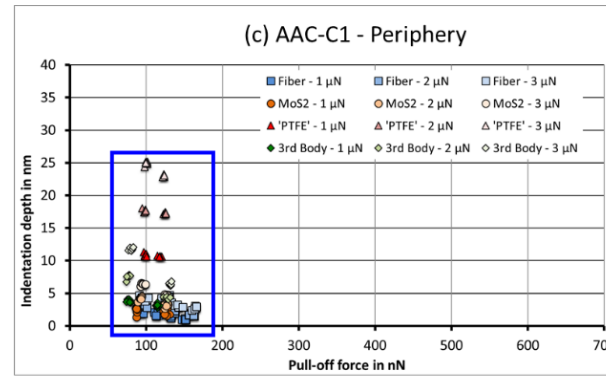
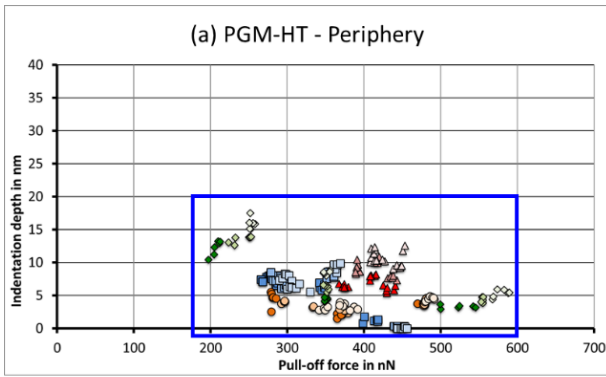
► High adhesion of fiber towards steel

► PTFE adheres to glass as much as to steel

► MoS2 and 3rd body adhere more to steel, *no accessible data in the most stressed region*

Good transfer but large abrasive fiber particle formation => Abrasion of transfer film & instabilities

Results of adhesion investigations

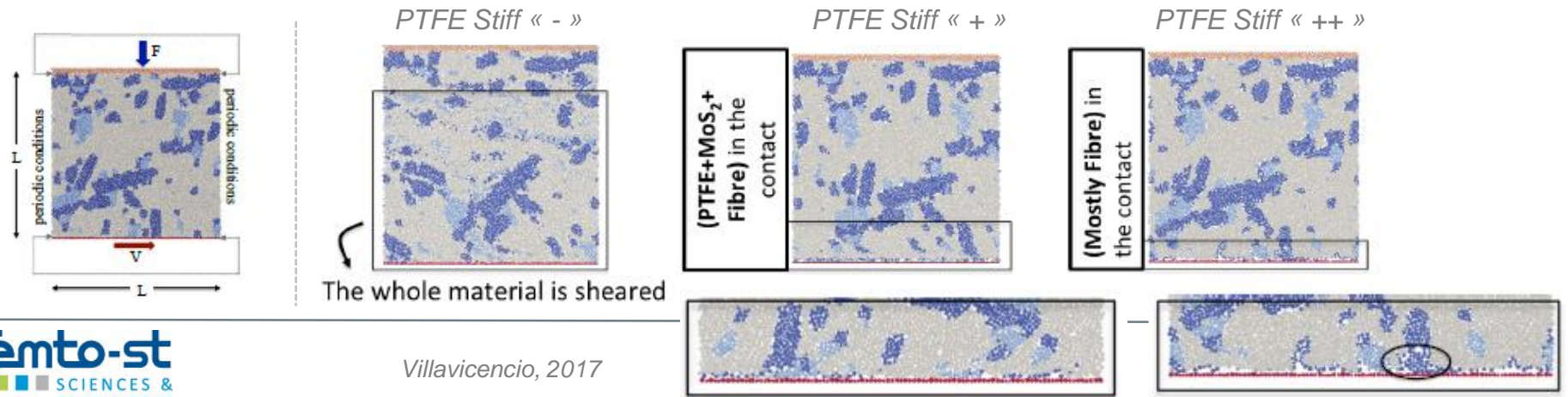


Indentation depth of similar range, slightly higher for C1

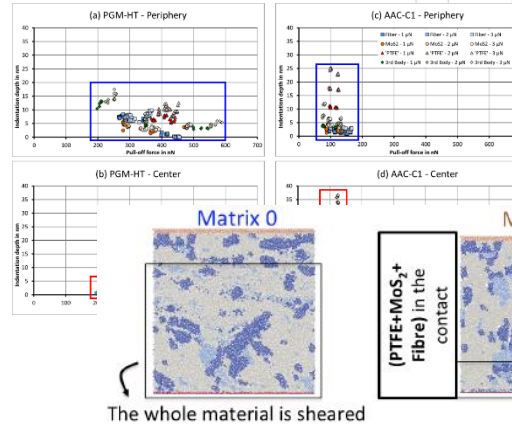
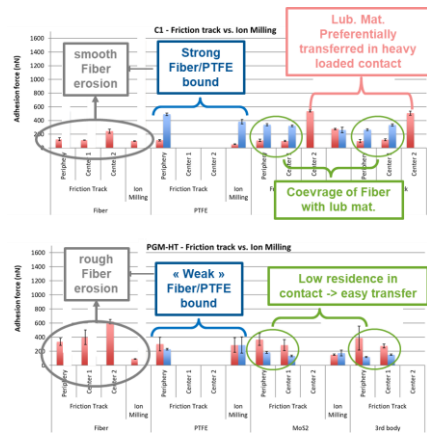
- ▶ Equivalent global elasticity?
- ▶ PTFE in PGM-HT stiffer?

Indentation depth higher for C1, for almost all components

- ▶ PGM-HT generates stiffer interfaces during friction?



Results of adhesion investigations



Krick, tribo. Int., 2016 & Deli, Wear, 1991
 Fragments of the hard filer in fluoropolymer composites may help modulating the mechanical properties of the transfer layer and improve wear resistance of the contact

Confirmation

C1

Smooth transfer + self protection against large abrasive fiber particle formation
 => few large particle & low instabilities

PGM-HT

Good transfer but large abrasive fiber particle formation
 => Abrasion of transfer film & instabilities