

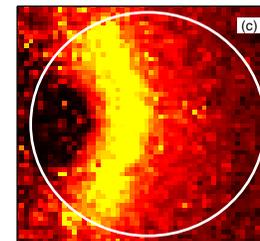
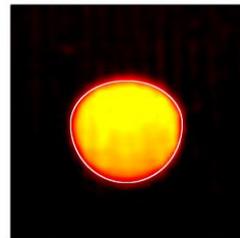
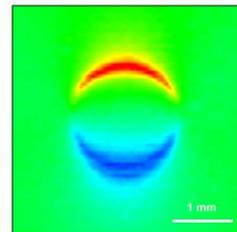
Approches locales du frottement d'élastomères



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ESPCI, Paris



Alexis Prevost & Elie Wandersman
Laboratoire Jean Perrin, Sorbonne Université



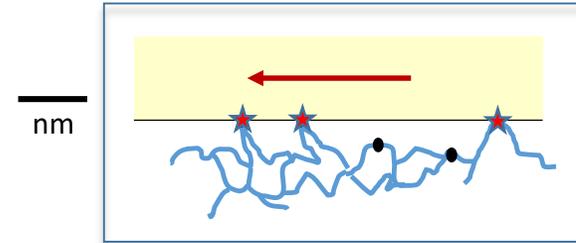
Frottement d'interfaces de contact en matière molle

Un problème de physique encore très ouvert

....Une grande variété d'échelles et de mécanismes

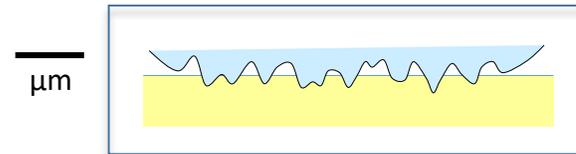
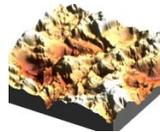
- Mécanismes dissipatifs
échelle moléculaire/atomique

Adsorption/désorption,
....



- Rugosités des surfaces

Interface multicontact



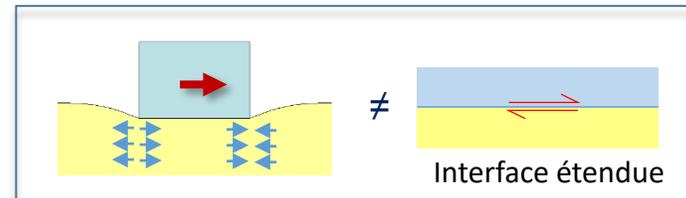
Géométrie des surfaces
Propriétés mécaniques (viscoélasticité) et adhésives

Aire de contact réelle \ll aire de contact apparente

- Taille finie des contacts

Hétérogénéités des champs de contraintes et déformation

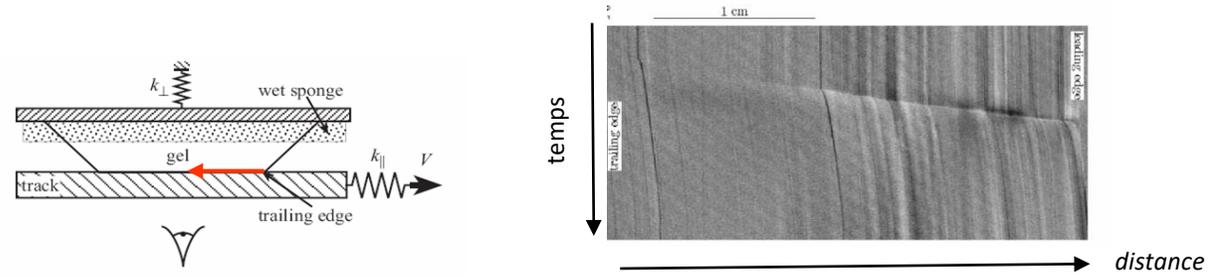
mm-cm



.....description locale des mécanismes de frottement?

Imagerie de contact des systèmes de la matière molle (caoutchoucs, gels,...)

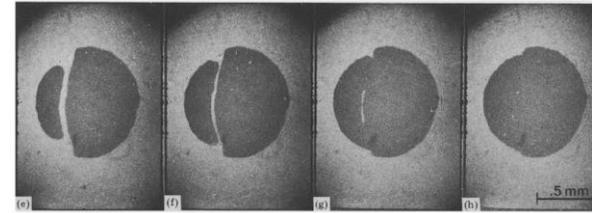
- **Fracture et frottement**



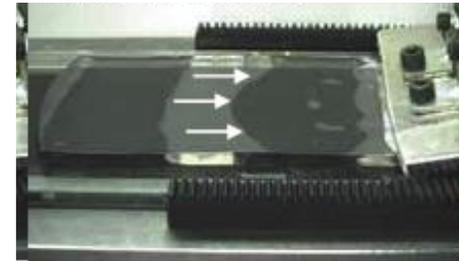
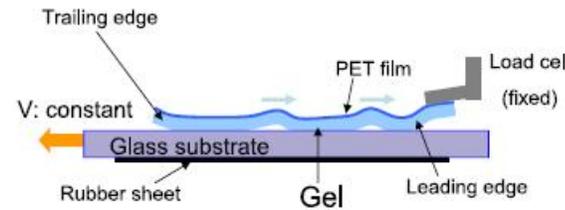
Baumberger *et al*, PRL (2002)

- **Instabilités de frottement**

Ondes de Schallamach



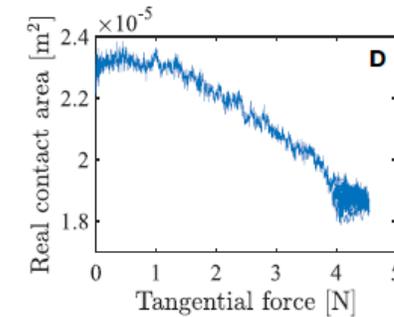
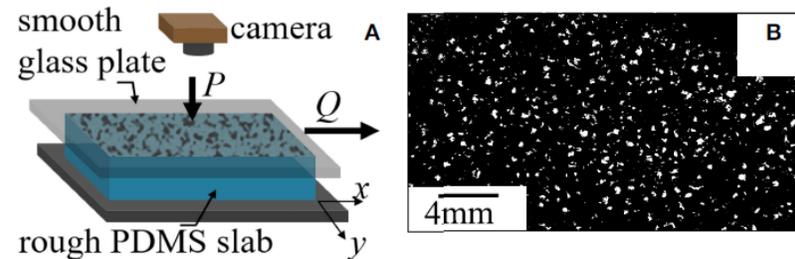
Barquins & Roberts *J Phys D* (1986)



Yamaguchi *et al*, J Phys Cond Matter (2009)

- **Frottement d'interface rugueuses**

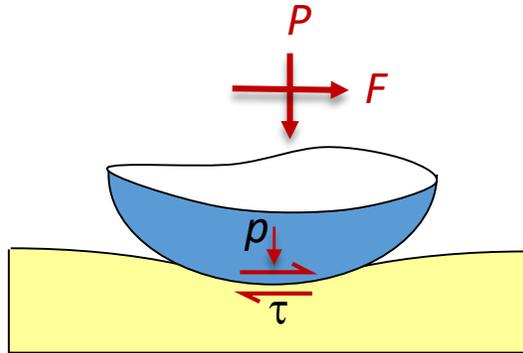
Mesure de l'aire de contact réelle



Scheibert *et al*, Frontiers in Mech Engng, 2020

Pour quels problèmes ?

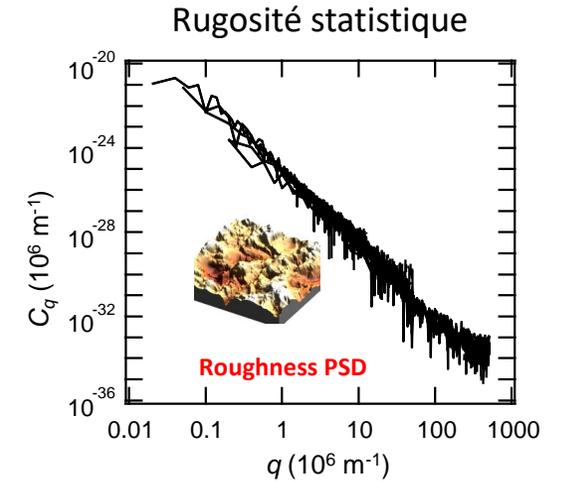
- Loi locale de frottement local $\tau(p)$



Rugosité des surfaces

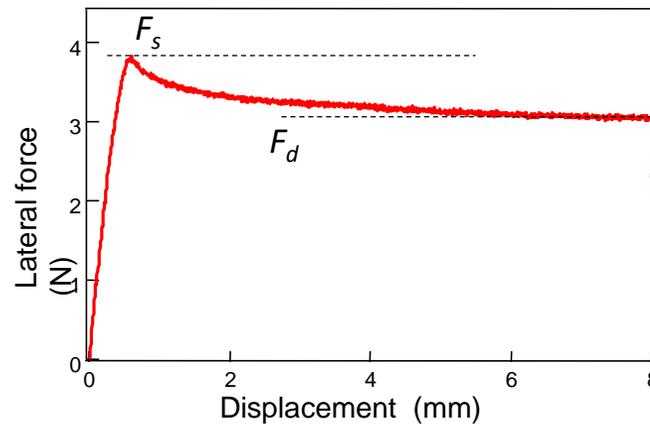
Théorie: Approches en champ moyen
Description spectrale des surfaces

Validation expérimentale ?
Effets locaux ?



- Régimes instationnaires : stiction, sauts de vitesse,....

Mise en glissement
d'un contact statique adhésif

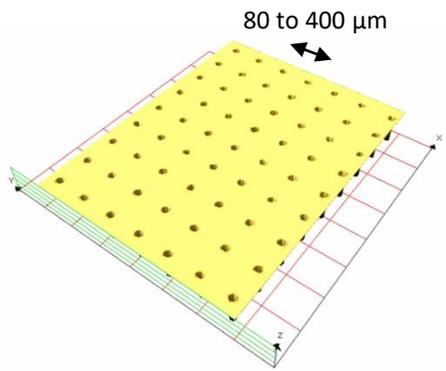
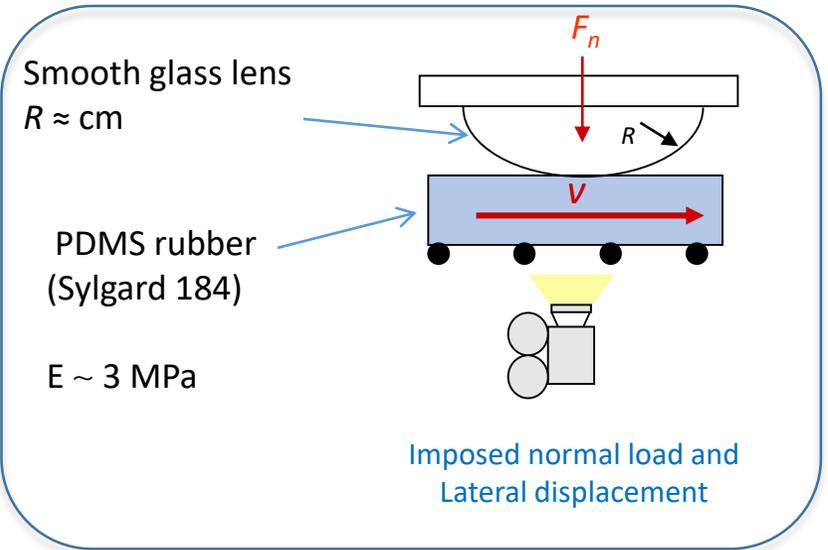


Au niveau macroscopique: frottement statique et dynamique

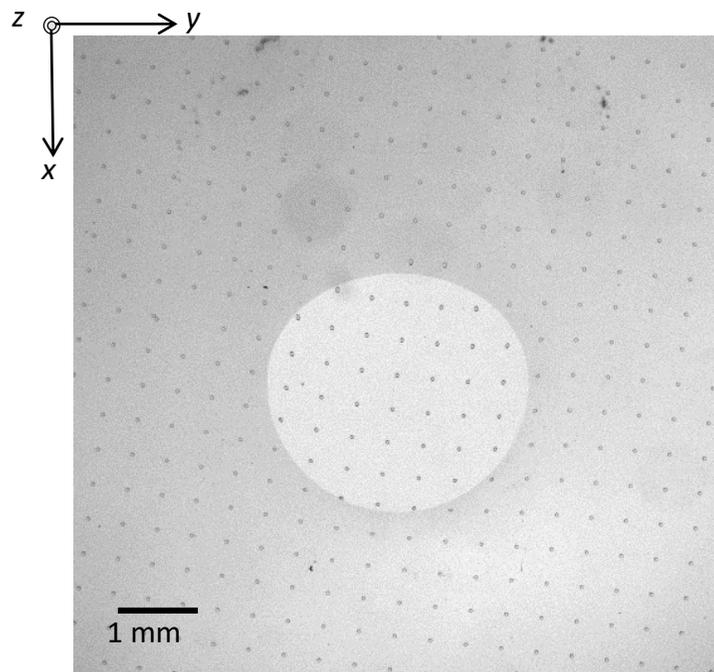
Hétérogénéités de glissement, précurseurs de glissement

Rôle de l'adhésion ?

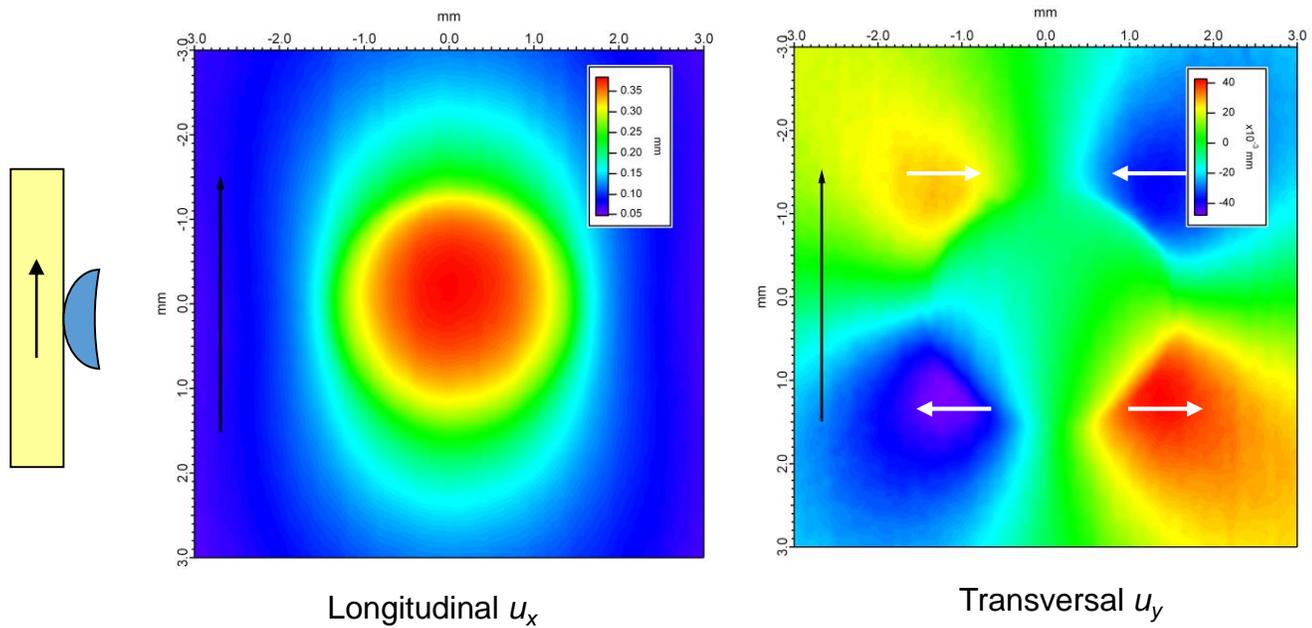
Mesure des champs de déplacements dans des interfaces verre/ élastomères



Surface marked PDMS substrate



Déplacements à la surface de l'élastomère

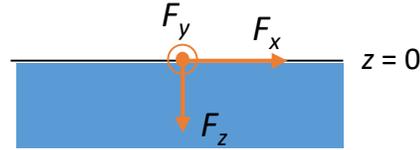


Résolution spatiale $\approx 10 \mu\text{m}$
Précision $< 1 \mu\text{m}$
(régime stationnaire)

A. Chateauminois *et al Eur. Phys. J. E* **27** (2008)
D.T. Nguyen *et al J. Adhesion* **87** (2011)

Inversion des champs de déplacements

- Elasticité linéaire : Tenseur de Green's



$$\begin{bmatrix} u_x \\ u_y \\ u_z \end{bmatrix} = \begin{bmatrix} G_{xx} & G_{xy} & 0 \\ G_{yx} & G_{yy} & 0 \\ 0 & 0 & G_{zz} \end{bmatrix} \begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} \quad G_{ij}(E, x, y) : \text{Green's functions}$$

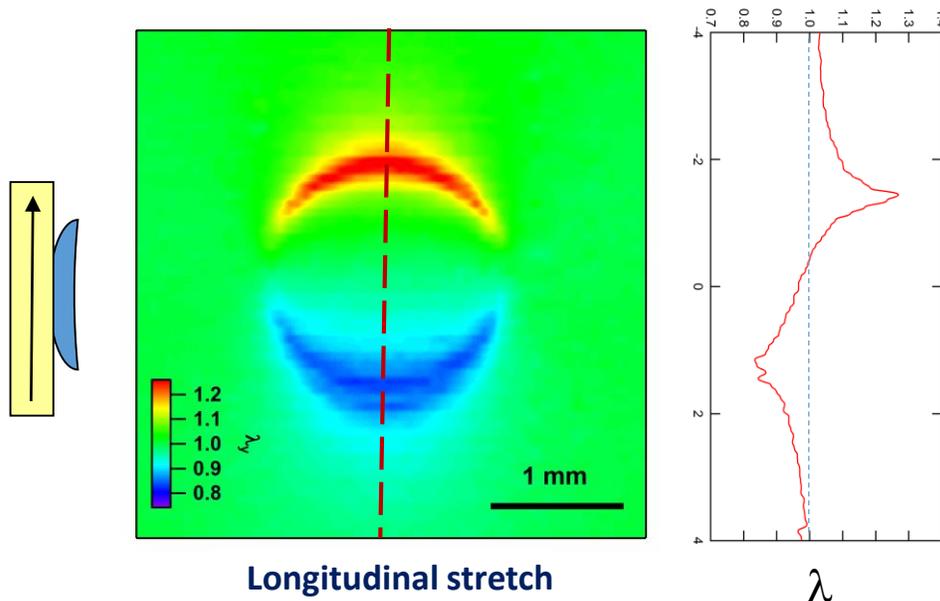
Matériaux incompressibles, $\nu=0.5$: découplage entre les directions normales et latérales

Lateral displacements

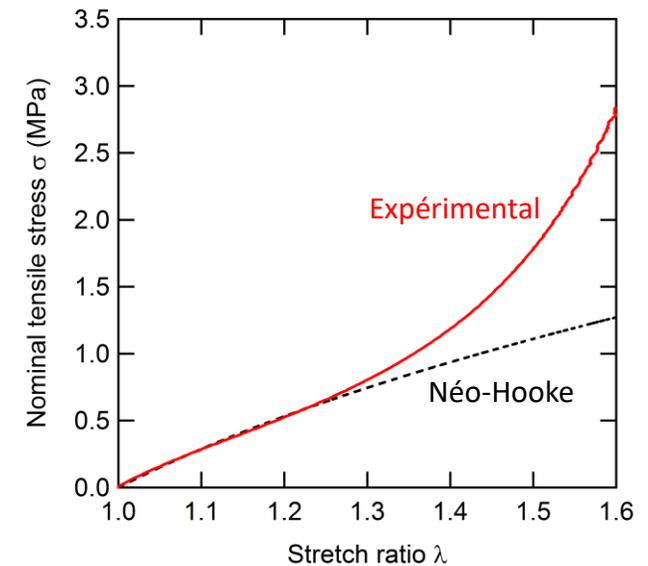
Vertical displacement

$$\begin{aligned} u_i &= G_{ij} * \sigma_{jz} \\ u_{zz} &= G_{zz} * \sigma_{zz} \end{aligned} \quad i, j = x, y$$

- Expérimentalement : déformations finies!

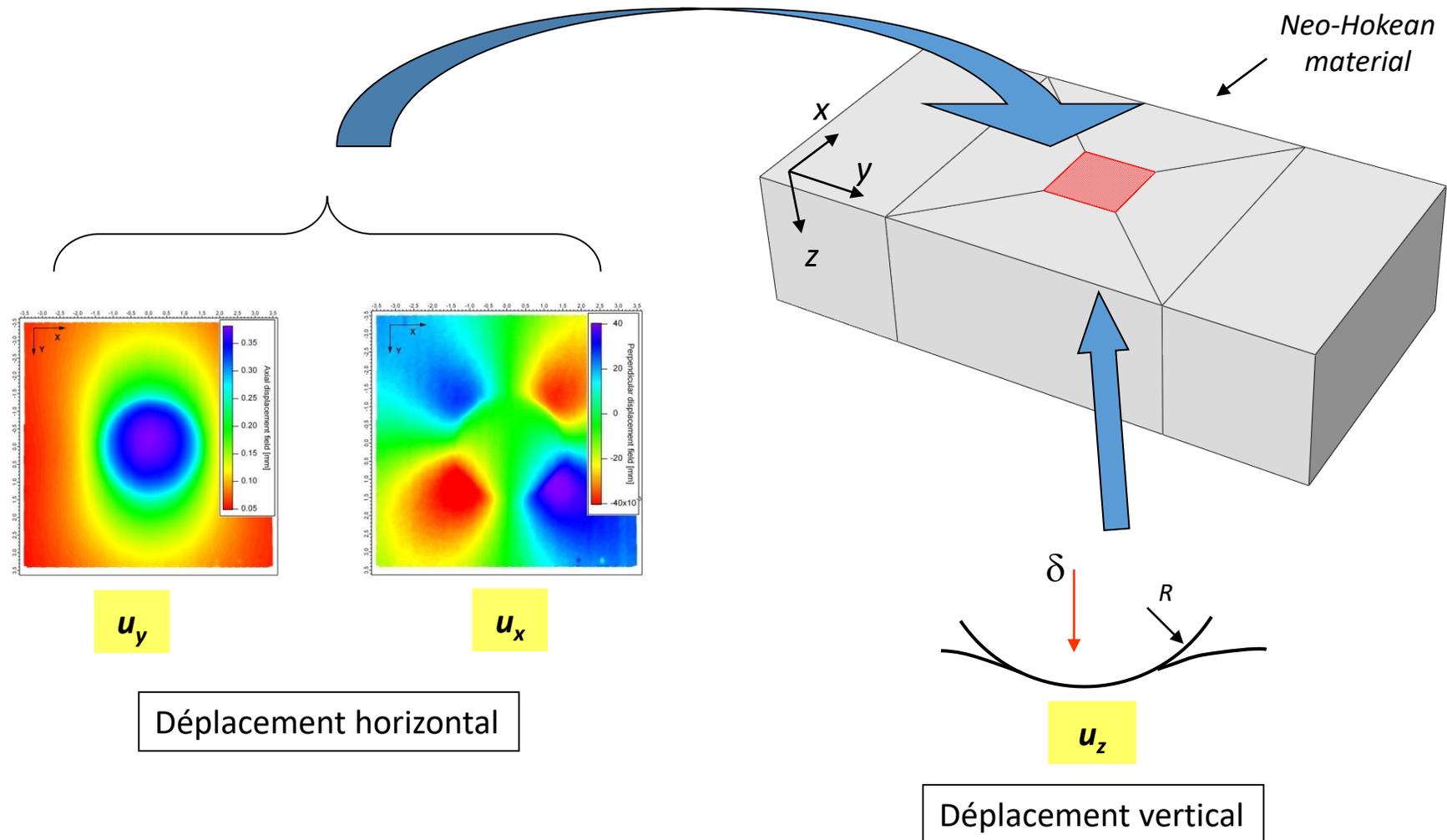


Courbe de traction du PDMS



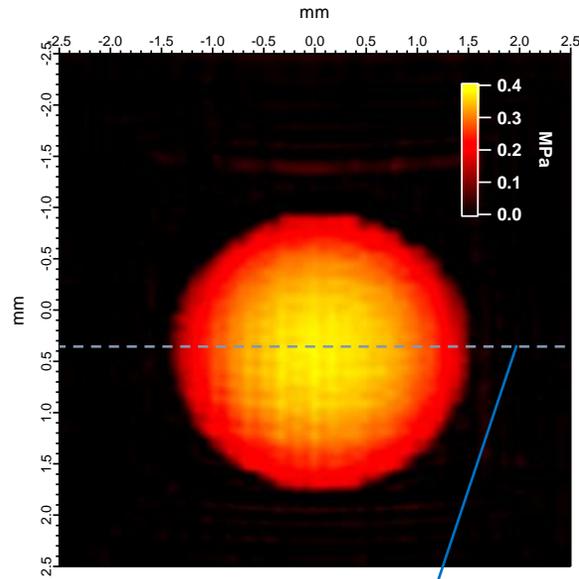
Inversion numérique des champs de déplacements

- Inversion par EF : prise en compte des non linéarités géométriques et de la loi de comportement.
- CL: déplacements mesurés en surface du PDMS.

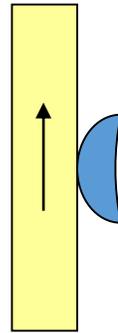


Contact lisse verre/PDMS

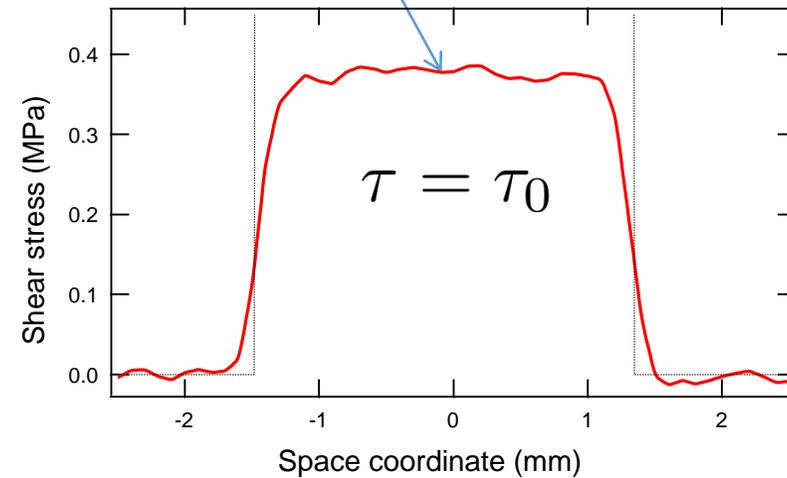
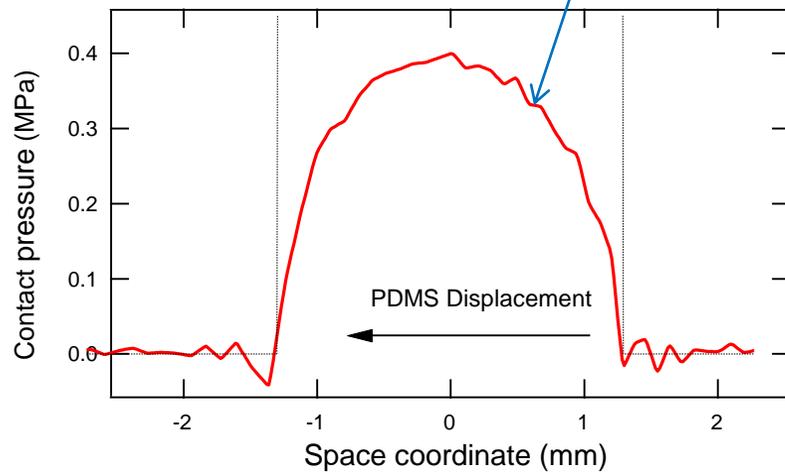
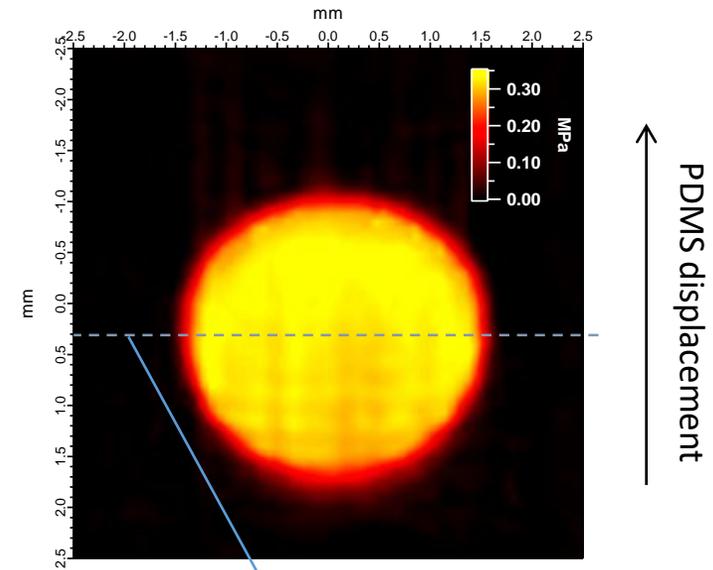
Contrainte normale



$R=9.3 \text{ mm}$, $P=1.4 \text{ N}$, $v=0.5 \text{ mm/s}$



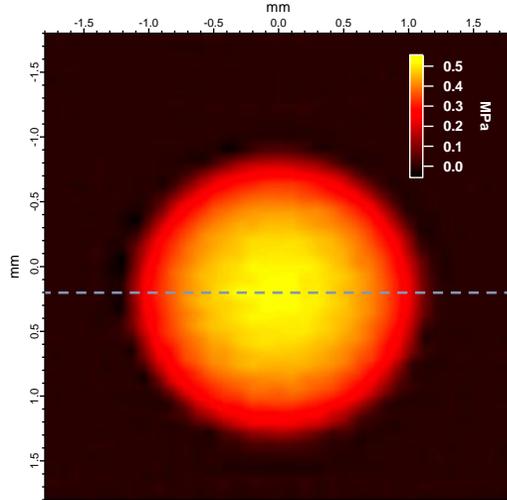
Cisaillement



Contrainte de frottement interfaciale indépendante de la pression de contact

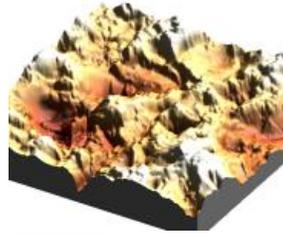
Contact verre rugueux/PDMS lisse

Pression de contact



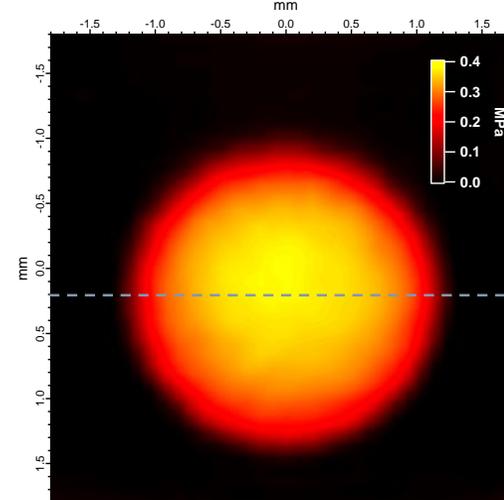
Rugosité gaussienne

Sand blasted glass lens

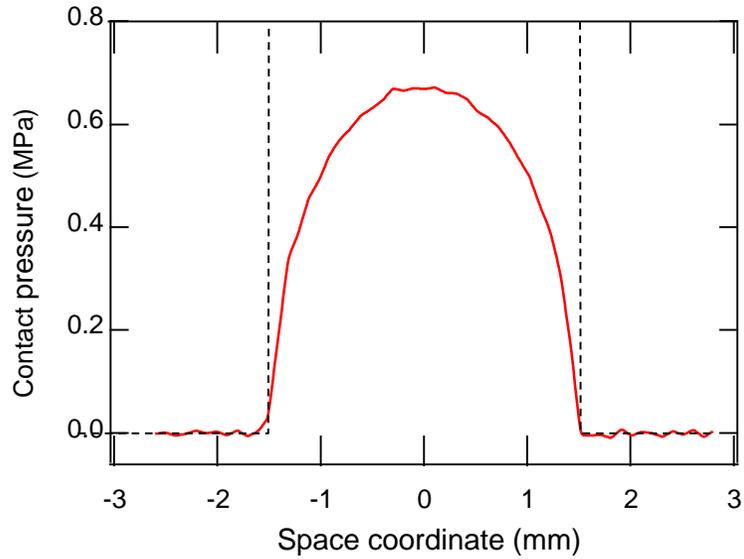
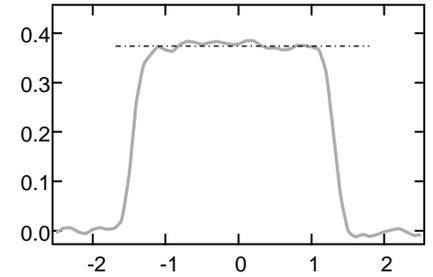


20μm

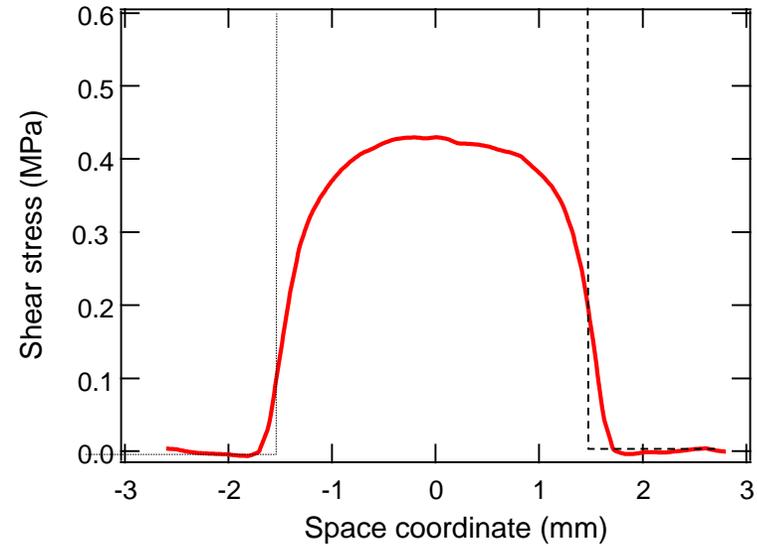
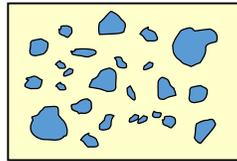
Contrainte de cisaillement



Contact lisse

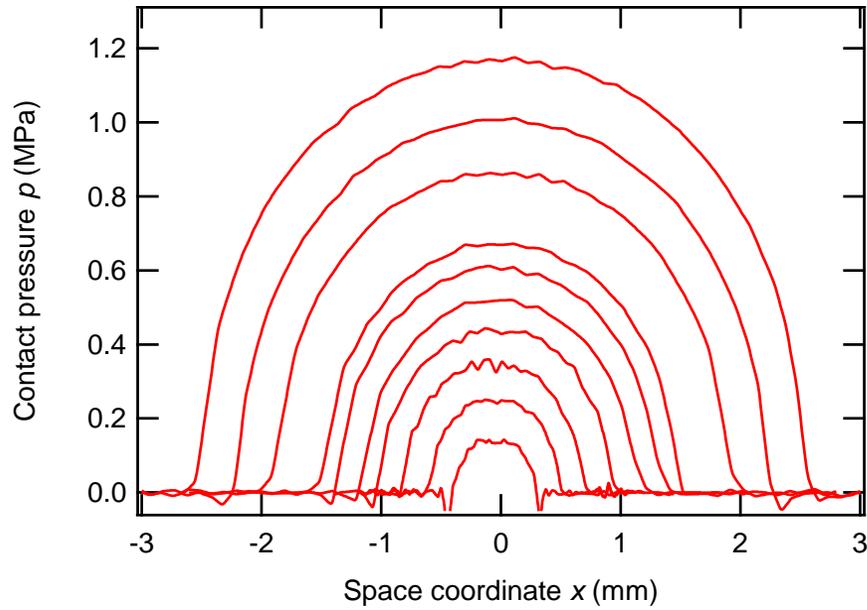


Interface multi-contacts



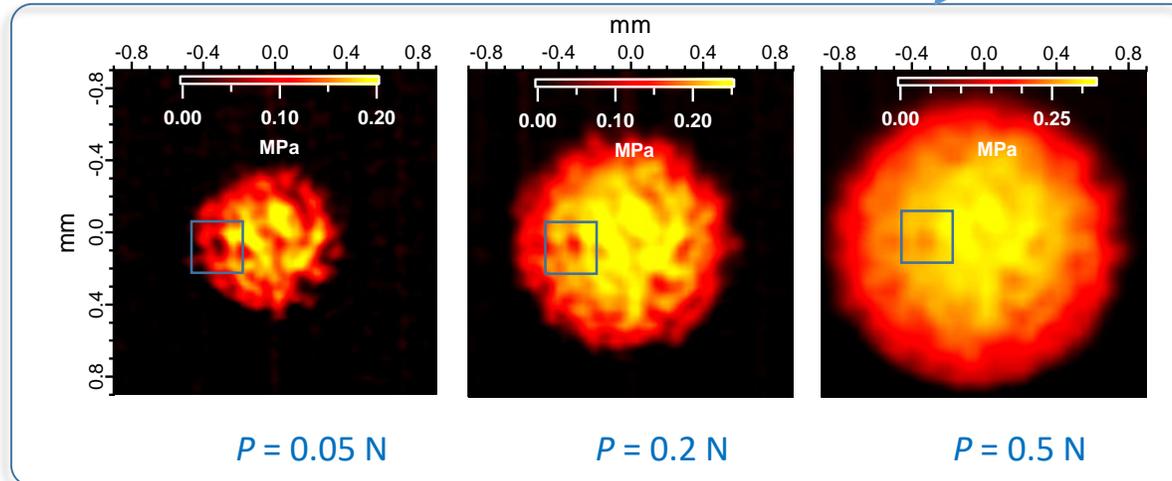
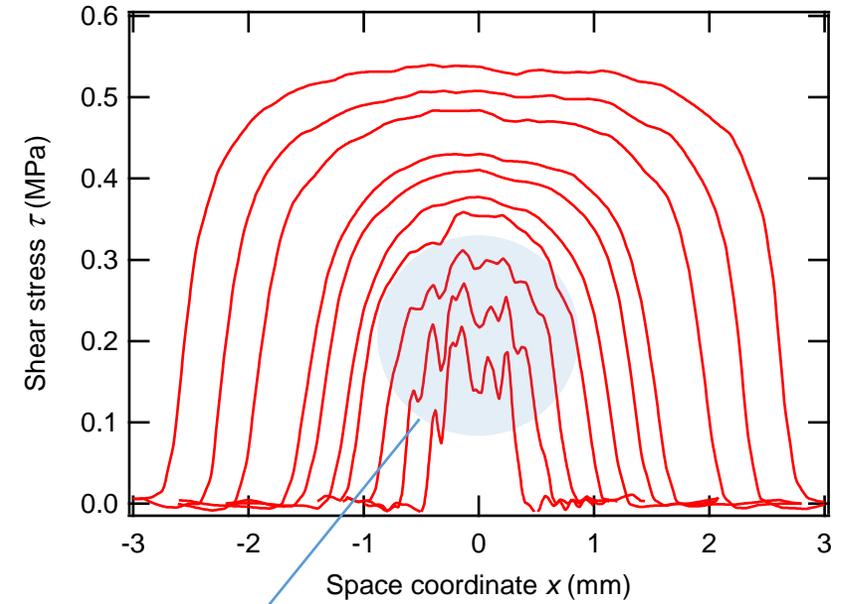
Contact rugueux: Profils de contrainte à charges normales croissantes

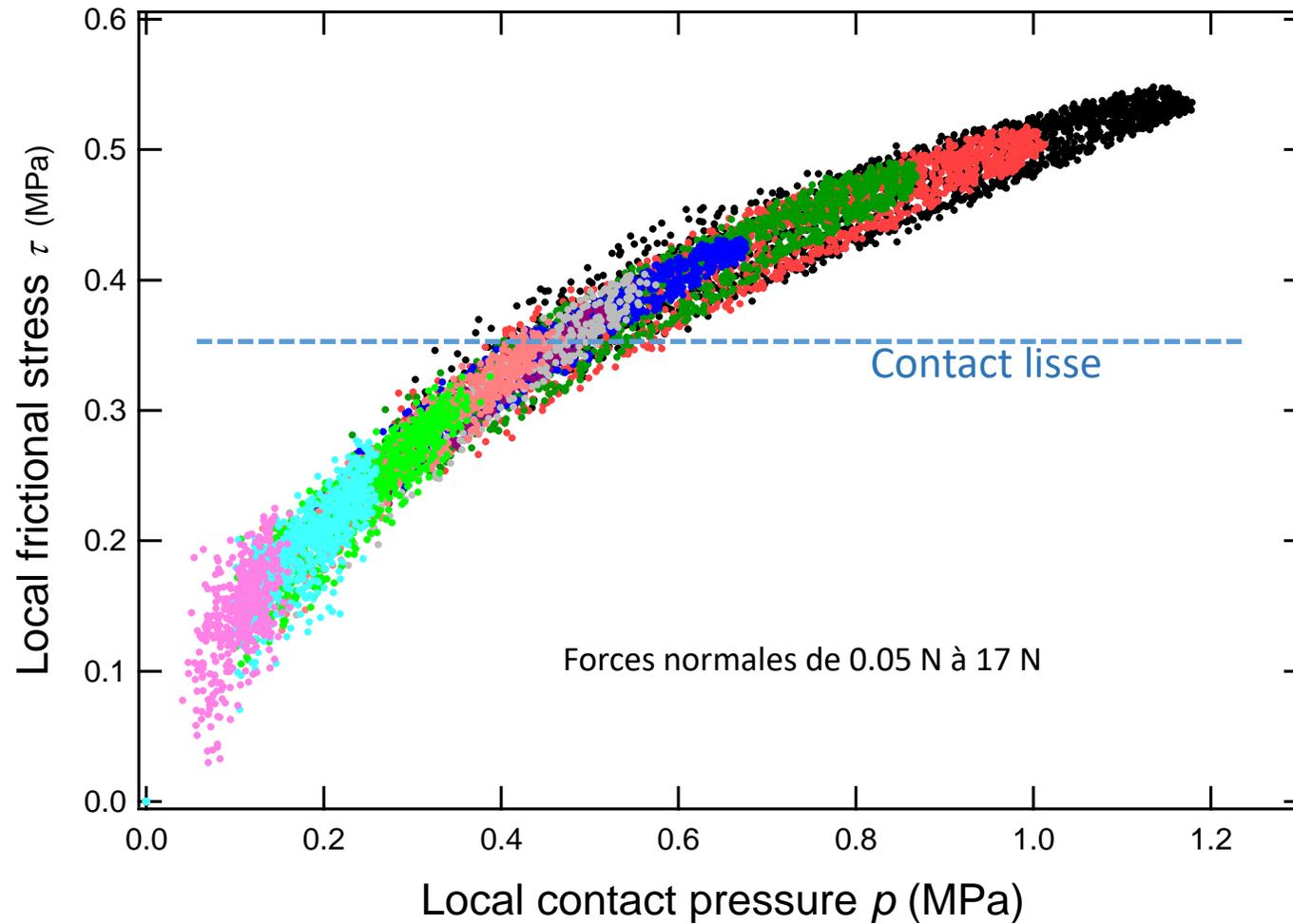
Pression de contact



Forces normales de
0.05 N à 17 N

Contrainte de cisaillement

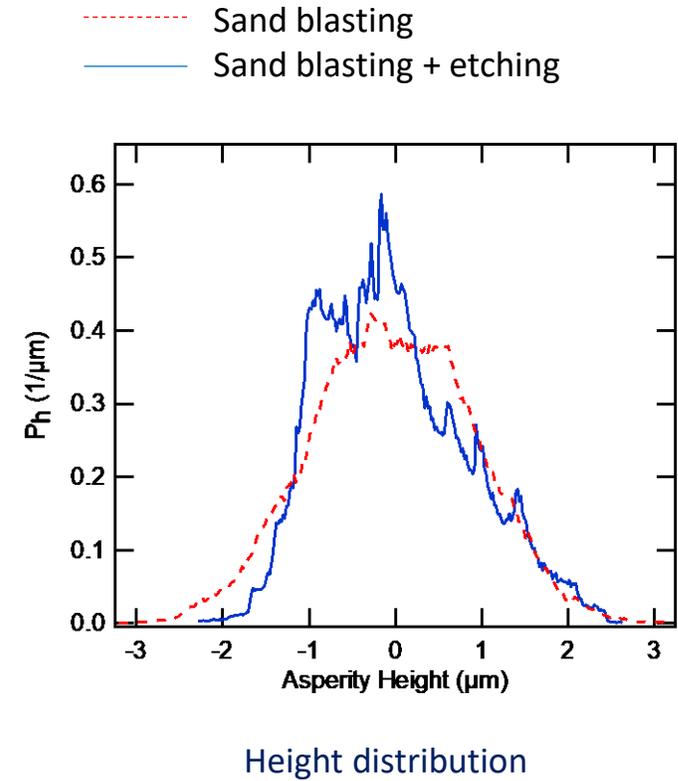
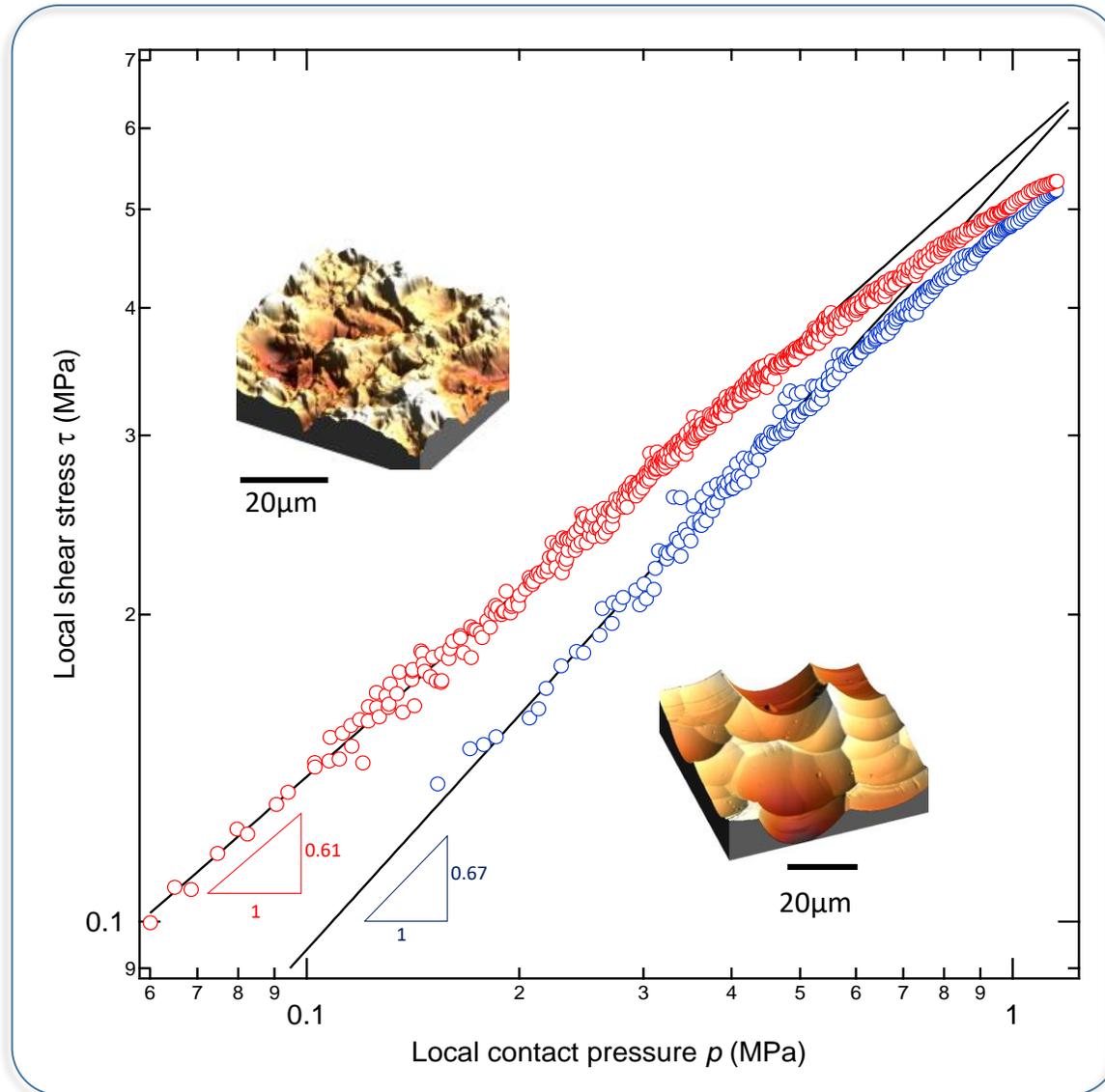




$$\tau \neq \mu p$$

.... Frottement non coulombien à l'échelle locale

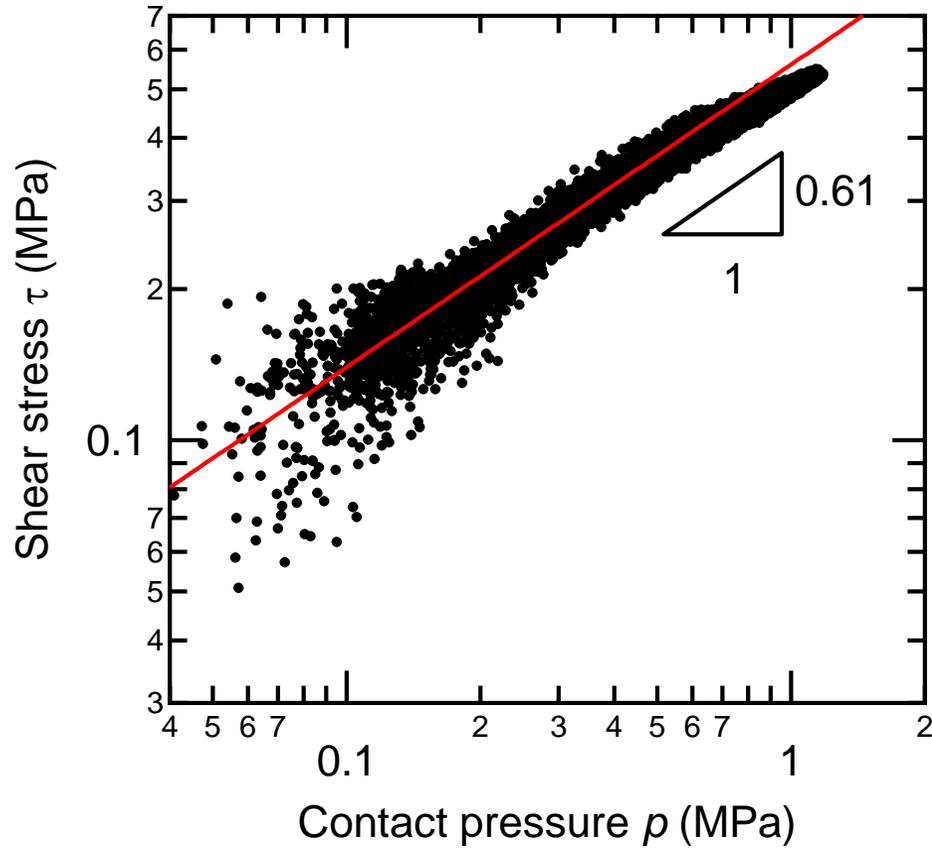
Rugosité gaussienne vs non gaussienne



Loi locale de frottement vs frottement macroscopique

Loi locale de frottement

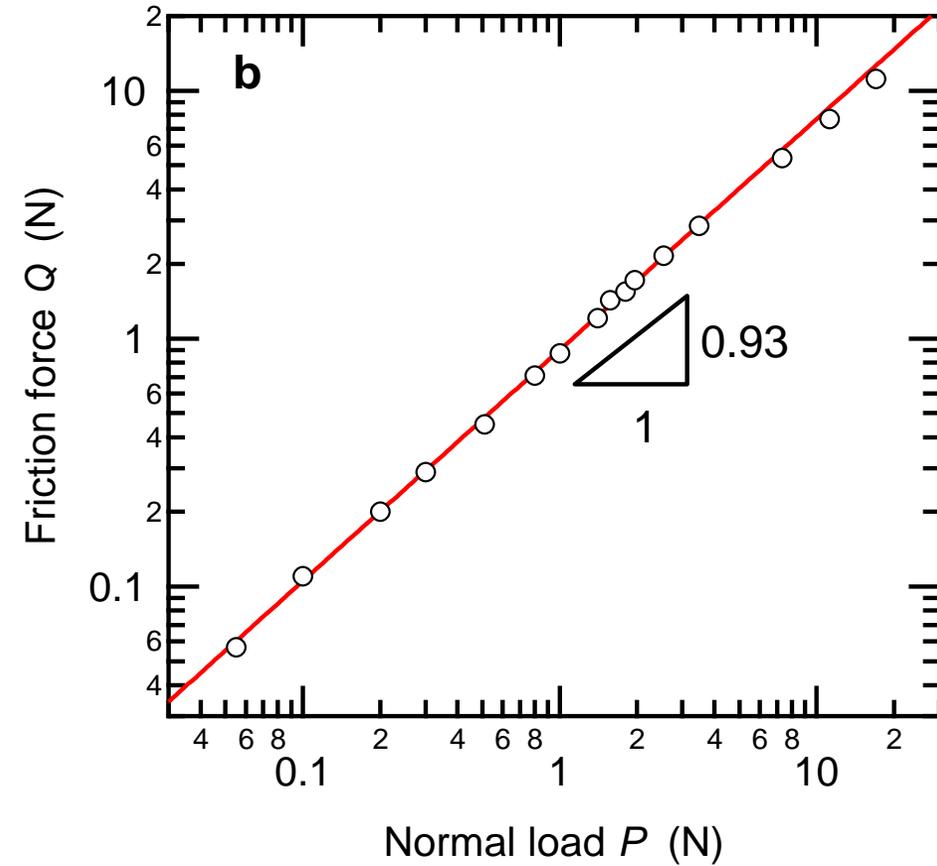
~ μm



$$\tau \propto p^n$$

Frottement macroscopique $F(P)$

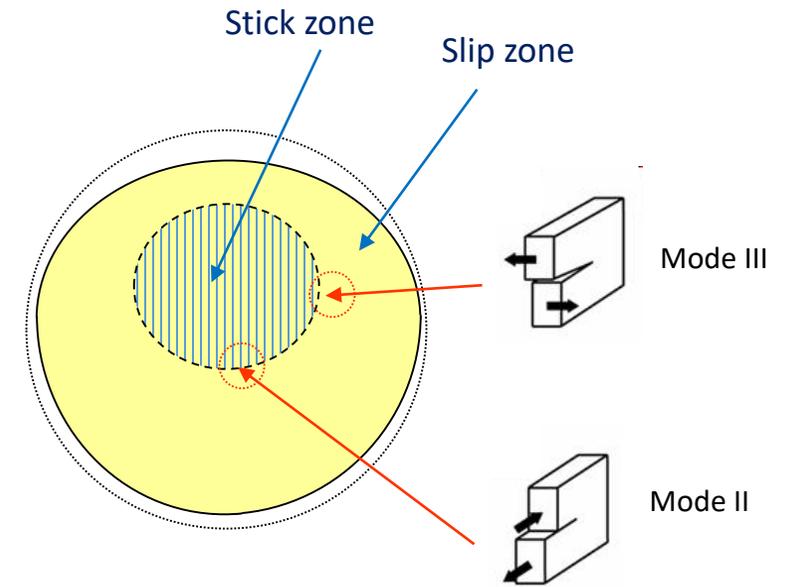
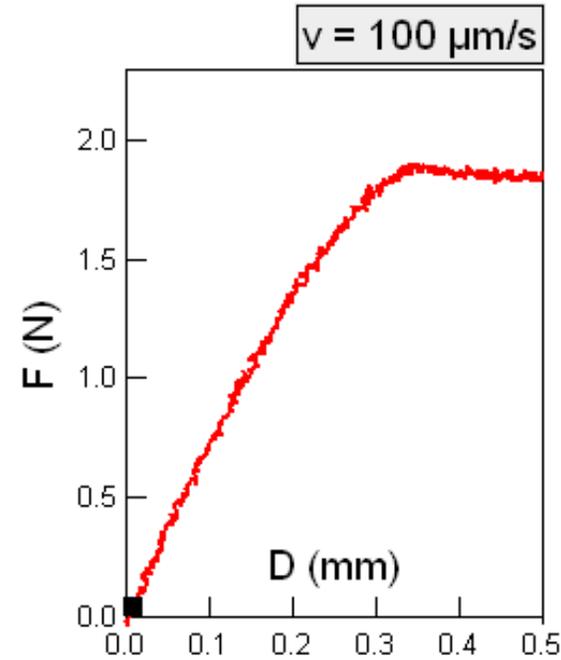
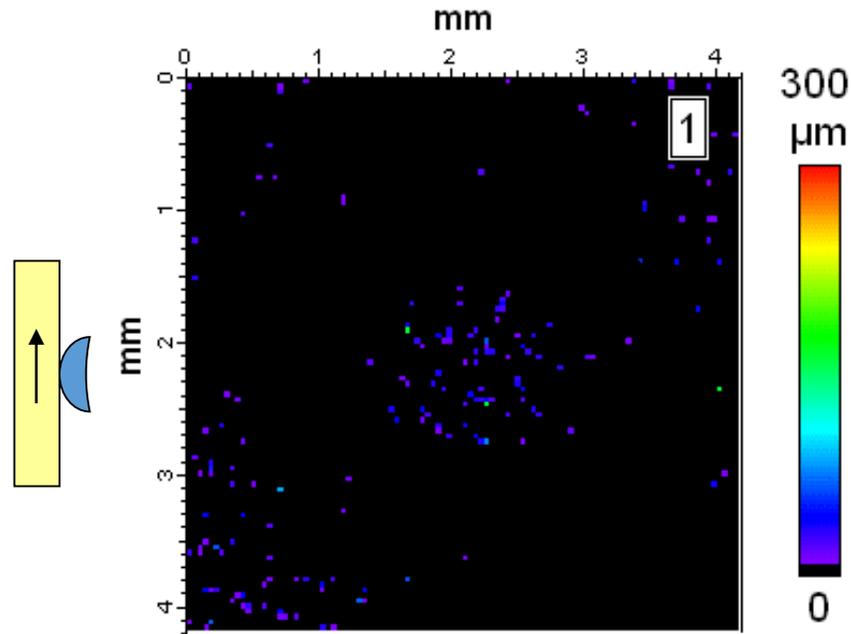
~mm



$$F \approx \mu P$$

Stiction de contacts adhésifs verre/PDMS

• Champ de déplacements à la surface du PDMS



Audry et al EPJE (2012)

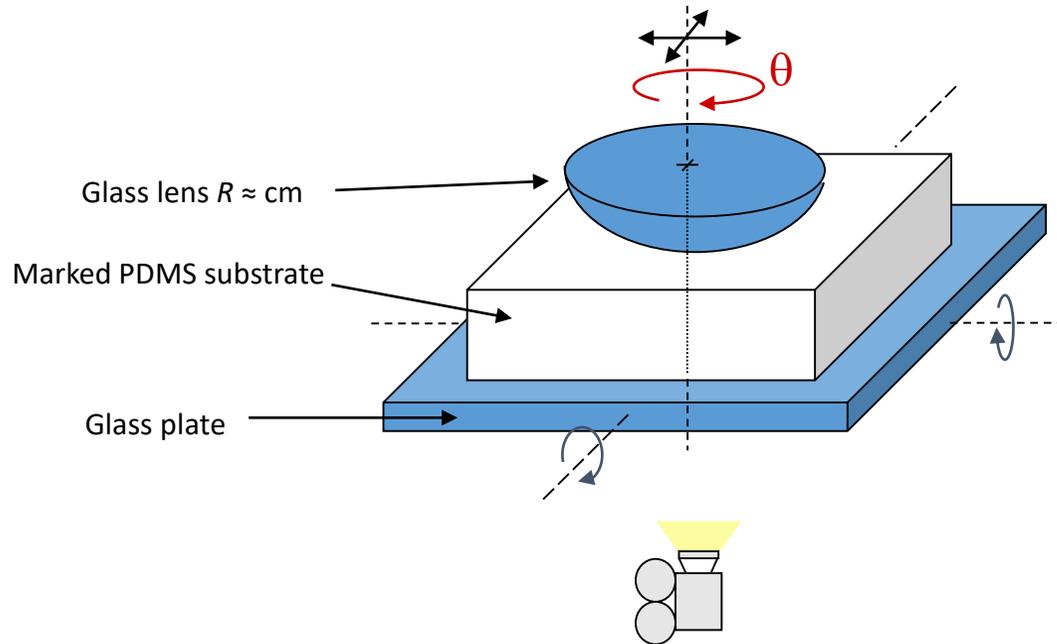
Stiction assimilable à la propagation d'une fracture interfaciale

..... Rupture d'adhésion en présence de frottement ?

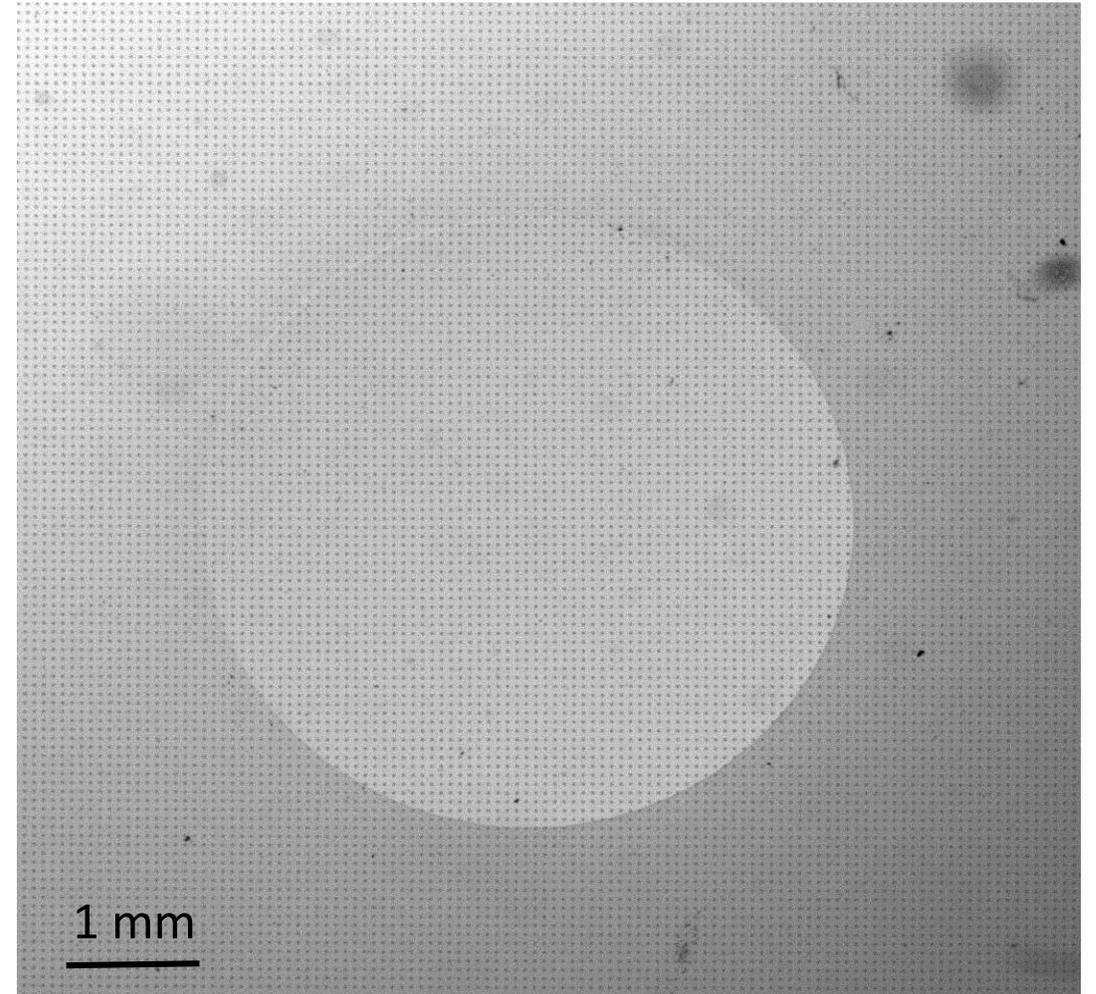
Une nouvelle configuration expérimentale : les contacts en torsion

✓ Symétrie cylindrique

✓ Ouverture de fracture en Mode III

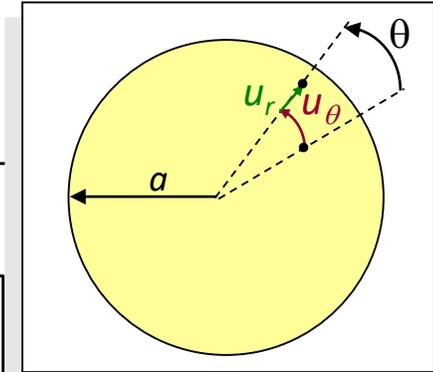
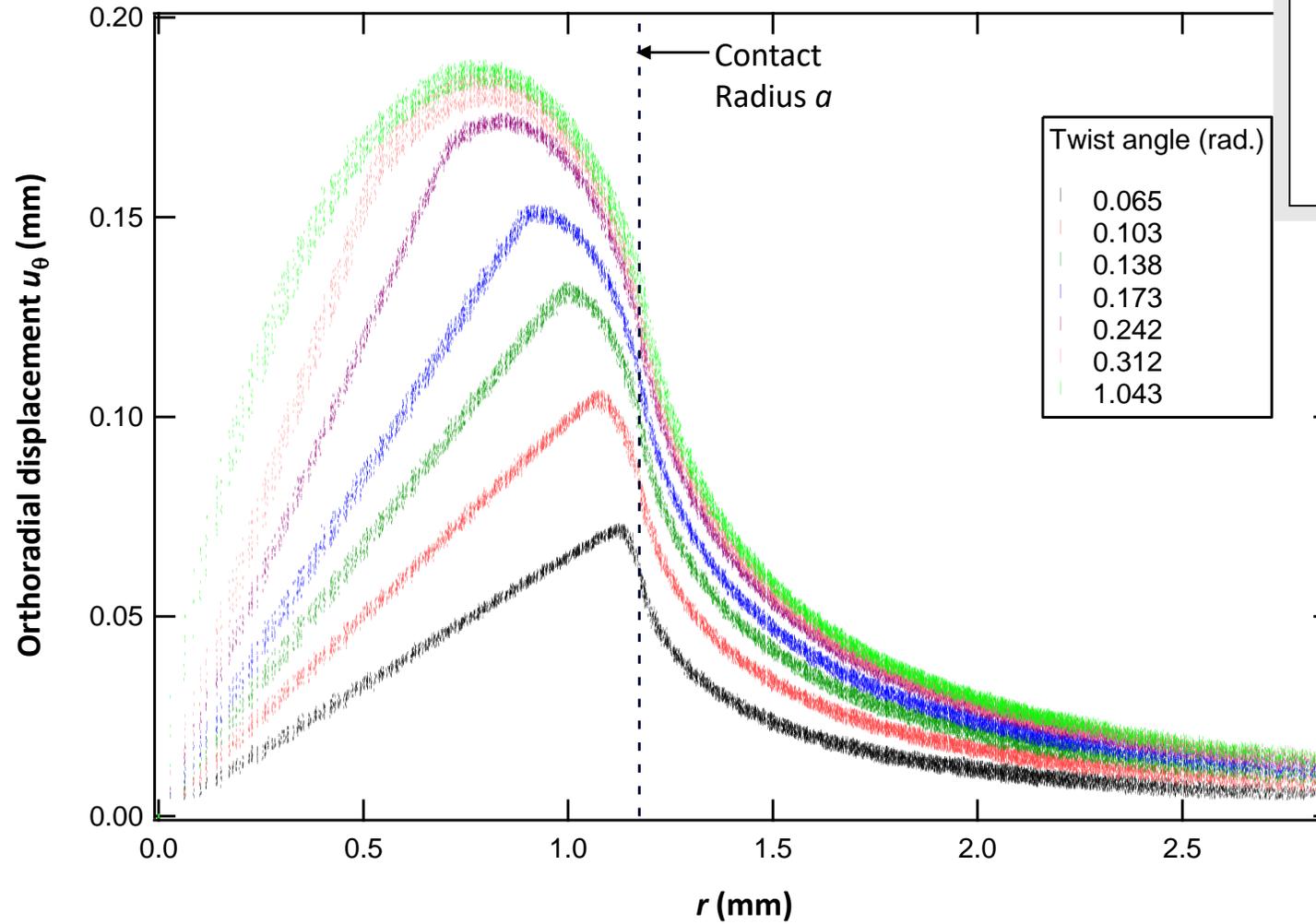


Imposed - normal displacement
- angular displacement



Déplacements pendant la phase de stiction

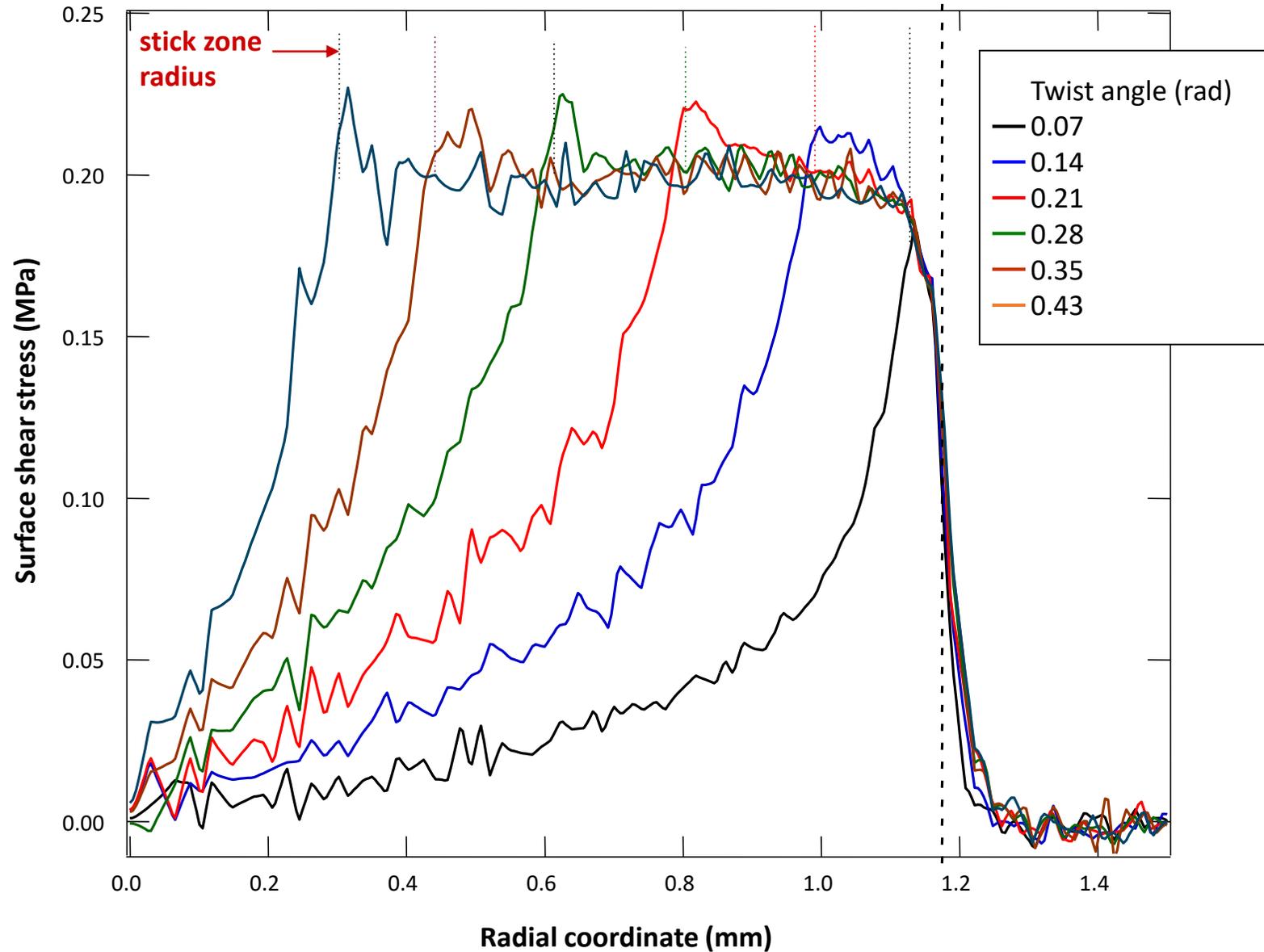
- Déplacement radial $u_r \sim 0$
- Déplacement orthoradial u_θ :



Distribution de la contrainte de frottement

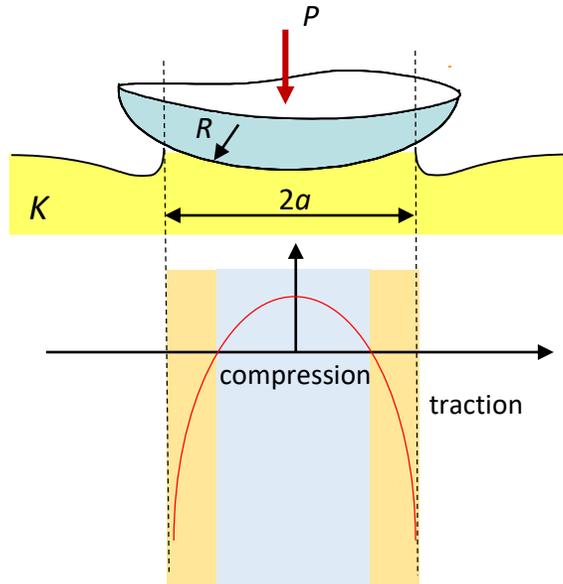
- Inversion du champ de déplacement orthoradial

$\theta = 0.1 \text{ deg. /s}$



Contact normal adhésif

Bord du contact assimilé à une fracture (Mode I)



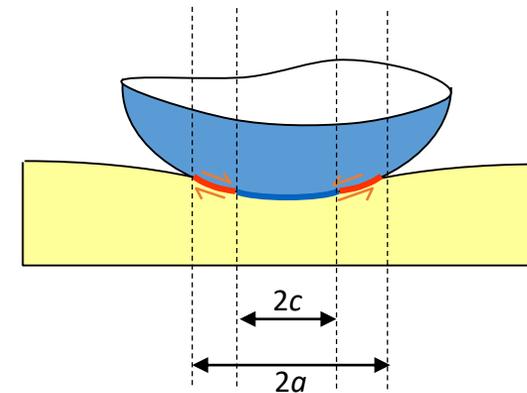
Critère d'équilibre de Griffith

$$w = \frac{(a^3 K / R - P)^2}{6\pi a^3 K}$$

w : énergie d'adhésion

Stiction

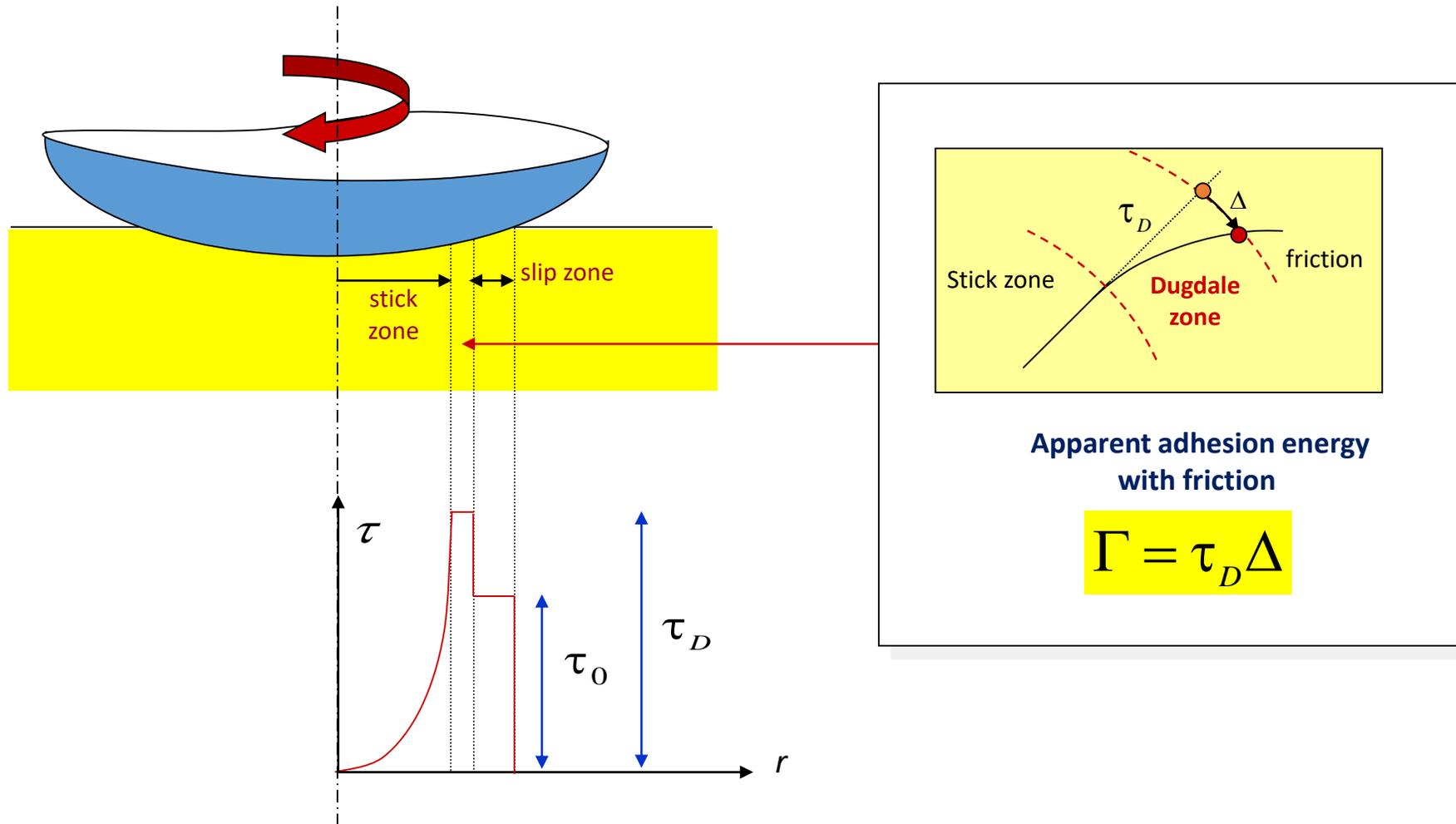
Fracture interfaciale (mode III)



Energie d'adhésion en présence de frottement??

Propagation d'une fracture interfaciale en stiction

Extension du modèle de Maugis-Dugdale en présence de frottement



Hyp: contrainte de cisaillement constante dans la zone de glissement

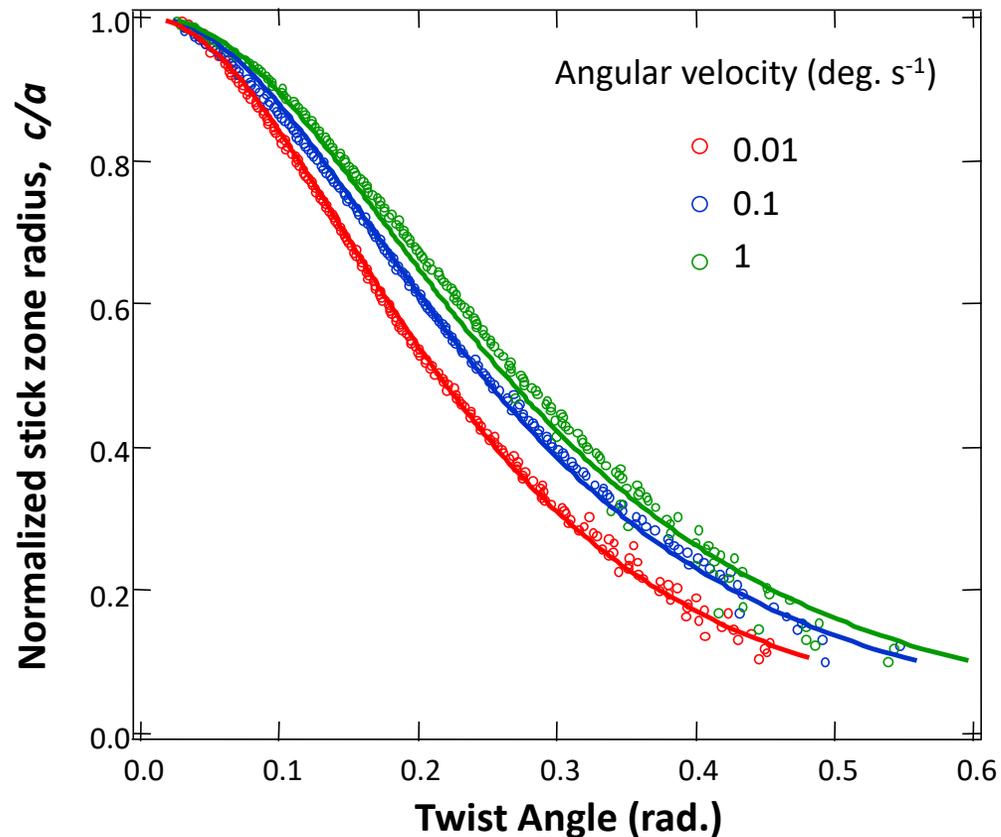
Energie apparente d'adhésion Γ

- Rayon de la zone collée en fonction de l'angle de rotation θ

$$2\theta - \alpha_0 \cosh^{-1} \frac{a}{c} = \sqrt{\frac{\pi\Gamma}{Gc}}$$

$$\alpha_0 = \frac{\tau_0}{G}$$

- Effets cinétiques lors de la stiction



$$\begin{aligned}\dot{\theta} = 0.01 \text{ deg/s} & \quad \Gamma \approx 30 \text{ mJ/m}^2 \\ \dot{\theta} = 0.1 \text{ deg/s} & \quad \Gamma \approx 130 \text{ mJ/m}^2 \\ \dot{\theta} = 1 \text{ deg/s} & \quad \Gamma \approx 300 \text{ mJ/m}^2\end{aligned}$$

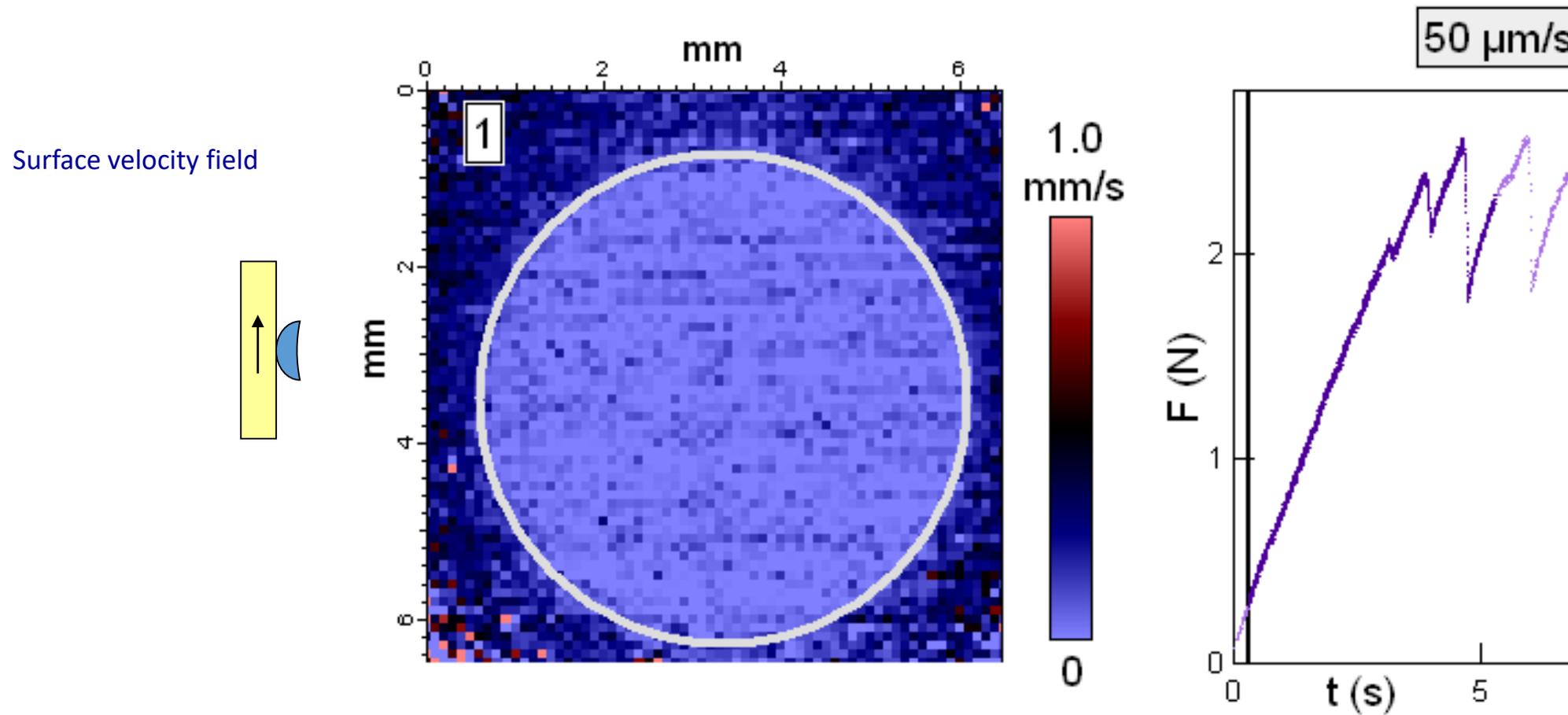


dépendance vis à vis de la
vitesse de la fracture

Dissipation viscoélastique

Stiction en présence de stick-slip

- Contact entre un substrat de PDMS et une lentille patternée



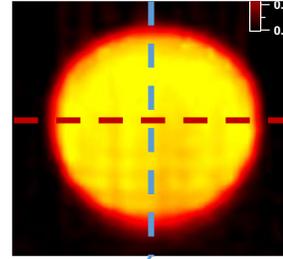
Crack like precursors to friction

Similar observations in other systems by J. Fineberg *et al.* and T. Bamberger *et al.*

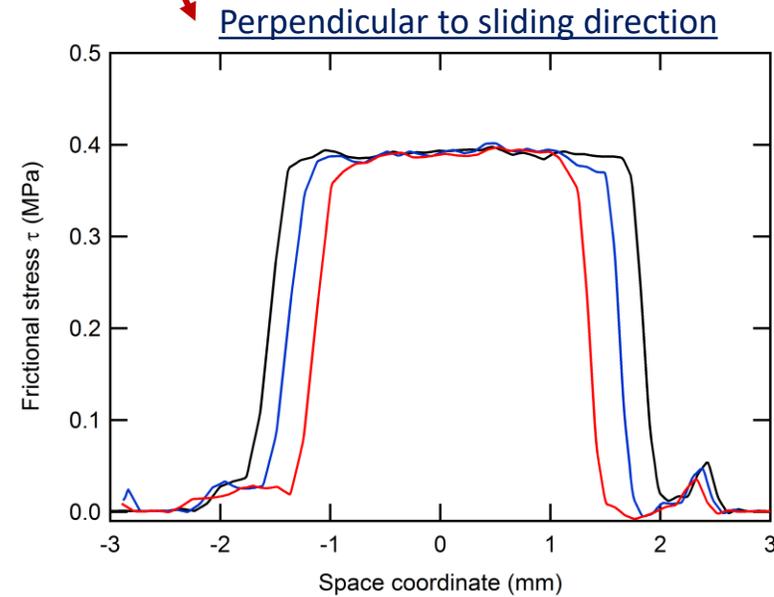
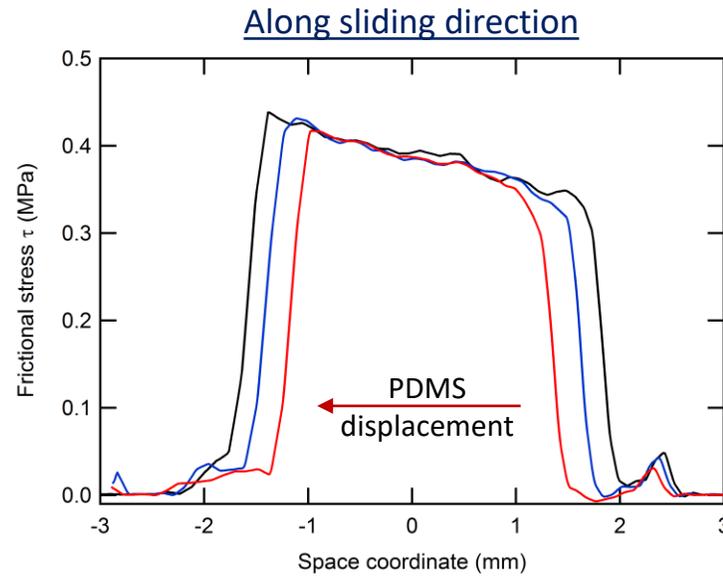
Frottement d'interfaces lisses verre / élastomère:

Modèles physiques de frottement

- Profils de cisaillement en surface



$R = 9.3 \text{ mm}$, $v = 0.5 \text{ mm s}^{-1}$



Normal load $P = 1.4, 2.3$ and 3.3 N

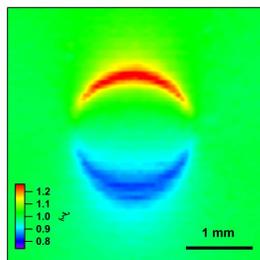
→ Gradient de la contrainte de frottement indépendant de la pression de contact

→ non attribuable à un effet viscoélastique

Relation entre la contrainte locale et le taux d'étirement local !

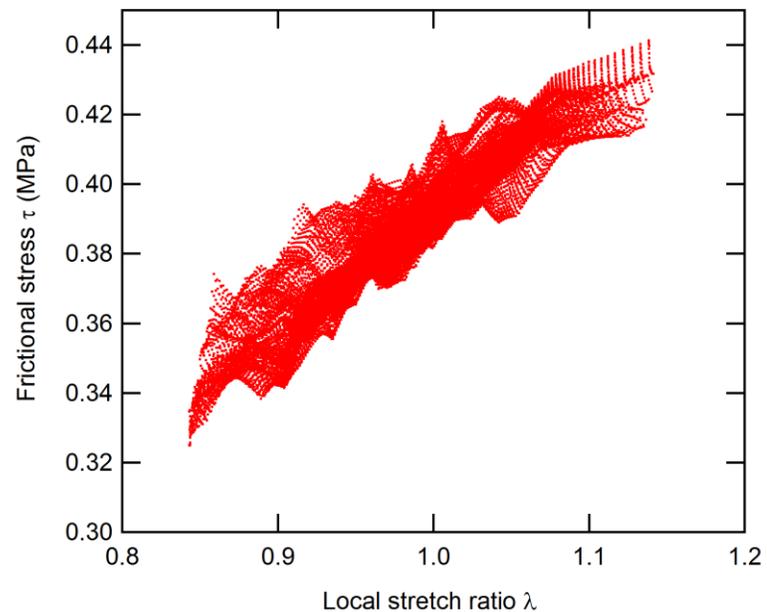
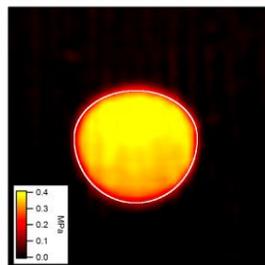
Taux d'étirement

λ



Contrainte de frottement

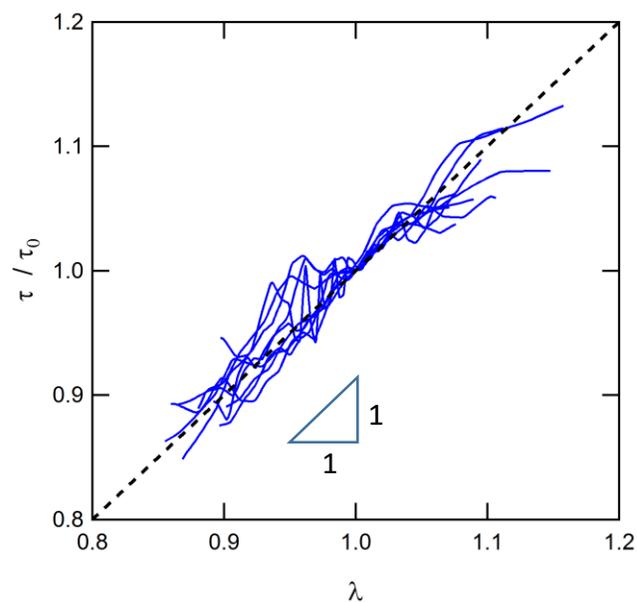
τ



$R=9,3$ mm
 $v=0.5$ mm s⁻¹
 $P=3.3$ N

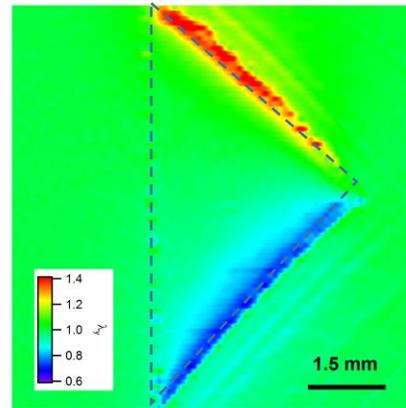
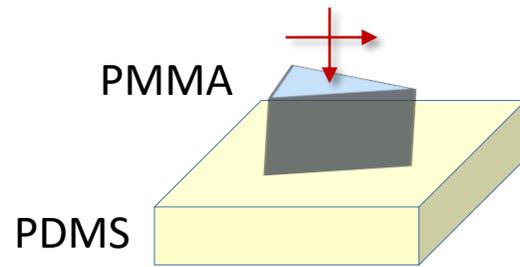
- Généralisation à différentes conditions de contact (géométrie sphère/plan):

$5.2 < R < 25.9$ mm
 $0,1 < v < 1$ mm s⁻¹
 $1.4 < P < 3.3$ N



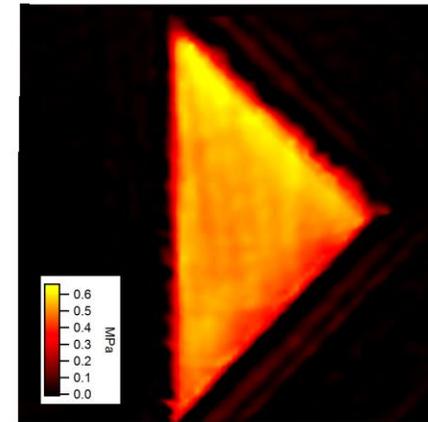
Contrainte de frottement
proportionnelle au taux
d'étirement

$$\tau = \lambda \tau_0$$

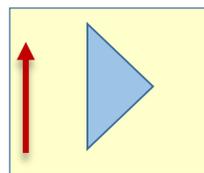
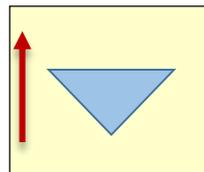


Longitudinal stretch ratio

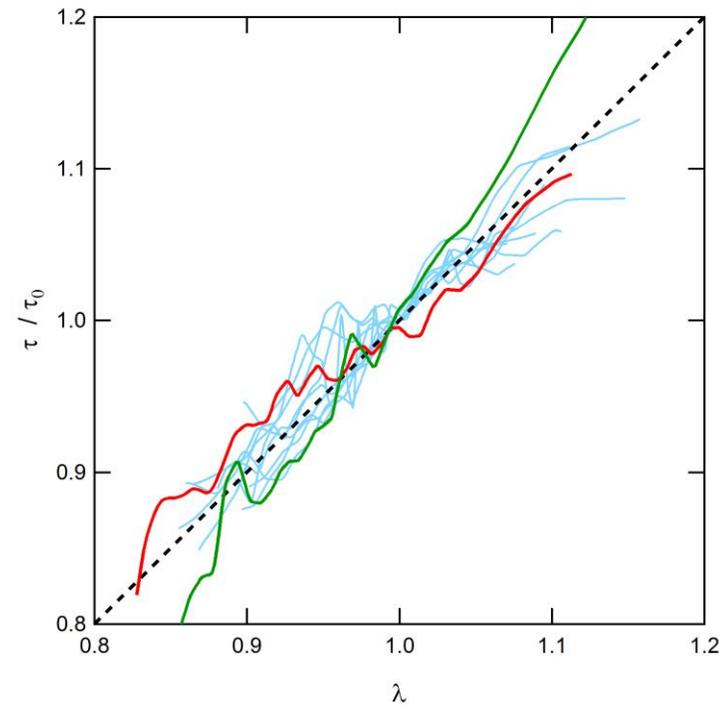
Displacement of the
PDMS substrate



Frictional shear stress

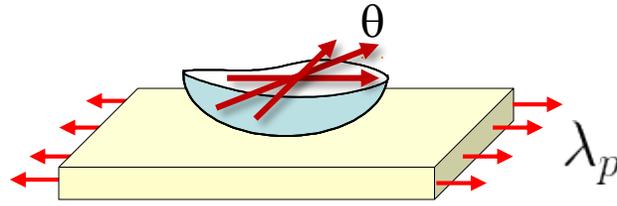


Sphère

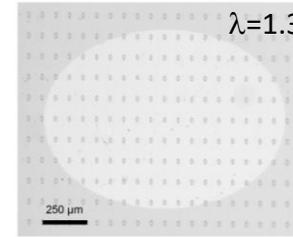


$$\tau = \lambda \tau_0$$

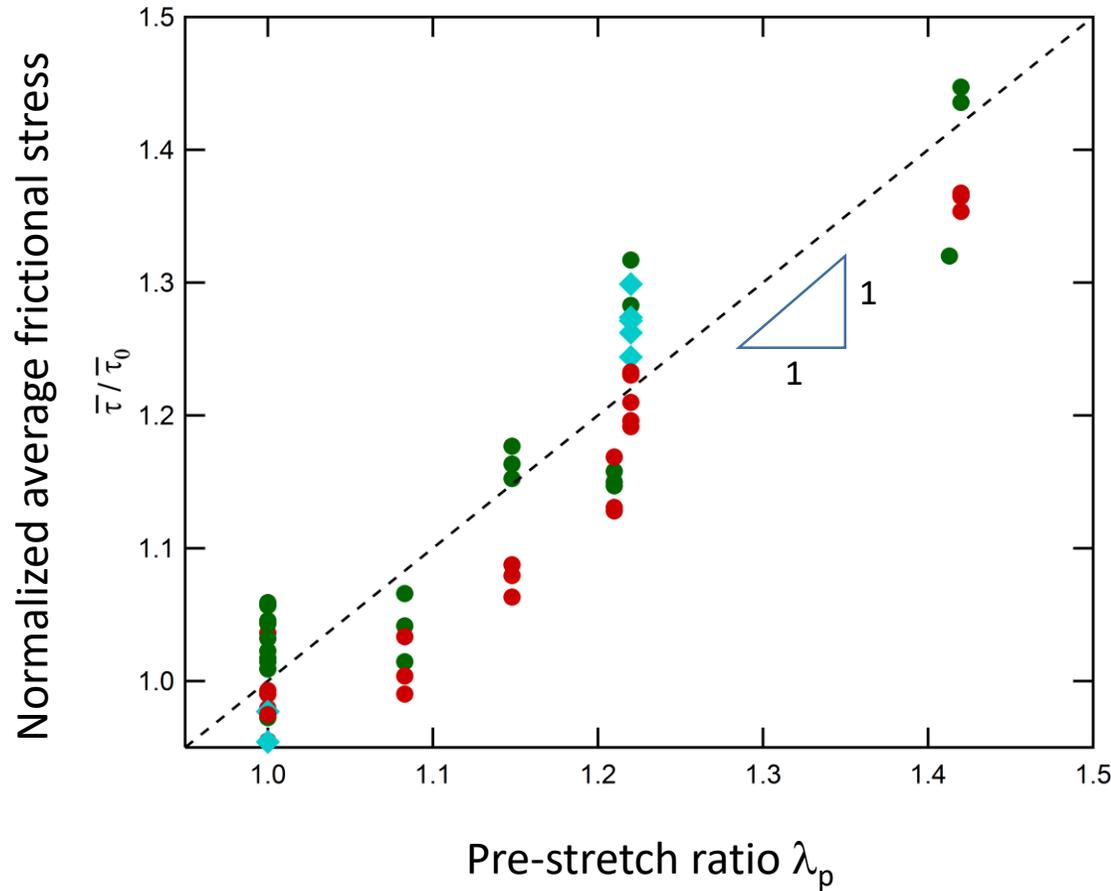
Indépendant de la géométrie du contact



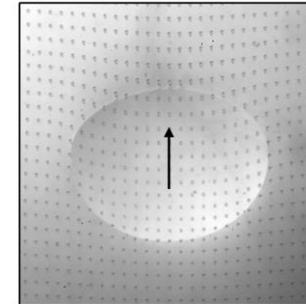
Static contact



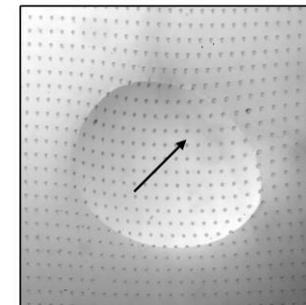
C. Frétygny & A. Chateauminois, *PRE*, 2017



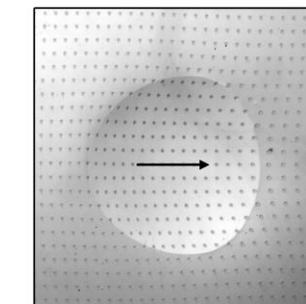
$\theta=0$



$\theta=\pi/4$



$\theta=\pi/2$

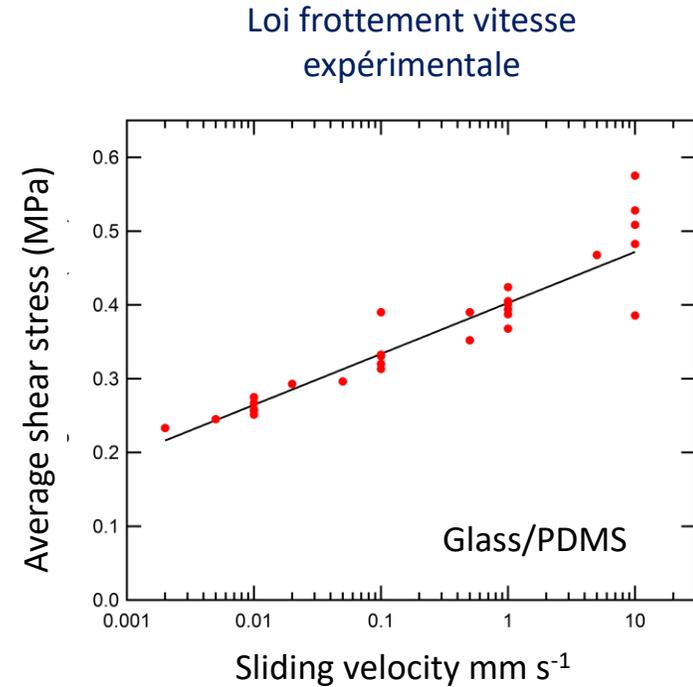
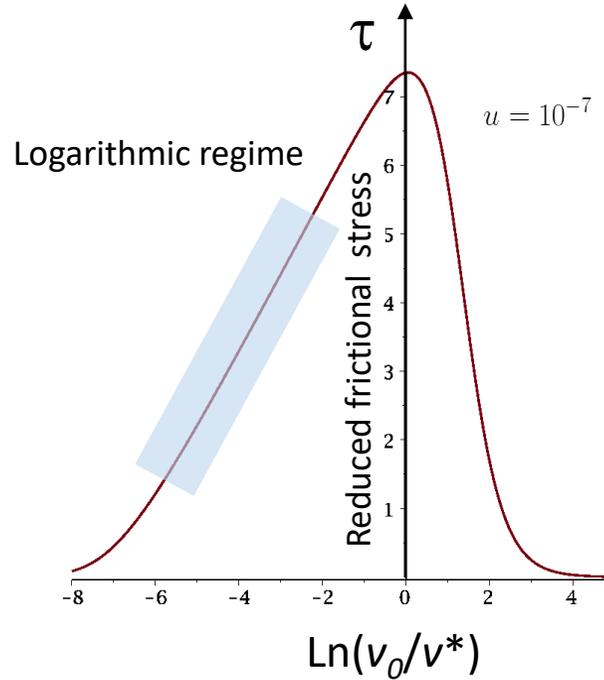
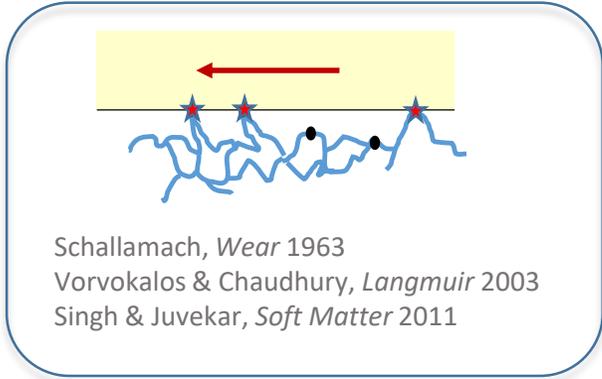


Stretch direction

No orientational effect in the stretch dependence of the frictional shear stress

$\tau = \lambda\tau_0$ surprenant pour un caoutchouc !!

- Modèle de Schallamach : régime de vitesse logarithmique



Contrainte de frottement:

$$\tau \sim \frac{N_0 k_B T}{2\zeta} \ln \frac{V_0}{u V^*}$$

➔ $\tau = \lambda\tau_0$

Possible seulement si le nombre de site d'adsorption disponible N_0 est proportionnel au taux d'étirement

L'étirement ferait migrer en surface des sites polaires d'adsorption enfouis au repos

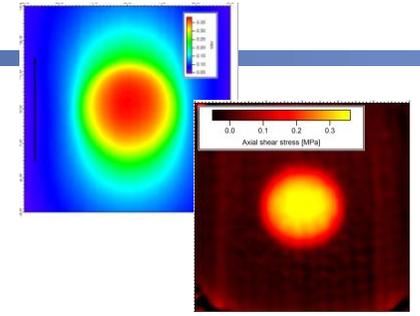
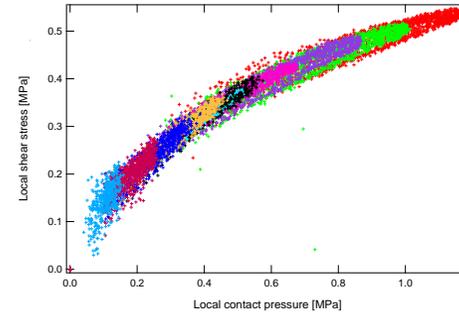
Mesure de champs de contraintes et déplacements dans des contacts avec des élastomères

✓ Frottement d'interfaces multi-contacts

Loi de frottement non coulombienne
Frottement local en fonction de la topographie des surfaces

Frottement d'élastomères viscoélastiques

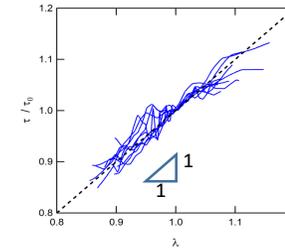
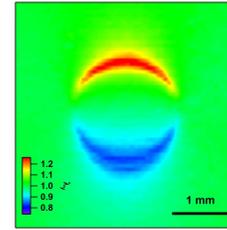
Trejo et al PRE (2013)



✓ Liens entre le frottement et la déformation des surfaces

Interface lisses

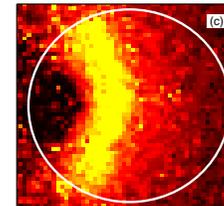
Contacts rugueux ??



✓ Hétérogénéités de frottement en régime transitoire

Liens entre adhésion et frottement

Stick-slip



... Réponse d'interfaces frottantes à des perturbations