Contact mechanics and elements of tribology

Lecture 7.

Wear and Fretting

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Outline

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Definition

Wear is a very general term which is defined as the degradation of the contact surface of a material in service. These degradations can be due to multiple factors, and it is now common to separate wear into 4 distinct families :

- adhesive wear ;
- abrasive wear ;
- chemical wear (corrosion) ;
- wear by contact fatigue.

We will first describe the first three types of wear, wear by contact fatigue will be discussed in more detail in section 2.

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Creation of strong bonds leading to the formation of junctions between the two materials at the level of asperities in contact.

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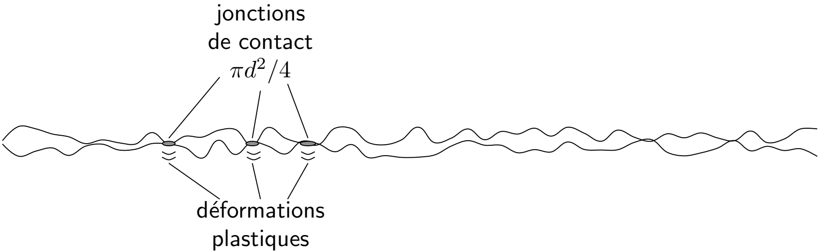


Adhesion index

The adhesion index provides information on the propensity for two materials to adhere to each other if they are brought into contact.
It is expressed as a function of the effective Young's modulus E^*, the average radius of curvature of the asperities R, the standard deviation of the height distribution of the asperities σ and the adhesive work W_{ad} :

$$\alpha = \frac{E^*}{W_{ad}} \left(\frac{\sigma^3}{R} \right)^{1/2}$$

In practice, if $\alpha \leq 5$, risks of adhesion are important.

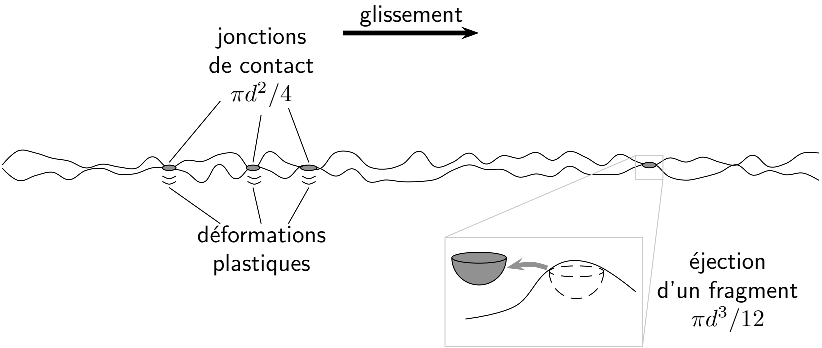
Plasticity index

The plasticity index provides information on the risk of plastic deformation of a rough surface subjected to a load P :

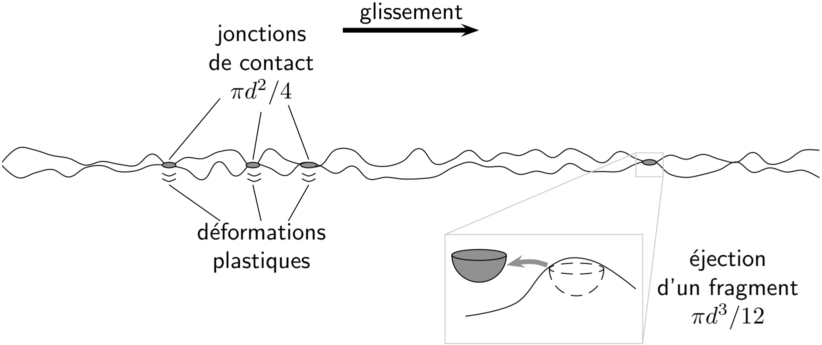
$$\psi = \frac{P}{H}\left(\frac{\sigma}{R}\right)^{1/2}$$

For $\psi \leq 0{,}6$ the deformation of the surface remains essentially elastic, while for values greater than unity, the deformation will be mainly plastic.
This index is used to predict the running-in periods, where a transition from the plastic domain to the elastic domain is observed.

Adhesive wear

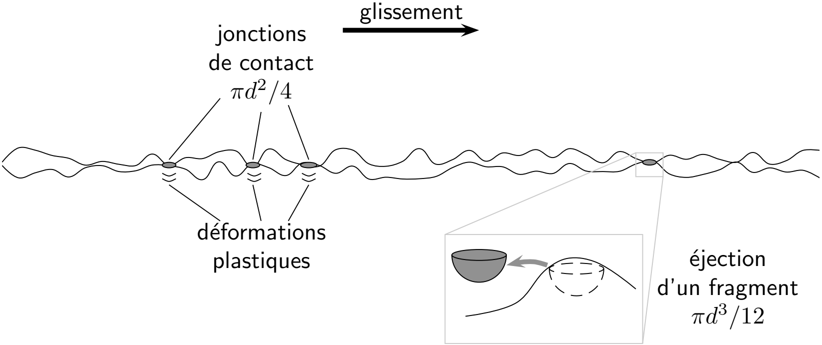


Adhesive wear



- In the presence of adhesion ($\alpha \leq 5$) and if sliding is imposed, wear will occur.

Adhesive wear



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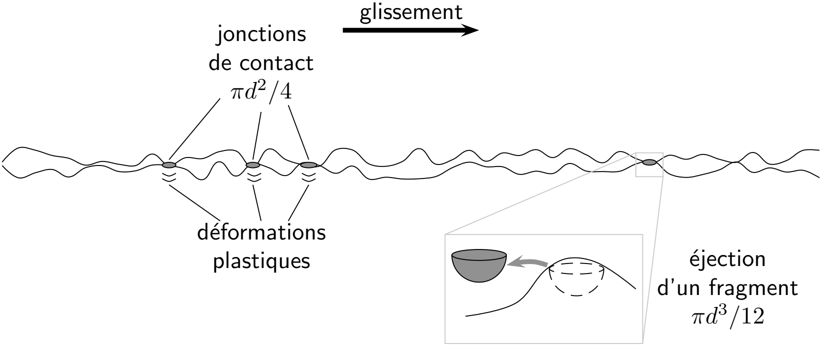
- Some junctions can break and lead to the formation of a material particle, which is usually transferred to the surface of the contacting body ; this particle can then be ejected later as debris.

Adhesive wear



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- Adhesive wear is directly related to the real contact area between the two bodies $\approx P/H$.

Archard Model

Simplified model[1] considering that the junctions have an average area of $\pi d^2/4$ and that the fragments of material removed are hemispherical of volume $\pi d^3/12$.

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Considering a displacement Δl, Archard supposes that each junction is broken after a distance d. Thus, N junctions will have formed such that :

$$N = n\frac{\Delta l}{d} = 4\frac{P}{H}\frac{\Delta l}{\pi d^3}$$

J. F. Archard, *Contact and rubbing of flat surfaces*, Journal of Applied Physics, p 981-988 (1953).

Archard Model

If K is the probability for a junction to give rise to the transfer of a particle, the used volume is expressed by $\Delta V = KN\pi d^3/12$.

The volume used per unit of slip is thus written :

$$\frac{\Delta V}{\Delta l} = \frac{KP}{3H}$$

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We observe that the wear volume is proportional to the contact load as well as to the distance Δl, but inversely proportional to the hardness of the material used. K is called the *wear coefficient* and allows to compare various materials with each other for their resistance to wear. The higher the value of K, the greater the wear.

Understanding the wear coefficient K

K represents the fraction of the contact junctions which will produce wear fragments.

- $K = 1$: Every junction involved in the friction process produces a wear fragment.
- $K = 0.1$: One tenth of the friction junctions produce wear fragments. For clean gold surfaces K is between 0.1 and 1. For clean-copper surfaces K is between 0.1 and 0.01. Clean gold surfaces wear about ten times more rapidly than clean copper surfaces.
- $K = 10^{-7}$: One contact junction in ten million produces a wear fragment.

Values of some wear coefficients

The following table presents values of wear coefficients for different combinations of materials in contact[1]. It should be noted that the presence of a lubricant allows the coefficient of wear to be reduced significantly.

Materials in contact	Wear coefficient K
Zinc on Zinc	$160 \cdot 10^{-3}$
Copper on Copper	$32 \cdot 10^{-3}$
Stainless steel on Stainless steel	$21 \cdot 10^{-3}$
Copper on Low carbon steel	$1,5 \cdot 10^{-3}$
Low carbon steel on Copper	$0,5 \cdot 10^{-3}$
Bakelite on Bakelite	$0,02 \cdot 10^{-3}$

M. Shaw M, *Friction and Wear*, p 657-673, Addison Wesley, Reading MA (1966).

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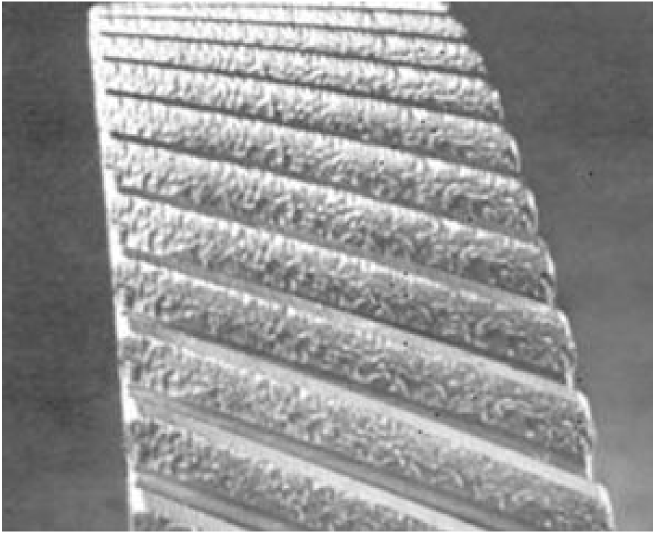
Abrasive wear



Abrasive wear description

- A hard surface penetrates a softer surface ;
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two-bodies wear
: when the two materials in contact have very different hardnesses

three-bodies wear
: when small, very hard particles are located between the two materials (introduced intentionally, as in the case of polishing, or generated by the first phases of two-body wear or tribochemical reaction).

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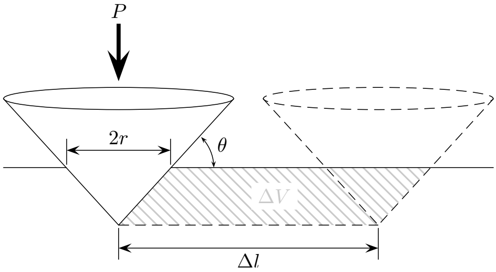
: when small, very hard particles are located between the two materials (introduced intentionally, as in the case of polishing, or generated by the first phases of two-body wear or tribochemical reaction).

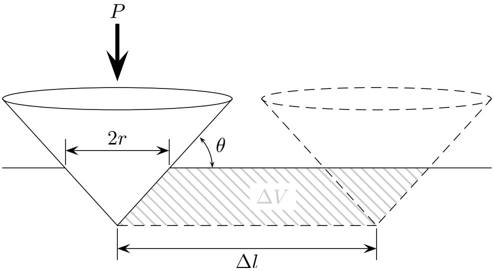
→ Wear manifests itself by the creation of plastic grooves on the surface of the worn material and the possible ejection of particles of material.

Prediction of the wear volume ΔV



Conical particle penetrating the softer material, displaced by a distance Δl.

Prediction of the wear volume ΔV



Conical particle penetrating the softer material, displaced by a distance Δl.

The volume of the groove created by the displacement of the conical particle is expressed by $\Delta V = r^2 \tan\theta \Delta l$, while the indentation pressure is directly related to the hardness H of the softer material and at the contact area : $P = \pi r^2 H$. We can therefore write :

$$\frac{\Delta V}{\Delta l} = \frac{\tan\theta}{\pi} \frac{P}{H}$$

Prediction of the wear volume ΔV

$$\frac{\Delta V}{\Delta l} = K' \frac{P}{H}$$

This law is globally of the same form as Archard's law except for the multiplicative coefficient. Compared to adhesive wear, wear coefficients depend essentially on the geometry of the abrasive particles and are more in the order of 10^{-3} for three-bodies wear and 10^{-2} for two-bodies wear. Two-bodies wear is therefore much more dangerous, with the third body playing the role of a solid lubricant.

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Tribochemical wear

Contact degradations in the presence of a reactive environment are qualified as tribochemical wear. Damage is dominated by chemical reactions occurring between the contact surfaces and / or the external environment. These phenomena interact with mechanical stresses which can sometimes facilitate reactions.

If the medium is corrosive, we can also observe a phenomenon of tribocorrosion activated by contact stresses in the same way as damage by stress corrosion. The deterioration of wear is then greatly increased.

Tribochemical wear

The formation of oxides under these conditions (tribo-oxidation) can have either beneficial or harmful effects on the mechanical strength of the parts :

- the oxide layer formed can limit mechanical stresses, by lowering the coefficient of friction or by adaptated plasticity (plastic shakedown) ;
- if this layer fractures under the action of mechanical contact stresses, it is quickly eliminated. The action depends on whether the debris will effectively play the role of third body by lubricating the contact. If this is not the case (hard and abrasive debris) the damage can quickly become catastrophic.

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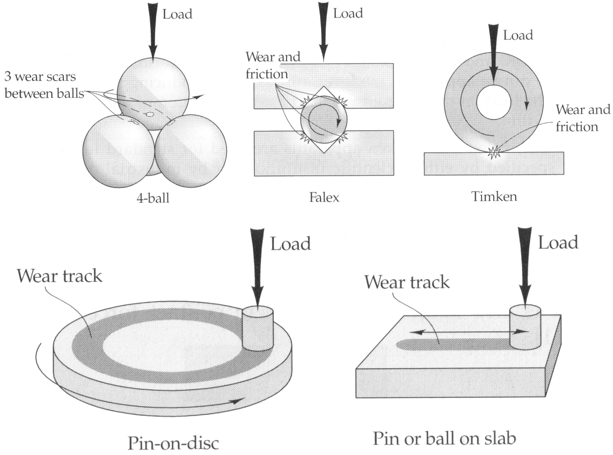
Tribometers

Schematic illustration of some sample configurations used in simulation of dry or partially lubricated sliding contacts :

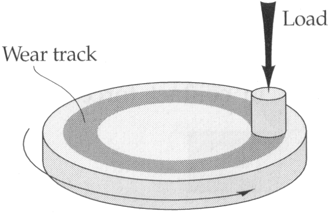


Pin on disk tribometer standards

DIN 50 324 Testing of friction and wear

ASTM G 99 - 95a Standard test method for wear testing with a Pin-on-Disk apparatus

ASTM G 133 - 95 Standard test method for linearly reciprocating ball-on-flat at sliding wear



Pin-on-disc

Comonly used parameters in the characterisation of tribological contacts

Operating parameters

- Load
- Sliding speed
- Sliding distance

Lubrication parameter

- Viscosity
- Flow rate
- Thermal conductivity
- Acidity
- Boiling point
- Solidification point

Material parameters

- Hardness
- Toughness
- Melting point

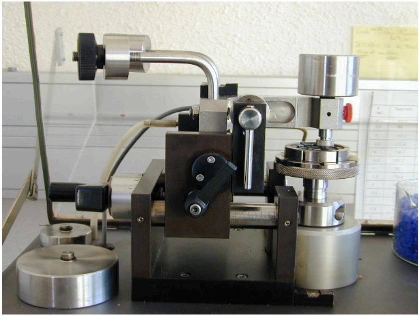
Environmental parameters

- Relative humidity
- Local air pressure
- Radiation level

Tribometers at CdM

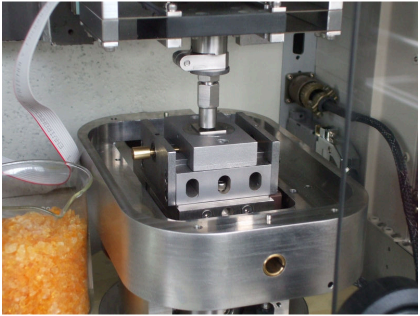
Pin on disc tribometer

- CSM company
- rotating specimen vs fixed pin
- environmental control chamber



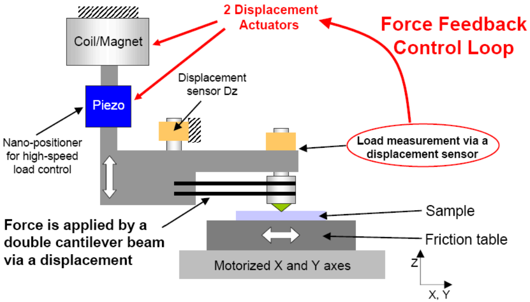
High load UMT TriboLab

- CETR (now Brucker) company
- reciprocating sliding
- motorized 500 N normal load



Scratch test

Investigation of the phenomena occuring along the scratch deformation : cracking, spallation, delamination or bulking.



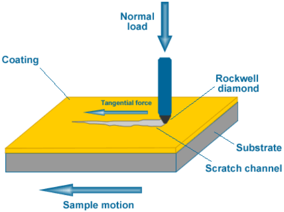
Quantify :

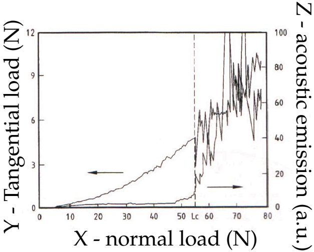
- Scratch resistance
- Adhesion of Coatings
- Friction Coefficient
- Viscoelastic properties
- Wear Testing
- Conventional Hardness

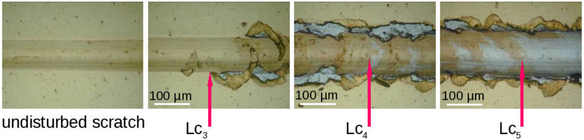
Scratch test to quantify coatings adhesion to substrate

→ scratching a surface with an indenter or ball to characterize the critical loads (L_C) at which the coating failure failure occurs.

www.iphoneincanada.ca





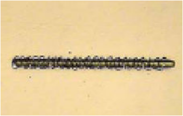


Standard EN 1071-3

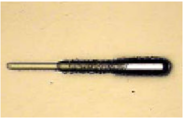
Three different scratching procedures :

- Progressive load scratch test (PLST)
  - loading rate 100 N/min
  - lateral displacement speed 10 mm/min

- Constant load scratch test (CLST)
  - loading rate 100 N/min
  - lateral displacement speed 10 mm/min
  - load step 1/5 of L_C



- Multipass scratch test (MPST)
  - repeated scratching under a constant sub-critical load within the same scratch track
  - lateral displacement speed 1operating parameter same as for CLST
  - load 1/2 of L_C
  - number of scratches until failure



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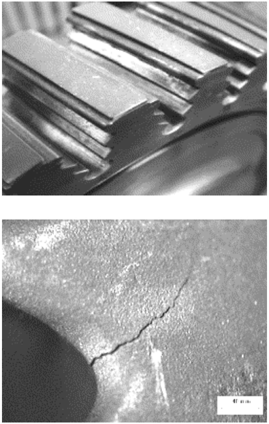
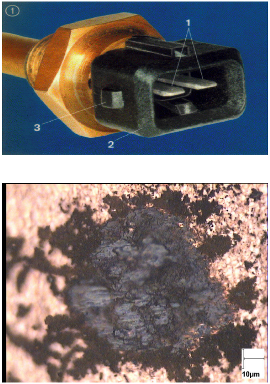
Fretting problems



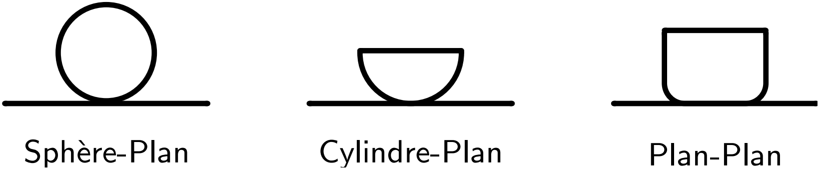
ex : turbine blade/disk contact (cracking)



ex : electrical contact (wear)

Contact configurations

Very complex real contact geometries → simplification of the geometry for laboratory testing.

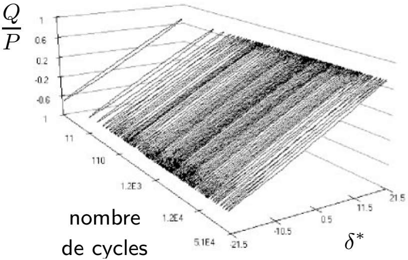


- The sphere-plane and plane-plane configurations are often used to study the kinetics of fretting wear ;
- rather, the cylinder-plane configuration is used to study fretting cracking.

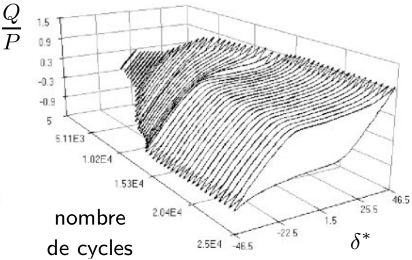
The differents slip regimes

The curve $Q(\delta)$ adopts two characteristic shapes depending on the loading parameters :

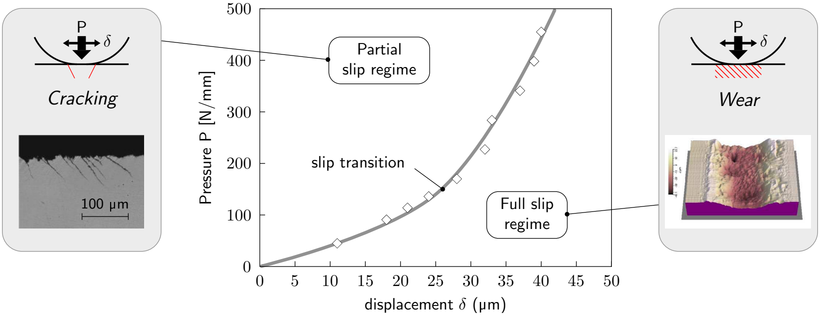
a)



b)



Running condition fretting map



- At low displacement amplitudes and high normal load : partial slip regime. Cracking is mainly observed.
- At large displacement amplitudes : full sliding regime. Wear is the dominant degradation mechanism.

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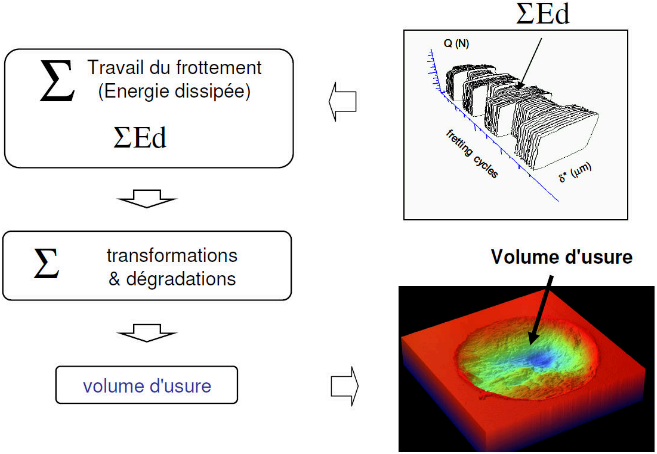
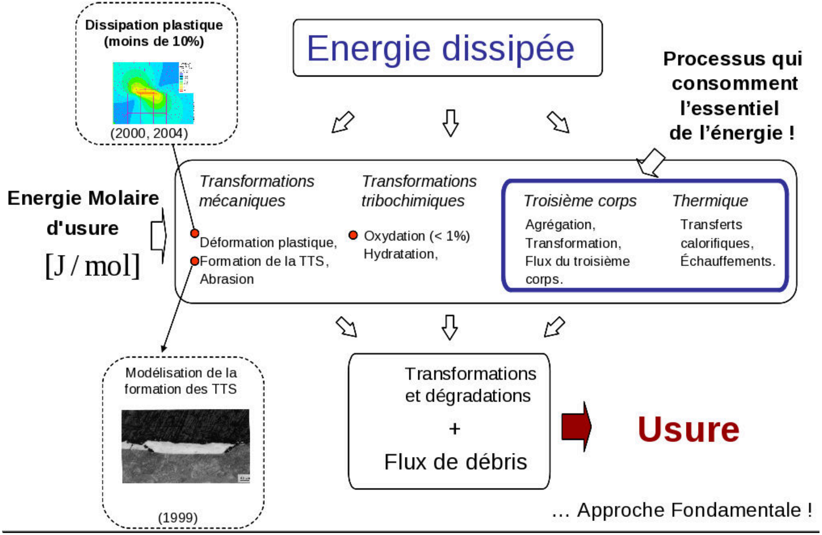
Fretting usure : approche energétique[1]



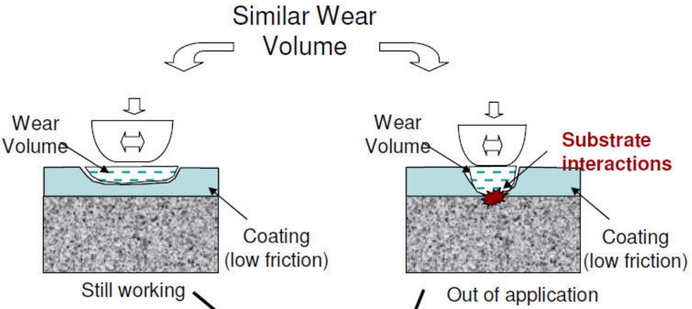
S. Fouvry, C. Paulin and S. Deyber, *Tribology International*, 42(3) :461-474 (2009).

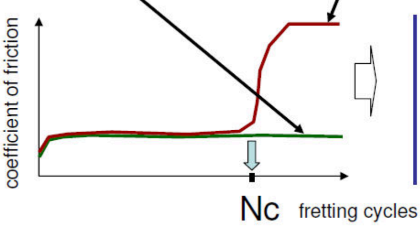
Fretting wear : thermodynamic approach



Fretting wear : local approach

Fretting Usure : Approche Locale



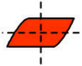


- Introduction of a coating endurance concept.

-Request a local analysis of wear : Replace the wear volume description by a wear depth extension.

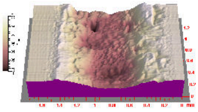
Friction energy capacity to predict surface coating endurance

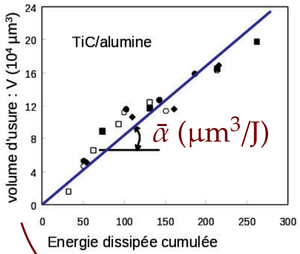
$E_d(J)$ Energie de frottement dissipée dans l'interface



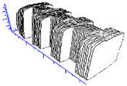
transformations et dégradations

Usure V (µm³)





$$V = \bar{\alpha}.E_d$$



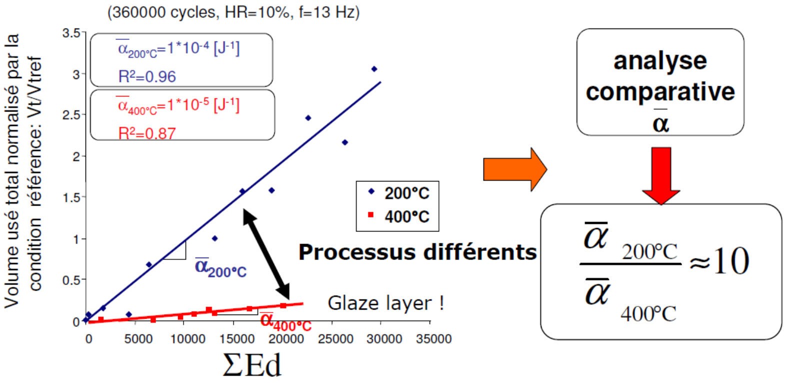
Validé pour des amplitudes variables

Travaux de S. Fouvry & T. Lieskiewicz[1]

T. Liskiewicz and S. Fouvry, *Tribology international*, 38(1) :69-79 (2005).

Example of Comparative analysis

Fretting Usure : Approche énergétique de l'usure



Ex. Contact Inox/Inox

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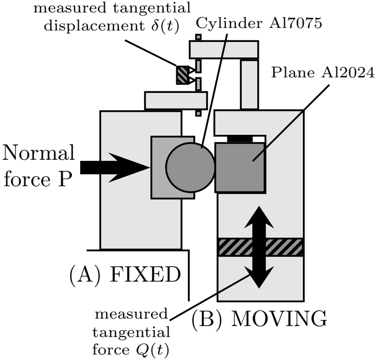
Example of experimental fretting tests

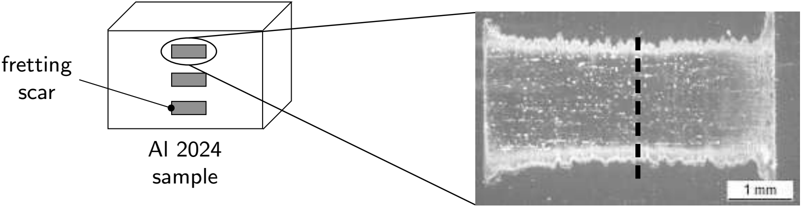
Fretting wear configuration

- Flat *vs.* Cylinder contact
- AA2024 damage tolerant aerospace alloy
- Partial slip condition
- Measure of P, $Q(t)$ and $\delta(t)$ during test
- number of cycles $0 < N \leq 4.10^6$

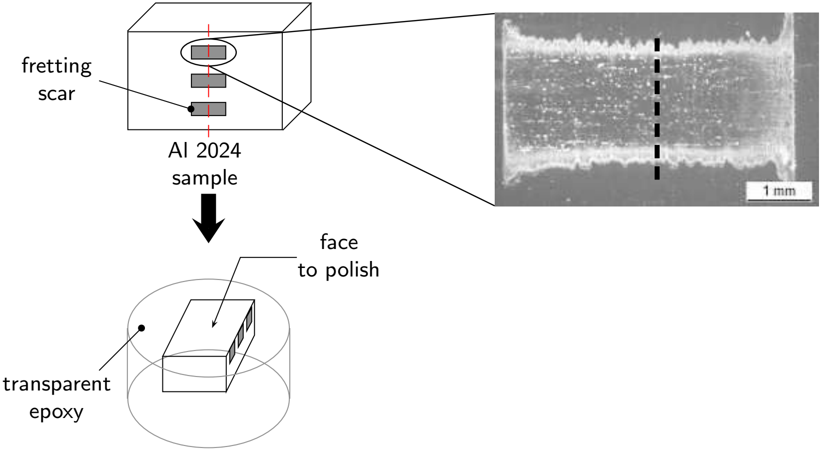


Fretting experiments carried out at Ecole Centrale de Lyon

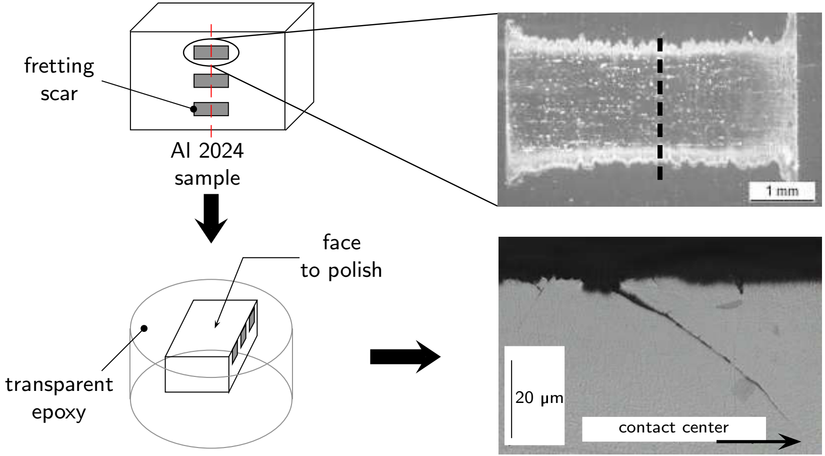
Fretting damage investigation



Fretting damage investigation

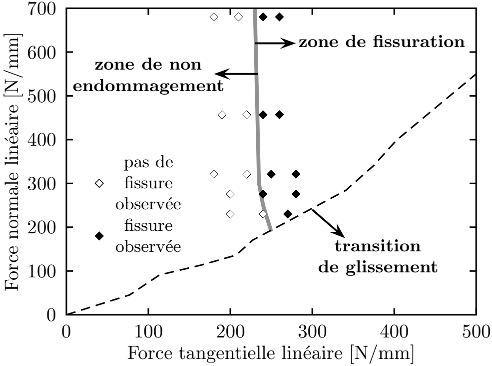


Fretting damage investigation



Fretting crack initiation boundary

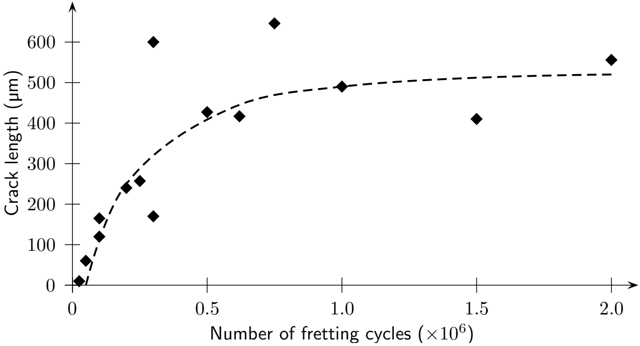
- crack initiation boundary at 50k cycles for a dry contact aluminium-aluminium
- no apparent role of the contact pressure
- tangential force crack initiation threshold $Q_c = 240$ N/mm. The initiation in this case seems driven by the surface shear.



Fretting crack propagation

Experimental conditions

- Fretting loading : p_0 = 325 MPa, δ = 20 μm ;
- Destructive characterisation : 1 experimental point ⇔ 1 test.



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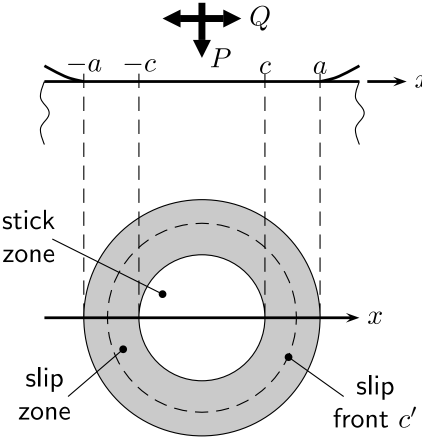
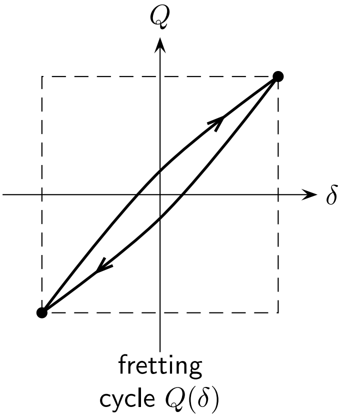
Fretting contact in the partial slip regime





Theory of superposition

Formulation by McEwen[1] and applied to contact loading like fretting by Johnson[2], later extended by Hills[3] :

- Analytical stress distribution for sliding contact
  $\underset{\sim}{\sigma} = \underset{\sim}{\sigma}^P + \underset{\sim}{\sigma}^Q$ (Hertz and Coulomb)

E. McEwen, *Philosophical Magazine*, 40 :454-459 (1949).

K. L. Johnson, *Contacts Mechanics*, Cambridge University Press, (1985).

D. Hills, D. Nowell and A. Sackfield, *Mechanics of Elastic Contacts*, (1993).

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Formulation by McEwen[1] and applied to contact loading like fretting by Johnson[2], later extended by Hills[3] :

- Analytical stress distribution for sliding contact

  $\underset{\sim}{\sigma} = \underset{\sim}{\sigma}^P + \underset{\sim}{\sigma}^Q$ (Hertz and Coulomb)

- Partial slip stress distribution (proposed by Cattanéo and Mindlin)

  $\underset{\sim}{\sigma}(\underline{X}, c') = \underset{\sim}{\sigma}^P + \underset{\sim}{\sigma}^Q(\underline{X}, c) + \underset{\sim}{\sigma}^Q(\underline{X}, a) - 2\underset{\sim}{\sigma}^Q(\underline{X}, c')$ load

  $\underset{\sim}{\sigma}(\underline{X}, c') = \underset{\sim}{\sigma}^P - \underset{\sim}{\sigma}^Q(\underline{X}, c) - \underset{\sim}{\sigma}^Q(\underline{X}, a) + 2\underset{\sim}{\sigma}^Q(\underline{X}, c')$ unload

E. McEwen, *Philosophical Magazine*, 40 :454-459 (1949).

K. L. Johnson, *Contacts Mechanics*, Cambridge University Press, (1985).

D. Hills, D. Nowell and A. Sackfield, *Mechanics of Elastic Contacts*, (1993).

Theory of superposition

Formulation by McEwen[1] and applied to contact loading like fretting by Johnson[2], later extended by Hills[3] :

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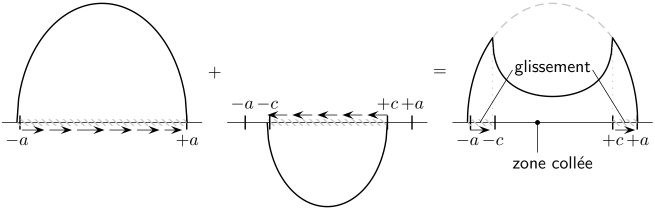
Example at the surface at the end of the fretting cycle ($c = c'$) :



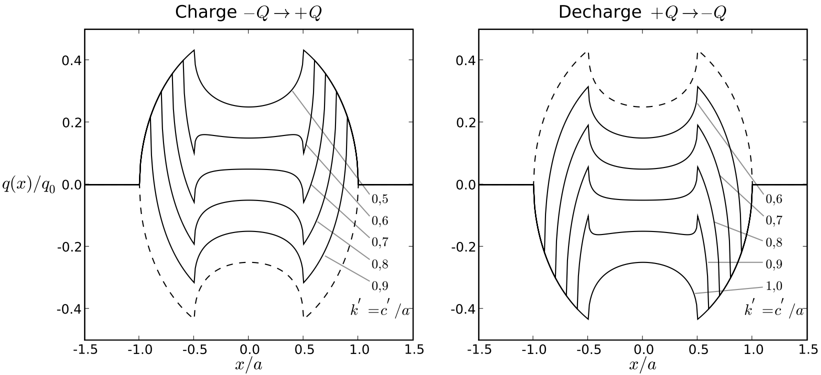
E. McEwen, *Philosophical Magazine*, 40 :454-459 (1949).

K. L. Johnson, *Contacts Mechanics*, Cambridge University Press, (1985).

D. Hills, D. Nowell and A. Sackfield, *Mechanics of Elastic Contacts*, (1993).

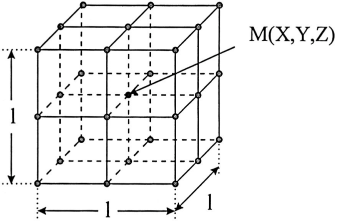
Shear stress during the fretting cycle

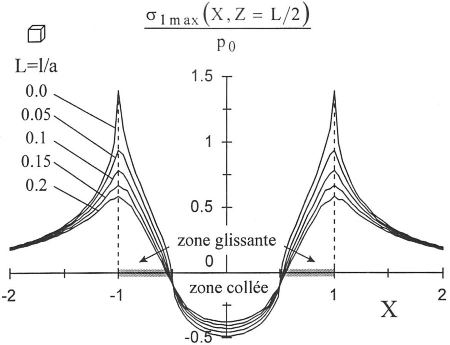
Evolution of the surface shear during the fretting cycle in partial slip predicted by the theory of Mindlin ($\mu = 0,5$ and $k = c/a = 0,5$) :



Multiaxial fatigue criterion for crack initiation

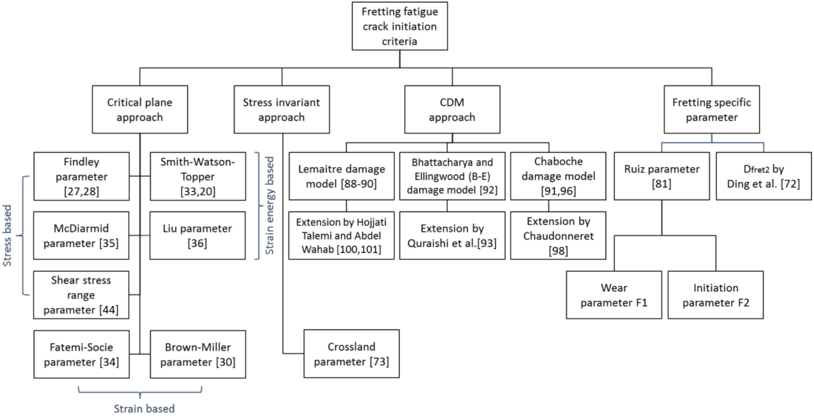
- From the stress fields and the elastic contants, the strain field can be derived (or computed numerically including plasticity effects).
- from $\underset{\sim}{\sigma}$ and $\underset{\sim}{\varepsilon}$ fields, a multiaxial fatigue criterion can be used to predict the initiation location and life.
- Due to the severe stress/strain gradients, a spatial averaging procedure is needed.





A fretting criterion classification

Review of the various criteria used to predict fretting crack initation[1]



Ex for the Findley Parameter :

$$FP = \frac{\tau_{max}}{2} + k_1 \sigma_{max}^n \quad \text{and initiation for} \quad \frac{\tau_{max}}{2} + k_1 \sigma_{max}^n = \tau_f'(2N_i)^{b'}$$

N. A. Bhatti and M. A. Wahab, *Tribological Transactions*, in press.

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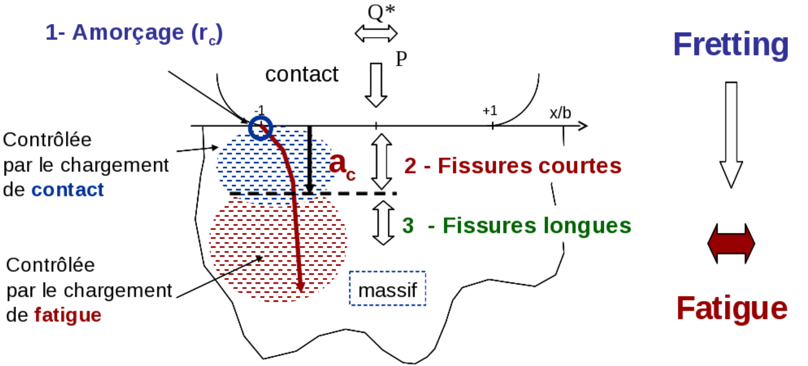
Fretting fatigue cracking

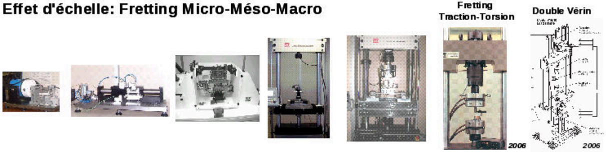


« Comment prédire la cinétique de fissuration en Fretting ? »

Fretting at LTDS, Lyon (France)

Plateforme expérimentale Fretting & Fatigue

Effet d'échelle: Fretting Micro-Méso-Macro



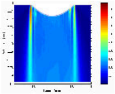
P = 0.5 N ⟷ **P = 100000 N**

Fluage traction
(composites)

Plateforme numérique Fretting & Fatigue

- Centre FEM ABAQUS (macro - 2D // Visco-Elasto-Plastique)
- Critères multiaxiaux de fatigue
- Propagation des fissures (Crack-Box, Fonctions de poids & Dislocations)
- Codes d'usure remaillage des surfaces (Wear-Box)

Fissure



Usure

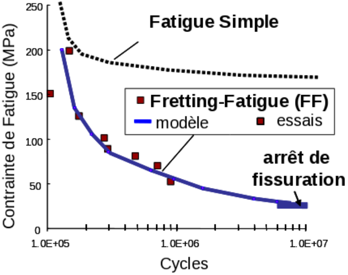
From fretting-fatigue maps to life predictions

$$N_T = N_A + N_{PFC} + N_{PFL}$$

amorçage (N_A)

propagation "régime fissures courtes" (N_{PFC})

propagation "régime fissures longues" (N_{PFL})



Fretting Fatigue (alliage 2XXX)

Th. K. Kubiak, 2005

Méthodes

- FEM (remaillage) : "Crack Box"
- Fonction de poids
- Distribution de Dislocations

Prédiction de l'endurance en FF
Formalisation du coefficient d'abattement
Fretting-Fatigue / Fatigue

S. Fouvry and K. Kubiak, *Wear*, 267(12) :2186-2199 (2009).

S. Fouvry and K. Kubiak, *International Journal of Fatigue*, 31(2) :250-262 (2009).

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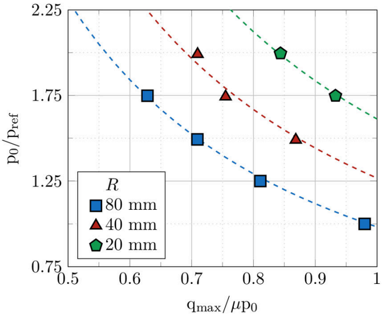
Problem

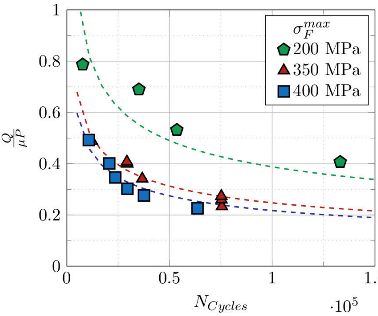
Fretting problems suffer from severe **stress gradients** located at the transition from stick and slip zones, which are known to imped classical fatigue approaches.

For instance :

- varying the contact radius in fretting tests ;
- varying the nominal fatigue stress in fretting fatigue tests

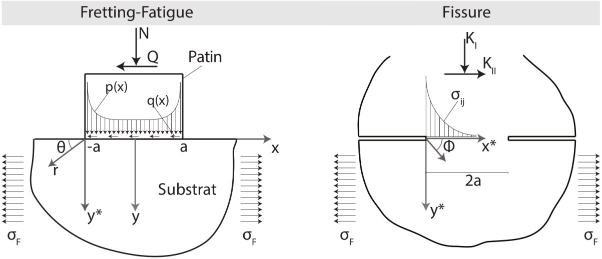
gives different crack initiation boundaries.





Crack analogue approach

For a **pure stick contact**, the stress fields at the root of the contact notch are similar to those present at a crack tip.

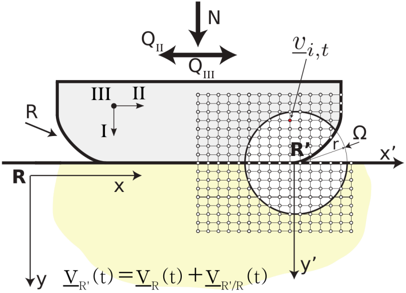


Using the contact stress field solution :

- $\sigma_{yy}(x \to a, y = 0) = \dfrac{N}{\pi \sqrt{2ar}} = \dfrac{K_I}{\sqrt{\pi a}}$ thus $K_I = -\dfrac{N}{\sqrt{\pi a}}$
- and similarly for mode II : $K_{II} = \dfrac{Q}{\sqrt{\pi a}}$

The stress intensity factors K_I and K_{II} depends on the applied load but also on a, directly **integrating the contact gradient**.

Proper Orthogonal Decomposition of the velocity field (computed using finite elements) using 5 modes.



$$\underline{v}(\underline{P}, t)_{R'} = \underline{v}_e(\underline{P}, t)_{R'} + \underline{v}_c(\underline{P}, t)_{R'}$$

linear part (stick contact) | non linear part (slip contact)

$$\underline{v}_e(\underline{P}, t)_{R'} \simeq \dot{I}_I(t)\underline{\phi}_I(\underline{P}) + \dot{I}_{II}(t)\underline{\phi}_{II}(\underline{P}) + \dot{I}_{III}(t)\underline{\phi}_{III}(\underline{P})$$

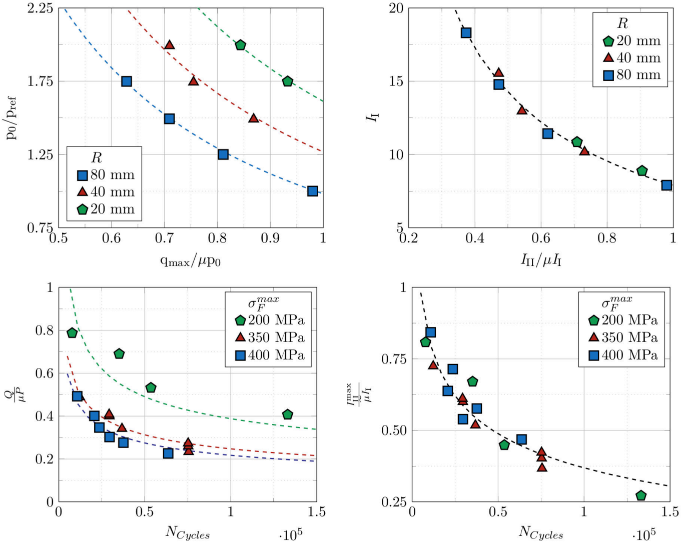
$$\underline{v}_c(\underline{P}, t)_{R'} \simeq \dot{I}^c_{II}(t)\underline{\phi}^c_{II}(\underline{P}) + \dot{I}^c_{III}(t)\underline{\phi}^c_{III}(\underline{P})$$

The 3D contact is approximated using 5 dof : $\dot{I}_I$, $\dot{I}_{II}$, $\dot{I}_{III}$, $\dot{I}^c_{II}$, $\dot{I}^c_{III}$

G. Rousseau, *Modélisation de la durée de vie en fretting-fatigue sous chargements complexes*, PhD thesis, Univ Paris-Saclay (2020).

A unified model for fretting fatigue predictions

The model is able to predict fretting and fretting fatigue life under many different conditions and stress gradients !



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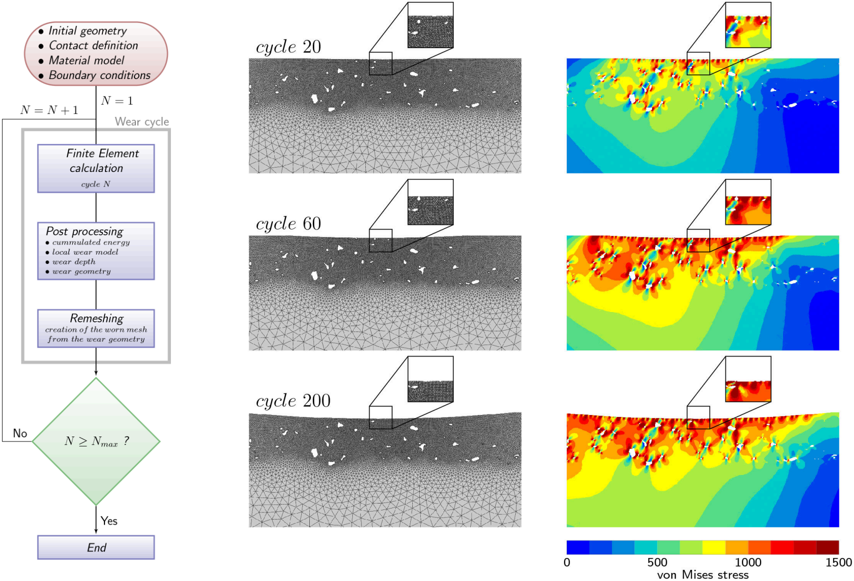
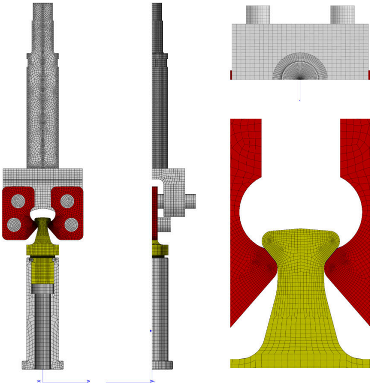
Wear models



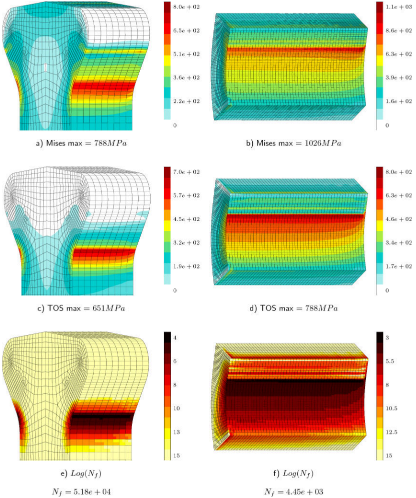
H. Proudhon *et al.*, Experimental and numerical wear studies of porous reactive plasma sprayed Ti-6Al-4V/TiN composite coating. *Wear*, (311) :159-166, 2014.

Fretting calculations on a technological specimen

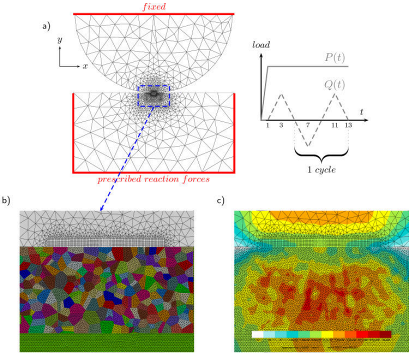


blade-disk technological testing at Safran

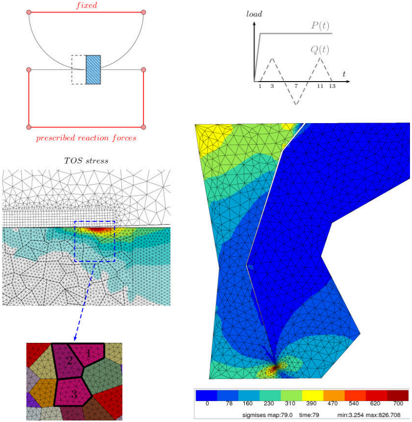
- elastoplastic coating with work hardening
- Fields transfer



Crack propagation model (polycristal)



Crack initiation (fatigue criterion)



Crack propagation (crystal plasticity)

PhD thesis L. Sun (2012), H. Proudhon *et al.*, *Matériaux et Techniques*, (101) :203, 2013.