# Fretting Fatigue

**"Etude & prédiction de la durée de vie"**


**S. Fouvry, K. Kubiak, H. Proudhon**

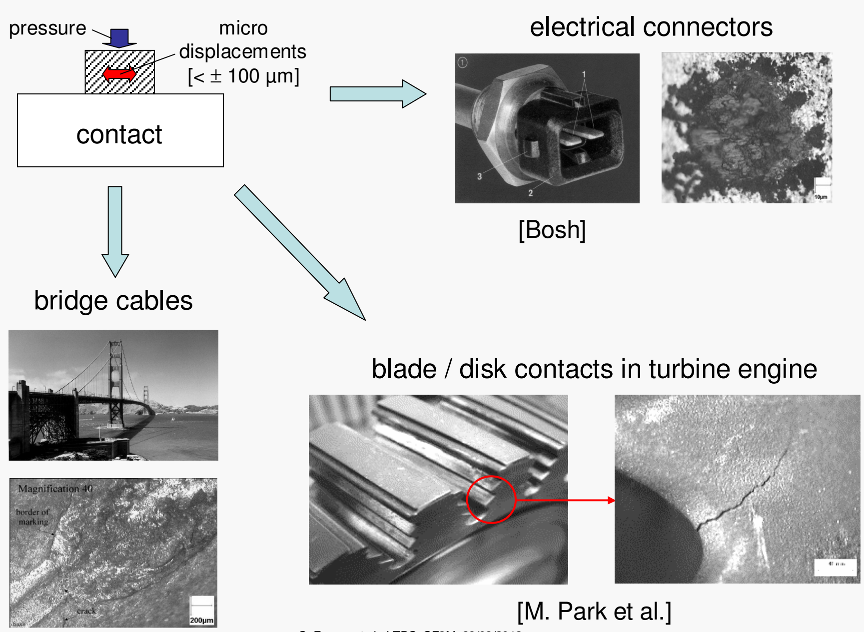
**LTDS, CNRS, Ecole Centrale de Lyon, Ecully , France**

**contact : siegfried.fouvry@ec-lyon.fr**

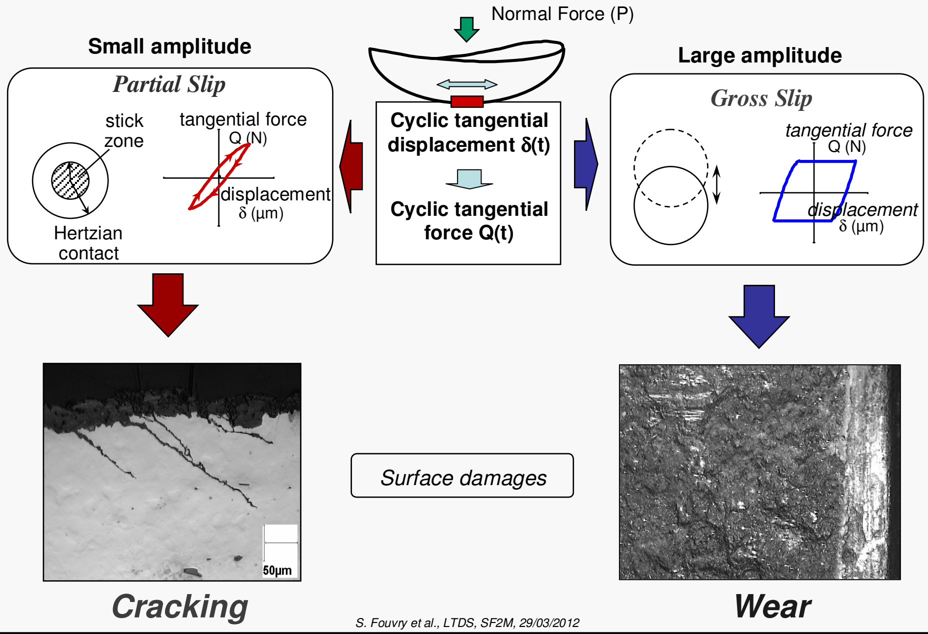

SF2M

SF2M – Commission Fatigue 29 mars 2012, PARIS
"Prise en compte des phénomènes aggravants dans la conception en fatigue"

## Context and challenges

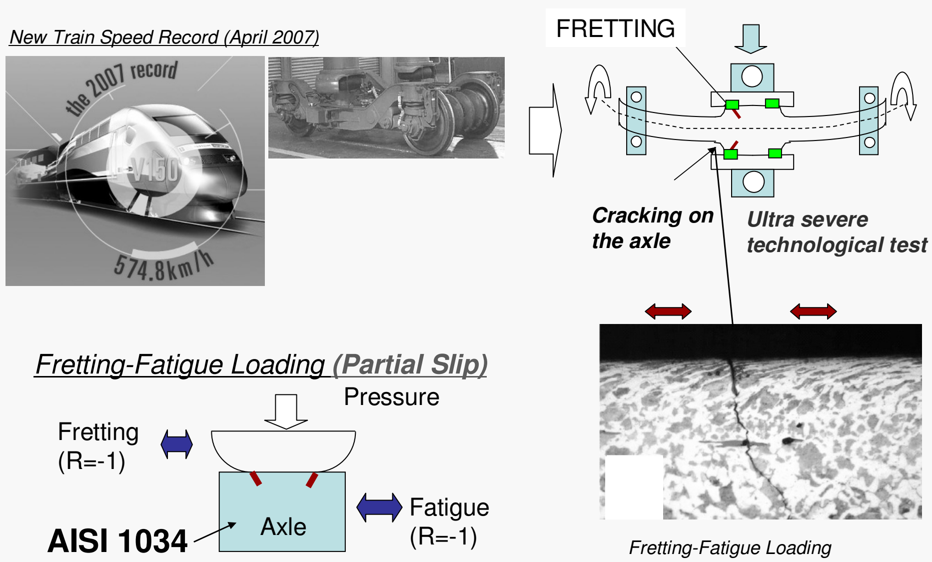


## Damage induced by plain fretting loading




S. Fouvry et al., LTDS, SF2M, 29/03/2012

## Industrial application : Pressed fitted Wheels-Axles contact




**Question : Are can be predicted the cracking risk ?**

S. Fouvry et al., LTDS, SF2M, 29/03/2012

**Part A : Prediction of the infinite Fretting Fatigue endurance Conditions (No crack nucleation or Crack Arrest conditions)**

**Part B: Prediction of finite endurance life time under Fretting Fatigue stressing**

**Part C: Palliatives against Fretting Fatigue**

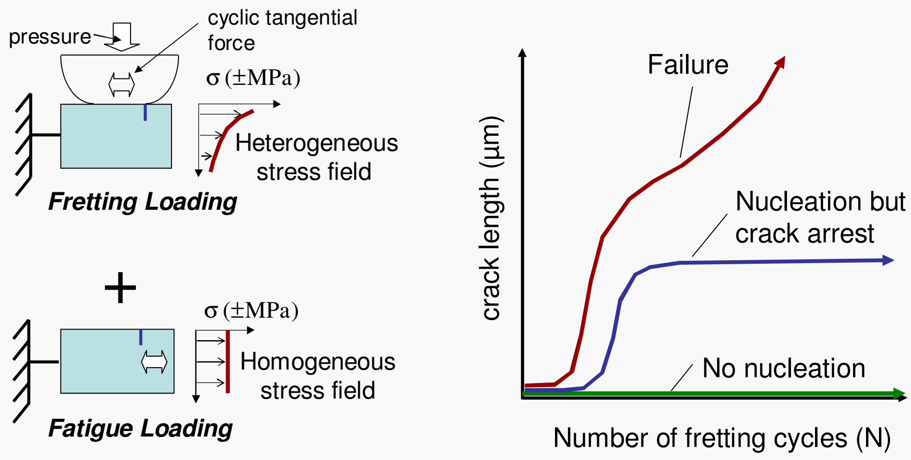


**Part A : Prediction of the infinite Fretting Fatigue endurance Conditions**

**$\Rightarrow$ Crack Nucleation Boundary**

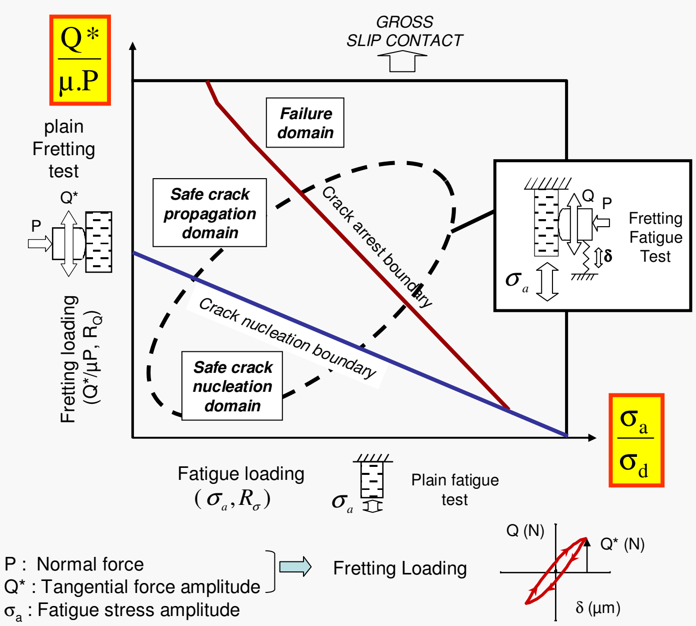
**$\Rightarrow$ Crack Arrest Boundary**

## Fretting Fatigue : Stress & Damage evolutions




S. Fouvry et al., LTDS, SF2M, 29/03/2012

## Fretting Fatigue : Fretting – Fatigue Map Concept (Partial Slip)




P : Normal force
Q* : Tangential force amplitude
$\sigma_a$ : Fatigue stress amplitude

→ Fretting Loading

S. Fouvry et al., LTDS, SF2M, 29/03/2012

## How can be formalized the Fretting Fatigue Mapping Concept ?

**(i.e. How can be predicted the different damage domains ?)**



## *Topics of the presentation*

**Materials**

**Experimental strategy (combined plain fretting & fretting fatigue tests)**

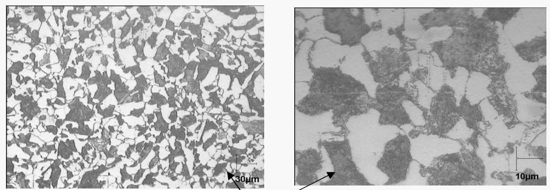
**Modelling (Contact stressing+ Crack Nucleation + Crack Propagation)**

**Prediction of the Fretting-Fatigue crack nucleation boundary**

**Prediction of the Fretting-Fatigue crack propagation boundary**

**Conclusions**

## Material : Low carbon steel (AISI 1034)




Ferrite - Perlite structure

**Mechanical properties**

| Matériau | Low carbon steel |
|---|---|
| Young modulus, E (GPa) | 200 |
| Poisson coefficient, $\nu$ (ratio) | 0.3 |
| Yield stress, $Re_{0.2}$ (MPa) | 350 |
| Maximum stress, Rm (MPa) | 600 |

**Crack propagation (long crack) & fatigue**

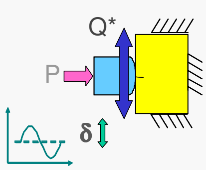
| | |
|---|---|
| SIF range threshold, $\Delta K_0$ | 7 $(MPa \cdot \sqrt{m})$ |
| maximum SIF, $K_c$ | 117 $(MPa \cdot \sqrt{m})$ |
| C coefficient (Paris law) | $2{\cdot}10^{-12}$ |
| m exponant (Paris law) | 3.5 |
| Fatigue limite (R=1) | 270 MPa |

Gros V. , Ph.D Thesis, Ecole Centrale de Paris, France,1996.

*S. Fouvry et al., LTDS, SF2M, 29/03/2012*

## Fretting Experiments : Coupling Between Plain Fretting & Fretting Fatigue tests

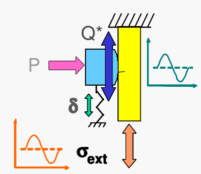
**Plain Fretting Test (fretting wear test)**

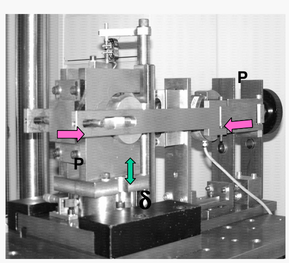


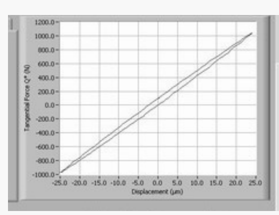

**Acquisition system**

**displacement**
**normal force**
**tangential force**
**temperature**
**humidity**

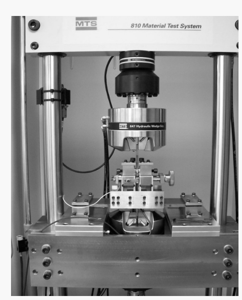
**Fretting Fatigue Test**



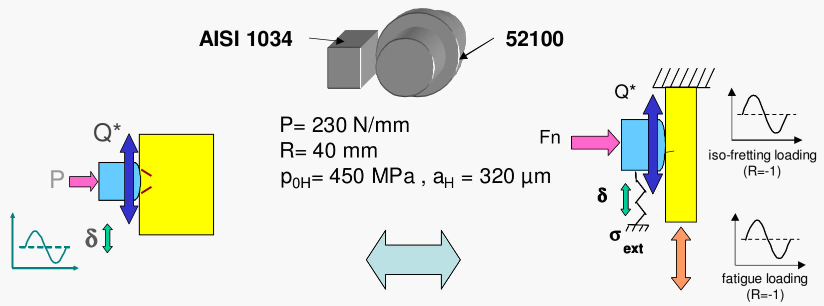

FRETING CYCLE
(Partial Slip)




*S. Fouvry et al., LTDS, SF2M, 29/03/2012*

## Fretting Experiments : Coupling Between Plain Fretting & Fretting Fatigue tests

### *Similar contact condition*




**Plain Fretting Test**

- Friction behavior **(Tribology)**
- Crack nucleation
- Short crack propagation (systematic crack arrest conditions)

**Fretting Fatigue Test**

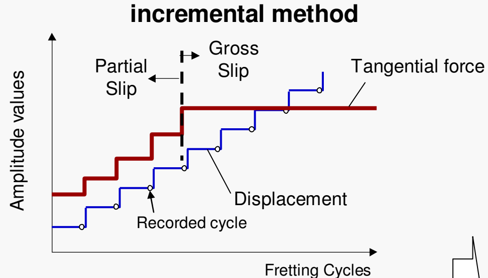
- Crack propagation (short & long)
- Crack arrest condition
- Lifetime endurance

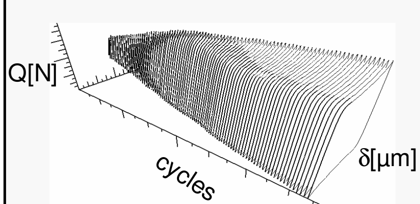
This combined Plain Fretting and Fretting Fatigue test allow us to dissociate the impact of contact and bulk cyclic loading on the fretting fatigue damage

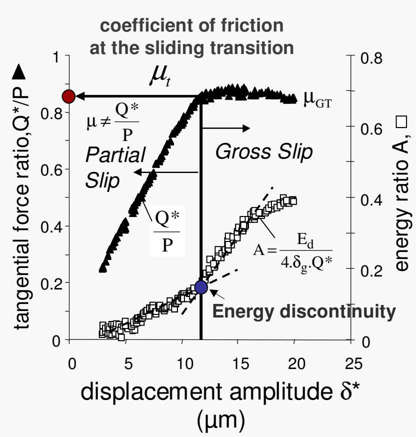
*S. Fouvry et al., LTDS, SF2M, 29/03/2012*

## Plain Fretting Wear Test → Friction analysis

### incremental method



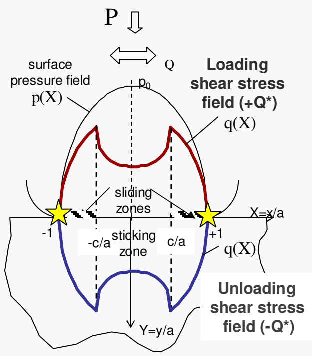




Coefficient of Friction ($\mu_t$) = 0.85

*S. Fouvry et al., LTDS, SF2M, 29/03/2012*

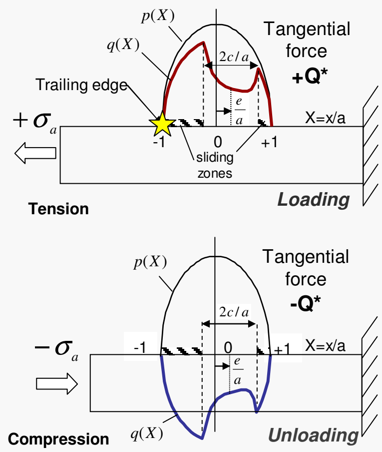
## Analytical description of Plain Fretting and Fretting Fatigue contacts

*Plain Fretting Contact*




*Mindlin et al, 1949*

*Fretting-Fatigue Contact*



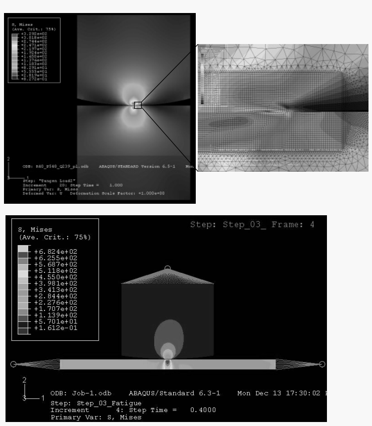

*Nowell et al, 1989*

- **Maximum loading located ☆ symetrically at the contact borders**
- **Maximum loading located at the trailling edges (at the Loading state)**



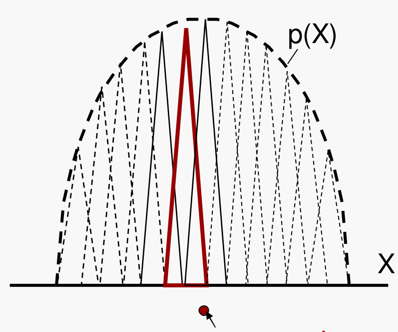
## Contact modeling: Stress field analysis

FEM ANALYSIS



- Can include plasticity
- Long and fastidious (inappropriate to develop A mapping investigation !!)

**Analytical formulation: Green's functions**
**Superposition of piecewise-line**
**Overlapping triangular elements**
**(K.L. Johnson, 1985)**
**[Elastic Half Space Hypothesis]**




$$\Sigma(M,t) = \Sigma \Lambda$$

- Very fast !!

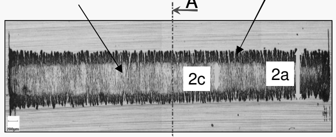
# Crack Nucleation Analysis

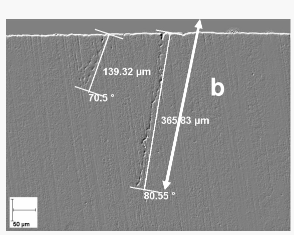
S. Fouvry et al., LTDS, SF2M, 29/03/2012

## Plain Fretting Wear Test → Friction Identification of the crack nucleation

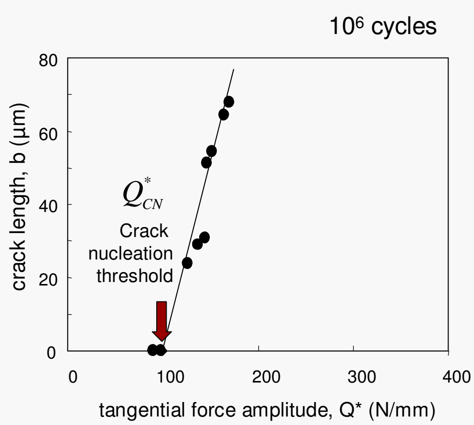
*Fretting Test : Q*=± 200 N/mm, $10^6$ cycles*

Surface observation




**Cross section observation: measure of the crack length**




P=230N/mm, µ=0.85
($10^6$ cycles, $p_0$= 450 MPa)

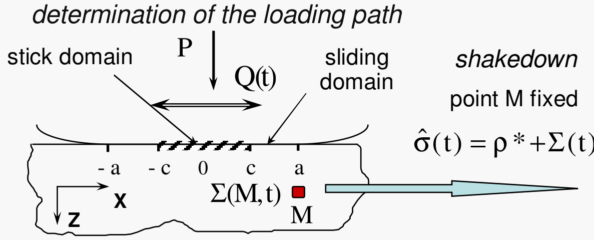
$$Q^*_{CN} = 100 N/mm$$

S. Fouvry et al., LTDS, SF2M, 29/03/2012

## Application of the Dang Van's (multiaxial criteria)

Plain Fretting

*determination of the loading path*

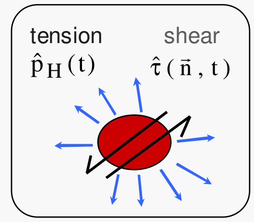



*shakedown*

point M fixed

$$\hat{\sigma}(t) = \rho^* + \Sigma(t)$$

***computation of the cracking risk (Dang Van)***




$$d_{DV} = \max_{t,\vec{n}} \left[ \frac{\|\hat{\tau}(\vec{n},t)\|}{\tau_d - \alpha.\hat{p}(t)} \right]$$

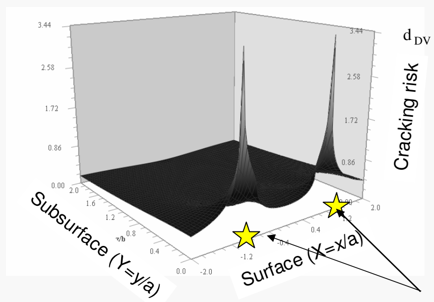
**if $d_{DV}$>1 cracking**

$$\alpha = (\tau_d - \sigma_d/2)/(\sigma_d/3)$$

$$\alpha_c = \frac{\tau_d - \sigma_d/\sqrt{3}}{\sigma_d/3}$$

$\sigma_d$ : alternating bending fatigue limit

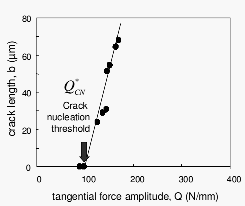
$\tau_d$ : alternating shear fatigue limit.




Cracking at the contact borders

*S. Fouvry et al., LTDS, SF2M, 29/03/2012*

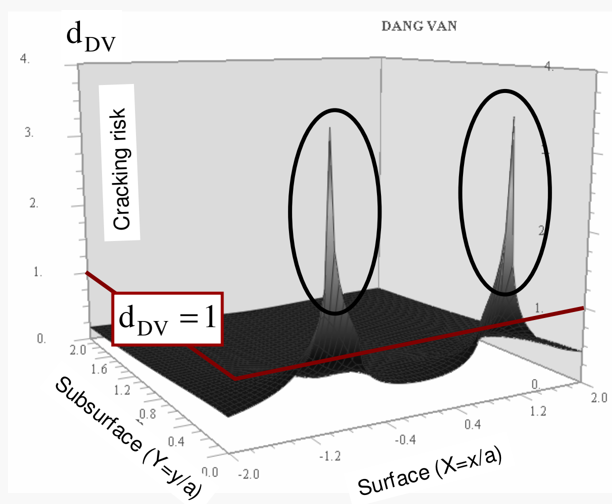
## Application of the Dang Van (Quantitative Prediction)




P=227N/mm, µ=0.85

($10^6$ cycles, $p_0$= 450 MPa)

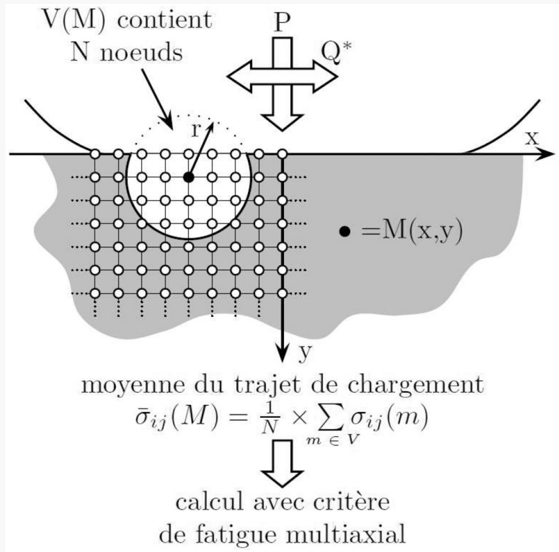
$$Q^*_{CN} = 100 N/mm$$




Overestimation of the cracking risk !!

*S. Fouvry et al., LTDS, SF2M, 29/03/2012*

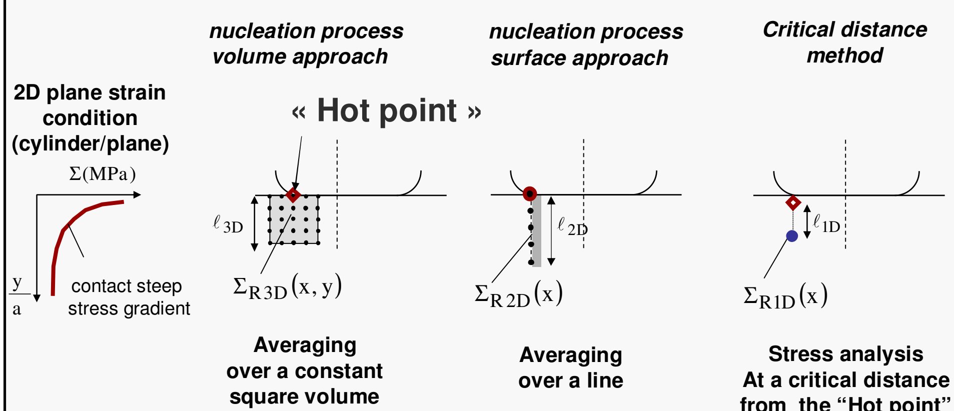
## “Non local approach” to capture stress gradient effects



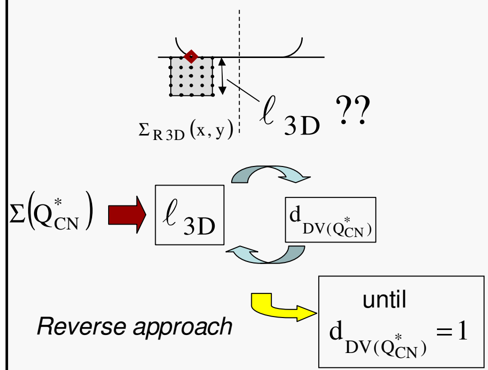


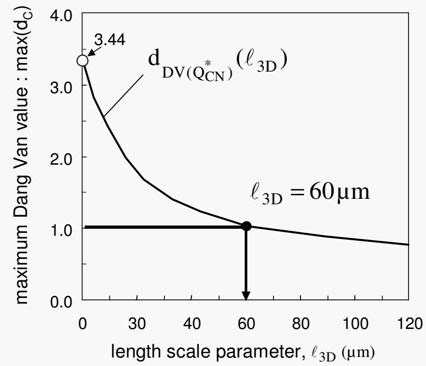

## “Non local approach” to capture stress gradient effects

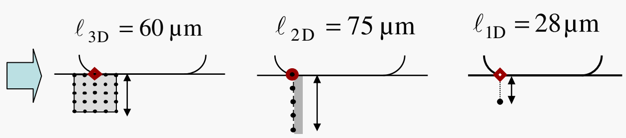
***Non local fatigue approaches***



## Identification of representative length scales (Dang Van)




$$\ell_{3D} \approx \ell_{2D} \approx \frac{\ell_{1D}}{2}$$

**Consistent with notch description (Taylor and al)**

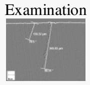
# Questions ?

**1 - What is the stability of the different "averaging approaches" regarding Fretting – Fatigue stressing ?**

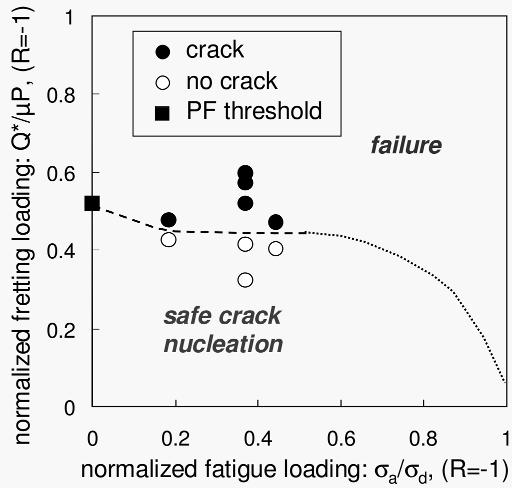
**2 - Is the length scale parameters defined from Plain Fretting configuration can be extrapolated to predict crack nucleation under Fretting Fatigue ?**

*S. Fouvry et al., LTDS, SF2M, 29/03/2012*

## Fretting – Fatigue Experiments : Identification of the crack nucleation Fretting Fatigue map

| Fatigue stress amplitude : $\sigma_a$ [MPa] (R=-1) | Tangential force amplitude Q* [N/mm] (R=-1) | Cross section Examination  |
|---|---|---|
| 50 | 92 | CRACK |
| 50 | 82 | NO CRACK |
| 100 | 115 | CRACK |
| 100 | 110 | CRACK |
| 100 | 100 | CRACK |
| 100 | 80 | NO CRACK |
| 100 | 62 | NO CRACK |
| 120 | 91 | CRACK |
| 120 | 78 | NO CRACK |

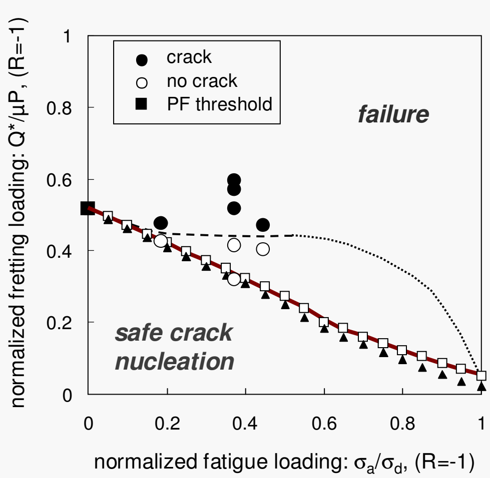
$10^6$ cycles



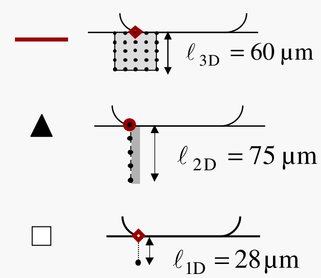

Low influence of fatigue stress amplitude in the low fatigue stress range !
(Conventional idea : crack nucleation is controlled by fretting)



## Correlation Experiments // Modelling (Dang Van)



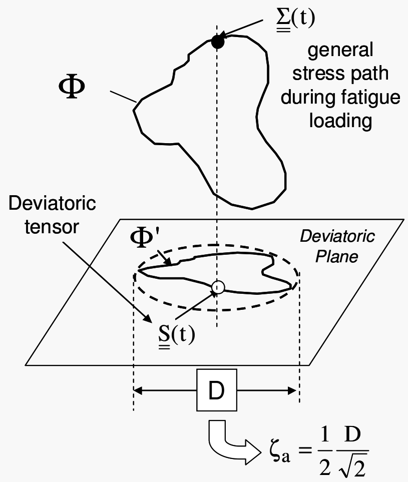

Theoretical prediction of the Fretting Fatigue crack nucleation boundary $d_{DV} = 1$




Similar tendencies !!

Pessimistic (i.e. secure) prediction of the safe crack nucleation domain from Plain Fretting identification !

## Comparison between Multiaxial Criteria (Crossland)




Crossland Criterion

$$\xi_a + \alpha_C \cdot P_{h\,max} < \tau_d$$

Hydrostatic pressure

$$P_{h\,max} = \max_{t\in T}\left(\frac{1}{3}\,\mathrm{trace}(\Sigma(t))\right)$$

$\sqrt{J_2(t)}$ component

$$\xi_a = \frac{1}{2}\max_{t_0\in T}\left\{\max_{t\in T}\left[\frac{1}{2}(\underline{\underline{S}}(t)-\underline{\underline{S}}(t_0)):(\underline{\underline{S}}(t)-\underline{\underline{S}}(t_0))\right]^{1/2}\right\}$$

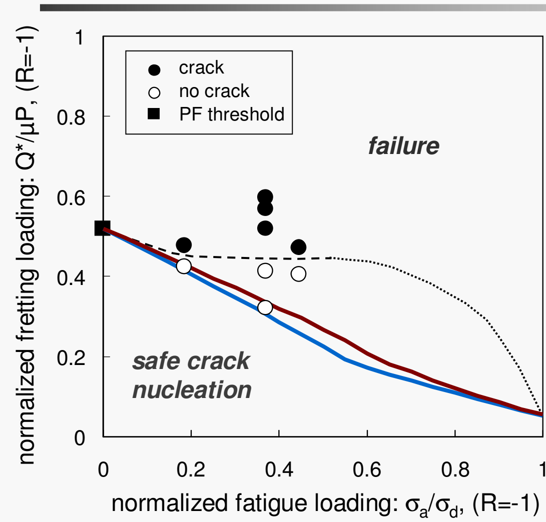
Fatigue material component $\alpha_C = \frac{\tau_d - \sigma_d/\sqrt{3}}{\sigma_d/3}$

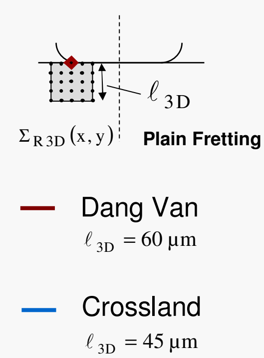
$$d_C = \frac{\xi_a}{\tau_d - \alpha_C \cdot P_{h\,max}}$$

- If is greater than or equal to 1, there is a risk of cracking;
- If remains less than 1, there is no risk of cracking.



## Comparison between Multiaxial Fatigue Criteria




**No differences between multiaxial fatigue criteria (Quasi uniaxial stress loading state at the contact border)**

**Selected "Non local Fatigue approach" => "Crossland +square averaging "**

How to prediction the Crack Arrest ?

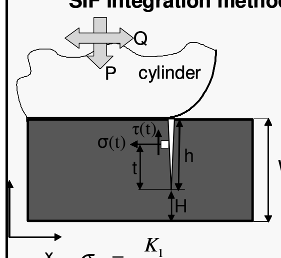


## SIF modeling at the fretting crack tip (decouple approach)

**Stress field extraction (FEM)**
**+**
**Weigth Functions (WF)**
**(Bueckner H.F.)**

Fretting Wear condition Q*= 125 N/mm
P= 230 N/mm

**SIF integration method by Weight Functions**




$$K1=\sqrt{\frac{2}{\pi}}\int M(t)\cdot\sigma(t)dt$$

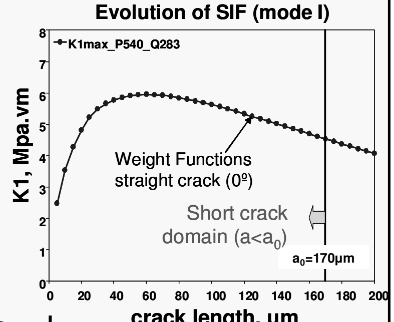
$$K2=\sqrt{\frac{2}{\pi}}\int M(t)\cdot\tau(t)dt$$

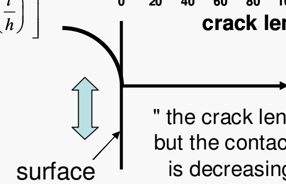
$$\sigma_{yy}=\frac{K_1}{\sqrt{2\pi r}}$$

$$\sigma_{yx}=\frac{K_2}{\sqrt{2\pi r}}$$

$$M(t)=t^{-\frac{1}{2}}\left[1+m_1*\frac{t}{h}+m_2*\left(\frac{t}{h}\right)^2\right]$$

**Evolution of SIF (mode I)**



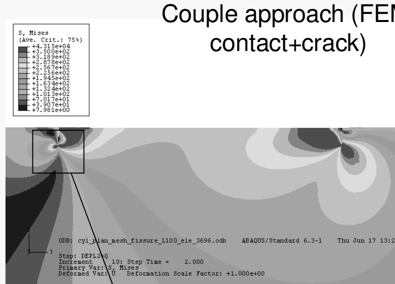



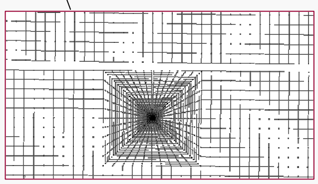

" the crack length increase but the contact stress field is decreasing very fast"

***Other approaches : Distributed Dislocations Dubourg et al. Nowell et al;***

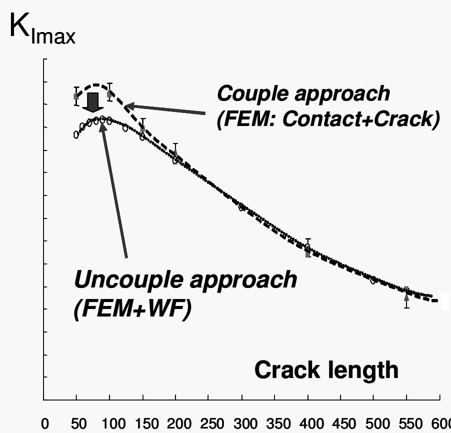
## Comparison : Couple (FEM: contact+crack) // Decouple FEM(contact) + WF

Couple approach (FEM: contact+crack)





"Crack box"- Automatic remeshing




**Selected "SIF computation" => " FEM + Weigth Functions "**



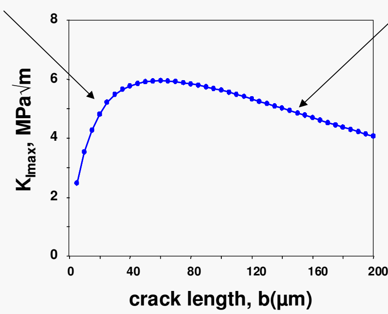
## Evolution of the SIF below the contact: Non monotonic evolution !

Plain Fretting condition

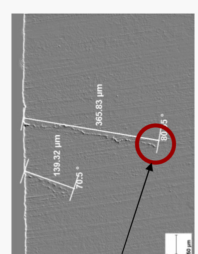
Q*= 125 N/mm
P= 230 N/mm

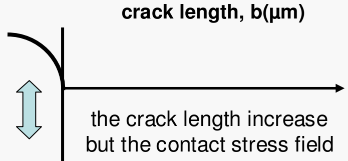
Increase of the crack length

Decrease of the contact Stress field




Plain Fretting





the crack length increase but the contact stress field is decreasing very fast

The crack stops !

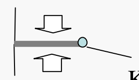
**The crack stops ! (situation of plain fretting condition)**

**Determination of the effective SIF (combining mode I and II)**

General formulation $\Delta K_{eff} = \sqrt{\Delta K_{Ieff}^{2} + \Delta K_{IIeff}^{2}}$

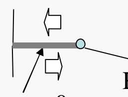

- Pure mode I (Usual hypothesis)

  $\Delta K_{eff\_I} = K_{Imax}$ Because R=-1 (closure effect)



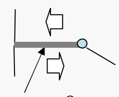

- Mixed Mode A (Crack edge with high friction)

  $\Delta K_{eff\_mixed(\mu c)} = \sqrt{K_{Imax}^{2} + K_{IImax}^{2}}$




- Mixed Mode B (Crack edge friction free)

  $\Delta K_{eff\_mixed(\mu c=0)} = \sqrt{K_{Imax}^{2} + (K_{IImax} - K_{IImin})^{2}}$



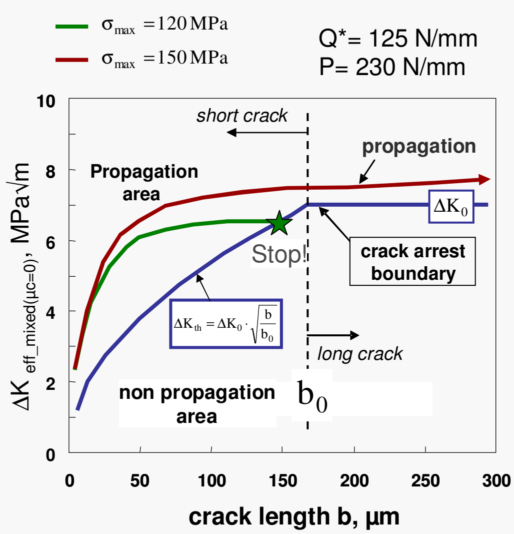

$$\Delta K_{eff\_I} < \Delta K_{eff\_mixed(\mu c=1)} < \Delta K_{eff\_mixed(\mu c=0)}$$



Identification of the crack arrest approach : KT's formulation

**Specific behavior of the crack arrest condition for the small crack !!!**

**Araujo J.A., Nowell D., Int. J. of. Fatigue, 1999, 21**




*Crack arrest approach based on the Kitagawa-Takahashi diagram*

if short crack ($b<b_0$) $\Delta K_{th} = \Delta K_0 \cdot \sqrt{\frac{b}{b_0}}$

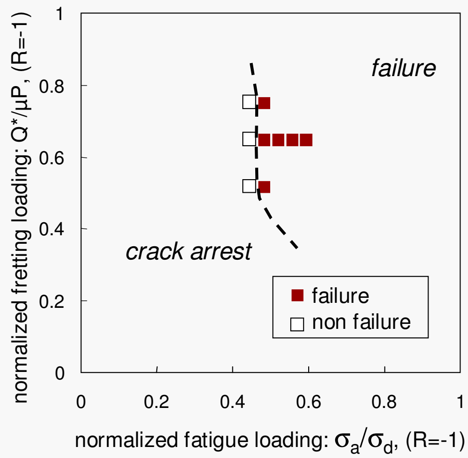
if long crack ($b>b_0$) $\Delta K_{th} = \Delta K_0$

$b_0 = \frac{1}{\pi}\left(\frac{\Delta K_0}{\sigma_f \cdot H}\right)^2$ **$b_0$ = 170µm**

## Fretting – Fatigue Experiments : Identification of the crack arrest Fretting Fatigue map

$10^7$ cycles

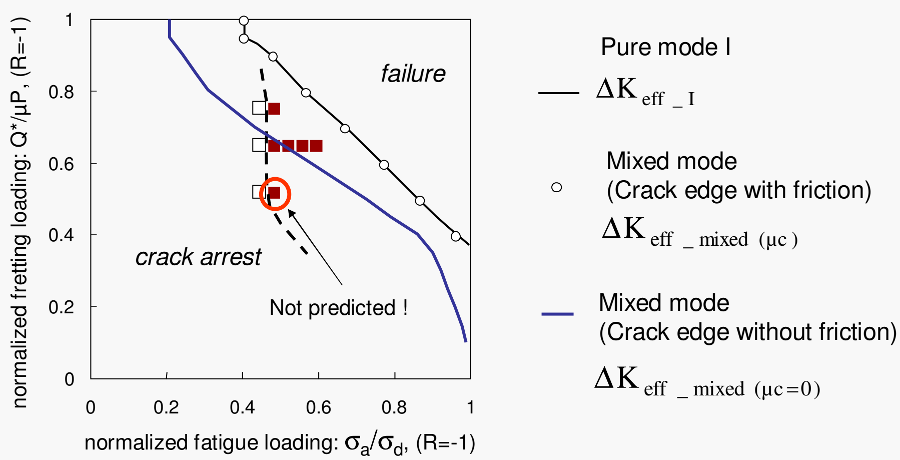
| Fretting Fatigue Test ($10^7$ cycles) | Fatigue stress amplitude : $\sigma_a$ [MPa] (R=-1) | Tangential force amplitude Q* [N/mm] (R=-1) | Maximum crack length expertised : b (µm) |
|---|---|---|---|
| FF10 | 120 | 145 | 344 |
| FF11 | 120 | 125 | 290 |
| FF12 | 120 | 100 | 59 |
| FF13 | 130 | 145 | broken |
| FF14 | 130 | 125 | broken |
| FF15 | 130 | 100 | broken |
| FF16 | 140 | 125 | broken |
| FF17 | 150 | 125 | broken |
| FF18 | 160 | 125 | broken |




Low influence of fretting stressing on the crack arrest boundary !
(Conventional idea : crack propagation is controlled by fatigue)



## Comparison between experiments & Model (KT's hypothesis of Crack arrest process)

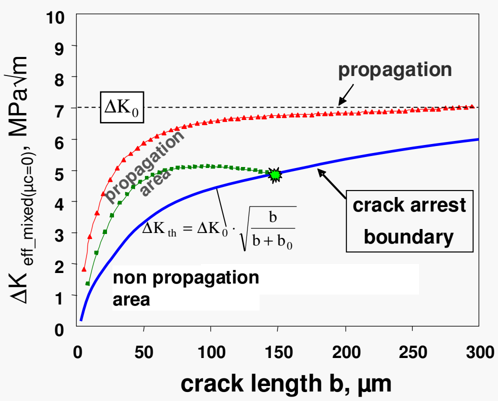



Provide too much optimistic prediction of the crack arrest boundary (non conservative)

## Alternative crack arrest approach : El Haddad et al. formulation

**Specific behavior of the crack arrest condition for the small crack !!!**

**El Haddad approach**




*Crack arrest approach based on the El Haddad et al approach*

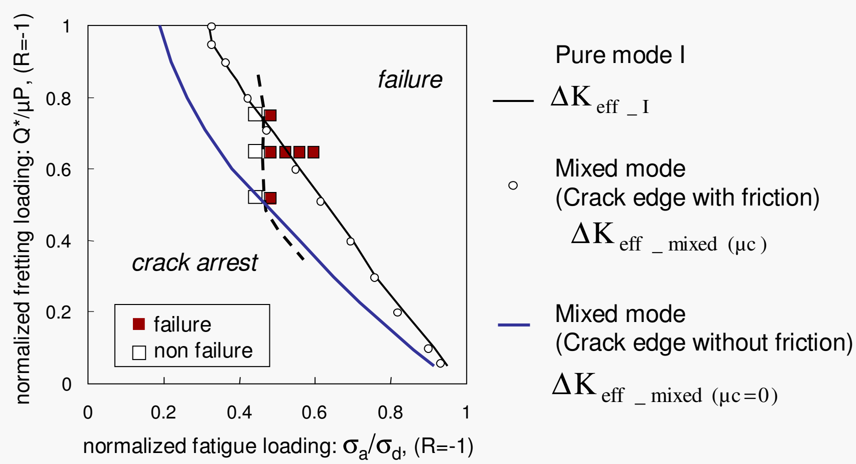
Crack Boundary

$$\Delta K_{th} = \Delta K_0 \cdot \sqrt{\frac{b}{b+b_0}}$$

⇨ Continuous evolution of the crack arrest boundary (more conservative)

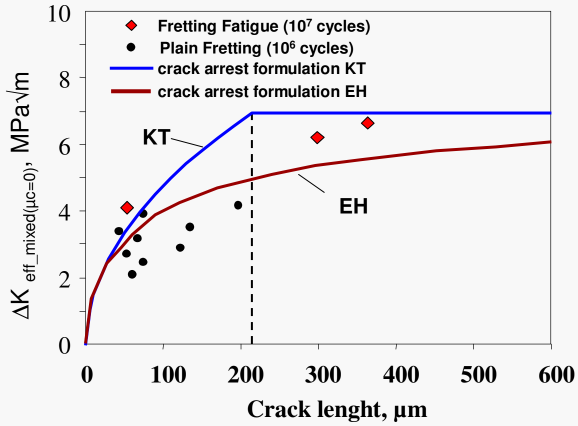


## CAFFM: Comparison between experiments & Modelling (EH et al. hypothesis of Crack arrest process)




Mixed mode (Crack edge without friction) $\Delta K_{eff\_mixed\ (\mu c=0)}$ + El Haddad's Short crack Arrest ⇨ Most representative & conservative prediction of the Crack arrest boundary

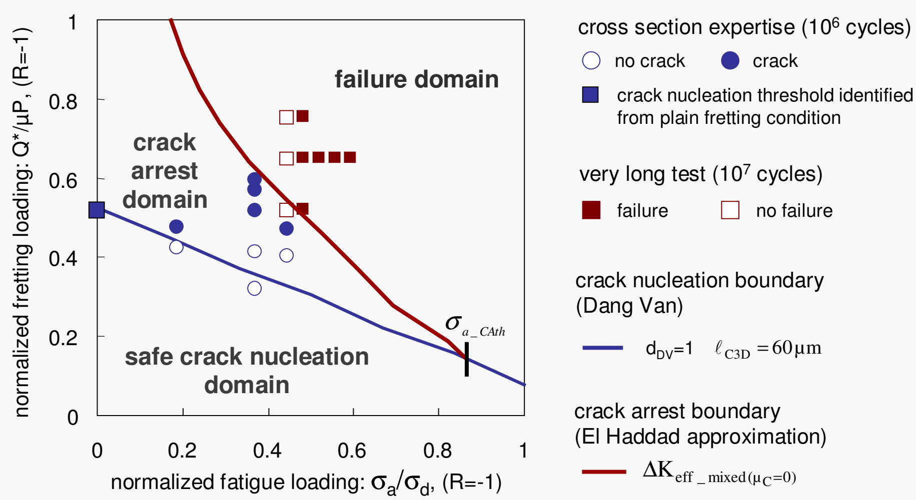
## Comparison of the crack arrest condition based on the crack length prediction




El Haddad et al. formulation provides a more conservative prediction of maximum crack length relate to crack arrest



## FFM: Synthetic Fretting Fatigue Map



## Conclusions

- A Fretting-Fatigue Mapping is introduced to formalize the cracking damages (Relative impacts of contact fretting & fatigue loadings are quantified)

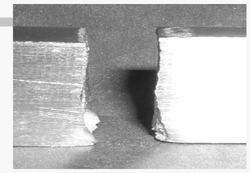
- The crack nucleation boundary can be predicted combining a Multiaxial fatigue approach (Dang Van , Crossland, etc ….) but taking into account stress gradient effects (Length scale identification from plain fretting test is validated : safe prediction of the crack nucleation boundary)

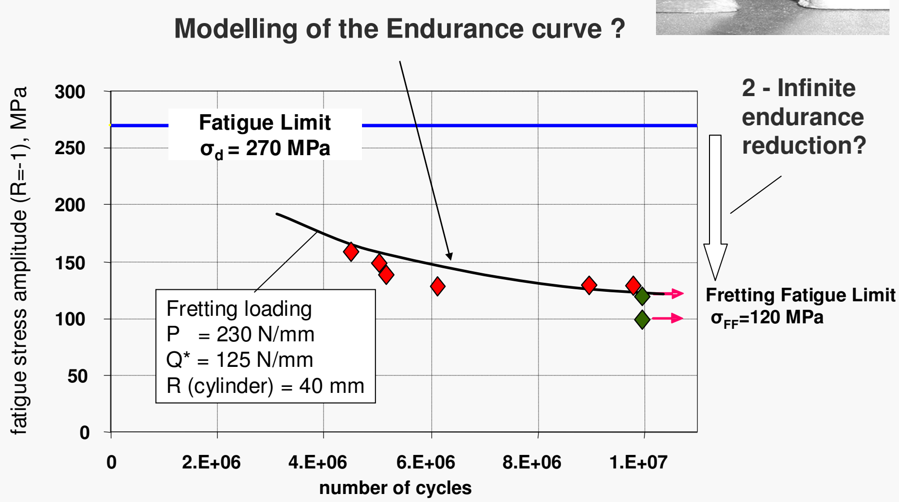
- The crack arrest boundary can be predicted combining mixed mode crack edge friction free estimation of the effective SIF range and a El Haddad description of the short crack arrest description.



# Part B : Prediction of the Finite Endurance Behaviour

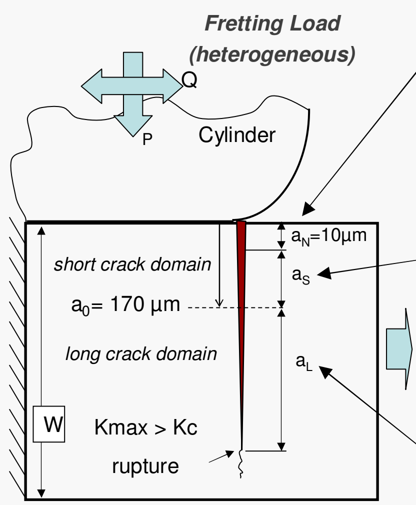
## Identification of the Fretting Fatigue Wohler curve for a constant fretting loading : "Iso fretting fretting-fatigue analysis"






S. Fouvry et al., LTDS, SF2M, 29/03/2012

## Modeling strategy




**1- Nucleation**

$N_N$ : Fretting Cycle Related to the crack nucleation

Finite endurance formulation

**2 - Short crack propagation**

$N_S$- Fretting cycles in short crack propagation ($a<a_0$)

Dowling N.E. et al. ASTM-STP- 637

Vormwald M. IJF, 28

$$N_{FC} = \int_{a_0}^{a} \frac{da}{C'(\Delta J)^{m'}}$$

**3 - Long crack propagation** **Paris Law**

$N_L$- number of cycles in long crack propagation regime ($a>a_0$)

Loi de Paris

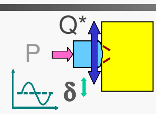
$$N_{FL} = \int_{a_0}^{a} \frac{da}{C \cdot (\Delta Keff)^{m}}$$

short crack transition $$a_0 = \frac{1}{\pi}\left(\frac{\Delta K_0}{\sigma_f \cdot H}\right)^2$$

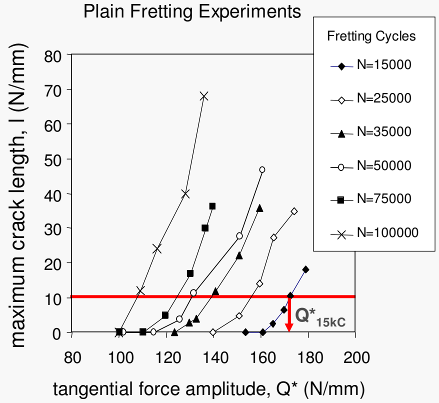
**Fretting Fatigue Endurance** $N_{Total}=N_N+N_S+N_L$

S. Fouvry et al., LTDS, SF2M, 29/03/2012

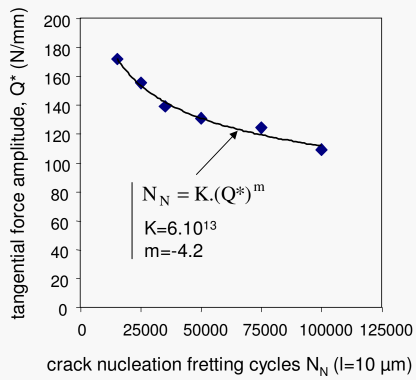
## Identification of the finite endurance behavior (reverse identification of plain fretting tests)




Plain Fretting Experiments



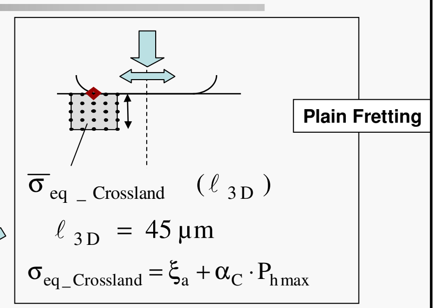

P= 230 N/mm
R= 40 mm
$p_{0H}$= 450 MPa , $a_H$ = 320 µm

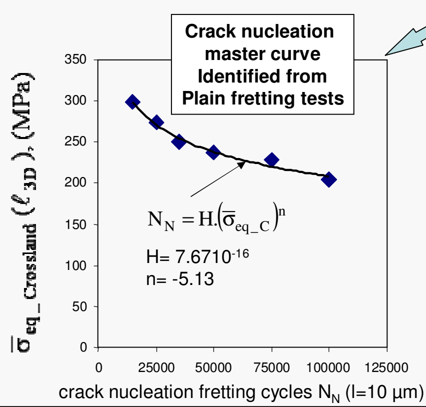


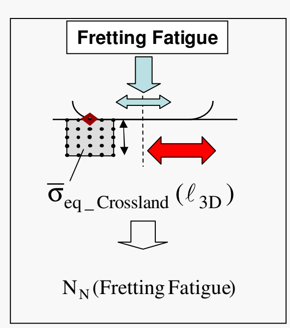

*S. Fouvry et al., LTDS, SF2M, 29/03/2012*

## Identification of the finite endurance behavior ($N_N$ computation)

Plain Fretting Test condition
P= 230 N/mm
R= 40 mm
$p_{0H}$= 450 MPa , $a_H$ = 320 µm
$N_N = K.(Q^*)^m$
K=6.10^-13, m=-4.2



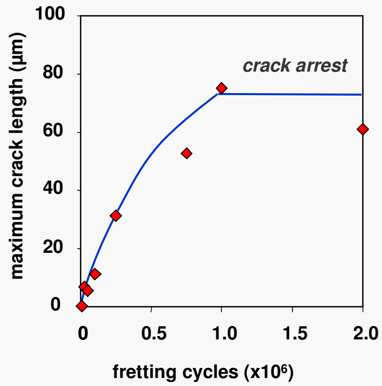



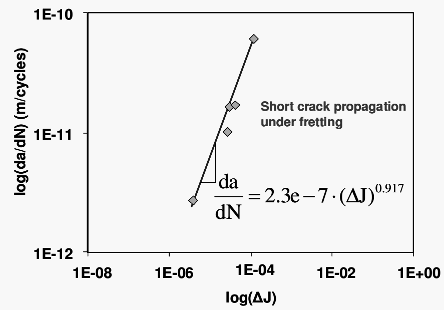




*S. Fouvry et al., LTDS, SF2M, 29/03/2012*

## Identification the short crack kinetics ($a < a_0$)

Plain Fretting Experiments



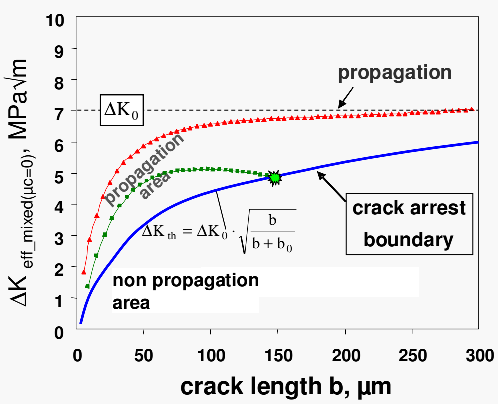

Q*= 125 N/mm
P= 230 N/mm

reverse indentification of the Vormwald law integration !!! (*da/dN=c'ΔJ*$^{m'}$)

*S. Fouvry et al., LTDS, SF2M, 29/03/2012*

## Identification of the crack arrest approach

**Specific behavior of the crack arrest condition for the small crack !!!**
**Araujo J.A., Nowell D., Int. J. of Fatigue, 1999, 21**




*Crack arrest approach based on the El Haddad et al approach*

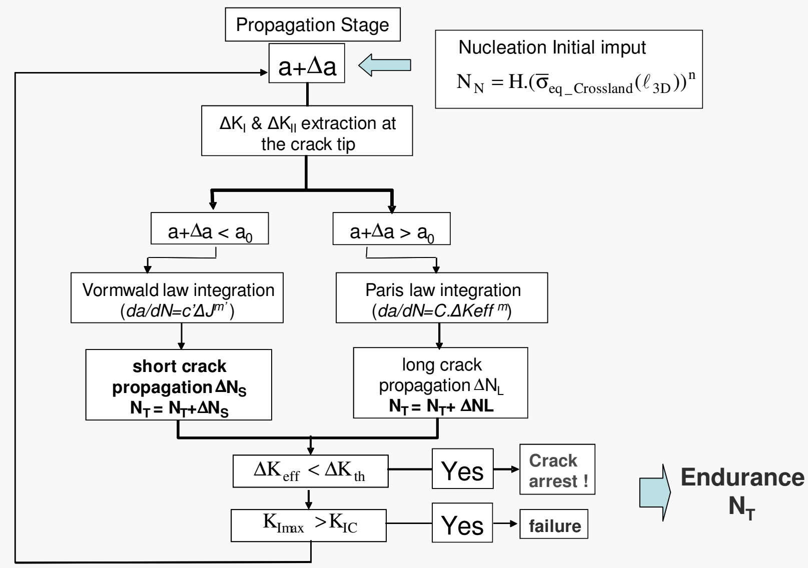
Crack Boundary

$$\Delta K_{th} = \Delta K_0 \cdot \sqrt{\frac{b}{b+b_0}}$$

Continuous evolution of the crack arrest boundary (more conservative)

*S. Fouvry et al., LTDS, SF2M, 29/03/2012*

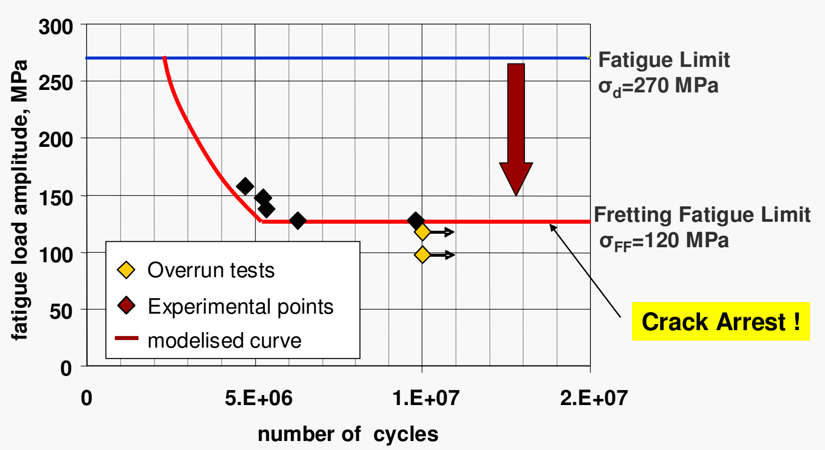
## Algorithm to identify the fretting fatigue endurance




$N_{total} = N_{Nucleation} + N_{Propgation\ (Short\ Crack)} + N_{Propagation\ (Long\ Crack)}$

S. Fouvry et al., LTDS, SF2M, 29/03/2012

## RESULTS : Prediction of the endurance and infinite life




Material limit reduction factor under fretting fatigue loading

$$K_{FF(N)}(\%) = \frac{\sigma_{dF}(N) - \sigma_{dFF}(N)}{\sigma_{dF}(N)} = 55\%$$

S. Fouvry et al., LTDS, SF2M, 29/03/2012

## Conclusions

- Combined Fretting Wear and Fretting Fatigue analysis appears as pertinent approach to quantify the different stages of the fretting fatigue damages

- It is shown that applying a reverse analysis of Fretting Wear crack length data it is possible to determine the short crack propagation kinetics but the fretting fatigue cycles to crack nucleation

- By summing successively the cycles related to the crack nucleation, short crack propagation and long crack propagation, a good approximation of the total fretting-fatigue endurance is achieved

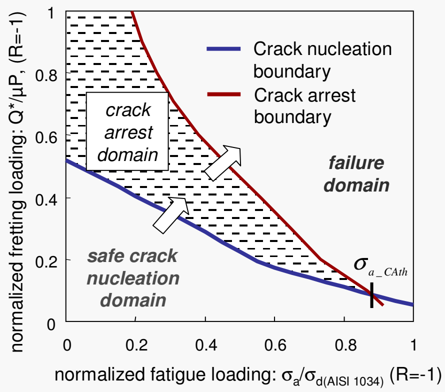


# Part C : Materials and Palliative Strategies

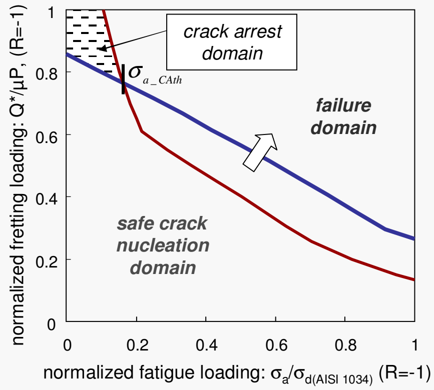
S. Fouvry et al., LTDS, SF2M, 29/03/2012

## Impact of material properties : ratio $\Delta K_0/\sigma_d$

**AISI 1034** : $\Delta K_0$= 7 MPa√m, $\sigma_d$=270 MPa




**TA6V** : $\Delta K_0$= 5 MPa√m, $\sigma_d$=450 MPa

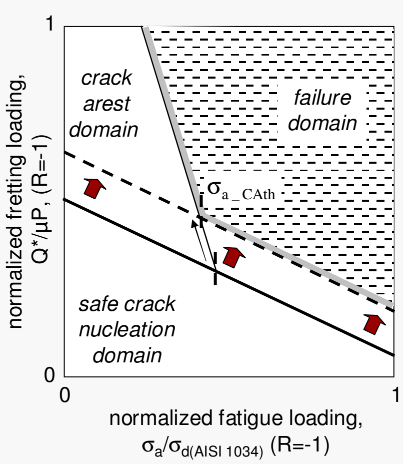



⇨ **A designing based on a crack nucleation prediction is secured by the presence of an extended Crack arrest domain**

⇨ **Very limited crack arrest domain:**
**A designing based on a crack nucleation prediction is unstable.**
**A damage tolerance approach appears more conservative than a crack Nucleation strategy !!!**



## Increase of the Safe Crack Nucleation domain

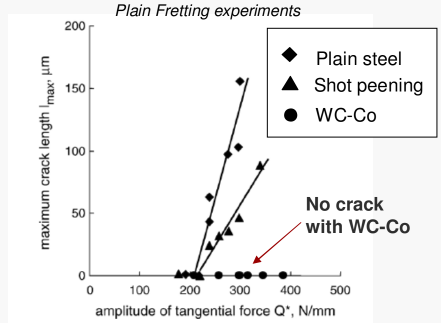



### Coatings !

-**Hard coating inducing very high and Stable compressive stresses on top surface (ex. TiN, etc ..)**

- **Soft coating : capacity to accommodate The deformation by plasticity (Thick CuNiln, Aluminum, Bronze, etc … )**

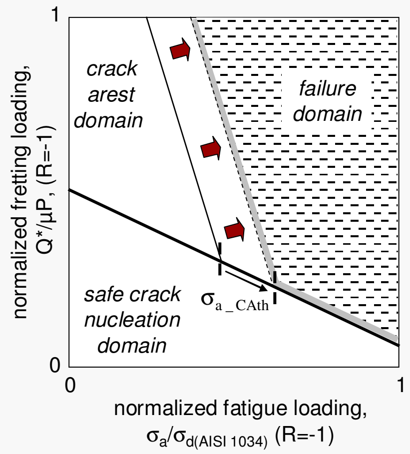
*Plain Fretting experiments*




*Surf. & Coat. Technology, 201, 2006*

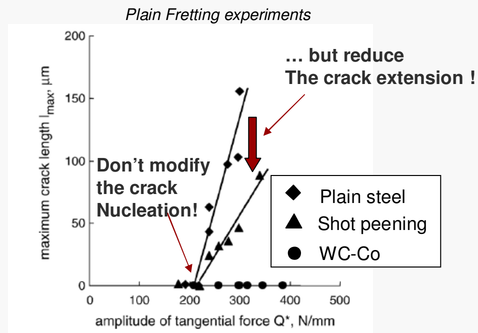
⇨ Pb. : Wear of Coating ?

## Increase of the Crack Arrest Domain




Solution: Shot peening, laser Peening !

**Introduction of compressive residual Stresses which block the crack Propagation…**

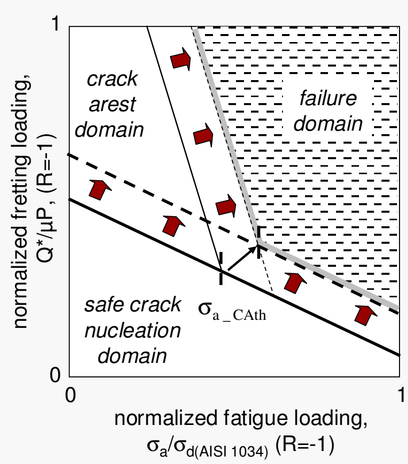



*Surf. & Coat. Technology, 201, 2006*

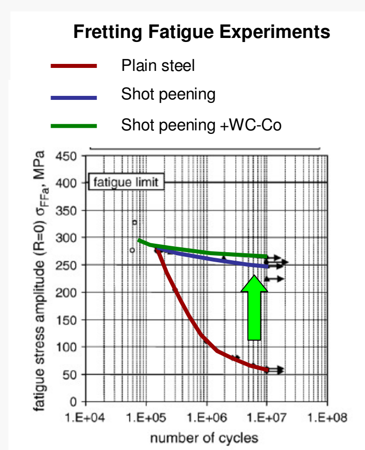
Pb. : Relaxation of residual stresses ?



## Combined approach : crack nucleation & crack Arrest domains extension



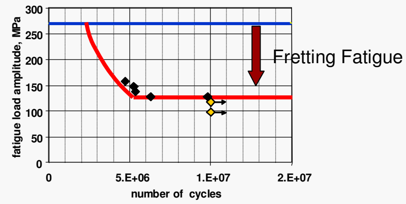

**Ex. : Shot peening + WC-Co (HVOF) !**




*Suf. & Coat. Technology, 201, 2006*

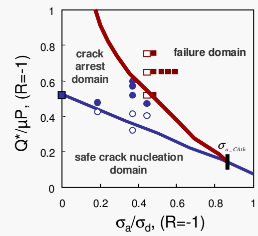
CONCLUSIONS

Different strategies are now effectives to predict the finite endurance induced by fretting fatigue loadings

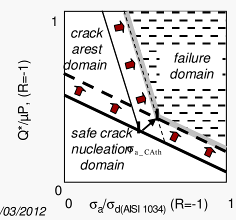



But also to identified the Fretting – Fatigue loading region where no crack can be nucleated
Or at least are supposed to stop !

- ***Non local fatigue approach***
- ***Short Crack Arrest pproach***



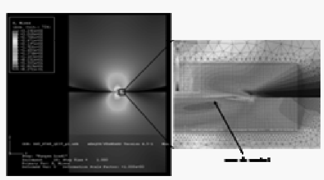

Adequate strategies can be developed to select Pertinent palliatives

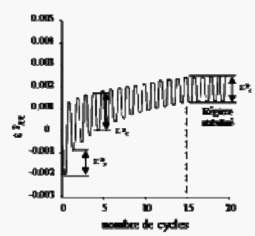



*S. Fouvry et al., LTDS, SF2M, 29/03/2012*

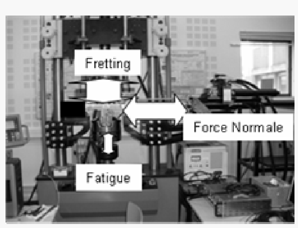
# Perspectives

**Plasticity !!!**

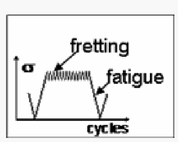




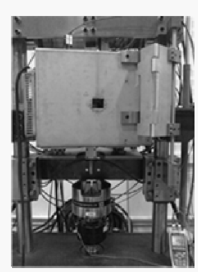

*Better take into account the plastic accommodation in contacts*




Fretting Fatigue Triple Actuators
(Ambient conditions)




*Complex &*
*Variable Loading Conditions*



Fretting Fatigue Double Actuator
(800°C)

*S. Fouvry et al., LTDS, SF2M, 29/03/2012*

References (LTDS => Send a Email for copy : siegfried.fouvry@ec-lyon.fr)


S. Fouvry, Ph. Kapsa, L. Vincent, K. Dang Van, "Theoretical analysis of fatigue cracking under dry friction for fretting loading conditions", WEAR, 195, (1996), p.21-34

S. Fouvry, Ph. Kapsa, F. Sidoroff, L. Vincent, "Identification of the characteristic length scale for fatigue cracking in fretting contacts", J. Phys. IV France 8 (1998), Pr8-159-166.

S. Fouvry, Ph. Kapsa, L. Vincent, "A Multiaxial Fatigue Analysis of Fretting Contact Taking into Account the Size Effect", Fretting Fatigue 1998,ASTM STP 1367, 2000, p.167-182.

H. Proudhon, S. Fouvry, and G.R. Yantio "Determination and prediction of the fretting crack initiation: introduction of the (P, Q, N) representation and definition of a variable process volume", International Journal of Fatigue, Volume 28, Issue 7, 2006, Pages 707-713.

S. Muñoz, H. Proudhon, J. Domínguez and S. Fouvry "Prediction of the crack extension under fretting wear loading conditions" International Journal of Fatigue, Volume 28, Issue 12, December 2006, Pages 1769-1779.

Kubiak K., S. Fouvry S., Marechal A.M., Vernet J.M, " Behaviour of shot peening combined with WC–Co HVOF coating under complex fretting wear and fretting fatigue loading conditions ", Surface & Coatings Technology 201 (2006) p. 4323-4328.

Proudhon H., Buffière J-Y. and Fouvry S., Three-dimensional study of a fretting crack using synchrotron X-ray micro-tomography, Engineering Fracture Mechanics, Volume 74, Issue 5, March 2007, Pages 782-793.

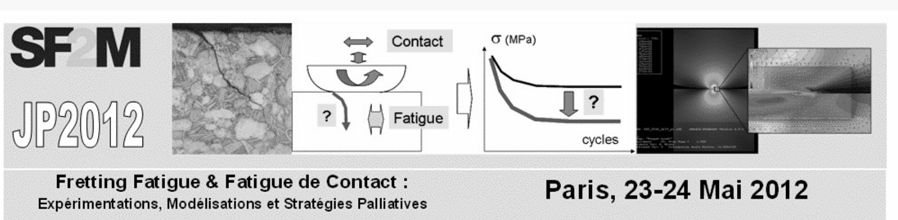
S. Fouvry, D. Nowell, K. Kubiak and D.A. Hills, Prediction of fretting crack propagation based on a short crack methodology, Engineering Fracture Mechanics, Volume 75, Issue 6, April 2008, Pages 1605-1622.

S. Fouvry, K. Kubiak, Introduction of a fretting-fatigue mapping concept: Development of a dual crack nucleation – crack propagation approach to formalize fretting-fatigue damage, International Journal of Fatigue (2009), 31, 250-262.

S. Fouvry, K. Kubiak, Development of a fretting–fatigue mapping concept: The effect of material properties and surface treatments, Wear (2009), 267, 2186–2199




## JP2012 : Fretting Fatigue & Fatigue de Contact
## Paris 23 – 24 mai 2012




**www.sf2m.asso.fr/JP2012/JP2012.htm**