Action Nationale de Formation (ANF)
METALLURGIE FONDAMENTALE
22 -25 Octobre 2012 à Aussois

# Fatigue of metals, view point and prospect

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Fatigue & structural durability

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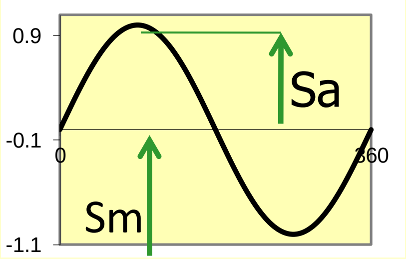
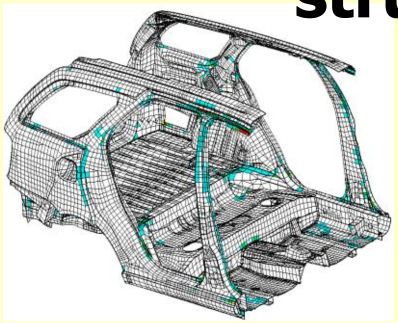
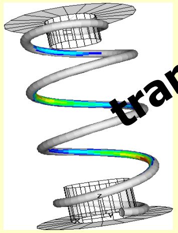
# Mechanical engineering applications

**What will be the response of a structure under a cyclic loading?**

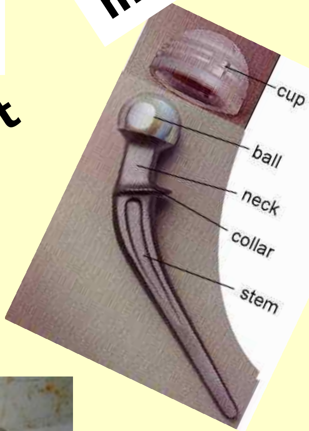


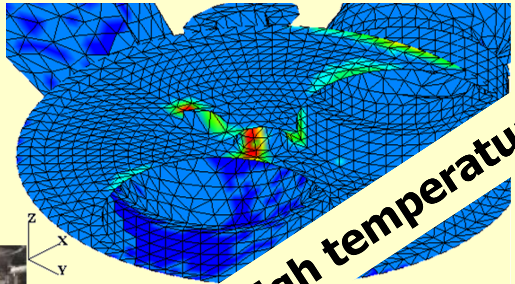


transport

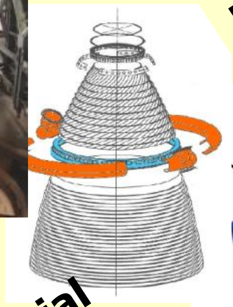
medical



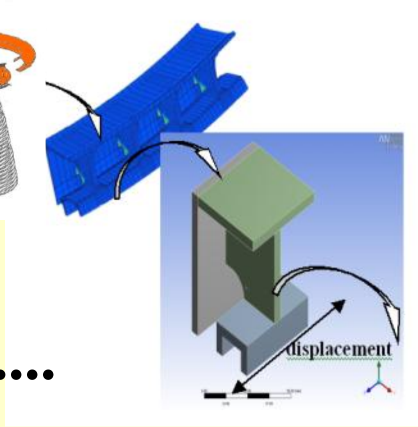

energy



High temperature



spatial

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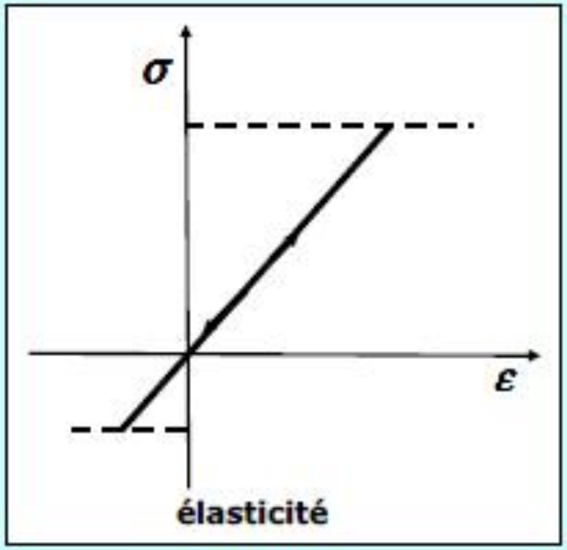
# Structures under cyclic loading

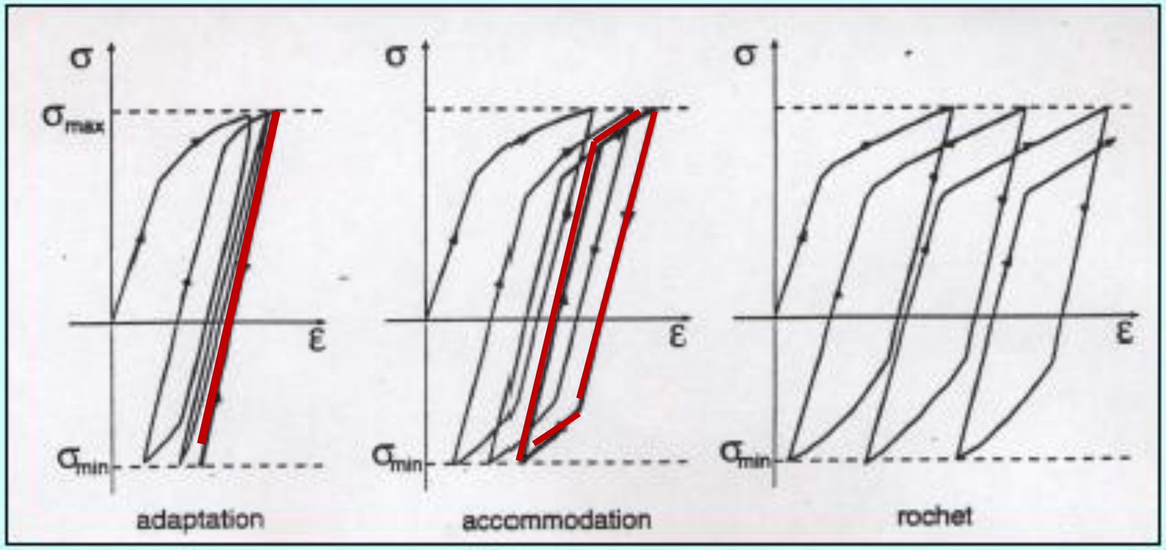
## Asymptotic states

**Asymptotic behavior of elasto-visco-plastic structures under thermomechanical cyclic loading:**

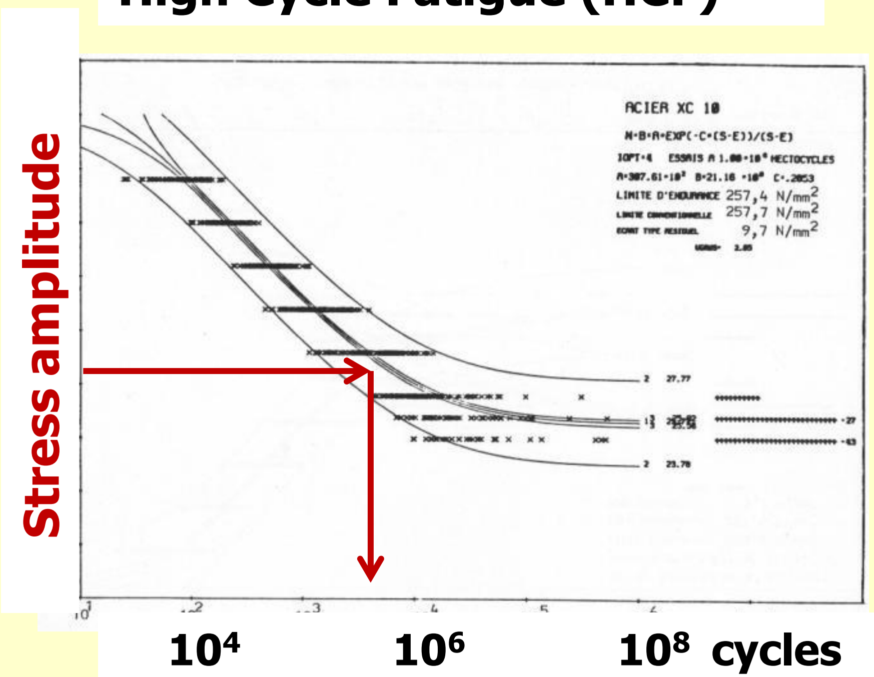
- **Elasticity**
- **Elastic shakedown**
- **Plastic shakedown**
- **ratcheting**

} **stabilized response**



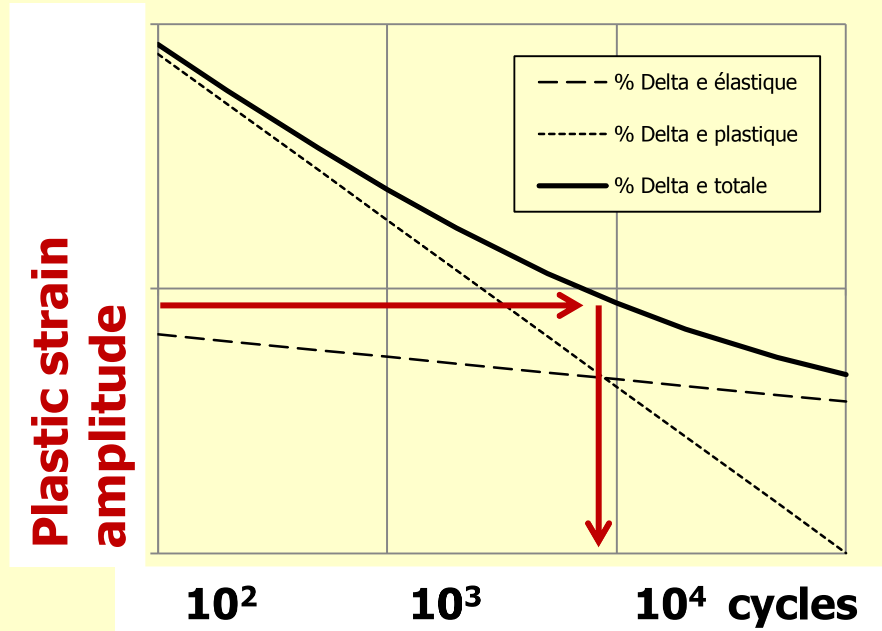



## High Cycle Fatigue (HCF)




**Fatigue life**
**Elasticity & elastic shakedown**

## Low Cycle Fatigue (LCF)

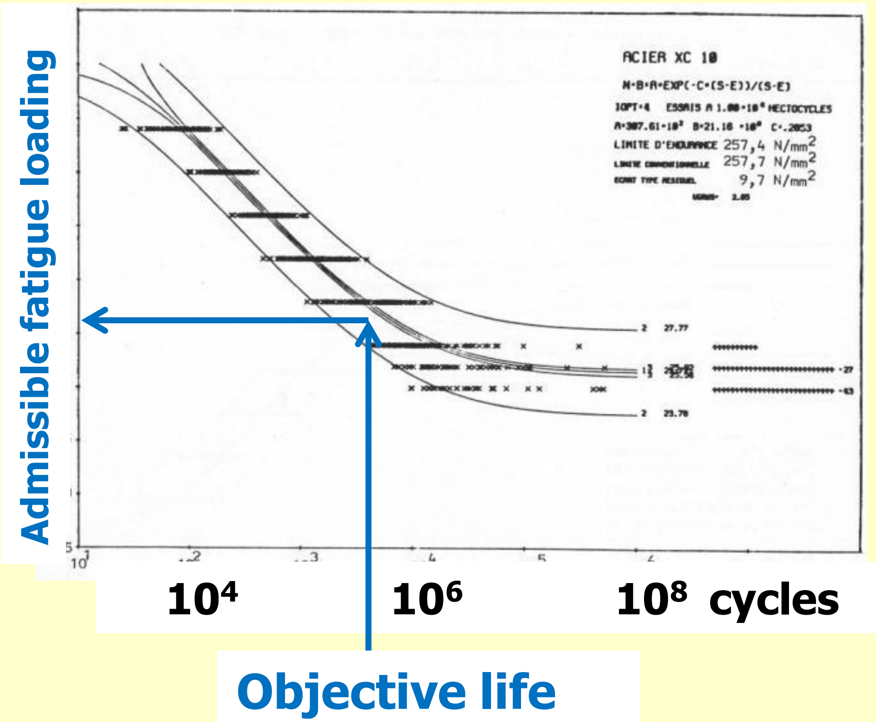



**Fatigue life**
**Inelasticity , plastic shakedown**

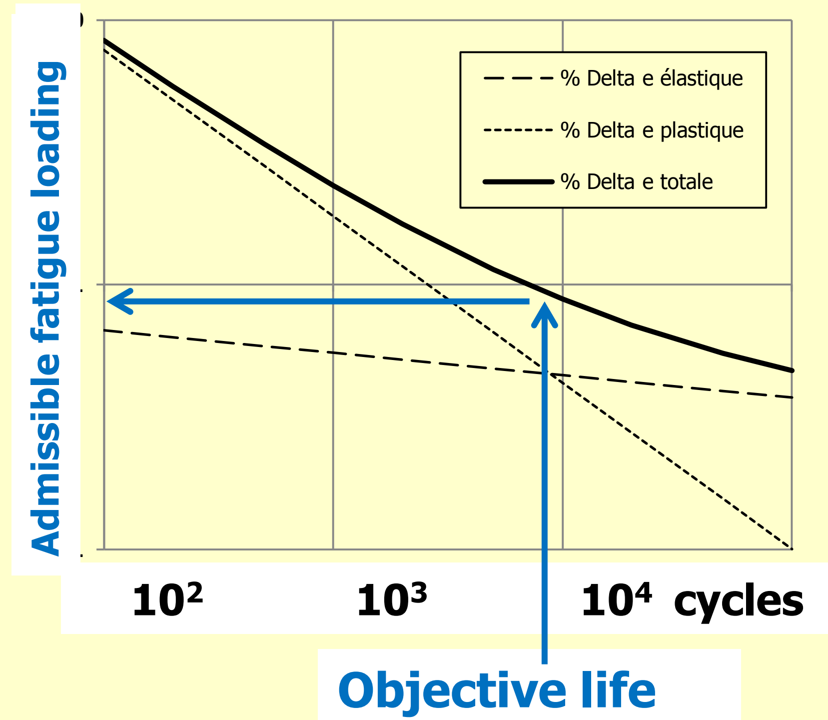
***+***
***mean stress effect***
***Multiaxial stress & strain effect***
***Small size defects & nonmetallic inclusions***

# Mechanical engineering applications

## High Cycle Fatigue (HCF)




## Low Cycle Fatigue (LCF)




**Define a technical specification**

- **shakedown theory / fatigue concept high cycle fatigue and low cycle fatigue**
- **Mechanical engineering applications**
- **View point & prospect**

# *The shakedown theory / fatigue concept*

- **Daniel C. Drücker, 1963**

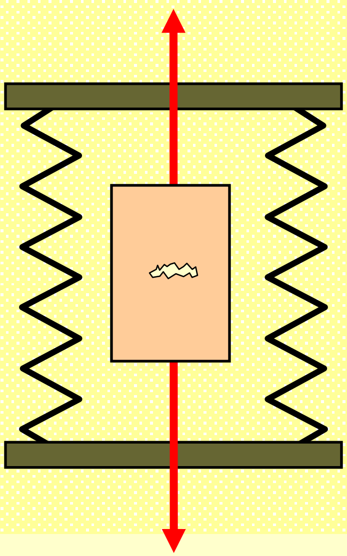
***'When applied to the microstructure, there is a hope that the concepts of endurance limit and shakedown are related and that fatigue failure can be related to energy dissipated in idealized material when shakedown does not occur "***

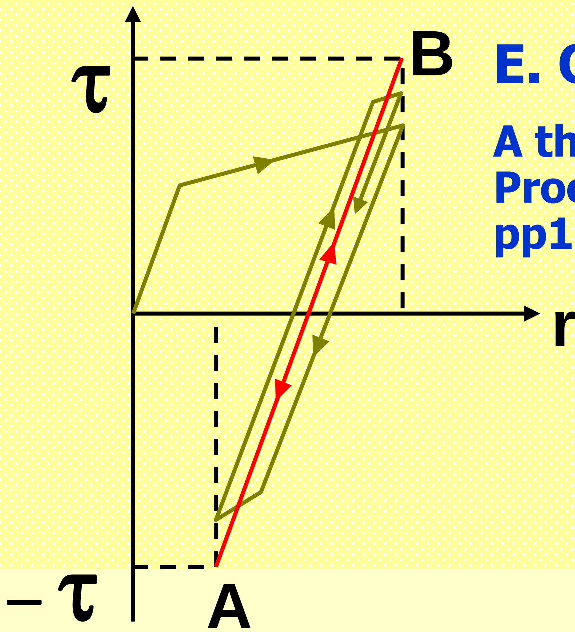
**On the macroscopic theory of inelastic stress-strain-time-temperature behavior.**
**in AGARD – Advances in material researchs in the NATO Nations pp 193-221, January 1963**

## A POSSIBLE APPROACH:

**THE MATERIAL IS CONSIDERED AS A STRUCTURE (MICRO-STRUCTURE) SUBMITTED TO CYCLIC (VARIABLE) LOADINGS**

- **Mathematical Results (Melan, Koiter theorem…)**
- **Results on the Theory of polycristalline agregates**






**E. Orowan, 1939,**

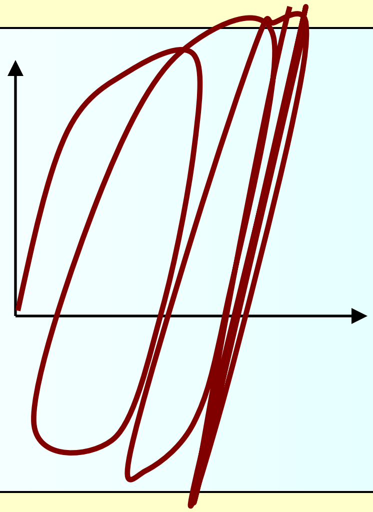
**A theory of the fatigue of metals, Proc. Royal Soc., London, A, pp171-179**

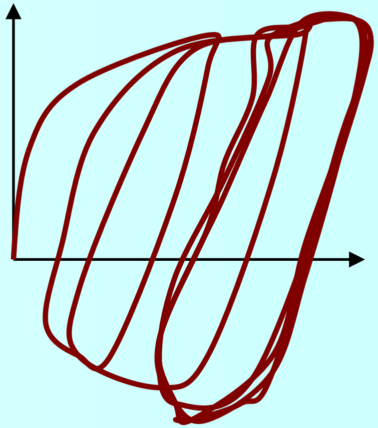
**Meso macro relationship**

## Meso/Macro Scales, Cyclic behaviour, Shakedown

**HCF** | **LCF**

**MACRO**
**Structure**

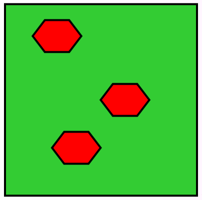




**Ratcheting**

**elastic shakedown** | **plastic shakedown**

**MESO**
**Grain**



**Energy dissipation!**

# *The shakedown theory / fatigue concept*

- **High Cycle Fatigue criterion**

**first damage** ➡ **grains : Meso scale**

***Scale of material description for relevant parameters ?***

***Meso scale*** ***Macro scale***

$$\sigma, \varepsilon, \varepsilon^p \qquad \Sigma, E, Ep$$

*LIN-TAYLOR:* $E=\varepsilon=\varepsilon_e+\varepsilon_p$

$\sigma = l.L^{-1}.\ \Sigma + l.(\varepsilon_p - E_p)$

$$\sigma = A:\Sigma + \rho \quad (\neq K:\Sigma)$$

**If** $\varepsilon_p \rightarrow E_p,\ \rho \rightarrow 0,$

$\sigma \approx \Sigma$ *(SACHS)*, $w_p \approx W_p$

***residual stress from loading cycle,***

***strongly dependant of the loading path***

# *At shakedown*

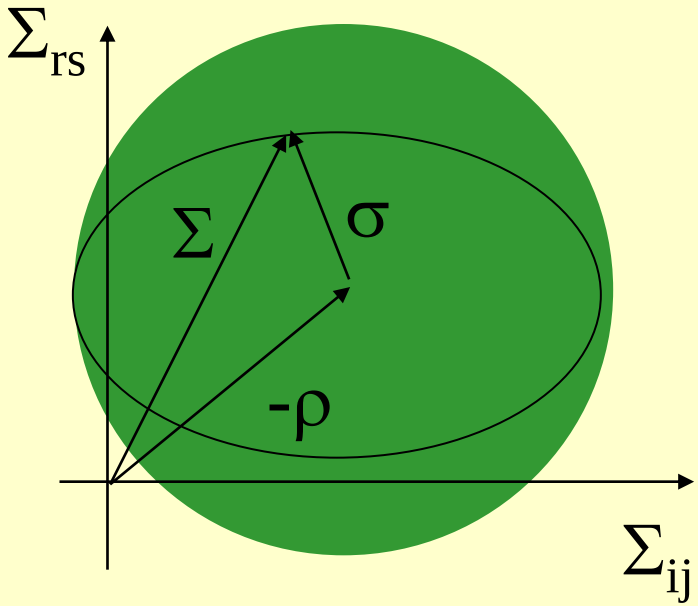
$\sigma(x,t) = \Sigma(x,t) + \rho(x)$

## *Polycyclic Fatigue criterion:*

$f(\sigma(x,t)) < 0 \Rightarrow$ ***no fatigue***

$f(\sigma(x,t)) \equiv a\,\tau(t) + p(t)$

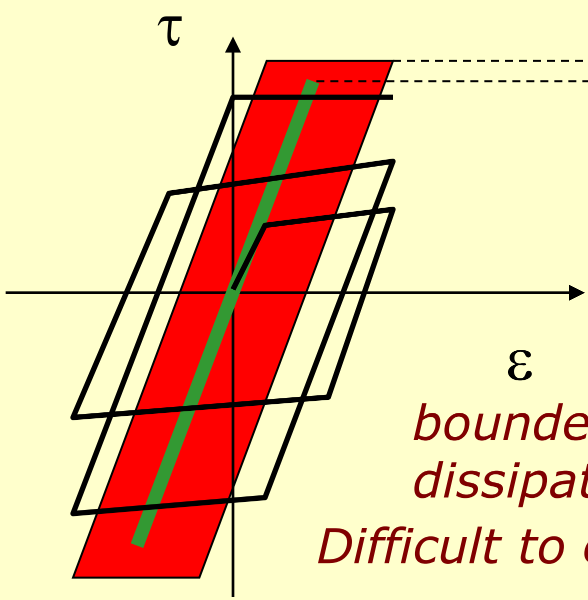
$\tau$: ***shear;*** $p = (\text{Trace}\ \sigma)/3$

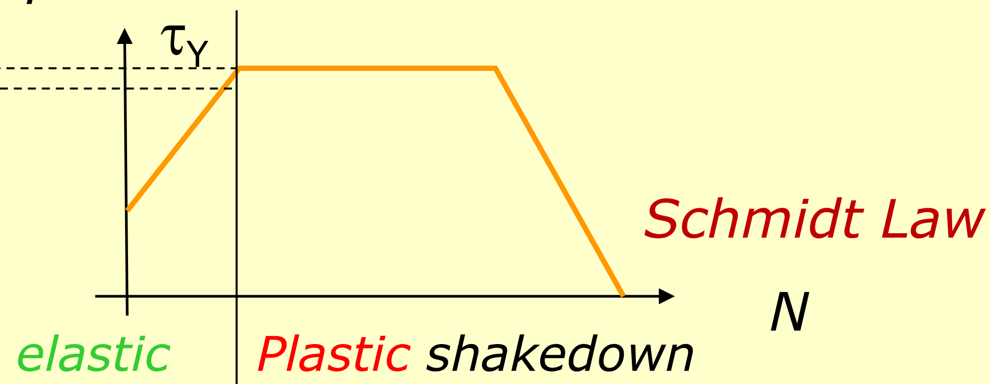


# ***HCF* : shakedown & dissipated energy**

***MACRO*** *Elastic (or Shakedown)*

***MESO*** *reasoning on a slip plane*




*bounded*
*dissipated energy*

Shakedown parameter σ

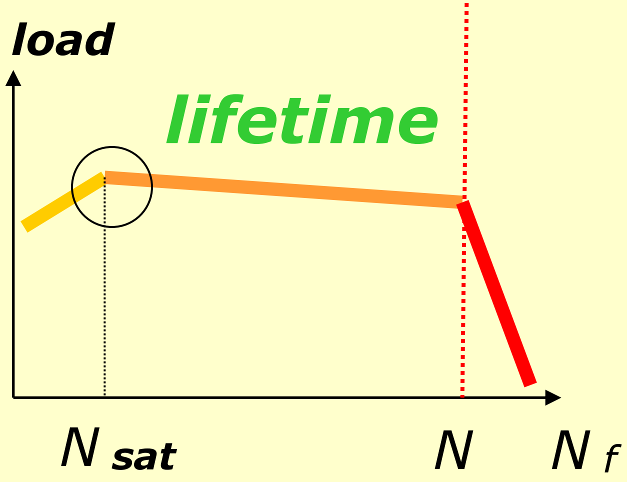
*Difficult to estimate:* *alternative approach in meso stress*

**The fatigue limit correspond to the limit of the elastic shakedown possibility of the material in the structure at the macro scopic scale and the meso scopic scale**

***Dang Van Criteria:***
*Papadopoulos, ...*

$$\max_t \left\{ \tau(t) + a p(t) \right\} \leq b$$

# LCF : shakedown & dissipated energy




**MESO** Skelton [1991]

- ***constant cumulated dissipated energy at saturation point***

**MACRO**

***Charkaluk & Constantinescu [2001]***
***Maitournam [2001]***

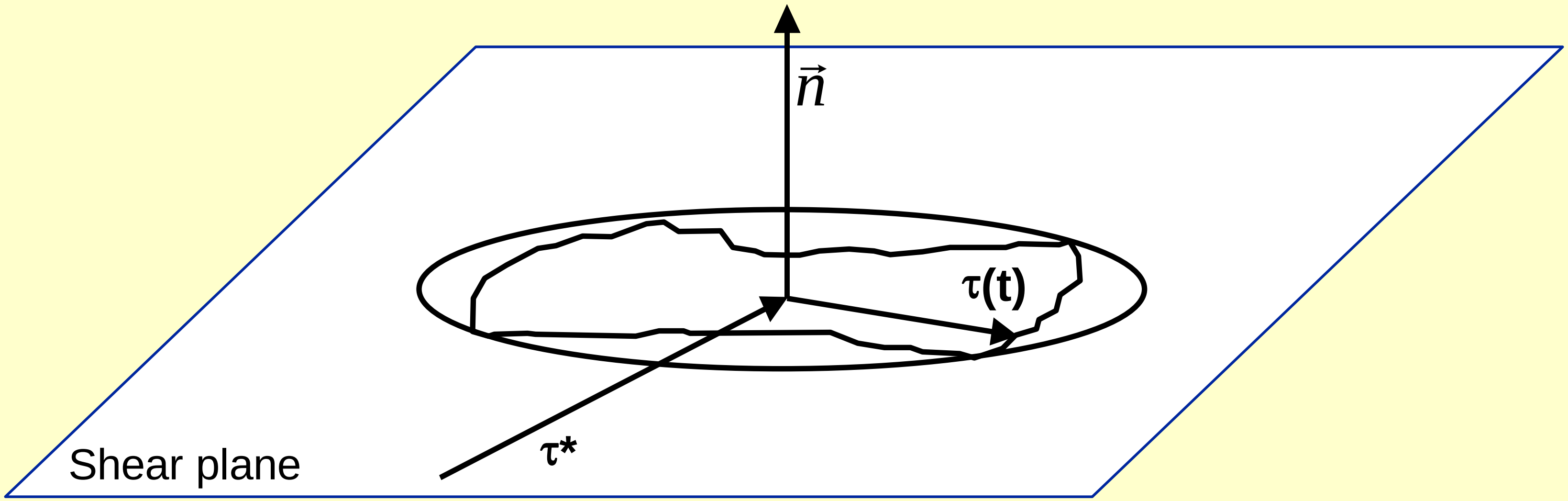
- *fatigue life determined by stabilized cycle at saturation point*

**LCF Criterion** $N_f = N = f(W_{sat})$

$W = C.N^{\beta}$

# HCF : Mechanical engineering applications

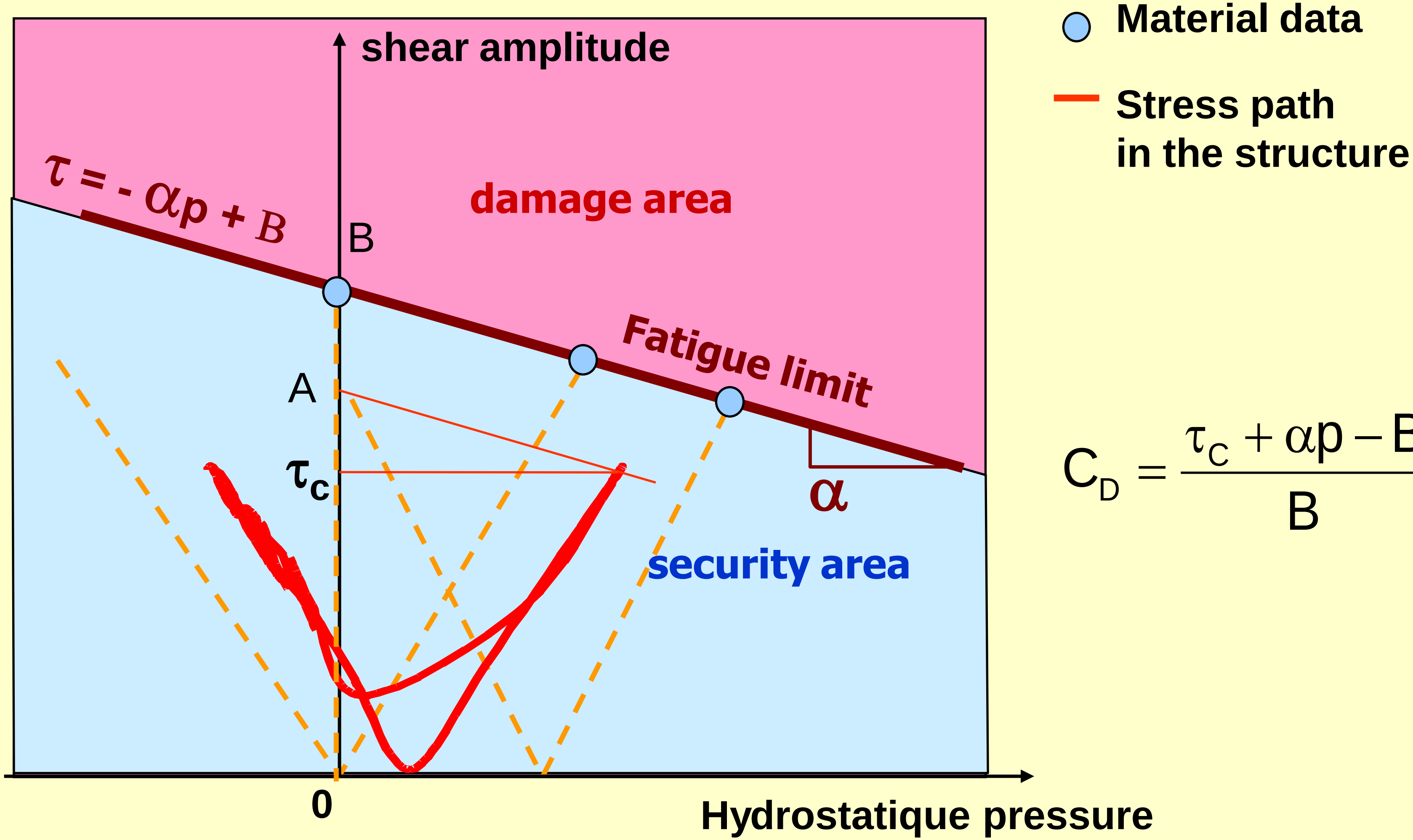
## DANG VAN'S CRITERION




- Computation of $\tau(t)$ et $p(t)$ at each instant
- Research, on each shear plane, of the smallest circumscribed circle of the loading path
- The fatigue criterion is : $\boxed{\tau + \alpha . p < B}$

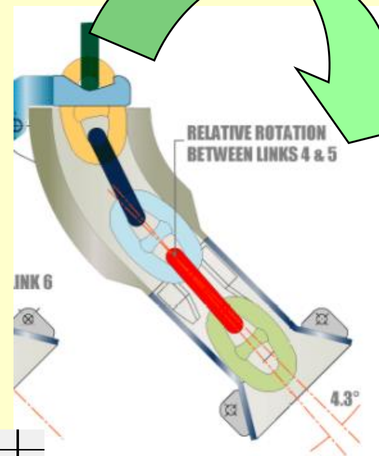
**$\tau$ : shear amplitude on the critical plane**
**p : hydrostatic pressure**

# HCF : Mechanical engineering applications




$$C_D = \frac{\tau_C + \alpha p - B}{B}$$

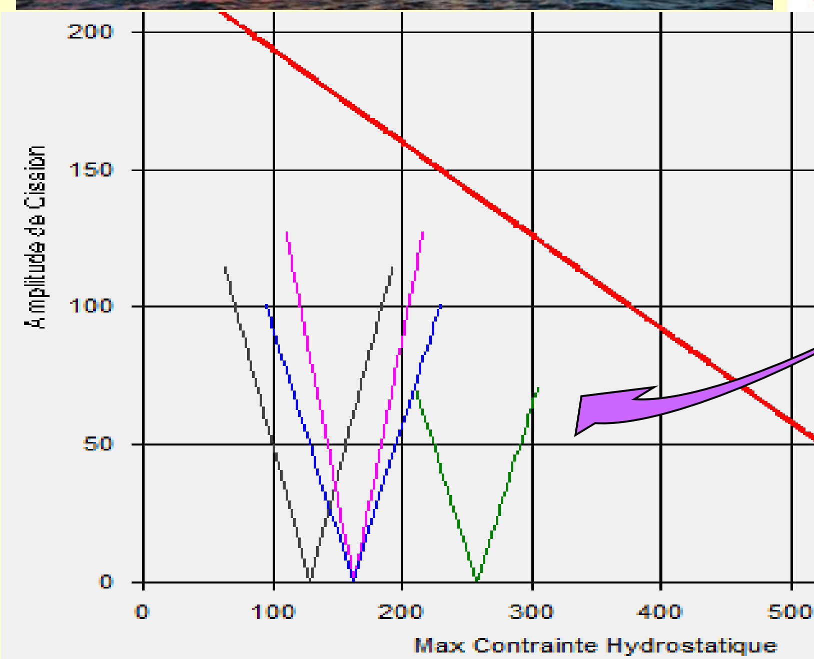
# HCF : Mechanical engineering applications

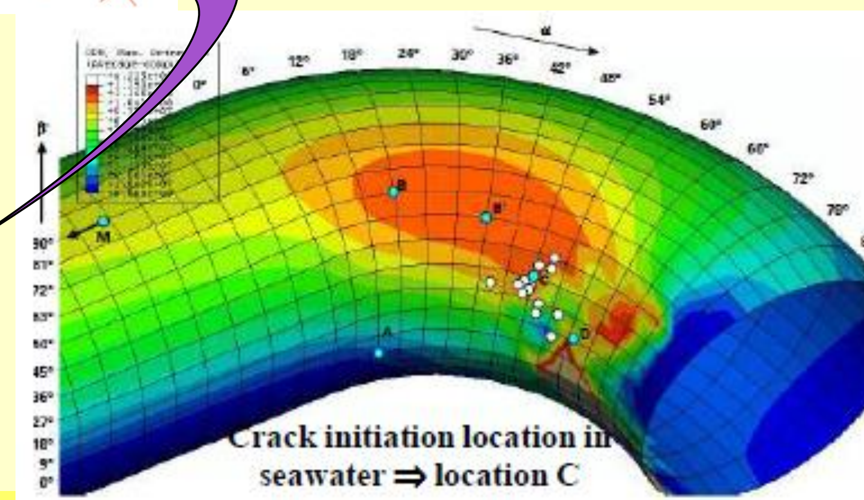




**Mooring chains,**
**deep offshore oil and gas**

**Operation loading**

- **Complex cyclic loading introduced in the calculation**
  - **Tension variation**
  - **In plane bending**
  - **Out of plane bending**



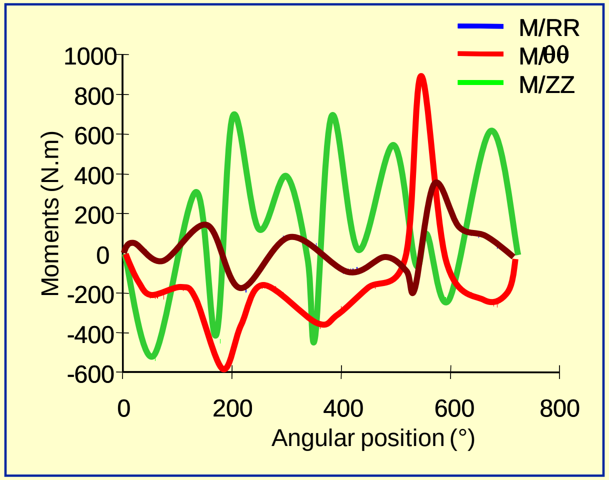




**results**

**in the Dang Van diagram**

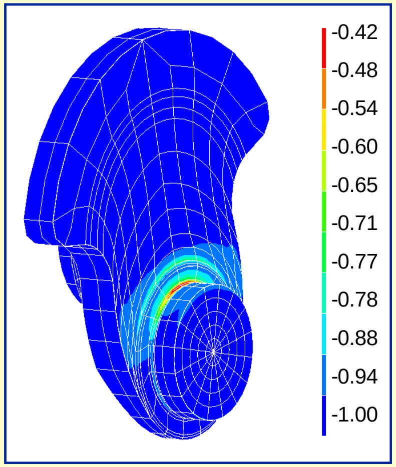
# HCF : Mechanical engineering applications

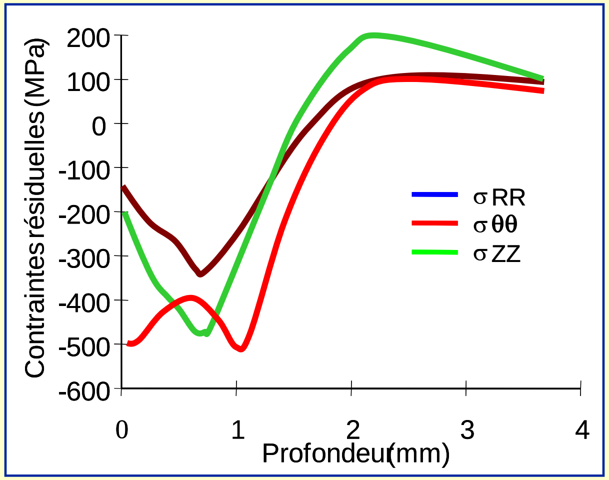
## FATIGUE CALCULATION OF A ROLLED CRANKSHAFT




APPLIED LOAD

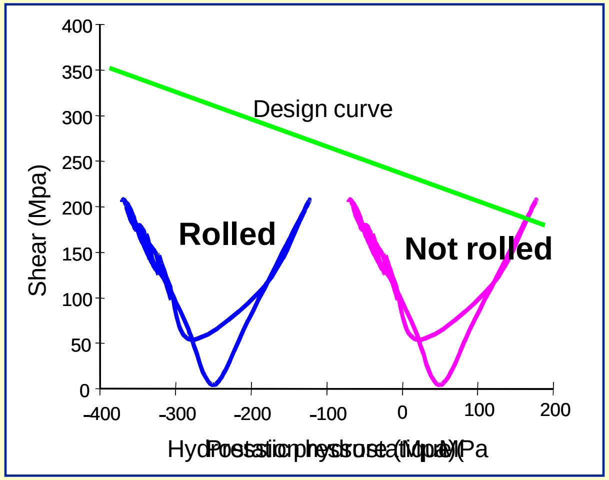
ISO VALUES OF DANG VAN'S CRITERION




RESIDUAL STRESSES FROM ROLLING

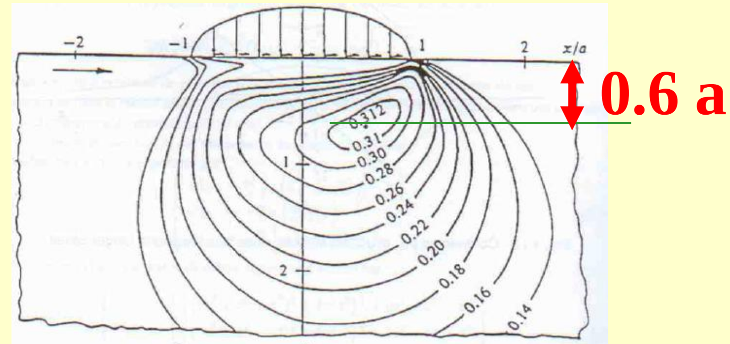
LOAD PATH AT CRITICAL POINT

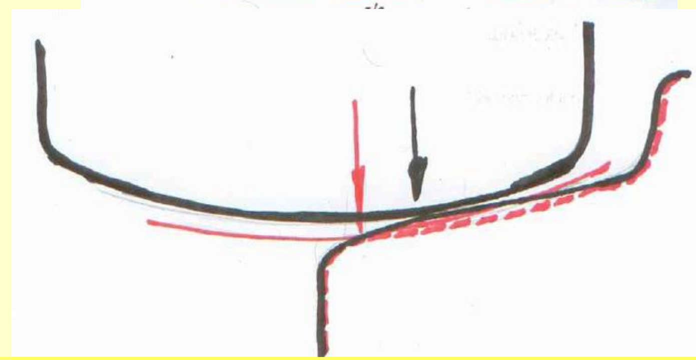


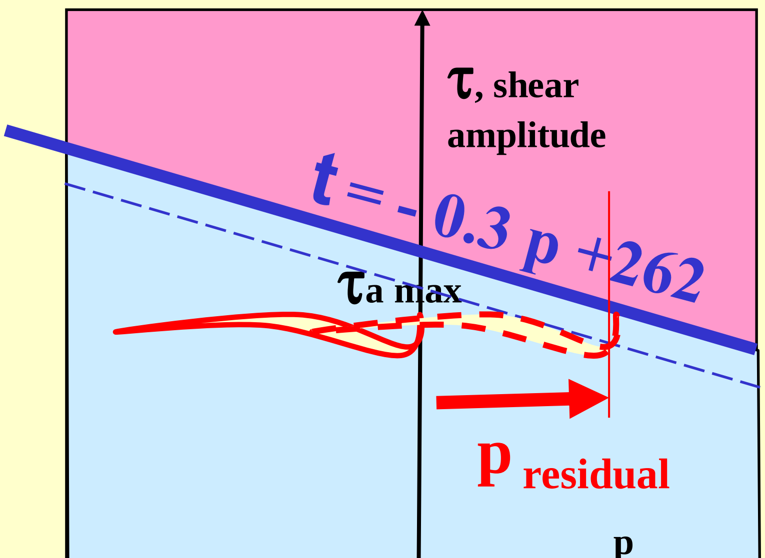
# HCF : Mechanical engineering applications

## Fatigue failure analysis of railroad vehicles wheel


**Contact fatigue**

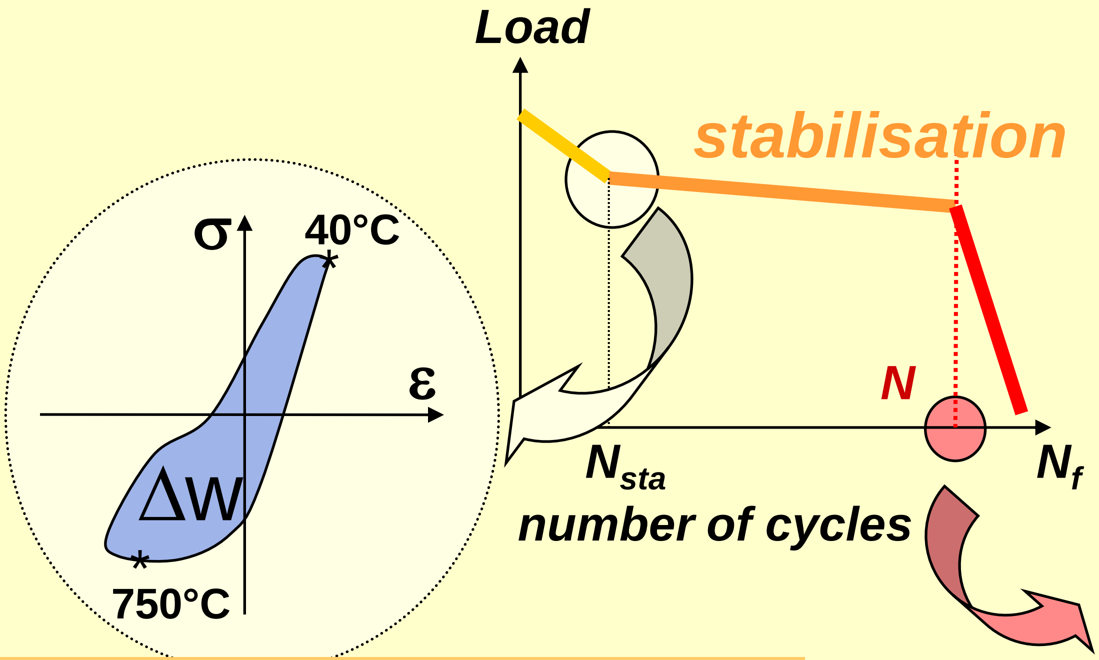





**Crack initiation only possible due to extremely severe braking which induced residual hoop stress > +400 MPa**

# LCF : Mechanical engineering applications




- *cyclic softening / hardening*
- *stabilised behaviour*
- *final failure*

Skelton (1991)

**Failure of the structure : initiation of a macroscopic crack**

**Stabilised cycle : representative of the cyclic life of the structure**

Charkaluk and Constantinescu (2000)

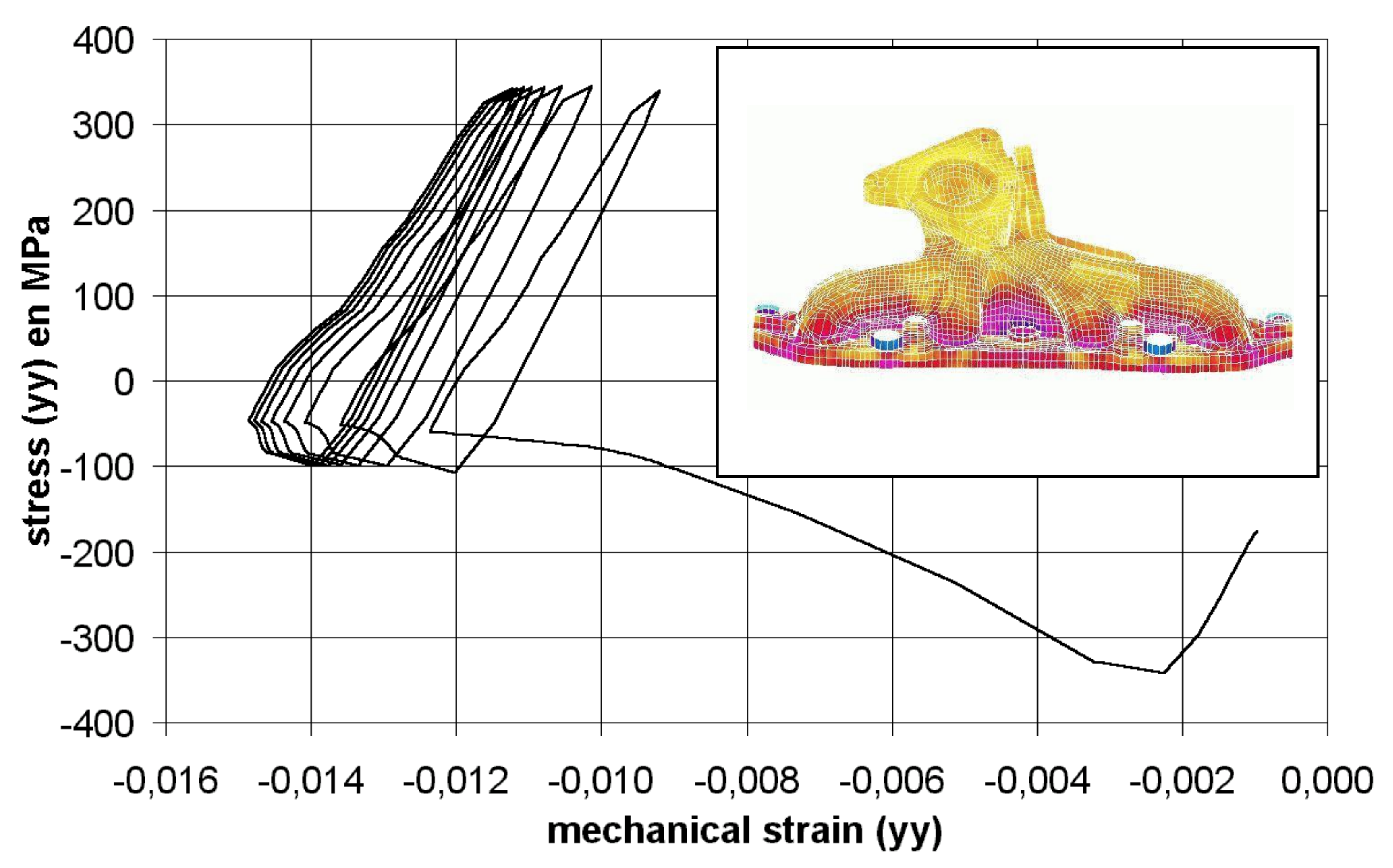
# LCF : Mechanical engineering applications

## *Material and structural behaviour model in structural calculation*

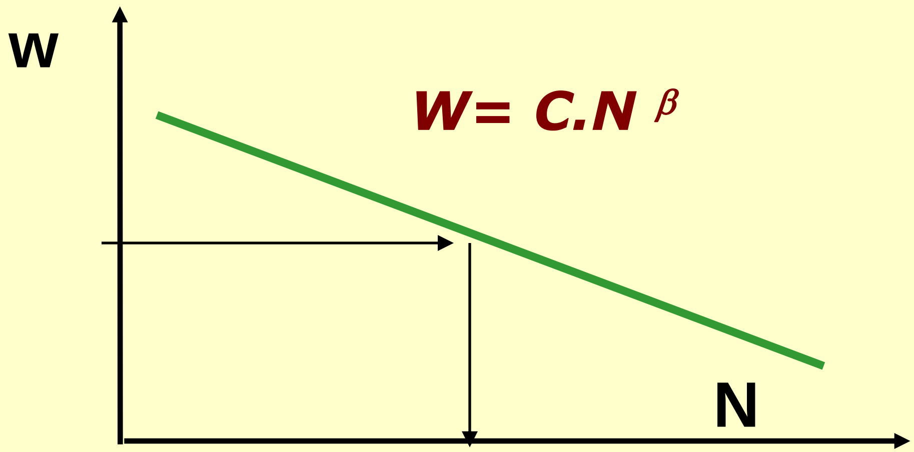
- **Representation of the material in the structure by constitutive equations with parameters of easy access**
  - **coupling with damage : leads to difficulties in**
    - ***parameter identification***
    - ***numerical implementation***
    - ***calculation time***
  - **without coupling with damage**
    - ***evolution cycle by cycle of the structure is sometime not necessary***
    - ***<u>identification on steady-state cycles and structural aged representativity</u>***

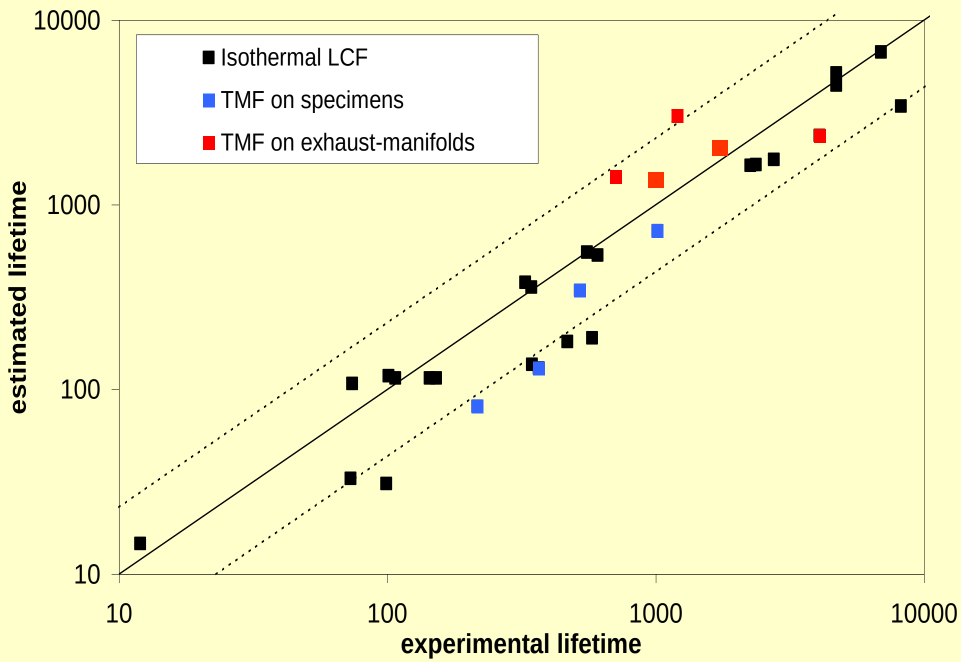
# LCF : Mechanical engineering applicatio

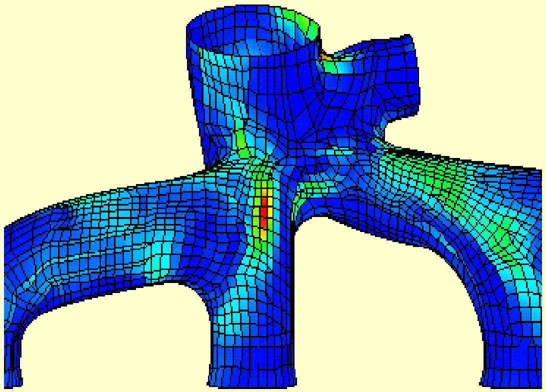
## Exhaust pipe

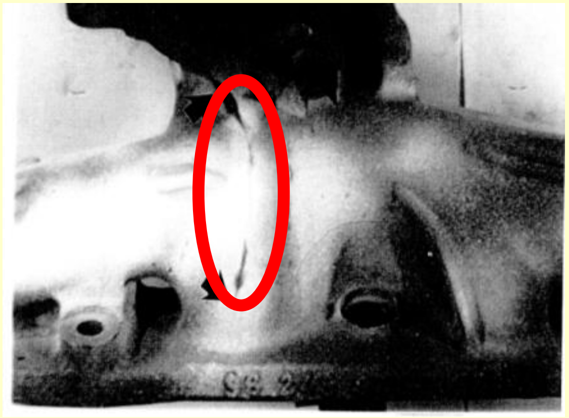


# LCF : Mechanical engineering applications





# High Cycle Fatigue:

**the structure is globaly elastic and fatigue phenomenon only initiates in some grains.**

**The fatigue limit corresponds to the shakedown limit at the meso scale**

**One can evaluate the local stress at the stabilized state :**

**from $\Sigma(x,t)$, we derive the local stress by constructing the smallest hypersphere that contains $\Sigma(x,t)$ and gives an estimation of the local stress tensor $\sigma(t)=\Sigma(t)+\rho$**

**From meso-macro relationship:**

**The fatigue criterion is given by:**

$$\tau(t) + \alpha p(t) \leqq B$$

# Low Cycle Fatigue:

**The macroscopic plastic strain is important and difference between Ep and $\varepsilon$p decreases so that there is few differences between MACRO and MESO parameters.**

**The dissipated energy per cycle at the stabilised state is proposed as a fatigue criterion**

$$W = C\,N^{\beta}$$

**it is a scalar parameter easy to compute**

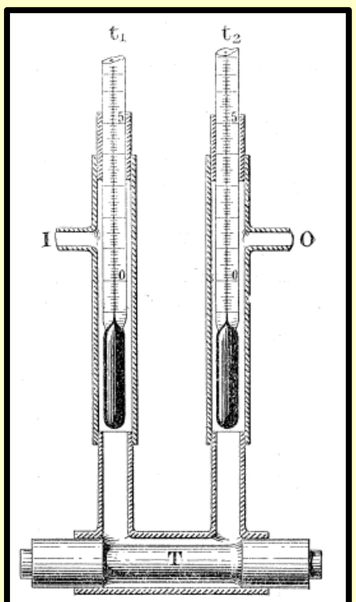
**which leads sometimes to fairly good predictions on structures**

**PROSPECT…..**

# Dissipation, temperature & Shakedown limit

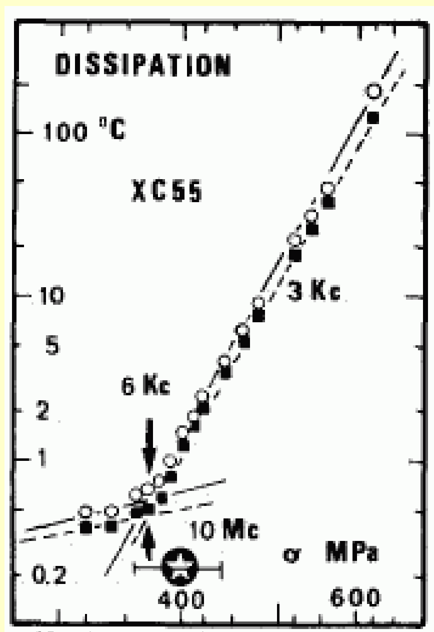
- Dissipative phenomena & cyclic plasticity : *temperature*
- Stabilized temperature evolutions : *asymptotic regime*
- *Shakedown limit* characterisation? Which *scale*? *Microstructure* influence?

Strohmeyer(1914)



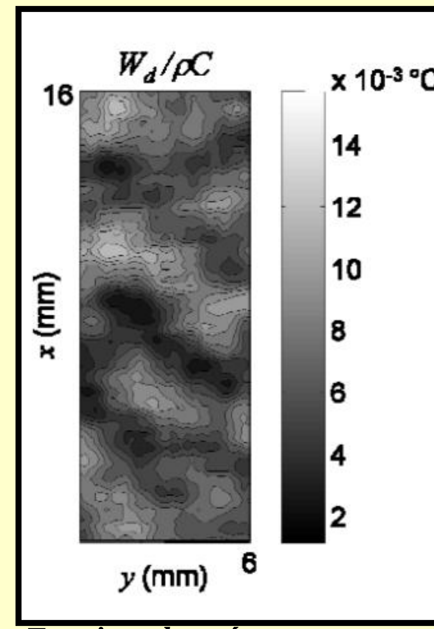

*Torsion alternée*
*Acier doux Bessemer*
*Calorimétrie*

Luong(1995) LMS




*Flexion rotative*
*Acier XC55*
*Thermographie IR (moyenne)*

Berthel(2007) LMGC




*Traction alternée*
*Acier Dual-Phase*
*Thermographie IR (champ macro.)*

# Dissipation, temperature : micro scale

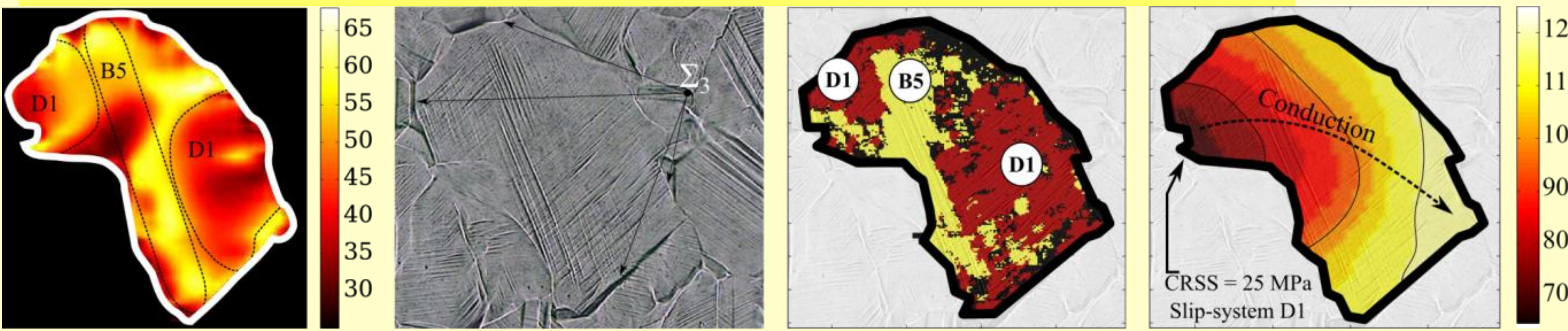
- Coupled measure of strain fields & temperature
- Steel 316L overquenched polycrystalin (grains mm)
- Plasticity activation : *critical resolved shear stress, stored energy*
- Coupling test / numerical simulations : *cristal thermoplasticity*

LABORATOIRE de MECANIQUE de LILLE UMR CNRS 8107
E.C. LILLE E.N.S.A.M. U.S.T.L.

GDR CNRS 2519 MESURES DE CHAMPS ET IDENTIFICATION EN MECANIQUE DES SOLIDES

CQ2M Calorimétrie Quantitative en Mécanique des Matériaux

**Does crack initiation correspond to a source of stored energy?**
**Why nano materials get high strength?**



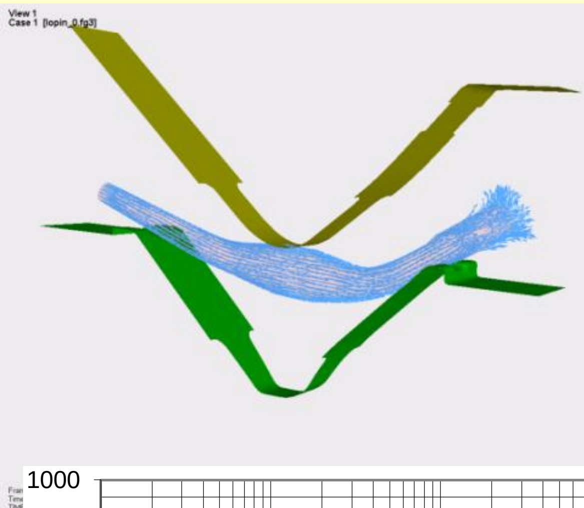

*Taux de stockage intragranulaire d'énergie* | *Microstructure après essai* | 200 µm | *Systèmes de glissement activés* | *Front de température durant la sollicitation*

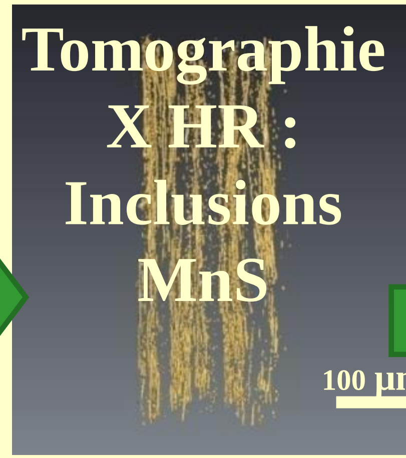
Monotonic loading Bodelot (2008), Seghir (2011)

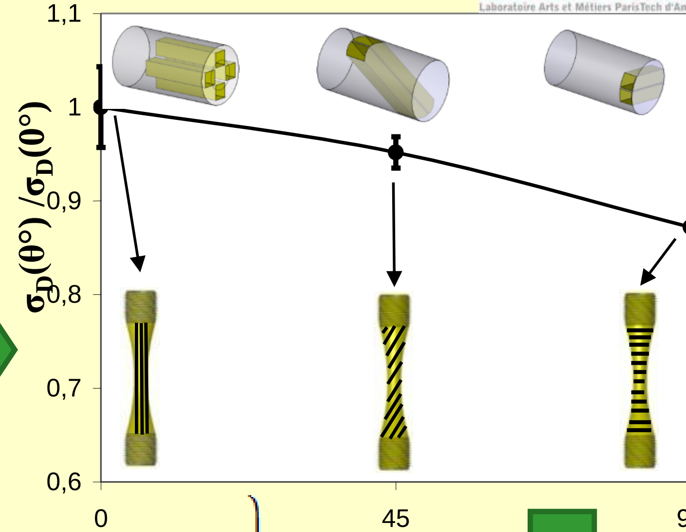
**Objective : microstructural effect on asymptotic regimes under cyclic loading?**

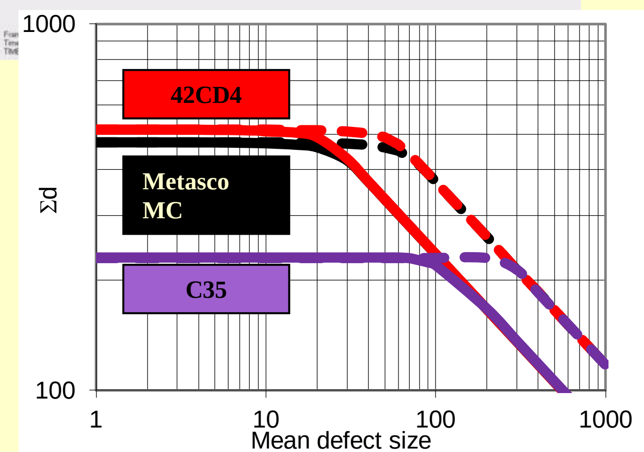
# Process & metallurgical parameters: micro scale

## 2. Procédés de fabrication et tenue en fatigue (E. Pessard)

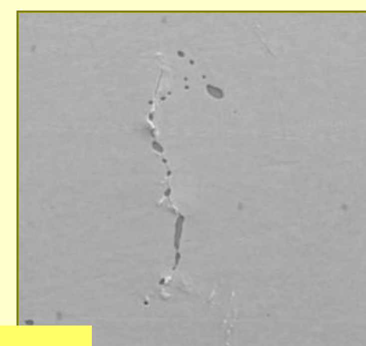


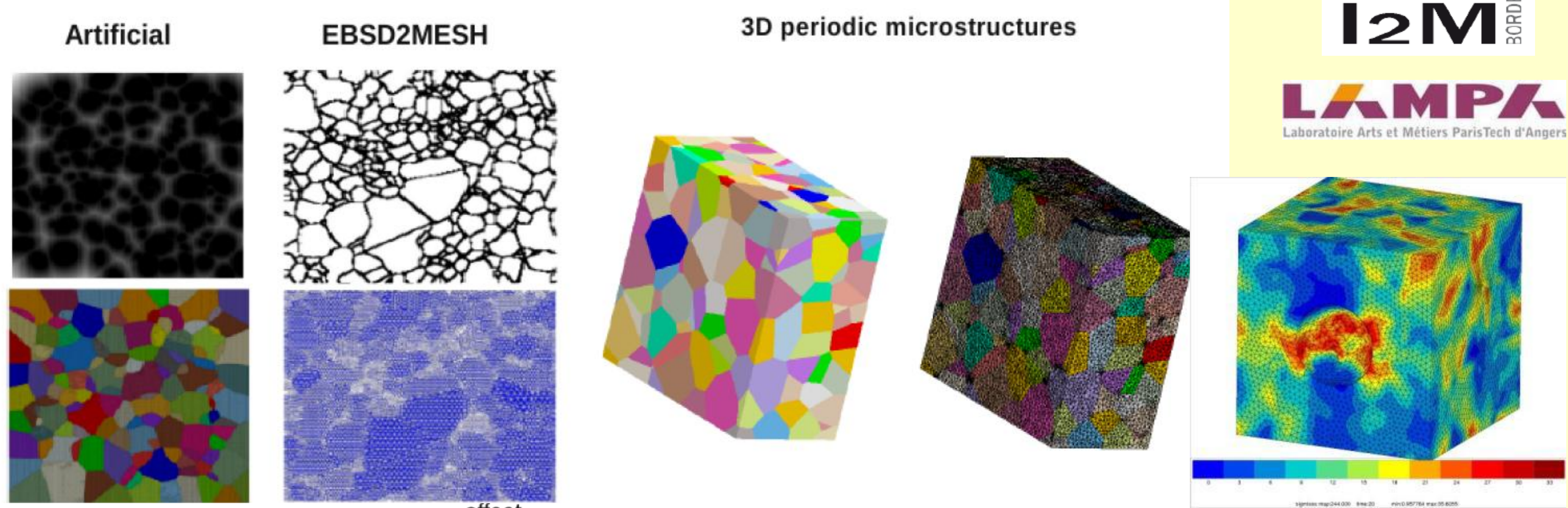

$$P_F(\theta) = 1 - \exp\left[\frac{-S}{S0}\left\{\frac{I_{m1}\times\tau_a^{\ m1}}{T_0^{\ m1}\Big/k\left(1+\frac{\Sigma_{H,a}}{\tau_a}\right)^{m1}} + \frac{J_{m2}(\theta)\times\Sigma_a^{\ m2}}{\Sigma_0^{\ m2}}\right\}\right]$$

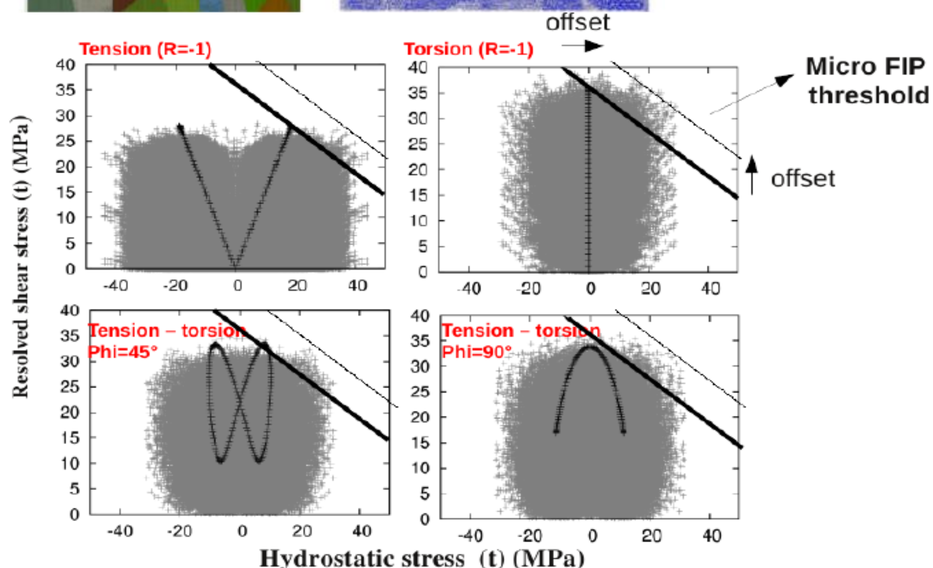


**Probabilist multiaxial Criterion including two damage mechanisms depending on the type of the leading microstructural heterogeneities.**

# Polycristalline agregates modeling: micro scale

## Numerical tools for 2D/3D Microstructure modeling




**With a sufficiently large number of different microstructures investigated, a critical analysis of the multiaxial fatigue criteria has been undertaken, using the local mechanical quantities.**

## Thank you for your attention

**Nature is complex,**
**there is still much to do**
**to understand**
**the microstructural effects**
**on fatigue**
**for actual and future**
**engineering & industrial challenges**