Amorçage et Propagation de fissures en fatigue : simulations du 316L par Dynamique des dislocations

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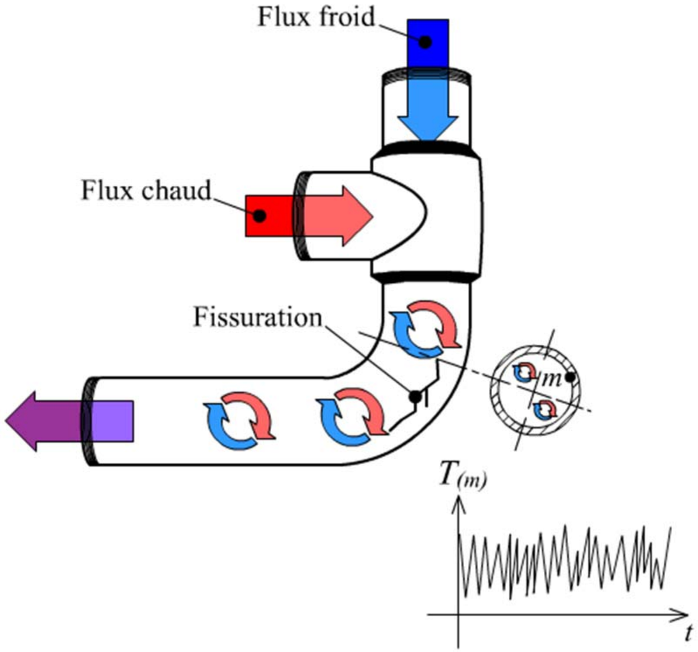
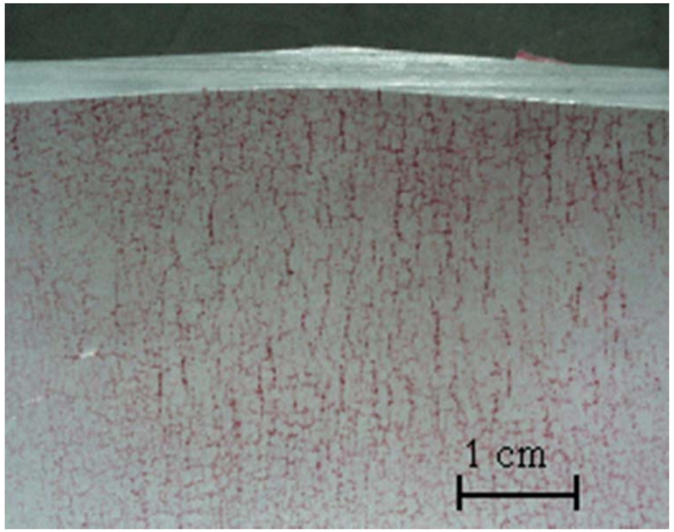
'Engineering' application: How do cracks initiate in fatigue ?
(AISI 316L surface grains)



Incident Civaux1
May 1998 :
leak 30m³/h



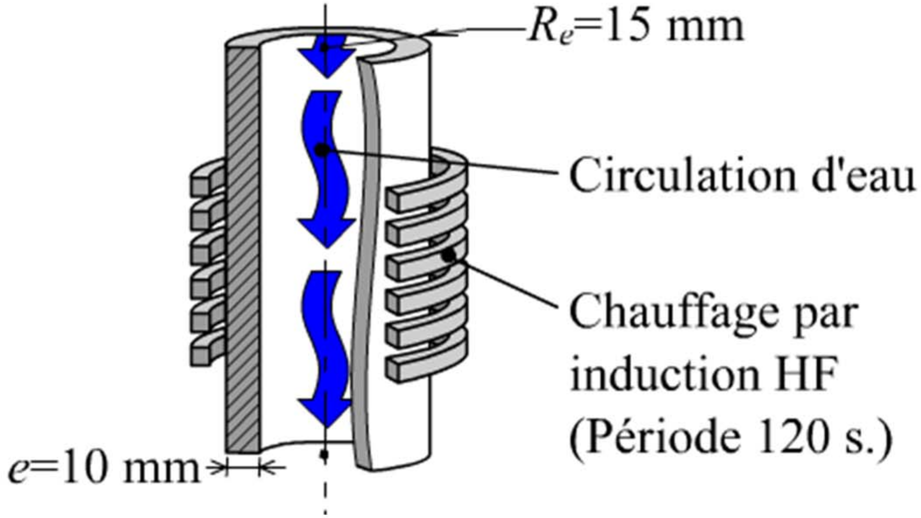
Transgranular crack network

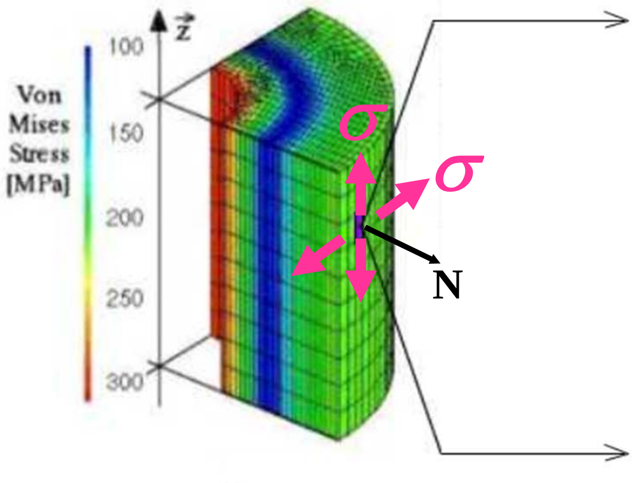
<u>Main objective :</u> Understand physical mechanisms at the origin of cracks

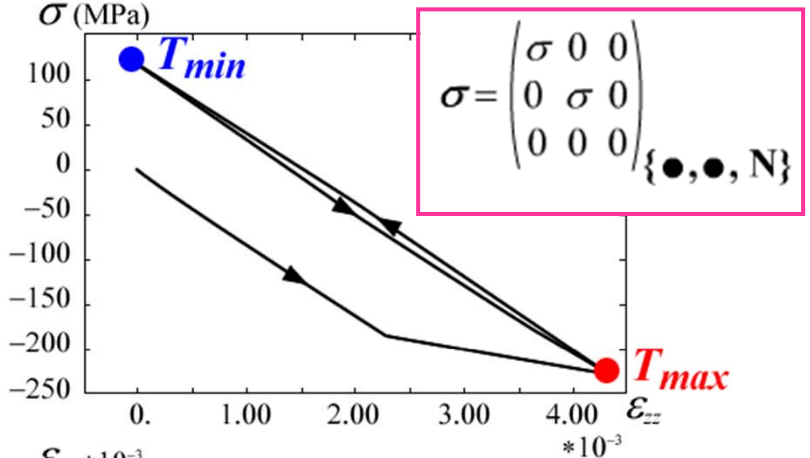
WHEN & WHY do cracks appear ?
HOW do craks propagate ?

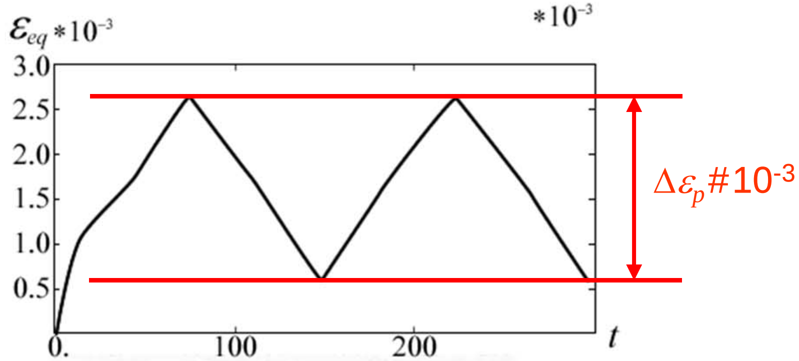
Experimental evidence: Controlled experiment

CYTHIA
(CYclage THermique par Induction des Aciers)







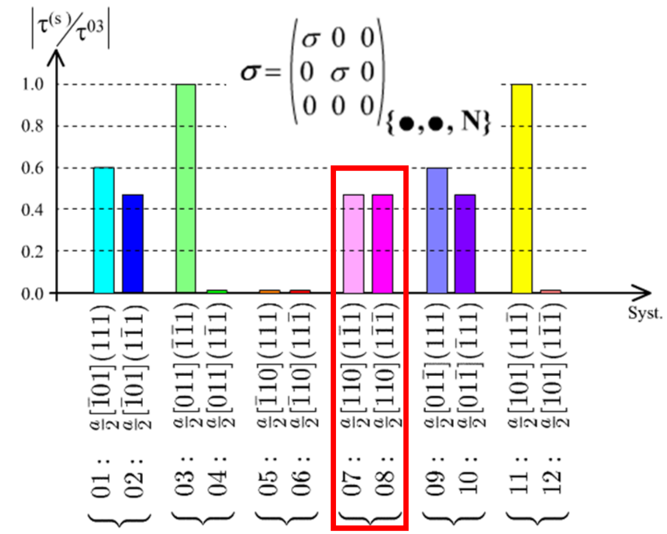


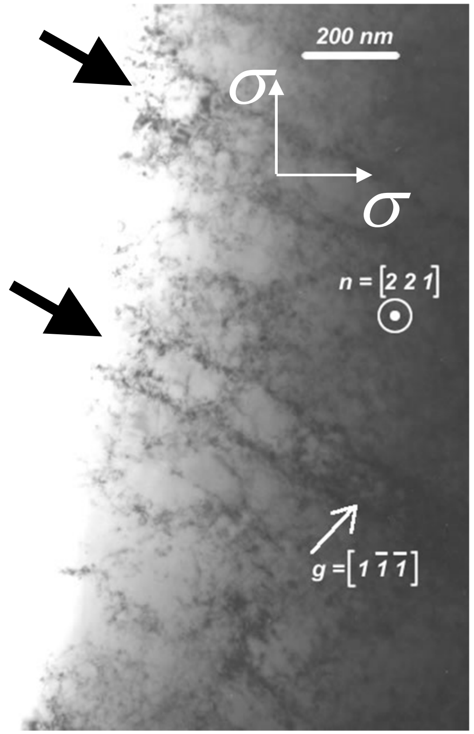
Experimental evidence: Observations

- *Transmission Electronic Microscopy (TEM)*

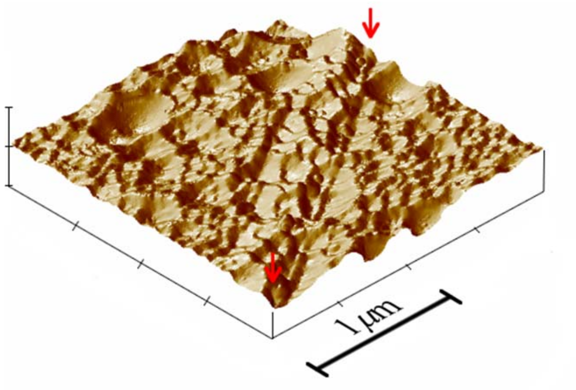
  → *Heterogeneous dislocation microstructure*

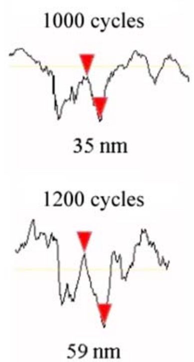
  → *Two slip systems identified*





- *Atomic Force Microscopy* (AFM)



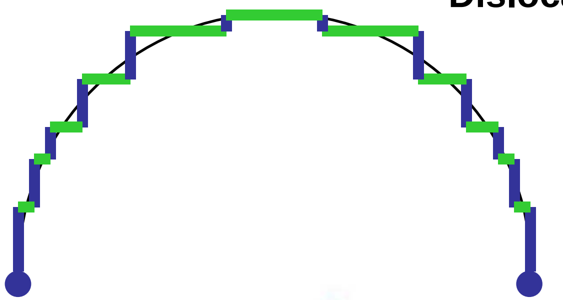


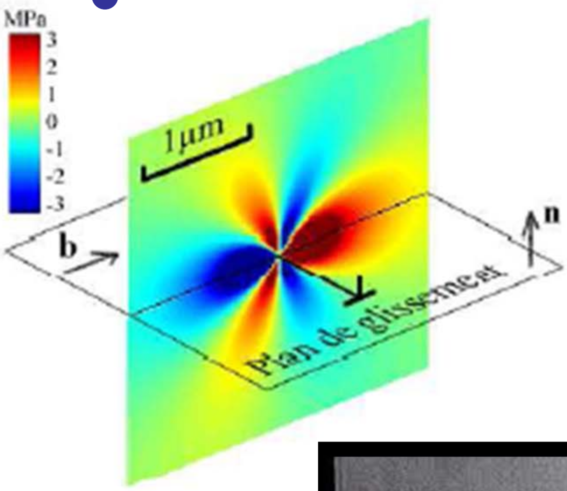
→ *Extrusion relief (time dependent)*

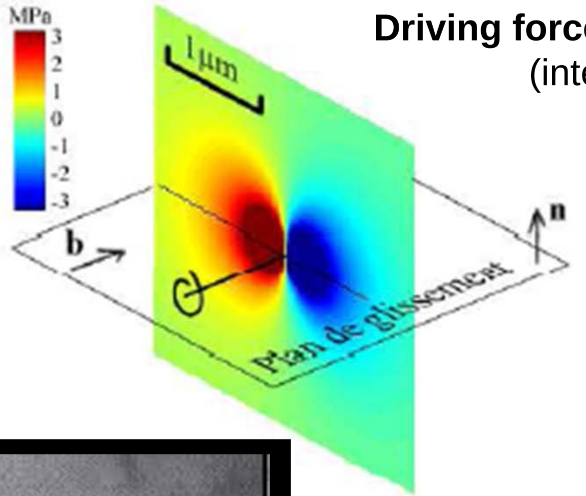
Discrete Dislocation Dynamics (code TRIDIS)

Dislocations = edge and screw segments embedded in an elastic continuum

(similar to elastic inclusions)





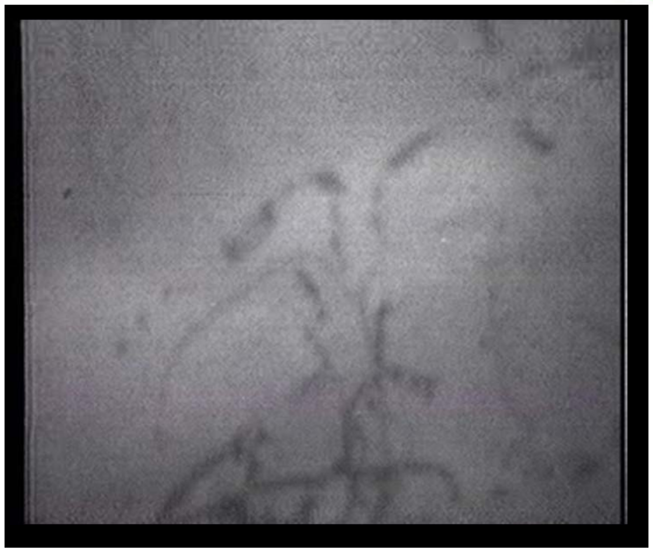


Driving force = elastic stress tensors

(internal + applied)

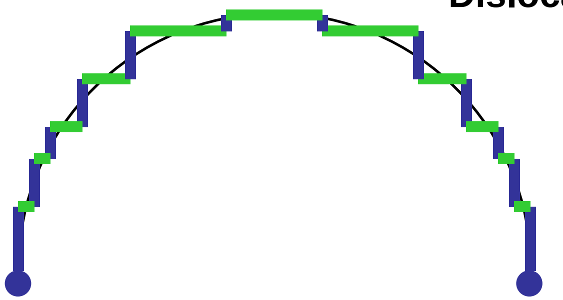
$$v = \frac{\tau b}{B}$$

Example :
Frank Read source



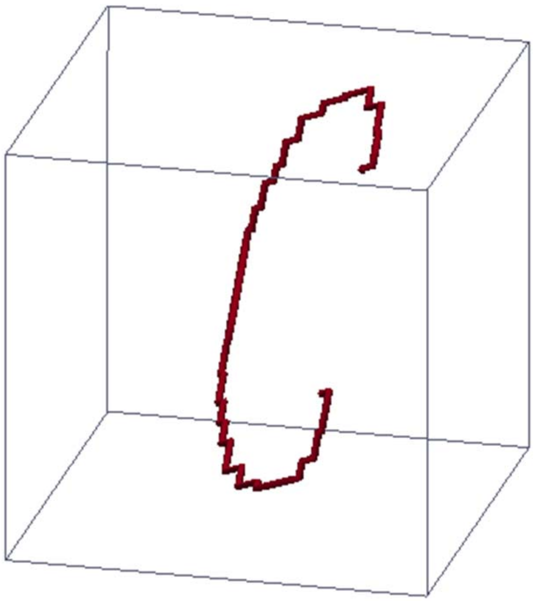
In situ TEM,
François LOUCHET, Grenoble

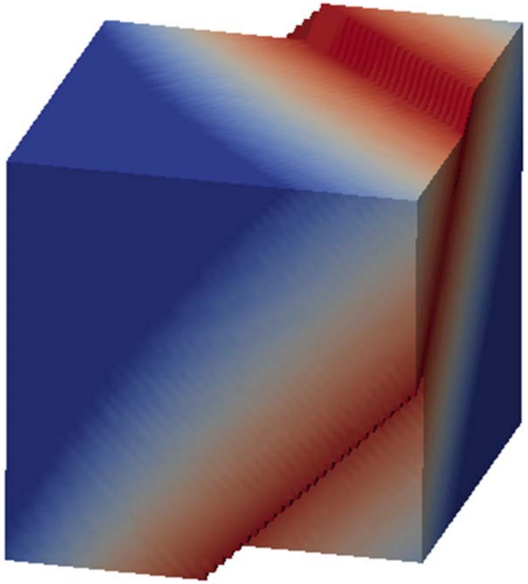
Discrete Dislocation Dynamics (code TRIDIS)



Dislocations = edge and screw segments embedded in an elastic continuum

(similar to elastic inclusions)

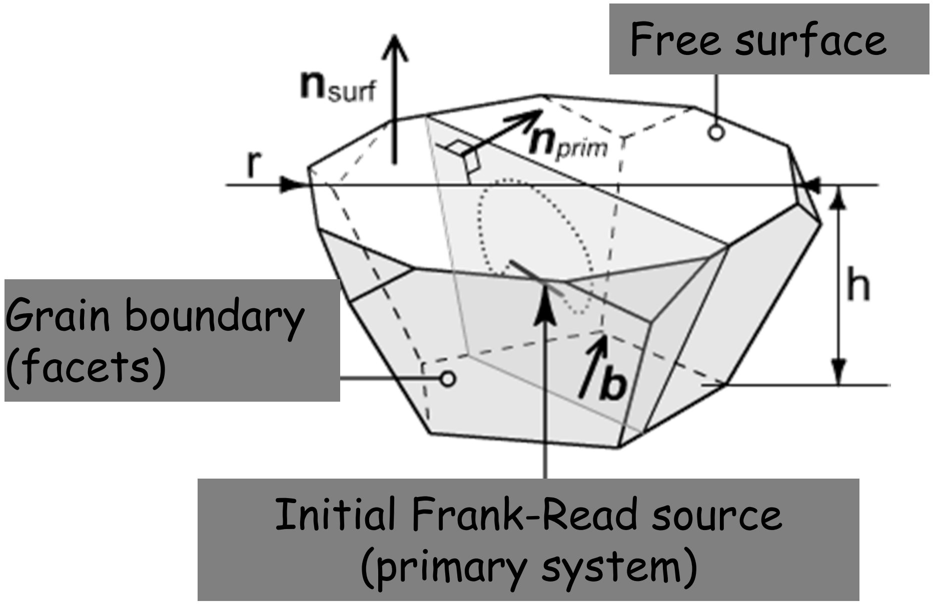




Example :
Frank Read source

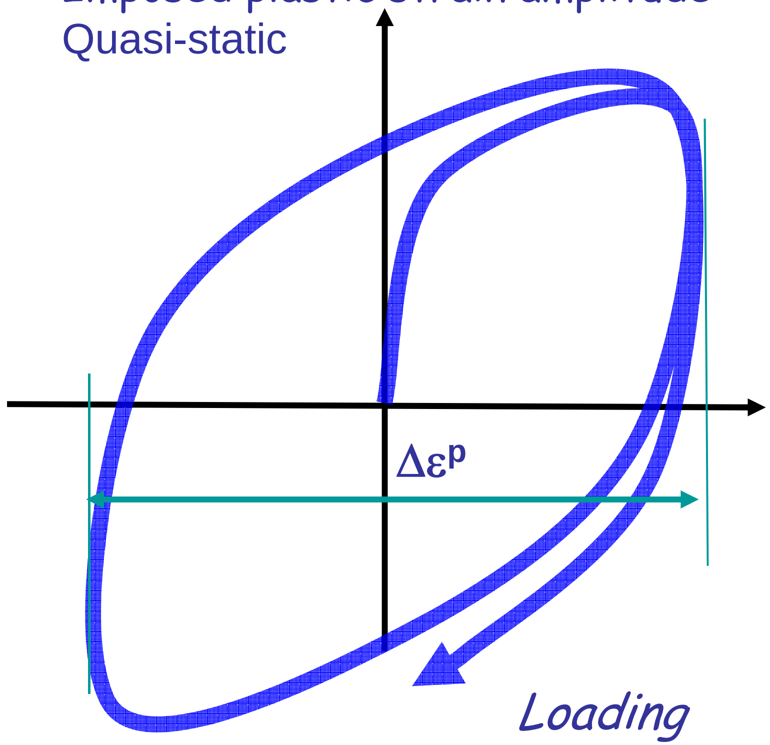
Plastic deformation: direct output

Discrete Dislocation Dynamics Modelling: Boundary conditions



Typical configuration
(motivated by thermal fatigue experiments)

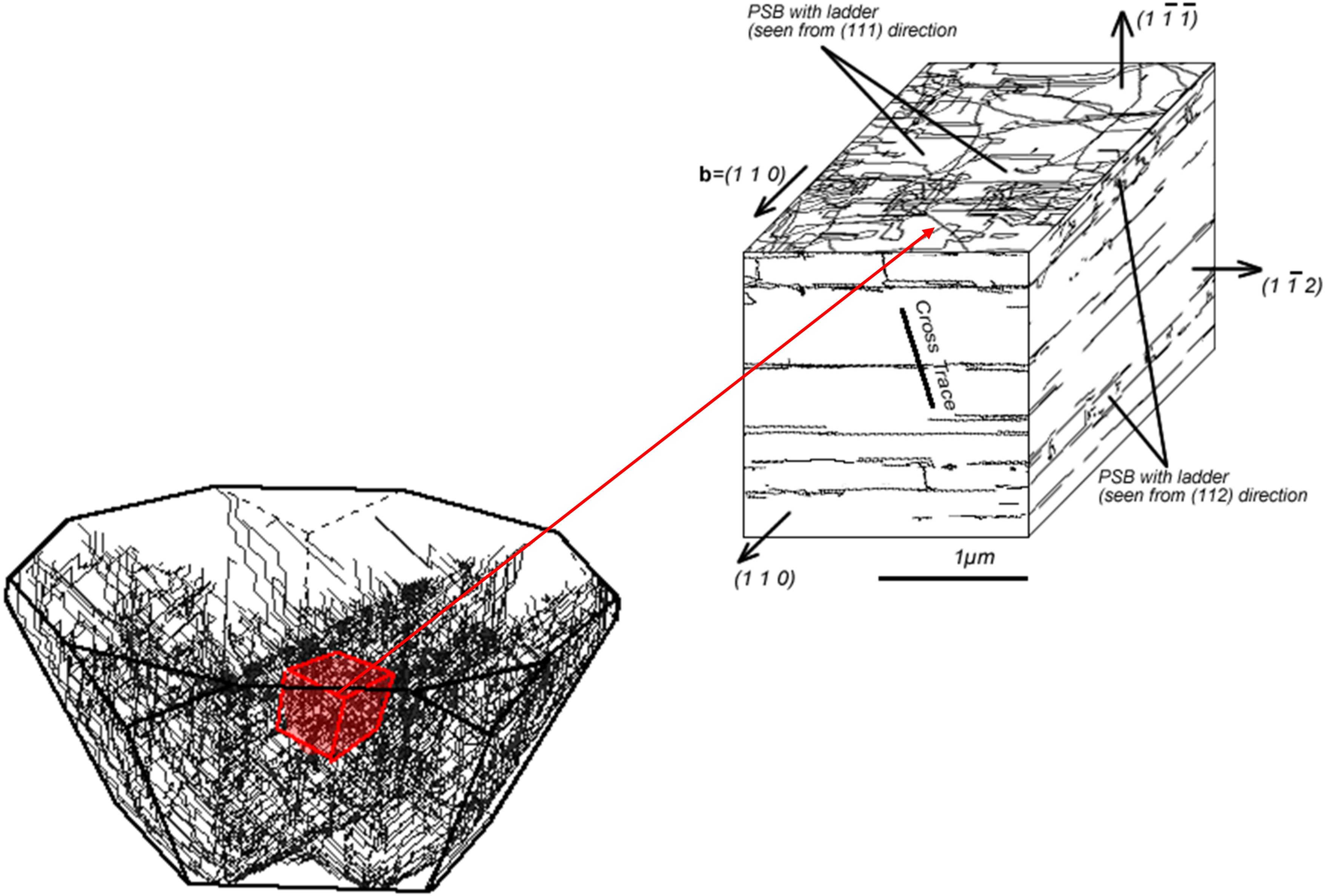
Imposed plastic strain amplitude
Quasi-static



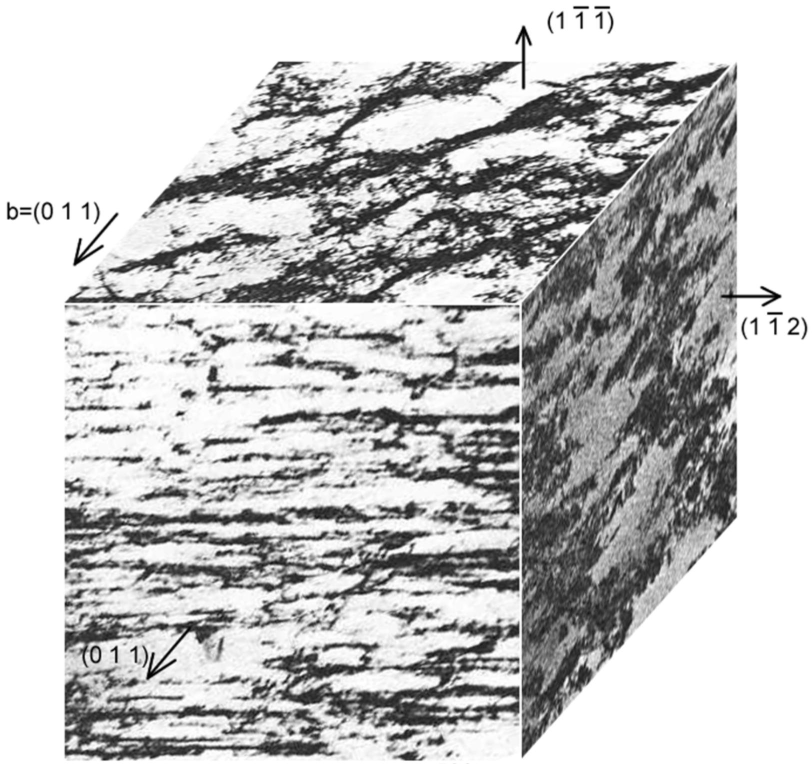
Output :

Dislocation microstructure
Mechanical response
Deformation of the free surface
Internal stresses
...

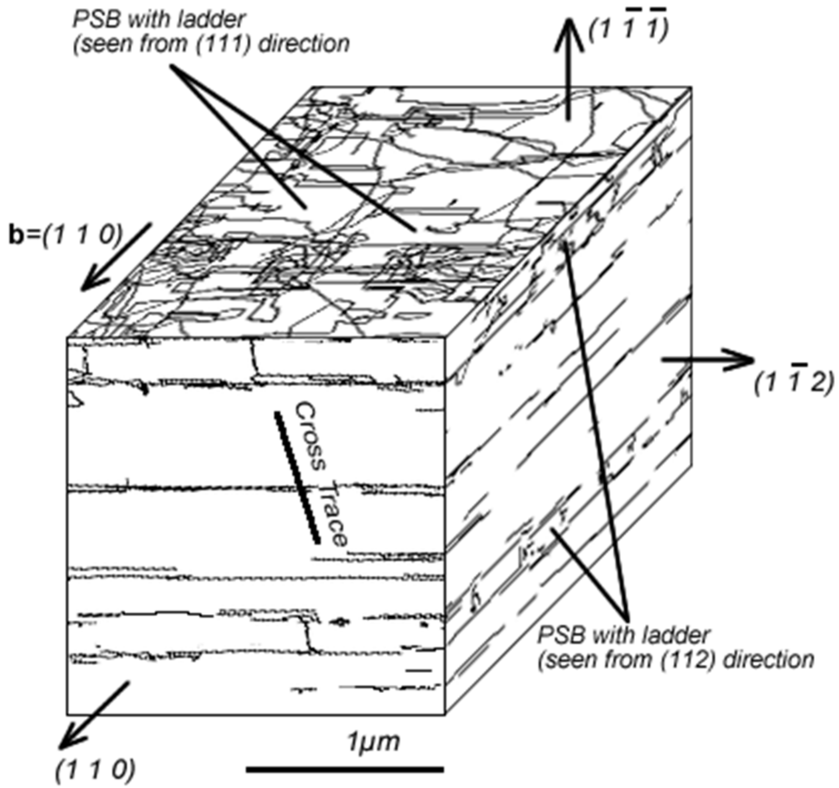
Model validation : single slip ($\tau_p = 3\tau_d$)



Model validation : single slip ($\tau_p = 3\tau_d$)



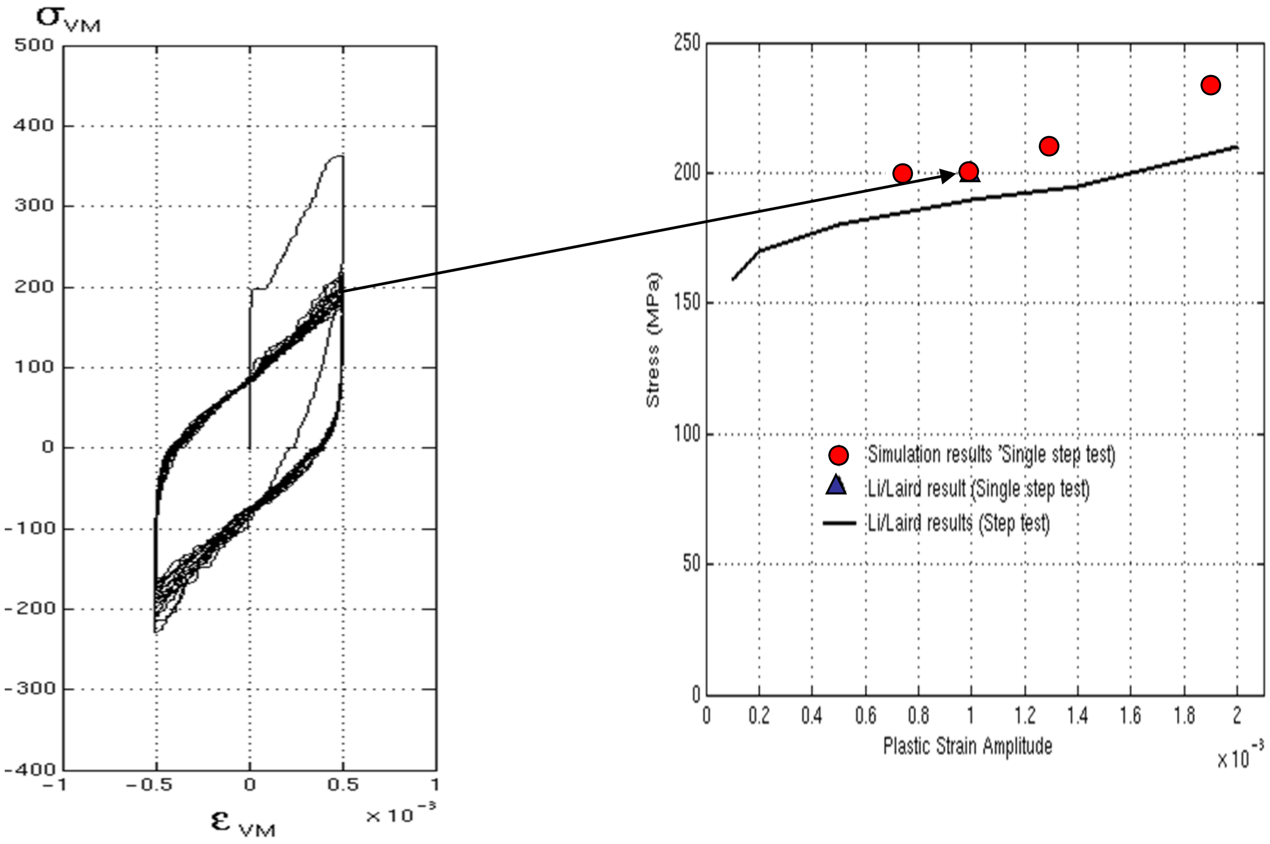
Obrtlik & al. (1994)



Dislocation microstructure ☑

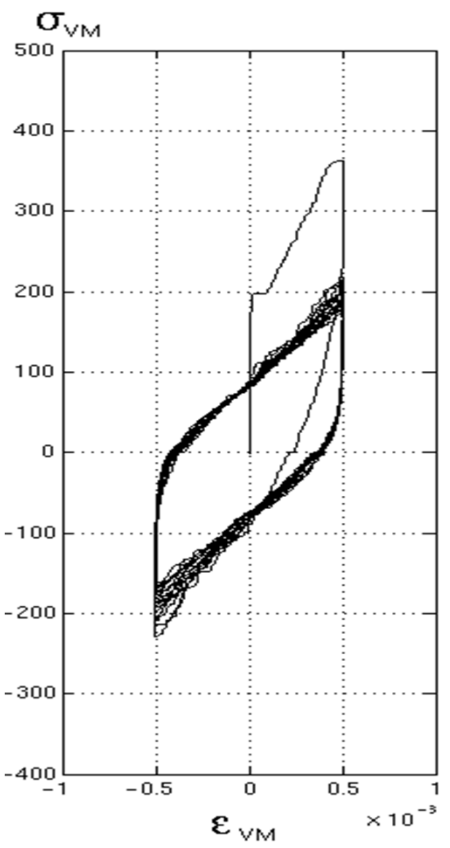
Model validation : single slip ($\tau_p = 3\tau_d$)

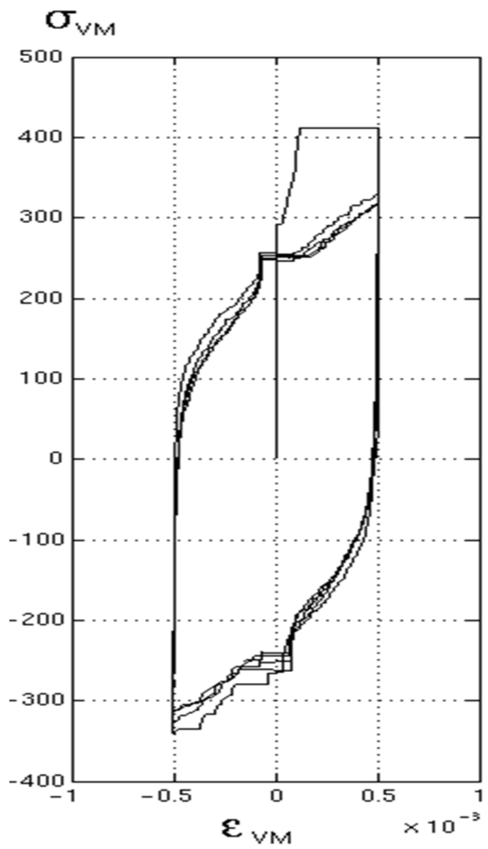
Single slip

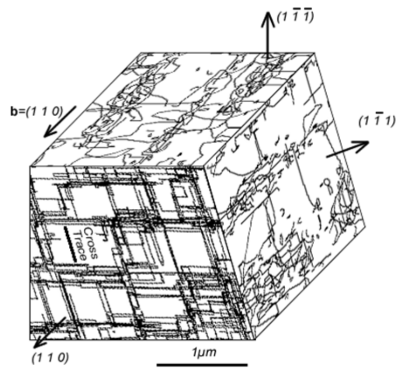


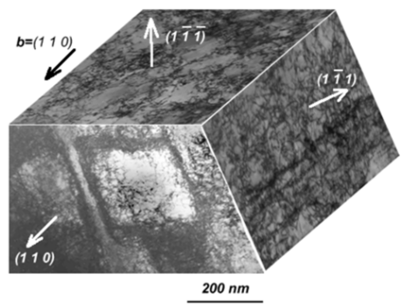
Single slip ($\tau_p = \tau_d$)

Double slip ($\tau_p = \tau_d$)





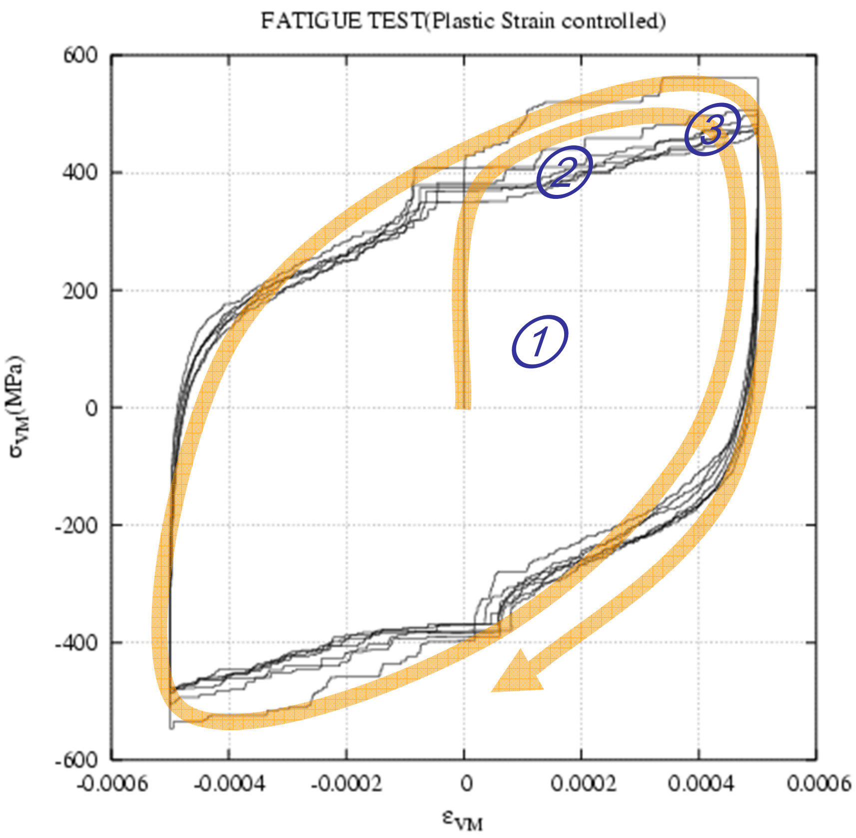


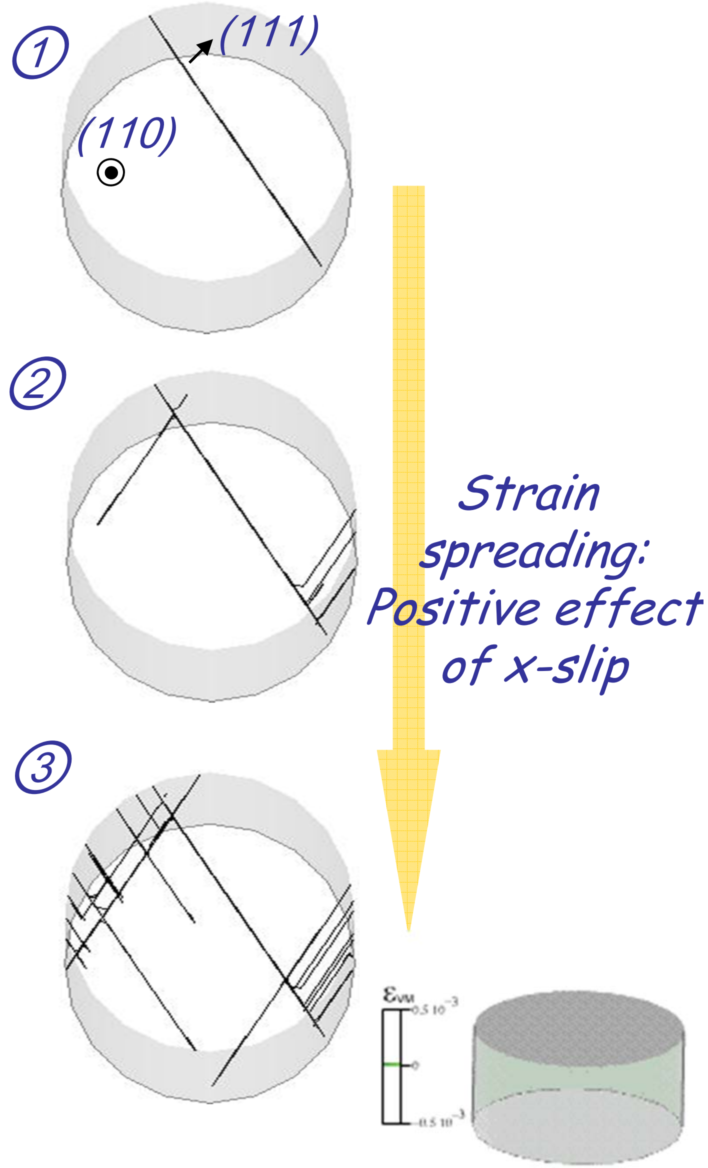


Dislocation microstructure ☑

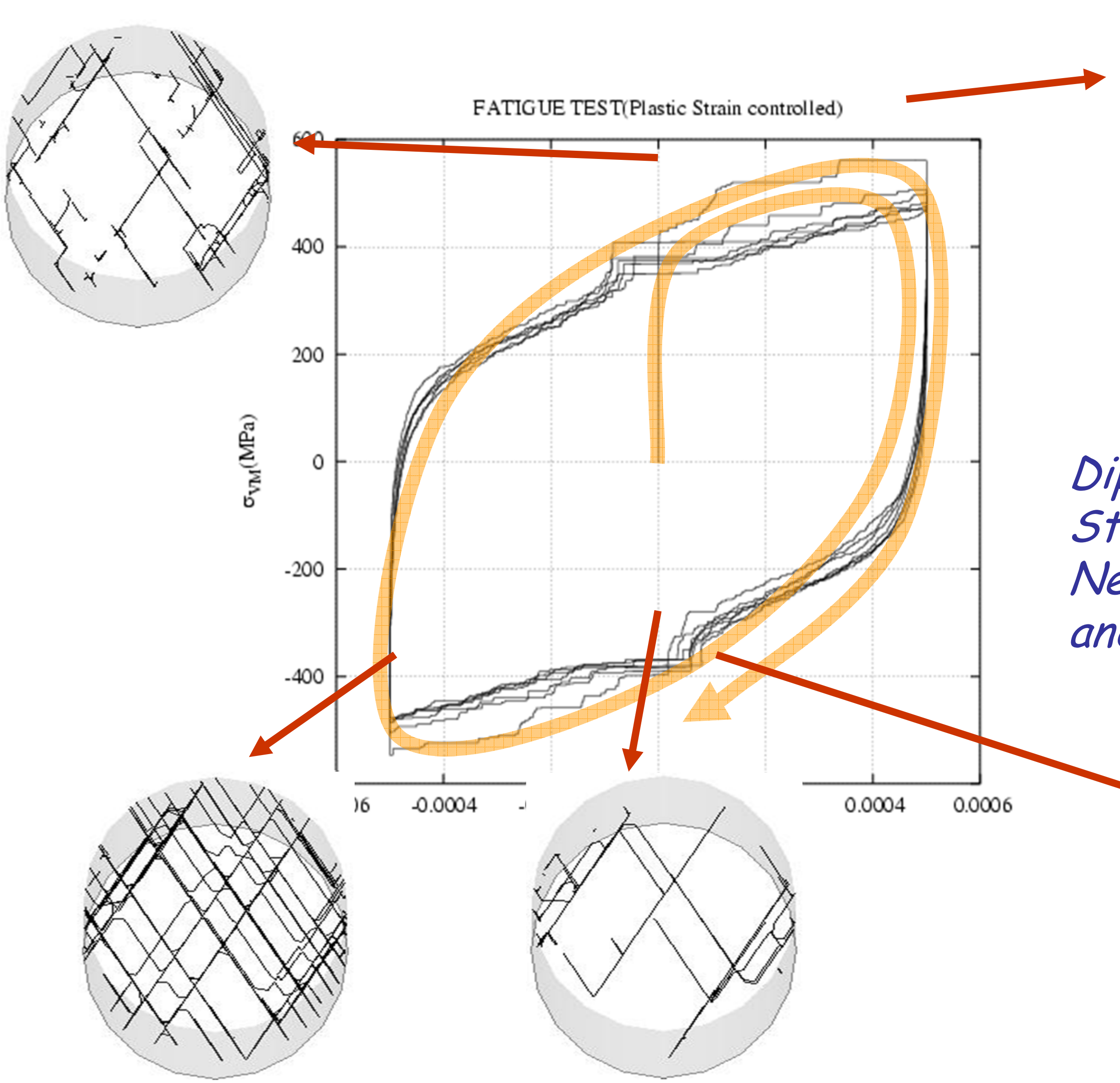
Mechanical response ☑

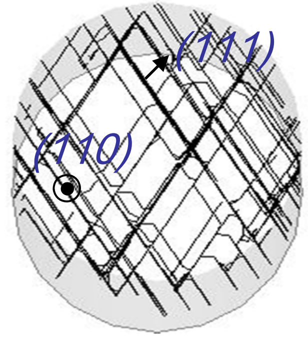
Strain localization mechanisms



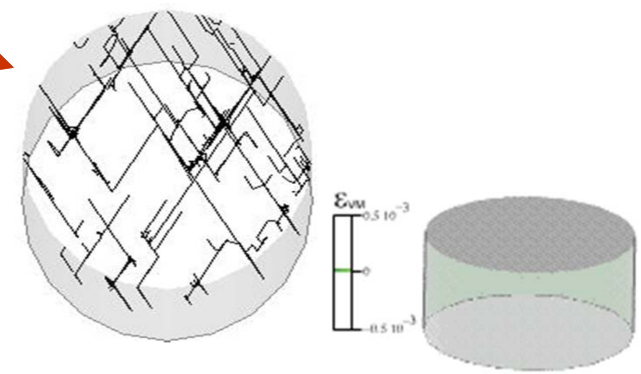


Strain localization mechanisms

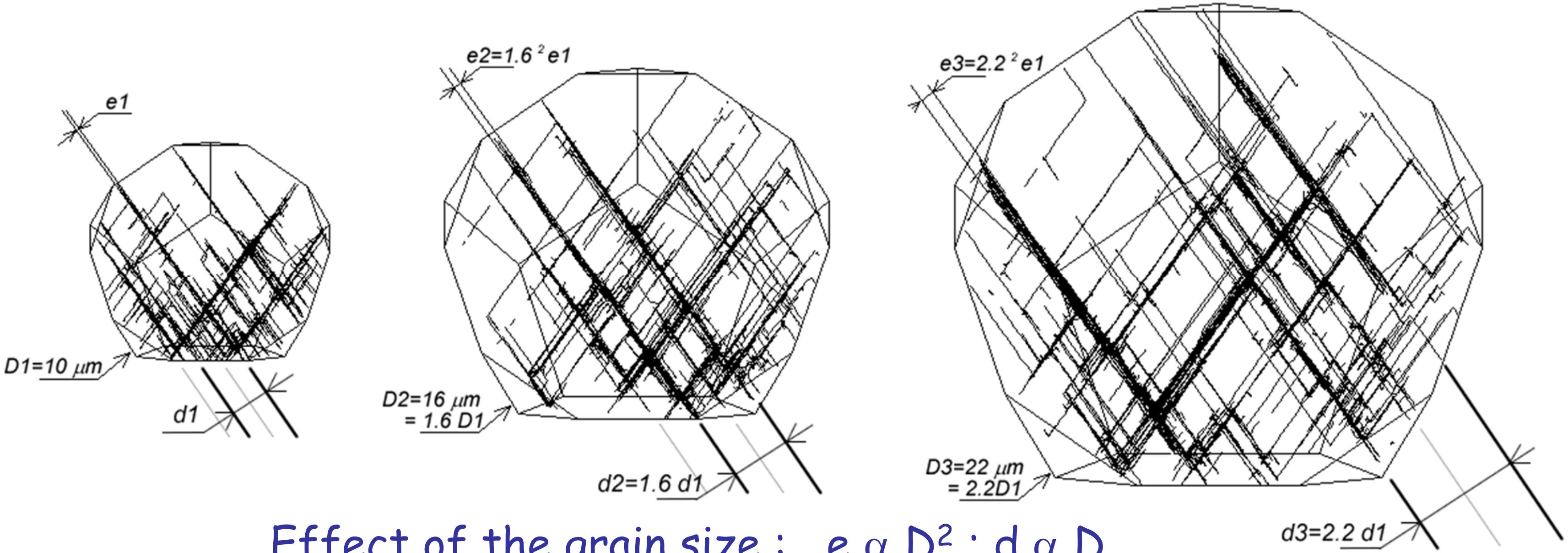




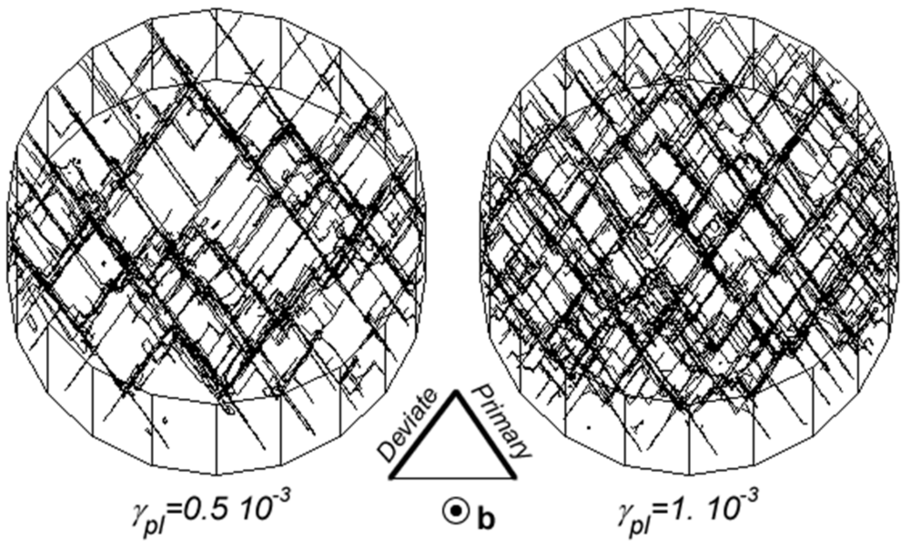
Dipole formation:
Strain localisation
Negative effect of x-slip
and dislocation interactions



Strain localization (double slip)

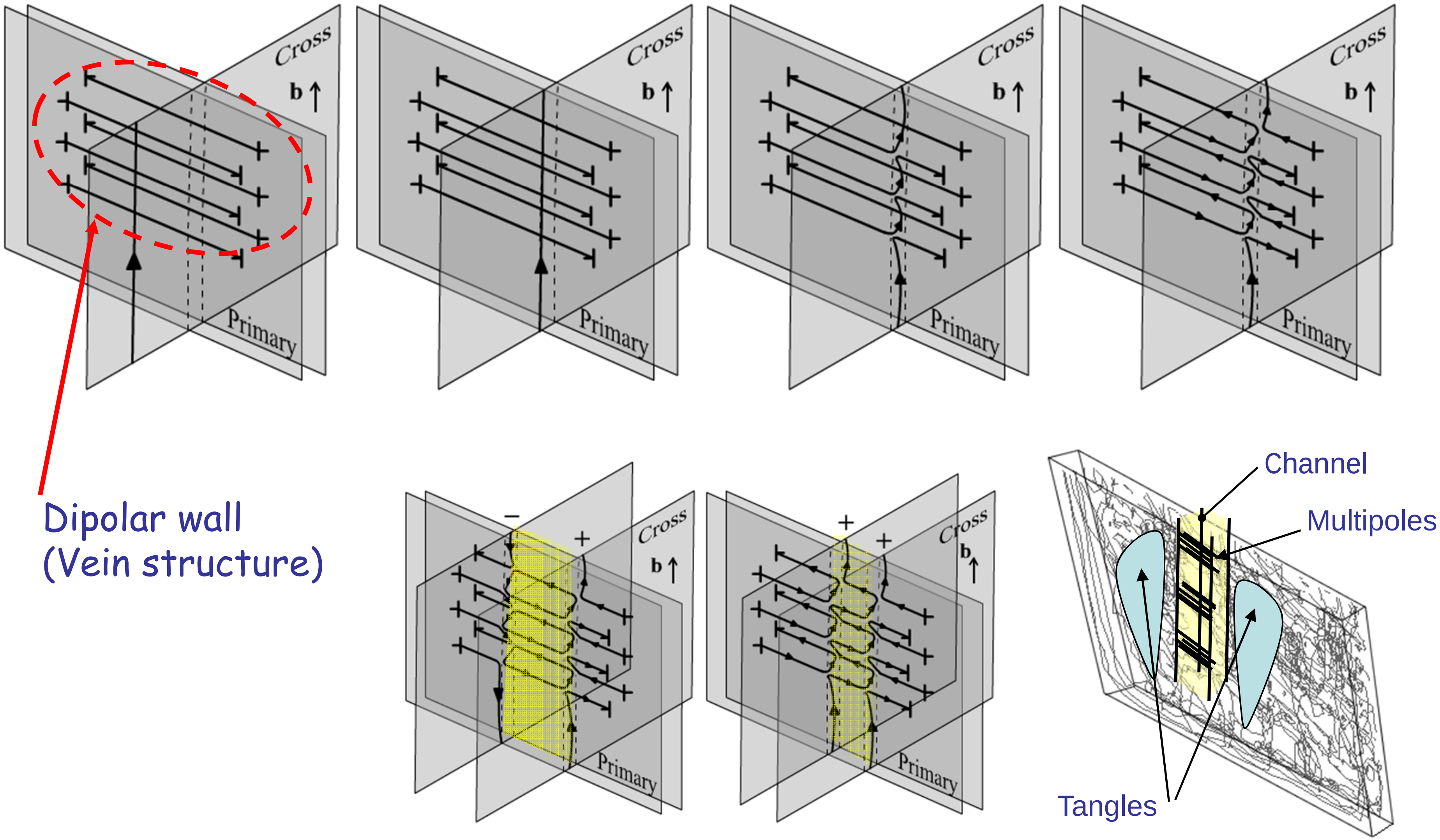


Effect of the grain size : $e \alpha D^2$; $d \alpha D$

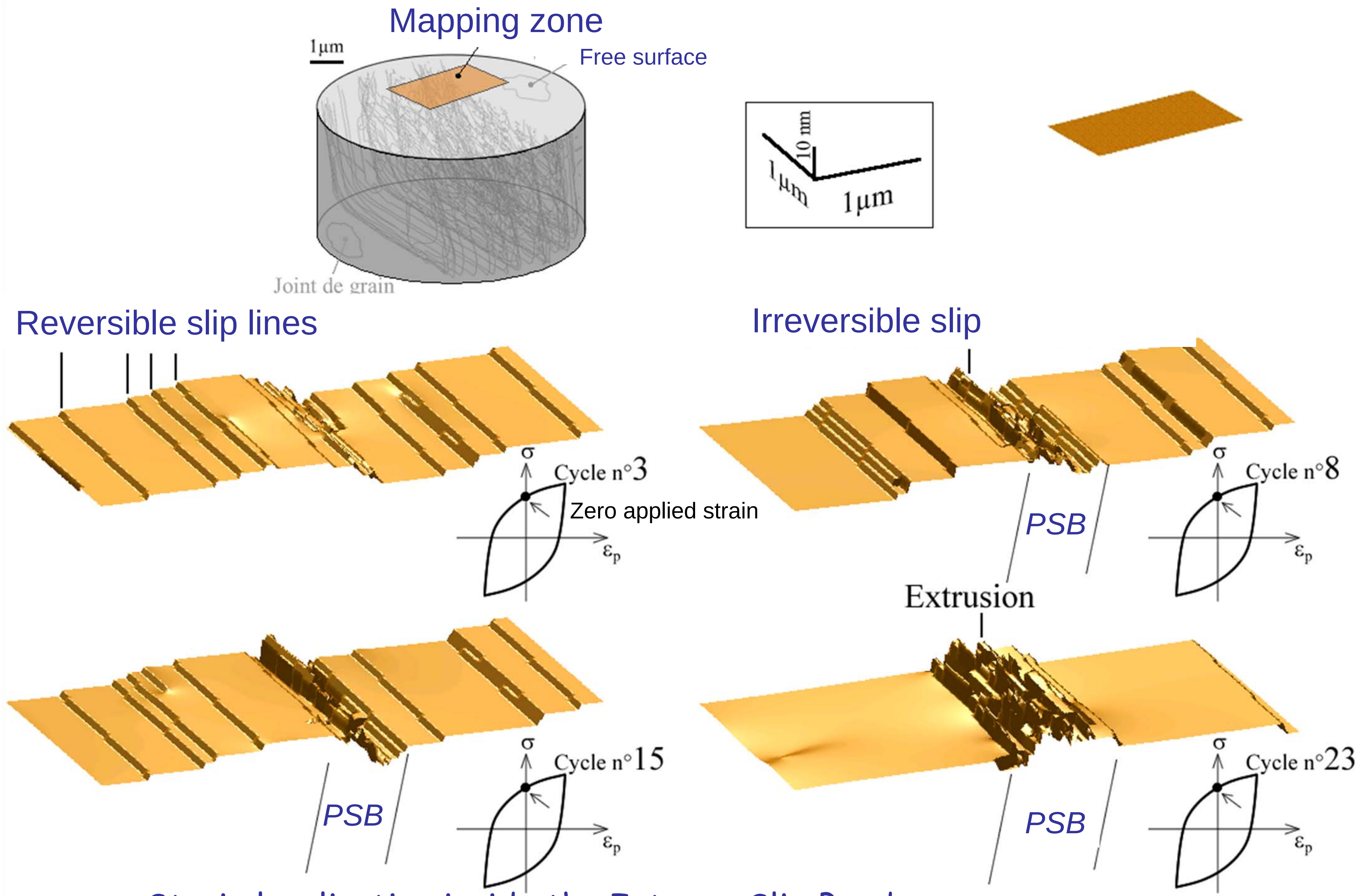


Effect of the strain amplitude :
e cstt ; $n \alpha \Delta\varepsilon^p$; $d \alpha 1/\Delta\varepsilon^p$

Mechanism for the **formation** of the persistent slip band

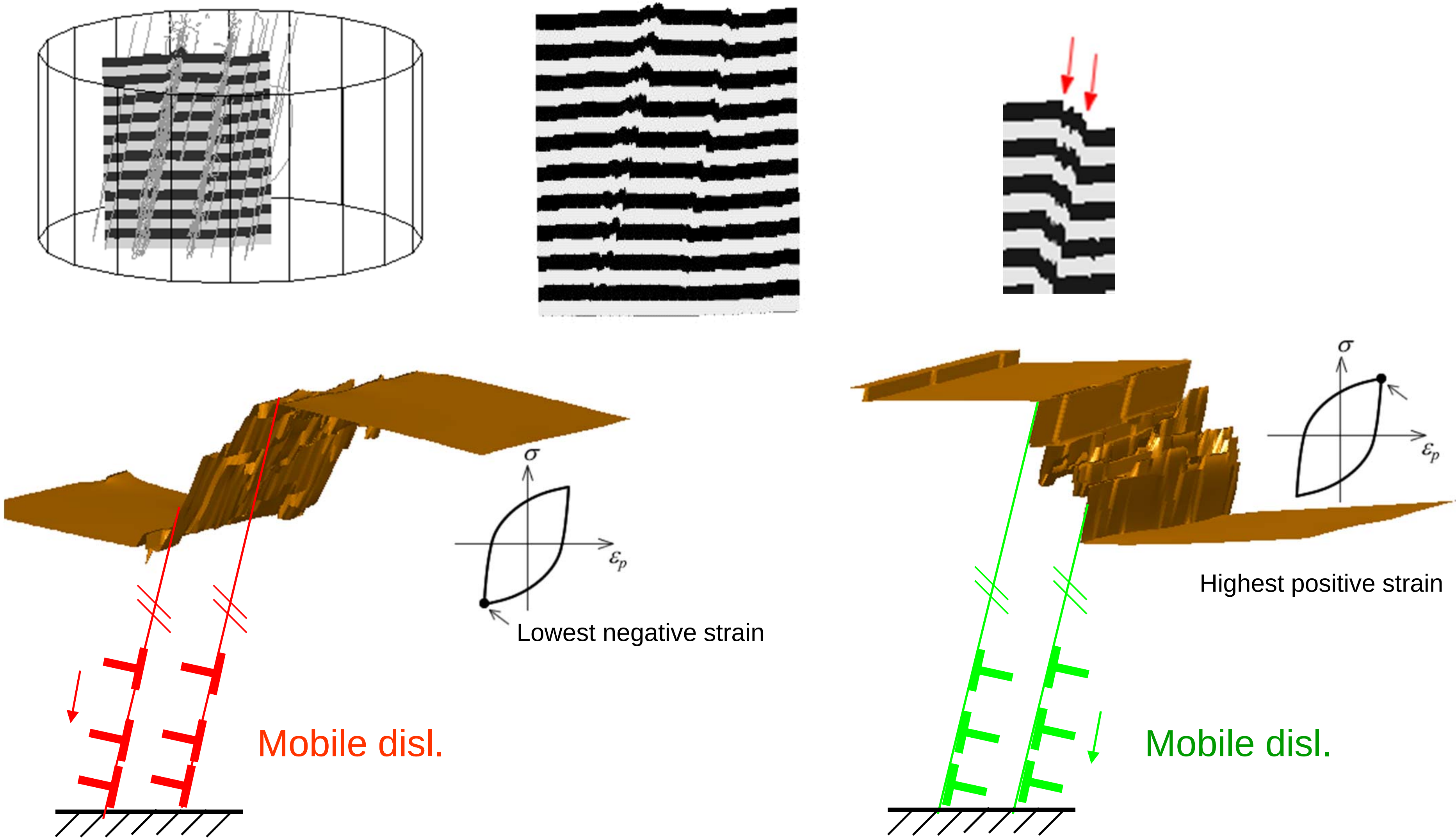


Kinetics of the persistent slip band (snapshots at ε=0)



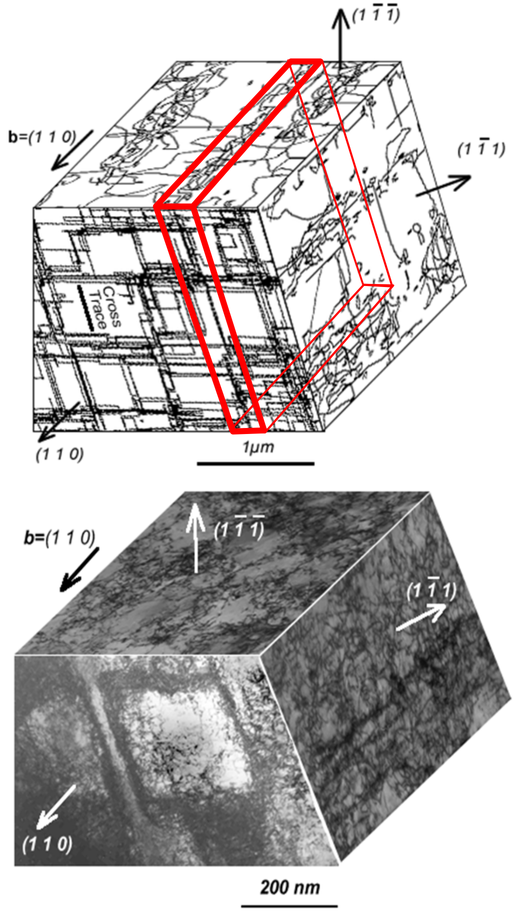
Strain localisation inside the Intense Slip Bands

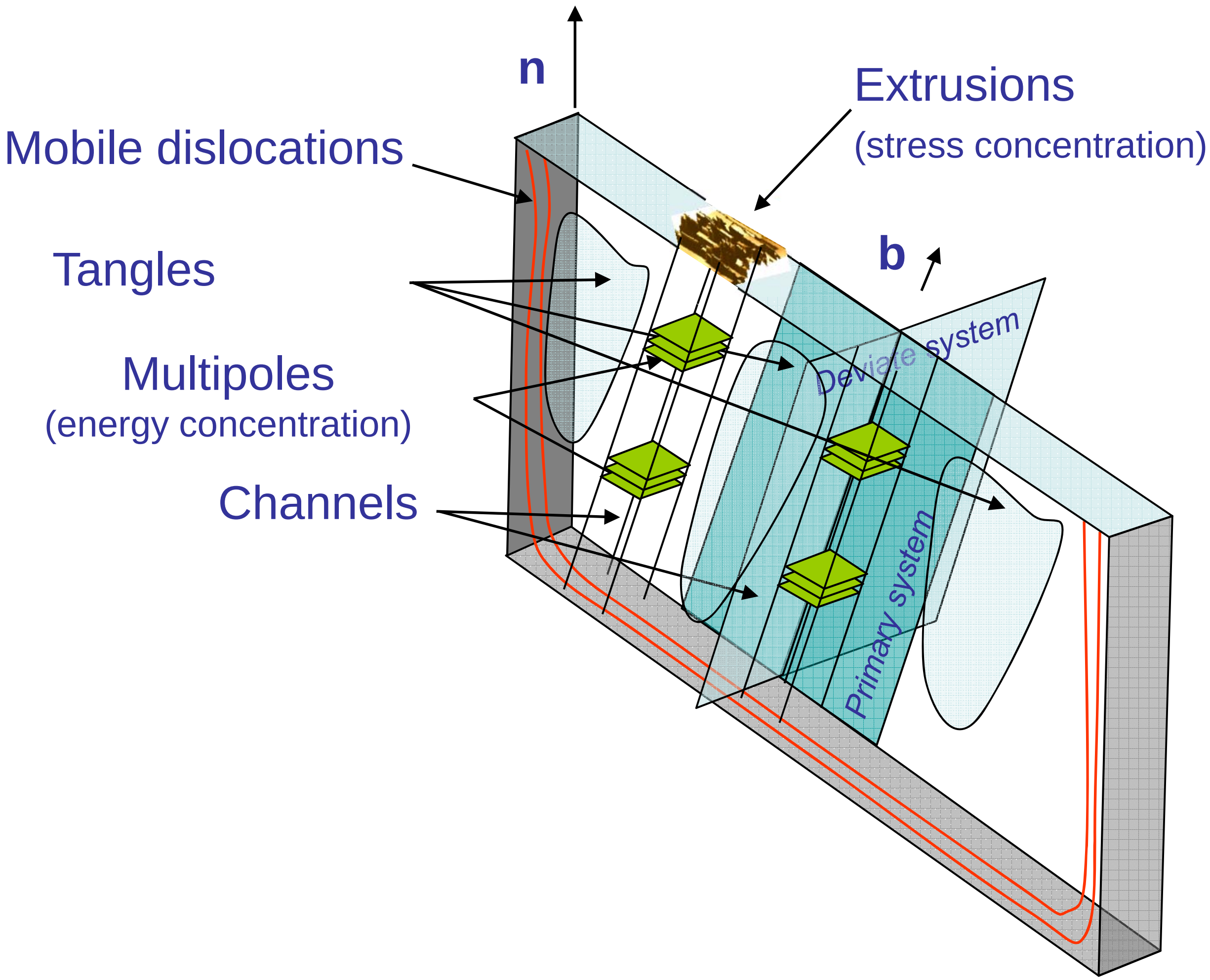
Kinetics of the persistent slip band (snapshots at $|\varepsilon|=\varepsilon_{max}$)



Plastic slip occurs at the band interface
(after stabilisation of disl. density (N> 10))

Schematic description of the Persistent slip band

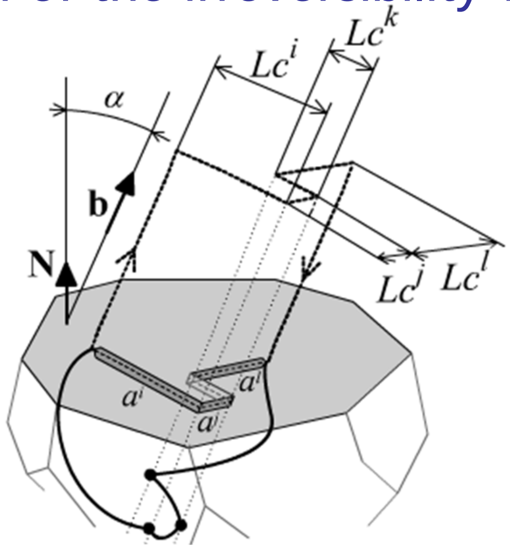




Sweeping of the prismatic loops (multipoles) by mobile interface dislocations

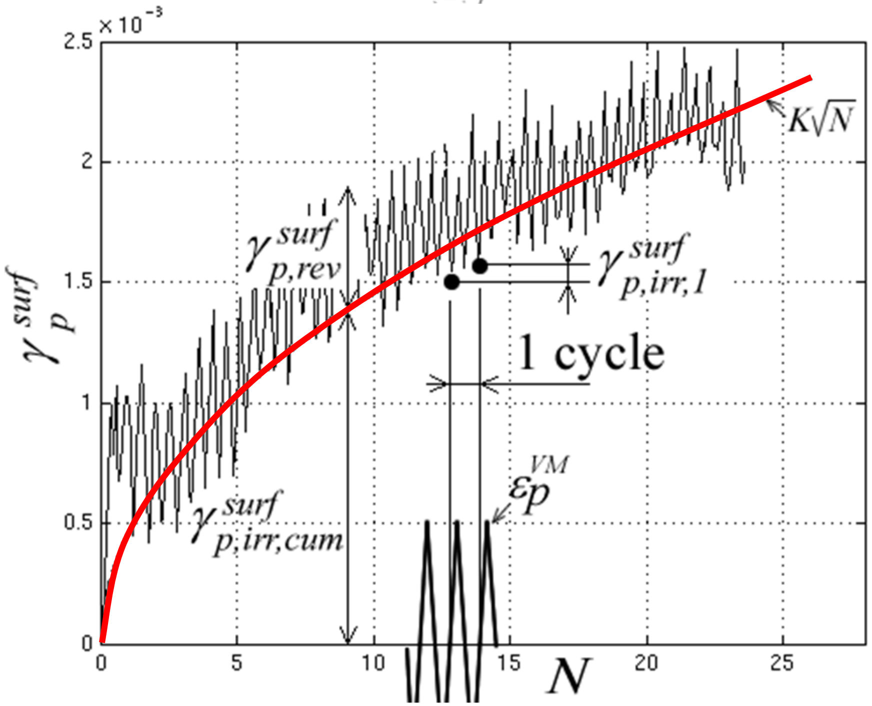
Reversible versus irreversible slip

Quantification of the irreversibility :



$$a_{cum} = \sum_{n_{coin}} \frac{L_c^i}{\cos \alpha}$$ = cumulated height

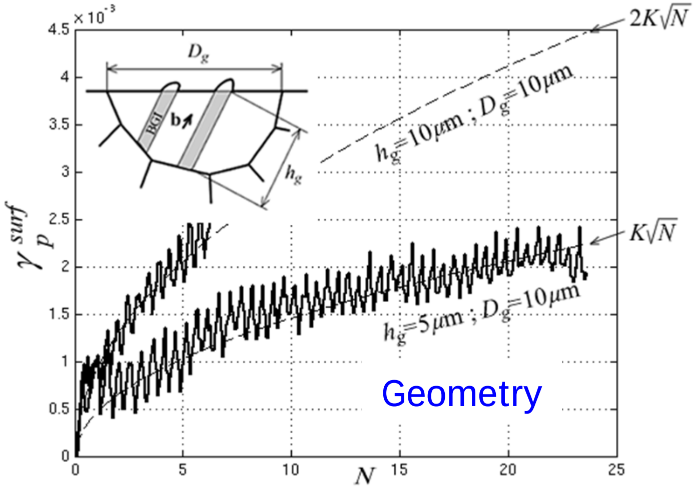
$$\gamma_p^{surf} = \frac{a_{cum}.b.\cos\alpha}{S}$$

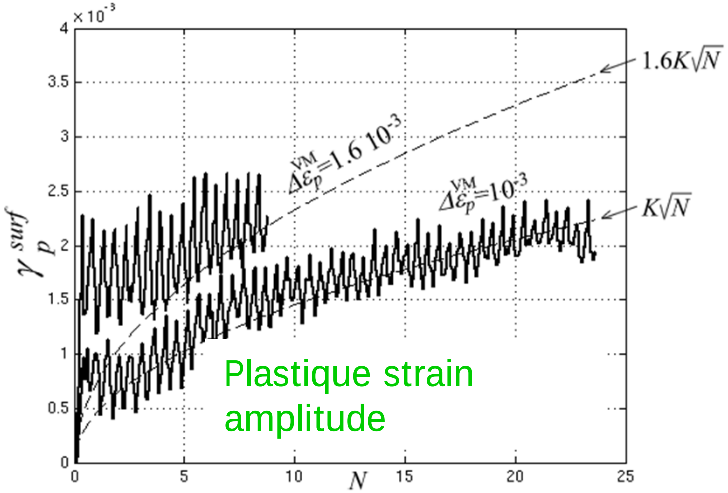


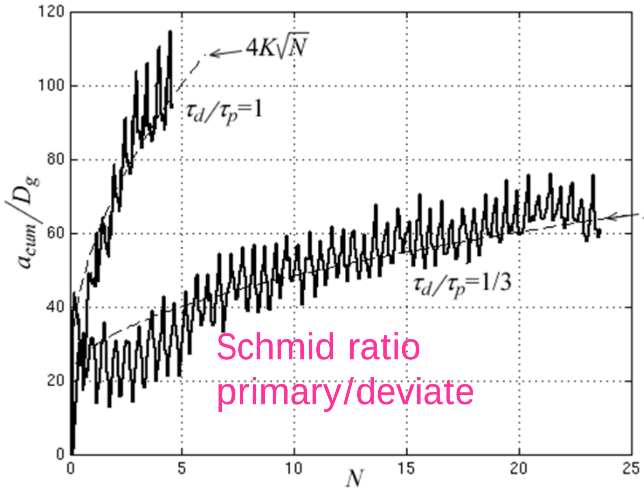
$$\gamma_p^{surf}(t) = \gamma_{p,rev}^{surf}(t) + \gamma_{p,irr,cum}^{surf}(t)$$

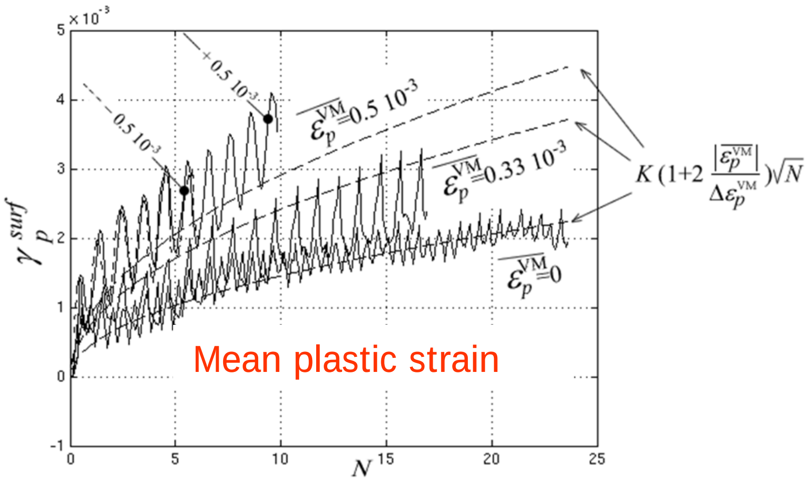
$$\gamma_{p,irr,cum}^{surf}(N) = K\sqrt{N}$$

Effect of different parameters



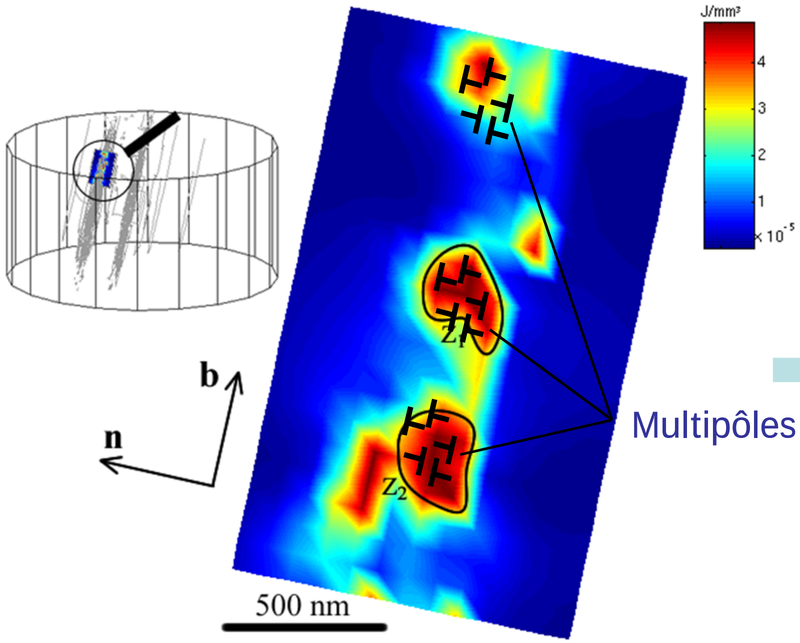


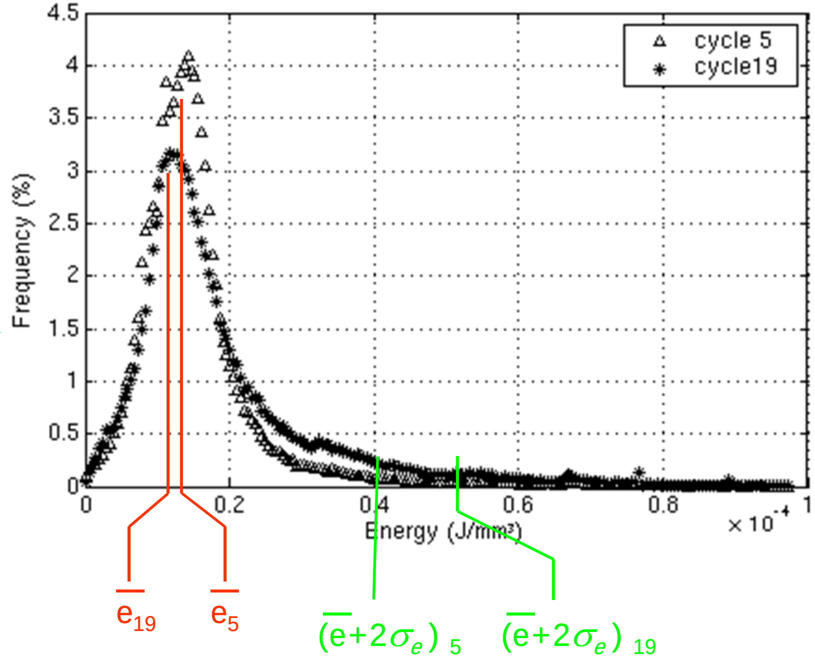


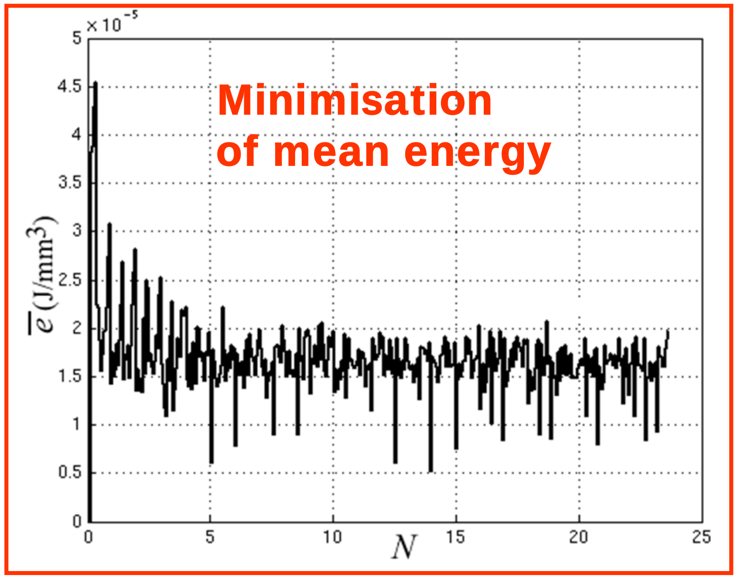


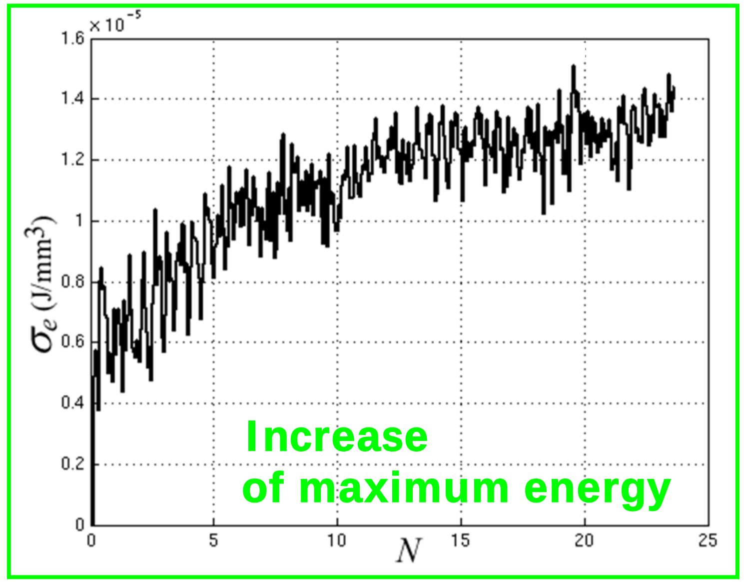
$$\gamma_{p,irr,cum}^{surf}(N) = K\underbrace{\frac{h_g}{D_g}}\underbrace{\Delta\epsilon_p^{VM}}\underbrace{f\left(\frac{\tau_{dev}}{\tau_{prim}}\right)}\underbrace{\left(1+2\frac{|\overline{\epsilon_p^{VM}}|}{\Delta\epsilon_p^{VM}}\right)}\sqrt{N}$$

Distorsion energy in channels

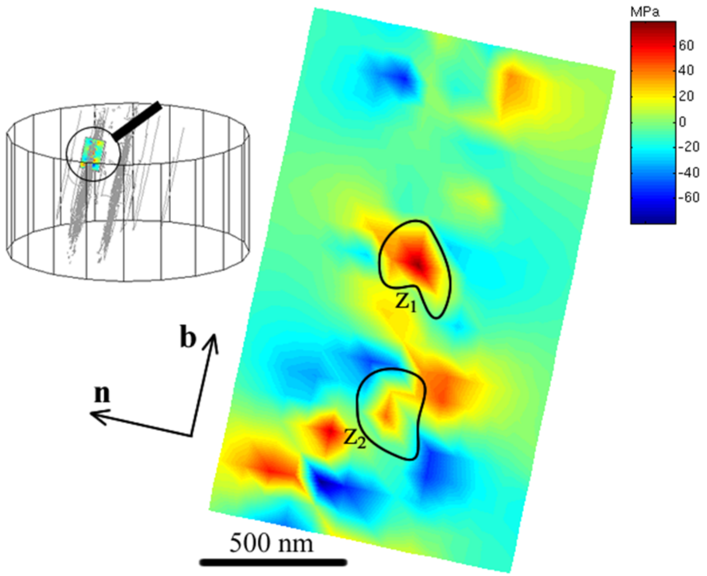


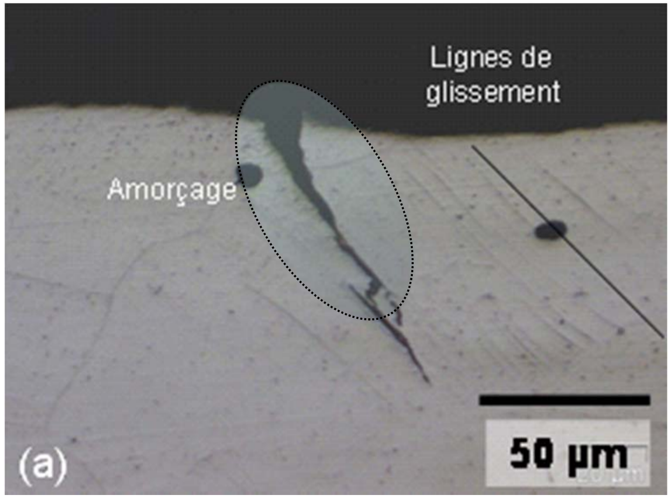


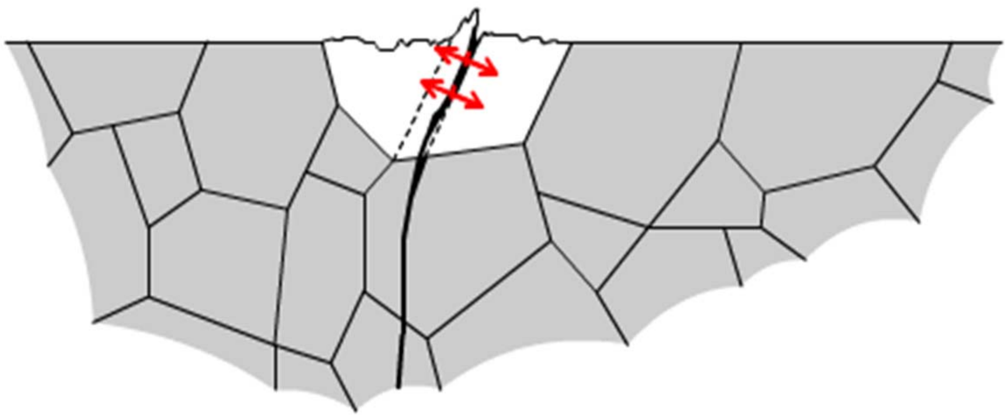




Stress state in channels







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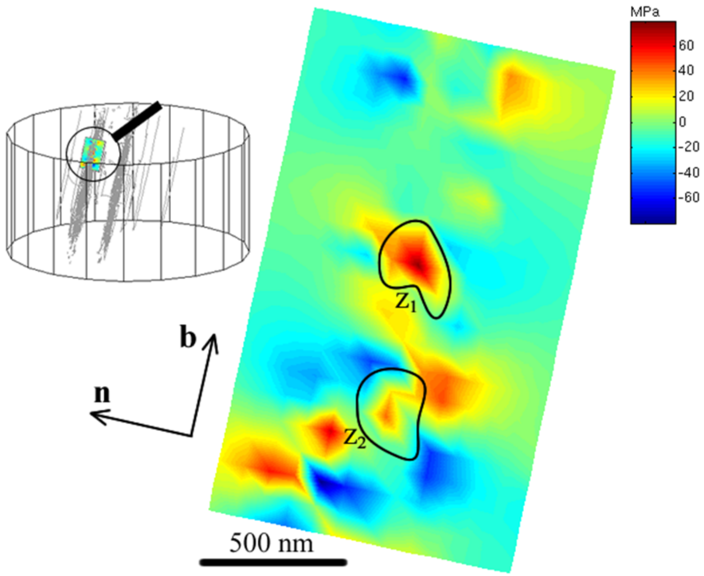
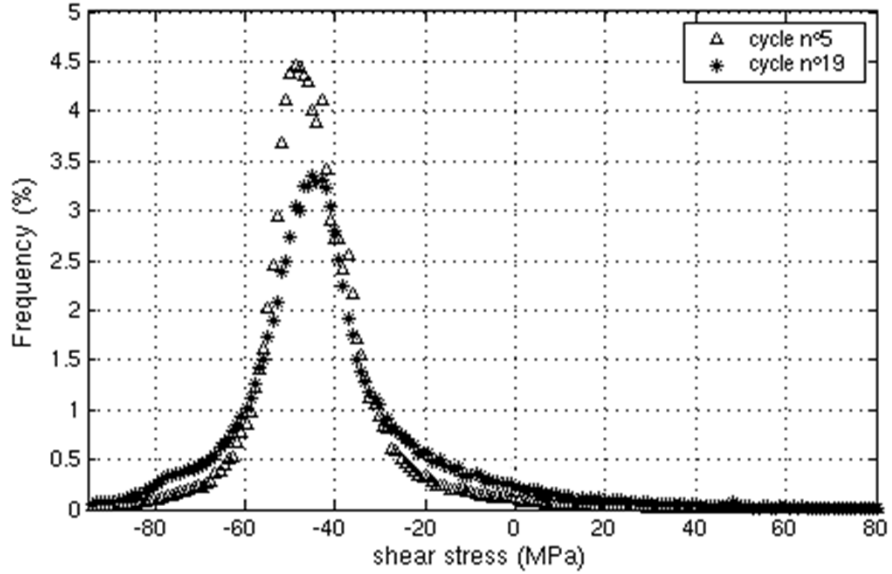
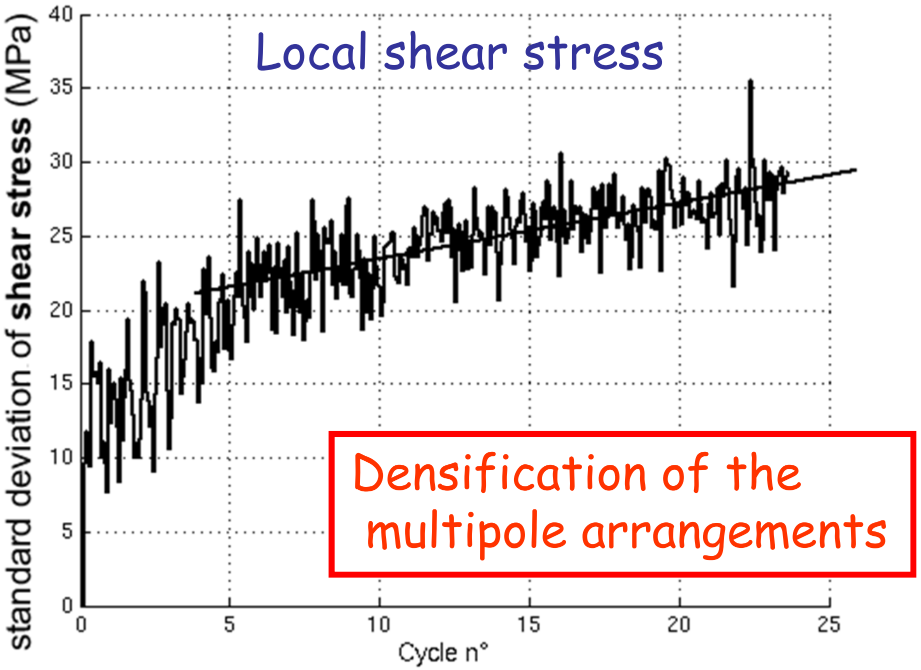
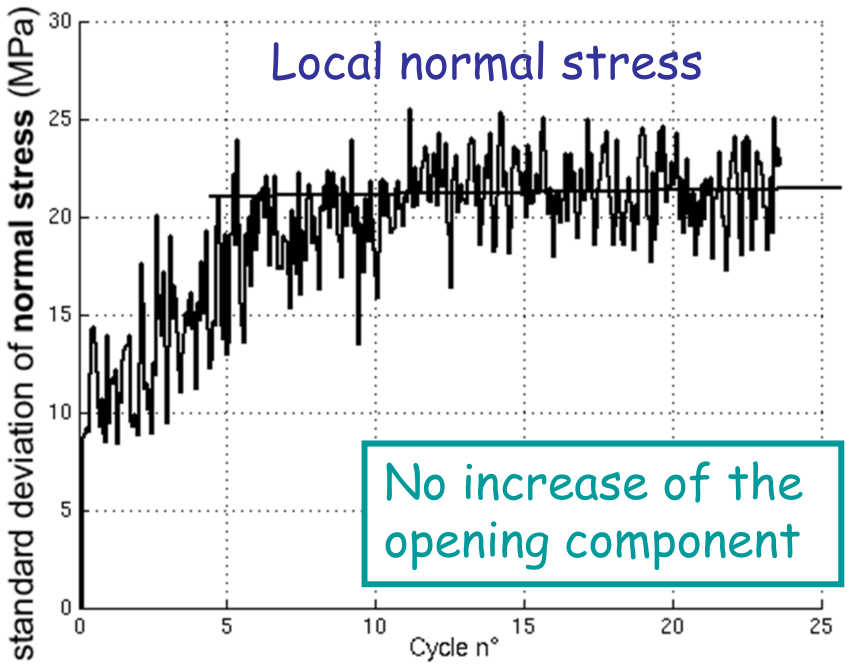
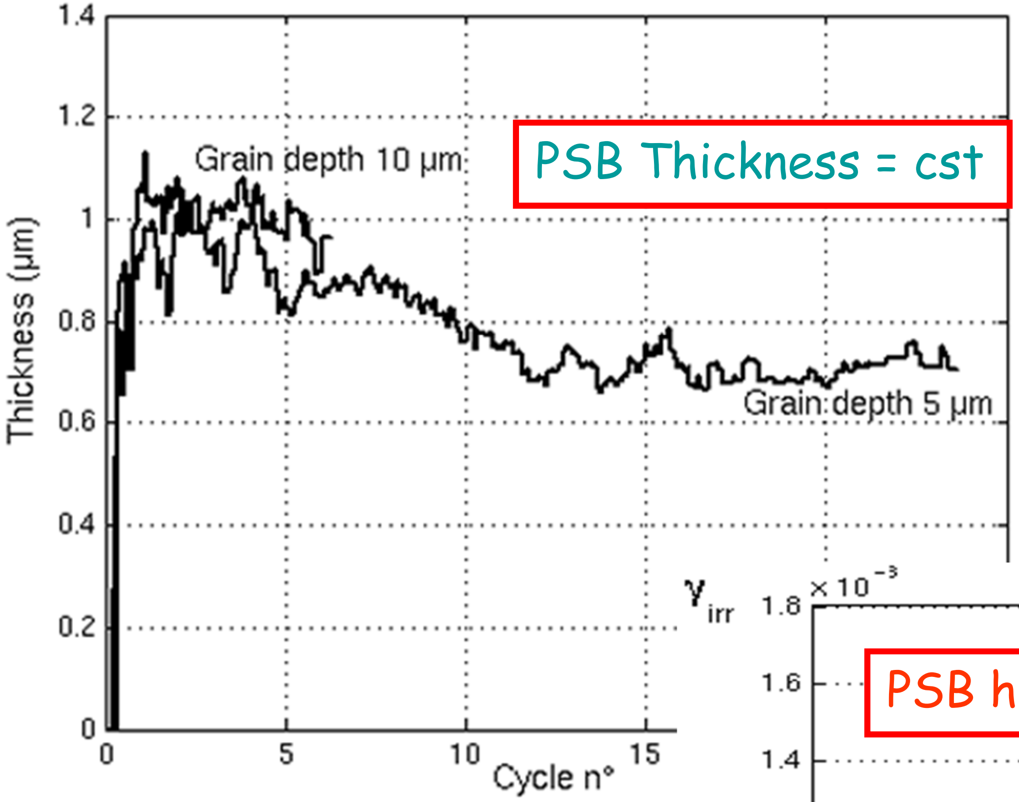
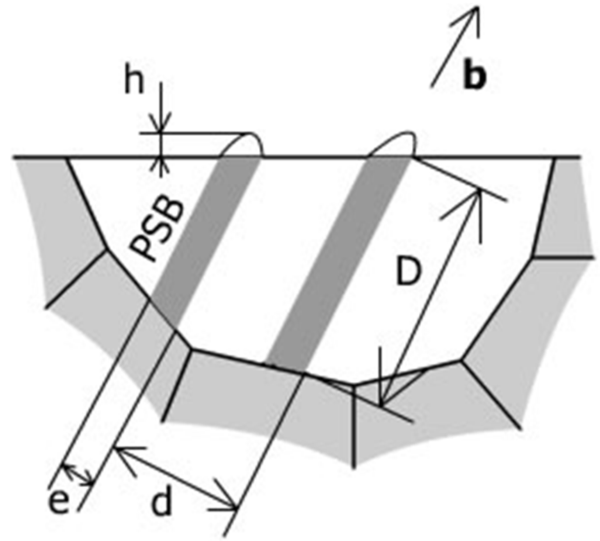


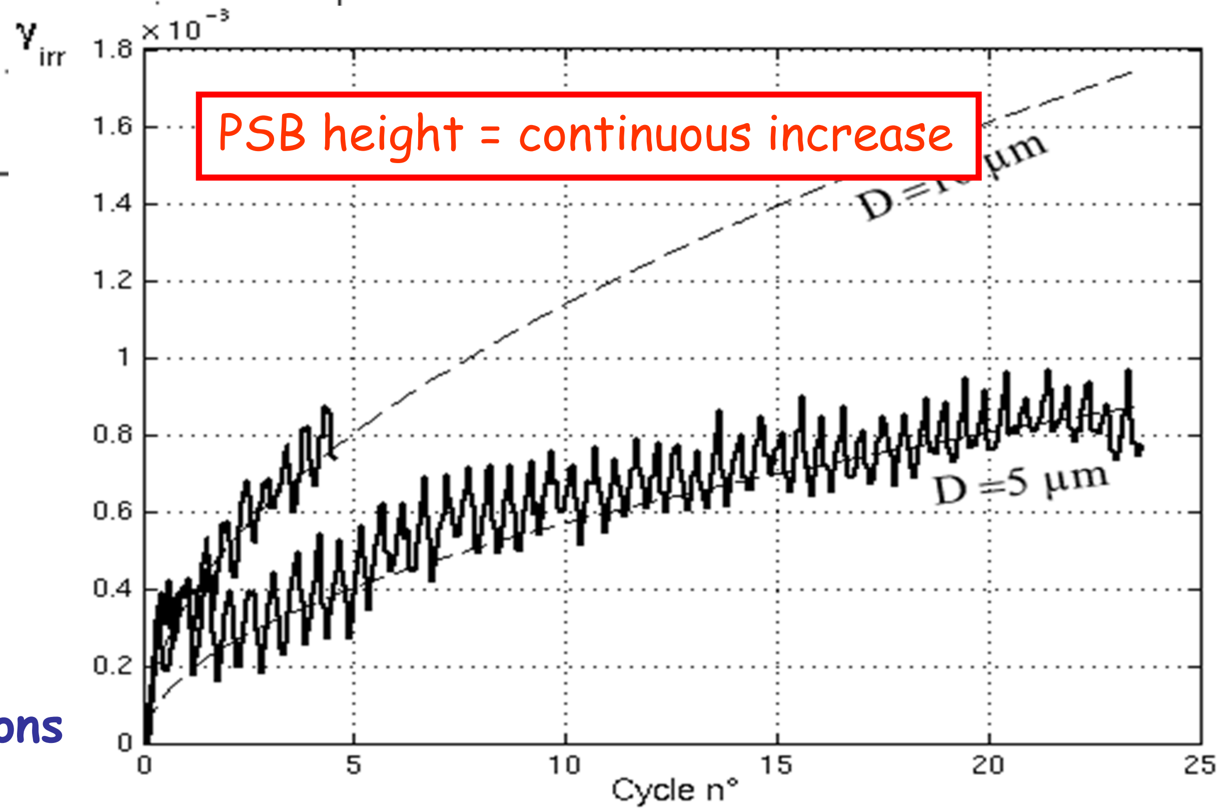








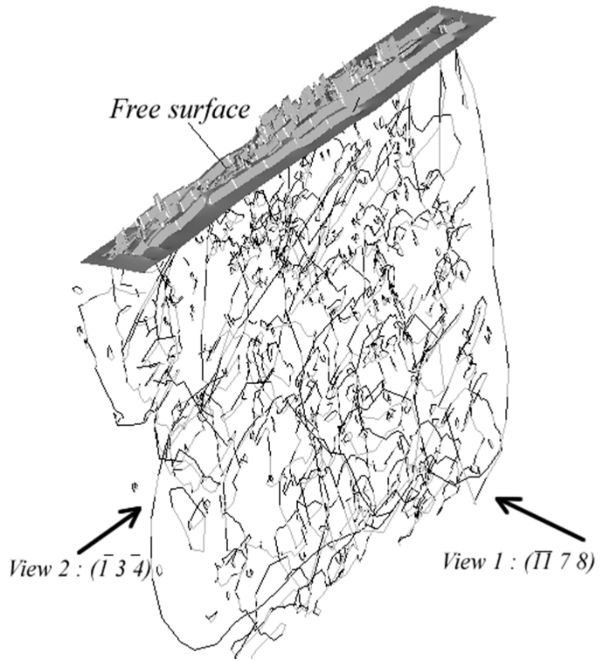


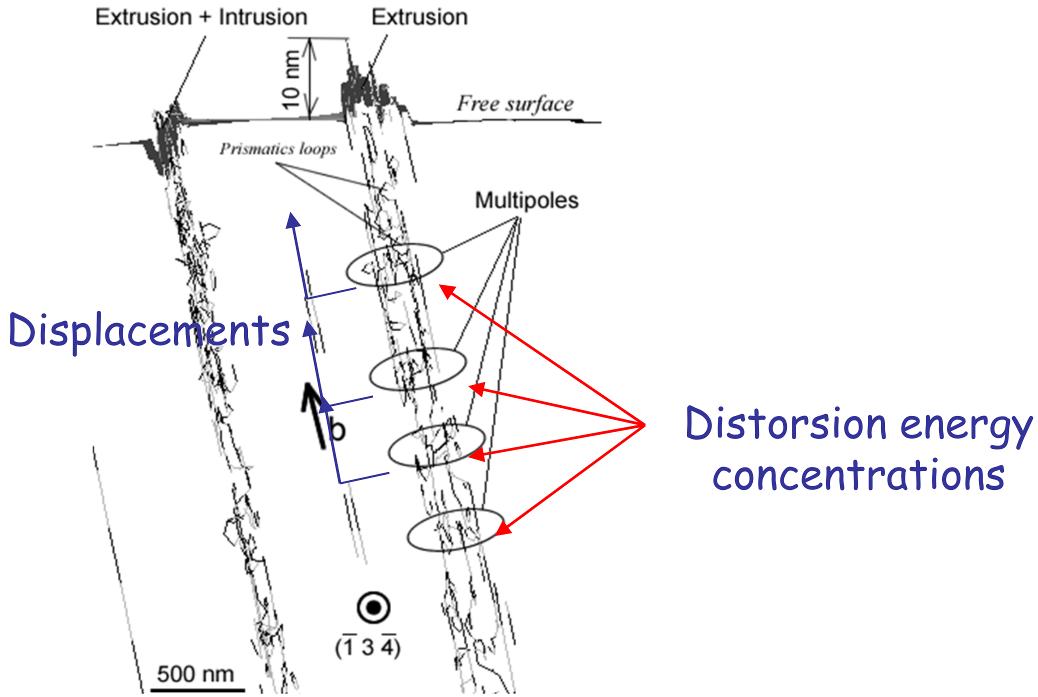


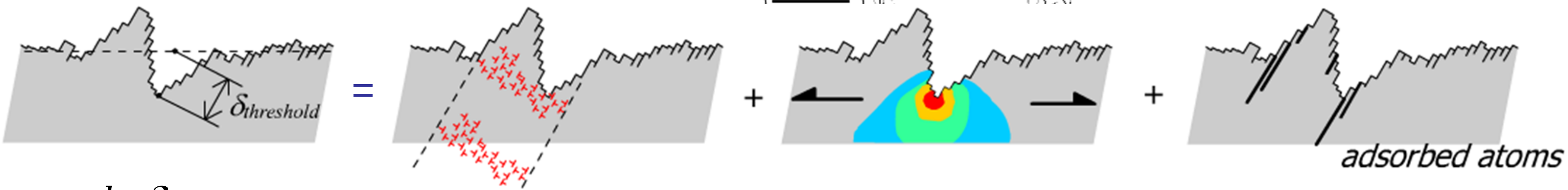
Increase of the extrusion shape factor

Continuous increase of opening component
at the surface
due to stress concentrations

Crack initiation criterion







$h > \delta_{threshold}$

Distortion energy concentrations

$$\iiint_V \underline{\underline{\sigma}} : \underline{\underline{\varepsilon}}\, dV$$

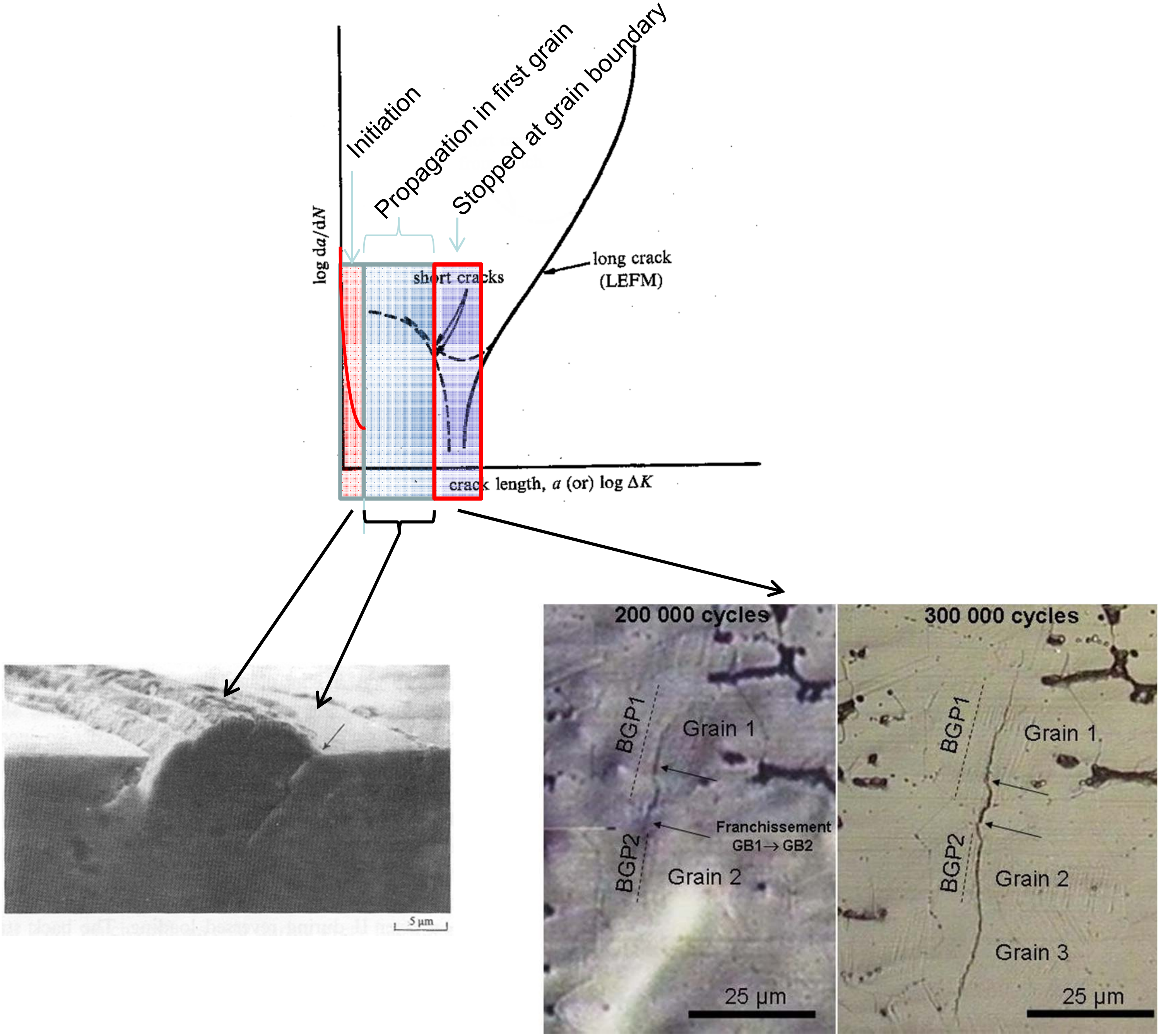
Driving force Fm
Evolution of h/e

$$\sigma_{nn} > \sigma_{SEPARATION}$$

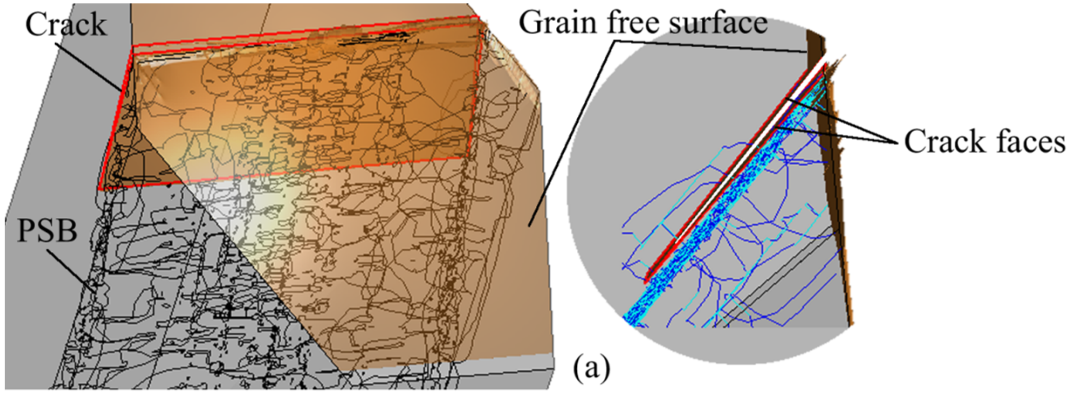
Threshold diminution

$$\Rightarrow N_{init} > \left(2\frac{k_2}{k_1}\frac{\delta_{threshold}\phi^2_{grain}}{V_{grain}} \cdot \left(\frac{\tau_p}{\tau_d}\right)^{\frac{1}{m}} \right)^{\frac{1}{\frac{1}{2}+\frac{\varepsilon_{moy}}{\Delta\varepsilon_p}}}$$

What about crack propagation ?

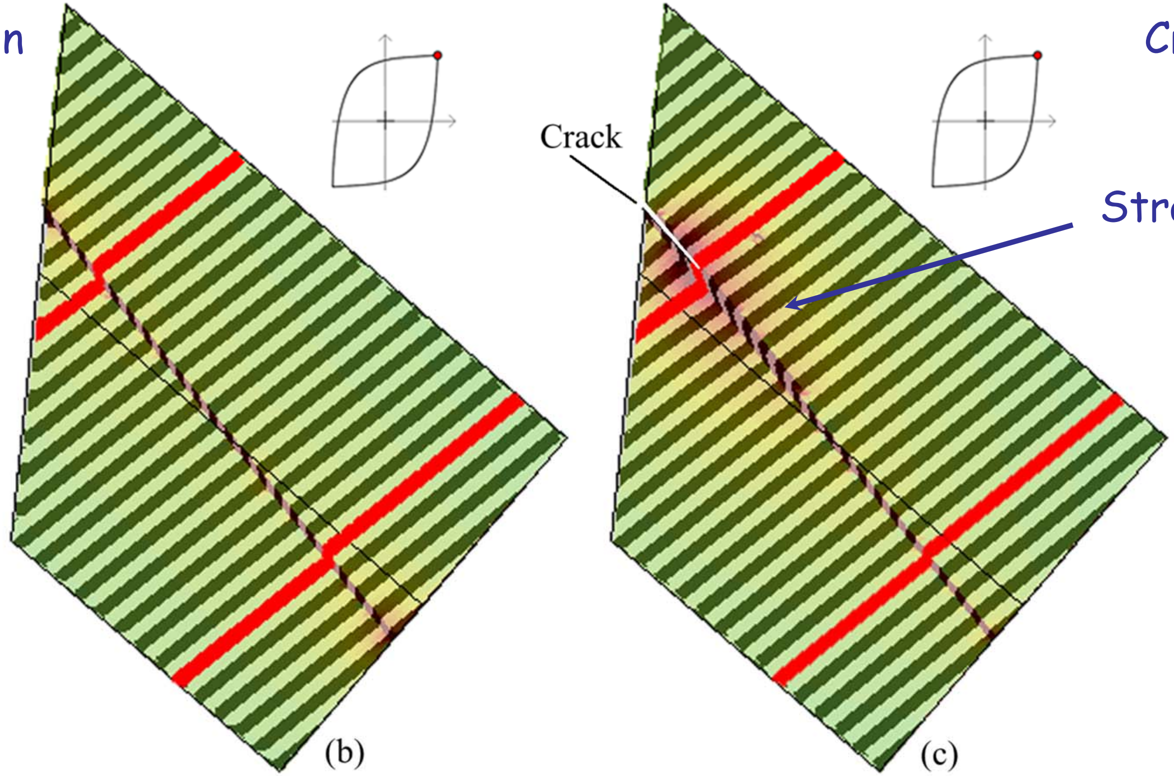


Crack growth in the first grain



Non cracked grain

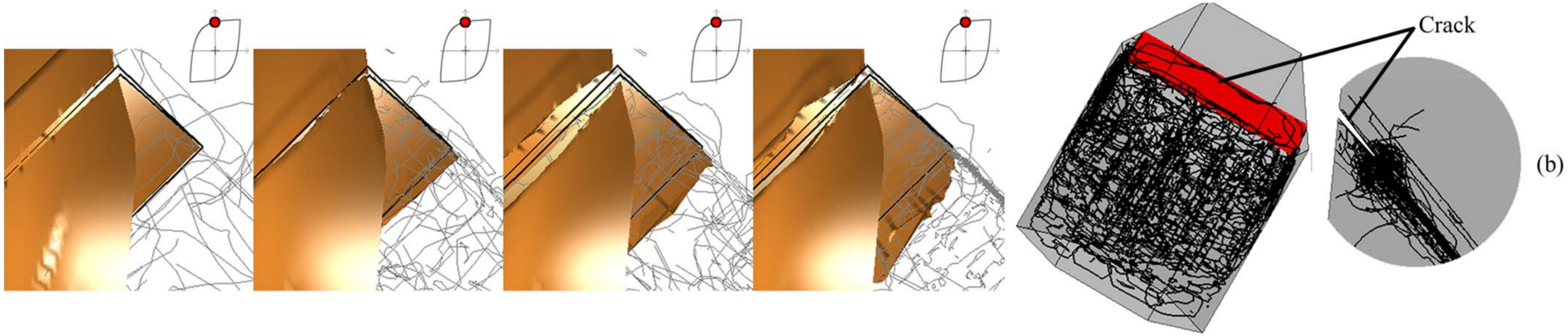
Cracked grain



Strain localization

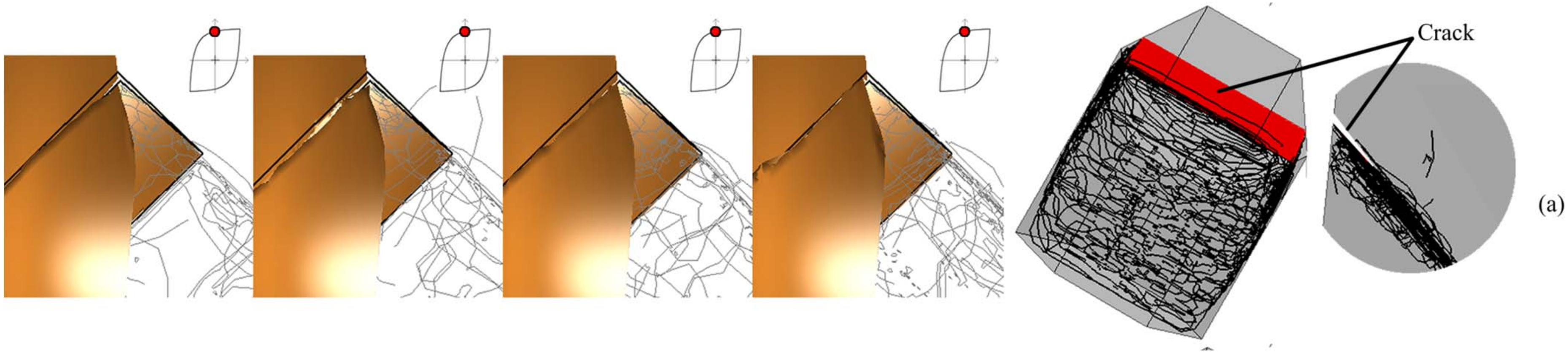
Crack growth in the first grain

Crack introduced from the beginning of the fatigue simulation



⇨ Change in crack shape and complex dislocation microstructure (not PSB)

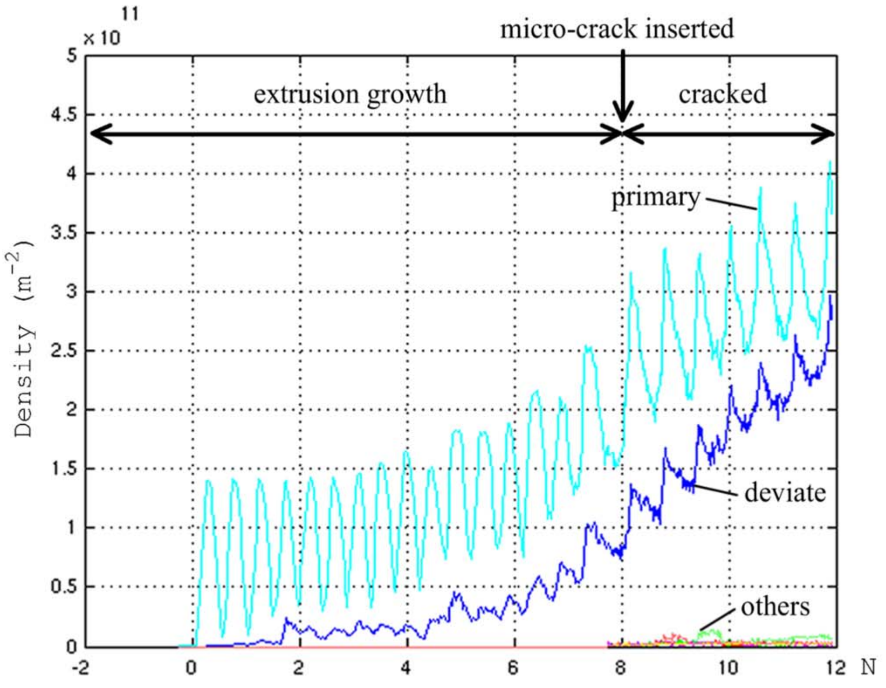
Crack introduced after the PSB is formed



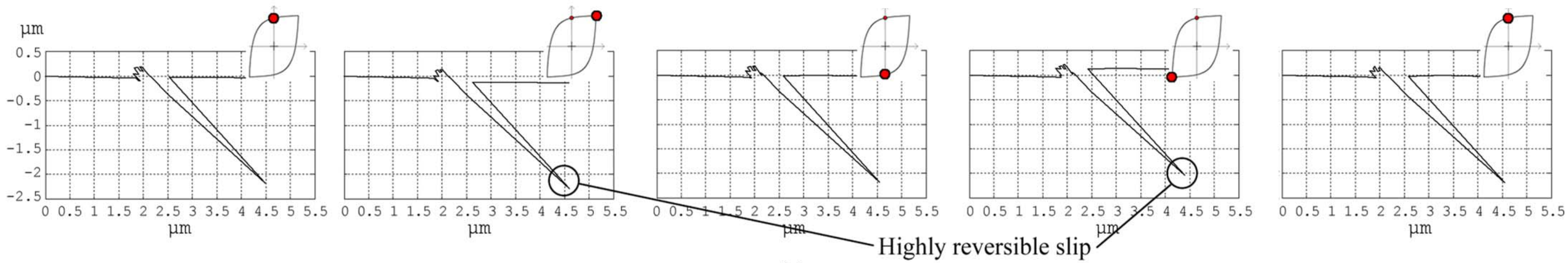
⇨ Crack shape not modified, dislocation microstructure unchanged

Crack growth in the first grain

Crack introduced after the PSB is formed

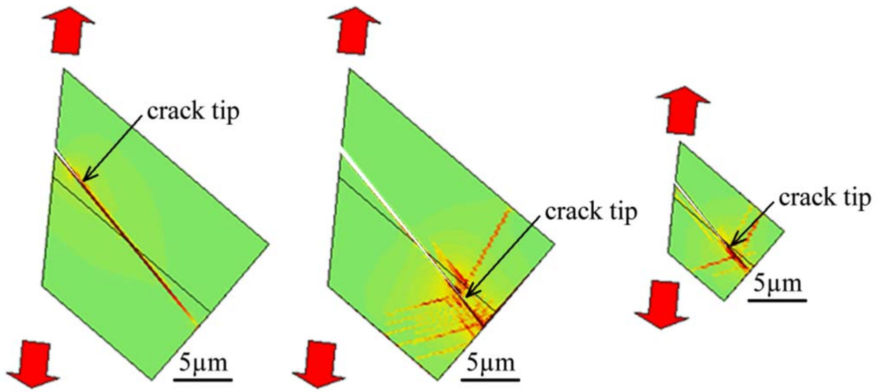


(c)

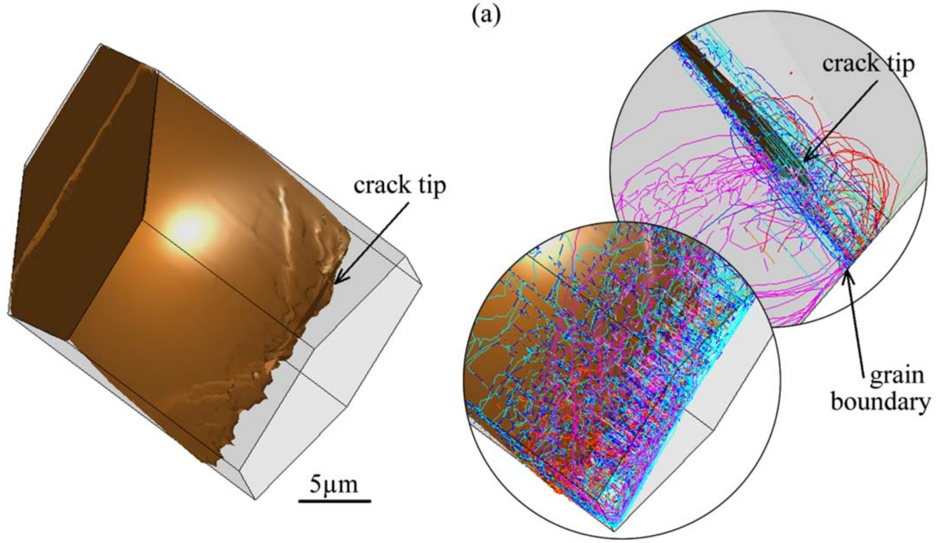


(e)

Grain size effect

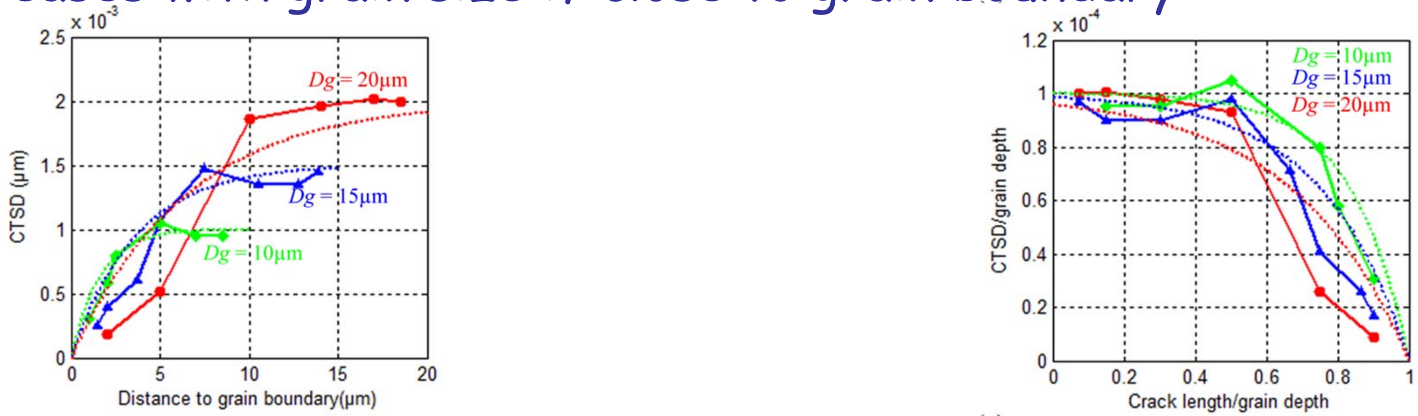


(a)



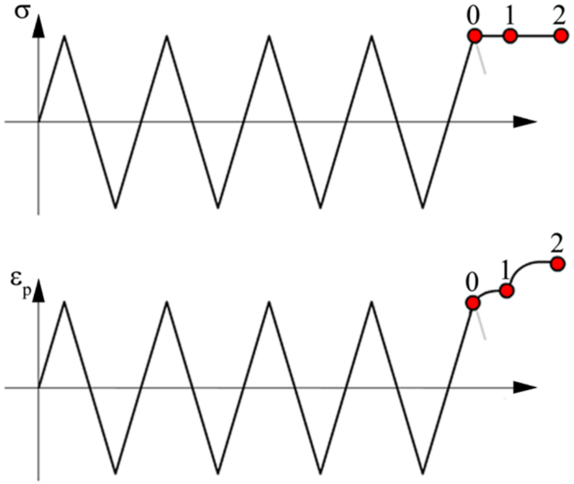
Slip dispersion

CTSD decreases with grain size if close to grain boundary



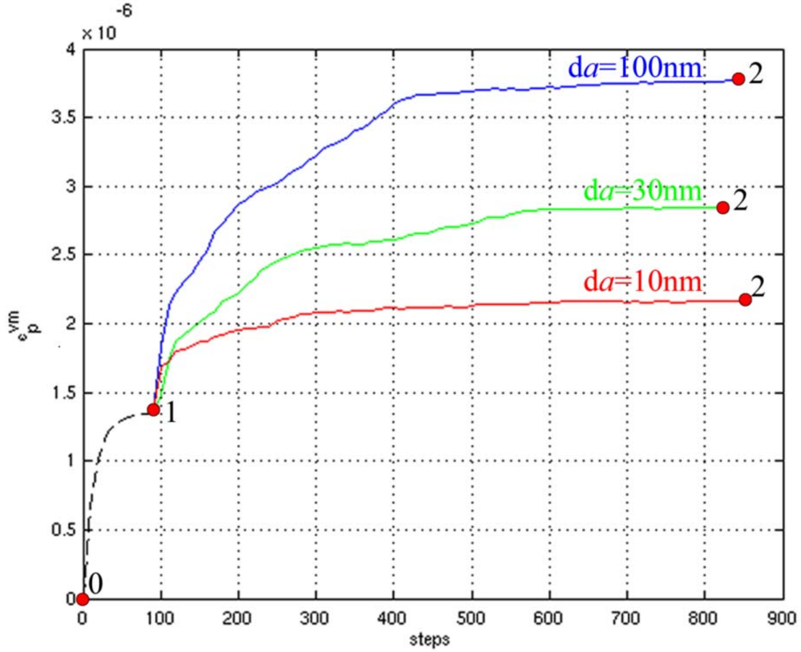
(c)

Crack advances

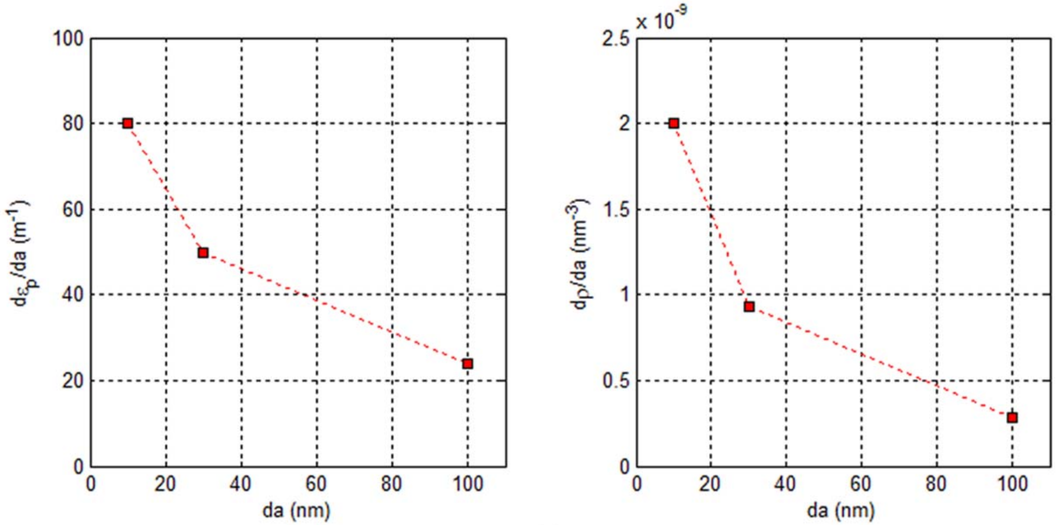


(c)

$$G_c \mathrm{d}A \le \mathrm{d}\left(\int_{\Omega} \frac{1}{2}\sigma : \varepsilon_e \mathrm{d}\Omega\right) + \Sigma_{\mathrm{app}} d\varepsilon_{\mathrm{p}}\Omega$$



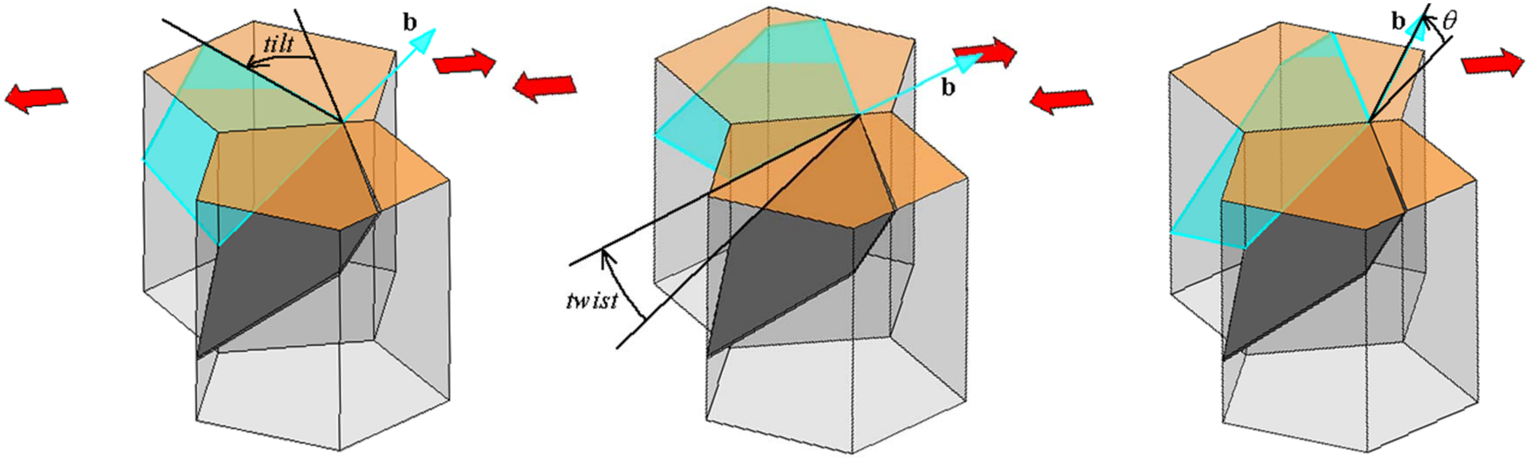
$$G_c \le \beta\mu b^2 \frac{\mathrm{d}\rho}{\mathrm{d}A} + \ldots + \Sigma_{\mathrm{app}} \frac{\mathrm{d}\varepsilon_{\mathrm{p}}}{\mathrm{d}A}\Omega$$



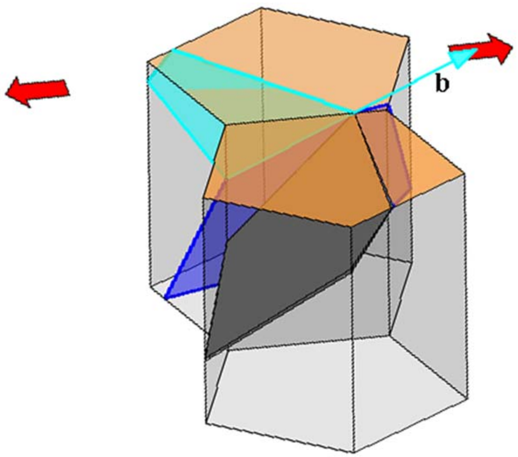
(c)

Small crack increments (<10nm)

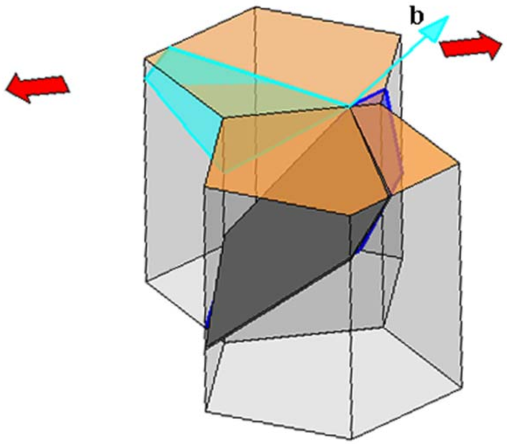
Crack propagation in second grain (indirect slip transmission)



Effect of local misorientation : tilt, twist, theta



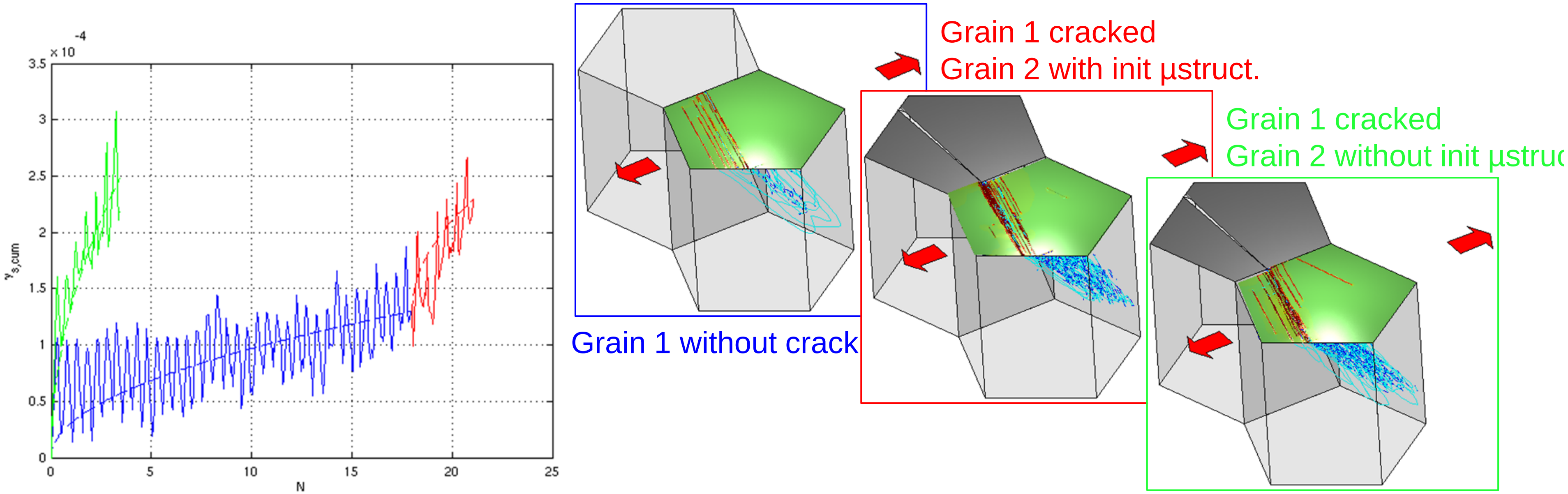
Tilt + Twist



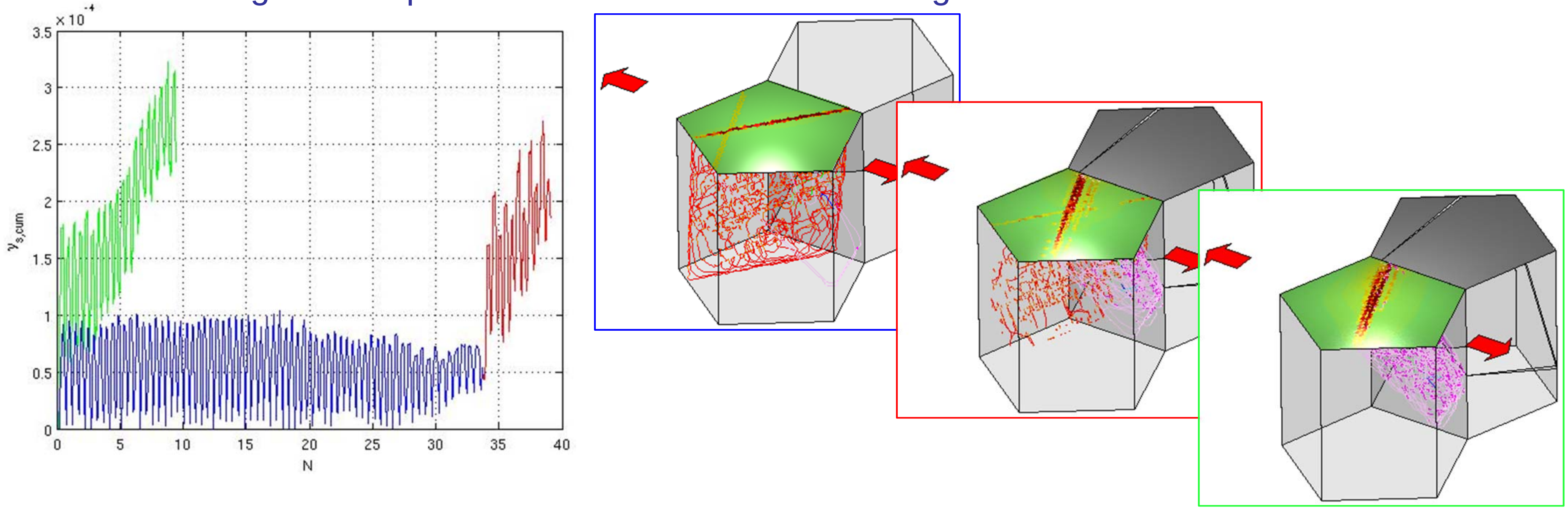
Tilt + Twist + θ

Crack propagation in second grain

1. Crack in grain 1 imposes crack growth rate in grain 2



2. Crack in grain 1 imposes new disl. Microstructure in grain 2



DDD modelling results:

1- Dislocation organisation in PSB
- → Intense slip bands formed by cross-slip and interactions
- → Slip band = Channels + Tangles + Pile-ups

[C. Déprés, C.F. Robertson, M.C. Fivel, *Phil. Mag.*, **84** (22), pp.2257-2275, (2004)]

2- Irreversibility at the surface
- → Extrusion and intrusions observed (without diffusion)
- → Extrusion = Tongue like (instead of ribbon like)
- → Extrusion width cstt
- → Extrusion height α $N^{1/2}$

[C. Déprés, C.F. Robertson, M.C. Fivel, *Phil. Mag.*, **86** (1), pp. 79-97, (2006)]

3- Crack propagation in the first grain
- → Crack at PSB/matrix interface can propagate
- → CTSD depends on the grain size if crack close to GB

[V.G. Prasad Reddy, C. Déprés, C.F. Robertson, M.C. Fivel, *submitted to Acta Materialia* 2013]

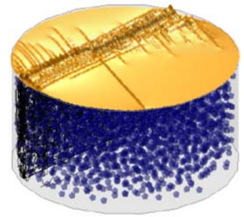
4- Crack propagation in the next grain
- → Crack in grain 1 imposes microstructure in grain 2
- → Large disorientations favour plastic strain spreading

[V.G. Prasad Reddy, C.F. Robertson, C. Déprés, M.C. Fivel, *submitted to Acta Materialia* 2013]

Limits and improvements under investigation:

→ Taking into account the image forces (negligible)

→ Effect of point diffusion → Need a coupling with diffusion theories



→ What if precipitates are present (e.g. Waspaloy):

[C.S. Shin, C.F. Robertson, M.C. Fivel, *Phil. Mag.*, **87** (24), pp. 3657-3669, (2007)]

→ Effect of neighbour grains

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