SOTERIA MIDTERM WORKSHOP

DOSE-DEPENDENT NANO-FEATURES AND THEIR EFFECT ON INTER-GRANULAR CRACKING SUSCEPTIBILITY

9TH APRIL 2018

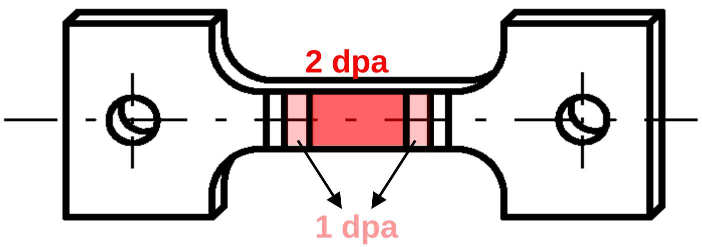
Contribution to SOTERIA WP2

Co-workers: B. Tanguy, J. Hure

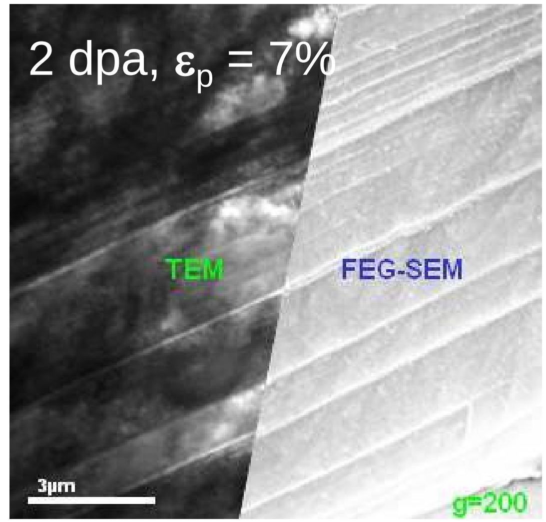
Speaker: **Christian Robertson**

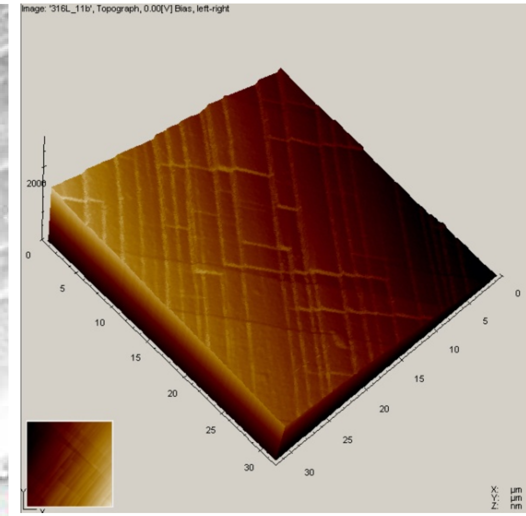
Post-irradiation plasticity mechanisms (P60)

Ions irradiations: p+ or Fe^{8+}, 300 °C



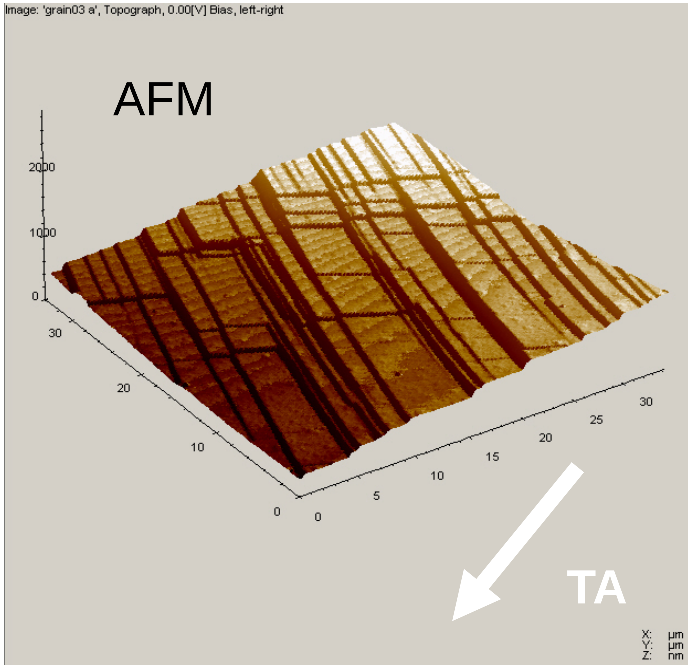
Ion irradiations & observations

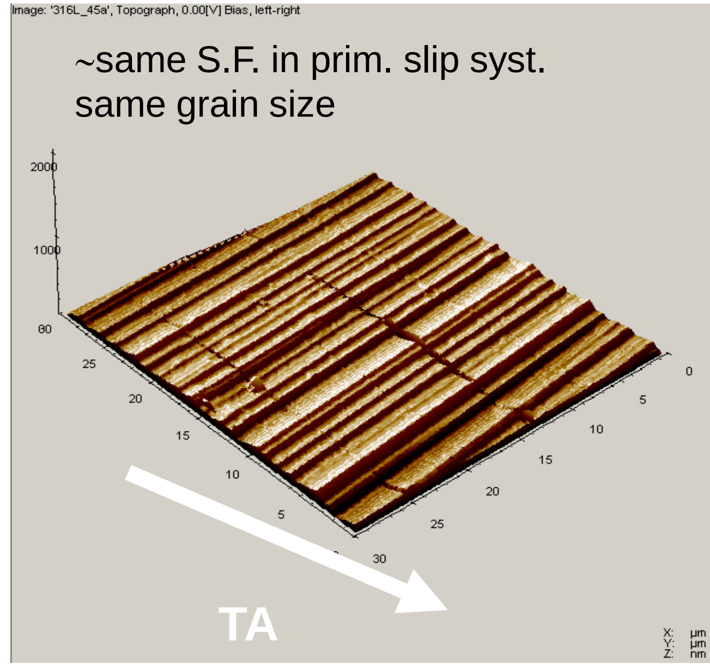




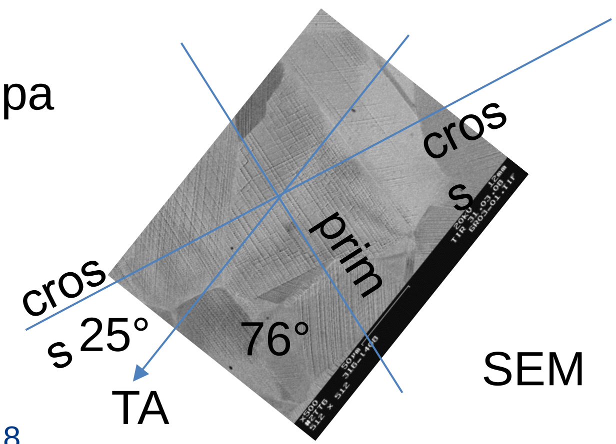
➢ Quantification of irradiation-induced strain localisation:
Post-irradiation: slip steps are fewer and taller

Post-irradiation plasticity mechanisms



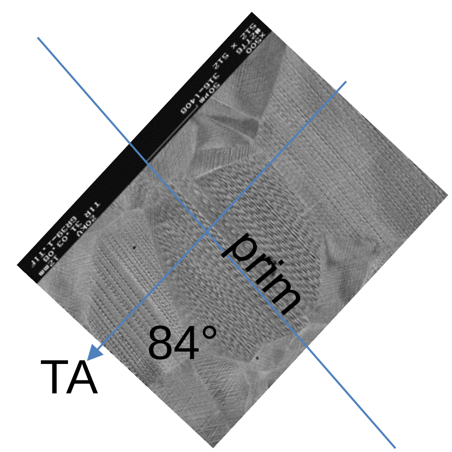


2 dpa



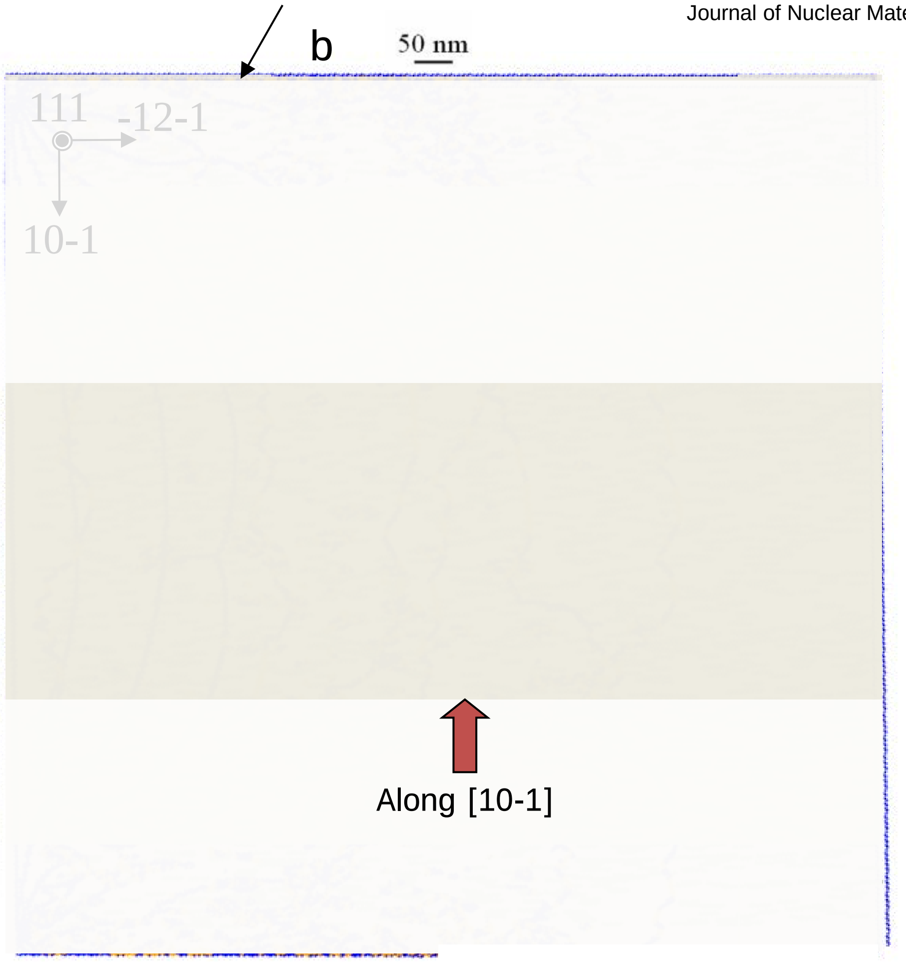
SEM

0 dpa



Shear band dislocation substructure

Journal of Nuclear Materials 380 (2008) 22–29



Leading dislocations

Dislocations with helix/jogs

Clear and broaden channels

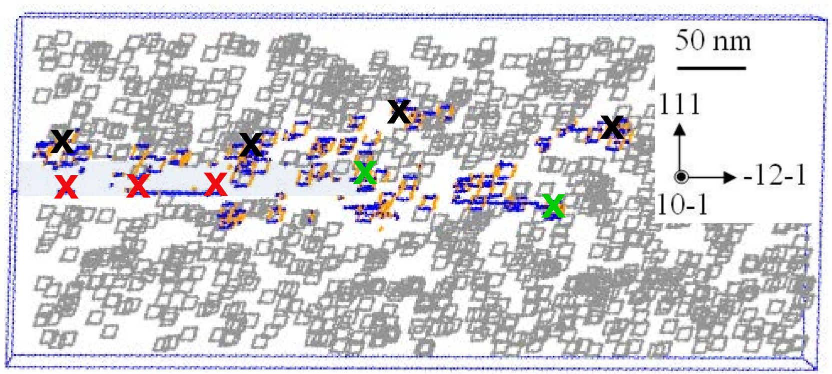
Trailing dislocations

Straight piled-up dislocations

“Push” the leading dislocations

At the channel periphery:

accumulation of coarse loop debris



X cleaning **dislocations**

X piled-up **dislocations**

X arrested **dislocations**

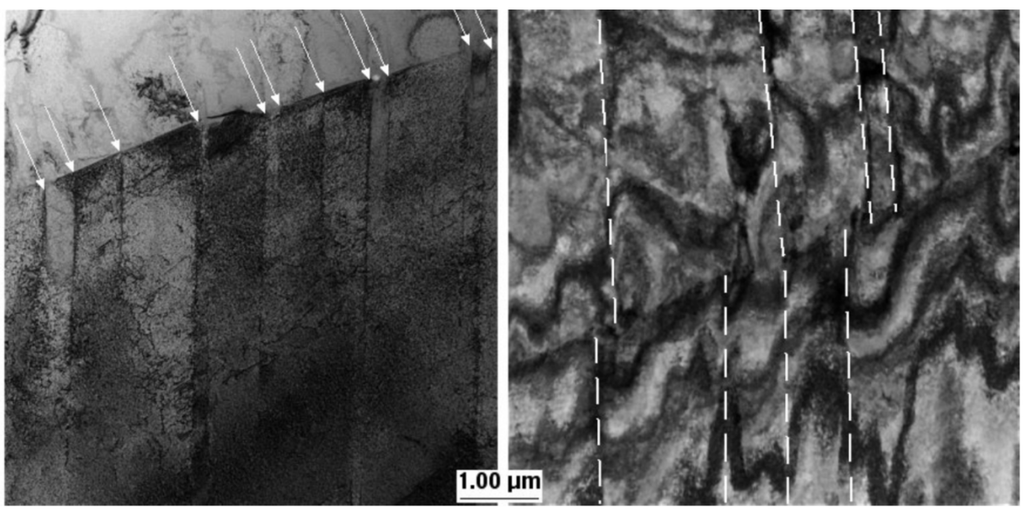
Partial summary… (from P60)

- Loop-depleted channel (or clear band) is merely a particular shear-band type, separated by channel-free zones

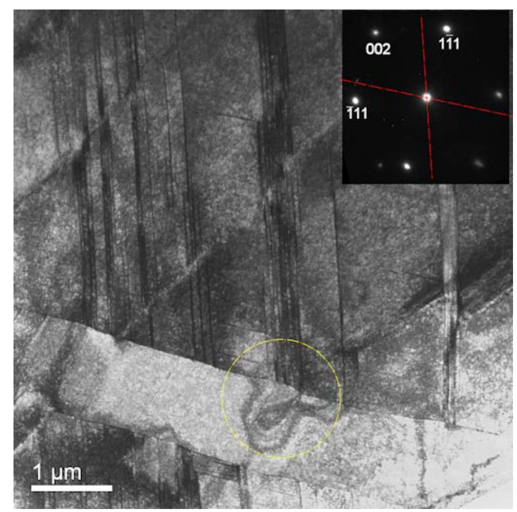
- In FCC crystals, channels include dislocation pile-ups (unlike in BCC, where tangles form), generating a long-range, out of plane stress field

- The characteristic channel thickness and spacing controls the stress concentration magnitude at the GBs and hence, crack initiation susceptibility thereof

W. Karlsen, VTT



0.89 dpa 304L
Tensile test B7, specimen ”nec4”



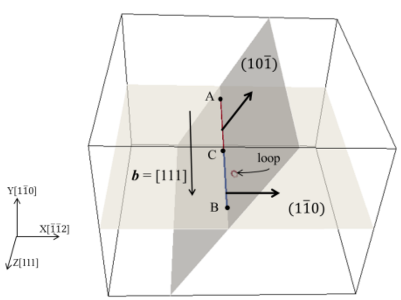
11 dpa CW 316
Tensile test B7, specimen ”nec4”

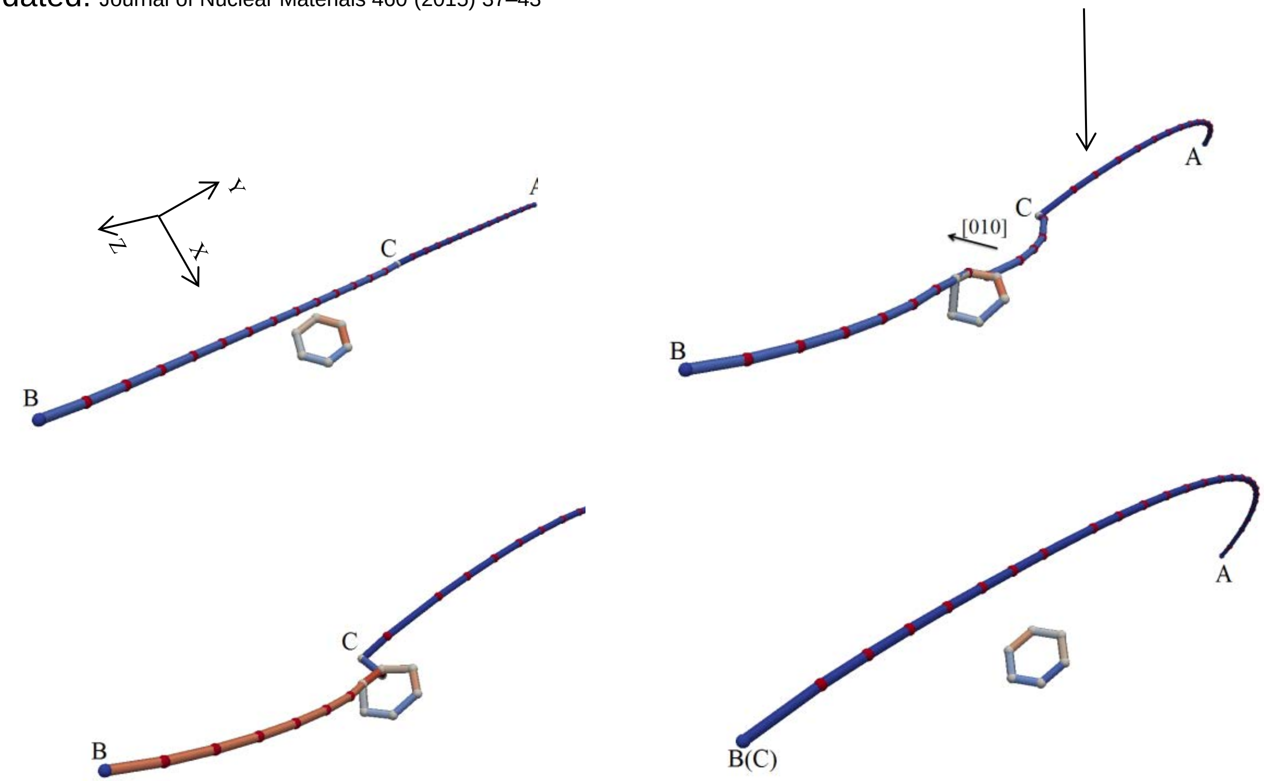
Next step: include role of cross-slip

With pinning points & cross-slipped segments
Interaction with 1$\bar{1}$1 & 111 loops

NUMODIS ☞ MD validated: Journal of Nuclear Materials 460 (2015) 37–43

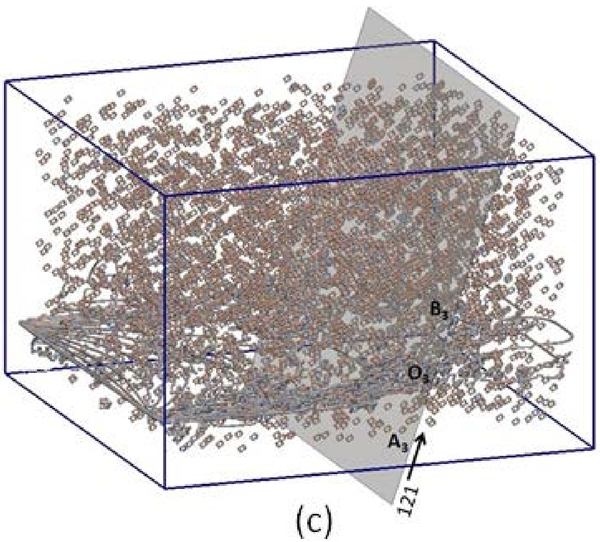
Cross-slipped segment





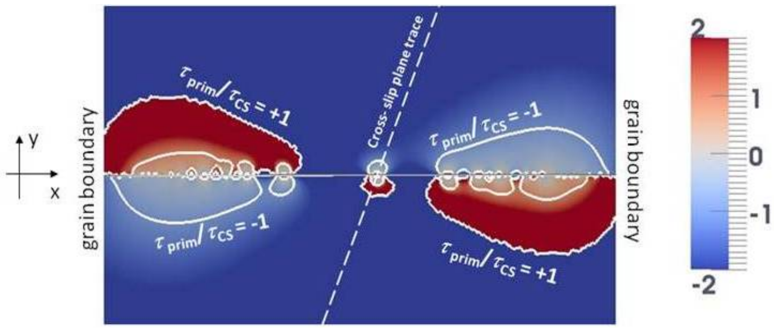
☞**In presence of cross-slip: interaction strenght < loop strength**
☞**Cross-slip provides an easy path to overcome the defects**

Shear band multiplication: cross-slip



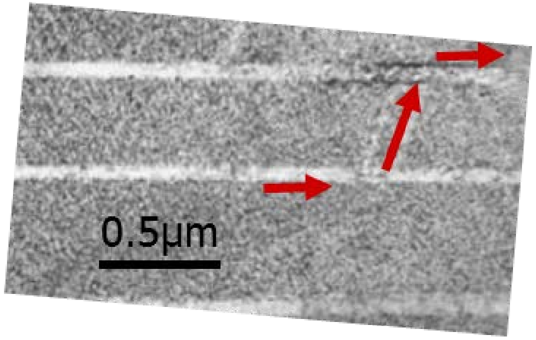
Phil. Mag. 95 No.12 (2015) 1368–1389

Cross-slip probability is highest: $\tau_{prim}/\tau_{CS} = \pm 1$



Stress mapping: τ_{prim}/τ_{CS}

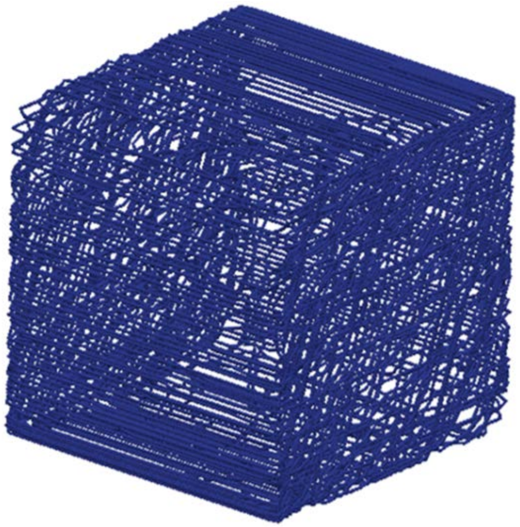
Typical shear band spacing scales with internal stress field characteristic distance

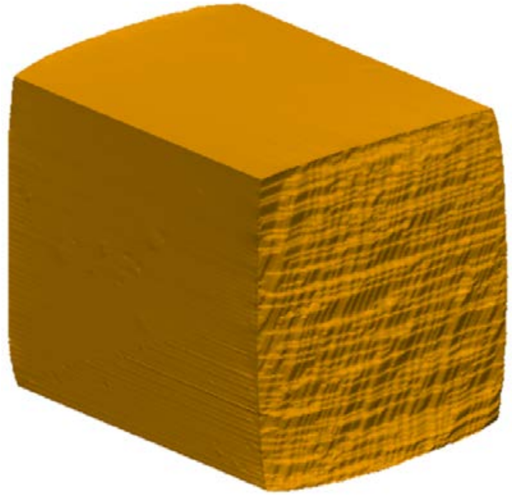


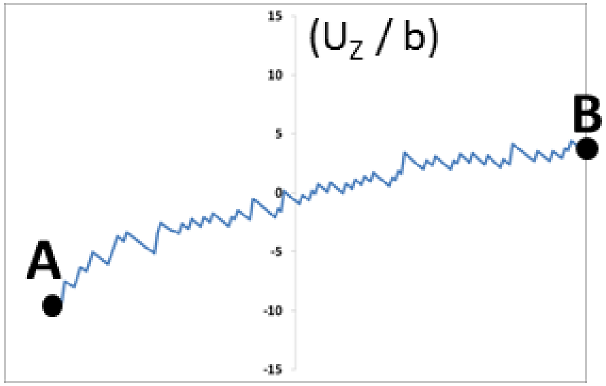
Regular inter-channel spacing

Secondary channel in X-slip planes: [Yao 2005]

Shear band spacing

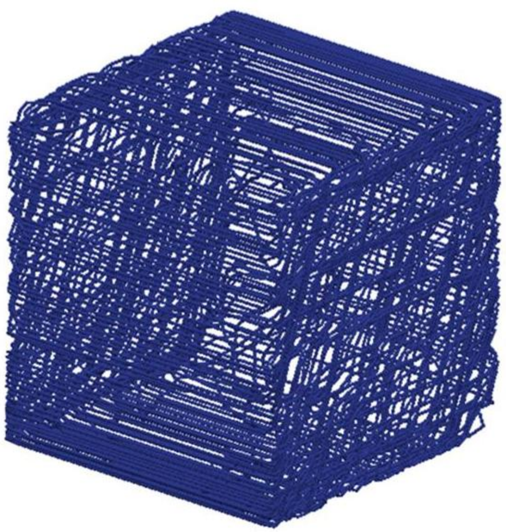


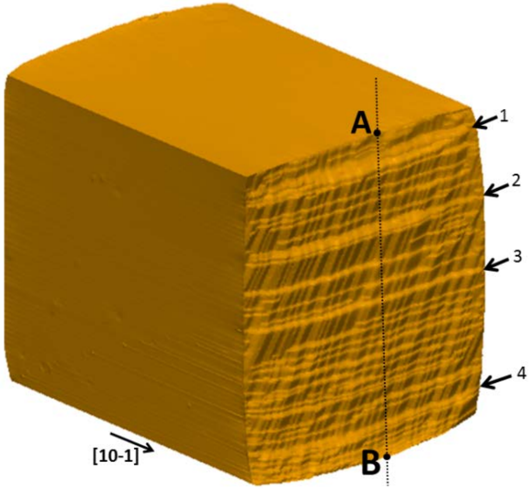


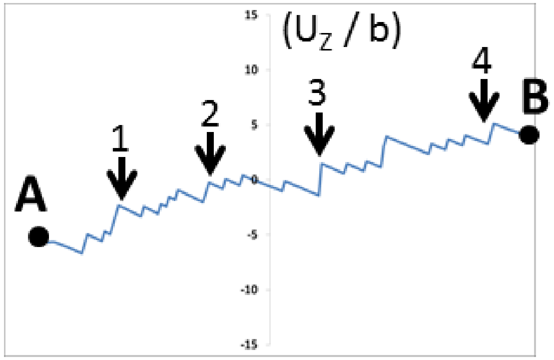


00 loops

$\varepsilon_p = 1,4 \times 10^{-3}$



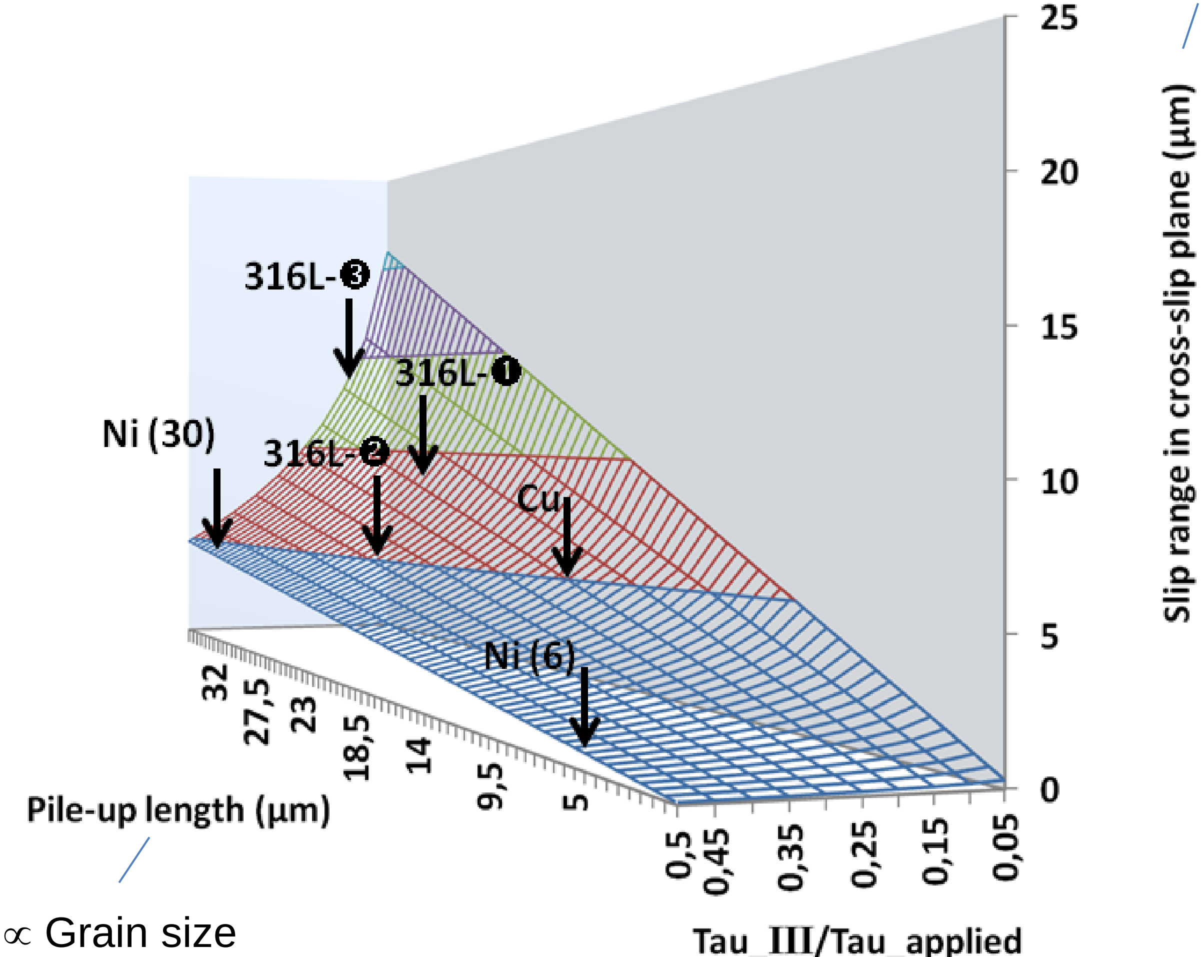




10^{22} loops/m^3 (~ 0.5 dpa)

Shear band spacing

$\propto$ distance « d »

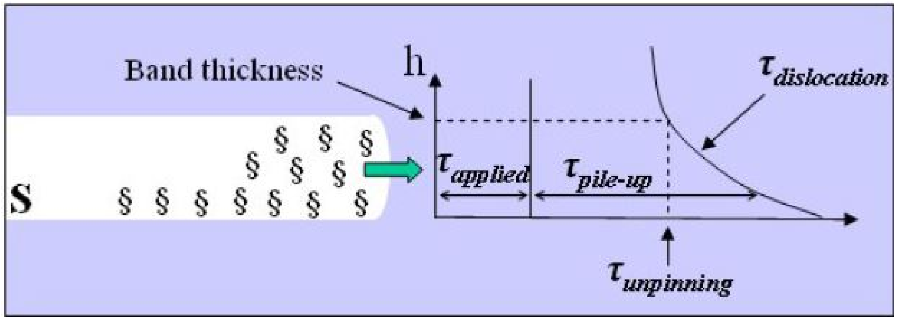


$\propto$ Grain size

$f(d_0)$, f(SFE)

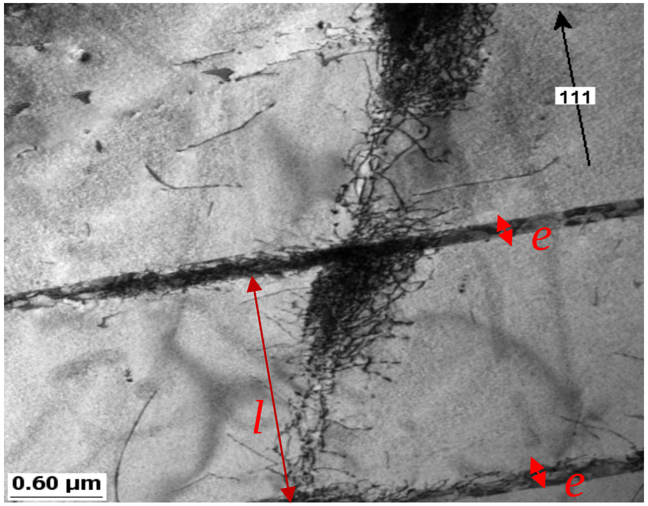
$\approx (\tau_{YS} - \tau_0) + \Delta\tau$ (irradiation-dose)

Shear band thickness ?



Dislocation glides inside shear bands wherever stress verifies:

$$\tau_{app} + \tau_{pu(band)} > \tau_{defect}$$



[W. Karlsen, VTT, 2006]

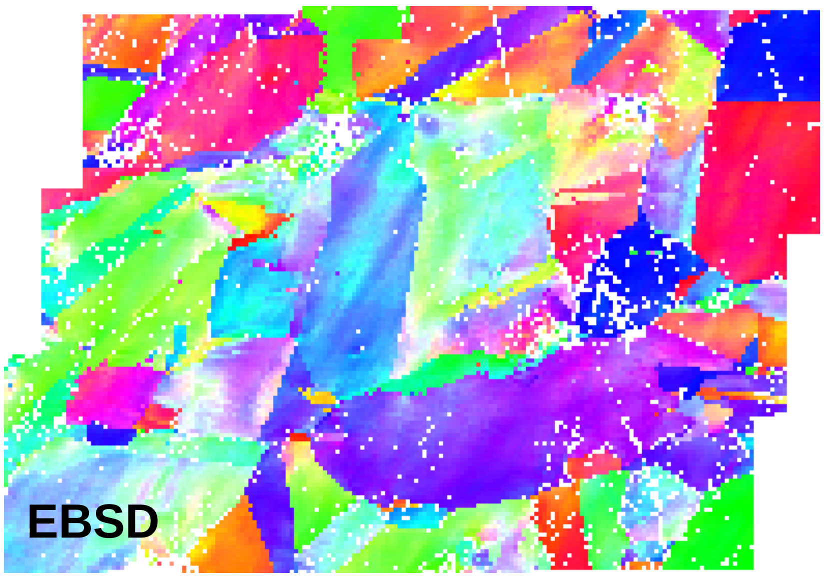
How to calculate τ_{defect} and τ_{app}?

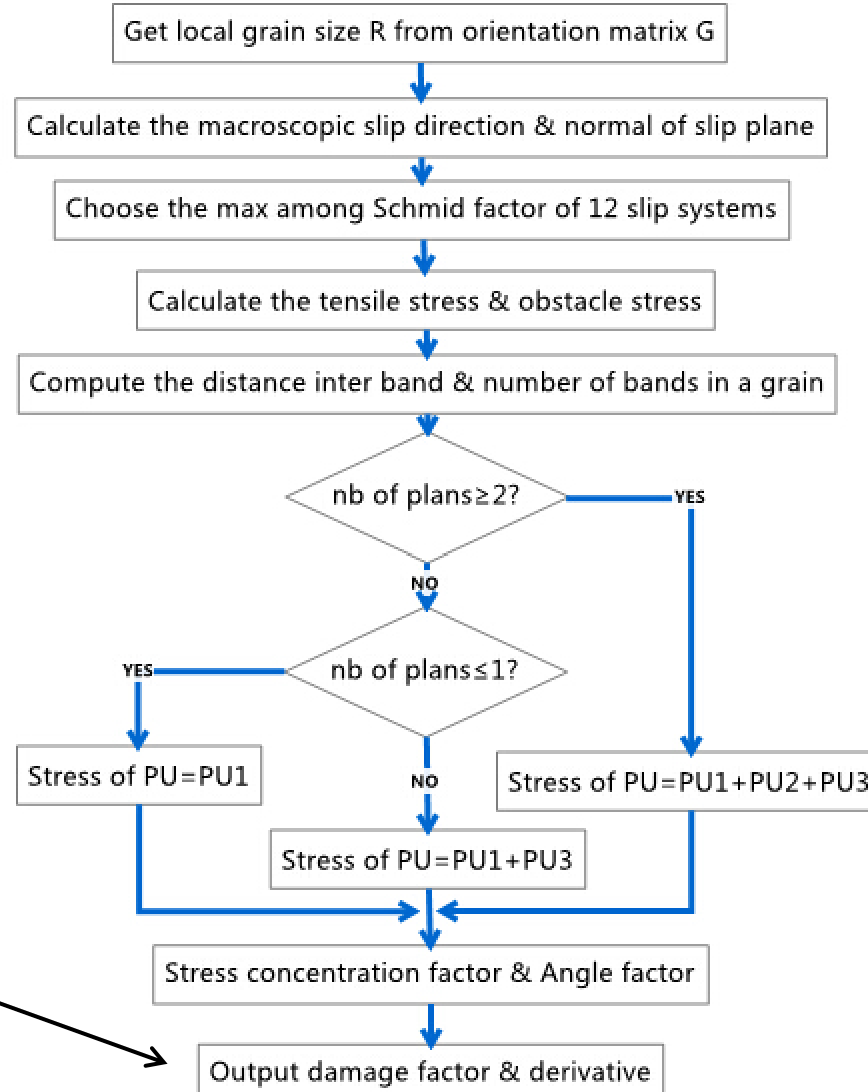
- ☞ Grain-wide pile-ups ∝ τ_{GB-pu} ∝ shear band spacing
- ☞ Inter-band wide pile-ups ∝ τ_{l-pu} ∝ shear band thickness
- ☞ Obstacle strength σ_{obs} (MD & continuum theory).
- ☞ Applied stress level σ_{app} (continuum theory & tensile testing data)

☞ Both σ_{obs} & σ_{app} relate to the irradiation conditions :

- Defect cluster size
- Defect cluster number density

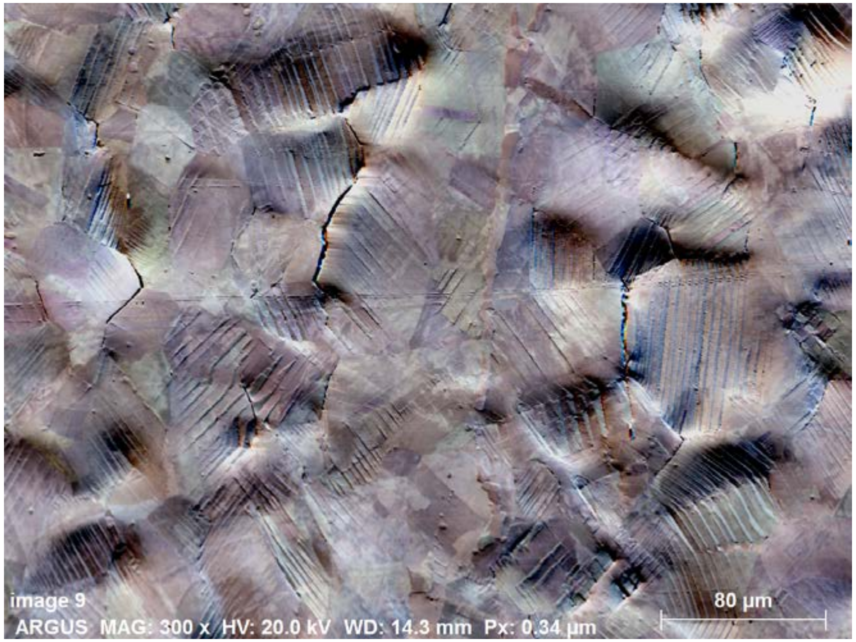
To apply these ideas to poly-crystals….

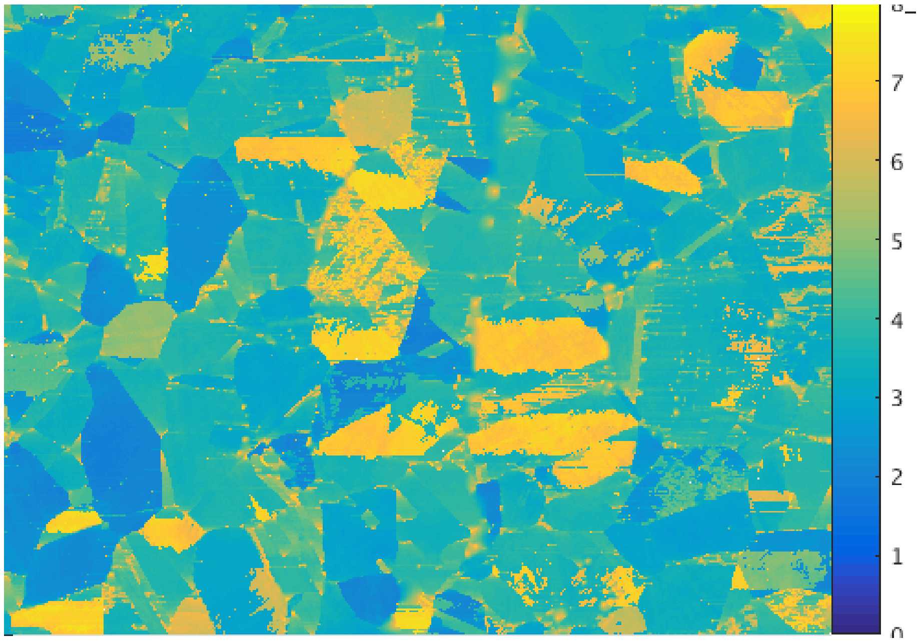




Damage factor include stress concentration and crystallographic orientation contributions.

Comparison with observation (P+ irradiation)

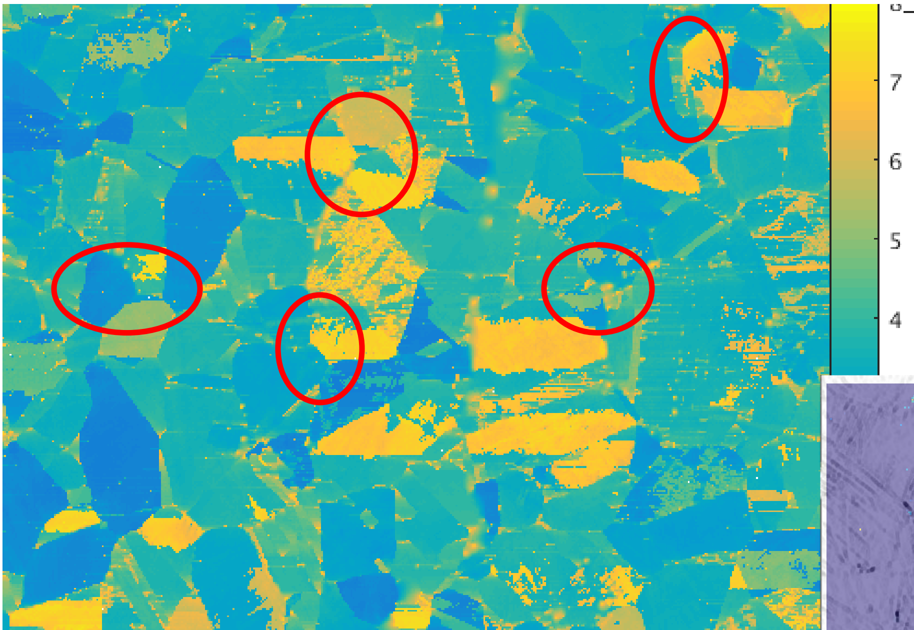




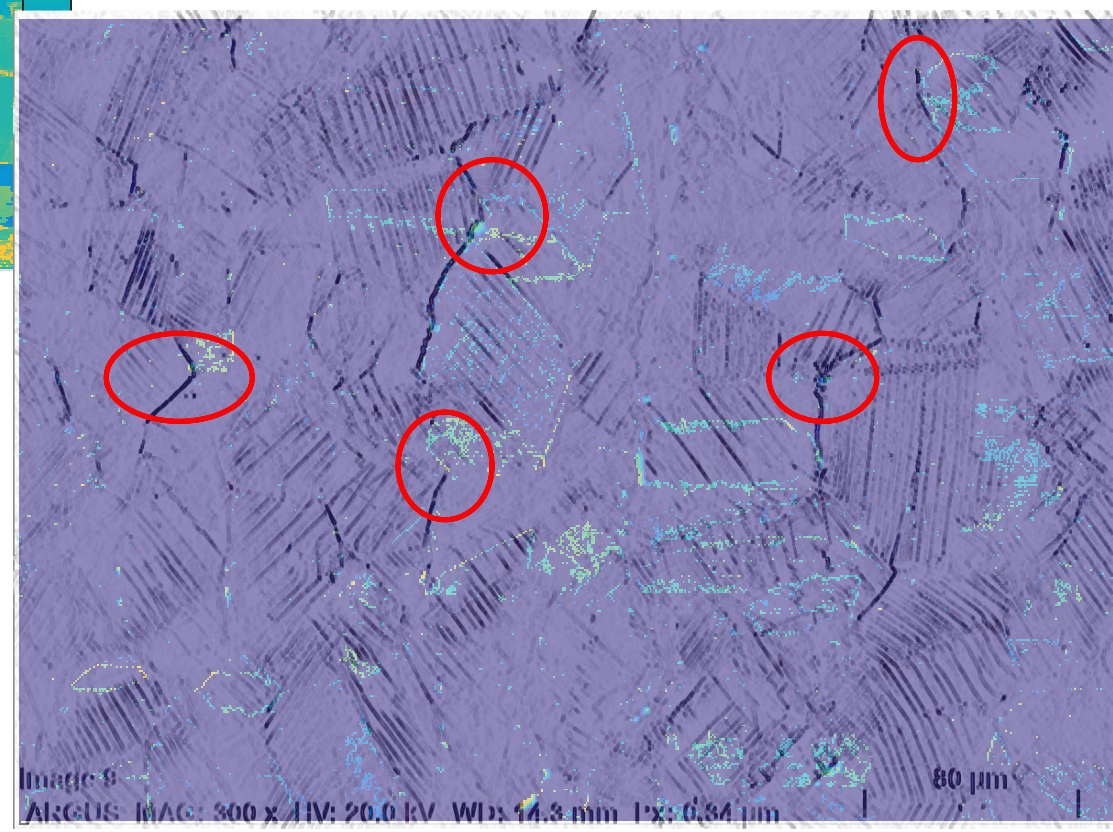
[B. Tanguy, 2014, DEN/DMN/SEMI]

Irradiated 316L steel p+ 2dpa/350℃, 10^{-7} s^{-1} up to $\varepsilon_P = 4\%$ in autoclave (primary water)
Applied stress considering the hardening effect: 684MPa, Area: 411.02 µm X 298.92µm
Defect cluster mean size: 13.8nm, defect number density 3.6e22 m^{-3}

Comparison with observation (P+ irradiation)



The most likely to crack nucleation sites: GB presenting the largest plastic strain contrast.



- Damage indicator able to predict crack nucleation location
- Crack nucleation probability in surface grains is 1.7%

Conclusion & Perspectives

In presence of disperse defect populations:

- Dislocation spreading is controlled by cross-slip: i-helps **overcoming** the disperse defect clusters, ii-helps **initiating** shear bands across the whole grain
- Shear bands dislocation substructures include dislocation **pile-ups**
- Shear band spacing controlled by **grain-wide** pile-ups
- Shear band thickening is gradual, controlled by **inter-band wide** pile-ups
- Grain boundary stress → depend on shear bands distribution
- Inter-granular crack initiation susceptibility is higher wherever the **plastic strain contrast** is maximal, between adjacent grain pairs

Perspectives:

- Improve the estimation of applied stress level, including additionnal hardening mechanisms (dislocation source decoration)
- Consider 3D effects of grain diameter versus grain depth
- Prediction of GB stress and comparison with macroscopic data (FEM)

The SOTERIA Consortium

SOTERIA

CEA — De la recherche à l'industrie

IRSN — Institut de Radioprotection et de Sûreté Nucléaire

ÚJV

KTH — Vetenskap och Konst

Arts et Métiers ParisTech

EDF

Vattenfall

UPC — Universitat Politècnica de Catalunya BarcelonaTech

grupo tecnatom

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framatome

wood.

PHIMECA — Solutions for robust engineering

HZDR — Helmholtz Zentrum Dresden Rossendorf

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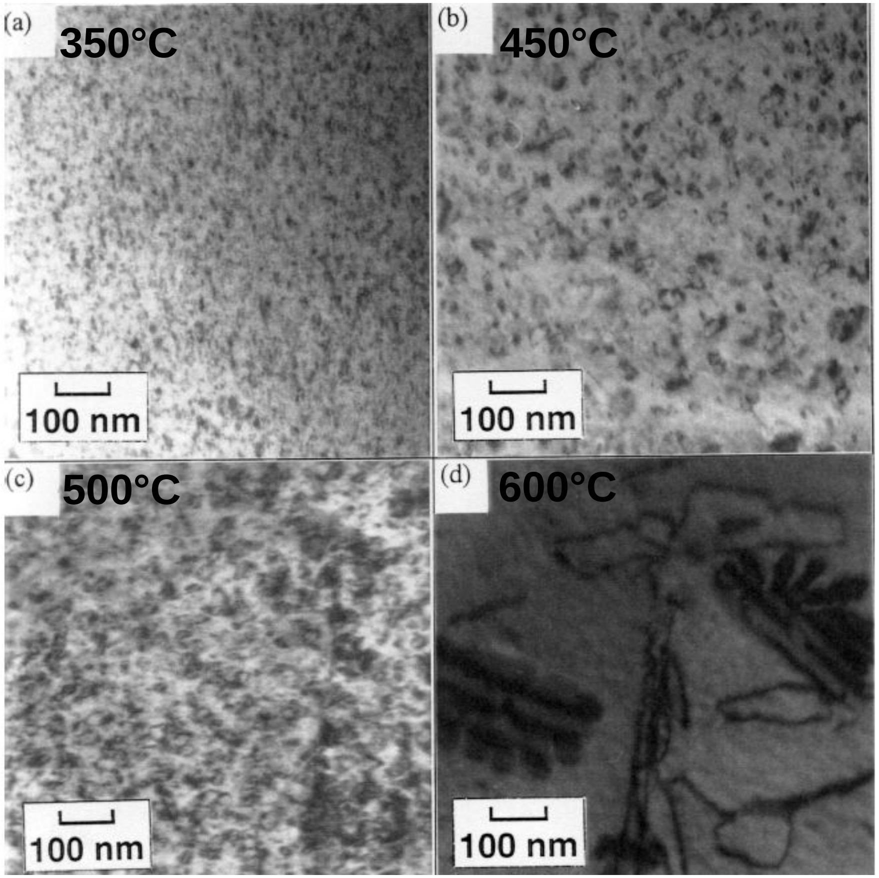
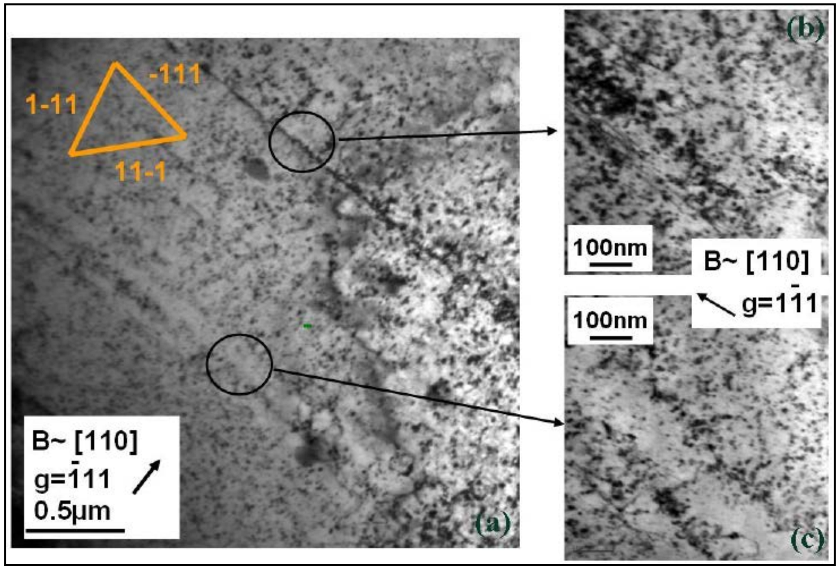
Defect microstructure due to irradiation



C.Robertson (1998)



Initial propagation of shear band:

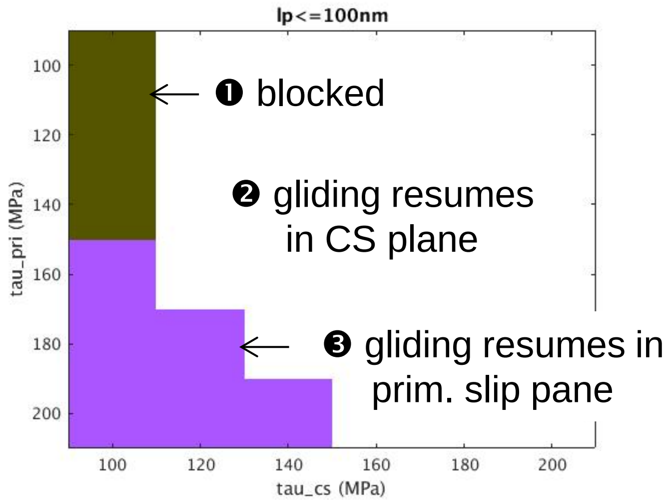
i. Formation of single-plane dislocation pile-up, with $L_{PU} \propto D_g$

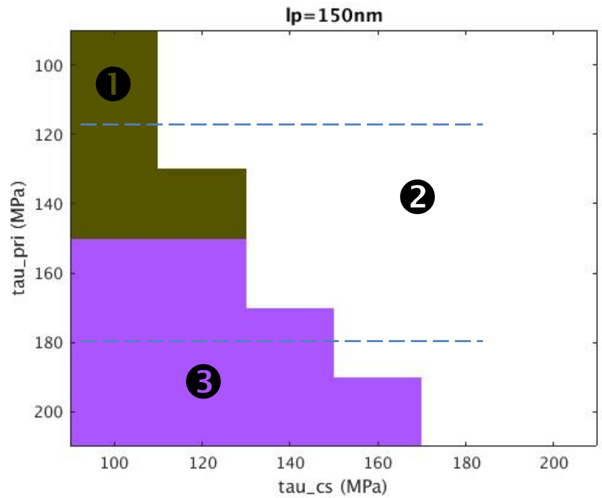
ii. Gradual shear band thickening, development of secondary bands

Shear band multiplication: cross-slip

L_p: segment length in primary SS
$L_p + L_{cs} = 300$ nm

☞ CS controlling the interaction: with rising L_{cs}





Shear band multiplication: cross-slip

Cross-slip of a bowed-out screw, due to obstacles

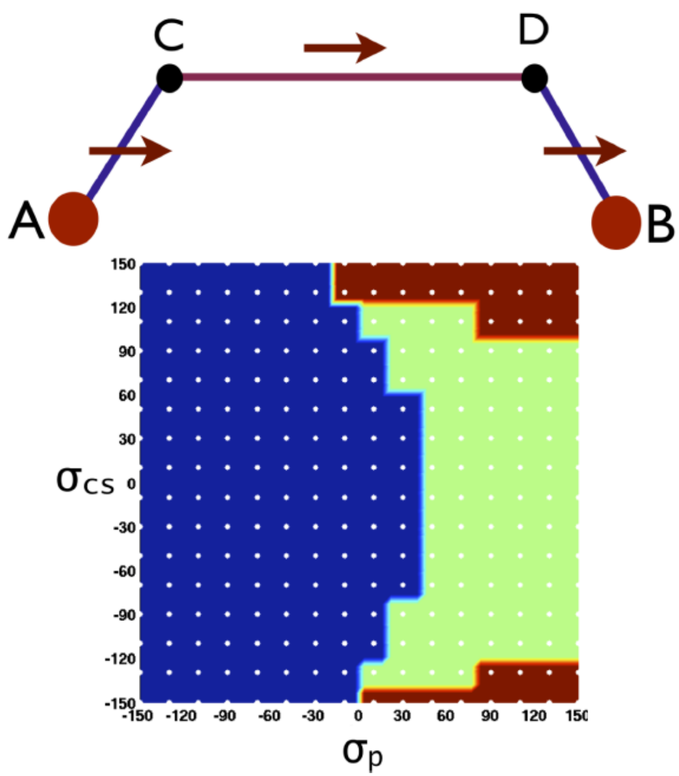


Figure 6.12 – *The set-up and result corresponding to the set 9 of the table 6.3. The image on the left is explained in the text. The image on the right corresponds to the result of primary and cross-slip stress acting on this configuration. The x-axis refers to the stress acting on the primary slip system, $\sigma_p = \overleftrightarrow{\sigma}.n_p.b$ in MPa and y-axis is the stress resolved in the cross-slip plane, $\sigma_{cs} = \overleftrightarrow{\sigma}.n_{cs}.b$ in MPa The regions in red indicate the (σ_p, σ_{cs}) combination that makes the length CD equal to AB, and region in blue indicates the (σ_p, σ_{cs}) combination that makes the length CD tend to zero. The regions in green indicate the (σ_p, σ_{cs}) values where the length of cross-slip segment CD neither goes to 0 nor equals distance between pinning points AB.*

- In presence of obstacles (radiation defects, GB, etc), cross-slip probability is maximal for $\boldsymbol{\tau_{prim}/\tau_{CS} = \pm 1}$
- This validates our model for predicting inter-band distance in irradiated metals (see 06/13)

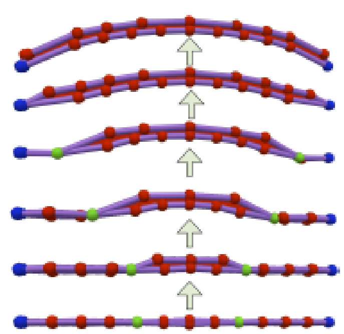


Figure 6.8 – *The evolution of a three segment split composite FR source of the form shown in the figure 6.5b. The figures from top to bottom illustrate the cross-slip segment spreading over the whole dislocation length.*