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The Irradiation-Assisted Stress Corrosion Cracking (IASCC) issue: some examples of studies carried out at CEA

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DEN, CEA Saclay

MINOS Workshop, Materials Innovation for Nuclear Optimized Systems
December 5-7, 2012, CEA – INSTN Saclay, France

Background : Structural integrity of Core Internals

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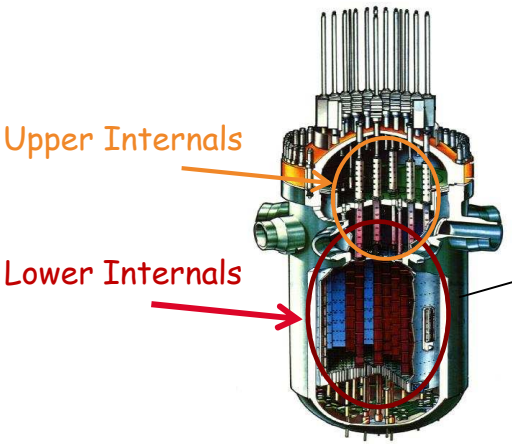
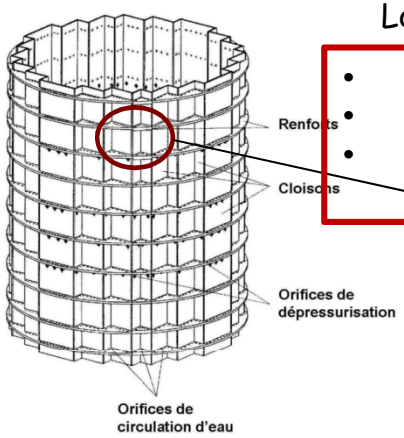
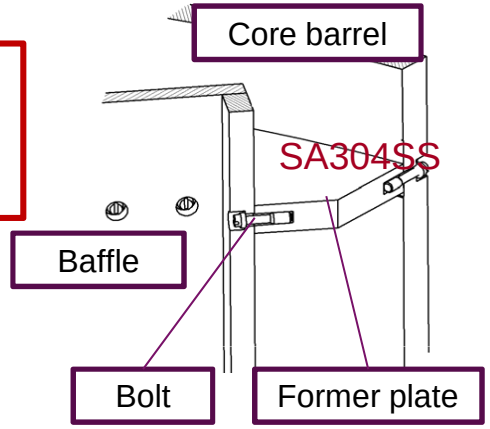
Severe irradiation conditions in PWR core (RPV+internals) → Material ageing and potential degradation → Limit of reactor operational life





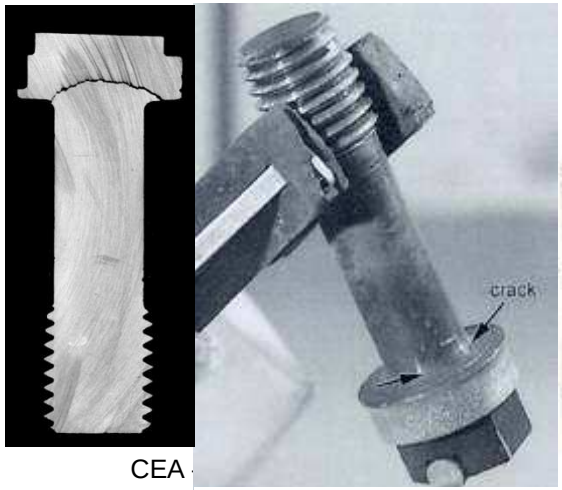
Lower Internals

- 10^{-7} – 10^{-8} dpa/s
- 290 – 380 °C
- 80 -100 dpa after 40 years



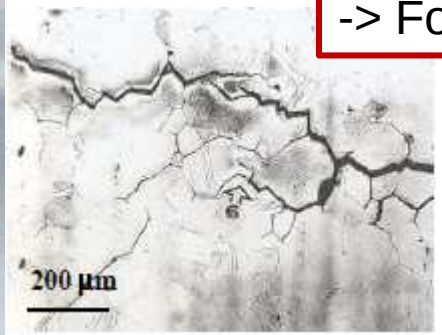
•**Field of experience:** IASCC of the baffle/former bolts

CW316SS 900-1000 bolts / reactor vessel



[Thomas, Fontevraud 2002]

->IG Crack at the head to shank transition region (8.5 dpa – 300°C)



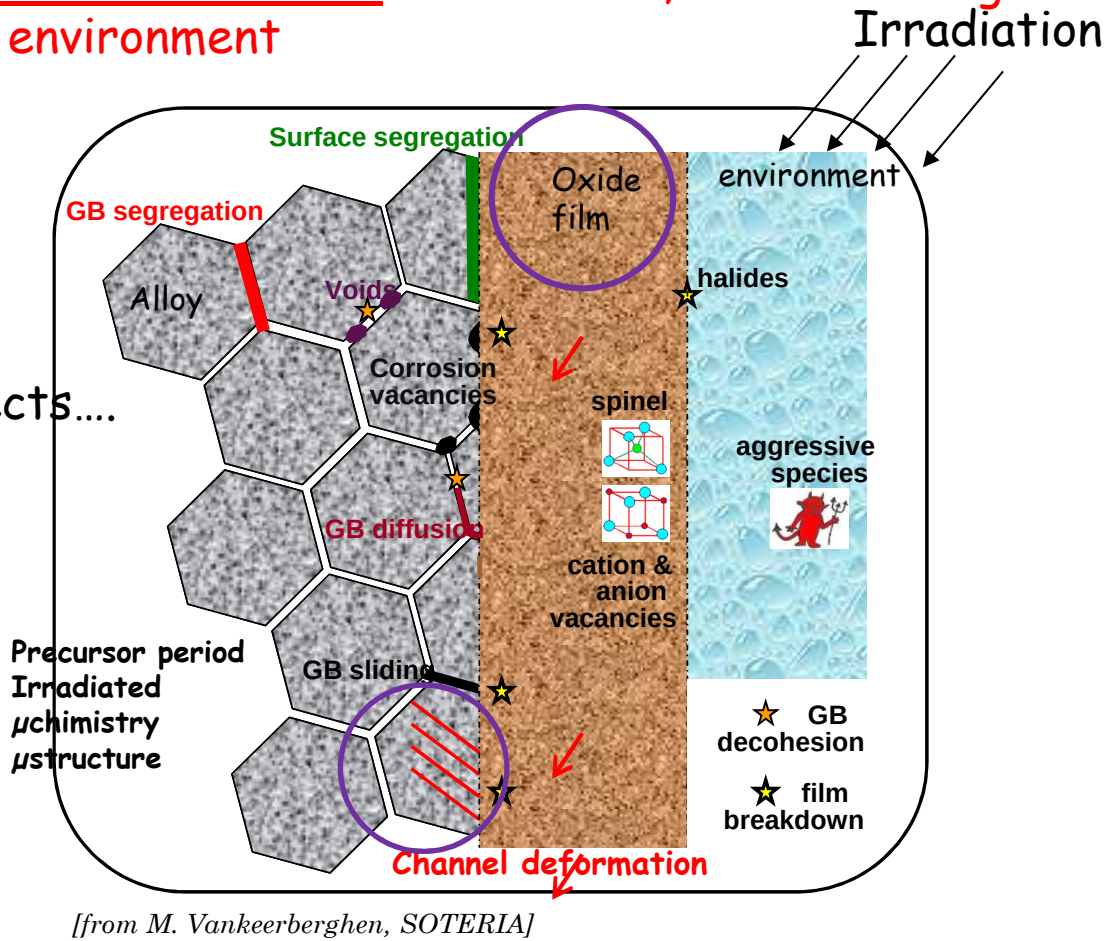
-> Focus on IASCC initiation for PWR's bolts

The internals lifetime has an important impact on the nuclear power plant lifetime because the cost and difficulty of their replacement

IASCC Initiation: Mechanistic issues

➢ Simultaneous effects of radiation, stress and high temperature water environment

+synergistic effects….



[from M. Vankeerberghen, SOTERIA]

-> mechanisms understanding of IASCC initiation and its modelling are still under investigation

CONTENT

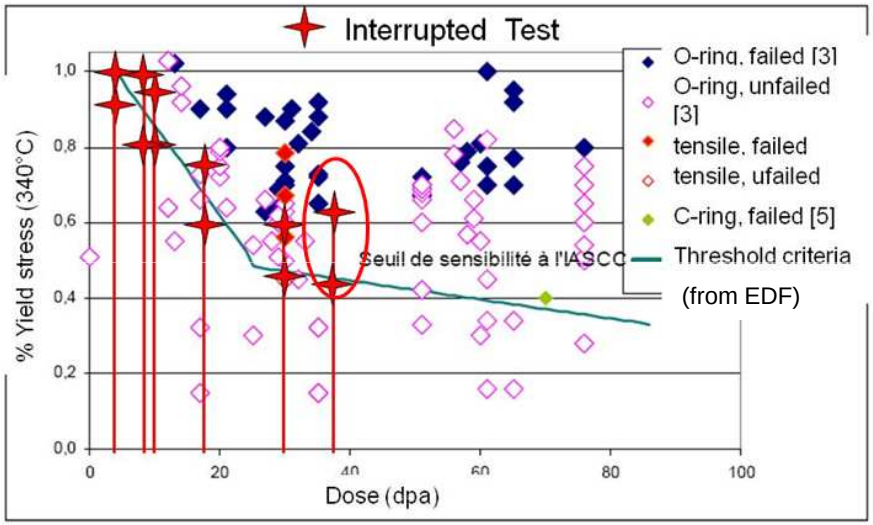
- Background
- Initiation Stress Threshold IASCC Criterion Assessment
- Influence of irradiation on the oxide layer growth mechanism and on diffusion process in the oxide layer
- Effect of localization on Grain boundary microcracks nucleation
- Investigation of clear bands formation mechanisms

INITIATION STRESS THRESHOLD IASCC CRITERION ASSESSMENT

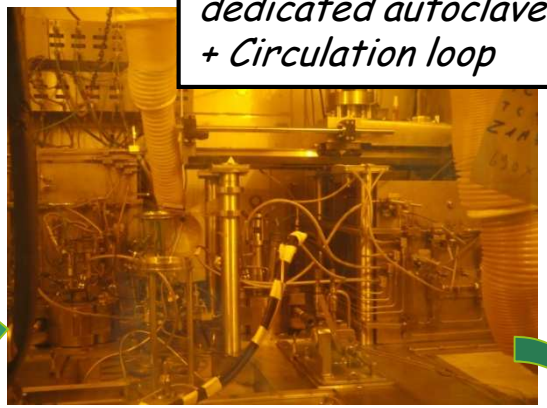
Section for Research on Irradiated Materials

Objectives and methodology

Motivation : Industrial interest to establish an IASCC fracture criteria to understand and predict life duration of the bolt assembly. Sensitivity to first order parameters (Temperature, stress, deformation mode, irradiation, chemical composition)



In-cell tensile test dedicated autoclave + Circulation loop



LECI nuclear facilities at CEA

In-cell SEM

- Environment: Simulated PWR: 1200 ppm B, 2 ppm Li, 25<H2<35 (cc/kg)
- T(test)=340°C
- Interrupted test (1000h+1000h) with two loading levels
- Loadings : **constant load** (α_i irradiated yield stress at considered dose)

Methodology & results examples

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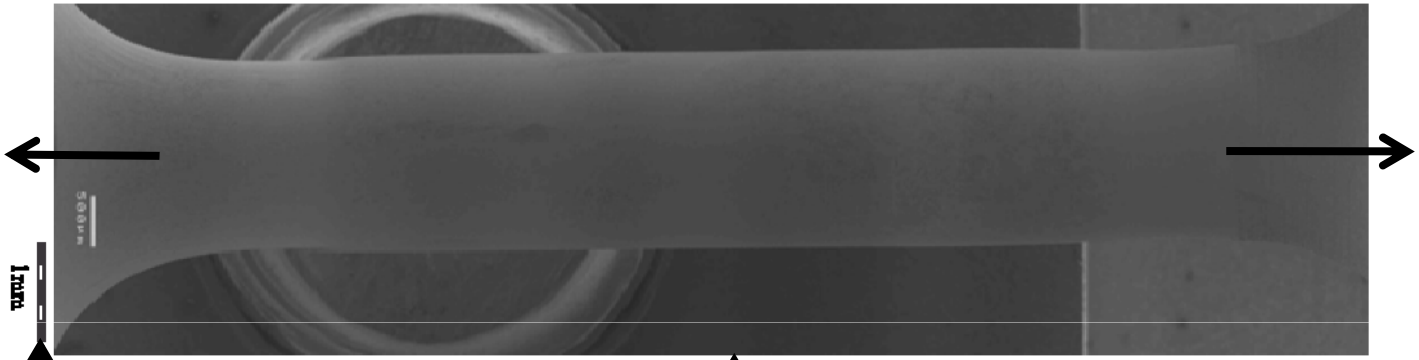
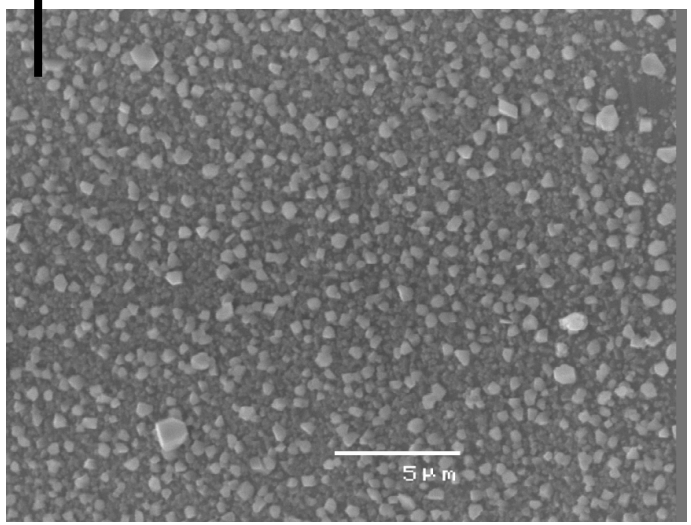
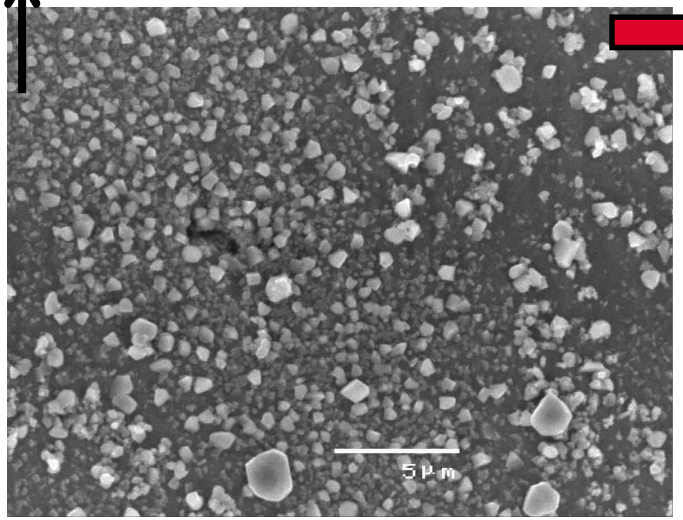
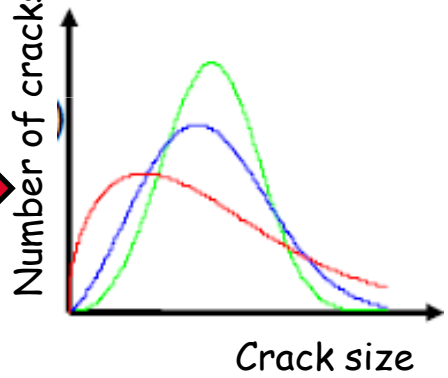
Surface characterization: surface oxidation features of irradiated stainless steels in primary PWR environment + microcracks distribution







Microcracks size distribution as a function of dose and applied stress



->On-going program

INFLUENCE OF IRRADIATION ON THE OXIDE LAYER GROWTH MECHANISM

Service de la Corrosion et du Comportement des Matériaux dans leur Environnement

Materials and methodology

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- CW316L , 3MeV proton-irradiated (~40µm depth, surface^{irr} Φ~1cm), 2.10^{12} protons/cm^2/s
- Sample preparation : SiC paper (→ 4000) + diamond + OPS
- Methodology -> Tracer experiments :
  - 1st corrosion sequence with H_2 ^{16}O media
  - 2nd corrosion sequence with H_2 ^{16}O/ H_2 ^{18}O
  - Localisation of ^{18}O and ^{16}O in the oxide layer

1st corrosion sequence: 620 hours

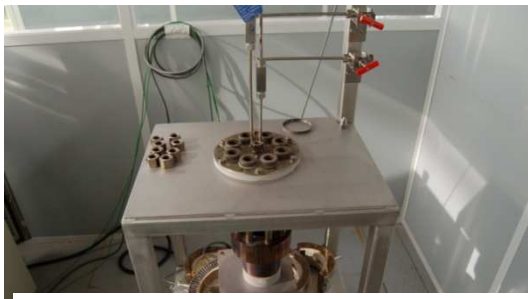
- 1000ppm [B], 2ppm [Li], [H2]dissolved = 1.3*10^{-3} mol.l^{-1}
- $pH_{325°C}$ = 7.2

Corrosion loop at LECA, T = 325 °C, P = 155 bar

->

2nd corrosion sequence:

- 1000ppm [B], 2ppm [Li], [H2]dissolved = 1.3*10^{-3} mol.l^{-1}
- $pH_{325°C}$ = 7.2
- ➢ 17 h: determination of **diffusion coefficient**
- ➢ 404h: determination of **corrosion mechanism**



Titanium autoclave (300ml), T = 325 °C, P = 128 bar

Effect of irradiation on the external layer (after 1st sequence)

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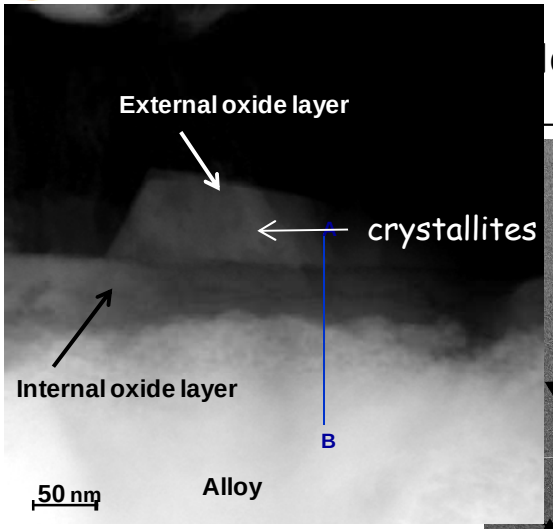
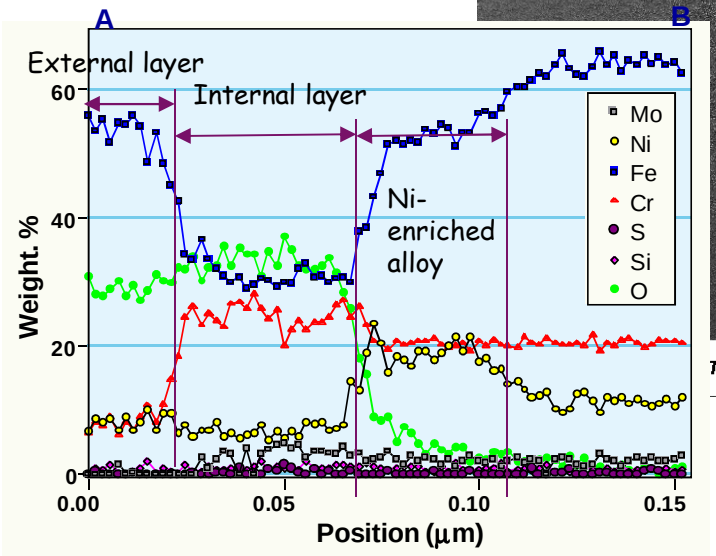
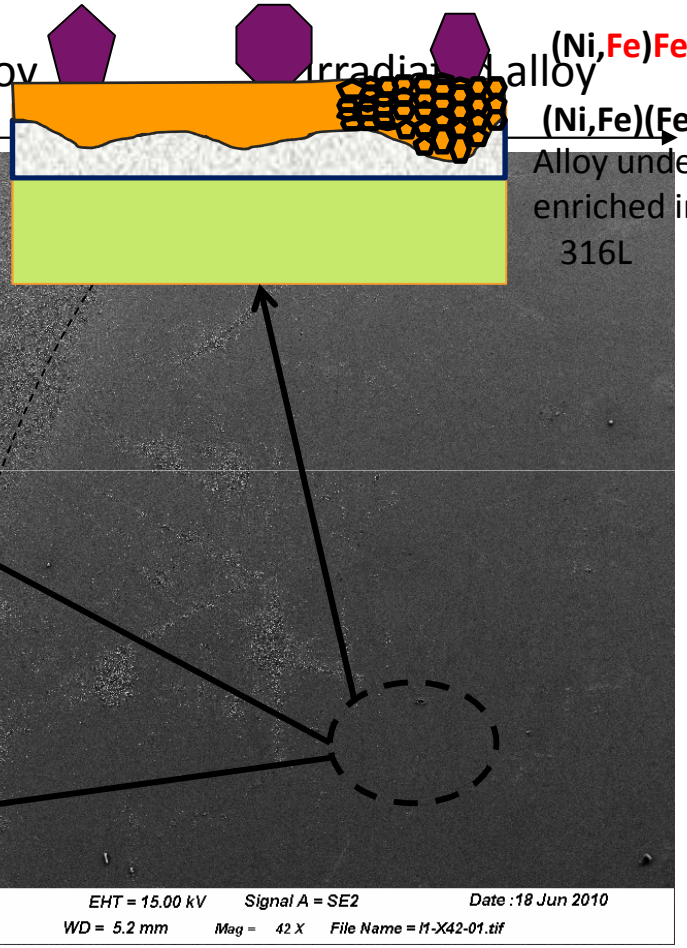
TEM Characterization after 1024 hours (coop. with M.Sennour and C. Duhamel (ENSMP))





EDX analysis



$(Ni,Fe)Fe_2O_4$ spinel

$(Ni,Fe)(Fe,Cr)_2O_4$ (small grain)

Alloy under the oxyde enriched in nickel

316L

(Same oxyde layer structure for irradiated area)

Effect of irradiation on the external layer (after 1st sequence)

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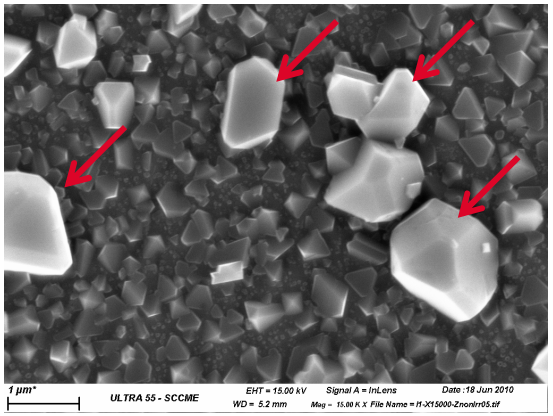
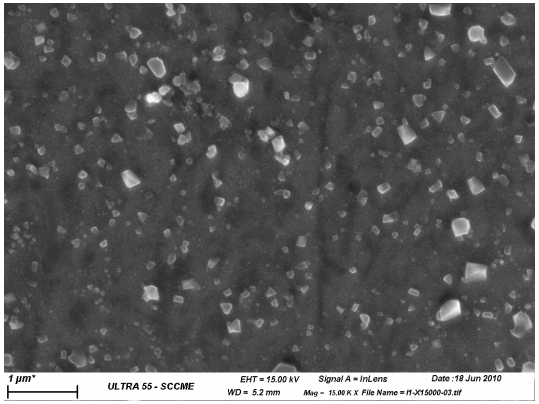
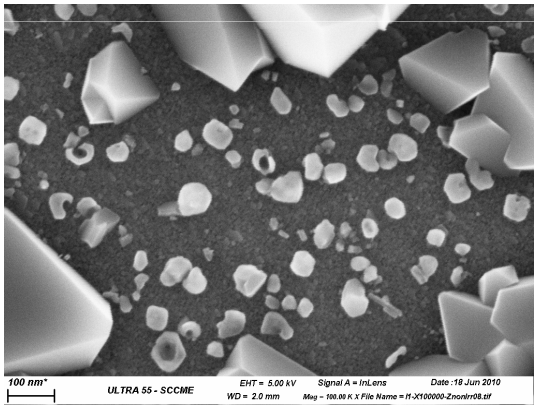
Non irradiated alloy

Irradiated alloy

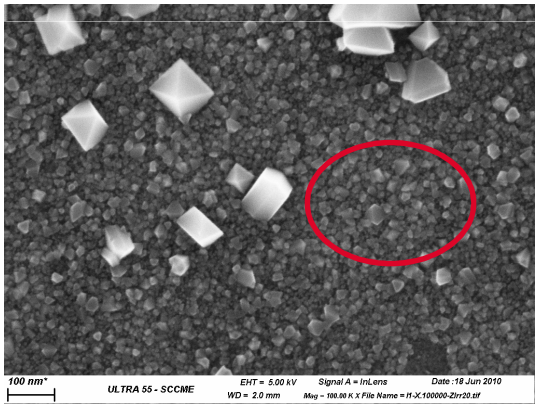


x15000





x100000



→ Bigger cristallites (external layer) on non irradiated sample

→ Lot of very small cristallites (external layer) on irradiated sample

→ influence of irradiation on nucleation/growth of external layer

Effect of irradiation on the internal layer (after 2nd sequence)

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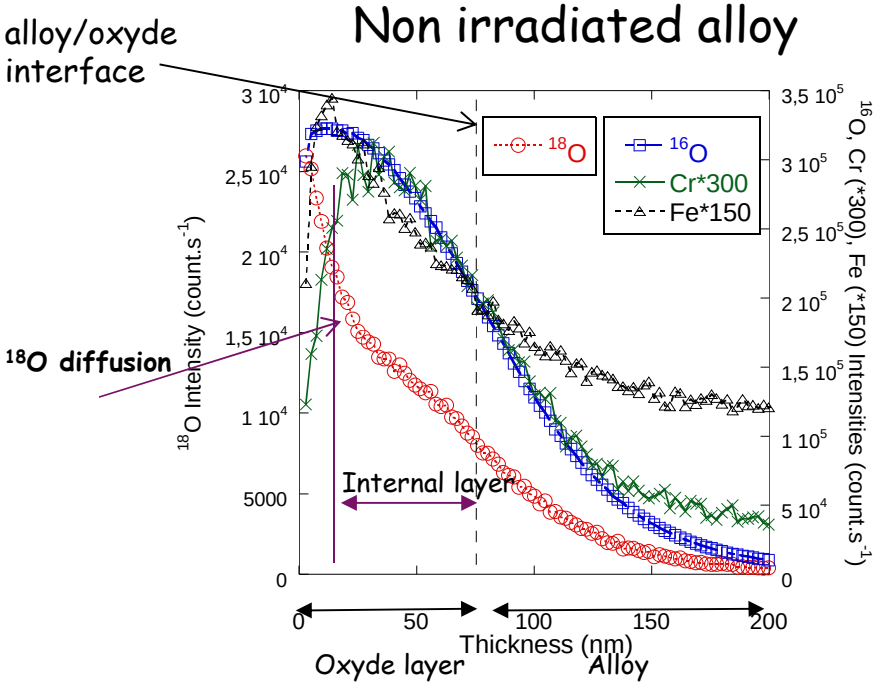
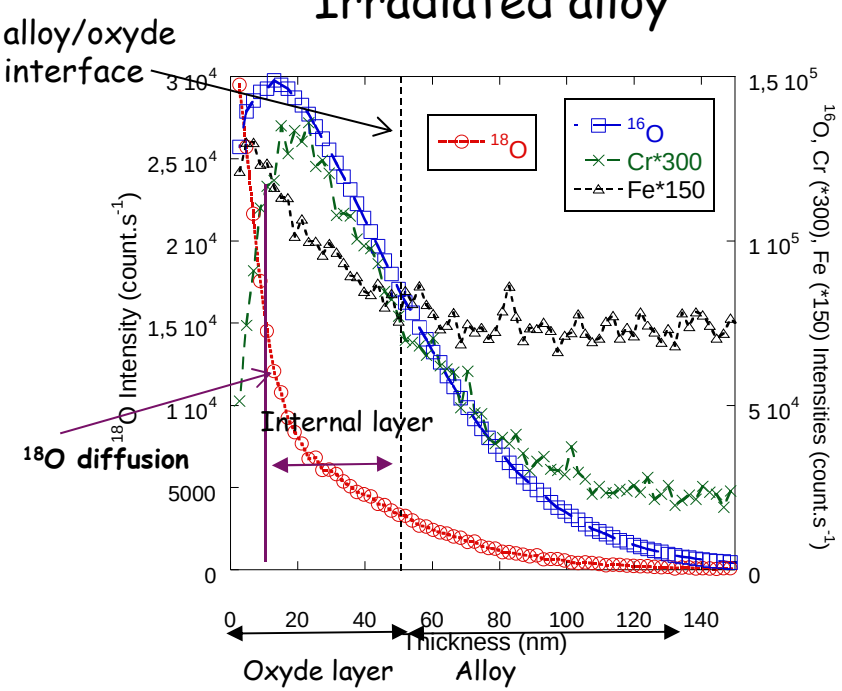
Short second sequence (no significant oxyde layer growth) -> determination of diffusion coefficient: Dgb

SIMS analysis (collaboration F. Jomard (CNRS))

Non irradiated alloy



Irradiated alloy



Diffusion at oxyde gbs

^{18}O diffusion profile → $C(x) = Kerfc\left(\frac{x}{2\sqrt{D_{GB}t}}\right)$ → Av. concentration

	Non irradiated	Irradiated
Dgb ($cm^2.s^{-1}$)	~3.10^{-16}	~5.10^{-17}

->diffusion is faster for non irradiated samples.

Effect of irradiation on the internal layer (after 2nd sequence)

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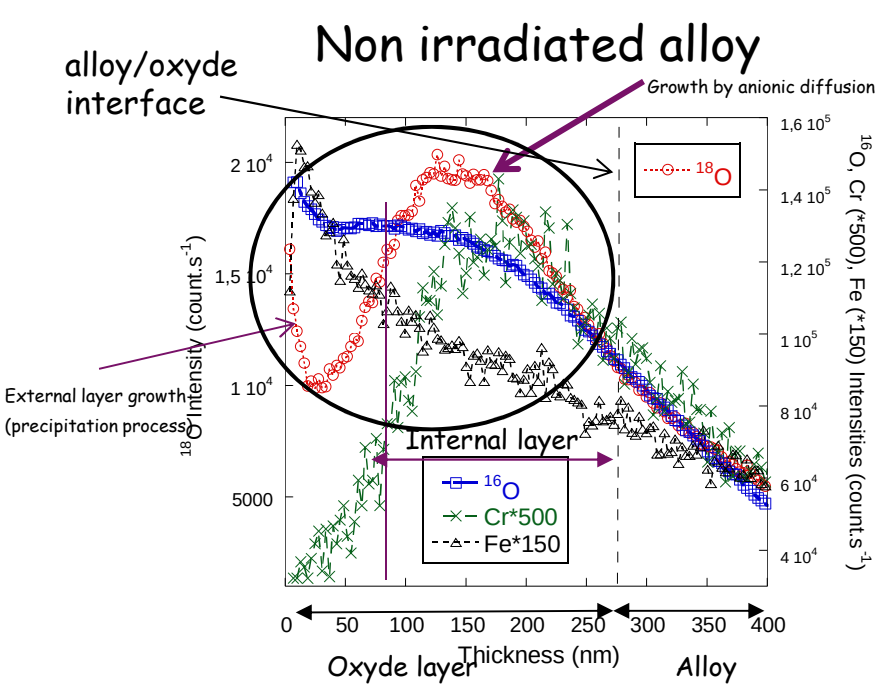
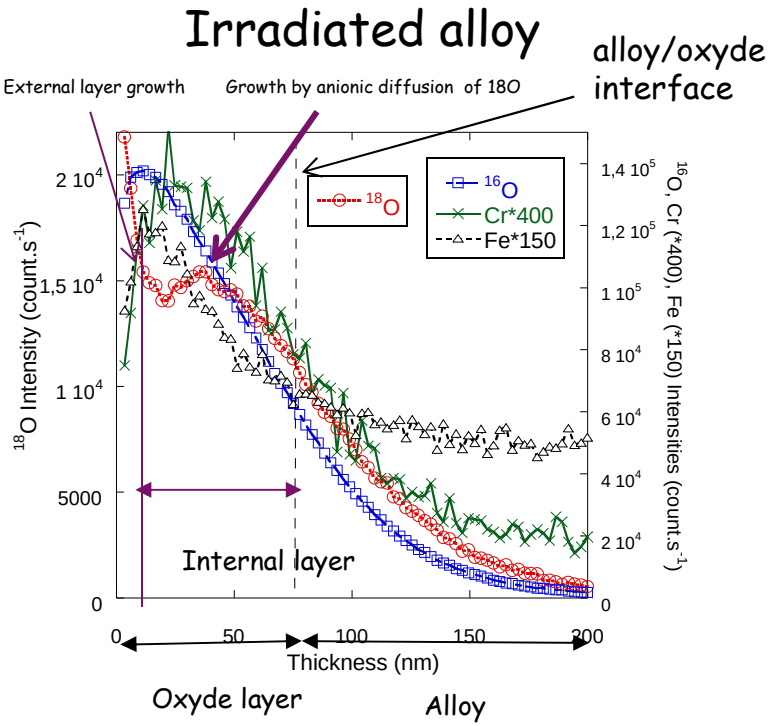
Long second sequence (growth of oxyde layer) -> determination of corrosion mechanisms

SIMS analysis (collaboration F. Jomard (CNRS))





➡ confirms that this diffusion is faster for non irradiated samples.

➡ Accumulation of ^{18}O close to the alloy-oxyde interface: anionic diffusion along the grain boundaries of the oxide as the mechanism of internal layer growth

EFFECT OF LOCALIZATION ON GRAIN BOUNDARY MICROCRACKS NUCLEATION

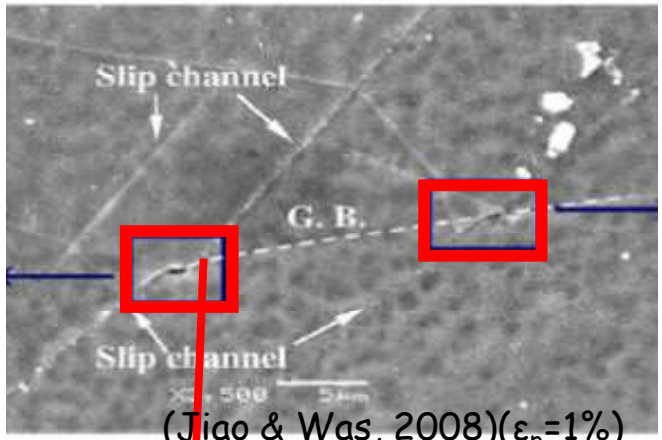
(DYNAMIC STRAINING)

Section for Research on Applied Metallurgy

Methodology: cristalline constitutive laws + FE simulations

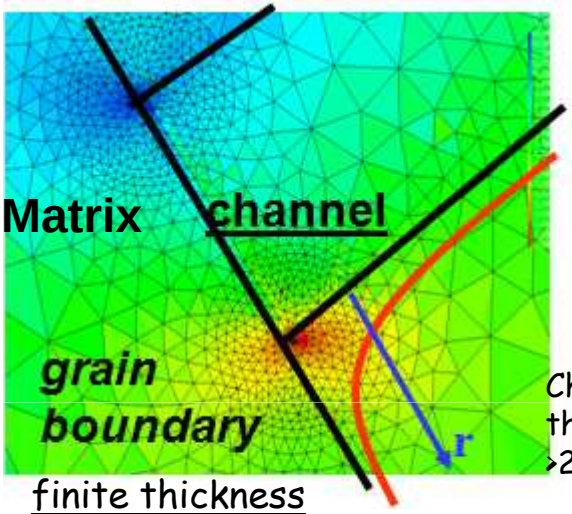
MINOS

SEM observations: microcrack nucleation observed at the intersections of channels & grain boundaries



(Jiao & Was, 2008)(ε_p=1%)

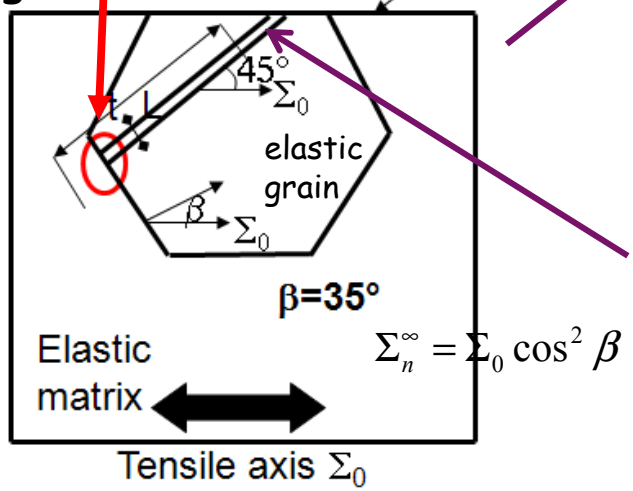
Grain boundary stress fields induced by the impingement of pre-existing channels



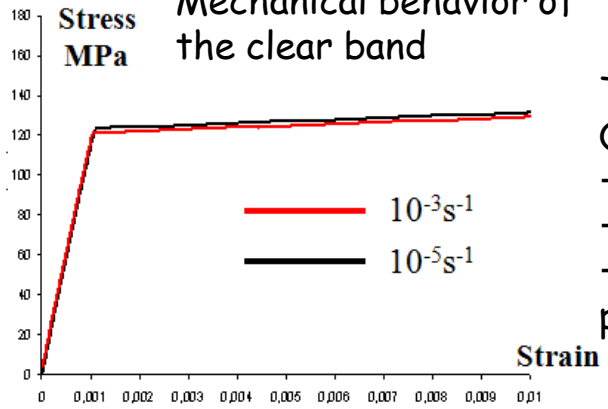
Channel thickness~50nm >200 atomic planes

finite thickness

Modelling



Mechanical behavior of the clear band



Time-independent behavior
Quasi perfect plasticity
→Critical shear stress: τ_0
→Hardening slope: H
→Latent hardening parameter: q

Comparison with the predictions of the pile-up theory: 'close-field' -'far-field'

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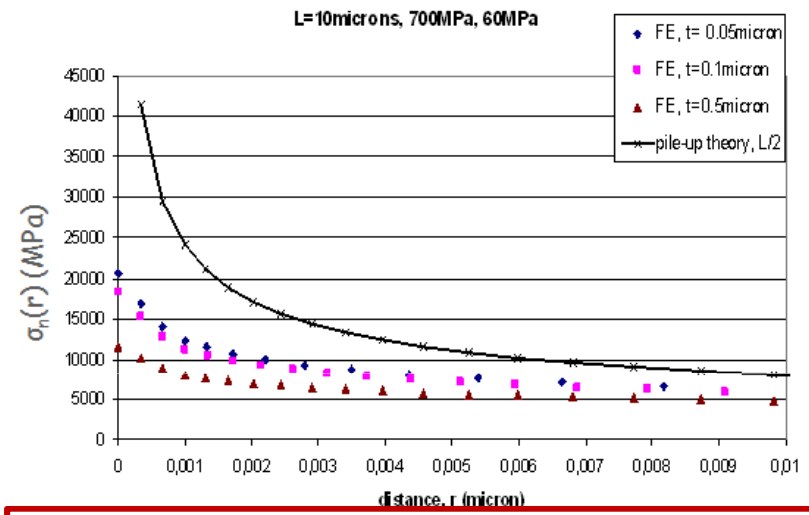
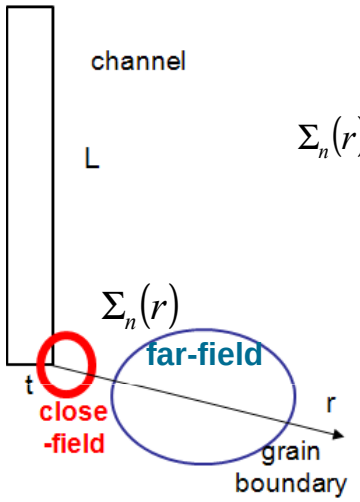
close-field

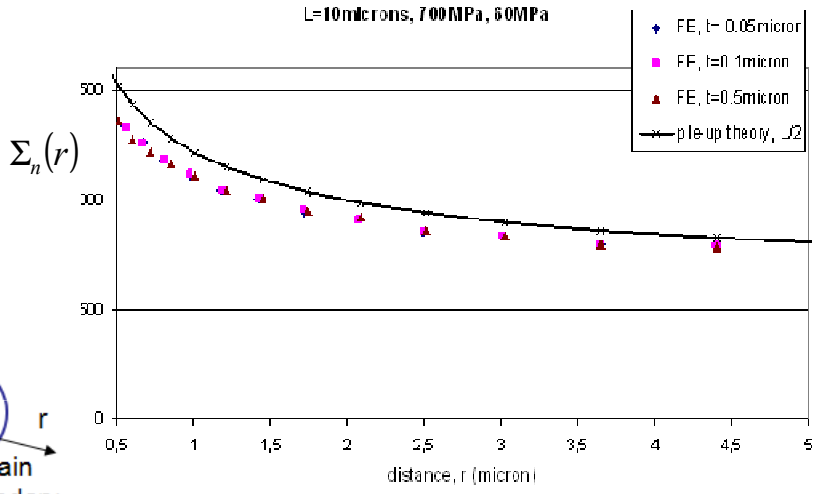
r<<t<L





far-field

t<r<<L



->Large overestimation by the pile-up theory (stress exponent: 0.5) using a length equal to one-half of the grain size

->Very close to the intersection of the channel and grain boundary: weaker singularity due to

- the notch effect → $\sigma_n(r) \sim 1/r^{\alpha}$, $\alpha = 0.32 < 0.5$ (t<<r)
- slip band plasticity
- single slip

-Whatever the grain size L and the aspect ratio, L/t, the discrepancy between the pile-up theory prediction and the curves computed by the FE method is lower 10%

-In fact, if r>t, the stress singularity is very close to the pile-up or crack one as expected (Leguillon et al., 2007)

Effect of localization on grain boundary crack nucleation

MINOS Prediction of remote stress to GB microcrack nucleation based on:

- An energy balance criterion (fracture energy: $\gamma_{fracture}$)
- A critical stress criterion using:

$$\sigma_c = \sqrt{\frac{Y\gamma_{fract}}{d_0}}$$

$$\Sigma_c = (1/f)(\tau_0 + \left(\frac{2\lambda}{YC}\right)^{1-\lambda} A^{1-2\lambda} \left(\frac{t}{L}\right)^{1/2} \left(\frac{d_0}{t}\right)^{1-\lambda} \sqrt{\frac{Y\gamma_{fract}}{d_0}})$$

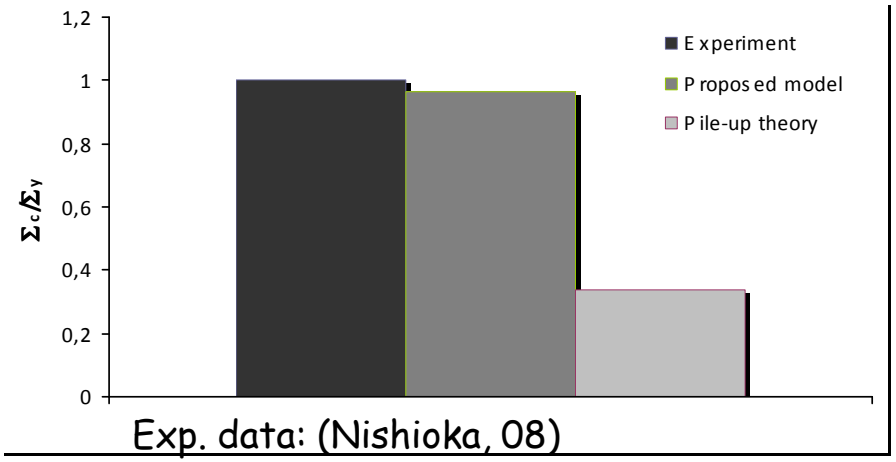
(Sauzay & Vor, Eng. Fract. Mech., in press)

channel lengths, t, L [microstructure, (dose)]

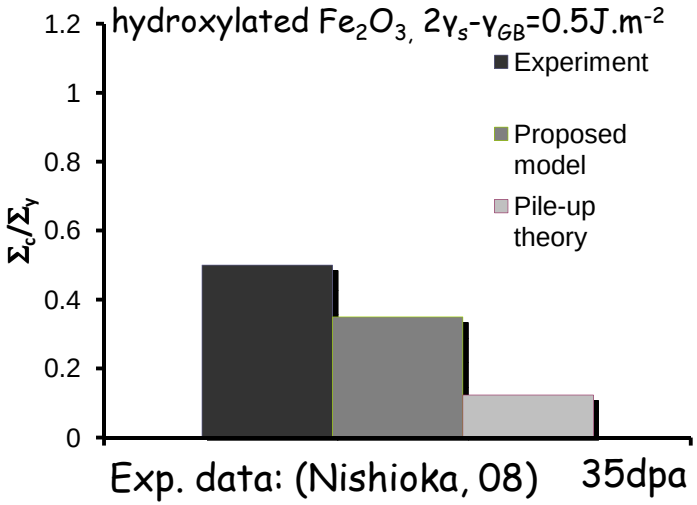
the Schmid factor, f, channel critical shear stress, τ_0 [dose]

fracture energy, ($2\gamma_s - \gamma_{GB}$) [oxydation, dose]

without oxidation:



PWR water tensile tests, 320°C



t=50nm, L=50µm, γ=2.5 J/m², general GB (γ_{GB}=1.2 J/m²)

-> Developped criteria leads to an improvment of experiments description

INVESTIGATION OF CLEAR BANDS FORMATION MECHANISMS

Section for Research on Applied Metallurgy

Methodology: 3D-DD simulations

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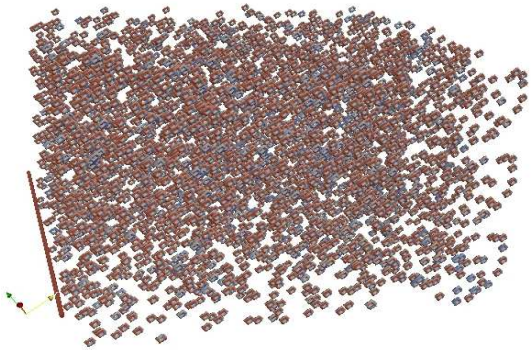
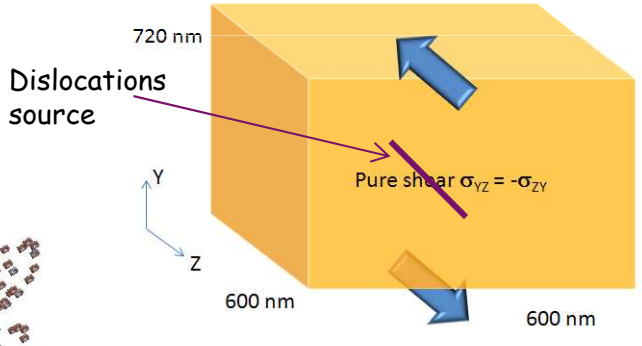
Type 1: boundary conditions simulation volume
-> investigation of single clear band formation mechanisms
•Random prismatic loop positions (D = 10 nm, L = 50 nm), 3.7*10^{22} loops/m^3(<1dpa)
•Loops resistance is intrinsic for srew dislocation

Type 2: boundary conditions simulation volume
-> investigation of clear band multiplication
•Random positions, loops=planar internal obstacles (facets, D = 10 nm), 1*10^{22} loops/m^3(<1dpa), ε_p=1.4*10-3
•Facets resistance=f(incoming dislocation type)

Random loops position



Thermally activated cross-slip is switch off



Cell borders as impenetrable grain boundaries

Single loop = 1 soft Facet

Dislocation-loop interactions based on MD simulations (type 1)

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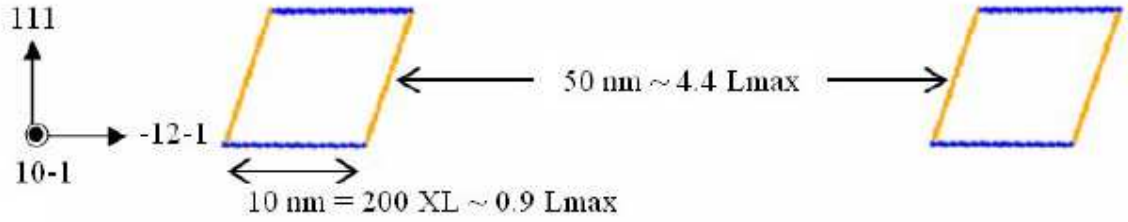
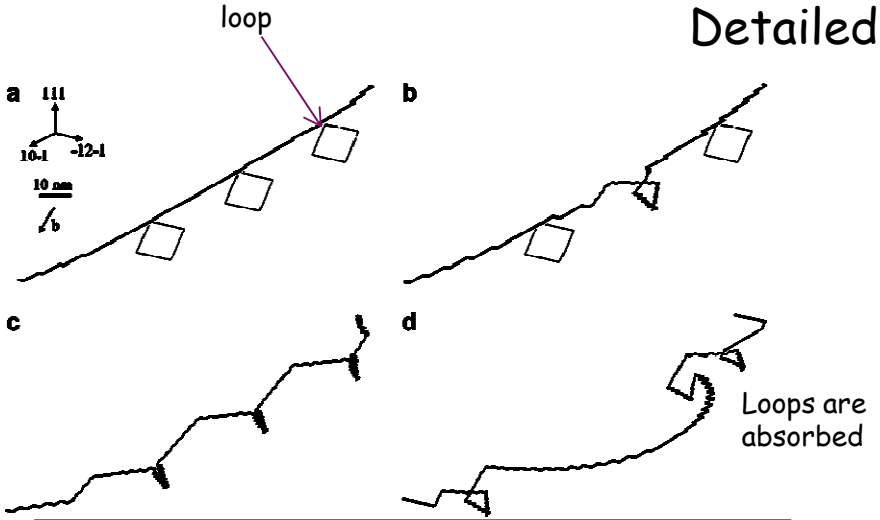
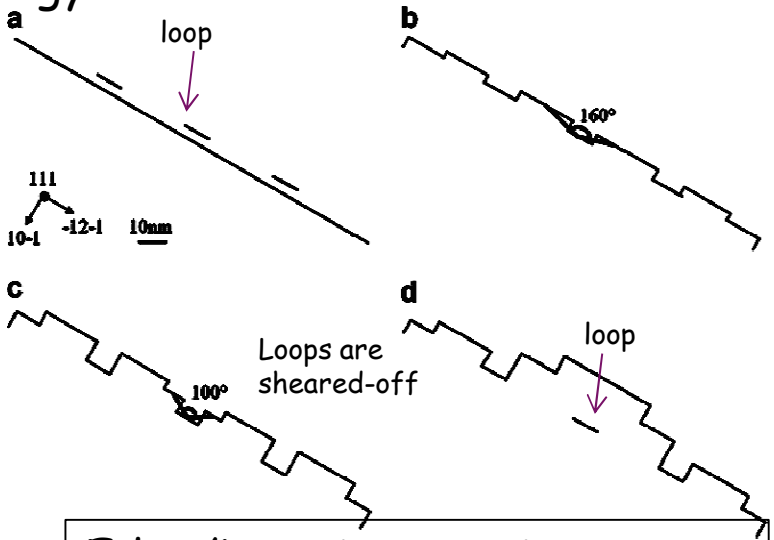
Goal: introduction of loop-induced evolutions in DD simulations



Detailed loop topology





Screw/Loop interactions:
Strong pinning force
Elevator *climb* effect (unpinning mechanism:re-emission of the dislocation in upper plane)

Edge/Loop interactions :
Weak pinning force
Planar dislocation motion

Details of single clear band formation (type 1 simulations)

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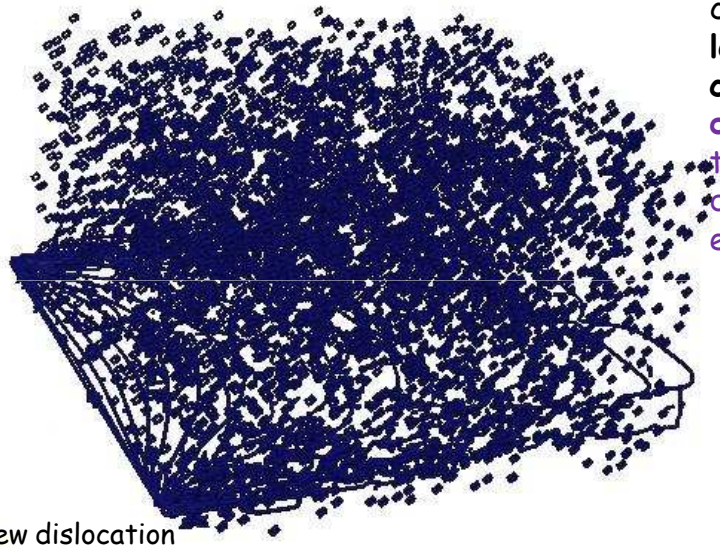
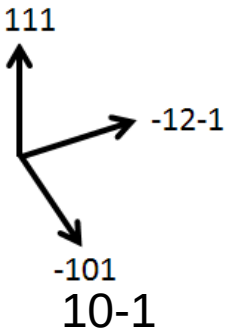
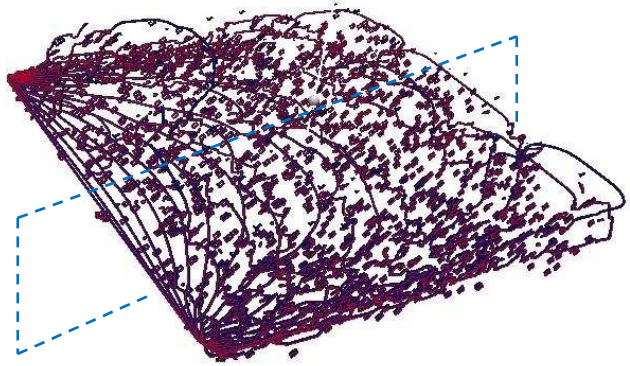
View of simulation cell after the clear band formation

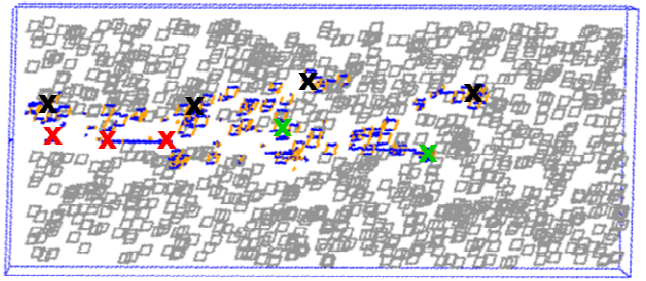


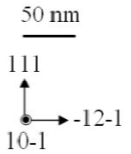
Screw dislocation source

-> Dislocation glide only possible through a collective mechanism : **leading dislocations clear the band**. **Trailing dislocations** concentrate the stress on leading dislocations by piling-up effect









X cleaning dislocation
X driving dislocation
X immobilized dislocation

-> clear band with finite thickness is due to collective dislocation effects: pile-up formation and arm exchange

Investigation of clear band multiplication (type 2 simulations)

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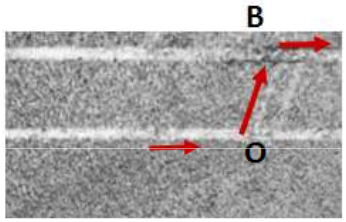
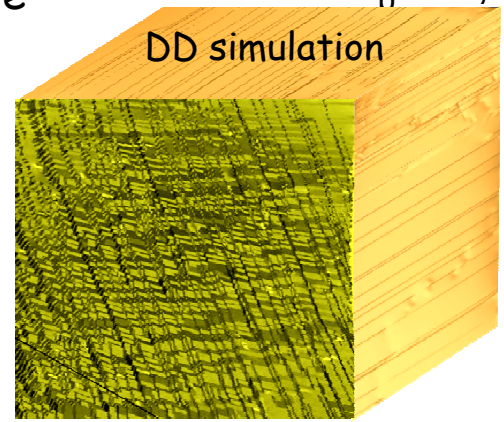
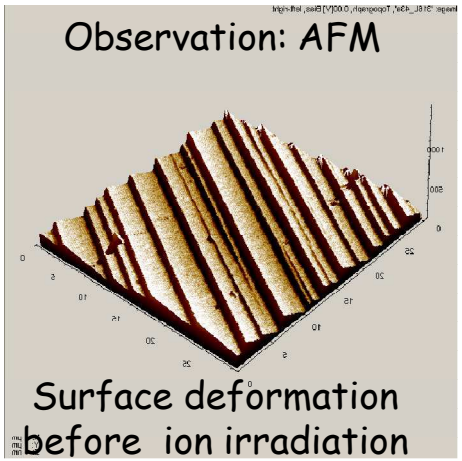
Acute cross-slip (long range mechanism): clear band multiplication mechanism



No loops

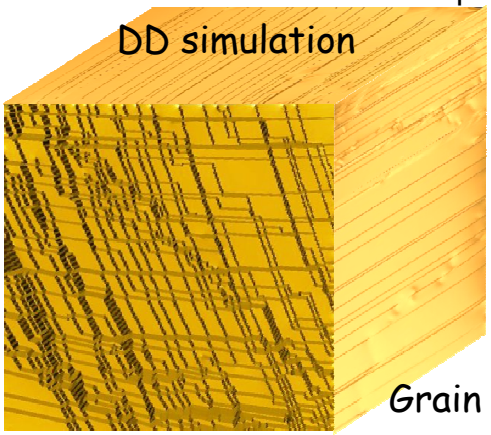
$\varepsilon_p = 1{,}4\times10^{-3}$



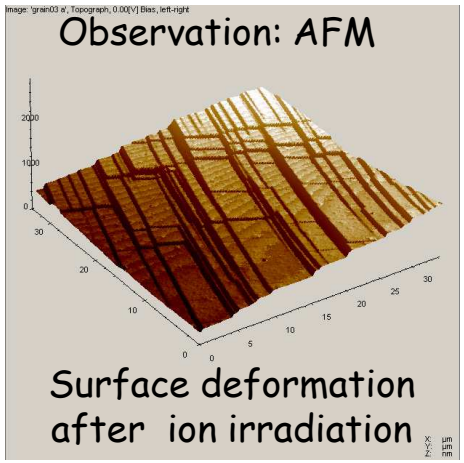


10^{22} loops/m^3 (~ 0.5 dpa)

$\varepsilon_p = 1{,}4\times10^{-3}$



Grain size~1 micron



The number of slip bands per unit volume: trends are correctly described
-> radiation-induced strain localization is well captured by DD model

Micro-mechanical model predictions (type 2 simulations)

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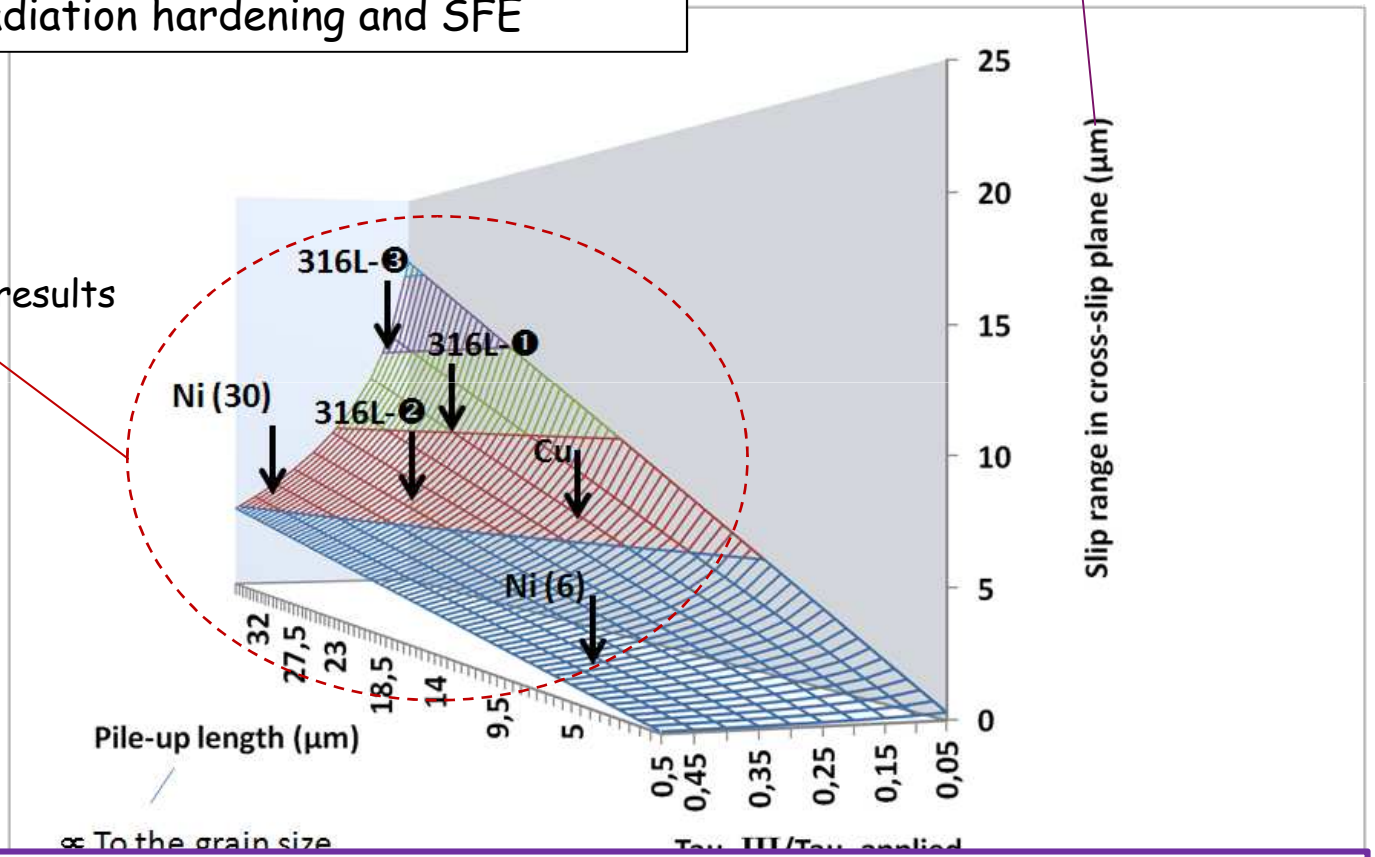
-> 3 influential parameters: grain size, irradiation hardening and SFE

∝ To distance between the clear bands

Experimental results



∝ To the grain size

-> Quantitative predictions of clear bands nucleation and multiplication under dynamic straining

n dose)

Conclusions: Overview of the studies related to Internals at CEA

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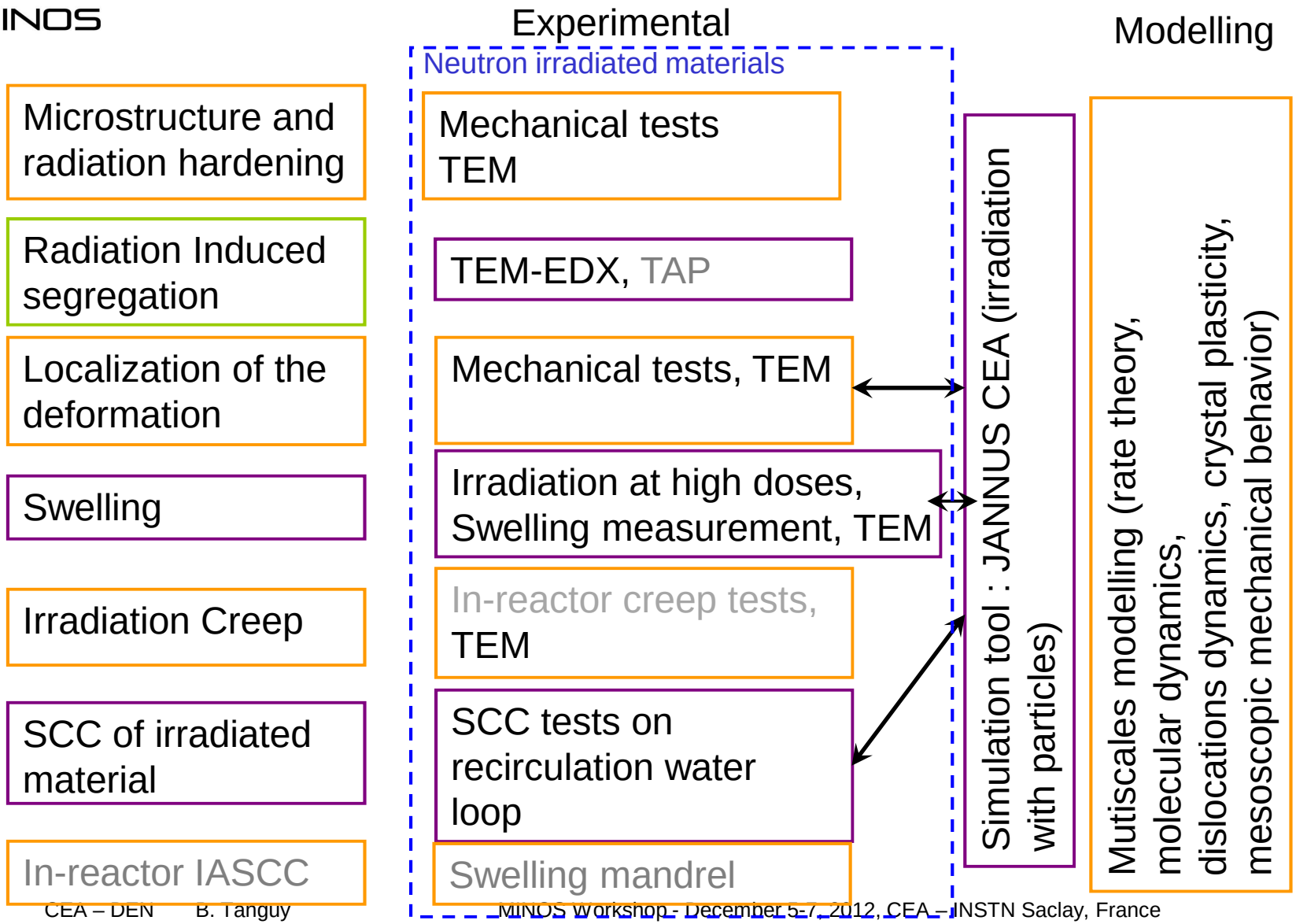

Thank you for your attention

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