

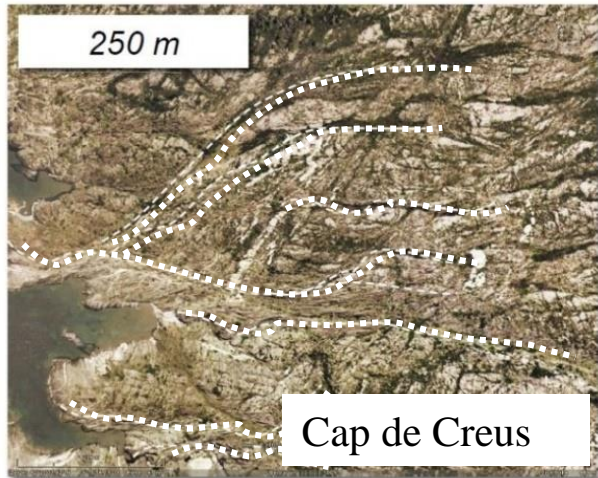
Crystal Slip and Grain Boundary Sliding: two stroke engine driving ductile localisation

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E. Héripré¹, W. Ludwig³, A. King⁴, H. Gharbi¹, A. Tanguy¹, S. Hallais¹,

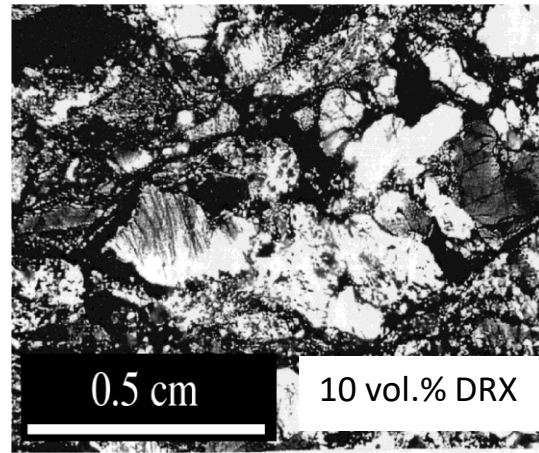
¹Laboratoire de Mécanique des Solides (EP); ²Navier (ENPC);
³Mateis (INSA Lyon)-ESRF; ⁴Soleil (Psiché)



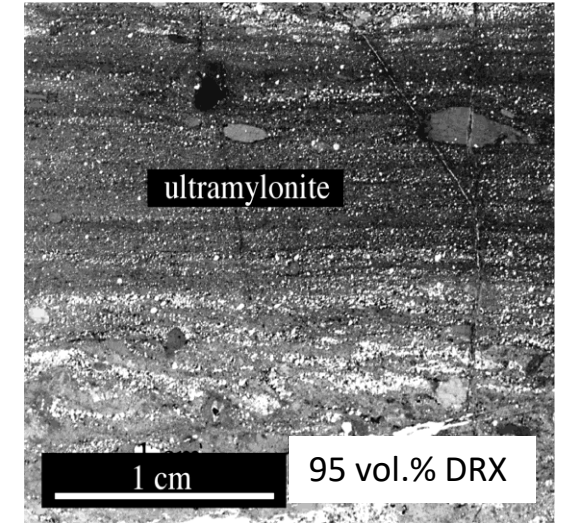
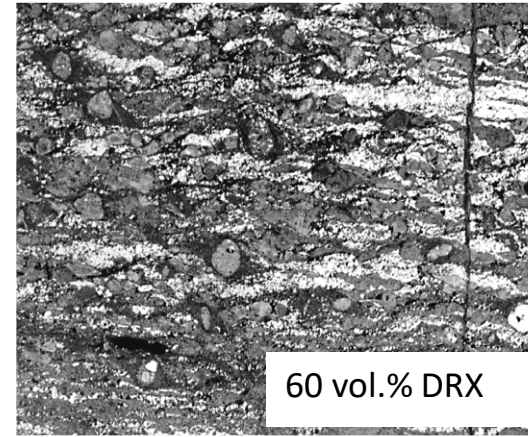
I. Introduction: multiscale localization in natural ductile shear zones



Careras (2001)



Ivrea Zone (Kenkmann & Dresen, 2000, 2002)



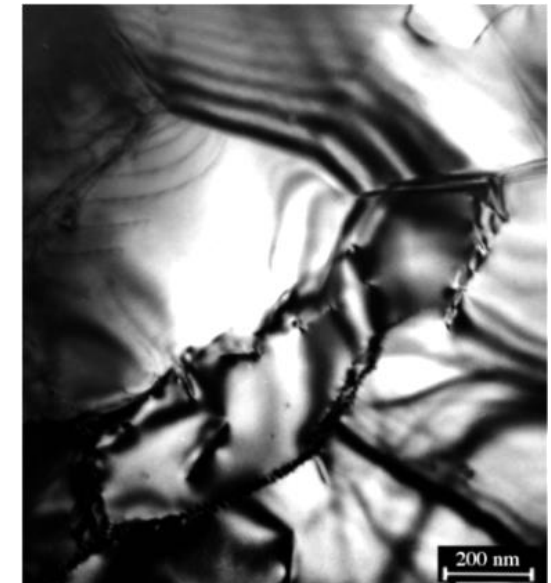
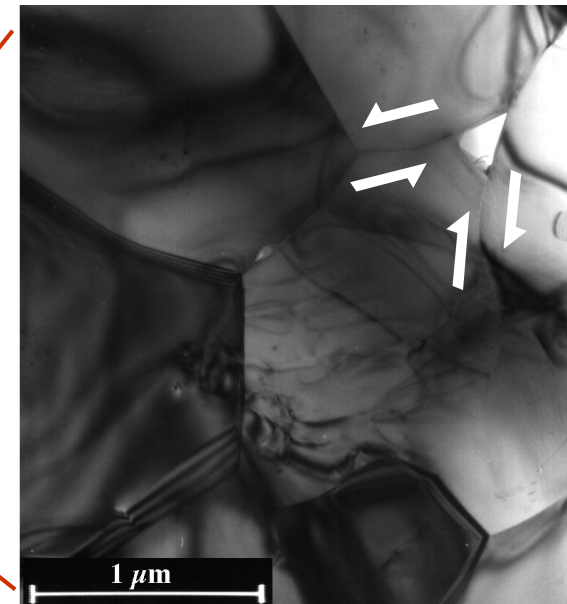
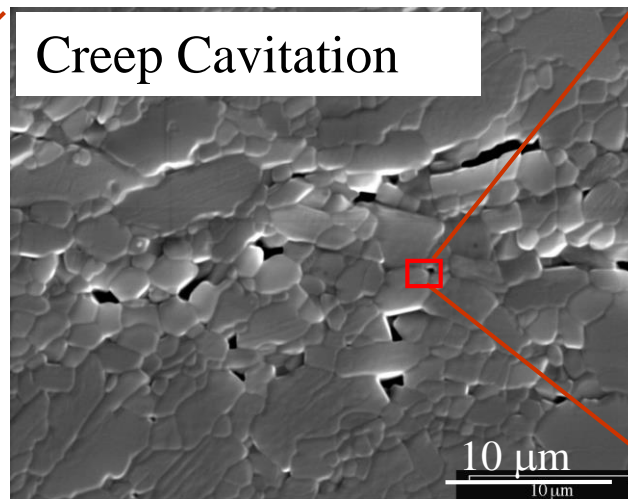
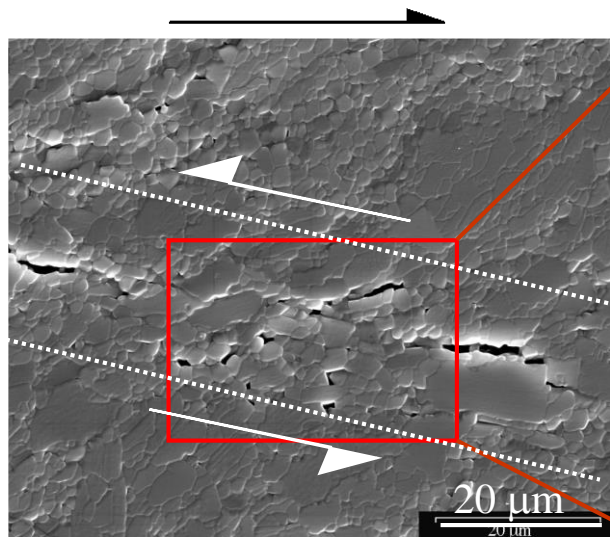
CSP & DRX

Grain size reduction

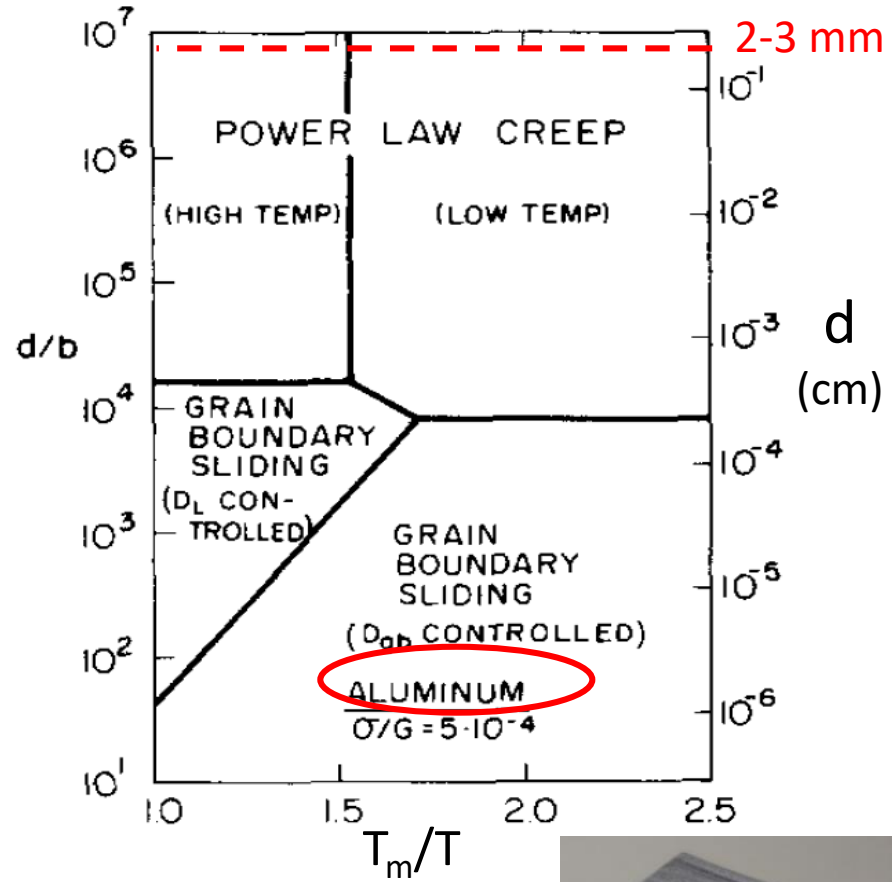


« Superplasticity »

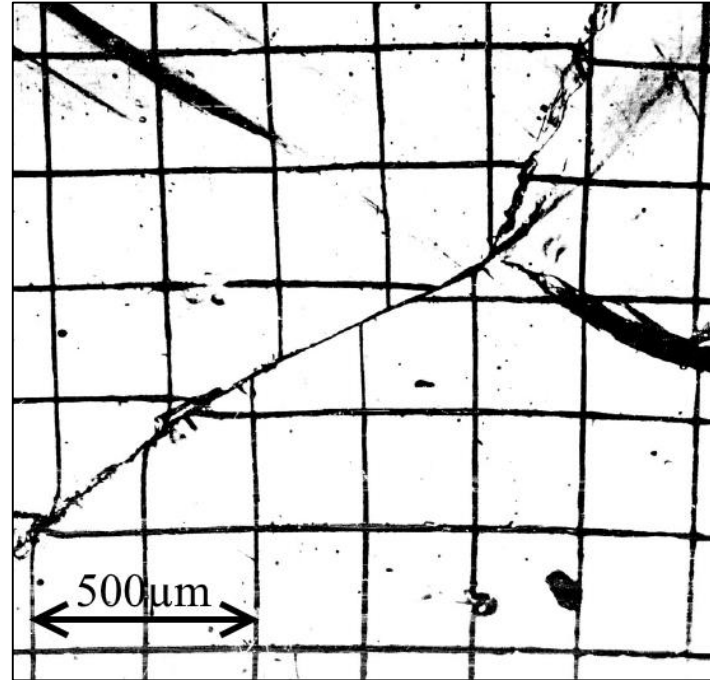
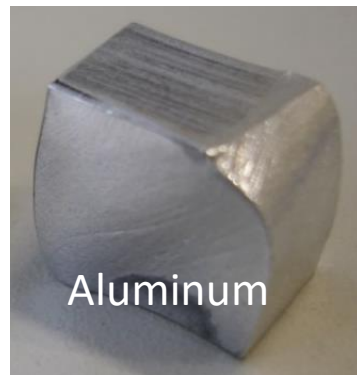
Grain Boundary Sliding, Diffusion mass transfer



I. Introduction: mechanisms maps

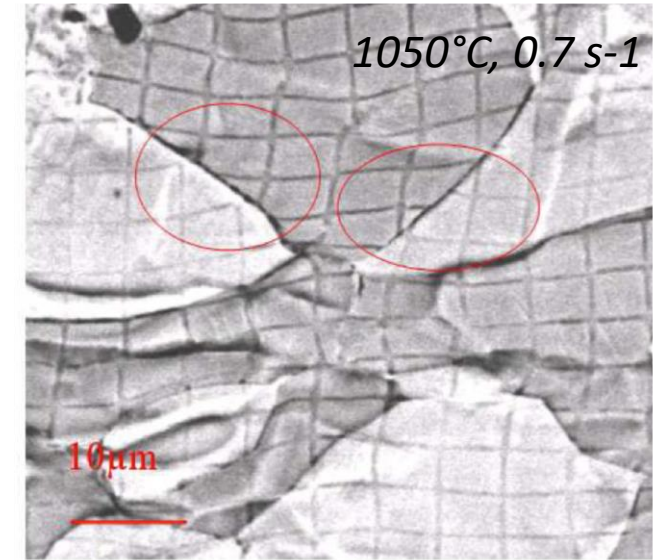


Luthy, White and Sherby, Mater. Sci. Eng (1979)

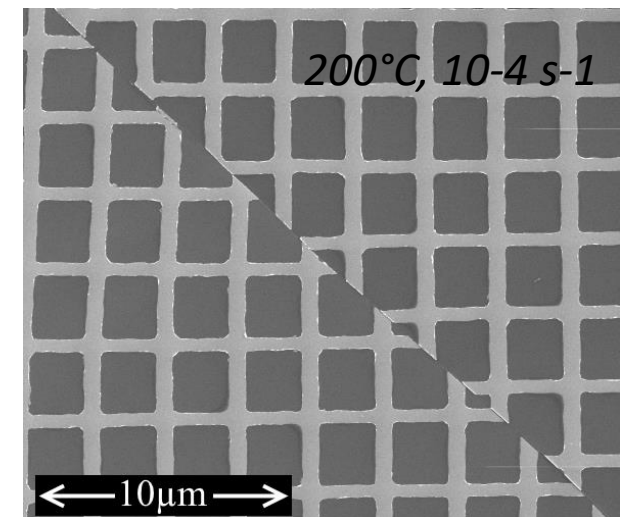


Creep of Al: 1,7 MPa, 340°C, $\epsilon=7\%$, Fazan, Sherby and Dorn, JOM, 1954

Rupin et al. 2007: Austenite – Ferrite steel

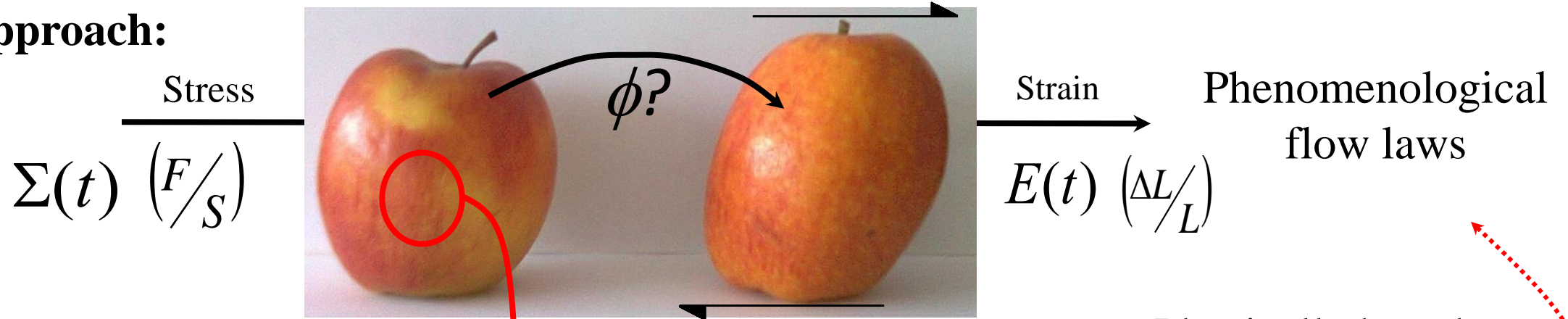


El Sabbagh et al: 2018: Al



II. Micromechanical approach: in situ testing and Full Field Measurements by DIC

Macro approach:

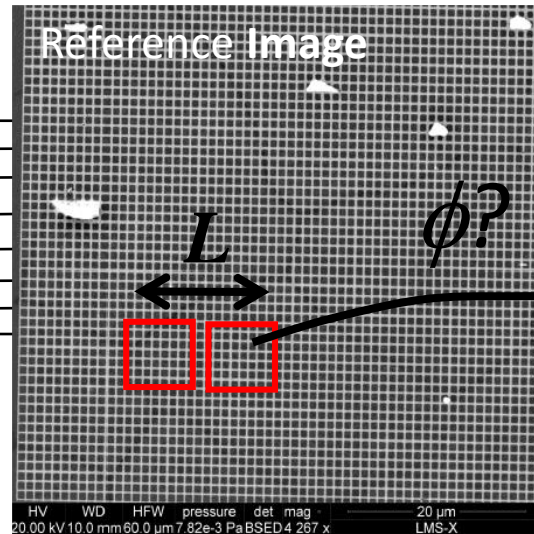


Micro approach:

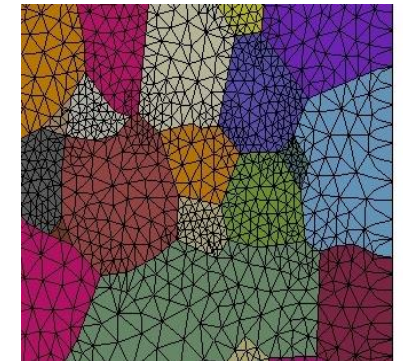
Full Field measurements by digital Image Correlation

- Microstructure
- Heterogeneities
- Scales (REV)
- Mechanisms
- Interactions

$\sigma(x, t)$



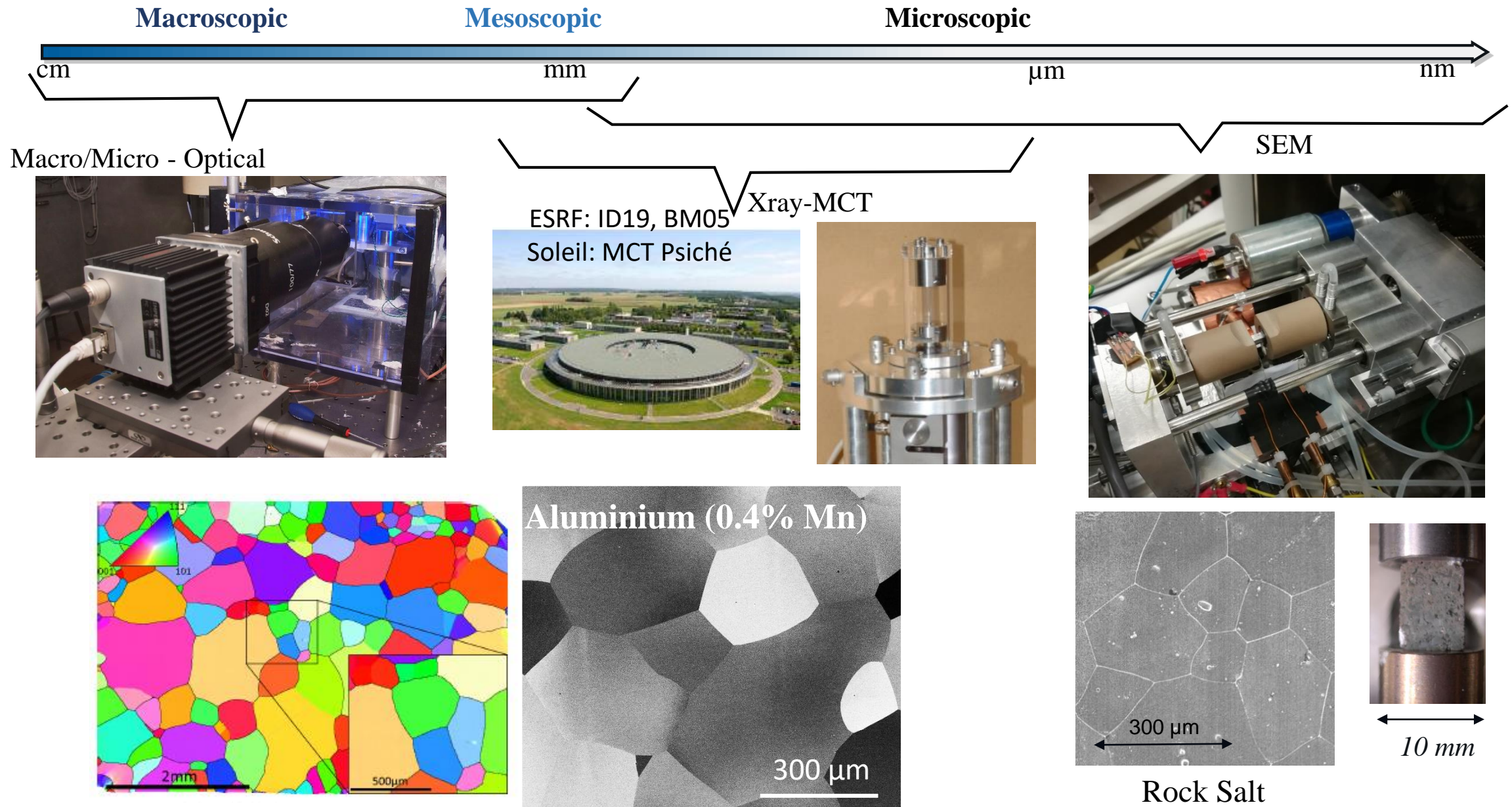
$\epsilon(x, t)$



$$F_{xx}^l(x) - 1 = \frac{u_x(x + L/2) - u_x(x - L/2)}{L}$$

Physically based
Numerical modelling

II. Micromechanical approach: in situ testing and Full Field Measurements by DIC & DVC

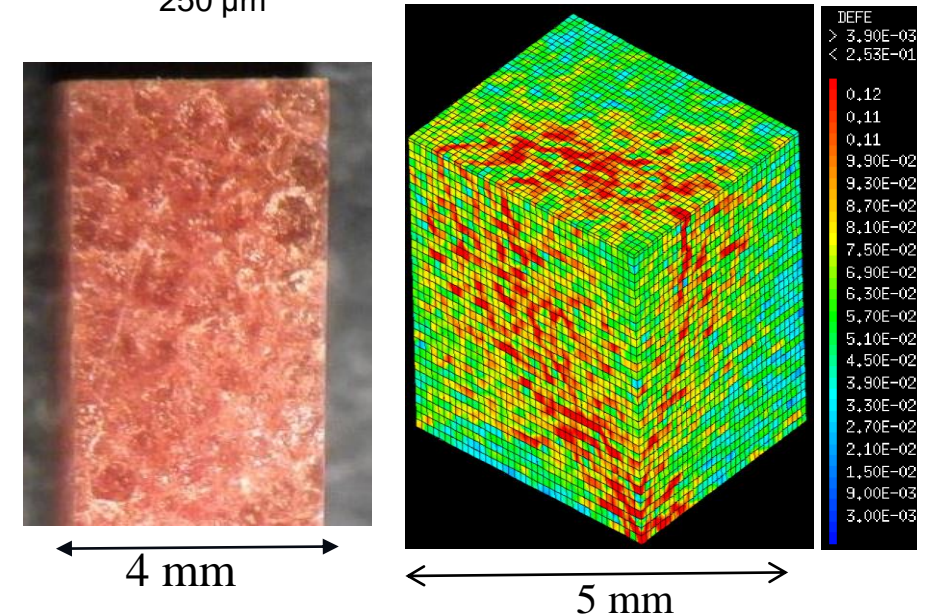
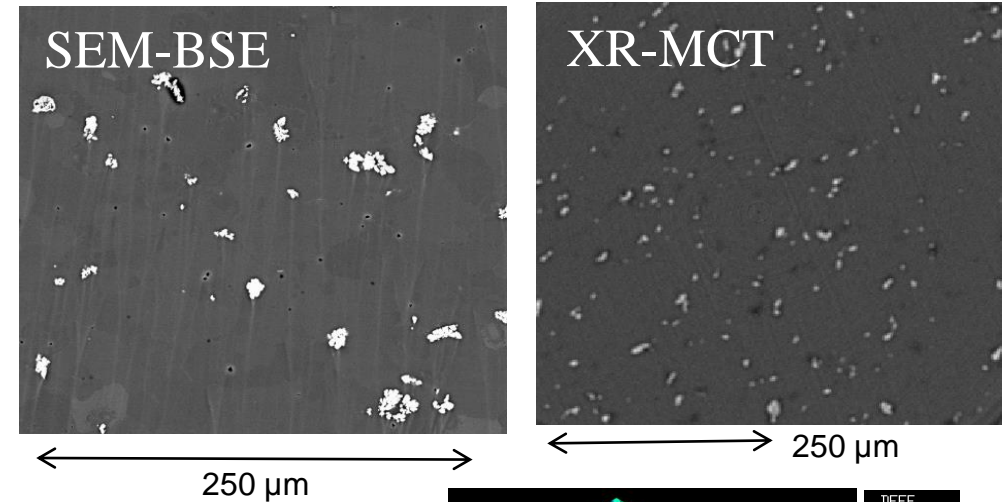
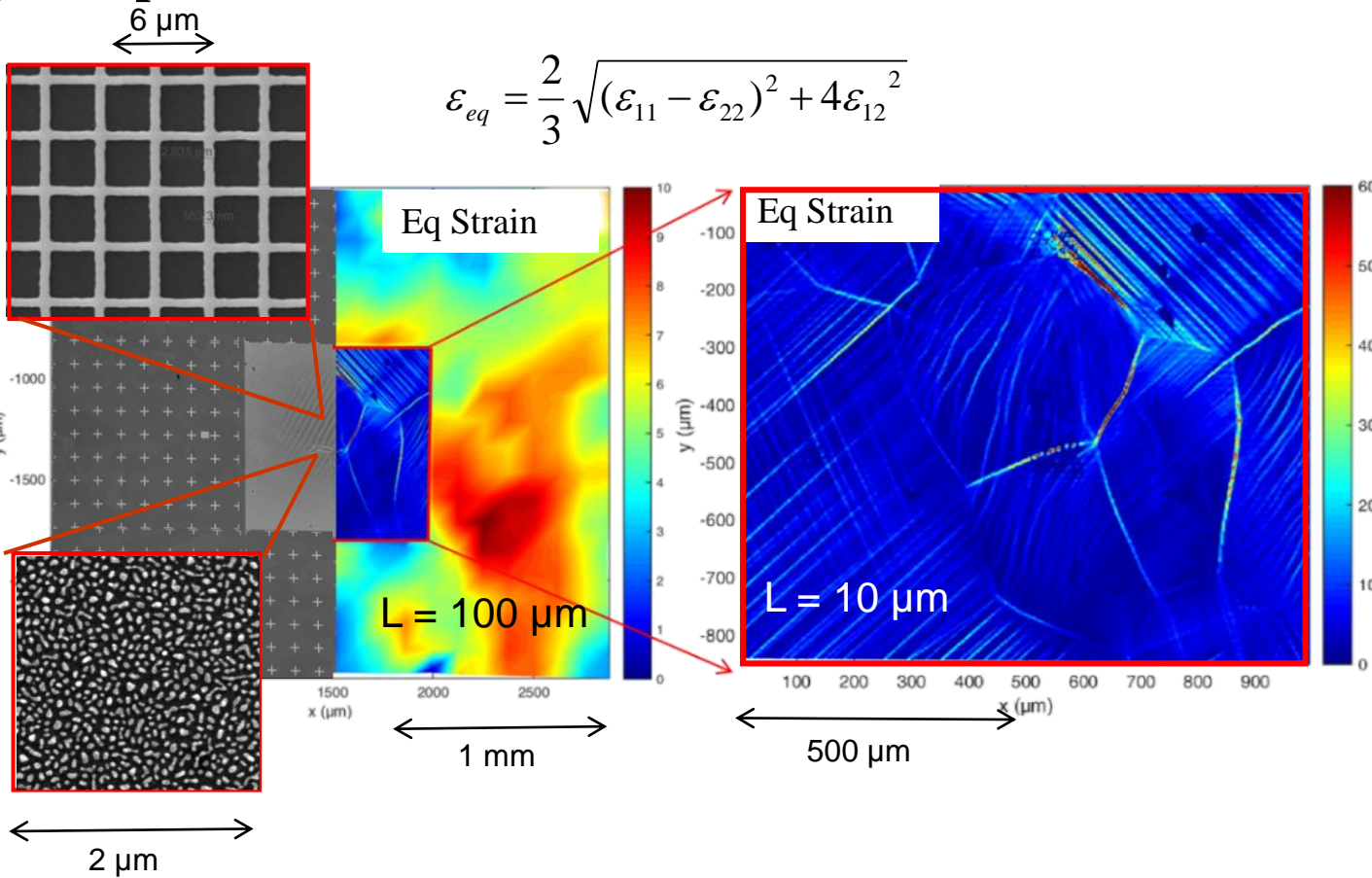


II. Micromechanical approach: in situ testing and Full Field Measurements by DIC & DVC

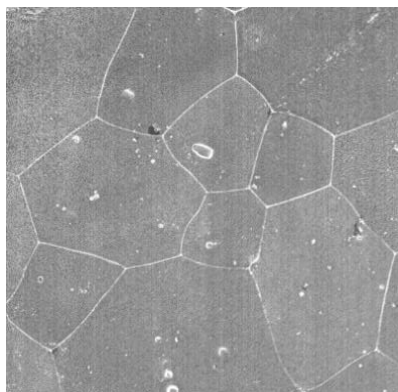
1) **Markers:** Au grids (e- lithography), Au particles (film dewetting). Volume dispersion of Cu particles

2) **Measurements:** of 2D & 3D kinematic fields by DIC & DVC

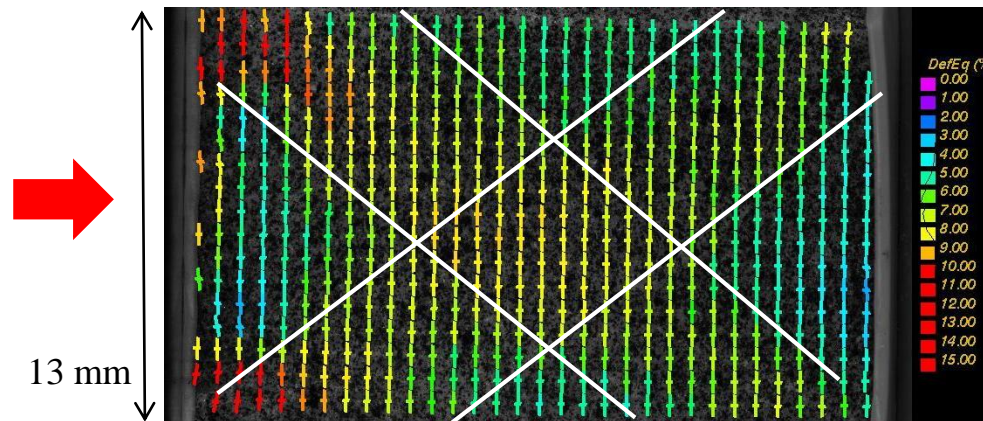
3) **Computation:** of surface & volume strain fields



III. Exemples of ductile localization: Rock salt (NaCl), Optical monitoring, sample scale

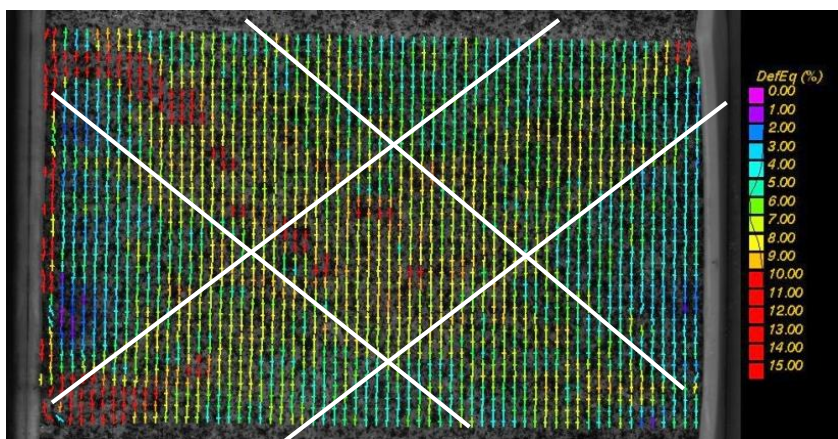


Grain size: $300\ \mu\text{m}$ \longleftrightarrow $300\ \mu\text{m}$

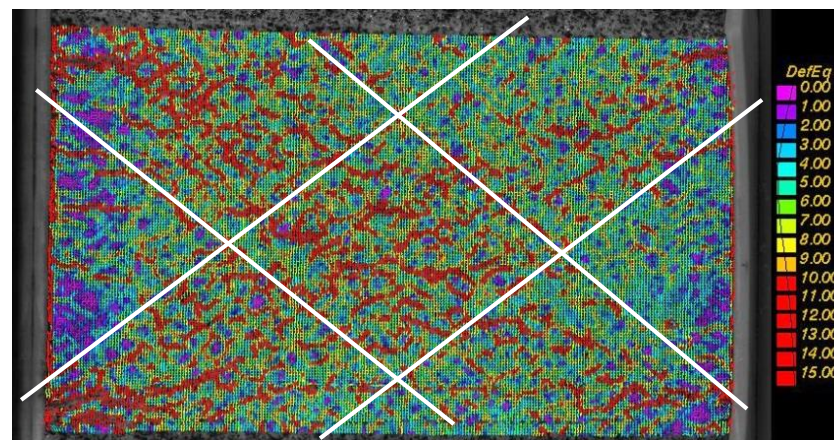


Conjugate Shear Localization at sample scale

$L = 1\text{mm}$



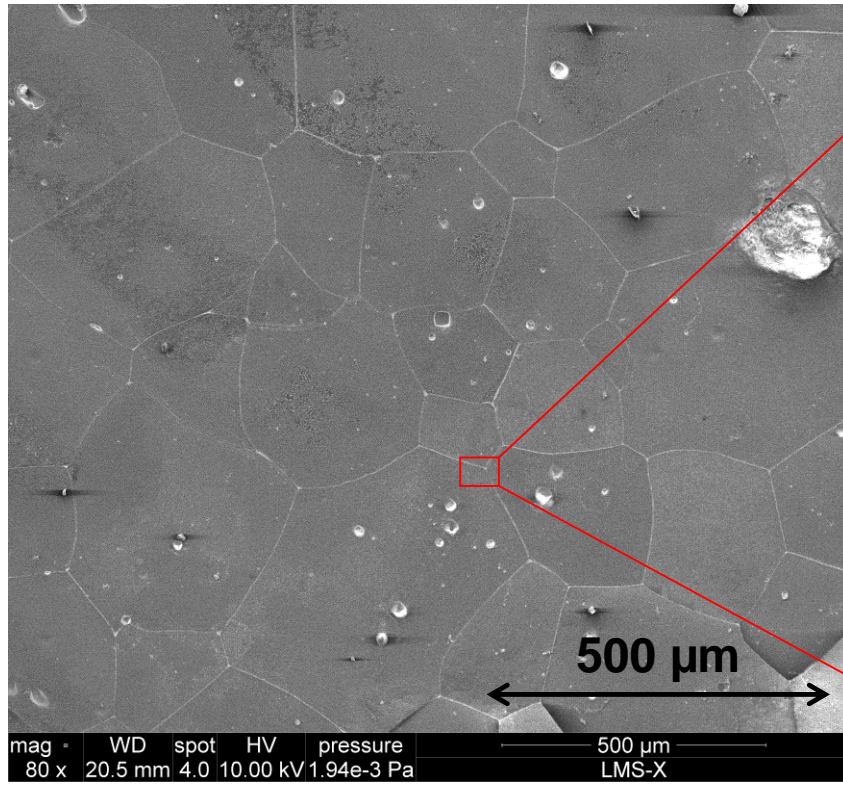
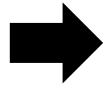
Conjugate Shear Localization & deformation bands at microstructure scale



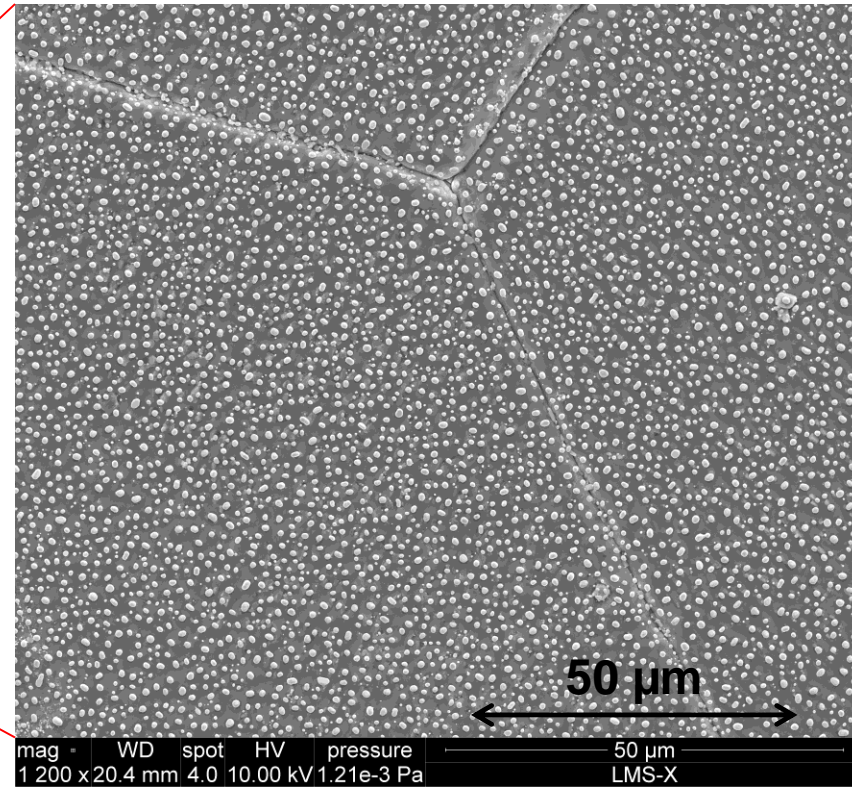
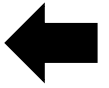
$L = 250\ \mu\text{m}$

Two scales of heterogeneity: characteristic length scale about 2 - 3 grain sizes

III. Exemples of ductile localization: Rock salt (NaCl), SEM monitoring, microstructure scale

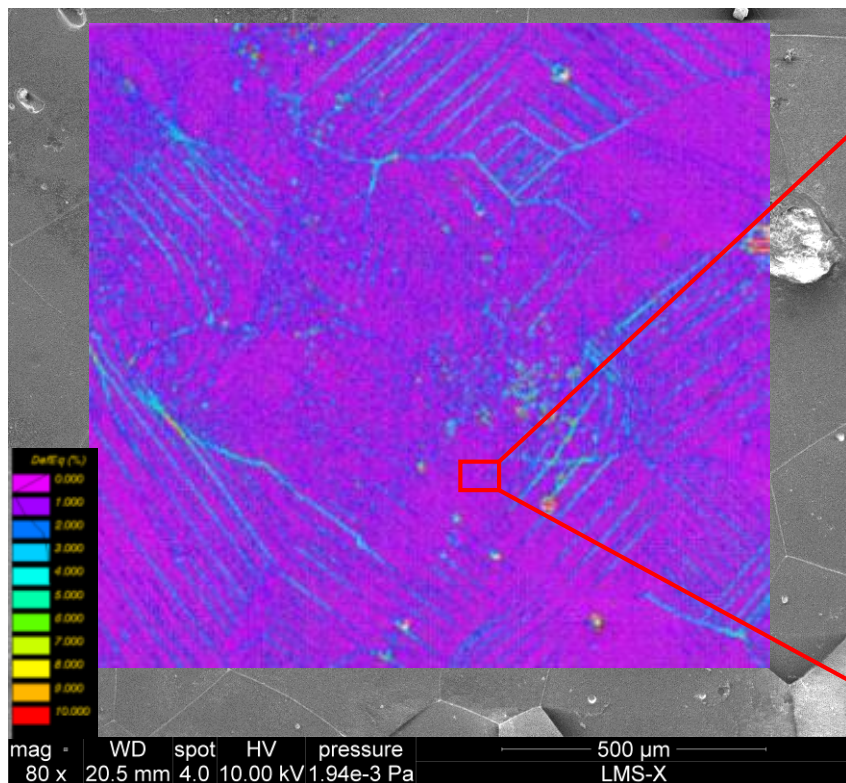
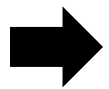


Meso/micro scale (polycrystal microstructure)

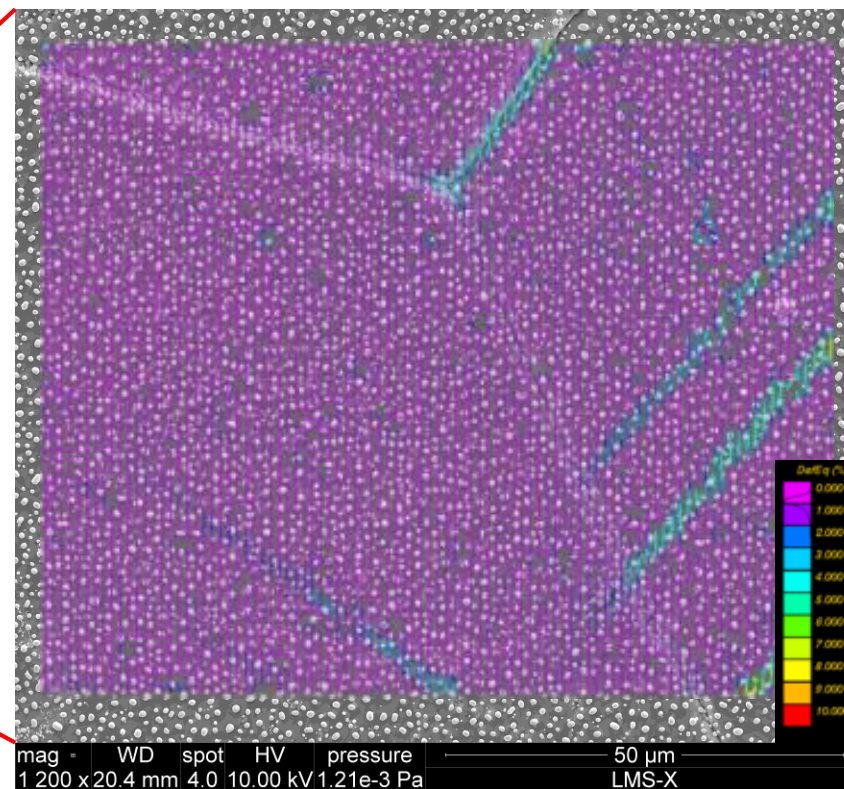
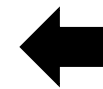


micro scale (grain)

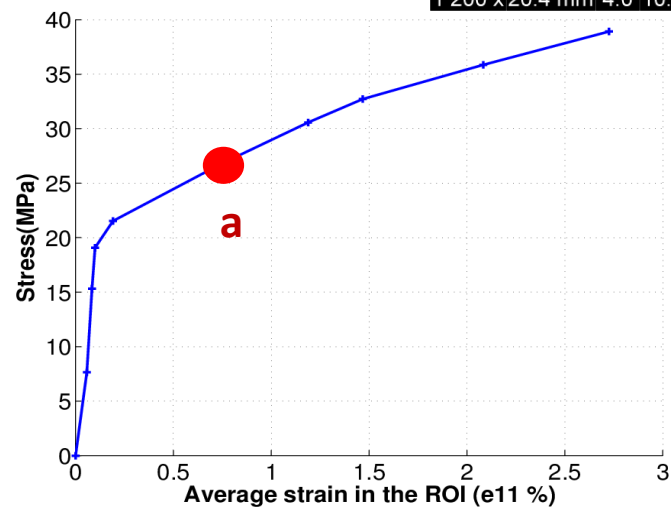
III. Exemples of ductile localization: Rock salt (NaCl), SEM monitoring, microstructure scale



$L \gg 10 \text{ mm}$

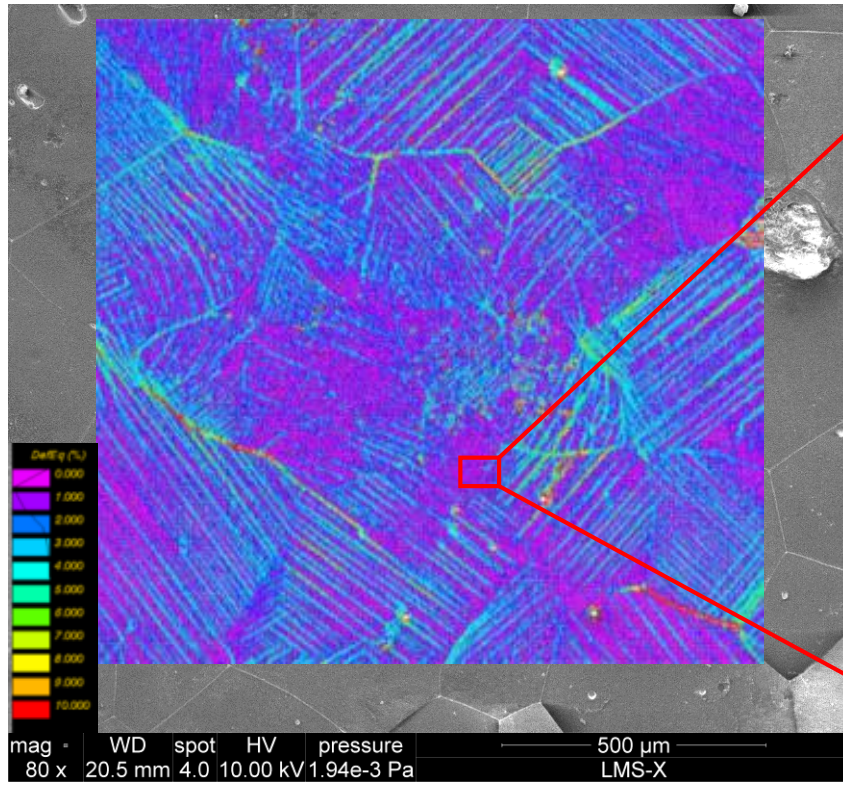
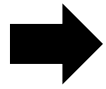


$L \gg 2 \text{ mm}$

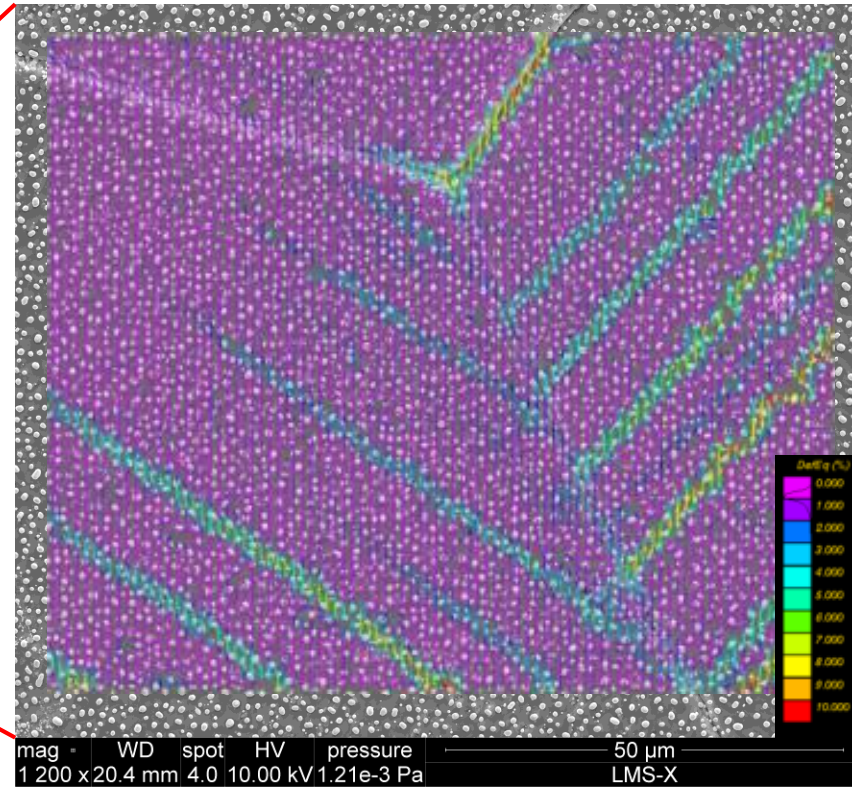
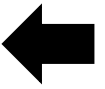


Bourcier et al 2013

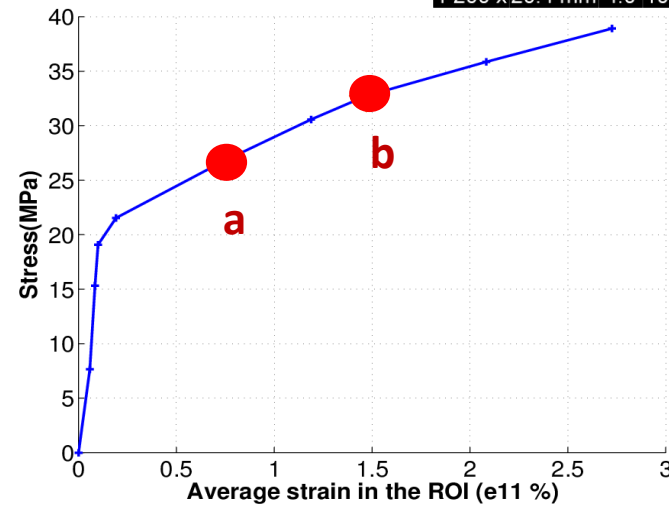
III. Exemples of ductile localization: Rock salt (NaCl), SEM monitoring, microstructure scale



$L \gg 10 \text{ mm}$

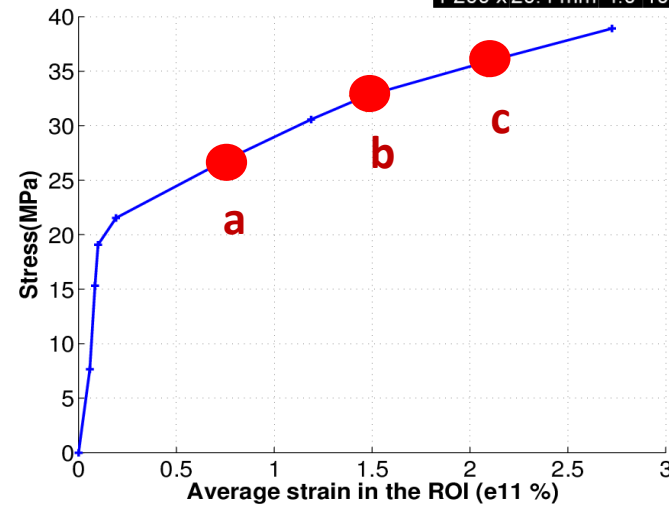
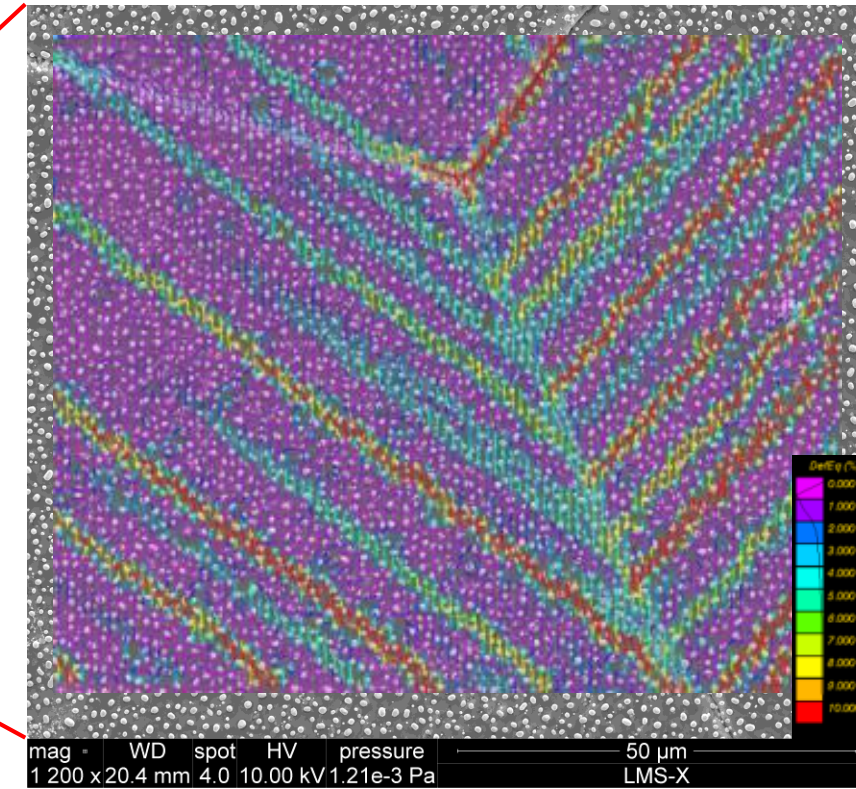
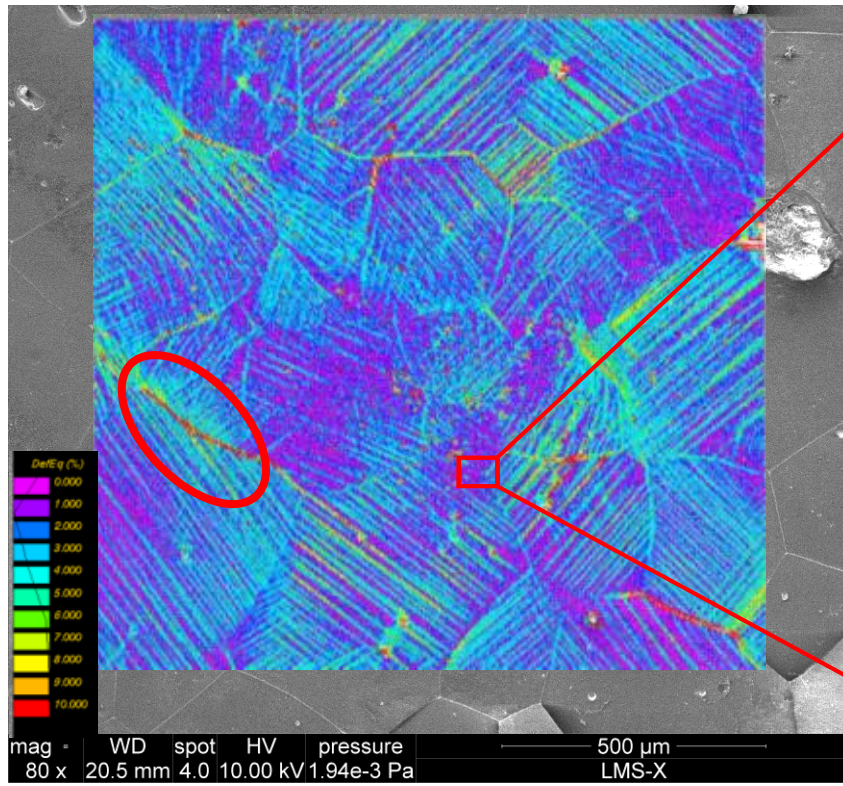


$L \gg 2 \text{ mm}$



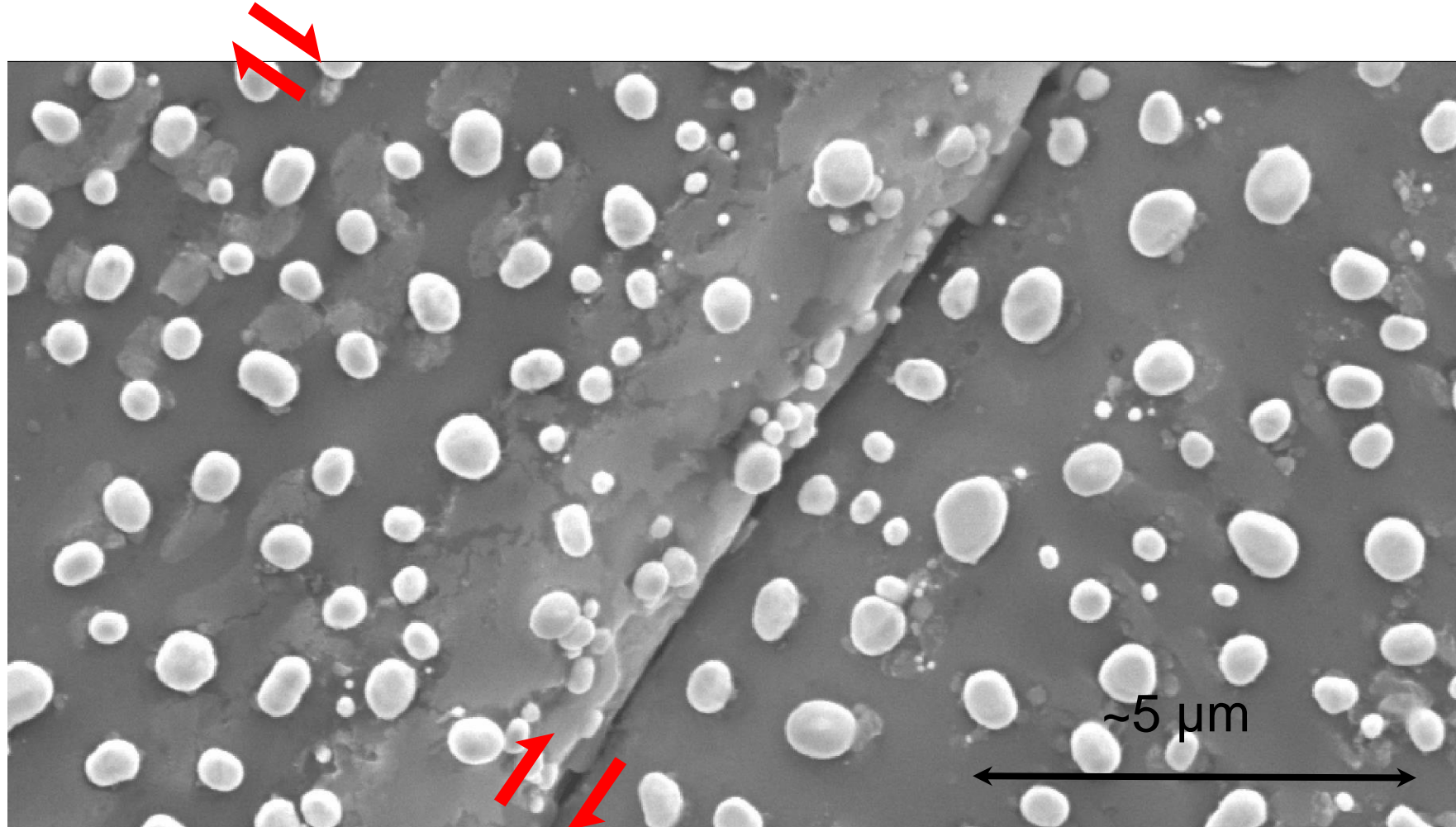
Bourcier et al 2013

III. Exemples of ductile localization: Rock salt (NaCl), SEM monitoring, microstructure scale



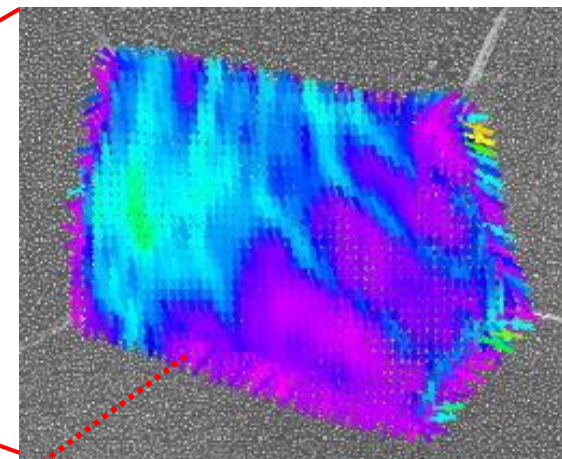
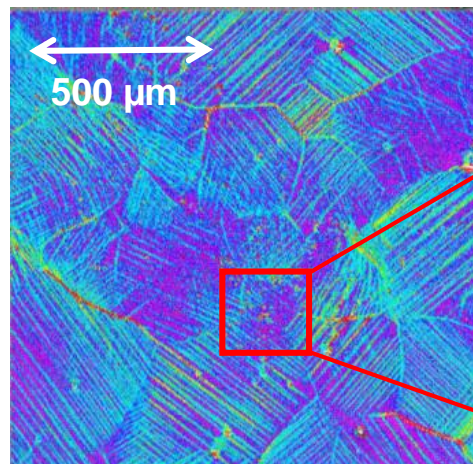
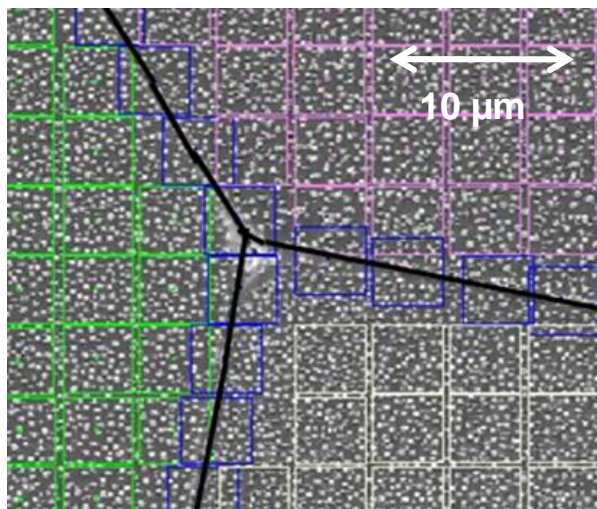
Bourcier et al 2013

III. Examples of ductile localization: Rock salt (NaCl), SEM monitoring: **CSP & GBS identification**



**Two simultaneous mechanisms:
Crystal slip plasticity (CSP) & Grain Boundary Sliding (GBS)**

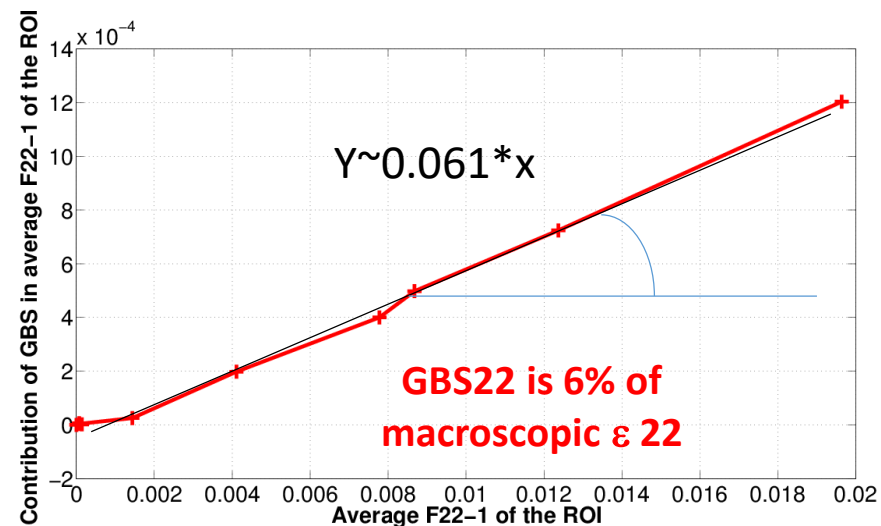
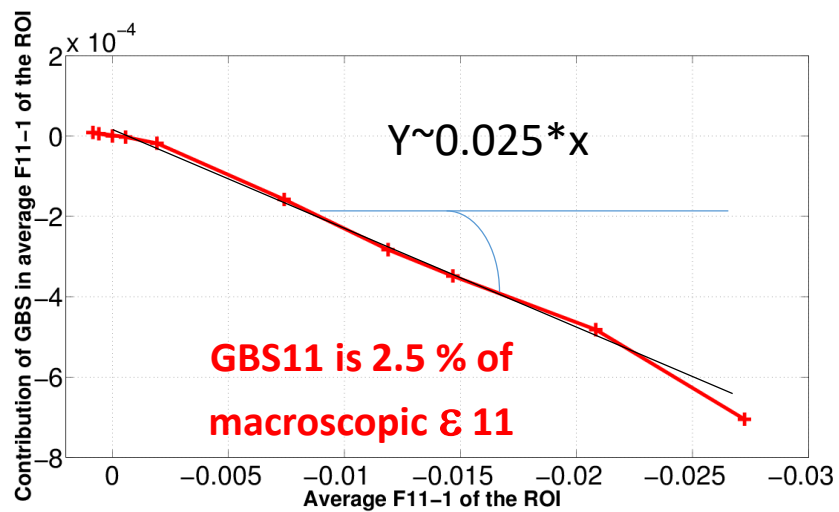
III. Exemples of ductile localization: Rock salt (NaCl), SEM monitoring: **GBS** quantification



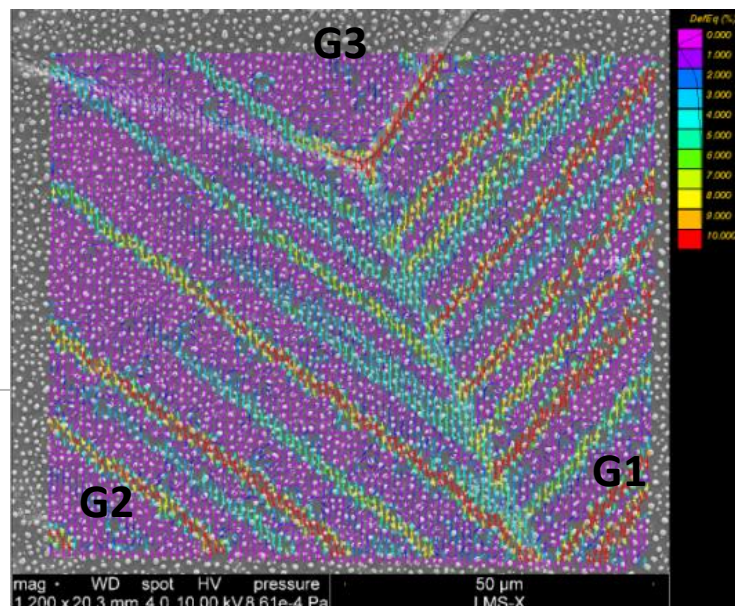
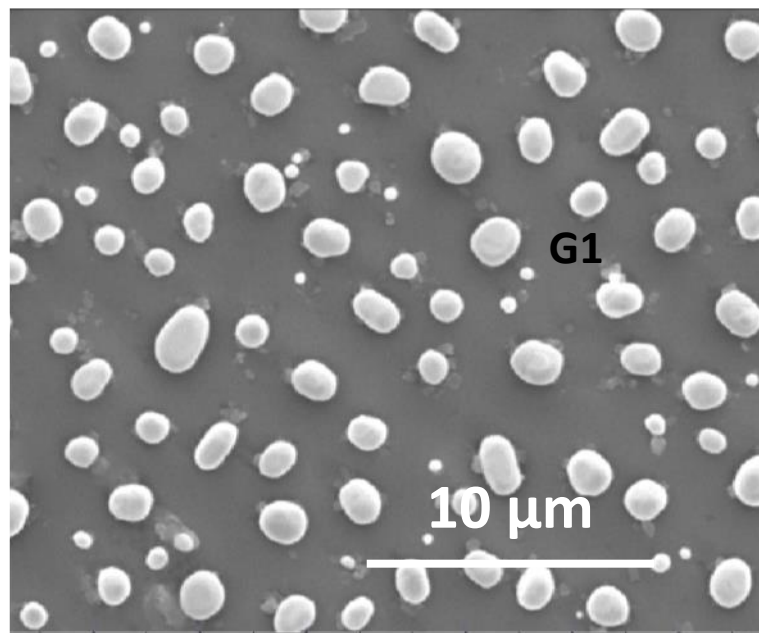
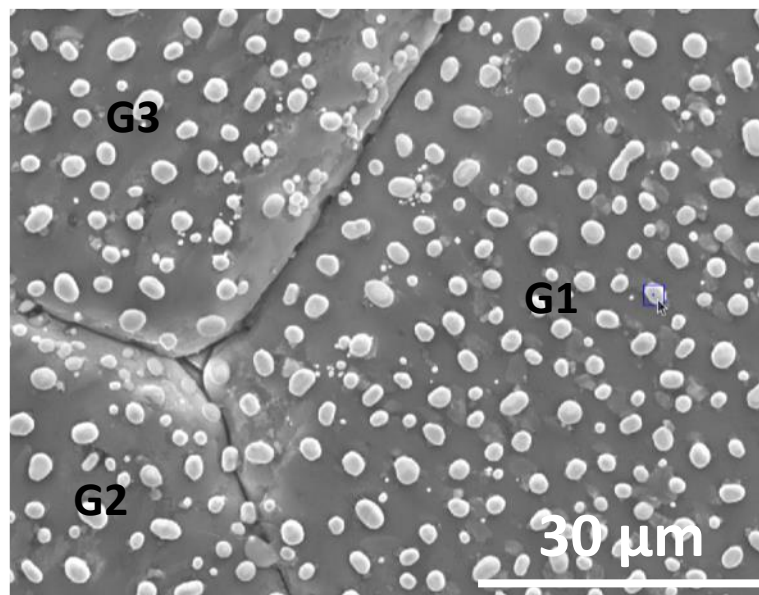
Average ROI strain

Average intragrain strain (CSP)

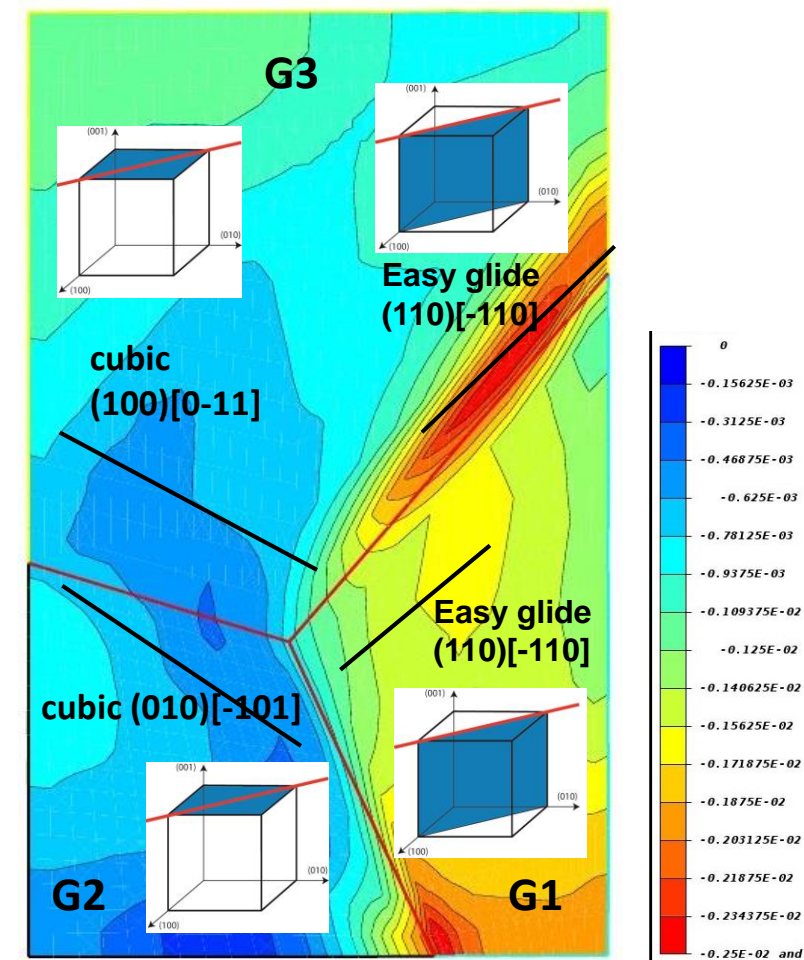
$$\text{GBS: } \underline{\underline{\Delta F}} = \underline{\underline{F}}_{\underline{\underline{\Omega}}} - \sum_{g=1}^G \omega_g \underline{\underline{F}}_{\underline{\underline{\Omega}}_g}$$



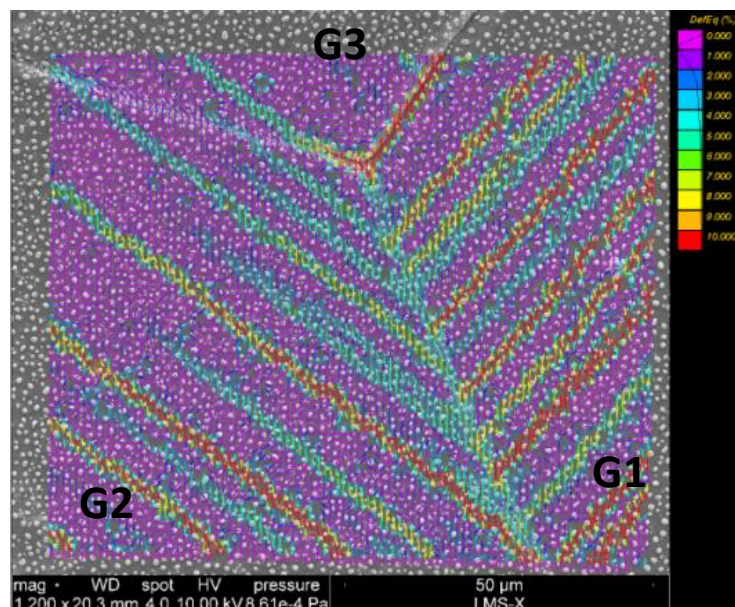
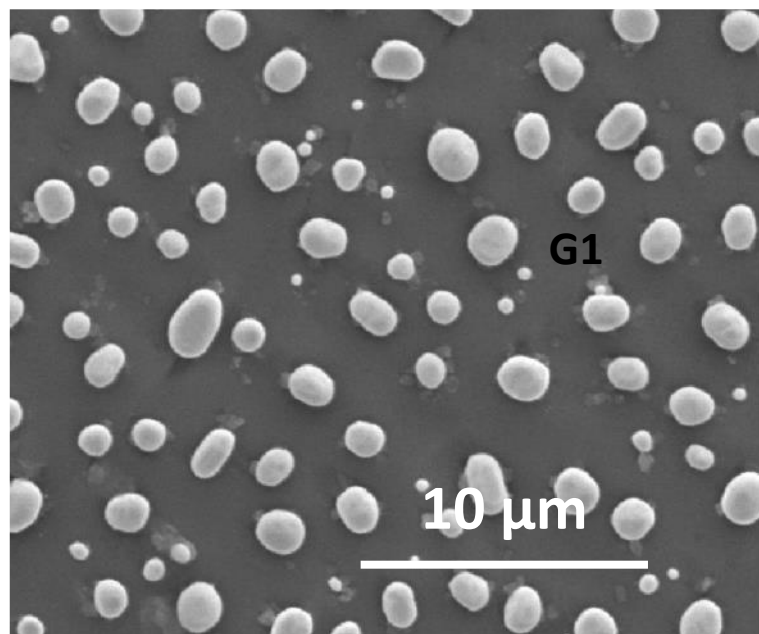
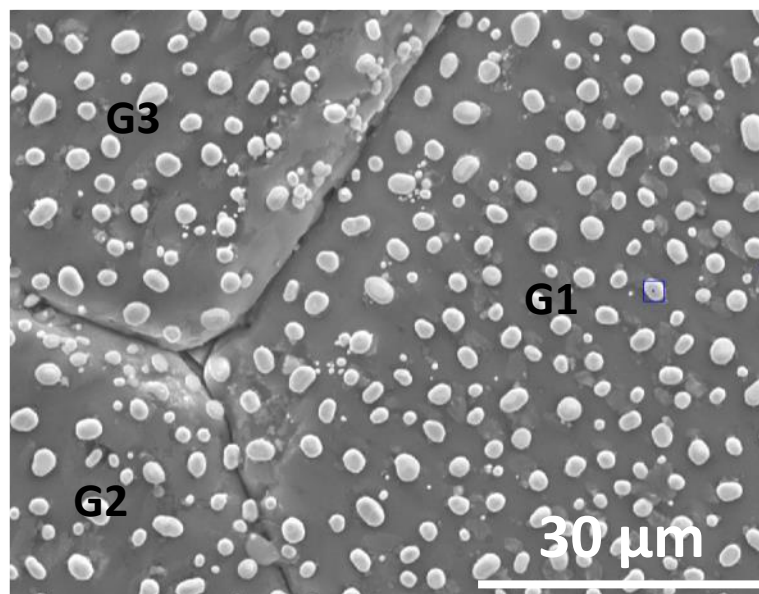
III. Exemples of ductile localization: Rock salt (NaCl), SEM monitoring: CPFEM modelling



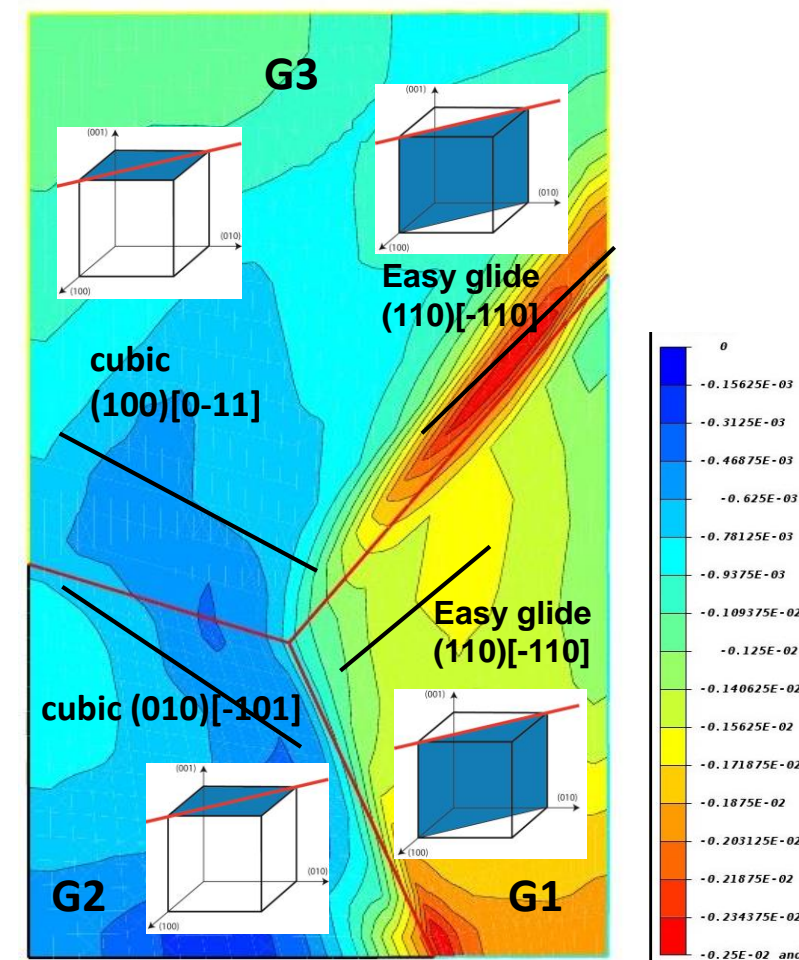
Axial strain CP-FEM



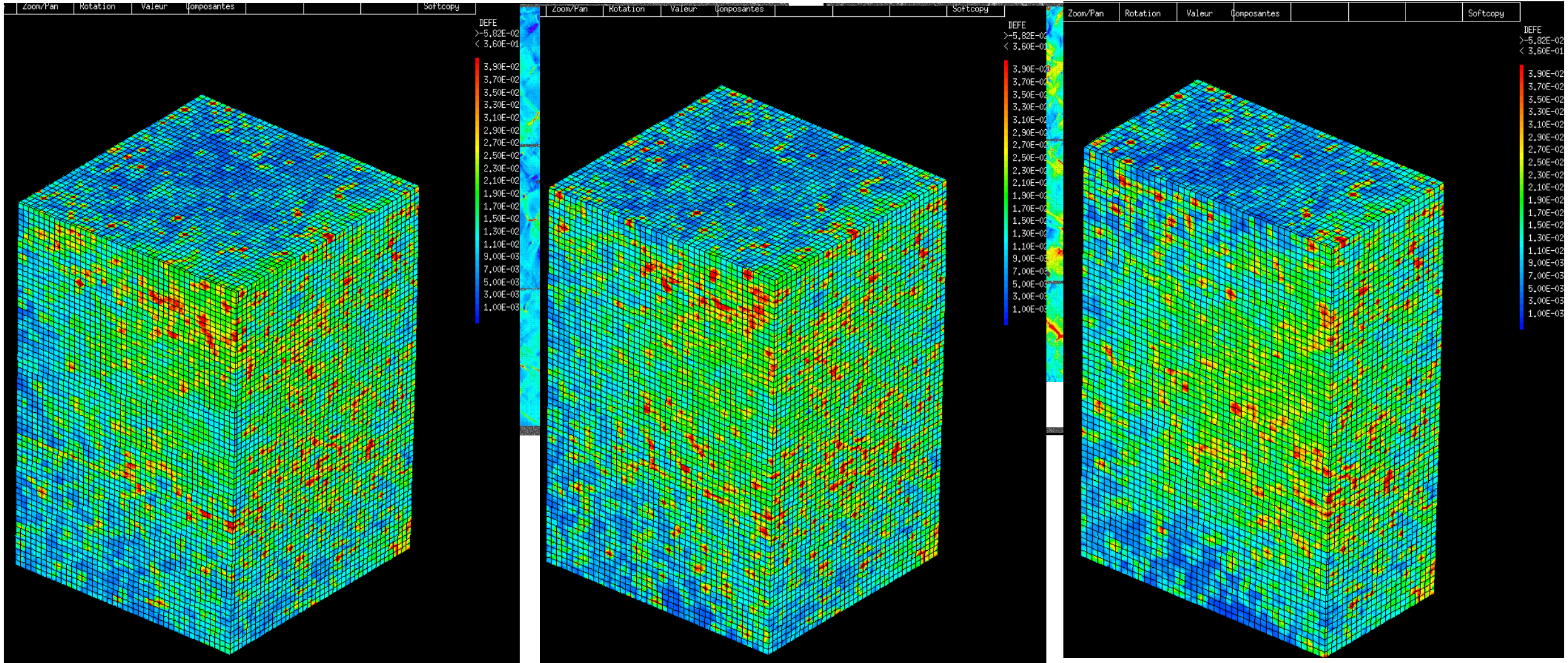
III. Exemples of ductile localization: Rock salt (NaCl), SEM monitoring: CPFEM modelling



Axial strain CP-FEM

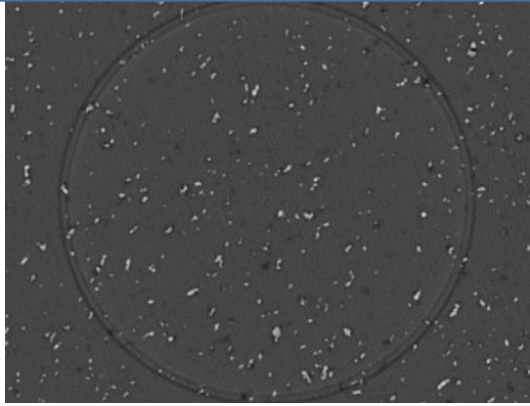


III. Exemples de ductile localization: Rock salt (NaCl), SEM & XR-MCT monitoring: deformation bands

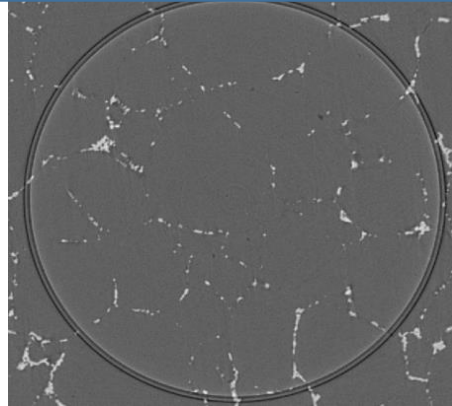


CSP and GBS are cooperative

III. Exemples of ductile localization: Rock salt (NaCl), SEM & XR-MCT monitoring: deformation bands

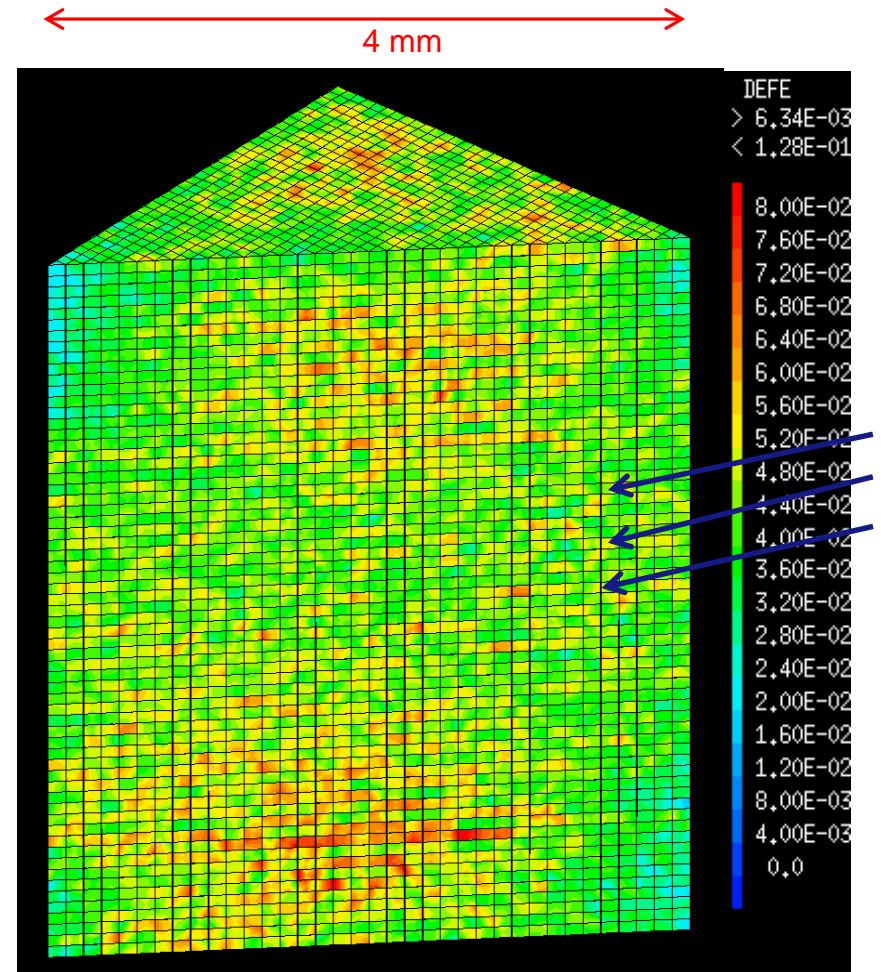
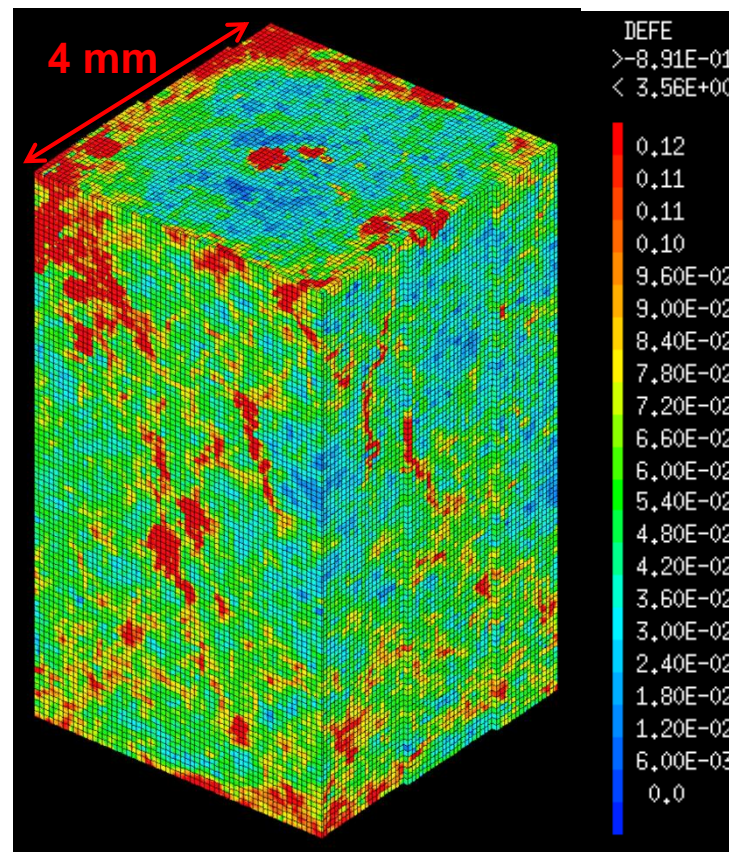
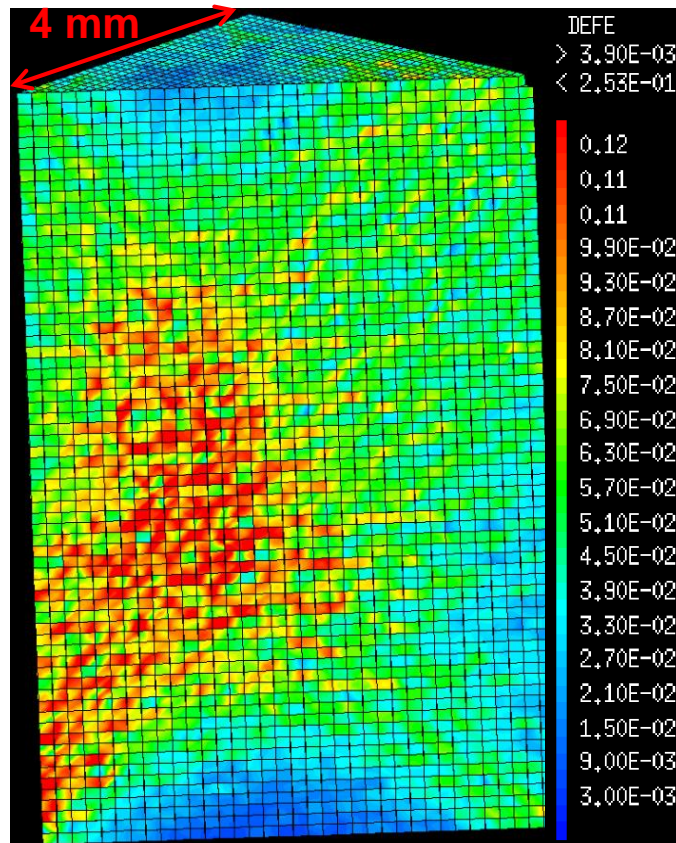


Grains ~ 50 - 100 μm , , L = 105 μm



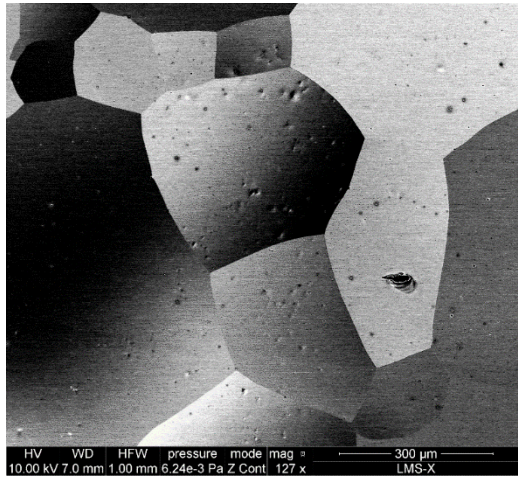
Grains ~ 100 - 300 μm , , L = 105 μm

2 scales of localization: sample & microstructure
Deformation bands spacing varies with grain size

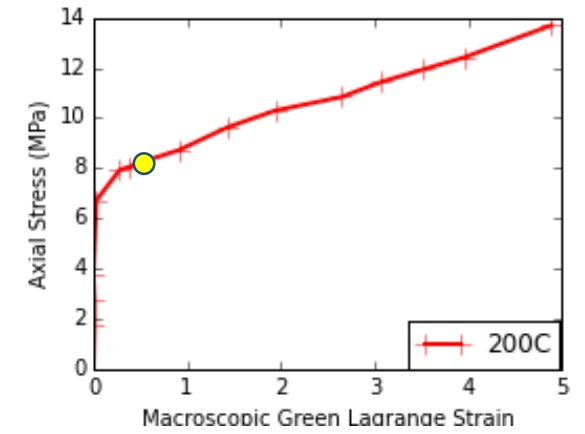
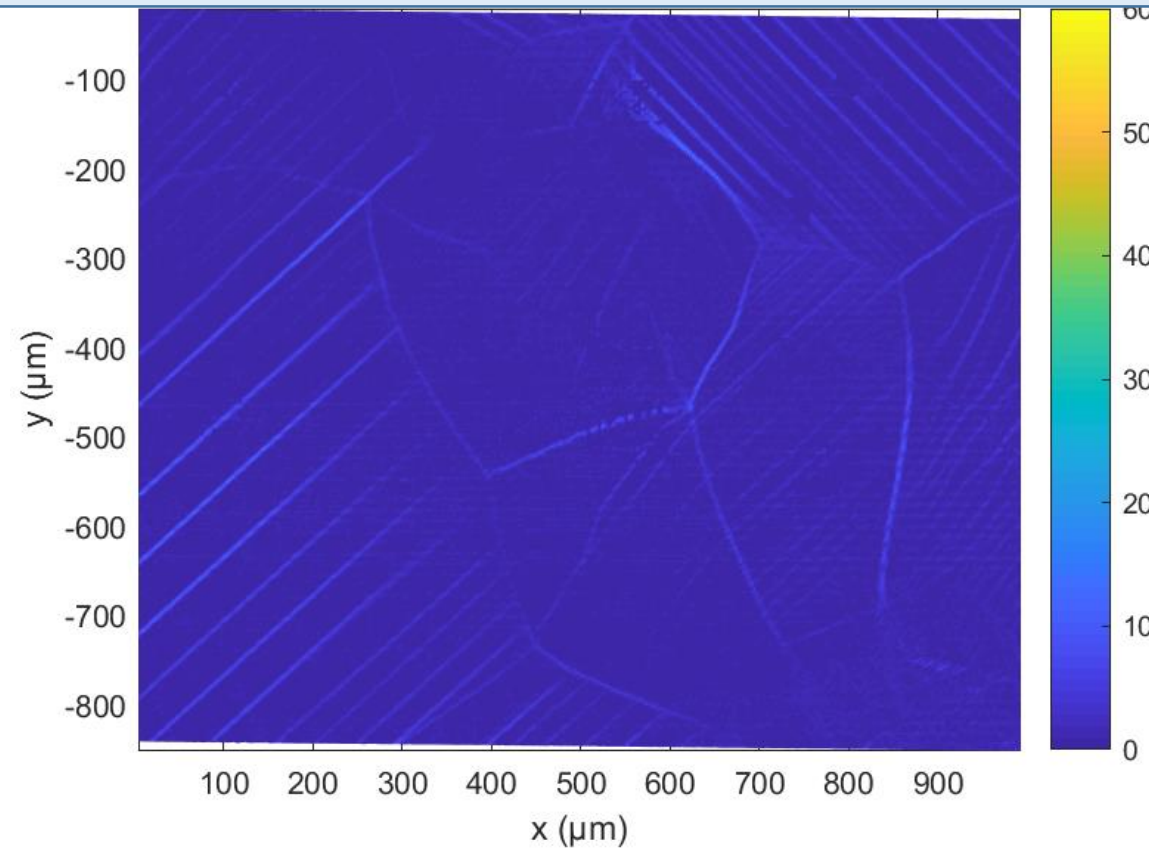


Same bands for 2 independent mesures

III. Exemples of ductile localization: Aluminium (0.4 Mn), SEM monitoring, microstructure scale

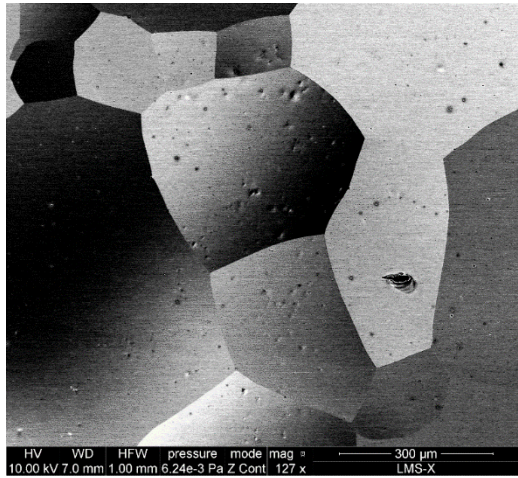


$0,1\mu\text{m}\cdot\text{s}^{-1}$ (10^{-5}s^{-1}), 200°C

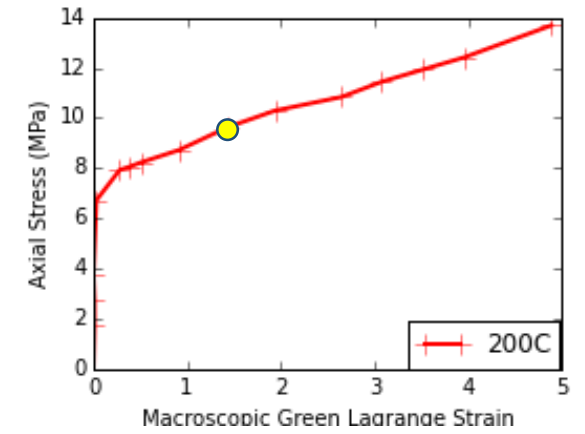
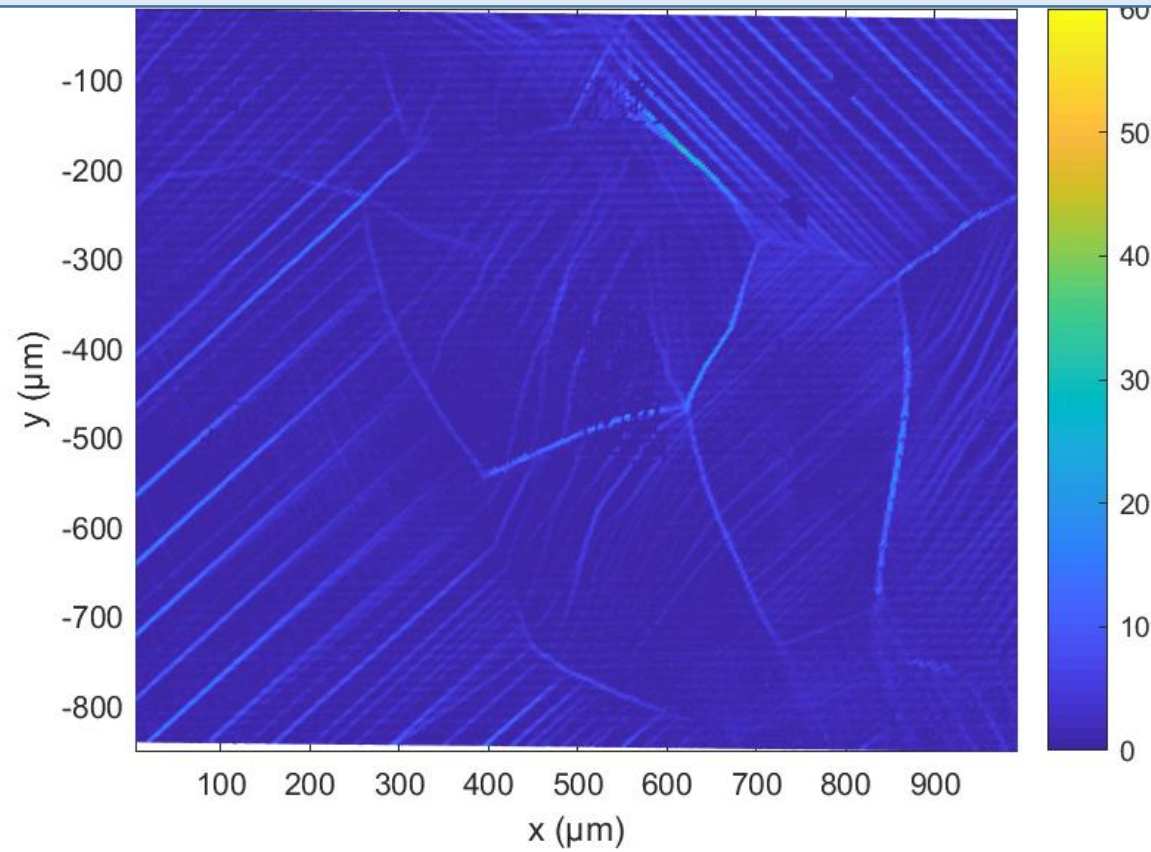


$E_{11}=0,5\%$

III. Exemples of ductile localization: Aluminium (0.4 Mn), SEM monitoring, microstructure scale

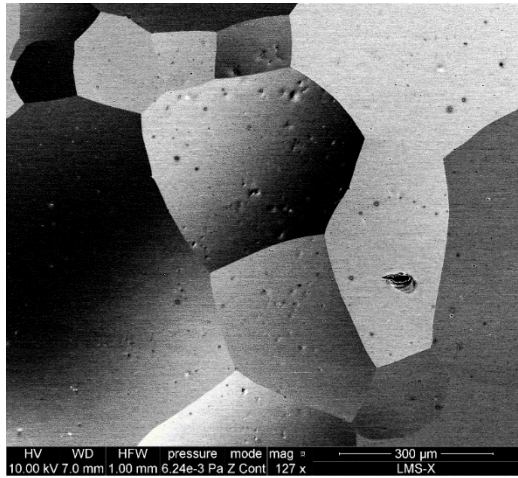


$0,1\mu\text{m}\cdot\text{s}^{-1}$ (10^{-5}s^{-1}), 200°C

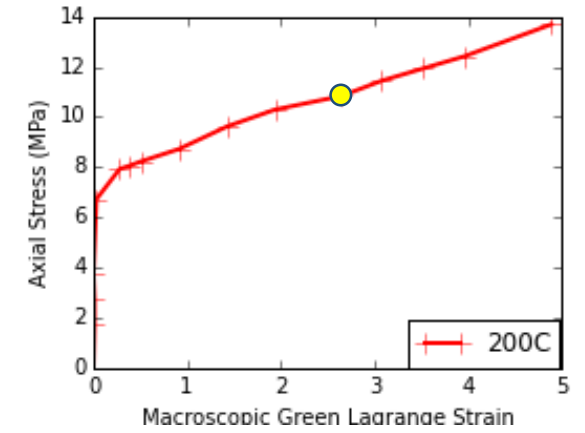
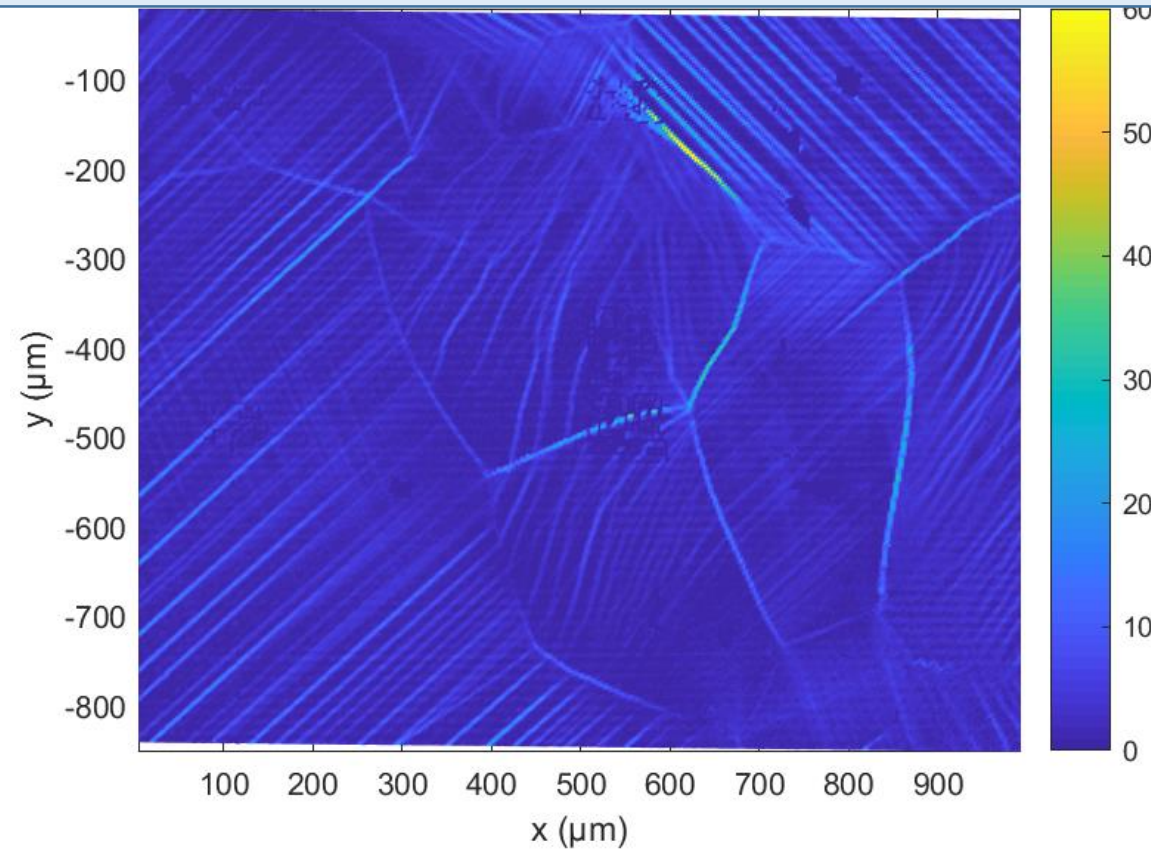


$E_{11} = 1,4\%$

III. Exemples of ductile localization: Aluminium (0.4 Mn), SEM monitoring, microstructure scale

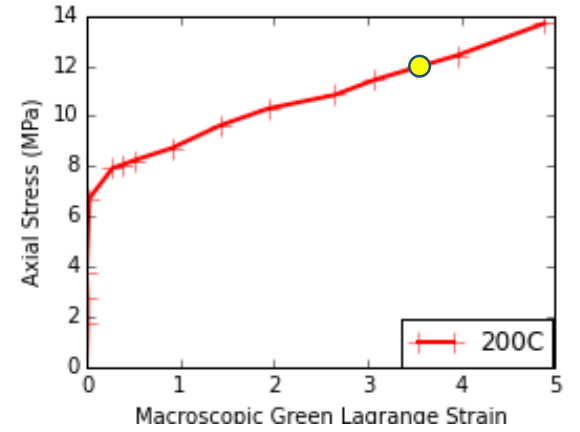
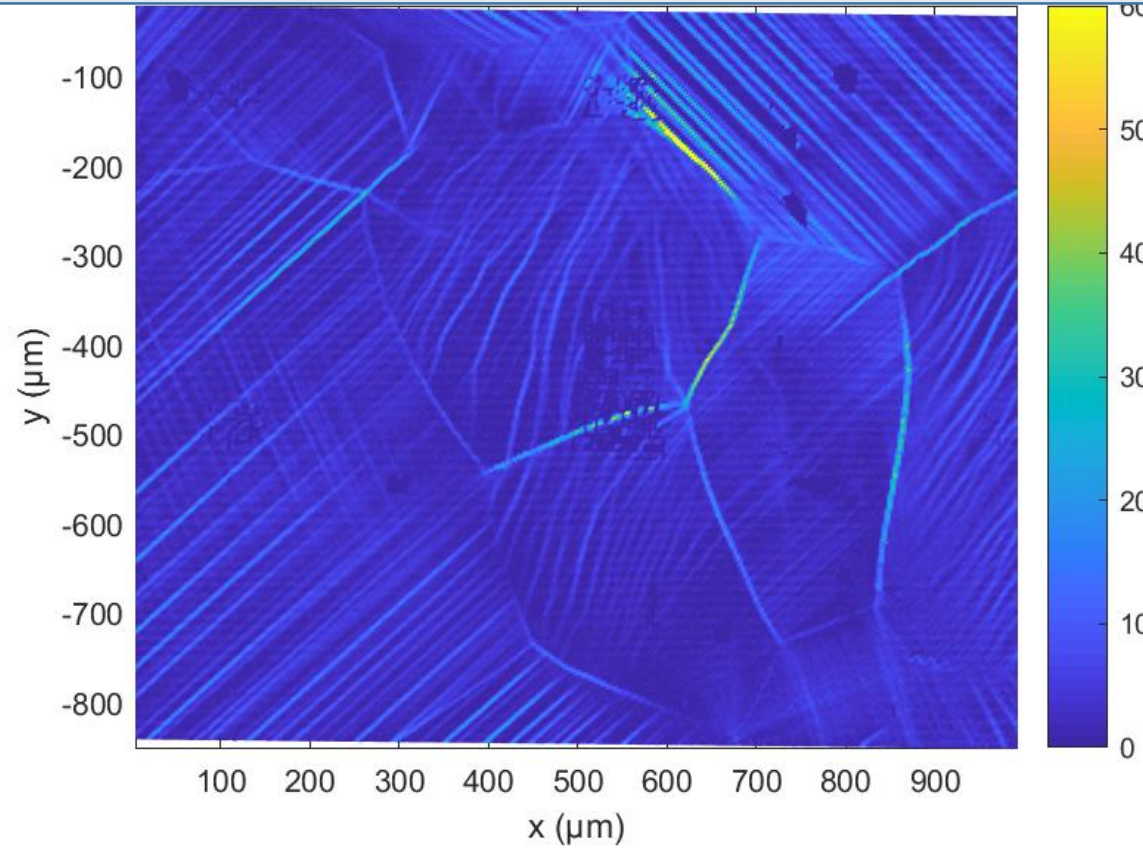
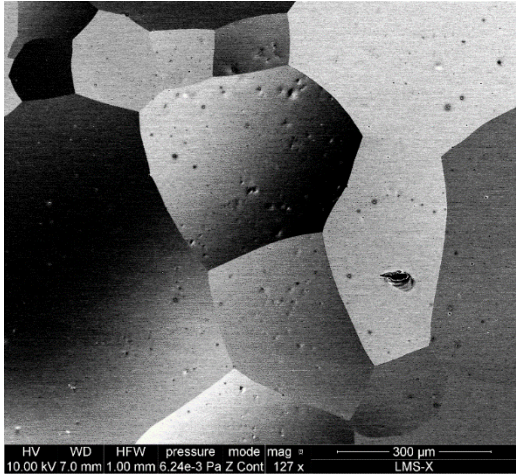


$0,1\mu\text{m}\cdot\text{s}^{-1}$ (10^{-5}s^{-1}), 200°C



$E_{11} = 2,6\%$

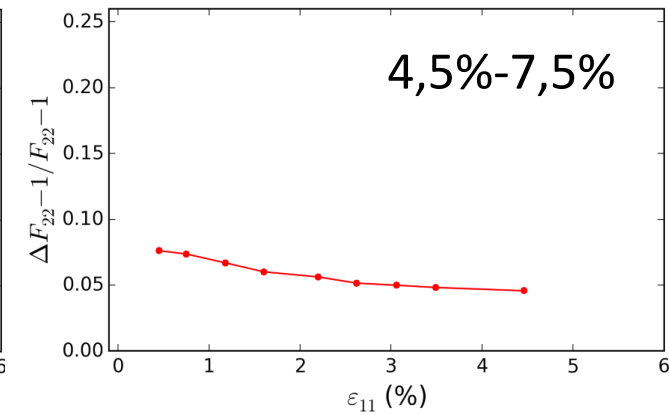
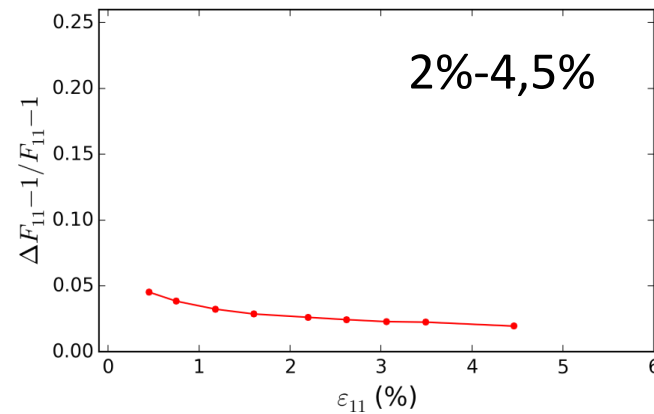
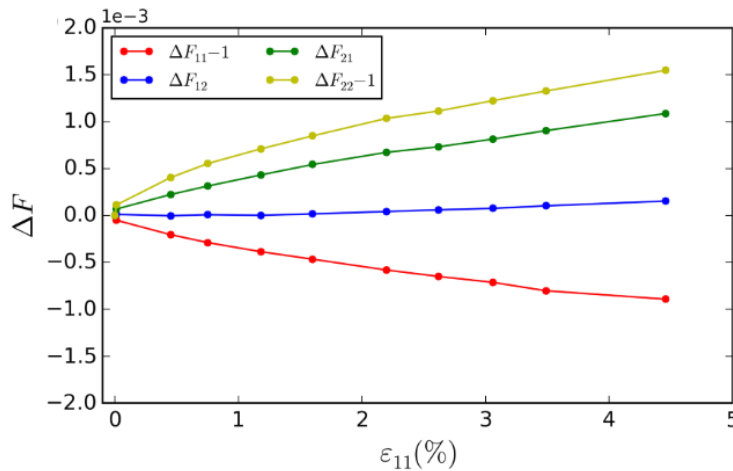
III. Exemples of ductile localization: Aluminium (0.4 Mn), SEM monitoring, microstructure scale



$0,1\mu\text{m}\cdot\text{s}^{-1}$ (10^{-5}s^{-1}), 200°C

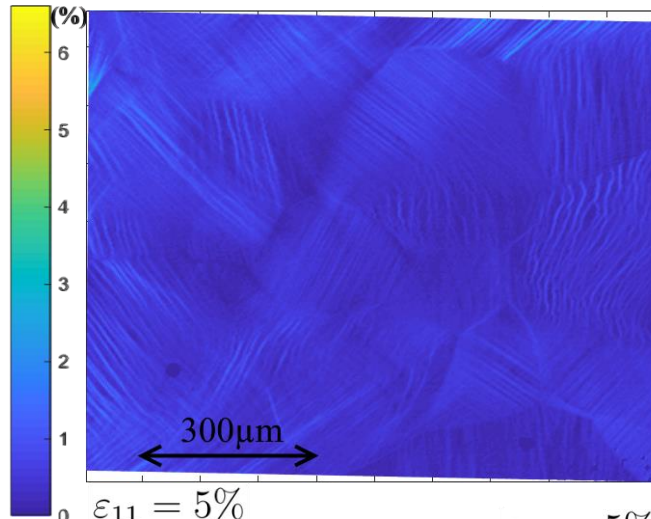
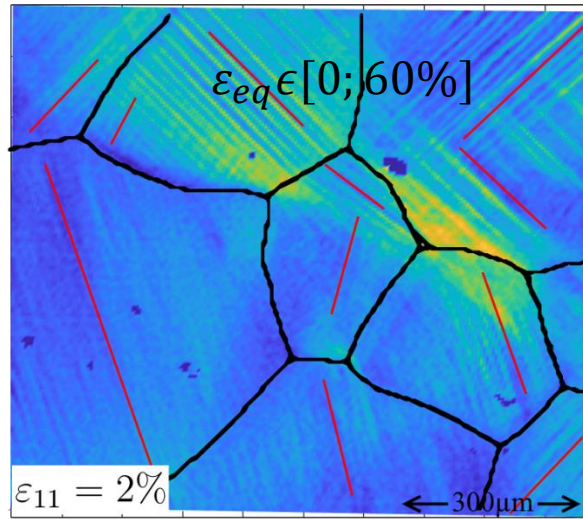
$E_{11} = 3,5\%$

$$\underline{\underline{\Delta F}} = \underline{\underline{F}}_{\Omega} - \sum_{g=1}^G \omega_g \underline{\underline{F}}_{\Omega_g}$$



Evolution of CSP

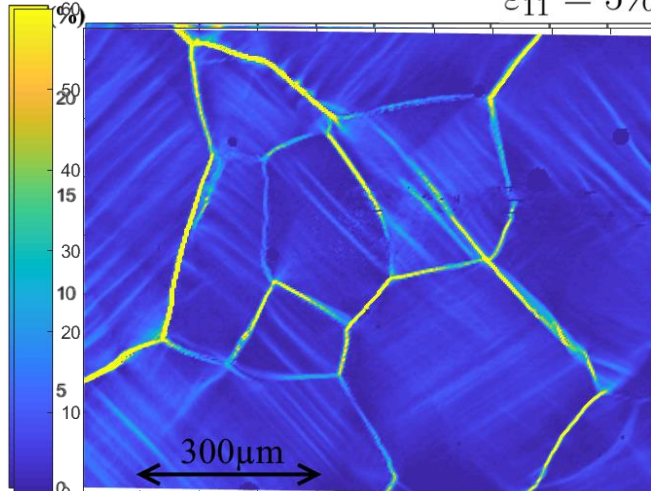
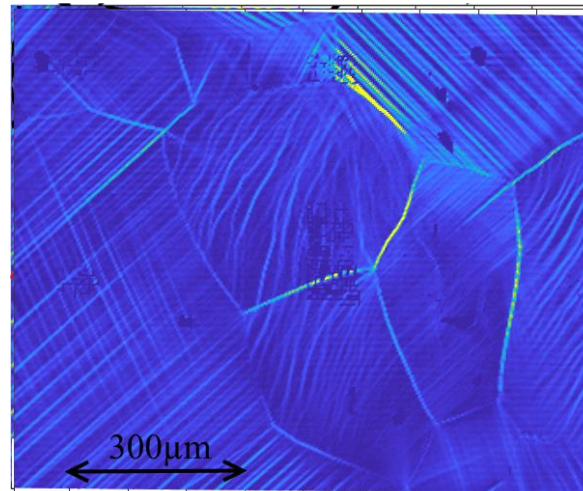
0,3 T_f
25 °C



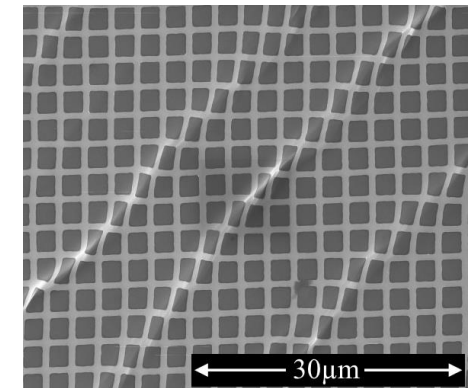
0,4 T_f
110 °C

- at 0,3 T_f : Straight slip bands
- at 0,4 & 0,5 T_f : Density of bands decrease
- Wavy slip bands

0,5 T_f
200 °C



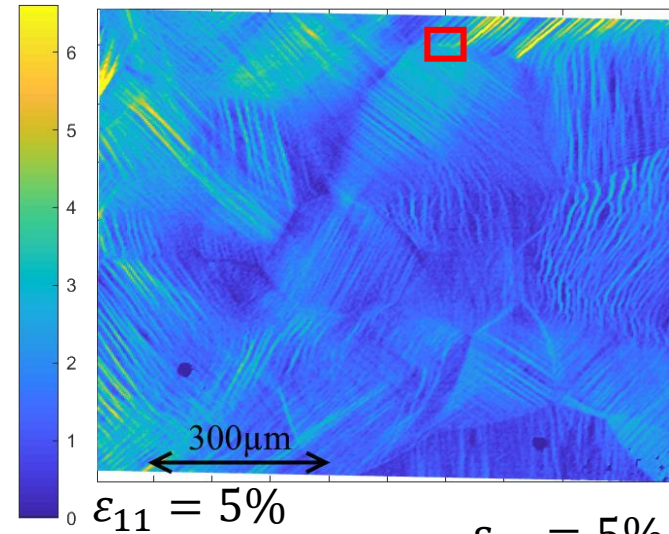
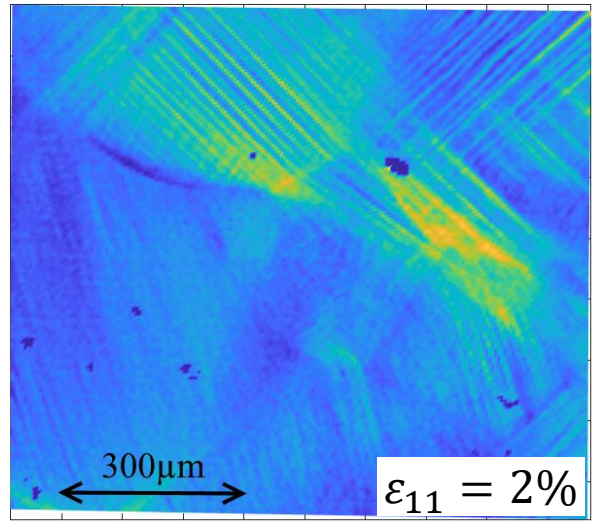
0,6 T_f
300 °C



- Octaedric & non octaedric slip
- Bands intensities increase

Evolution of GBS

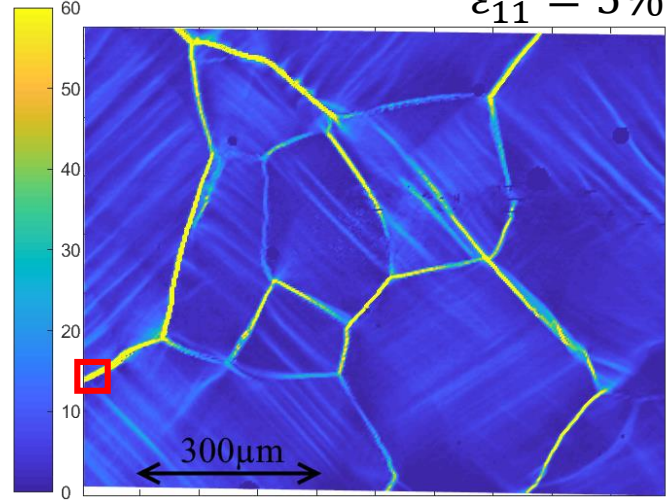
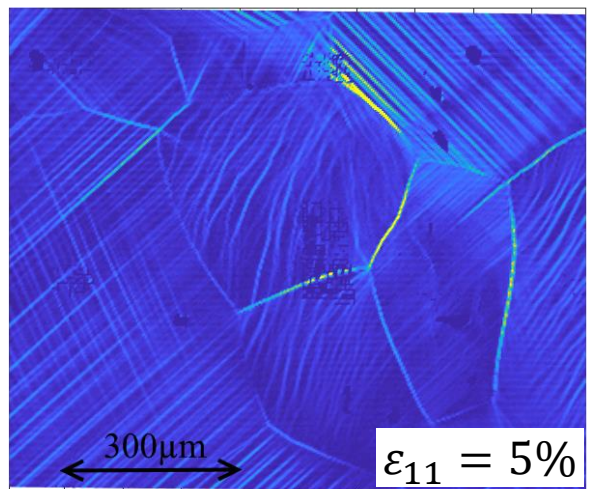
0,3 T_f
25 °C



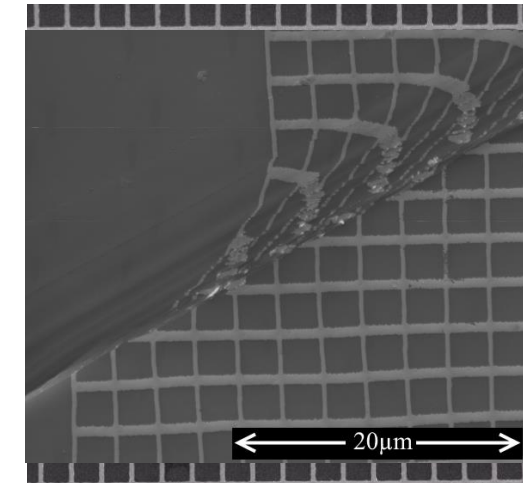
0,4 T_f
110 °C

- Heterogeneities, but no GBS at 0,3 T_f
- GBS at 0,4 T_f
- GBS intensity increases at 0,5 T_f
- GBS out of plane at 0,6 T_f

0,5 T_f
200 °C



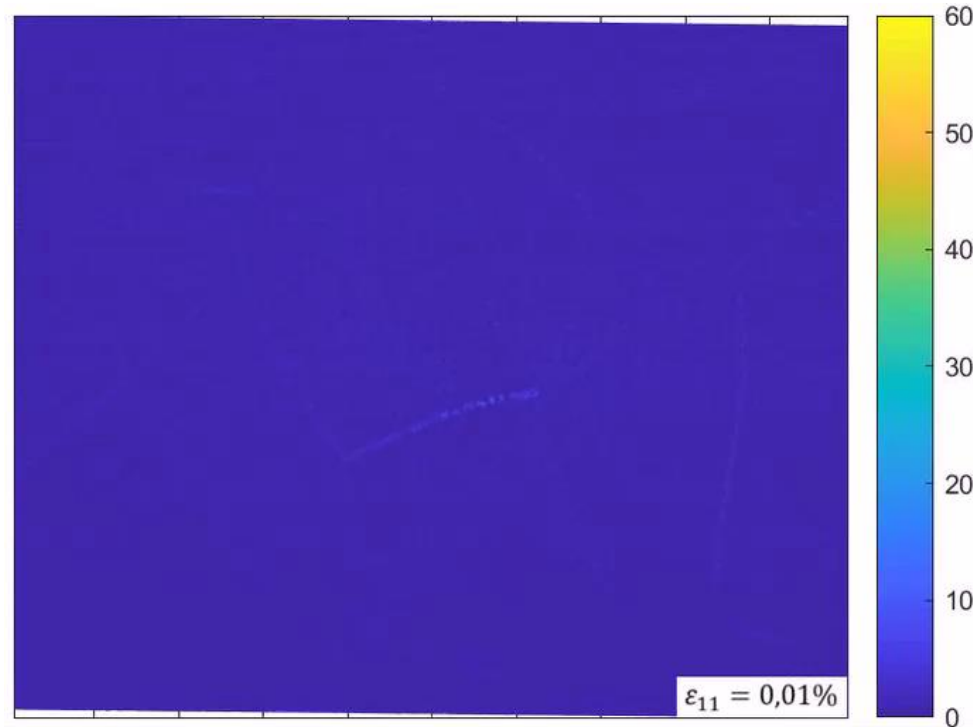
0,6 T_f
300 °C



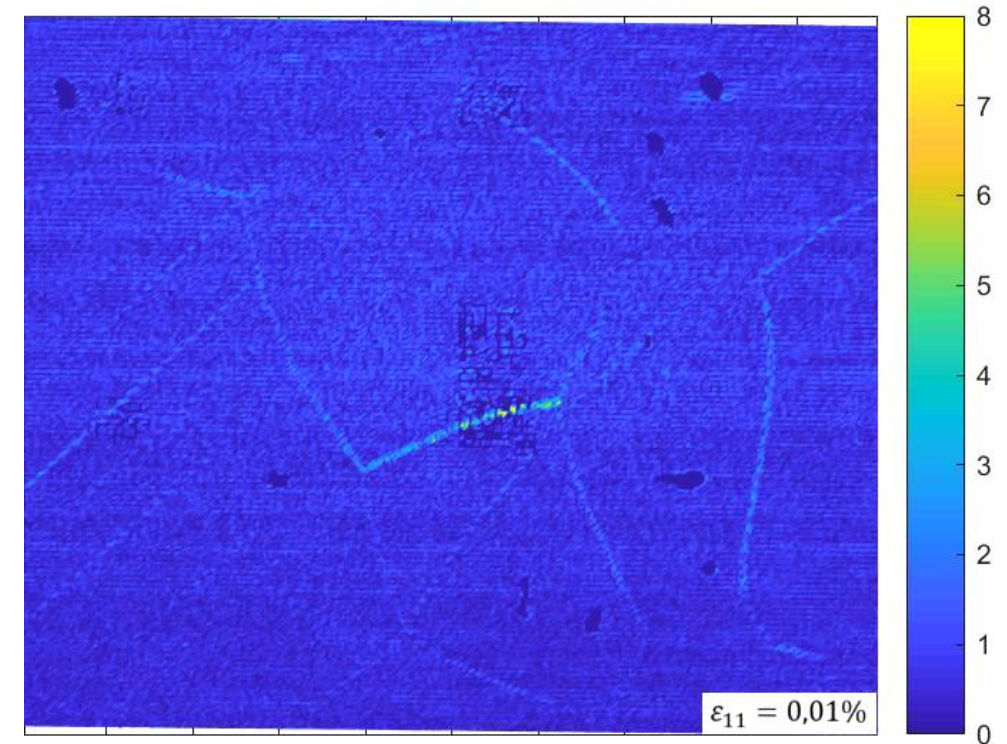
chronology

0,5 T_f

Cumulated



Incremental

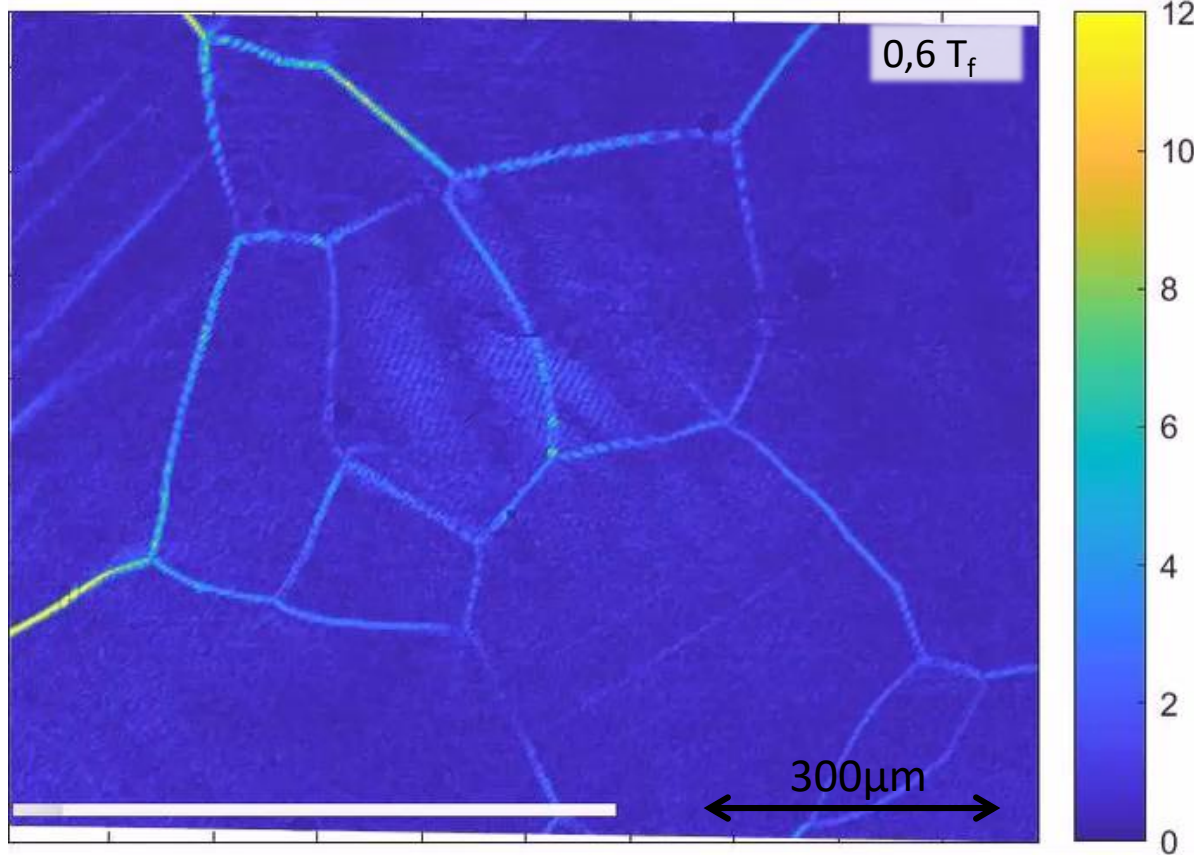


- Simultaneously active CSP & GBS.
- Simultaneously active octaedric & non-octaedric slip.

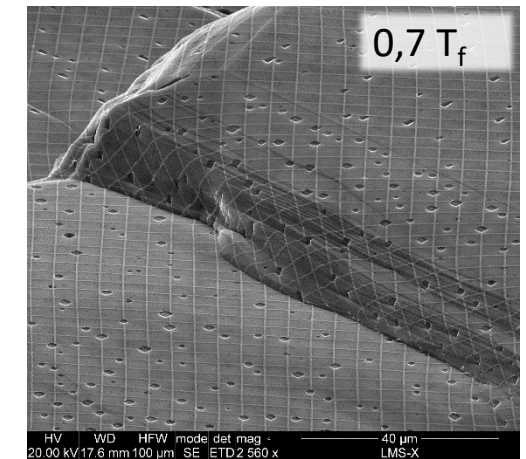
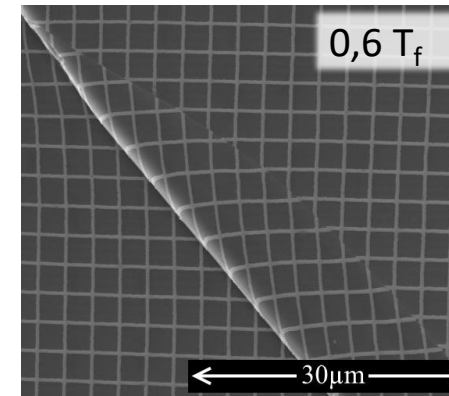
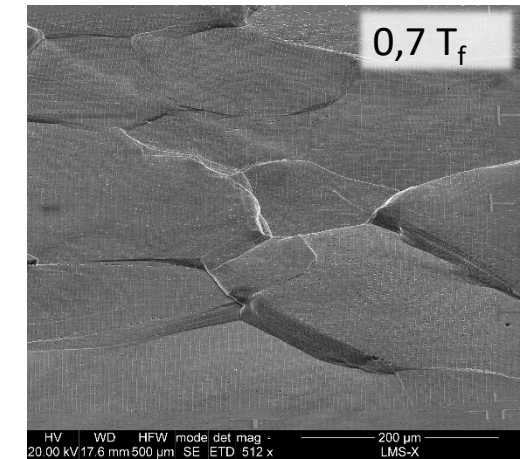
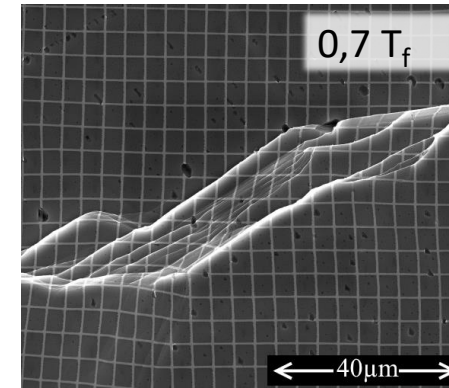
- Évolution of localisation intensities

GBS and GB migration/thrusting

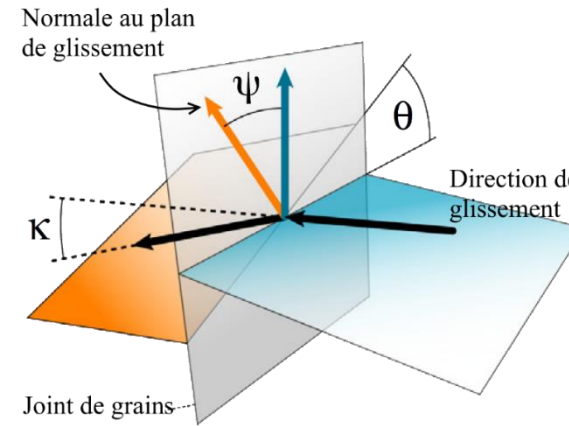
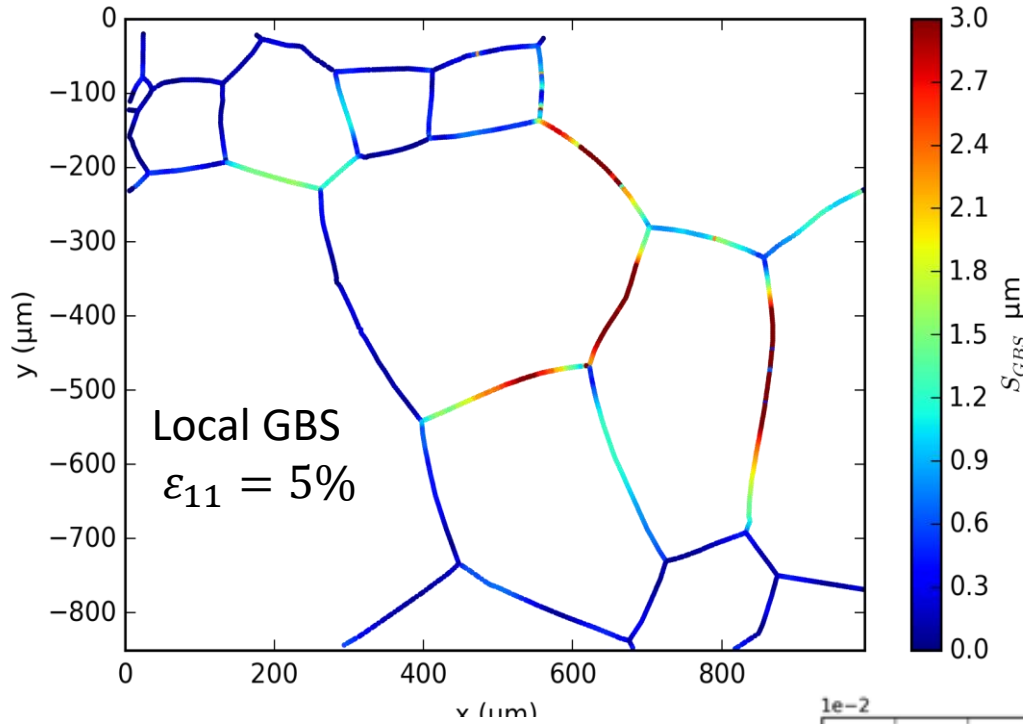
Coupled GBS & GB migration
Incremental



Out of plane sliding & thrusting

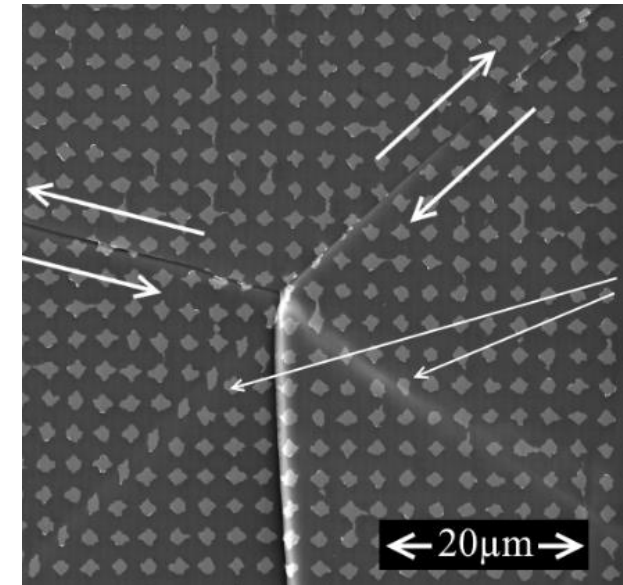
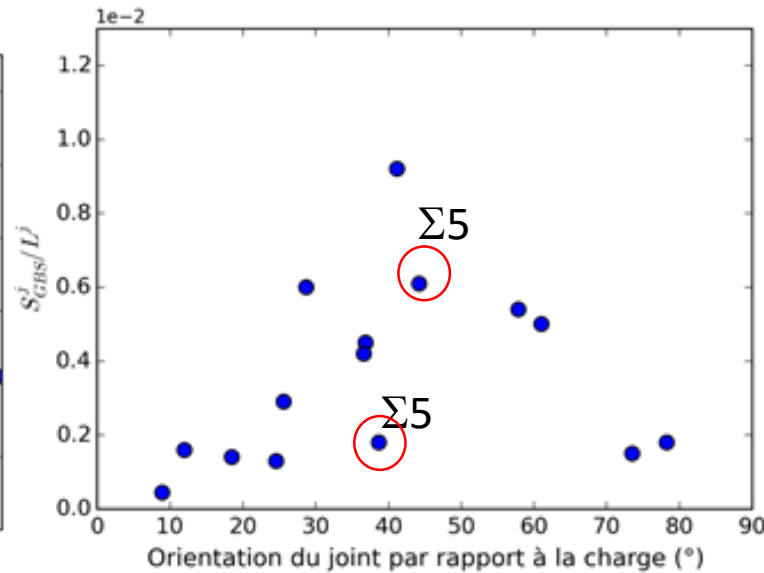
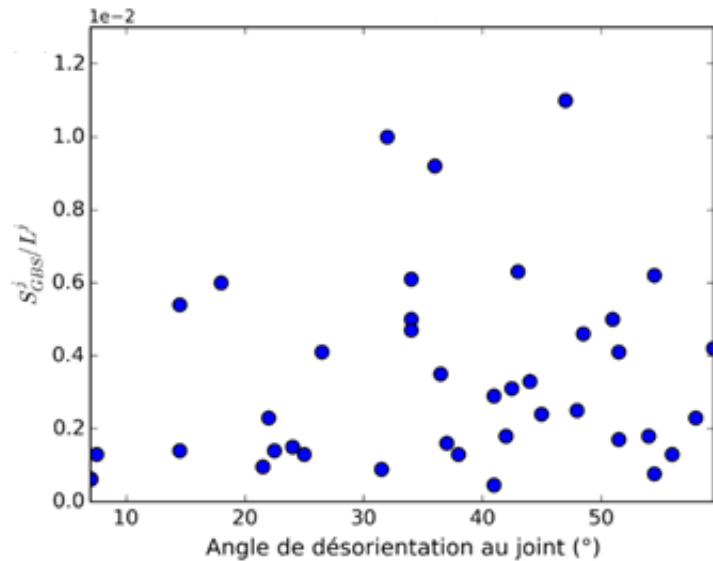
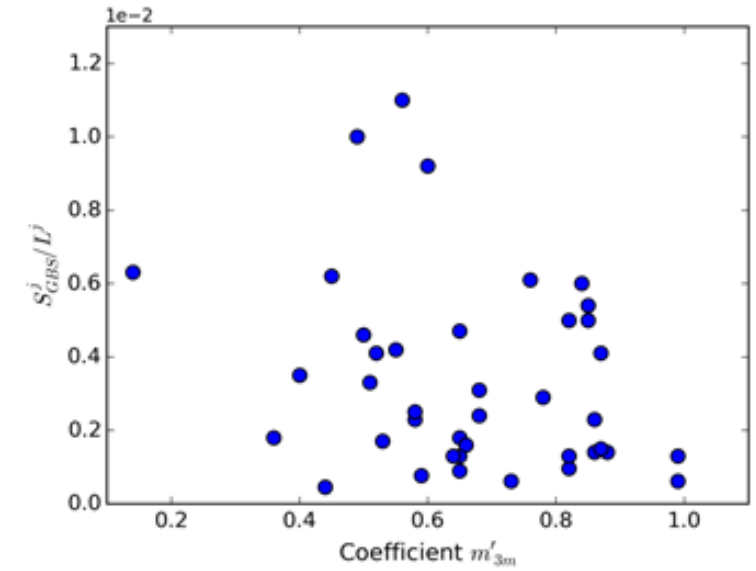


III. Exemples de ductile localization: Aluminium (0.4 Mn), SEM monitoring, microstructure scale



$$m' = \cos(\psi) \cos(\kappa)$$

Bieler et al. (2014)

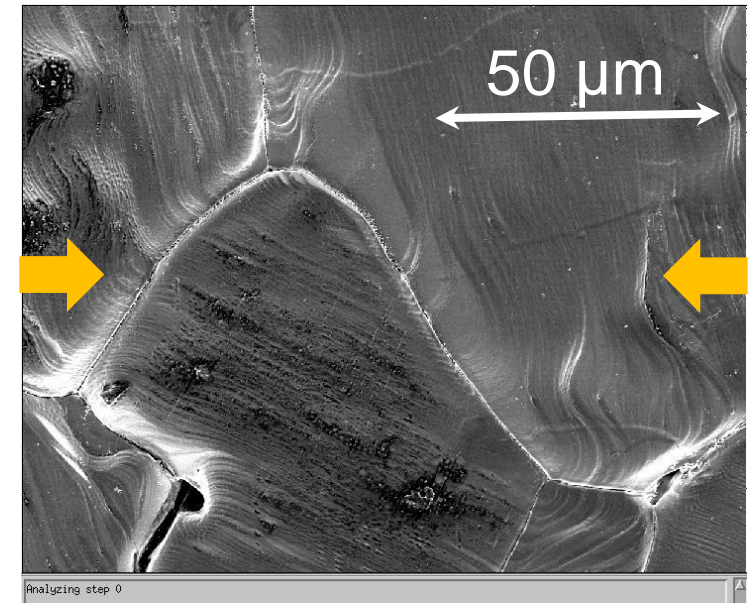


CONCLUSIONS

CSP and GBS cooperation lead to the formation and spreading of deformation bands at the microstructure scale

Dominant CSP needs minor contribution of GBS

Dominant GBS needs minor contribution of CSP



Appropriate criteria for GBS activation are still lacking

Developpements of micro / nano testing of bi-crystals in situ dual beam

