Ductile damage studied by X-ray attenuation and diffraction imaging

S. Dancette[1],
E. Maire[1], C. Le Bourlot[1], W. Ludwig[1 2],
+ collaborators at UCL, Arcelormittal, ESRF beamlines,...

[1]MATEIS Lab, INSA Lyon, Fr

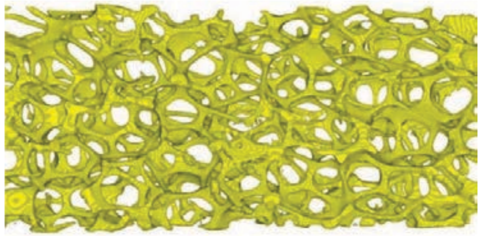
[2]ESRF, Grenoble, Fr

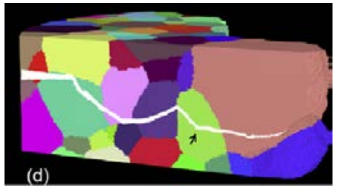
GDR MePhy, Nouveaux défis en mécanique de la rupture
27-28 novembre 2017, Campus Jussieu

Outline

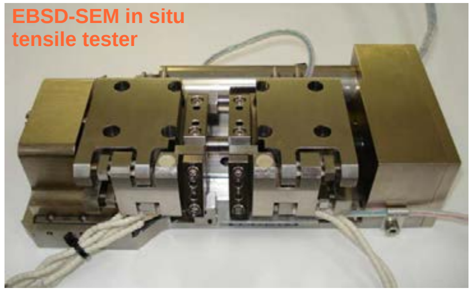
1. Introduction
   - Background on ductile damage
2. Attenuation and phase imaging
   - Experimental setups
   - "Routine" experiments
   - High resolution
   - Cavity tracking
3. Diffraction imaging
   - Diffraction constrast tomography (DCT)
   - DCT based CPFEM
4. Conclusion - Outlook

Context





Herbig et al., Acta Mat. 2011



Damage investigation at MATEIS-METAL

- Structure, microstructure $\Longrightarrow$ damage development.
- 2D and 3D in-situ, non destructive, experiments (tension, compression, torsion, indentation, fatigue, ...)

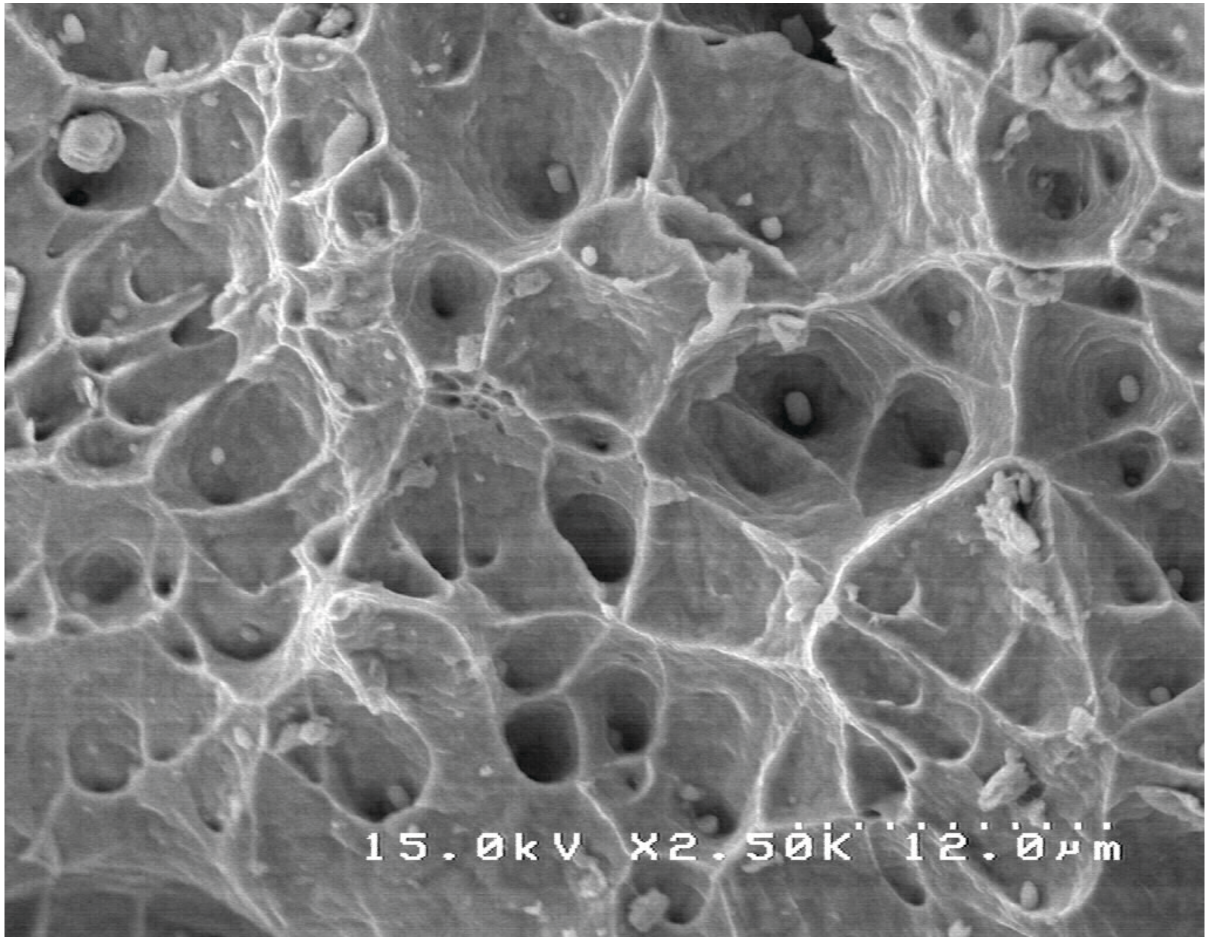
Outline

1. Introduction
   - Background on ductile damage
2. Attenuation and phase imaging
   - Experimental setups
   - "Routine" experiments
   - High resolution
   - Cavity tracking
3. Diffraction imaging
   - Diffraction constrast tomography (DCT)
   - DCT based CPFEM
4. Conclusion - Outlook

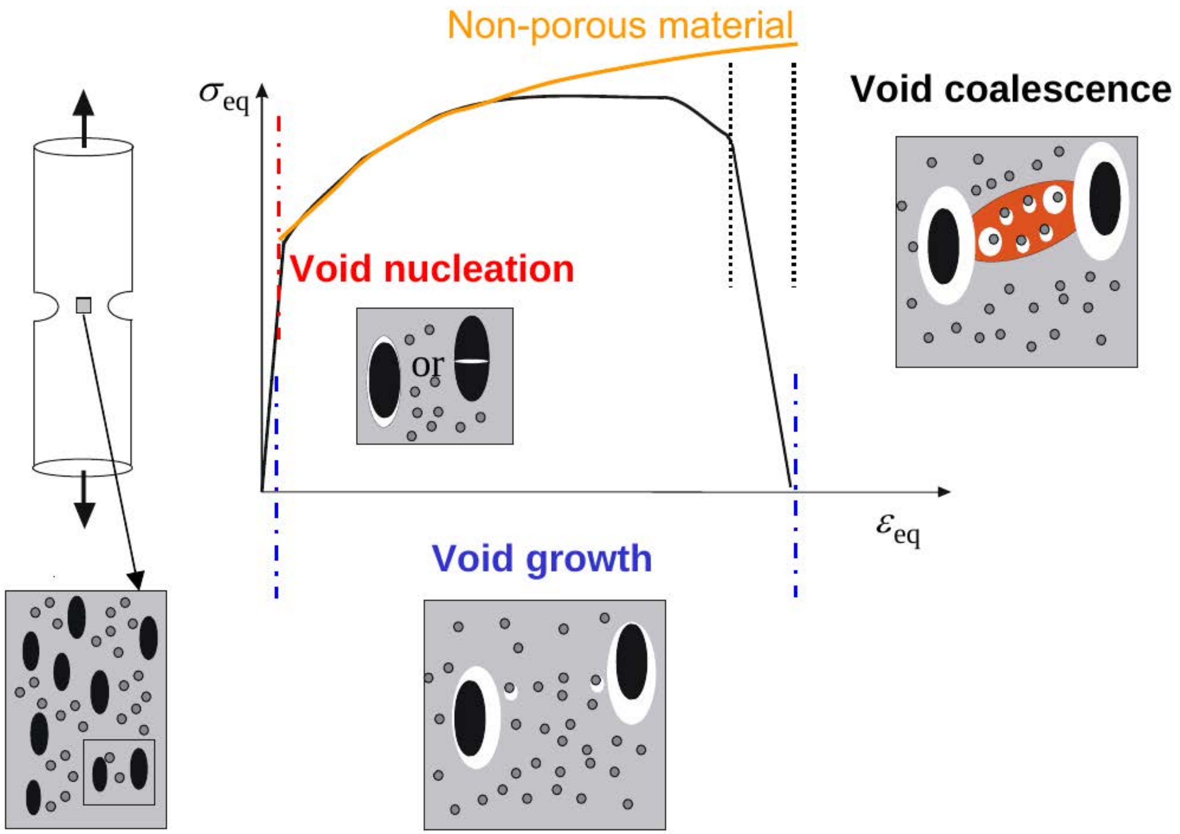
INSA INSTITUT NATIONAL DES SCIENCES APPLIQUÉES LYON Mateis cnrs

Ductile fracture: macrosopic

Ductile fracture: microscopic



Ductile damage



Courtesy of Prof. T. Pardoen, UCL

- nucleation, growth and coalescence of cavities
- lots of models (especially for growth)...,
- little experimental comparison (before ∼ 2000).

A long history of science

Ductile fracture occurs in the bulk of opaque samples... Observation ?

- post-mortem fractography,
- post-mortem sectioning,
- in-situ observation in a SEM,
- ... none really quantitative.

- Need for quantification of nucleation, growth and coalescence.
- $\sim$ Years 2000: in-situ tensile tests under synchrotron tomography, right scale of 1 micron.

Motivations / Open questions

Better observing and quantifying ductile damage

- Do it in the bulk, non destructively,
- for the 3 stages of ductile damage: nucleation, growth and coalescence.

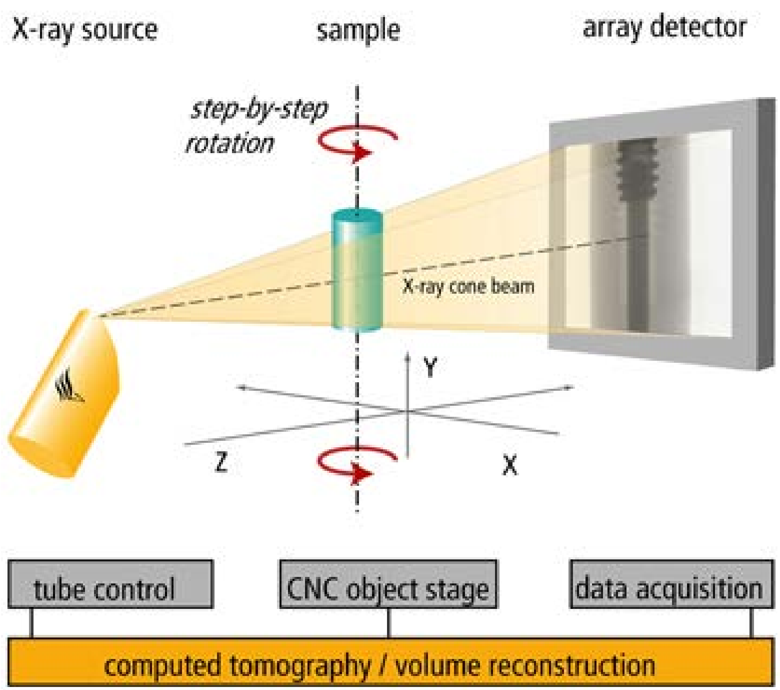
Effect of local microstructure

- Behavior of individual cavities during deformation ? How heterogeneous ?
- Relate the individual behavior to
  - local microstructure configuration ?
  - local crystallographic orientation of grains ?

Outline

1. Introduction
   - Background on ductile damage
2. Attenuation and phase imaging
   - Experimental setups
   - "Routine" experiments
   - High resolution
   - Cavity tracking
3. Diffraction imaging
   - Diffraction constrast tomography (DCT)
   - DCT based CPFEM
4. Conclusion - Outlook

X-ray computed tomography



(from Phoenix X ray)

Figure: Lab tomography.

- Lab or synchrotron X-rays.
- Diverging or parallel beam.
- Scan time: 0.05s to hours.
- Resolution: 25nm to centimeters.
- Absorption or phase contrast.
- Non destructive: in-situ/in-operando testing.

Synchrotron tomographs: high resolution / high speed

APS
BNL
Berkeley

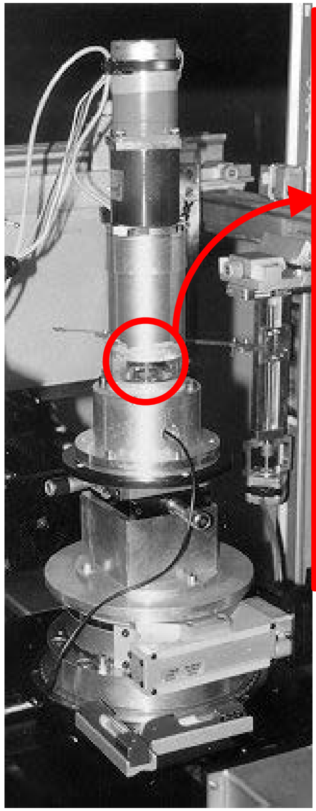
ID 19
-Home Page-

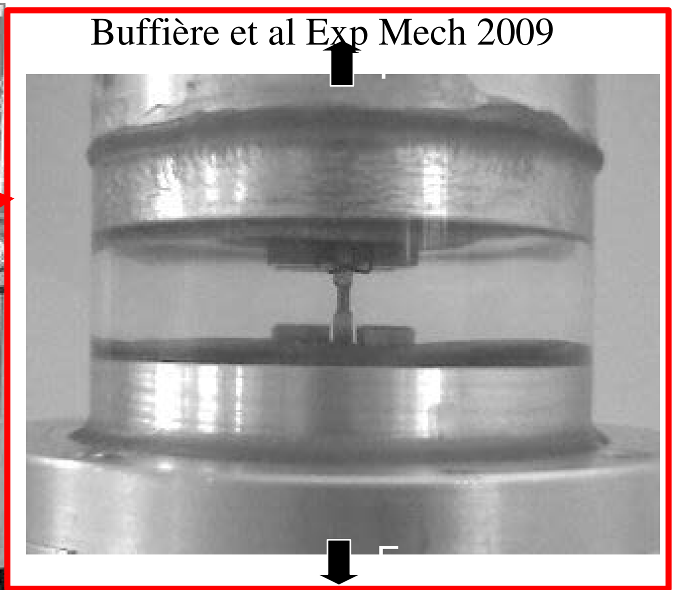
ID15 fast acquisition
ID22 Very high resolution

In situ tensile rig

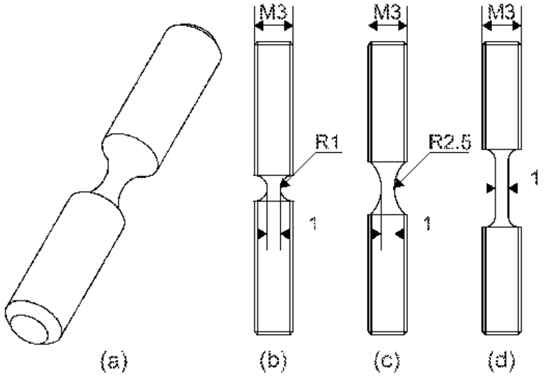
Tension, compression

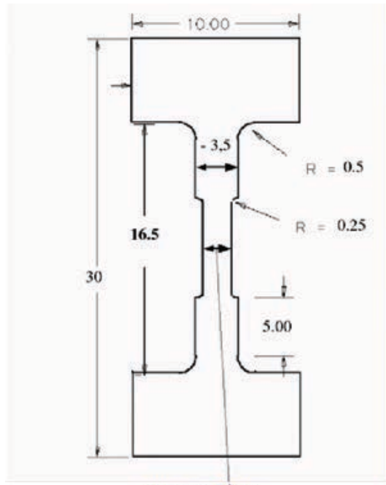
Buffière et al. Acta Mater 1998
Buffière et al Exp Mech 2009





- Stepping motor
- Reductor
- F and U recorded
- 10^{-5} – 1 mm/s
- Force sensors : 50 – 5000 N
- Grips adapted for different geometries





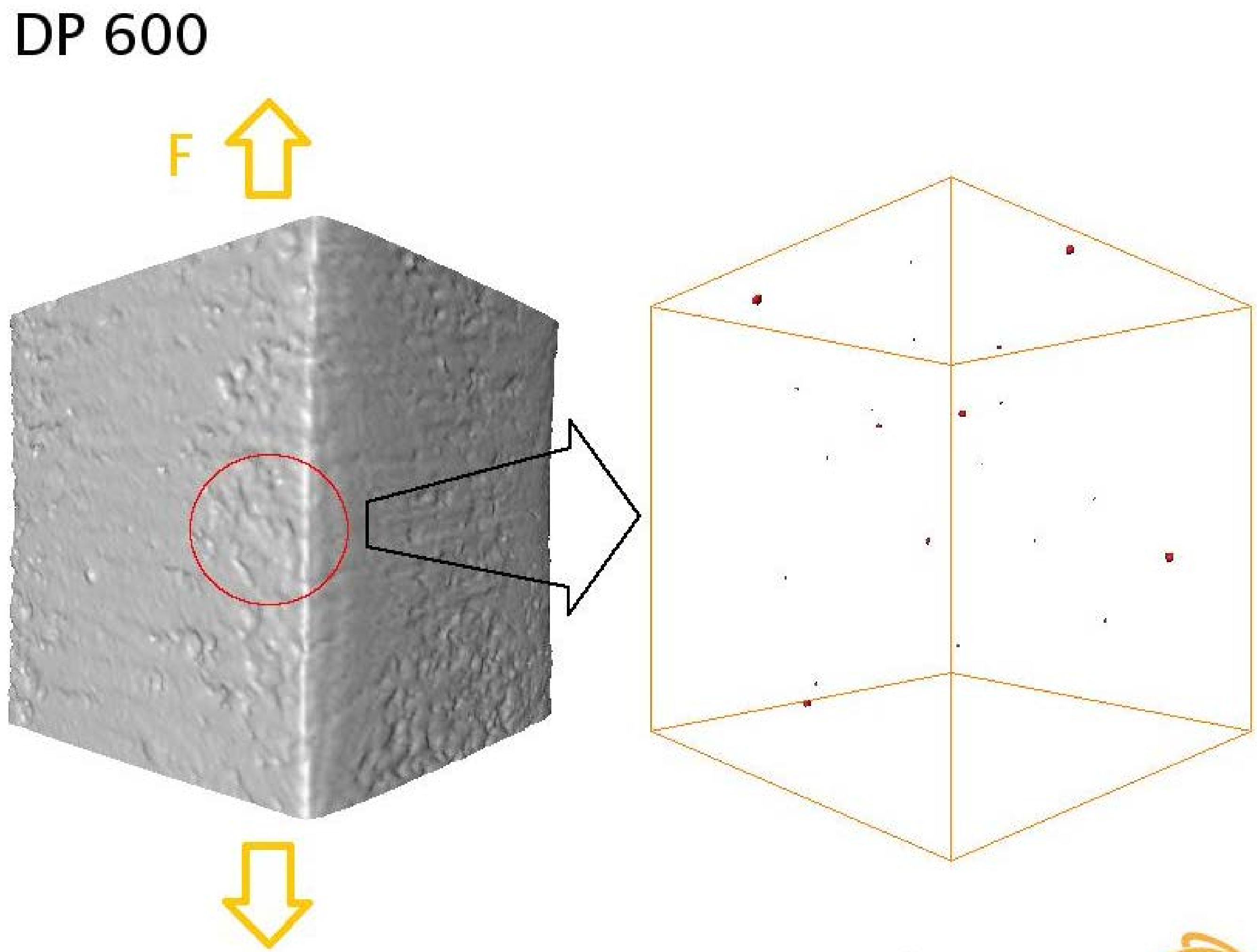
Width = 1,5 mm
thickness of the all sample : 1,5 mm

Outline

1. Introduction
   - Background on ductile damage
2. Attenuation and phase imaging
   - Experimental setups
   - "Routine" experiments
   - High resolution
   - Cavity tracking
3. Diffraction imaging
   - Diffraction constrast tomography (DCT)
   - DCT based CPFEM
4. Conclusion - Outlook

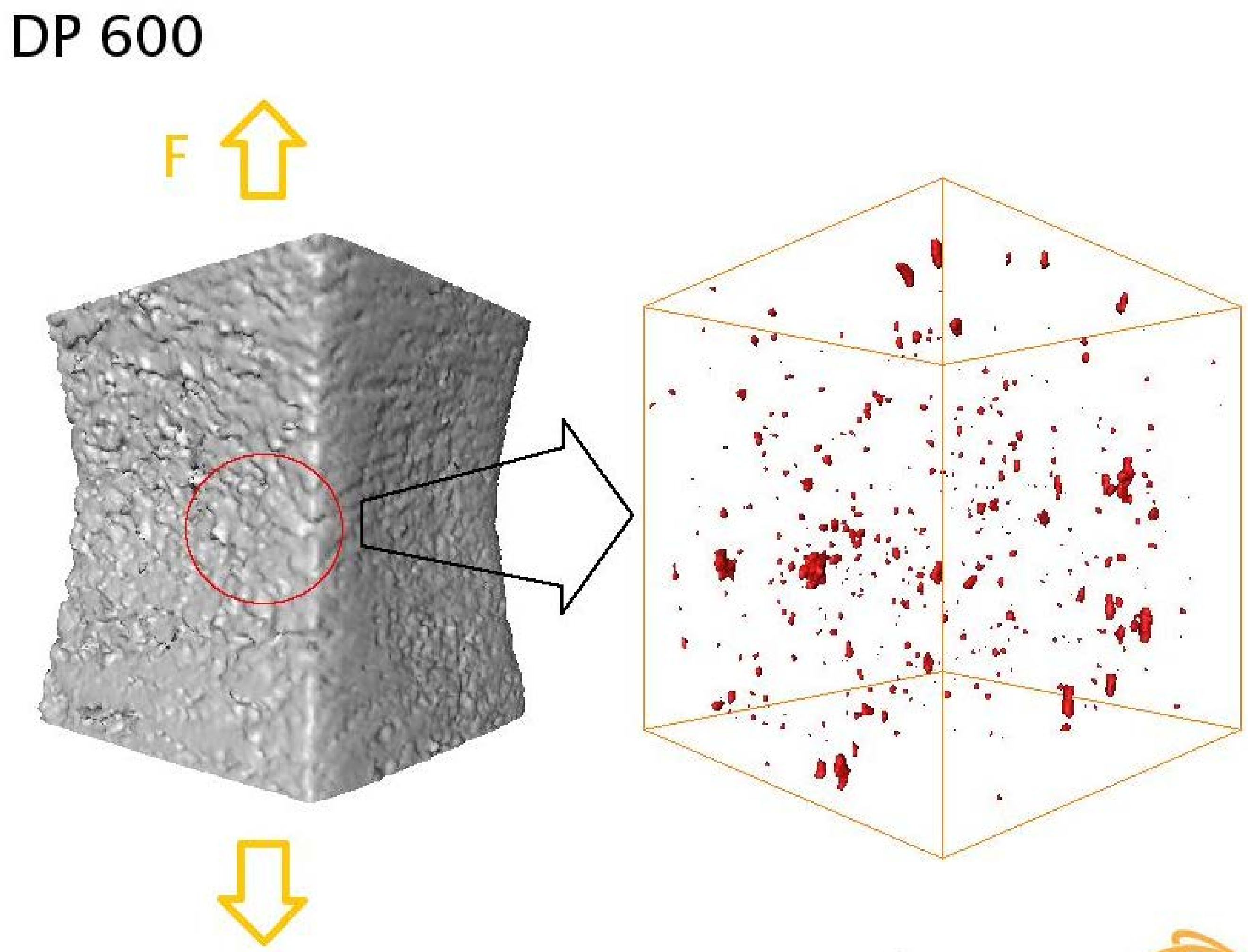
Typical result

1 mm sample diameter, $\sim$ 1 micron voxel size, 300 microns central box for analysis



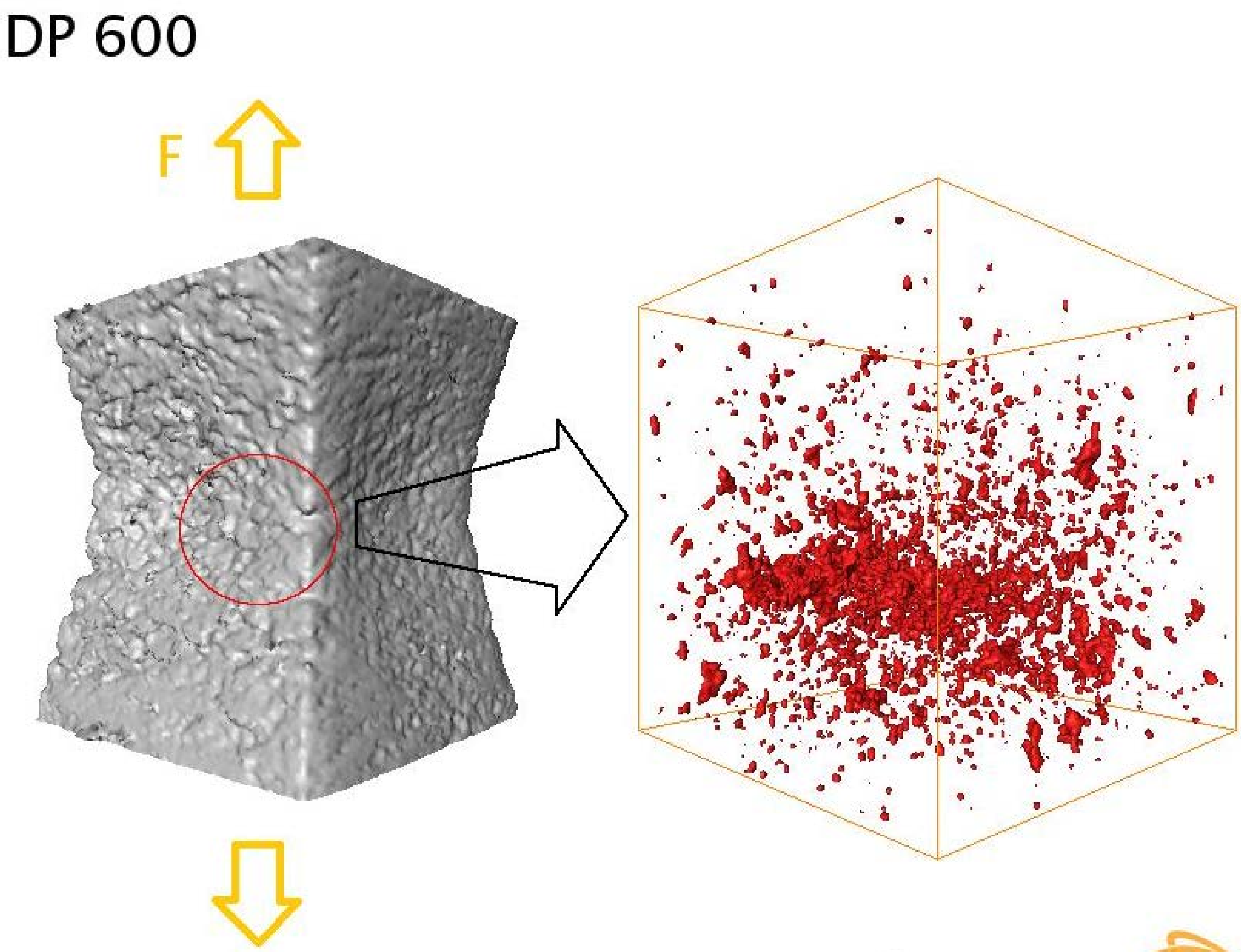
Typical result

1 mm sample diameter, $\sim$ 1 micron voxel size, 300 microns central box for analysis



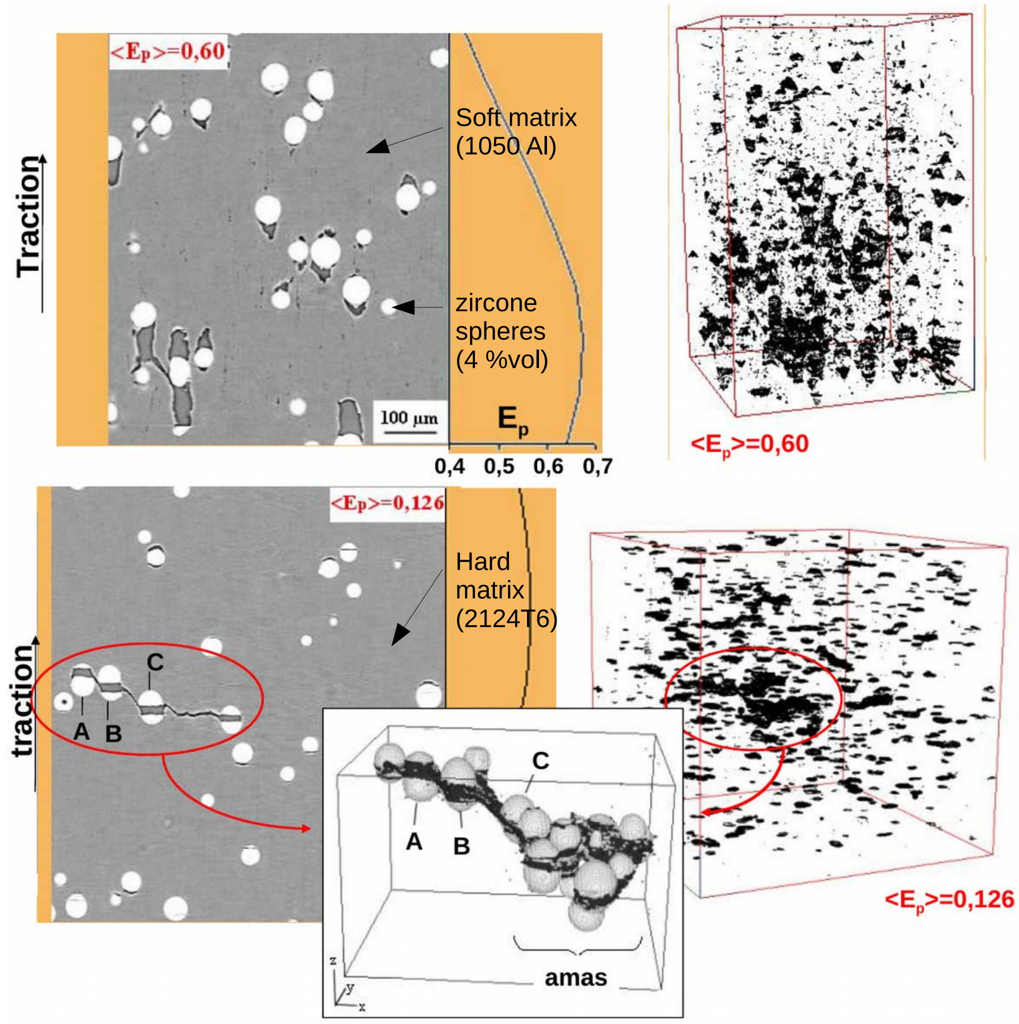
Typical result

1 mm sample diameter, ∼ 1 micron voxel size, 300 microns central box for analysis



3D imaging: *qualitative* observations

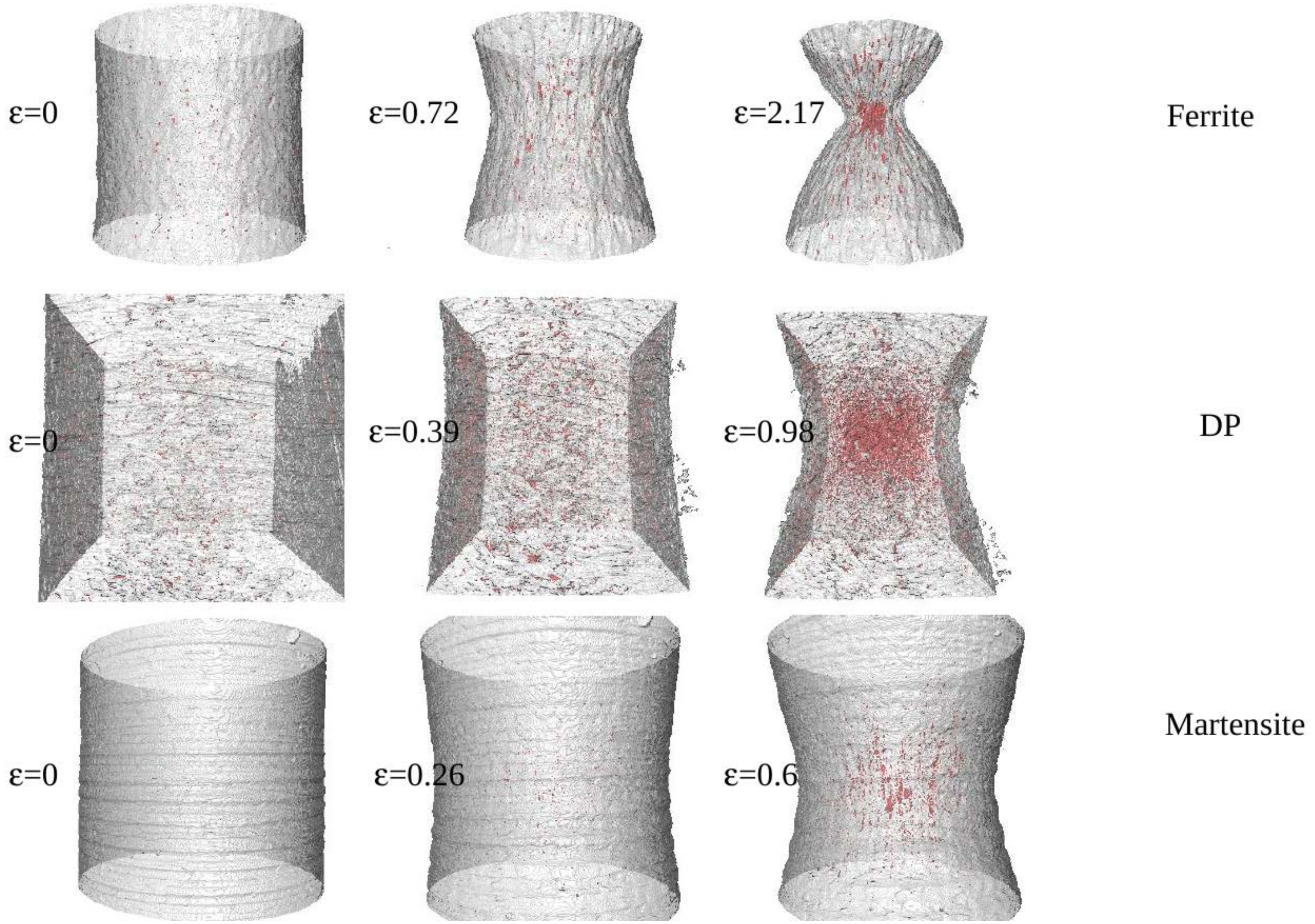
Model materials



[Babout et al., Acta Mat. 52 (2004) 2475–2487]

3D imaging: *qualitative* observations

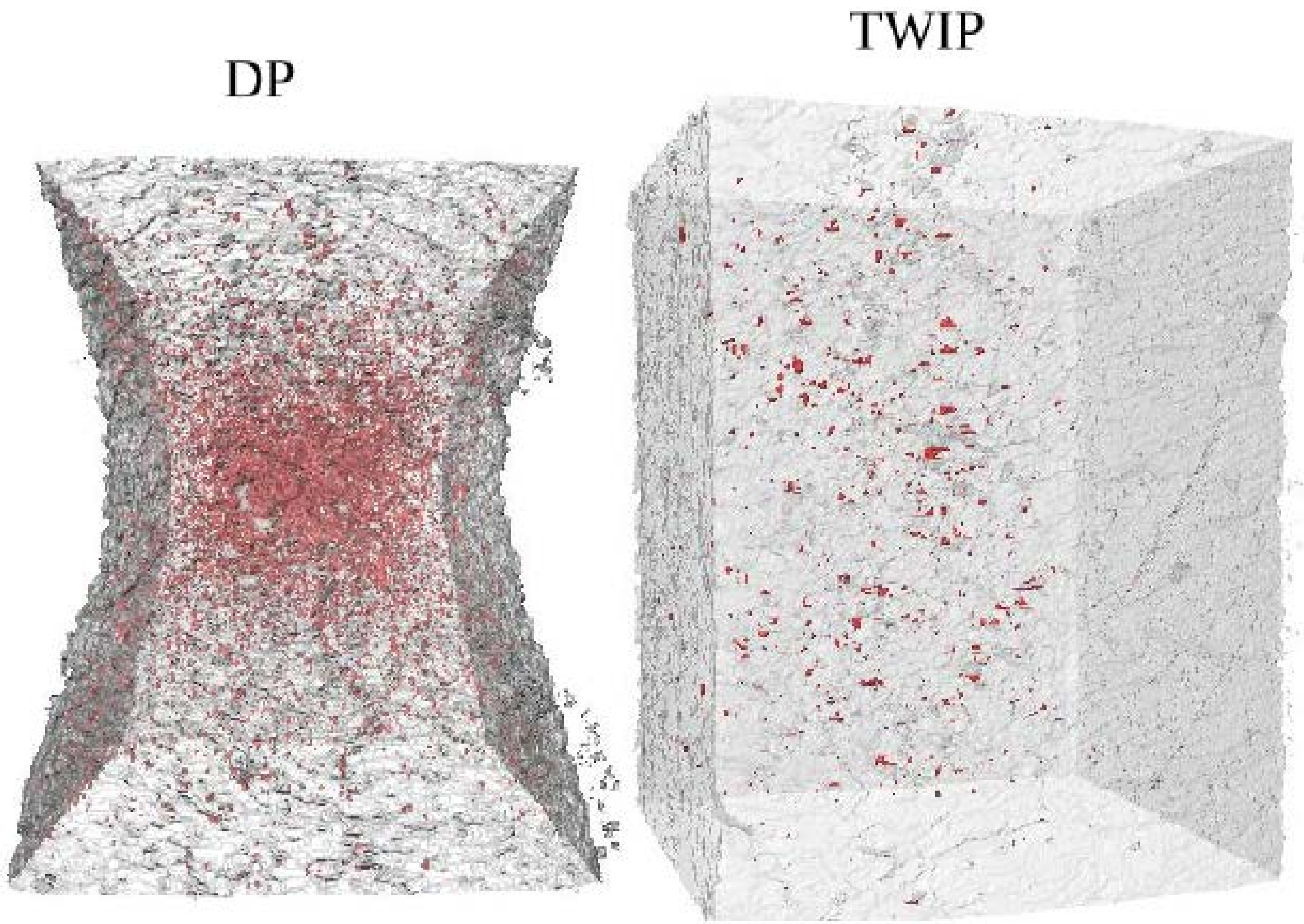
Ferritic steels - different hardening behaviors



[C. Landron PhD, INSA Lyon 2011]

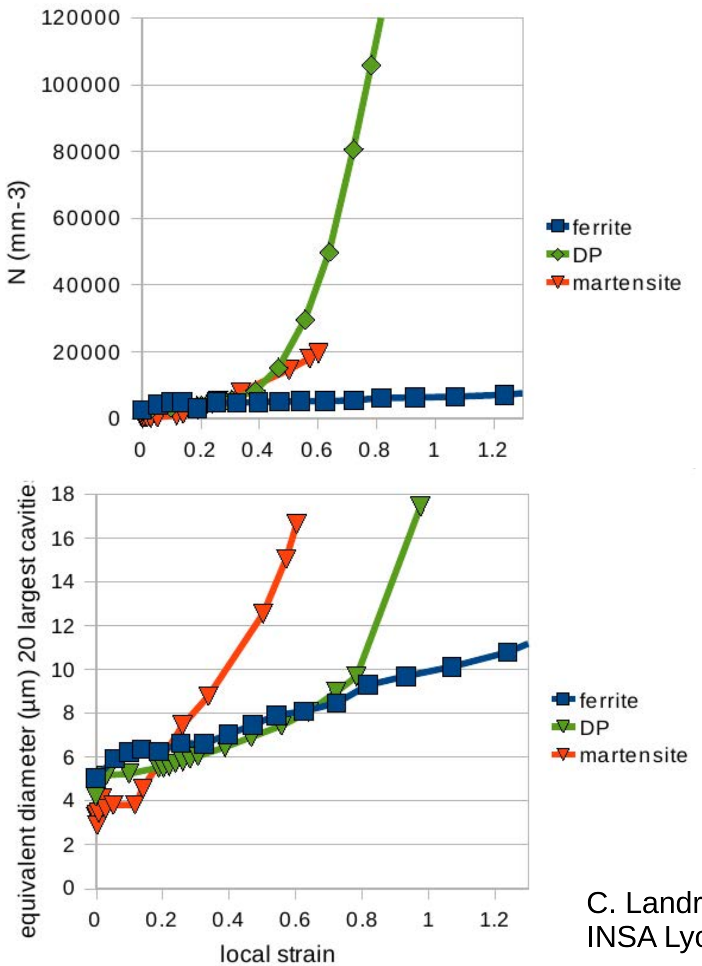
3D imaging: *qualitative* observations

Different steel designs



[C. Landron PhD, INSA Lyon 2011]

3D imaging: *quantitative* measurements

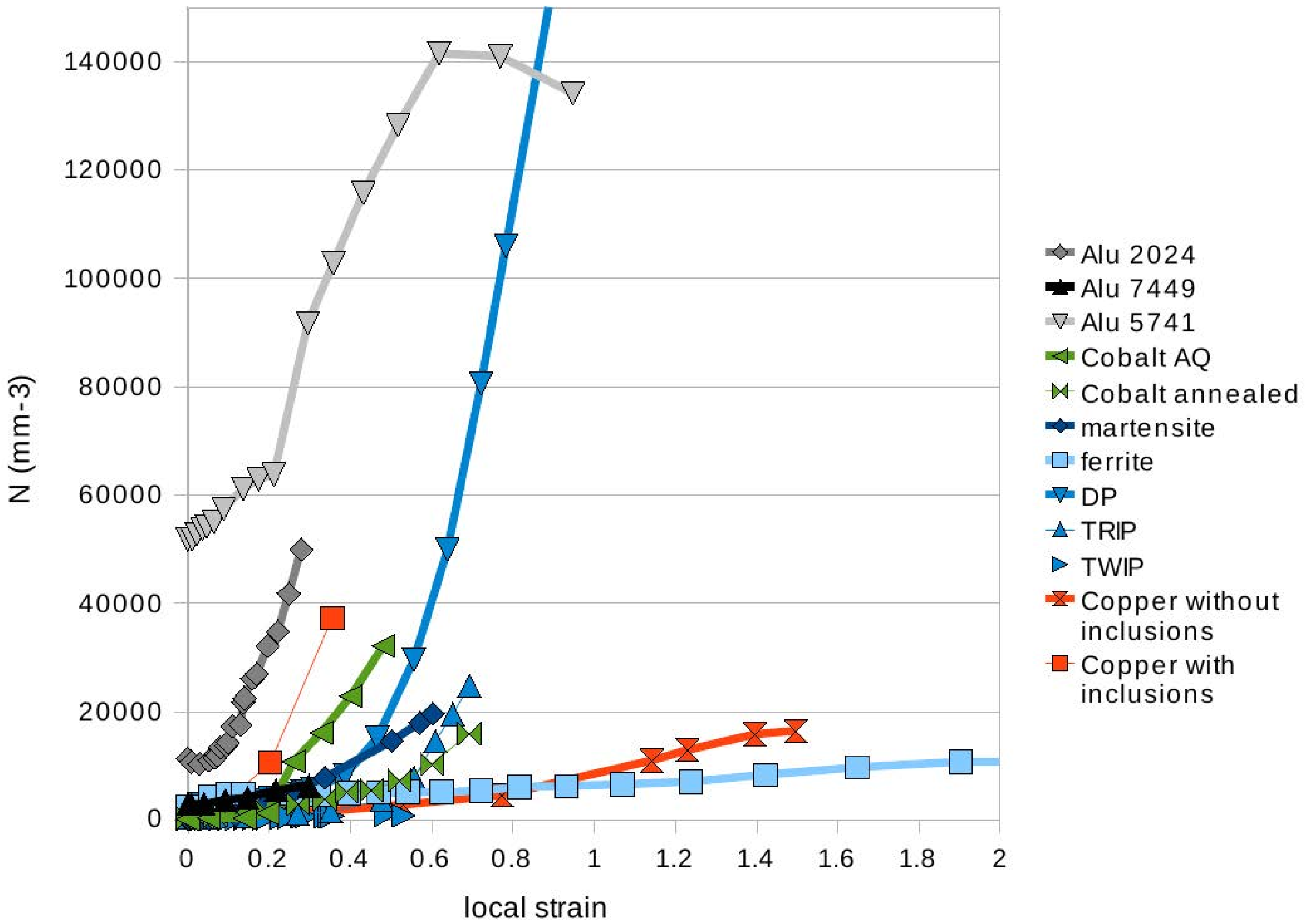


C. Landron PhD,
INSA Lyon, 2011

- nucleation:
  e.g. nbr of cavities/mm^3
- growth:
  e.g. equivalent diameter of biggest cavities.
- coalescence:
  e.g. cavity spacing.
- $\Longrightarrow$ comparison to models!

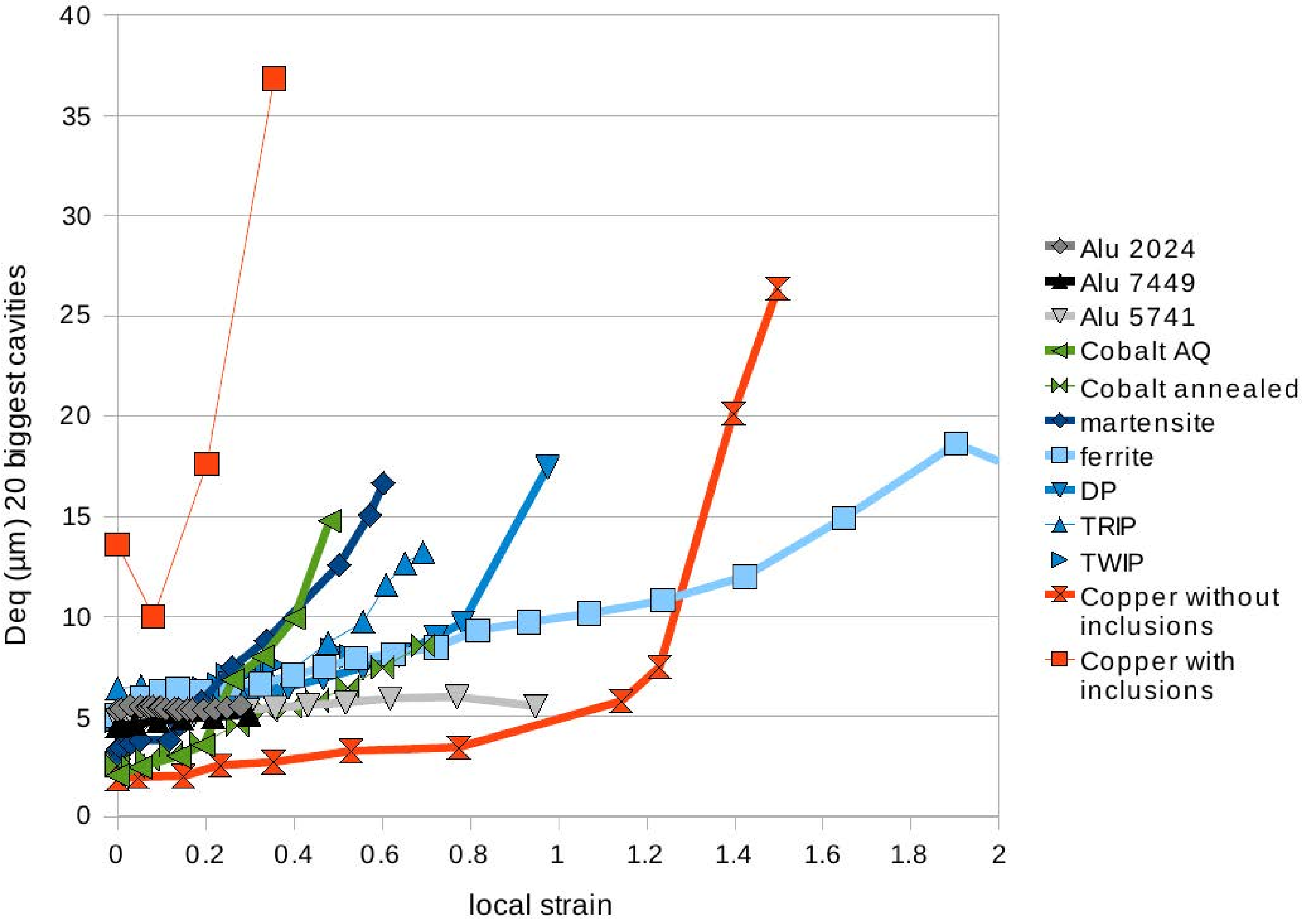
3D imaging: *quantitative* measurements

nucleation



3D imaging: *quantitative* measurements

growth

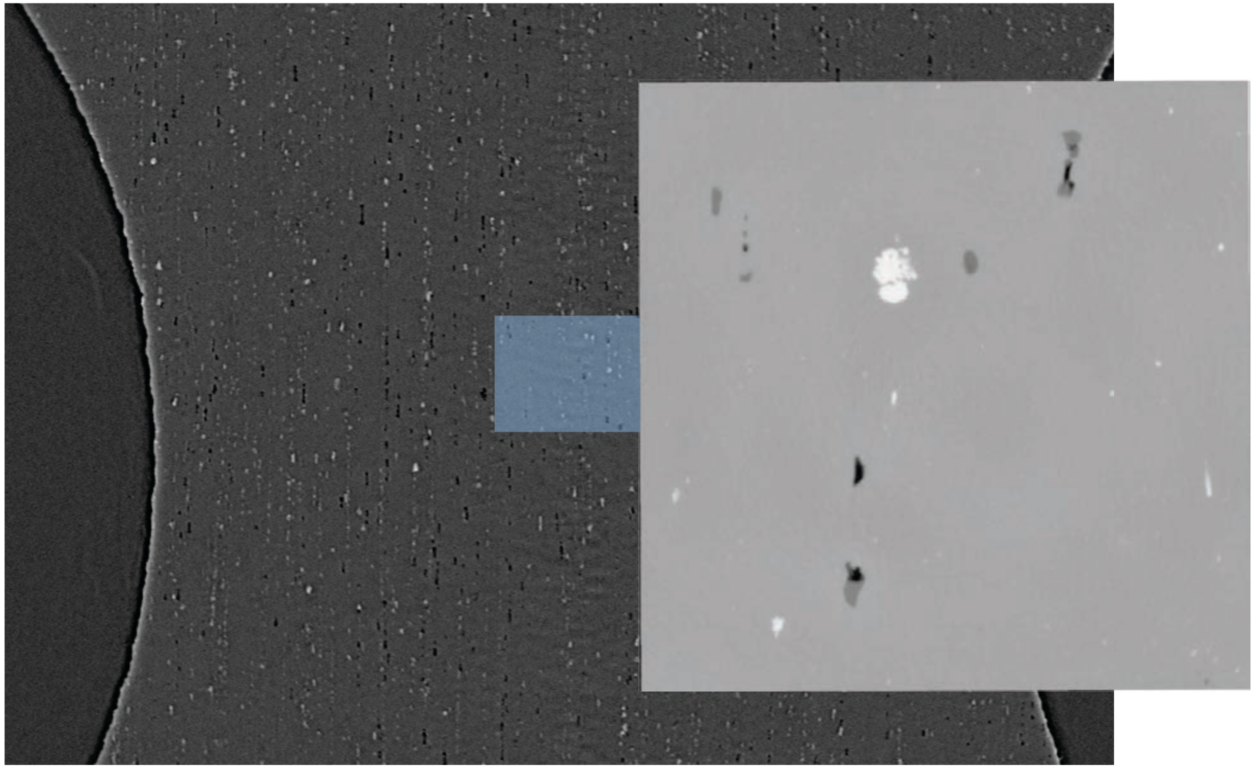


Outline

1. Introduction
   - Background on ductile damage
2. Attenuation and phase imaging
   - Experimental setups
   - "Routine" experiments
   - High resolution
   - Cavity tracking
3. Diffraction imaging
   - Diffraction constrast tomography (DCT)
   - DCT based CPFEM
4. Conclusion - Outlook

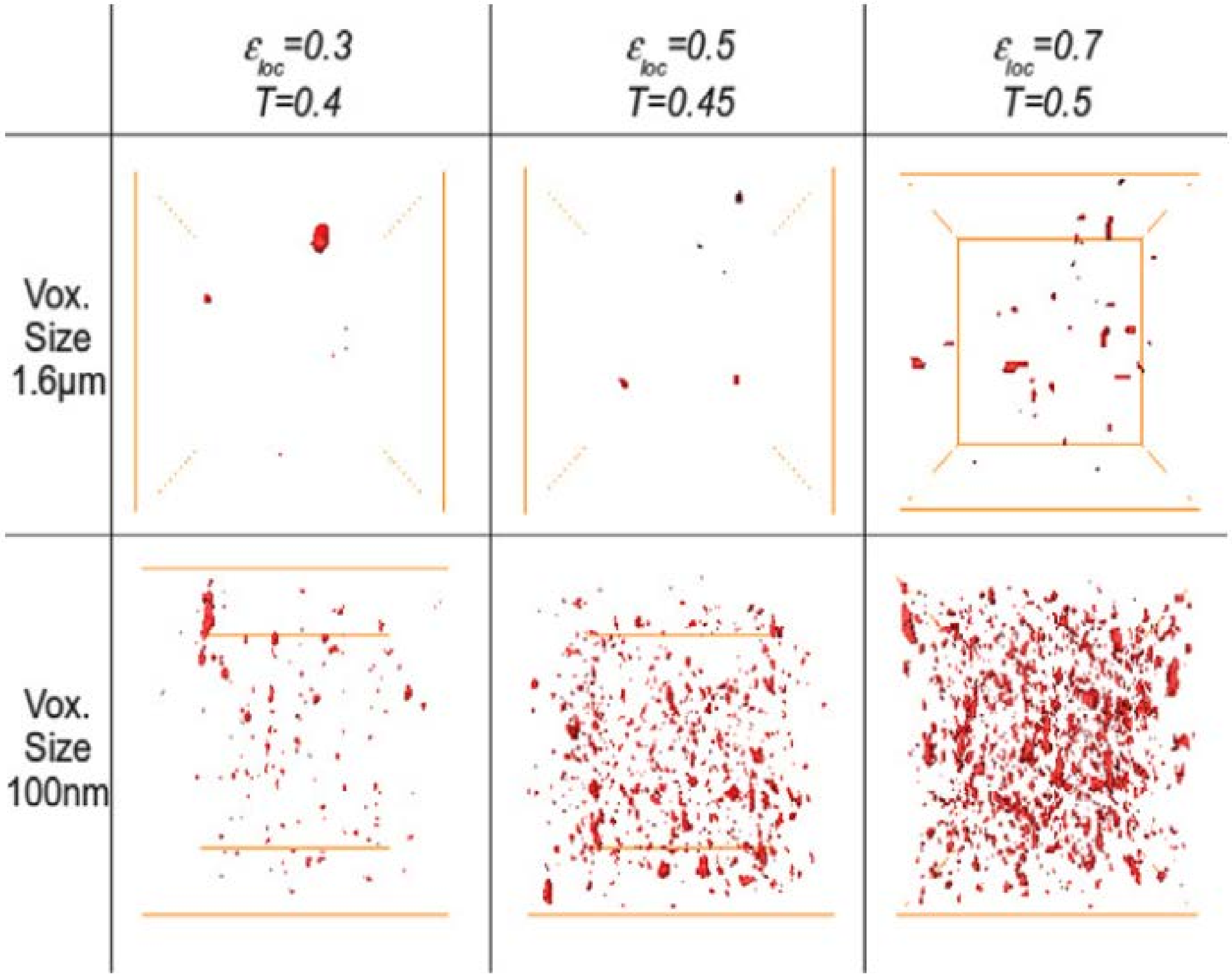
High resolution

Down to 25 nm voxel size at ID16-B beamline, ESRF

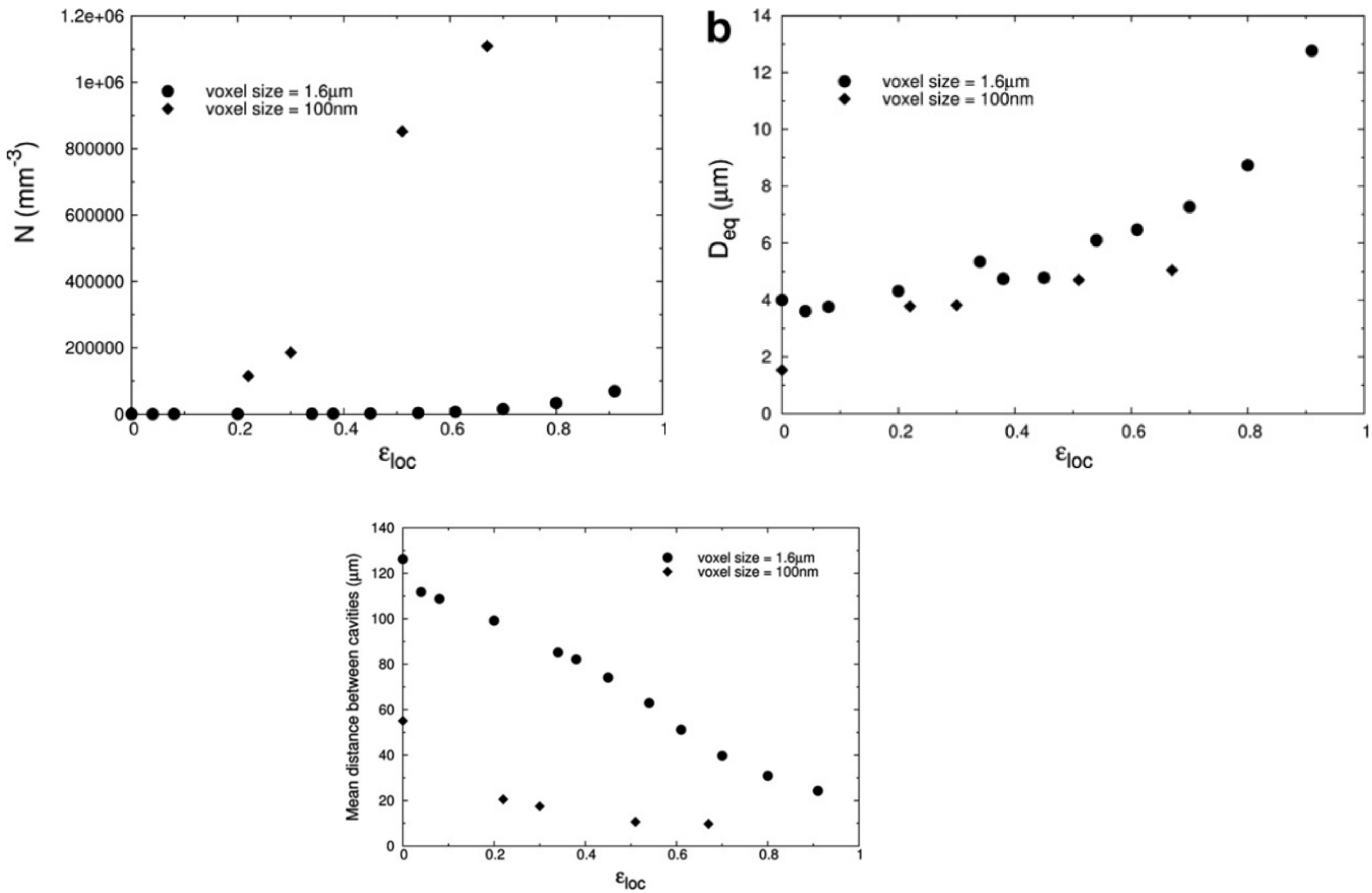


- Local tomography: $\sim$ 50 or 100 μm wide region in the sample.
- Exploiting phase shift of incident X-ray beam on microstructure.

Comparing standard and high resolution



Quantification with high resolution



Motivations / Open questions

Better observing and quantifying ductile damage

- Do it in the bulk, non destructively,
- for the 3 stages of ductile damage: nucleation, growth and coalescence.
  $\Longrightarrow$ attenuation and phase contrast tomography

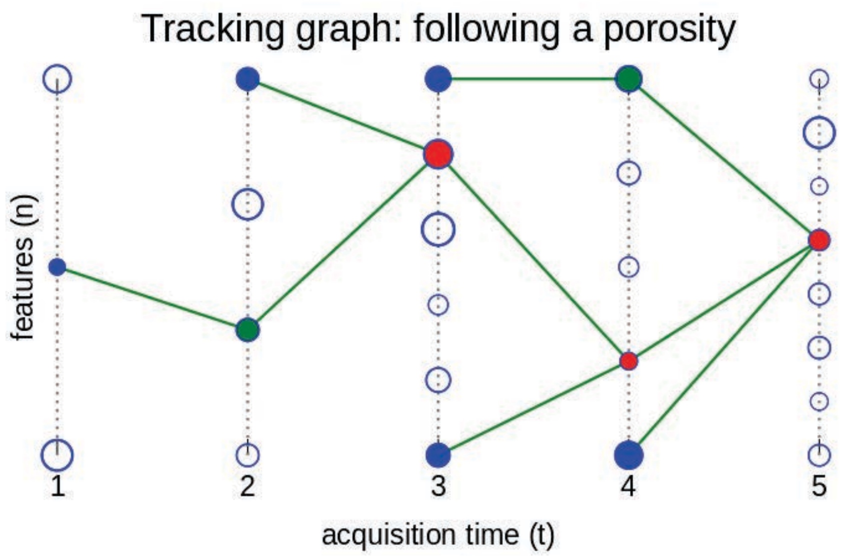
Effect of local microstructure

- Behavior of individual cavities during deformation ? How heterogeneous ?
  $\Longrightarrow$ automatic cavity tracking
- Relate the individual behavior to
  - local microstructure configuration ?
  - local crystallographic orientation of grains ?

Outline

1. Introduction
   - Background on ductile damage
2. Attenuation and phase imaging
   - Experimental setups
   - "Routine" experiments
   - High resolution
   - Cavity tracking
3. Diffraction imaging
   - Diffraction constrast tomography (DCT)
   - DCT based CPFEM
4. Conclusion - Outlook

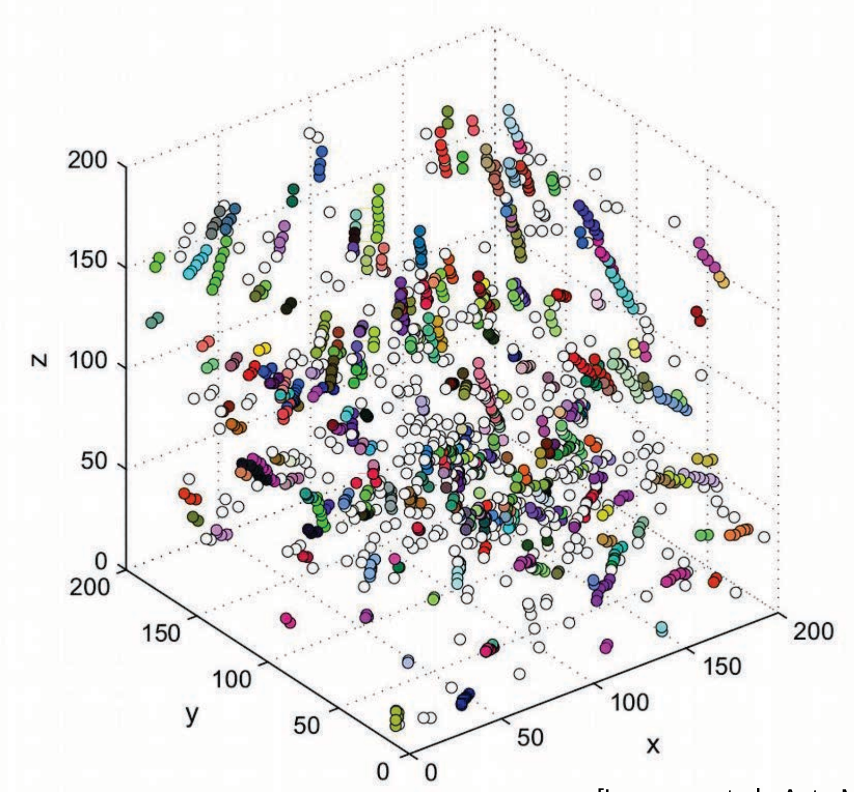
Cavity tracking

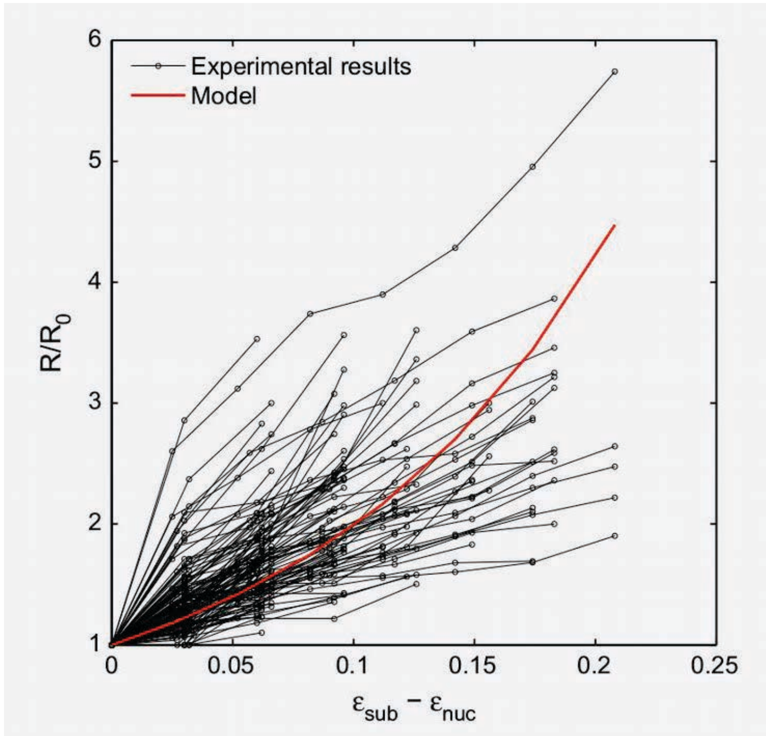


tracking anim

- Graph-based algorithm to track cavities/particles in successive in-situ volumes.
- [Lecarme et al., Acta Mat. 2014], [Hannard et al., Acta Mat. 2016]

Cavity tracking





[Lecarme et al., Acta Mat. 2014]

- Highly heterogeneous growth.
- Strong influence of local microstructure.
- Not predicted by standard damage models...

Motivations / Open questions

Better observing and quantifying ductile damage

- Do it in the bulk, non destructively,
- for the 3 stages of ductile damage:
  nucleation, growth and coalescence.
  $\Longrightarrow$ attenuation and phase contrast tomography

Effect of local microstructure

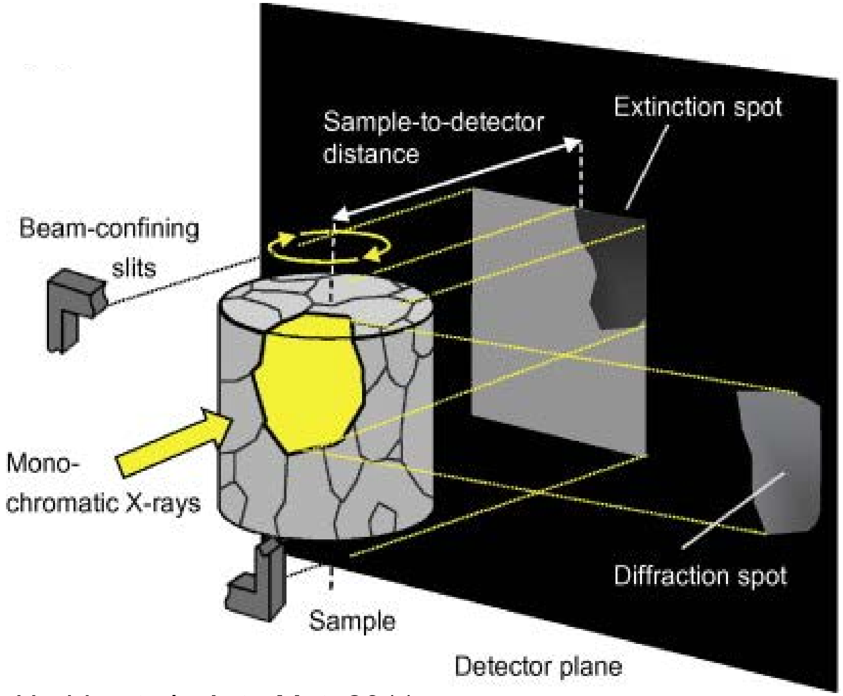
- Behavior of individual cavities during deformation ?
  How heterogeneous ?
  $\Longrightarrow$ automatic cavity tracking
- Relate the individual behavior to
  - local microstructure configuration ?
  - local crystallographic orientation of grains ?

  $\Longrightarrow$ Diffraction Contrast Tomography (DCT)

Outline

1. Introduction
   - Background on ductile damage
2. Attenuation and phase imaging
   - Experimental setups
   - "Routine" experiments
   - High resolution
   - Cavity tracking
3. Diffraction imaging
   - Diffraction constrast tomography (DCT)
   - DCT based CPFEM
4. Conclusion - Outlook

Diffraction Contrast Tomography (DCT)

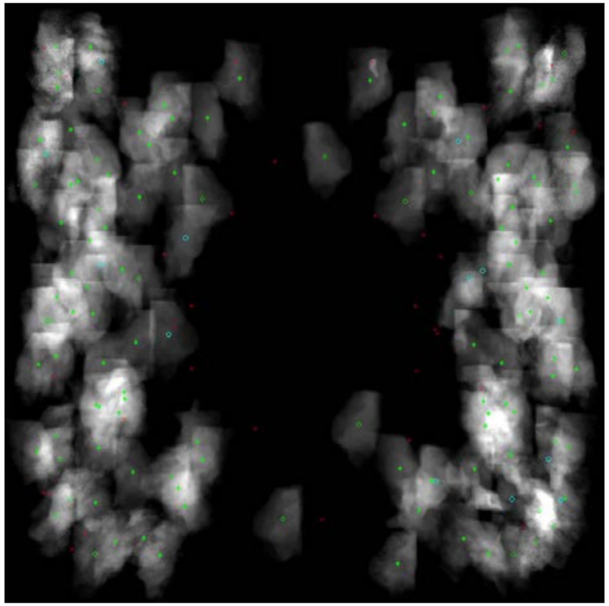


Herbig et al., Acta Mat. 2011

Grains on detector.

- Often followed by phase contrast tomography (PCT) to monitor damage development.
- Setup available at ESRF, ID11 beamline.
- [Ludwig et al., Rev. Sci. Inst. 2009]

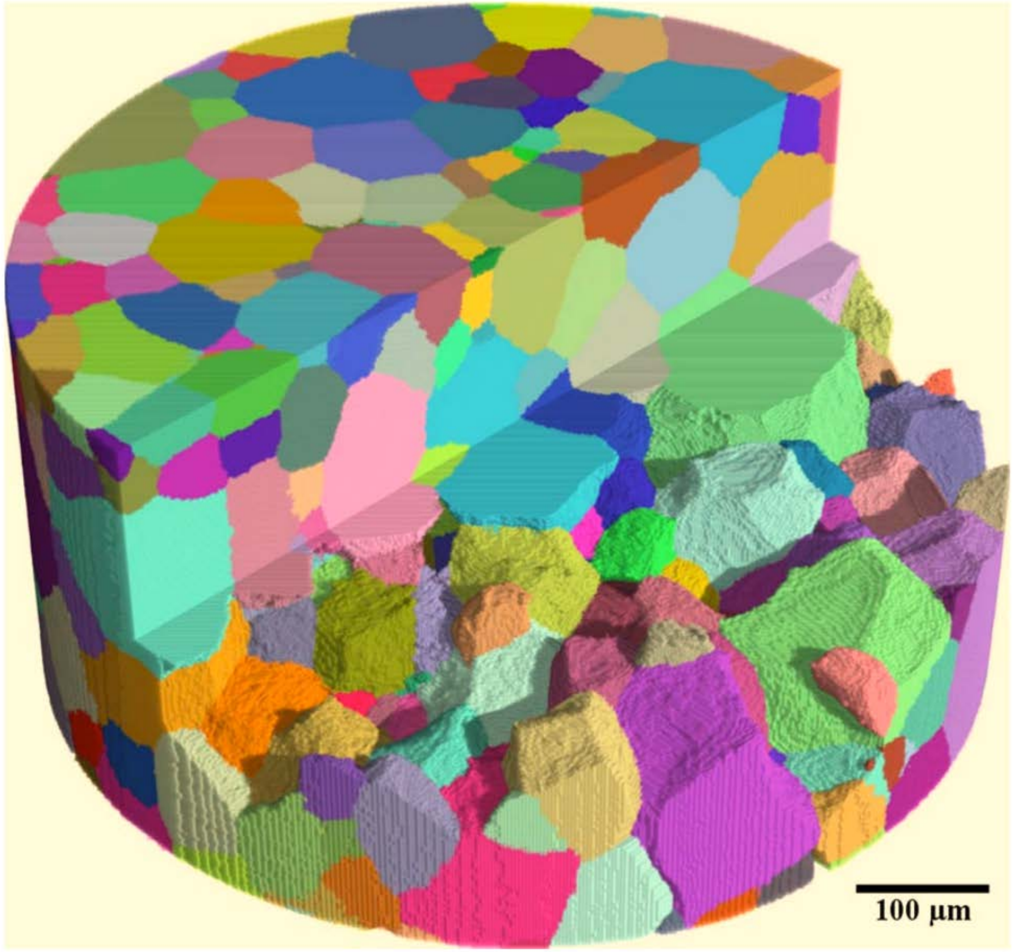
DCT reconstruction



- Identification of *hkl* and $\bar{h}\bar{k}\bar{l}$ diffraction spots (Friedel pairs) for each grain.
- Regrouping sets of pairs per grain $\Longrightarrow$ crystal orientation.
- Algebraic reconstruction of 3D grain shapes from diffraction spots.

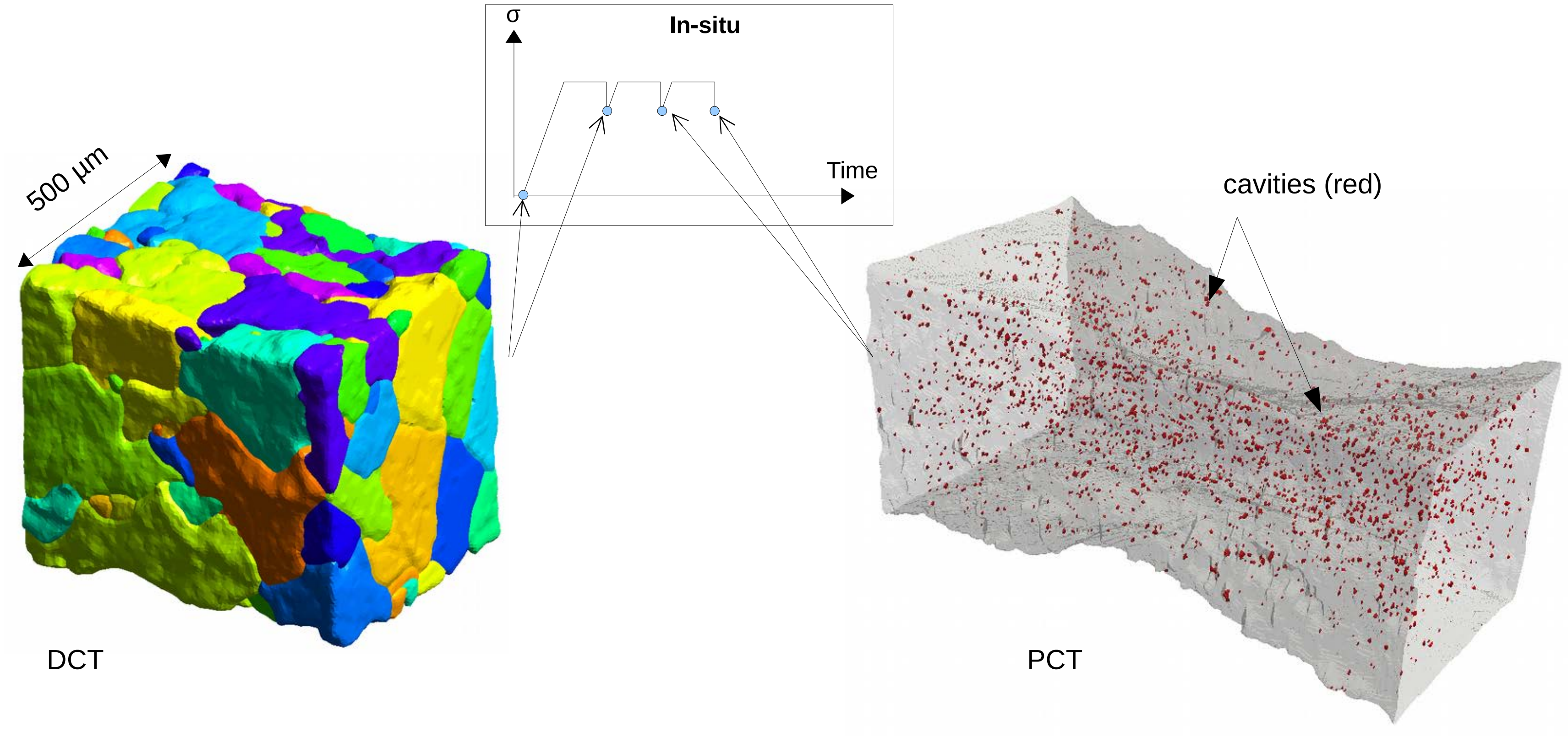
DCT reconstruction

Example of a $\beta-$Ti alloy



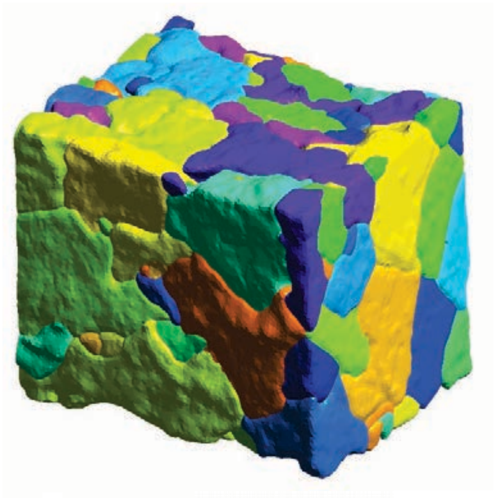
[Ludwig et al., Rev. Sci. Inst. 2009]

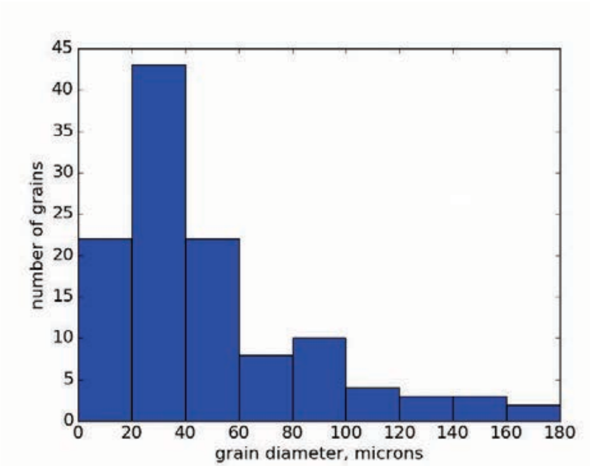
Sample used in this illustration

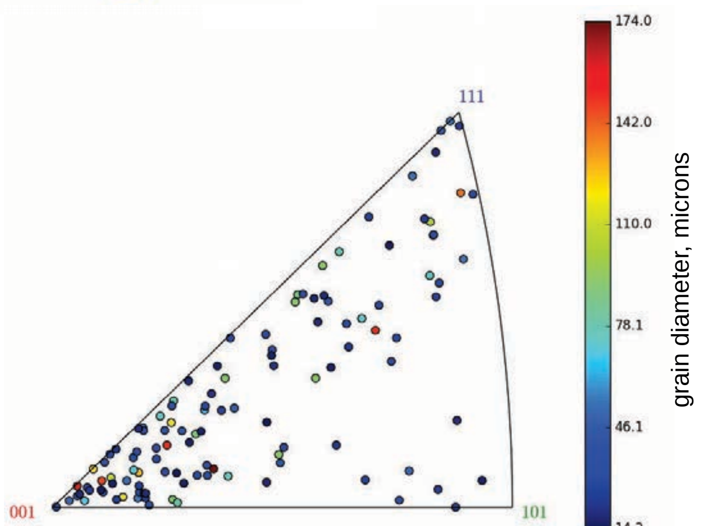


- 1050 Al alloy loaded in-situ, ID11 beamline, ESRF.
- Initial state and first 2% of plastic deformation followed by DCT and far-field diffraction.
- Ductile damage further followed by PCT.

Initial polycrystal reconstruction, DCT







Tensile axis IPF

- 1050 Al alloy, recrystallized
- $\sim$ 120 grains
- Avg diameter: 73 μm
- Average ini. disorientation: 0.1°

Outline

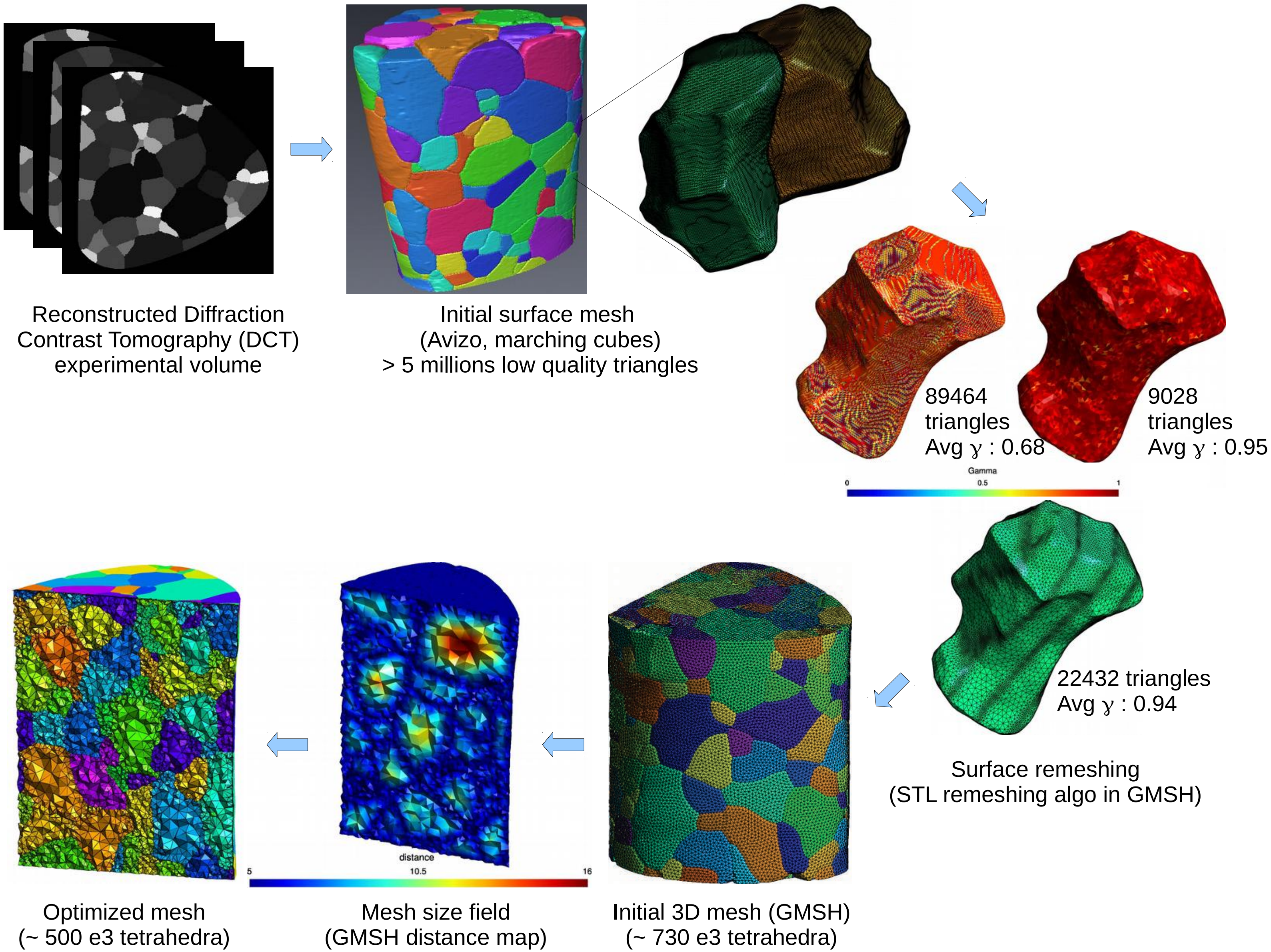
1 Introduction
- Background on ductile damage

2 Attenuation and phase imaging
- Experimental setups
- "Routine" experiments
- High resolution
- Cavity tracking

3 Diffraction imaging
- Diffraction constrast tomography (DCT)
- DCT based CPFEM

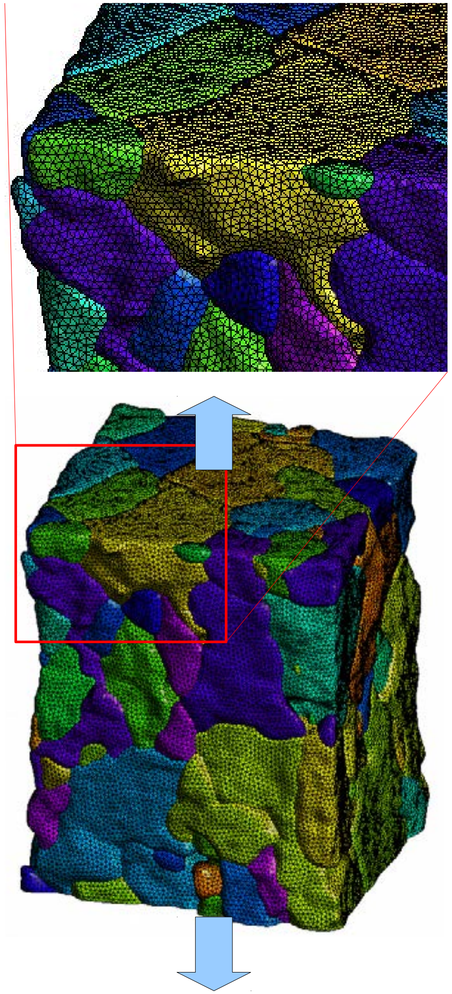
4 Conclusion - Outlook

3D meshing


Reconstructed Diffraction
Contrast Tomography (DCT)
experimental volume
Initial surface mesh
(Avizo, marching cubes)
> 5 millions low quality triangles
89464
triangles
Avg γ : 0.68
9028
triangles
Avg γ : 0.95
Gamma
0
0.5
1
22432 triangles
Avg γ : 0.94
Surface remeshing
(STL remeshing algo in GMSH)
Optimized mesh
(~ 500 e3 tetrahedra)
distance
5
10.5
16
Mesh size field
(GMSH distance map)
Initial 3D mesh (GMSH)
(~ 730 e3 tetrahedra)

1050 Al model

Crystal Plasticity Finite Element Modeling (CPFEM)



DCT-based CPFEM mesh

- Elasto-viscoplastic UMAT [Delannay et al., Int. J. PLast. 2006] .
- 12 FCC $\{111\}\langle 110\rangle$ slips systems for aluminum.
- Voce hardening of the slip systems.
- Initial grain orientation from DCT.
- Scale transition: DCT-based CPFEM (full field).
- 50% tensile deformation.

CPFEM - heterogeneity of stress

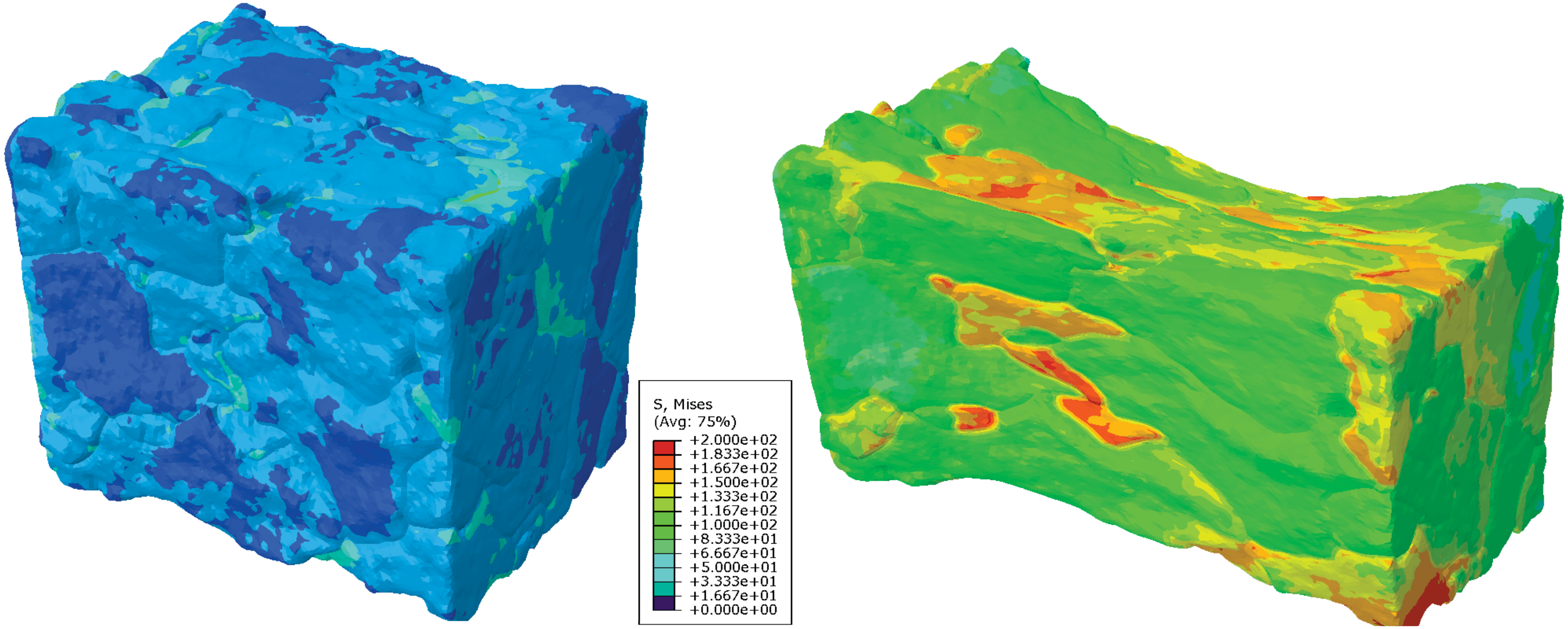
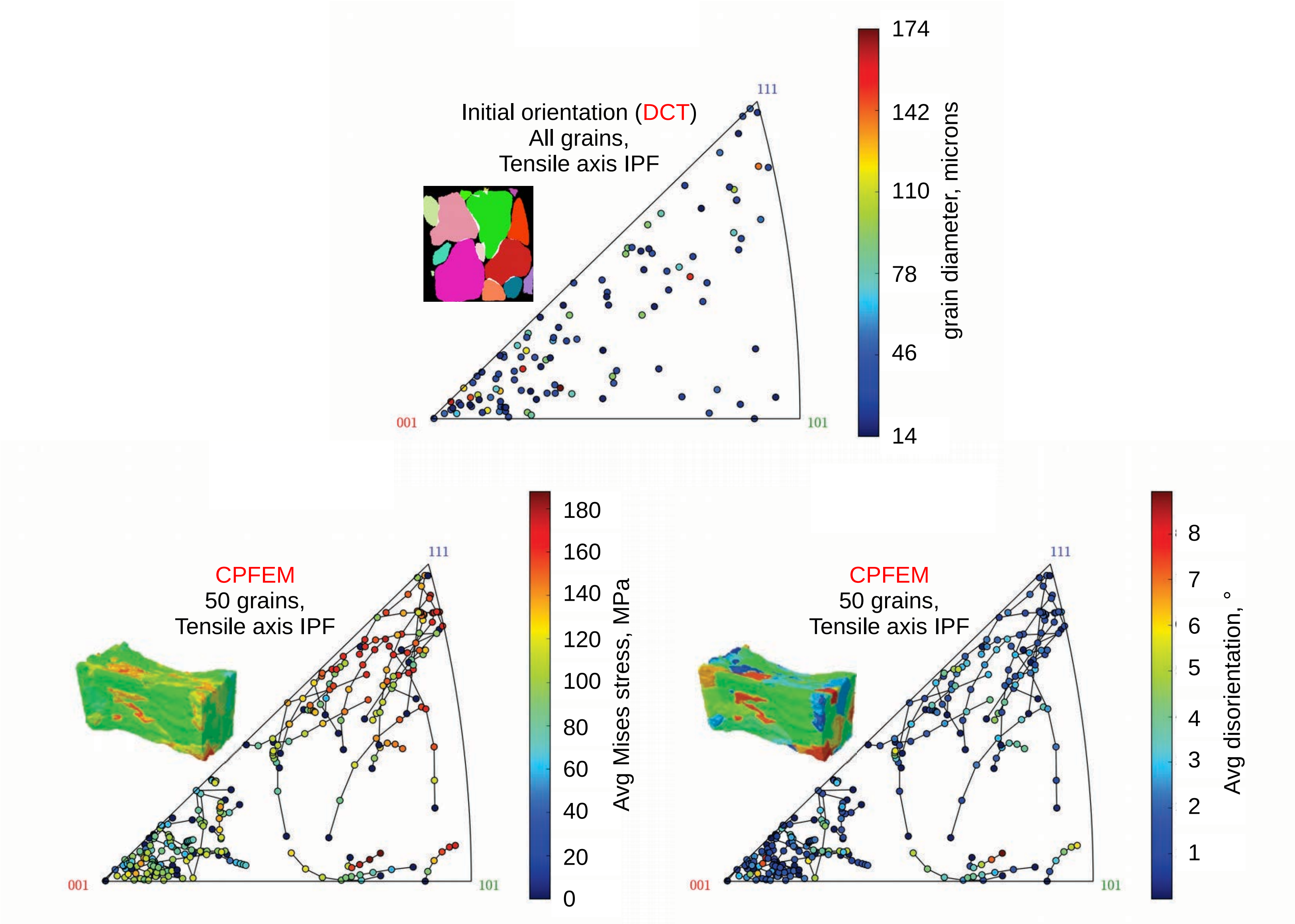


Figure: Von Mises from the initial to deformed configurations.

CPFEM - crystal rotations



Cavity growth, on-going

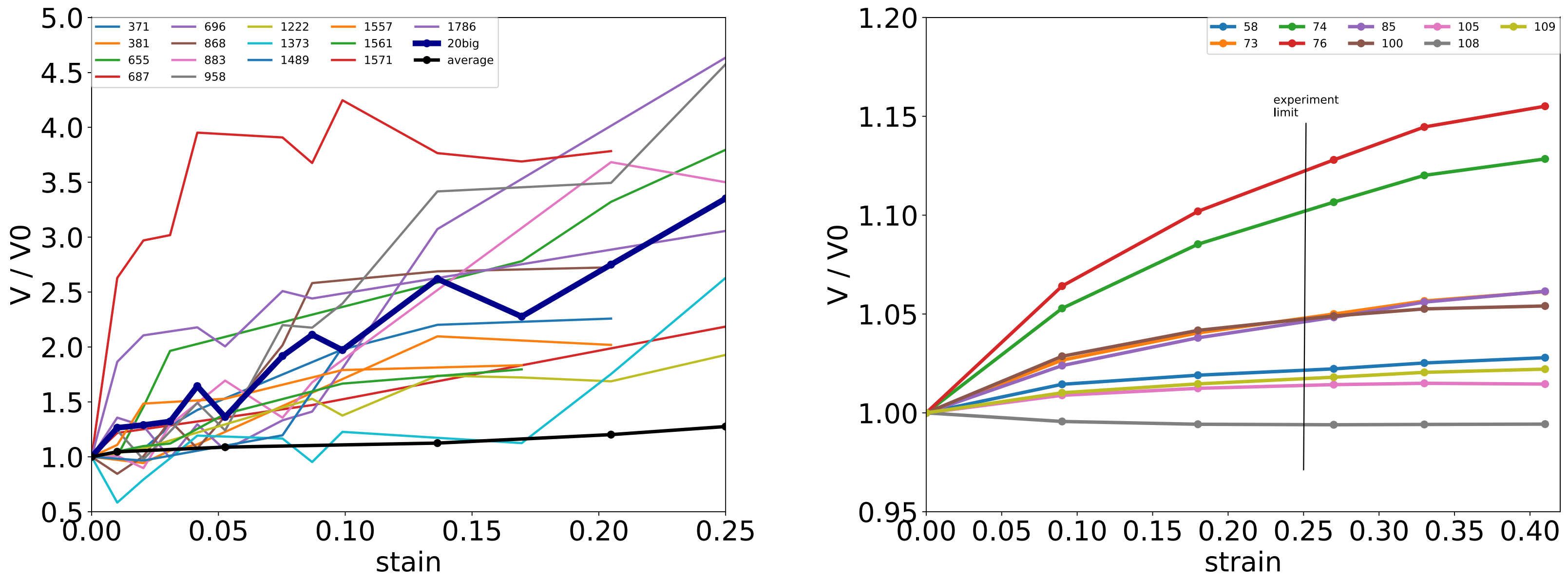


Figure: cavity growth, experiment vs. simulation

- Cavity growth strongly affected by local neighborhood.
- Local heterogeneity of plastic flow analyzed by DCT-based CPFEM.

Conclusion - Outlook

- A lot has been learned about ductile damage in the last 20 years.
- New tools are available:
  - cavity/particle tracking,
  - fast imaging,
  - high resolution,
  - but also DVC, laminography, FE-based modelling, ...
- The vision has changed.
- Still a lot to do/discover:
  - H_2 embrittlement,
  - new materials,
  - Development of microstructure-based models

Conclusion - Outlook

- A lot has been learned about ductile damage in the last 20 years.
- New tools are available:
  - cavity/particle tracking,
  - fast imaging,
  - high resolution,
  - but also DVC, laminography, FE-based modelling, ...
- The vision has changed.
- Still a lot to do/discover:
  - H_2 embrittlement,
  - new materials,
  - Development of microstructure-based models

Conclusion - Outlook

- A lot has been learned about ductile damage in the last 20 years.
- New tools are available:
  - cavity/particle tracking,
  - fast imaging,
  - high resolution,
  - but also DVC, laminography, FE-based modelling, ...
- The vision has changed.
- Still a lot to do/discover:
  - H_2 embrittlement,
  - new materials,
  - Development of microstructure-based models

Conclusion - Outlook

- A lot has been learned about ductile damage in the last 20 years.
- New tools are available:
  - cavity/particle tracking,
  - fast imaging,
  - high resolution,
  - but also DVC, laminography, FE-based modelling, ...
- The vision has changed.
- Still a lot to do/discover:
  - H_2 embrittlement,
  - new materials,
  - Development of microstructure-based models