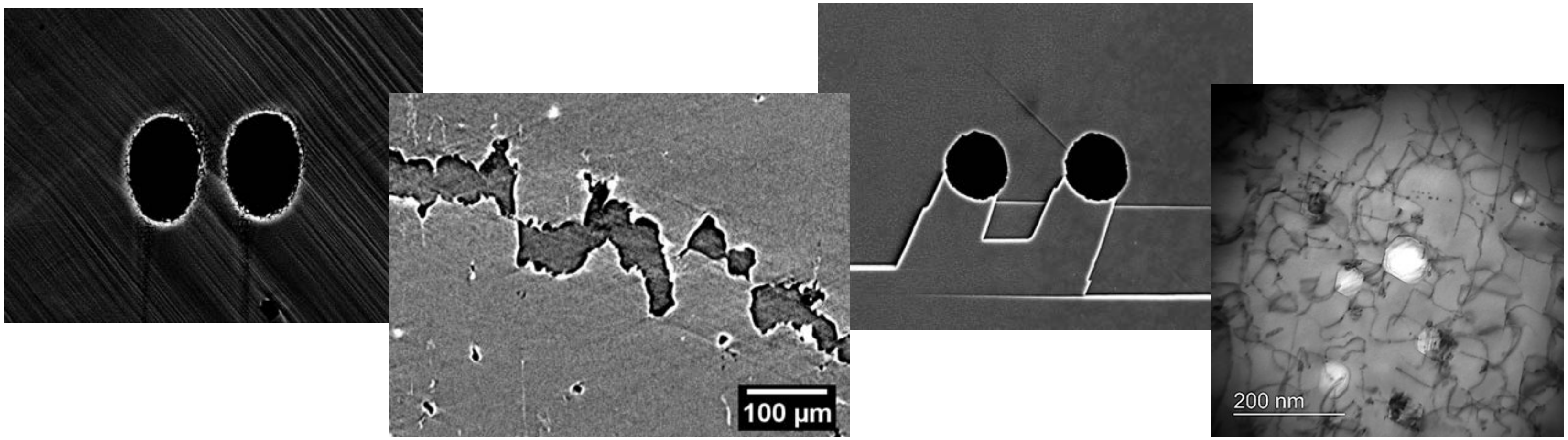
Ductile fracture (of metals)



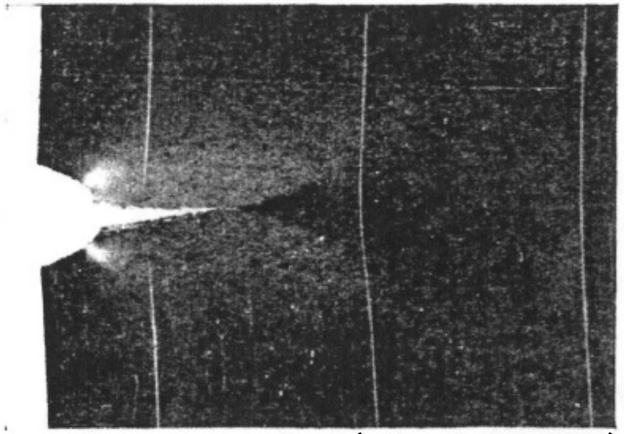
An introduction

Jérémy Hure
CEA Saclay, Department of Materials for Nuclear Applications

GDR MePhy - Atelier "Nouveaux défis en mécanique de la rupture" - 27-28 Novembre 2017

Special thanks to : Tom Petit, Pierre-Olivier Barrioz, Arnaud Courcelle (CEA), Kim Nielsen (DTU)

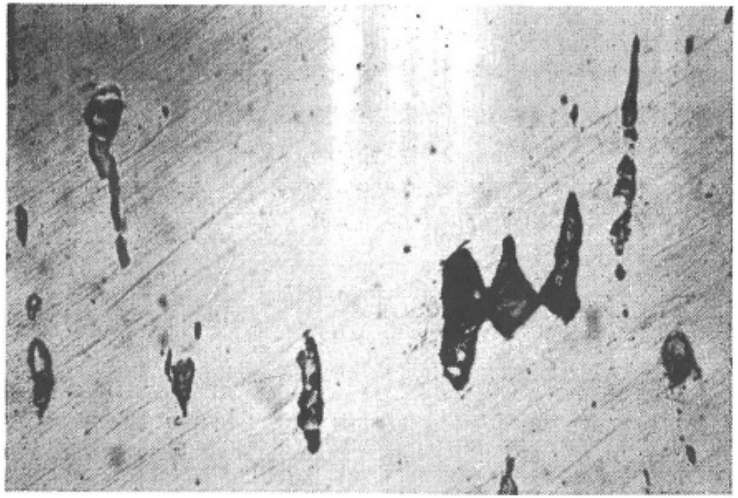
Engineering definition : Fracture associated with a large amount of plastic strain



(Tipper, 1949)

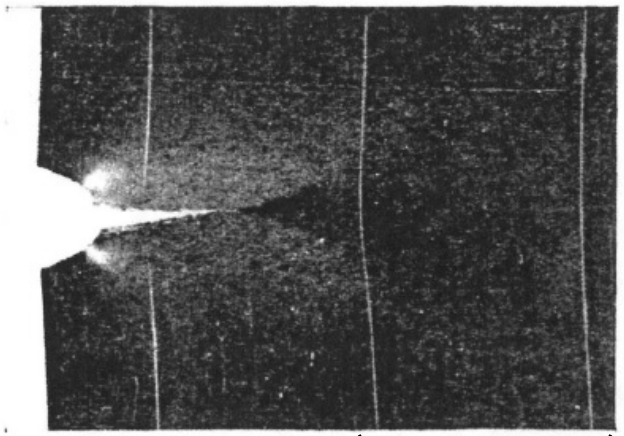
(Yesterday's) observations after mechanical loading

(Tipper, 1949)



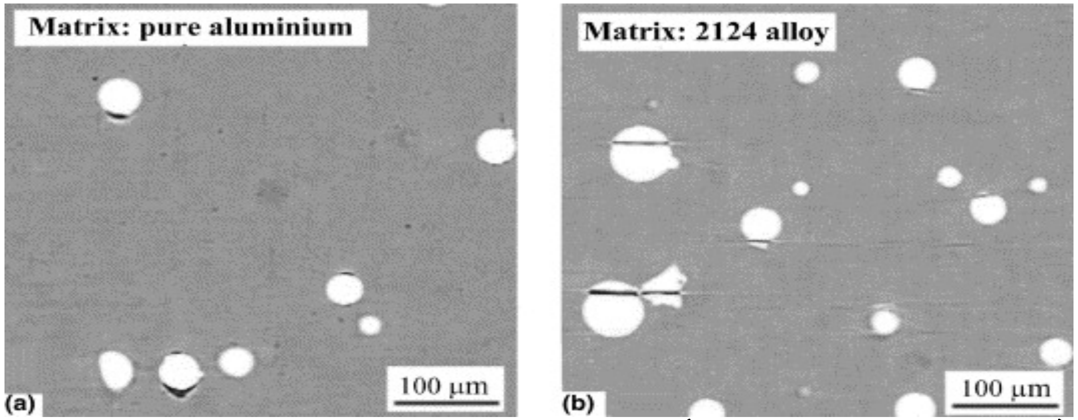
(Puttick, 1959)

Engineering definition : Fracture associated with a large amount of plastic strain

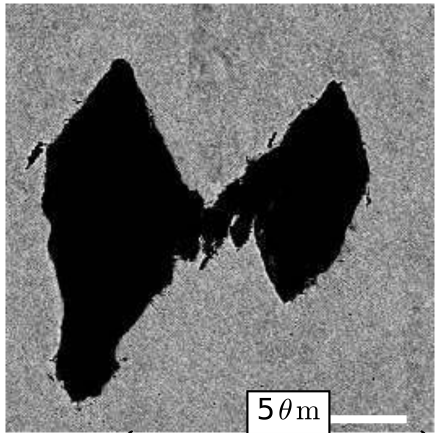


(Tipper, 1949)

(Today's) observations after mechanical loading

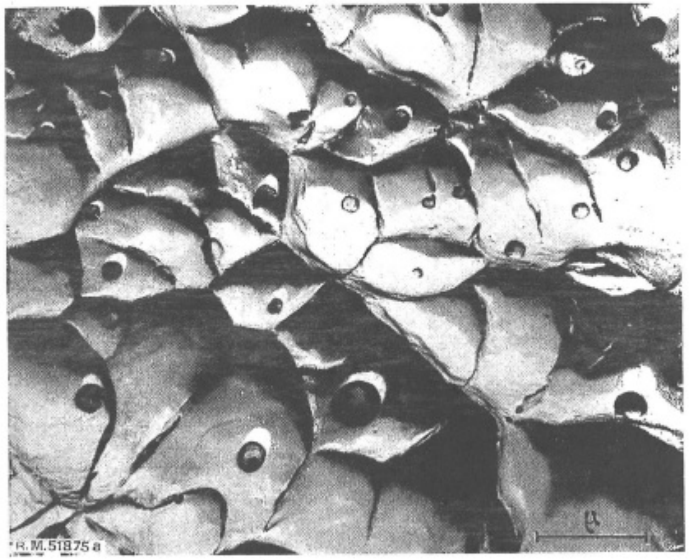


(Babout et al, 2004)

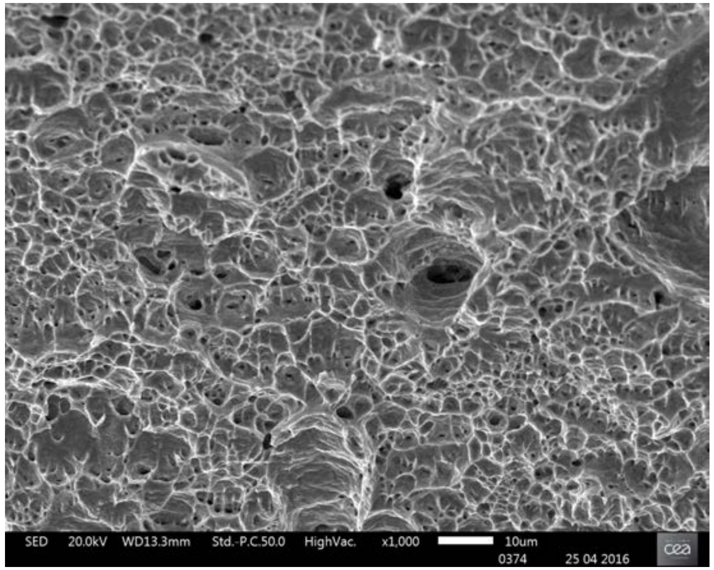


(Benzerga, 1999)

Fractographic observations



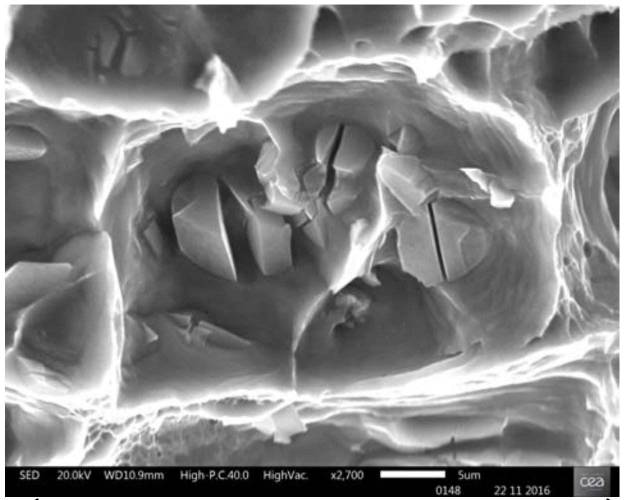
(Plateau et al., 1957)



(Courcelle, CEA)

Characteristics of ductile fracture surfaces

- Dimples
- Broken inclusions



(Petit & Morgeneyer, CEA, CDM)

Three different phases

Nucleation

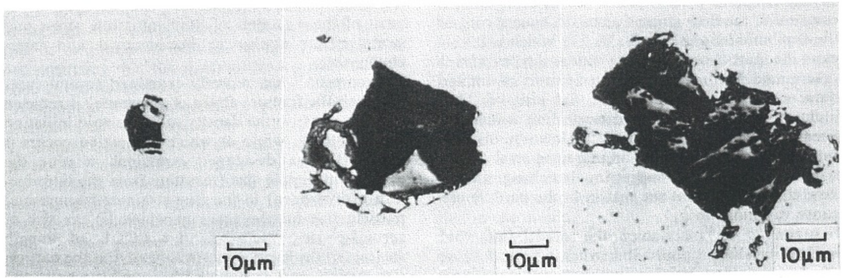
- Voids nucleate from particles
  - Decohesion from the matrix
  - Fracture of the particle

(Puttick, 1959)

→ **The material becomes porous**

Growth

- Enlargement of voids
  - Through diffuse plastic flow
  - Without interactions between voids

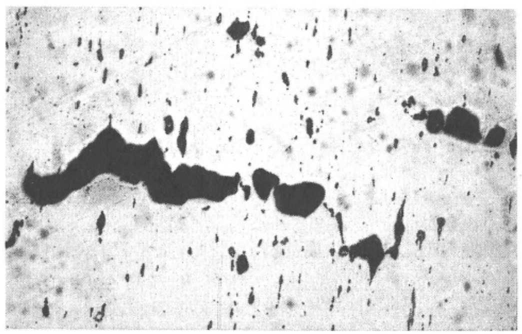


(Cox, 1973)

→ **The porosity increases**

Coalescence

- Enlargement of voids
  - Through localized plastic flow
  - With interactions between voids



(Puttick, 1959)

→ **The porosity increases**

Nucleation criteria (from particles)

Energetic approach (Gurland & Plateau, 1963)

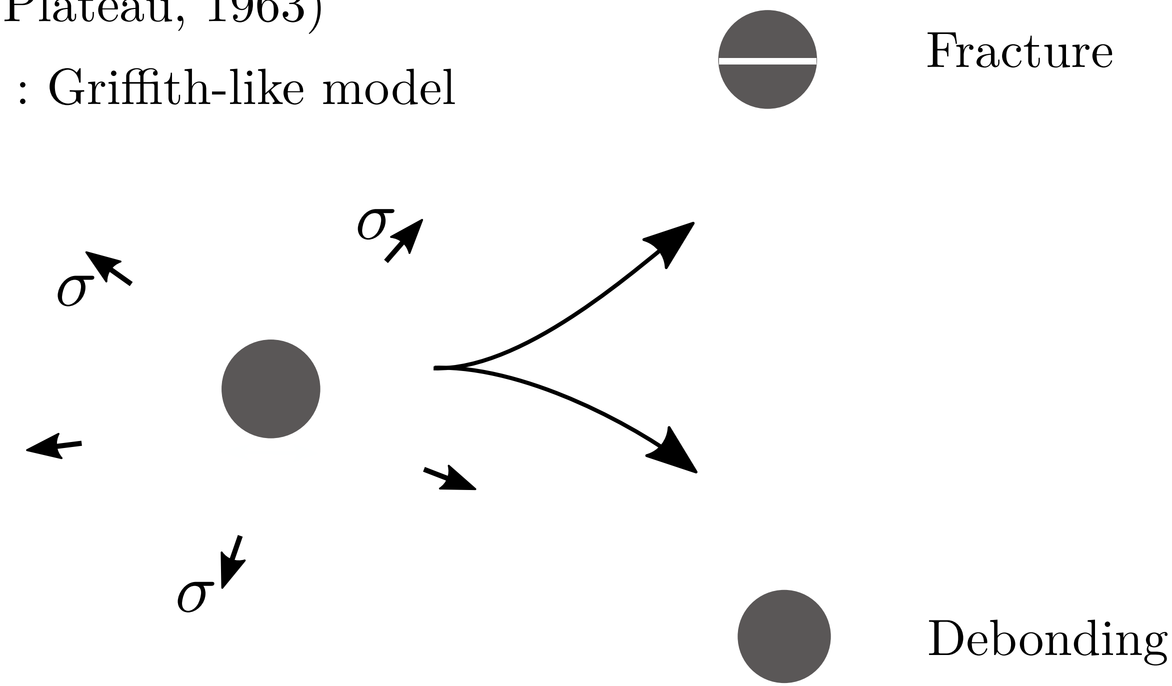
- Brittle particles (or interfaces) : Griffith-like model

$$\underbrace{(\sigma_c^2/E)R^3}_{\text{Elastic energy}} \gtrsim \underbrace{\gamma R^2}_{\text{Surface energy}}$$

$$\Downarrow$$

$$\sigma_c \gtrsim \sqrt{\gamma E/R}$$

$$\left.\begin{array}{l} \gamma \sim 1\text{J.m}^{-2} \\ E \sim 100\text{GPa} \\ R \sim 1\mu\text{m} \end{array}\right\} \quad \sigma_c \sim 100\text{MPa}$$



Interfacial strength / Fracture stress σ_c

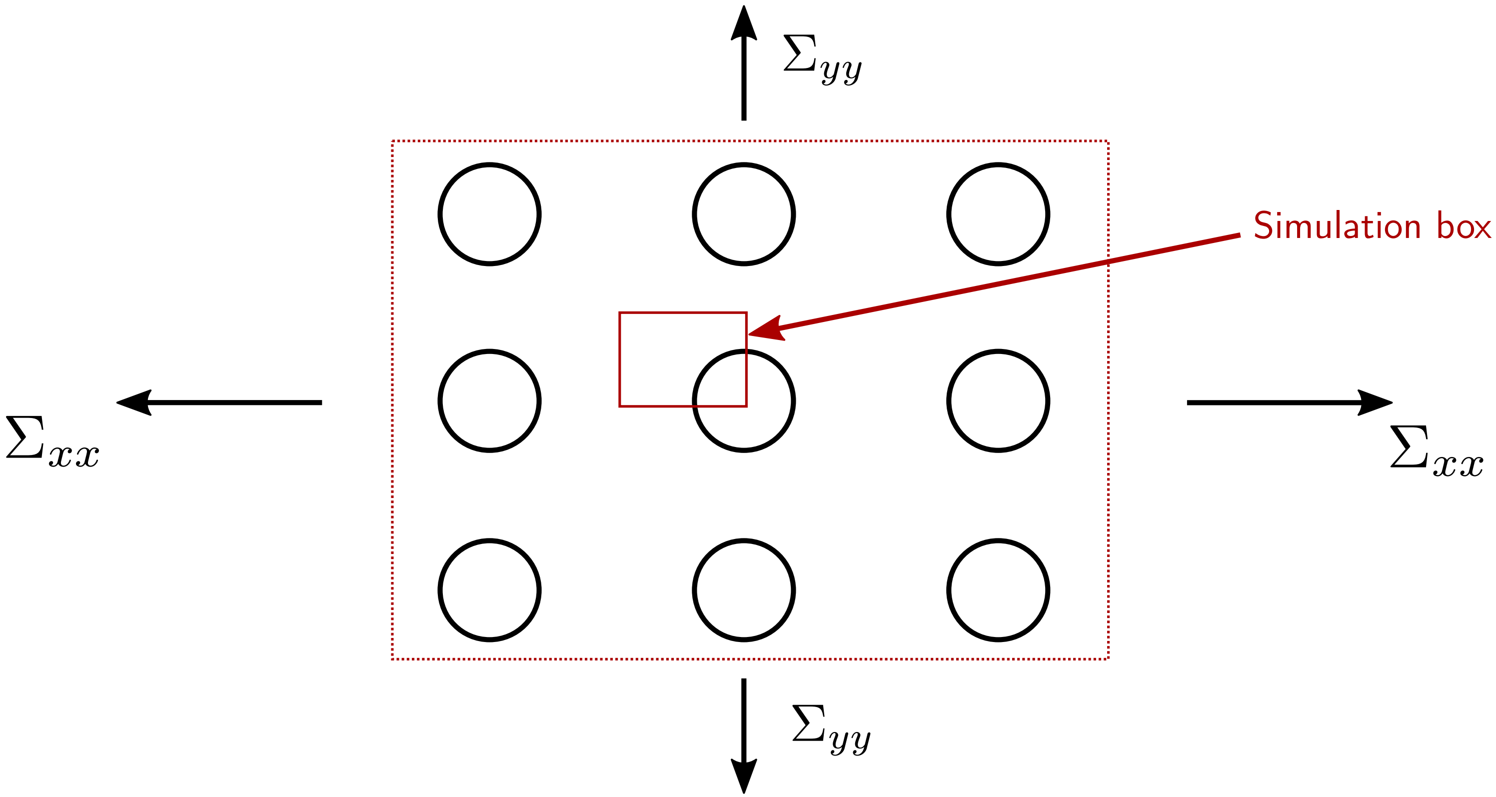
Models used in ductile fracture modeling

$\boxed{\text{Porosity} \quad f = \dfrac{V_{\text{cavities}}}{V_{\text{total}}}}$

Initial $\quad f_0$

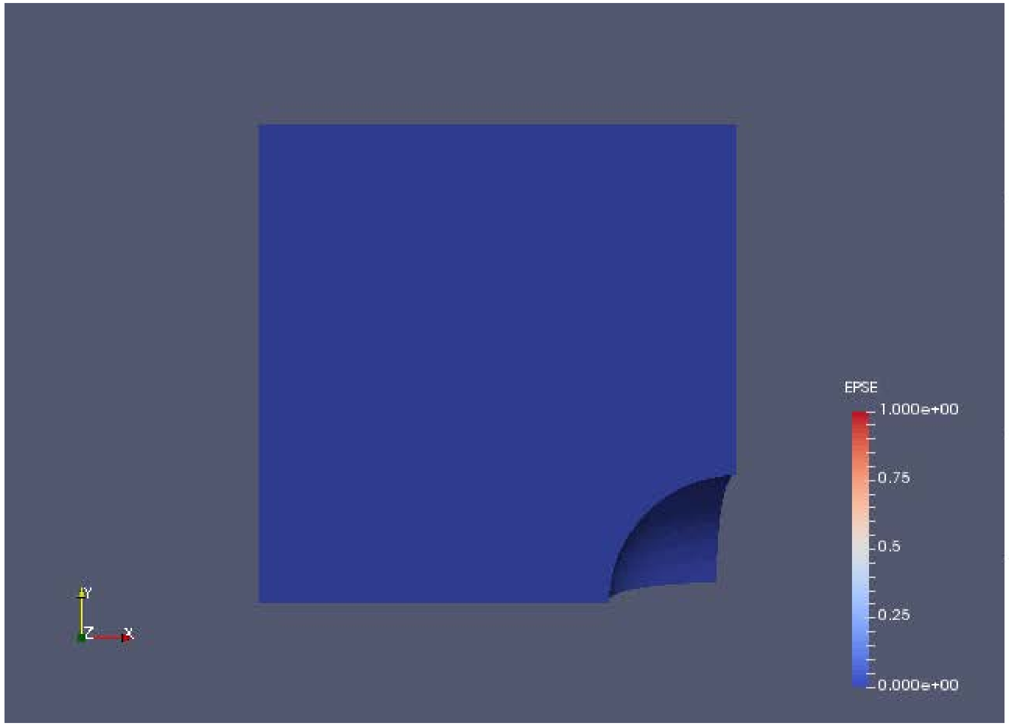
From particles $\quad \dot{f} = \mathcal{F}(\epsilon, \sigma)$

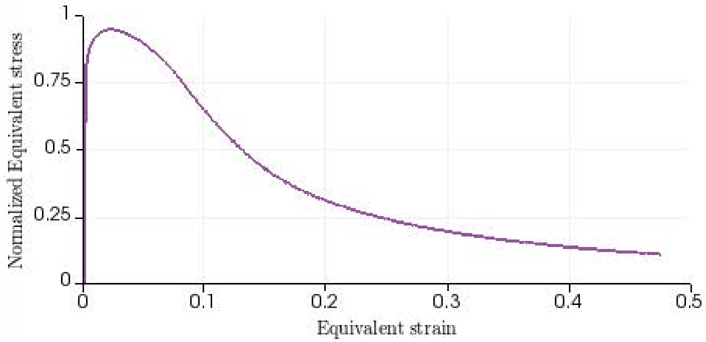
Simplified case: Periodic arrangement of voids of porosity f

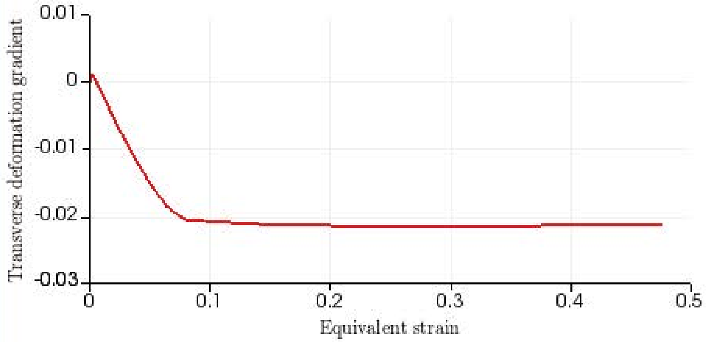


Numerical simulations à la (Koplik & Needleman, 1988)

- Average stress Σ_{xx}
- Porosity evolution



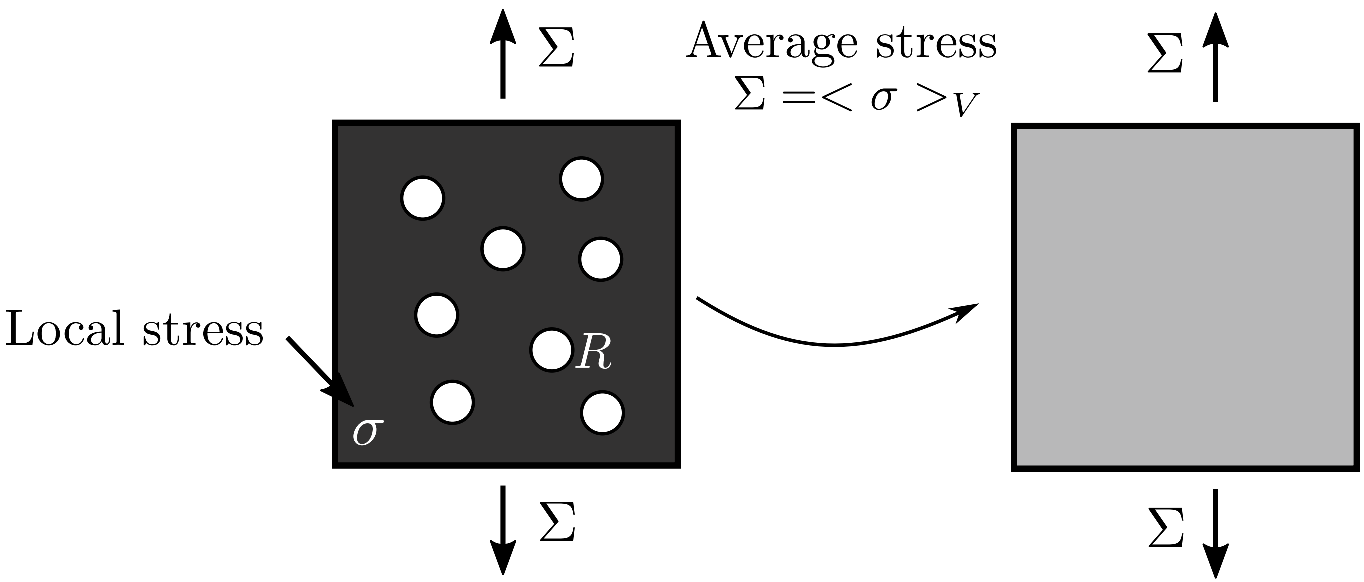




- Void growth to coalescence
- (Average) Stress: Softening due to the increase of porosity

$\Rightarrow$ Towards an **analytical homogenized model**

Macroscopic (representative volume element scale) behavior



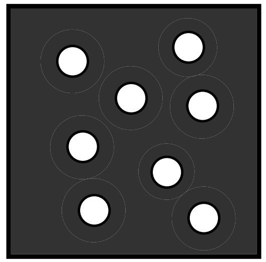
Homogenized behavior law

$$\Sigma = \mathcal{G}\left(f, ...\right)$$

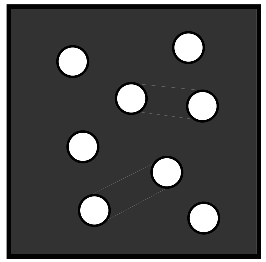
Void size / Porosity evolution

$$\dot{R} = \mathcal{F}\left(\Sigma, f, ...\right)$$

in the growth regime



in the coalescence regime

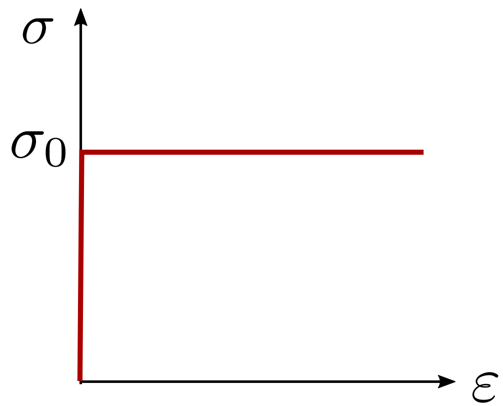


A simplified model to describe the material **around the voids**

Rigid (no elasticity)

Perfectly plastic (no hardening)

Isotropic



Constitutive equations

Plastic yield criterion $\mathcal{F}(\sigma', \sigma_0) = \sigma'\sigma' - \sigma_0^2$

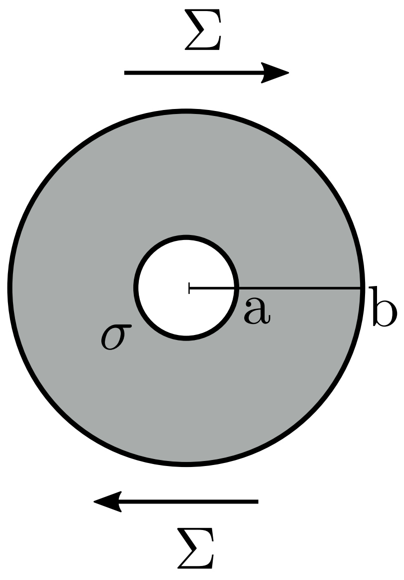
σ' = Stress - Hydrostatic pressure

Metal plasticity (without voids) is only sensitive to **local shear** (dislocations motion)

Plastic flow $$\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} = \frac{\sigma'}{\sigma_0} \text{ if } \mathcal{F}(\sigma', \sigma_0) = 0$$ **Isochoric** deformation

Rigid perfectly plastic $\sim$ ***Bingham plastic fluid***

Macroscopic yield criterion / yield stress Σ_0



- **Under shear**

$$\Sigma \approx \frac{\sigma(b^3 - a^3)}{b^3} \quad \Rightarrow \quad \boxed{\Sigma_0 \approx (1-f)\sigma_0}$$

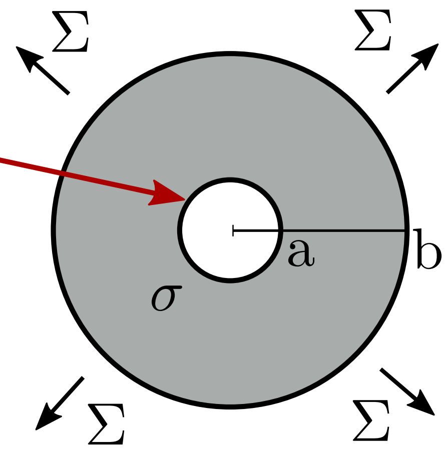
"Average Shear"

$$f = \frac{V_{\text{cavity}}}{V_{\text{total}}} = \left(\frac{a}{b}\right)^3$$

- **Under hydrostatic pressure**

"Shear"

$$\left.\begin{array}{c} \dfrac{d\sigma_{rr}}{dr} + \dfrac{2}{r}\left(\sigma_{rr} - \sigma_{\theta\theta}\right) = 0 \\ \Downarrow \\ \displaystyle\int \frac{d\sigma_{rr}}{dr} \approx \int \frac{\sigma_0}{r} \end{array}\right\} \quad \boxed{\Sigma_0 \approx -\ln(f)\sigma_0}$$



Macroscopic yield criterion for porous material (spherical voids)

Shear

$\Sigma_0 \approx (1-f)\sigma_0$

Hydrostatic pressure

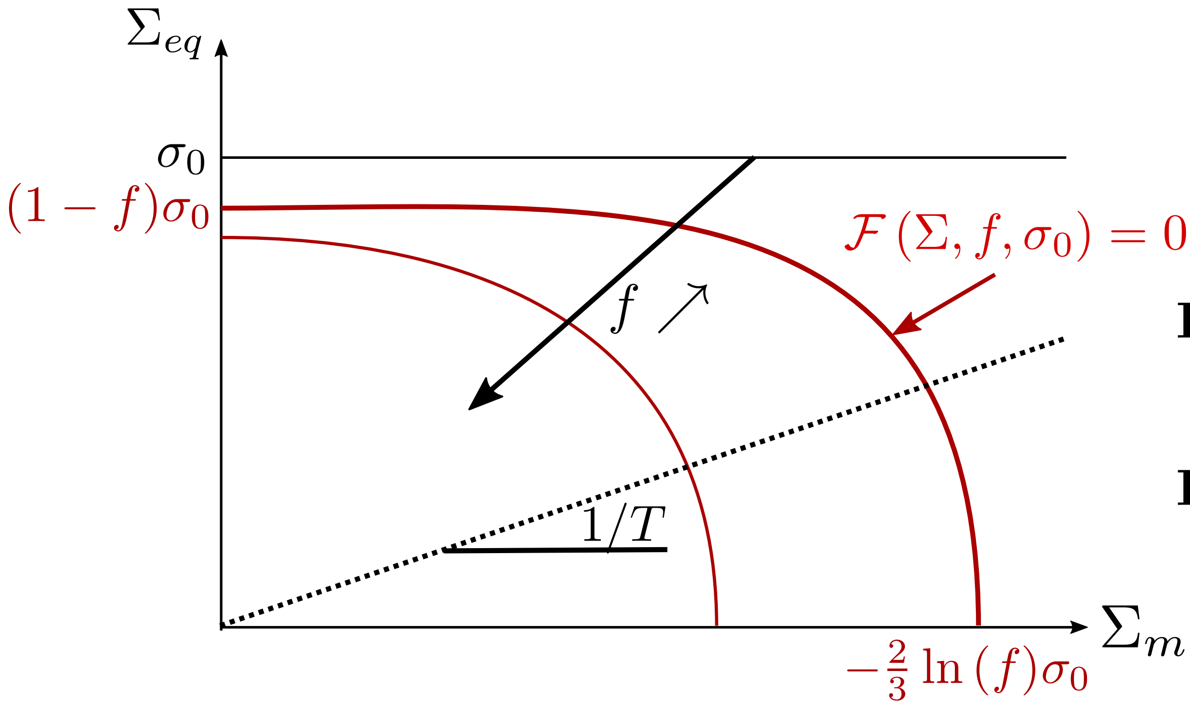
$\Sigma_0 \approx -\ln(f)\sigma_0$

$$T = \frac{\Sigma_m}{\Sigma_{eq}}$$

$$\mathcal{F}(\Sigma, f, \sigma_0) = \left(\frac{\Sigma_{eq}}{\sigma_0}\right)^2 + 2q_1 f \cosh\left(\frac{3}{2}q_2\frac{\Sigma_m}{\sigma_0}\right) - 1 - q_3 f^2$$

Stress triaxiality

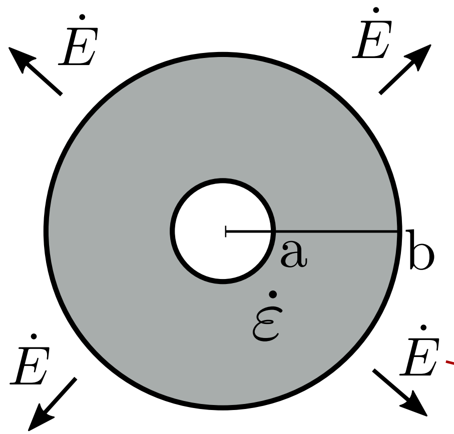
Gurson-Tvergaard-Needleman (GTN) criterion (1977, 1981, 1984)



Reduced yield stress as f increases

Plastic flow ?

Plastic flow under hydrostatic pressure



Yield criterion

$$\Sigma_m = -\frac{2}{3}\ln(f)\sigma_0$$

$$\exp\left(\frac{3}{2}\frac{\Sigma_m}{\sigma_0}\right) = \left(\frac{b}{a}\right)^3$$

Material incompressibility

$$V_m = \frac{4}{3}\pi(b^3 - a^3)$$

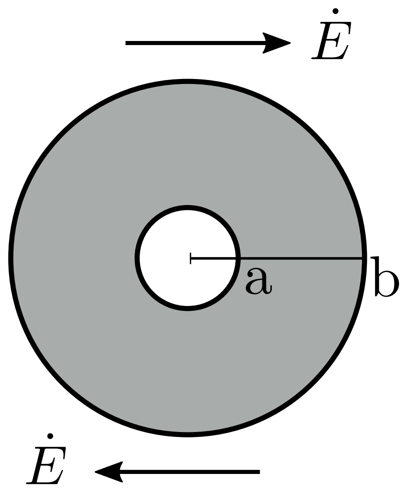
$$\Delta V_m = 0 \Rightarrow b^2\dot{b} = a^2\dot{a}$$

$$\boxed{\frac{\dot{a}}{a} = \frac{\dot{b}}{b}\exp\left(\frac{3}{2}\frac{\Sigma_m}{\sigma_0}\right)}$$

Rice & Tracey law (1969)

Void growth

Plastic flow under shear



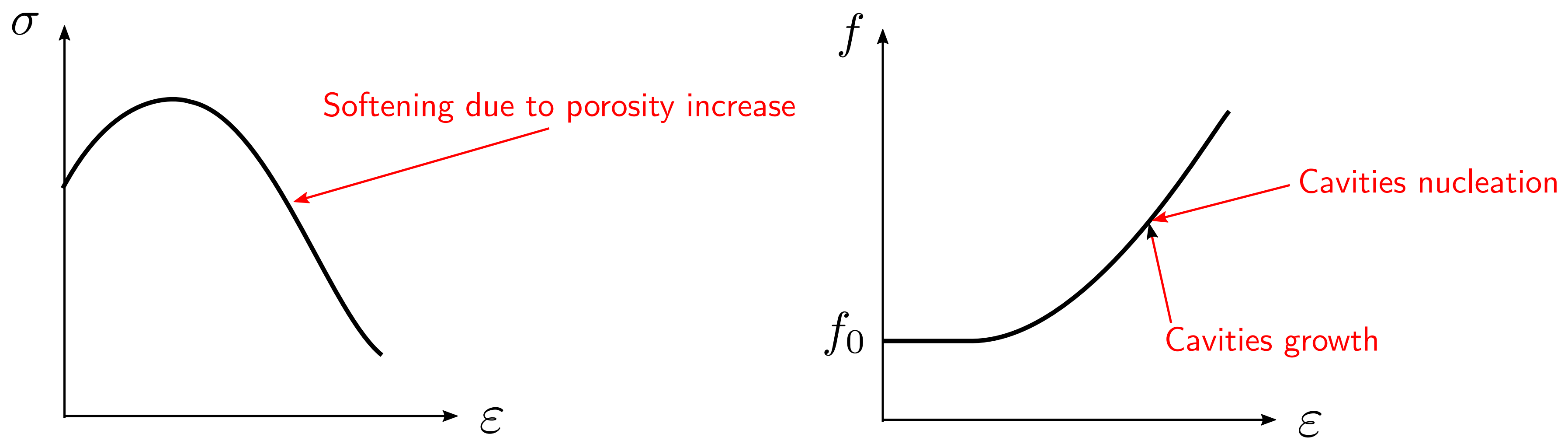
Material incompressibility

$$\cancel{\Delta V_{\text{total}}} = \cancel{\Delta V_{\text{m}}} + \Delta V_{\text{cavity}}$$

$$\Delta V_{\text{cavity}} = 0 \Rightarrow \frac{\dot{a}}{a} = 0$$

No void growth, but ...

Macroscopic behavior



Other (important) consequence: Localization

The **homogenized model** can be used in **numerical simulations:**

- Fracture corresponds to the case $f \to 1$
- **Example** : Finite element simulation of ductile tearing

$\Longrightarrow$ ***Other example: Talk of Jean-Philippe Crété***

Plastic behavior of porous materials

(Felter & Nielsen, 2017)

Strain-hardening

- Competition between void softening and matrix hardening

$$\Sigma \dot{E} = < \sigma(\bar{\varepsilon}) \, \bar{\varepsilon} >_V \qquad \text{(Gurson, 1977)}$$

Coalescence modeling

- Phenomenological law for the evolution of porosity in the coalescence regime

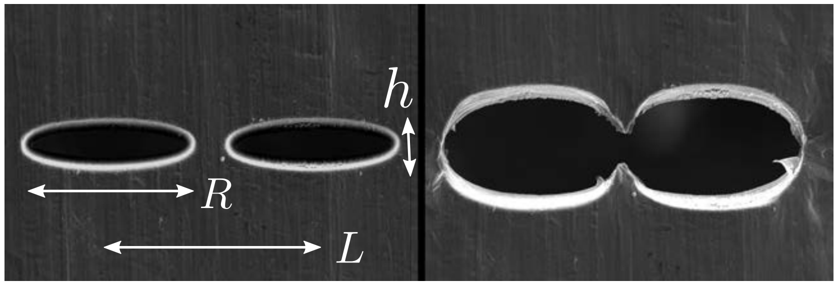
$$f \rightarrow f^{\star} = \alpha \, f \qquad \text{(Tvergaard \& Needleman, 1984)}$$

- Homogenization in the coalescence regime

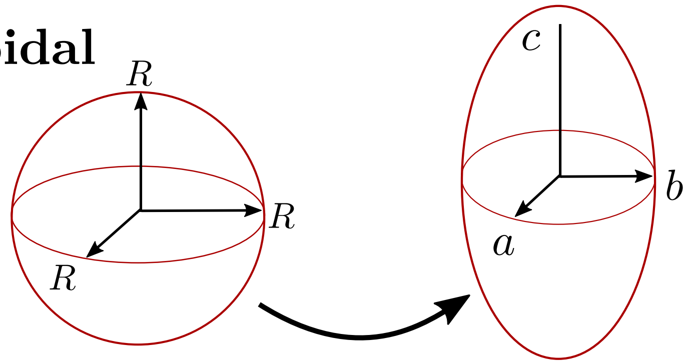
$$\mathcal{F}\left(\Sigma, f, \sigma_0\right) \rightarrow \mathcal{F}\left(\Sigma, W, \chi, \sigma_0\right) \qquad \text{(Thomason, 1985)}$$

New dimensionless parameters:

$$\chi = \frac{R}{L} \qquad W = \frac{h}{R}$$



Void shapes: Spherical to spheroidal to ellipsoidal



$$\mathcal{F}\left(\Sigma, f, \sigma_0\right) \rightarrow \mathcal{F}\left(\Sigma, f, W_1, W_2, \sigma_0\right)$$

$$W_1 = \frac{c}{a} \qquad\qquad W_2 = \frac{b}{a}$$

(Gologanu et al., 1993; Ponte Castaneda & Zaidman, 1994 ; ...)

Material : Isotropic to orthotropic: von Mises to Hill plasticity

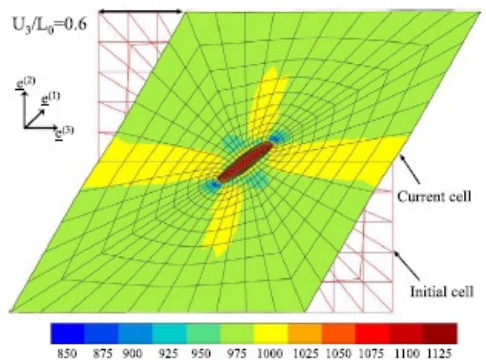
(Benzerga & Besson, 2001; ...)

$\Longrightarrow$ ***Talk of Kostas Danas***

Models for low stress triaxialities (shear dominant loading)

(Tvergaard, 2008; Nahshon & Hutchinson, 2008; ...)

$\Longrightarrow$ ***Talk of Léo Morin***



(Cao et al., 2015)

Continuum Models of Ductile Fracture: A Review

J. Besson*

2010

Ductile Fracture by Void Growth to Coalescence

A. Amine Benzerga[1] and Jean-Baptiste Leblond[2]

2010

Failure of metals I: Brittle and ductile fracture

A. Pineau [a, **], A.A. Benzerga [b, c, d, *], T. Pardoen [e]

2016

Ductile failure modeling

Ahmed Amine Benzerga · Jean-Baptiste Leblond · Alan Needleman · Viggo Tvergaard

2016

Some actual research efforts and challenges in ductile fracture modeling not discussed in the previous recent reviews

- Void nucleation without inclusions
- Physical mechanisms through model experiments

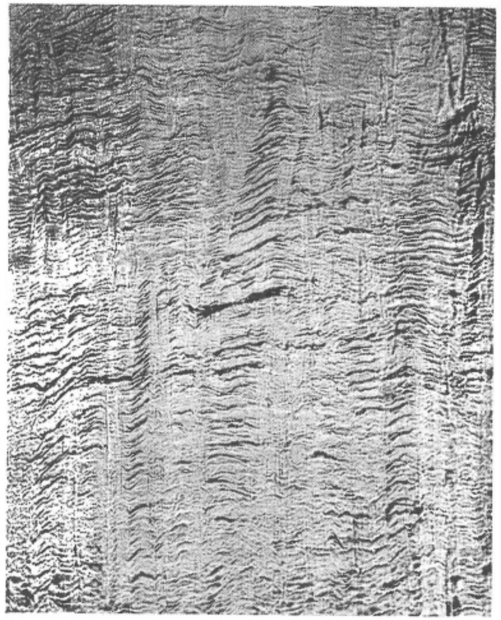
} Mechanisms ?

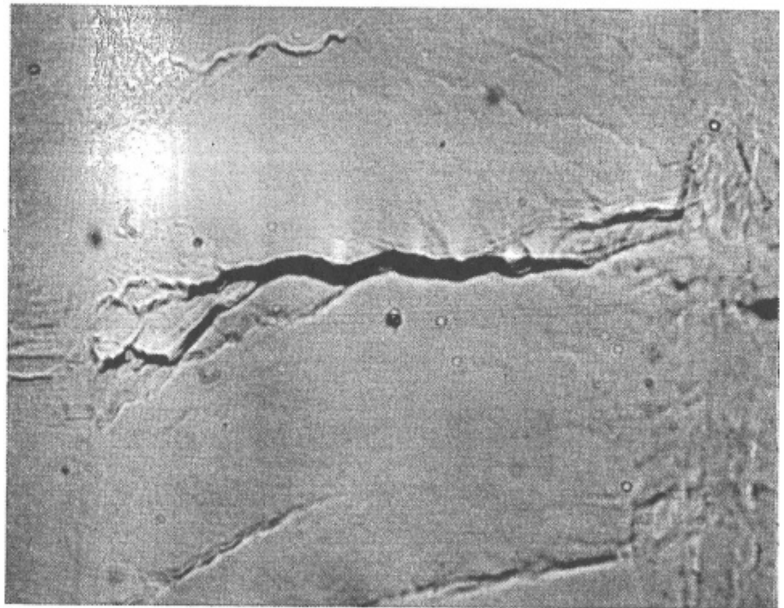
- Physical mechanisms through direct imaging
- Void growth in highly anisotropic materials
- Size effects in ductile fracture

} Small voids ?

Classical models involved particles breaking or debonding but :

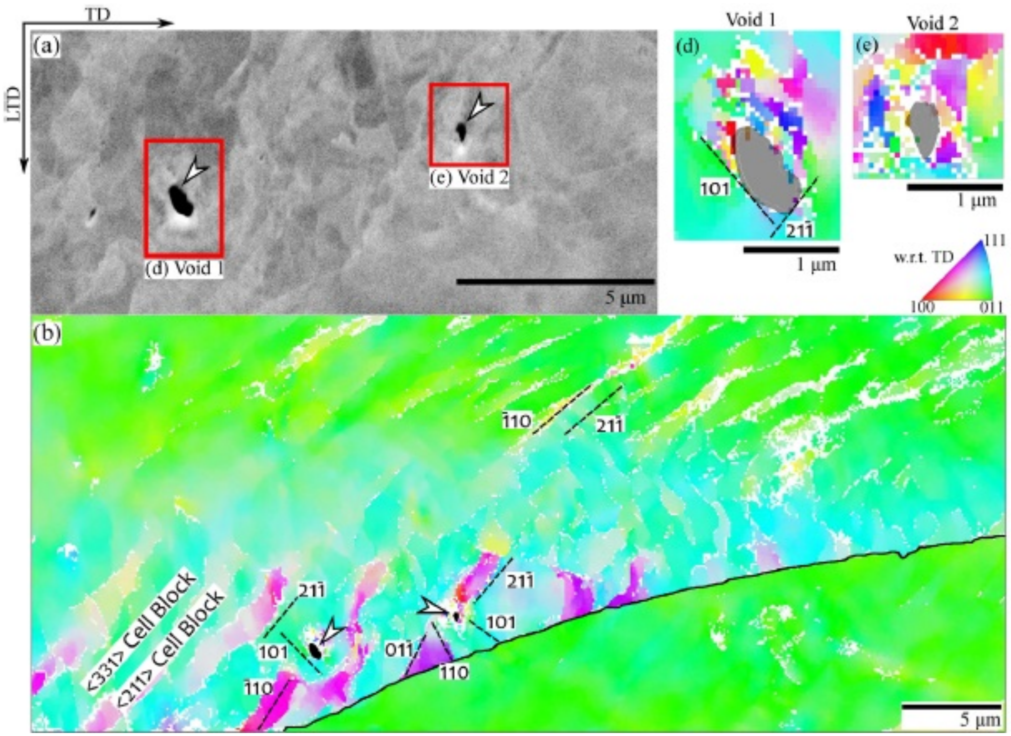
- Other mechanisms to nucleate voids / Cracks ?
- Materials with (almost) no inclusion : Pure metals ?



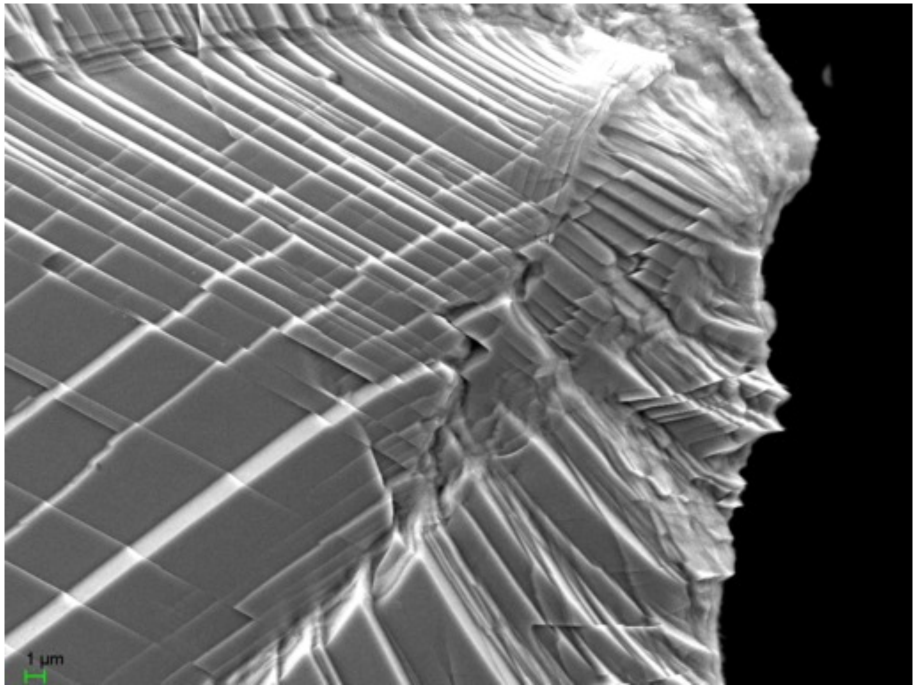


(Beevers & Honeycombe, 1962)

- Crack initiation along slip bands / Highly localized plasticity



(Noell et al., 2017)



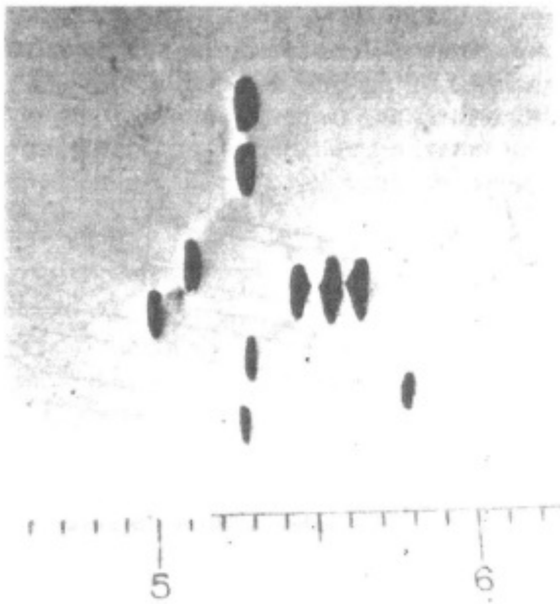
(Barrioz, CEA)

$\Downarrow$ Vacancies condensation ?

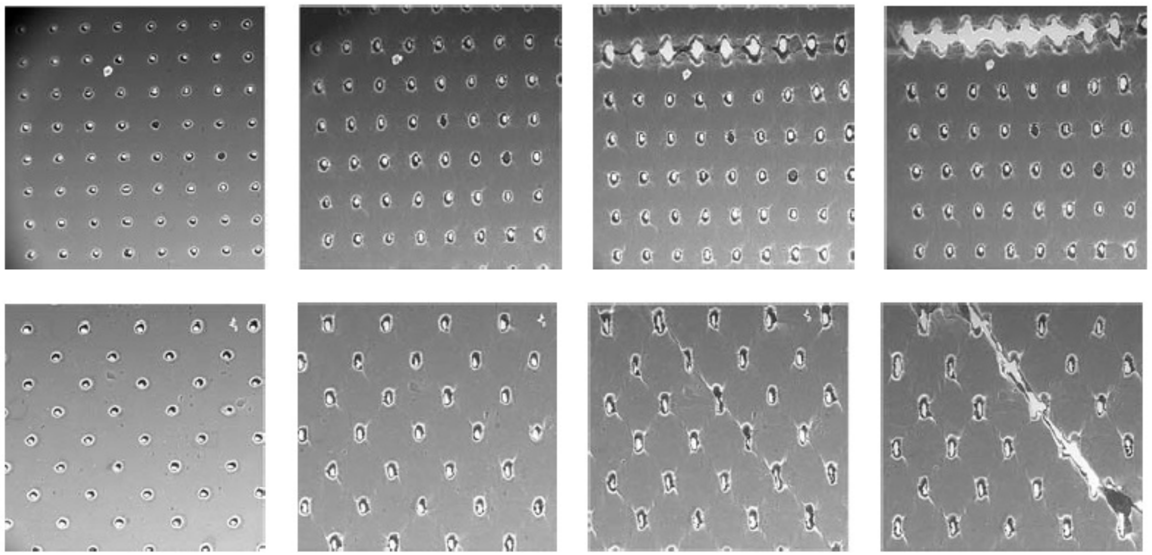
$\Downarrow$ Grain boundary cracking ?

Models to use in these situations ?

Voids drilling (Laser, Focused-Ion Beam, ...) through plates



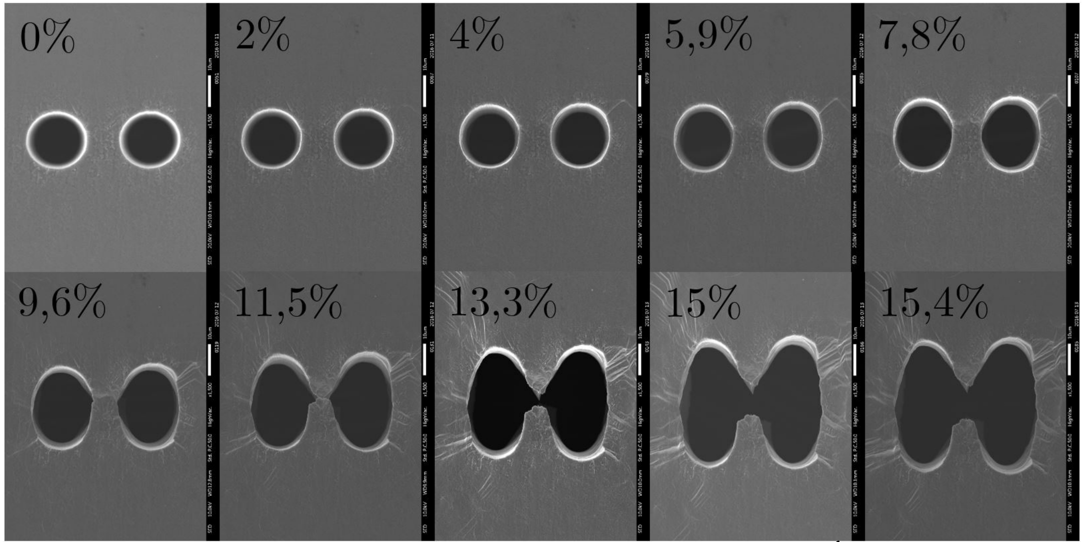
(Rhine, 1961)



(Weck & Wilkinson, 2008)

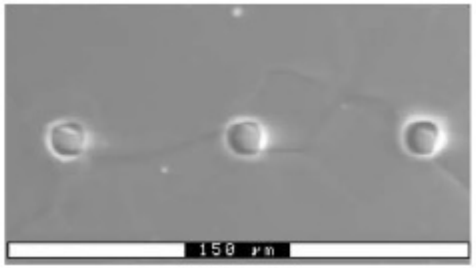
- Precise control of voids geometry
- Essentially 2D, but can be done in 3D
- Allows assessing physical mechanisms for void growth and coalescence

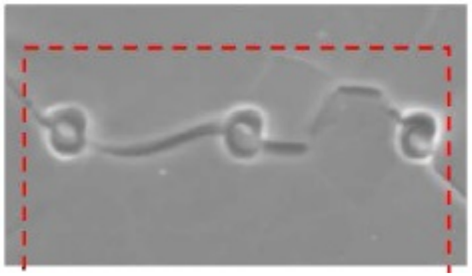
Sometimes, mechanisms are what we believe they are:



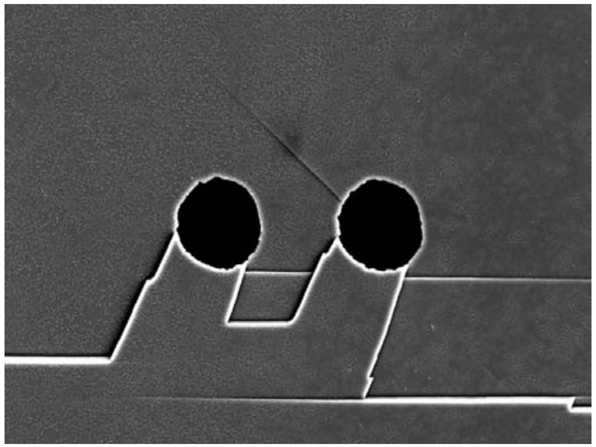
(Barrioz, CEA)

Sometimes not ...





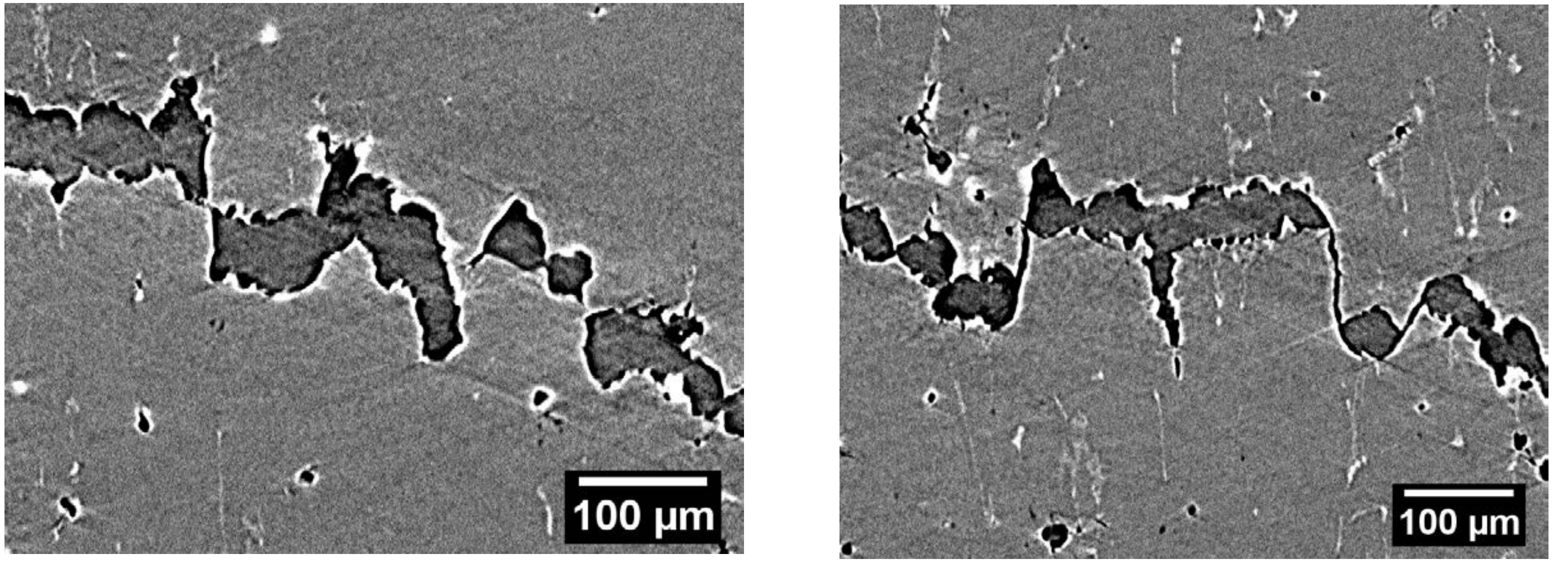
(Nemcko & Wilkinson, 2016)



(Barrioz, CEA)

Models to use in these situations ?

X-ray tomography to look inside the material

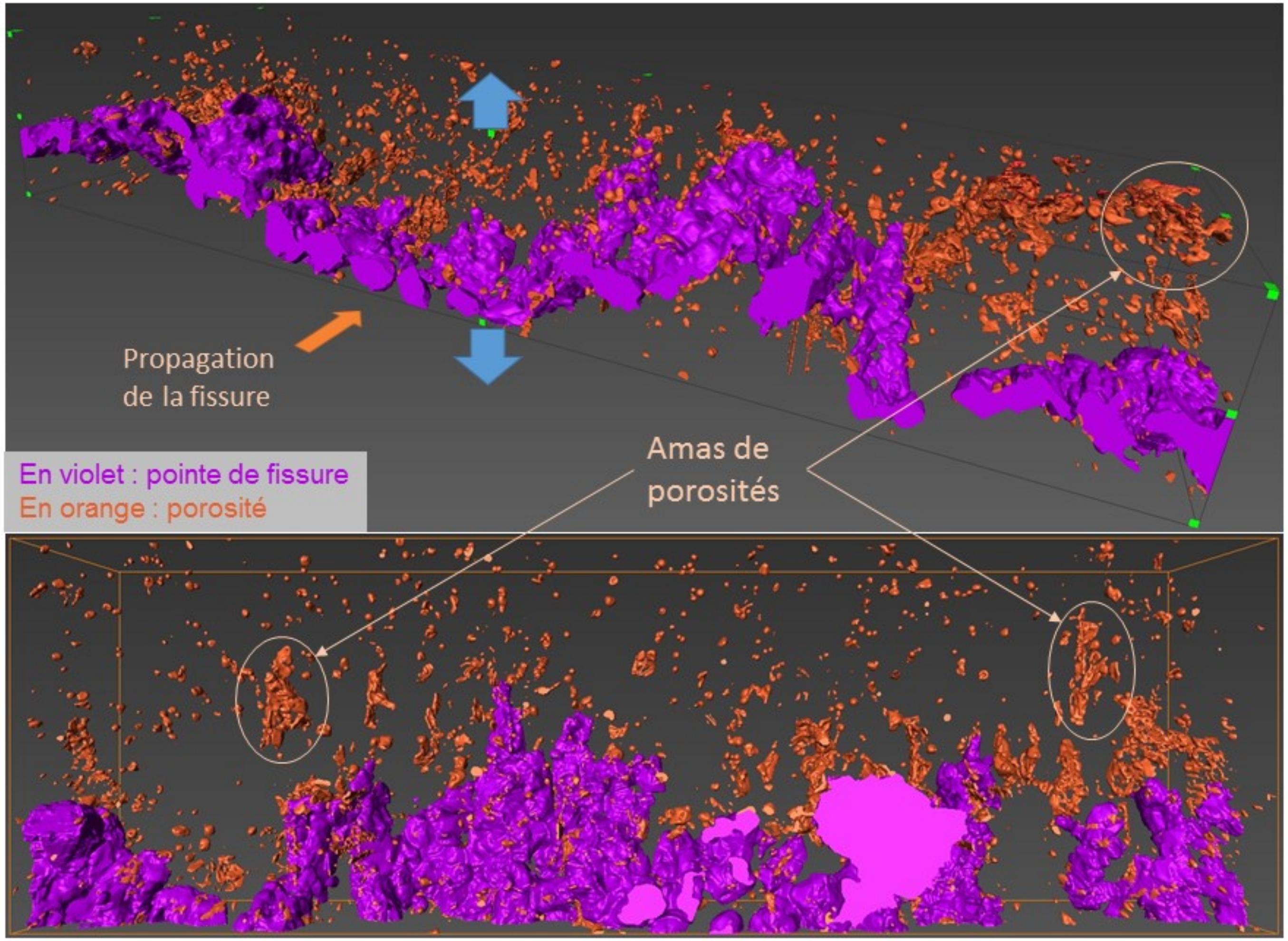


(Petit & Morgeneyer, CEA, Centre des Matériaux Mines)

- Allows visualizing voids inside materials
- Spatial resolution : down to hundreds of nanometers

⟹ ***Talk of Sylvain Dancette***

X-ray tomography to look inside the material



(Petit & Morgeneyer, CEA, Centre des Matériaux Mines)

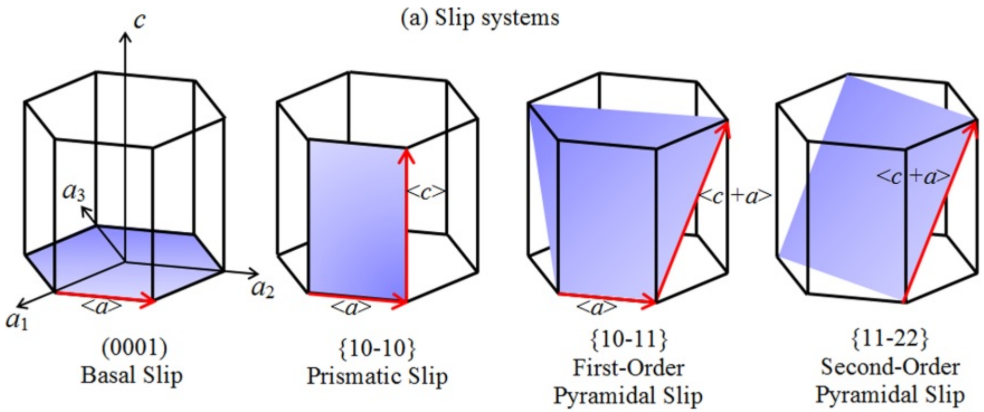
Models accounting for heterogeneities ?

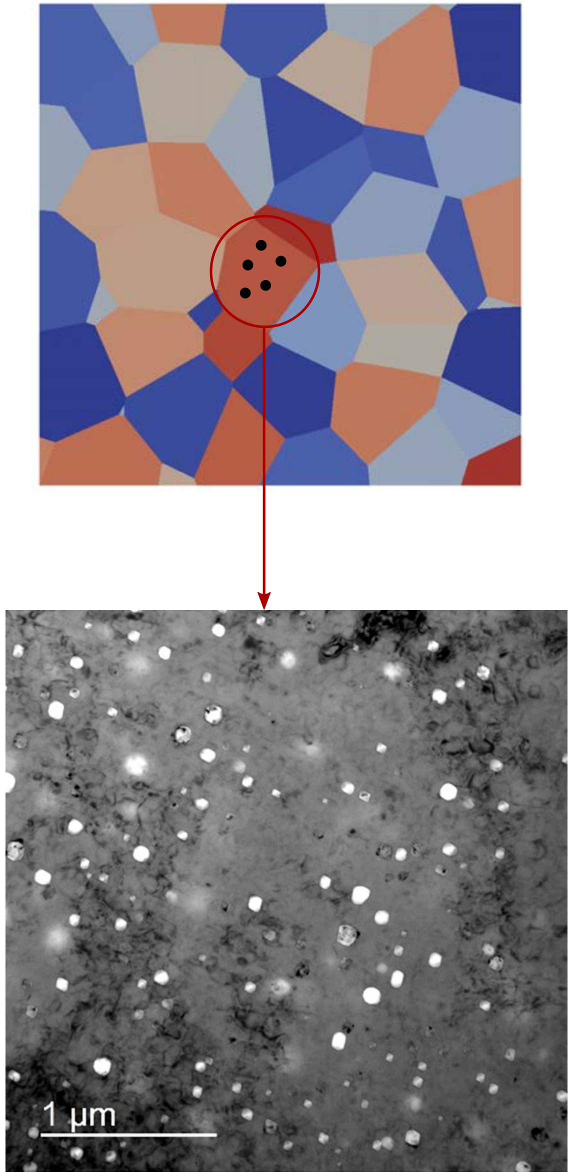
Voids at the crystal scale

- Small voids in polycrystalline materials
- Large voids in single crystals

What's different ?

- Plastic slips along well-defined directions / planes
- Strong effects of crystallographic orientations

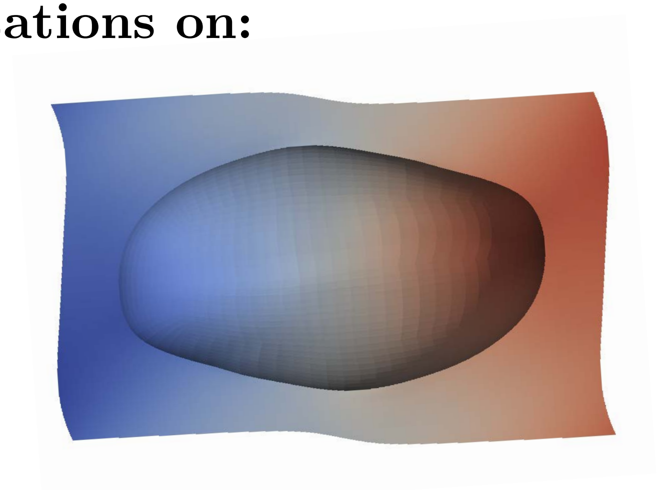


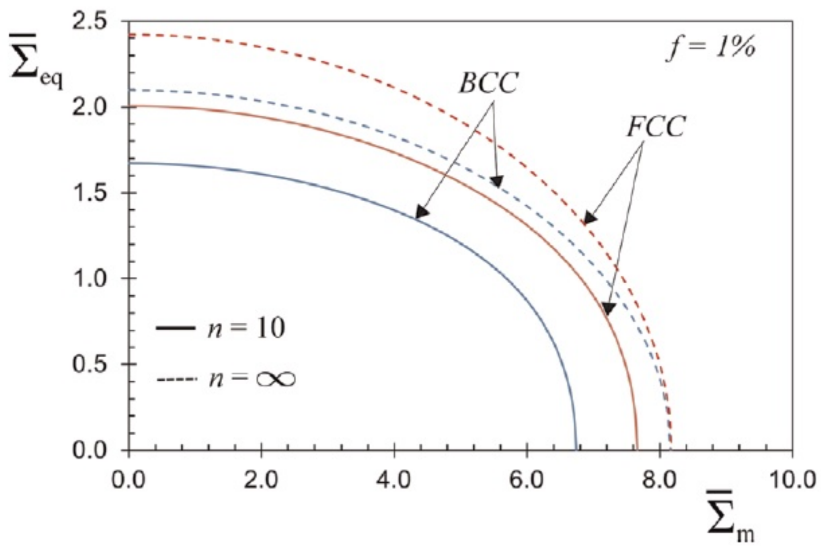


(Barrioz, CEA)

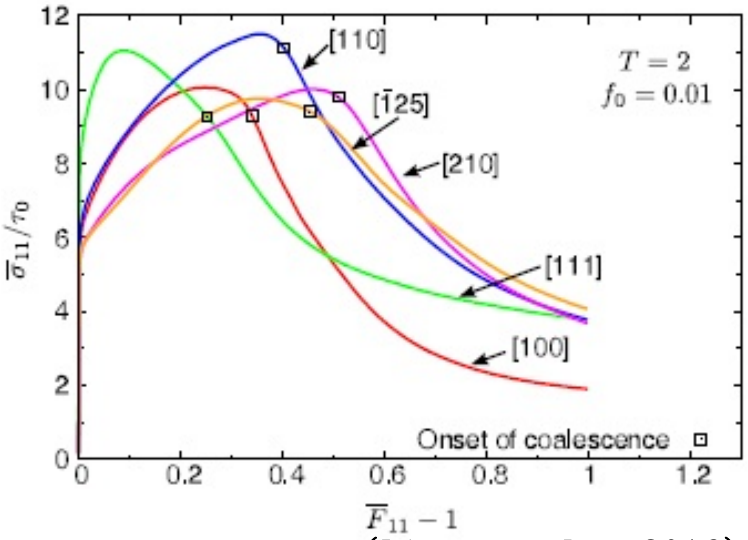
Strong influence of crystallographic orientations on:

- Homogenized yield criterion
- Porosity evolution
- Void shape





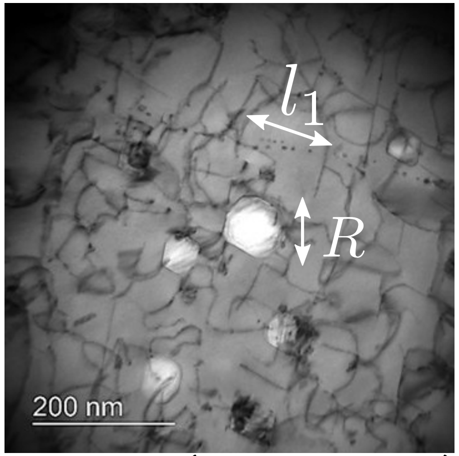
(Mbiakop et al., 2015)



(Ling et al., 2016)

$\Longrightarrow$ ***Talk of Kostas Danas***

Classical ductile fracture models have no lengthscale, but physical lengthscales appear naturally at lower scales

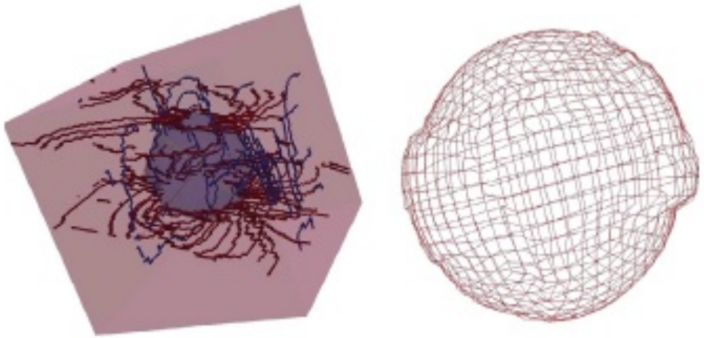


(Barrioz, CEA)

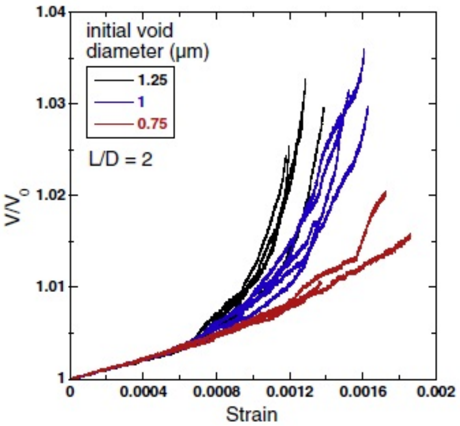
- Dislocation density ρ (m/m^3) "Plasticity lengthscale" $l_1 = 1/\sqrt{\rho}$

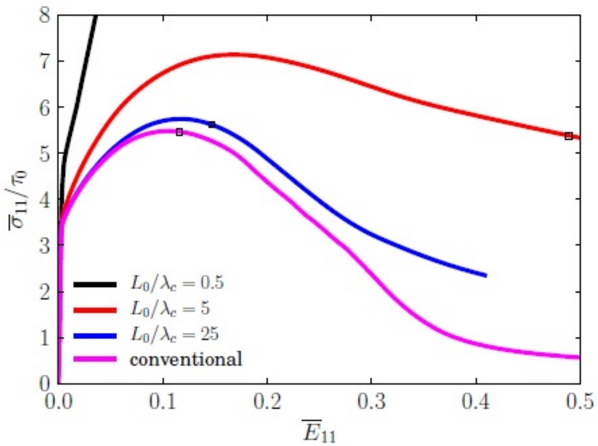
Dimensionless parameter $\boxed{\mathcal{P}_1 = R\sqrt{\rho}}$

  - $\mathcal{P}_1 \gg 1$ = Continuum case
  - $\mathcal{P}_1 \lesssim 1$



(Chang et al., 2015)

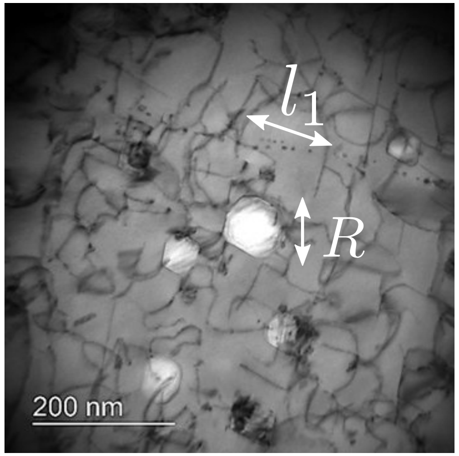




(Ling et al., 2017)

$$\left.\begin{array}{l}\bullet\ \text{Limited void growth due to dislocation starvation}\\[2em] \bullet\ \text{Additional hardening to strain gradient effect}\end{array}\right\}\ \textbf{Experimental results ?}$$

Classical ductile fracture models have no lengthscale, but physical lengthscales appear naturally at lower scales



(Barrioz, CEA)

- Dislocation density ρ (m/m^3) "Plasticity lengthscale" $l_1 = 1/\sqrt{\rho}$

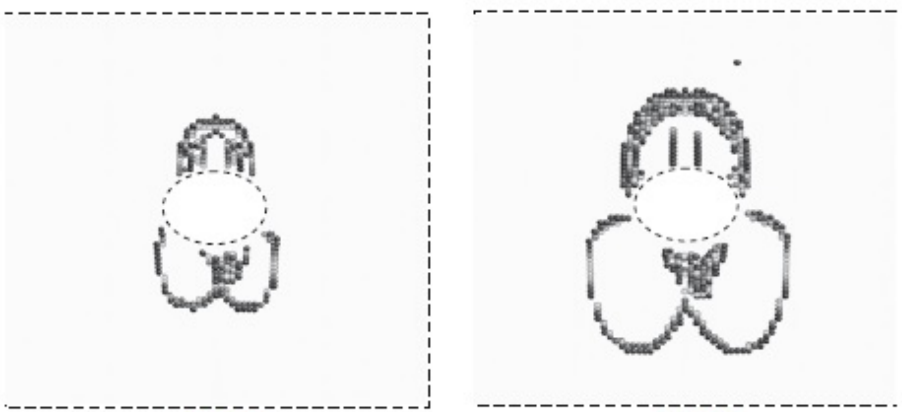
Dimensionless parameter $\boxed{\mathcal{P}_1 = R\sqrt{\rho}}$

- $\mathcal{P}_1 \gg 1$ = Continuum case
- $\mathcal{P}_1 \lesssim 1$

If no dislocations around:

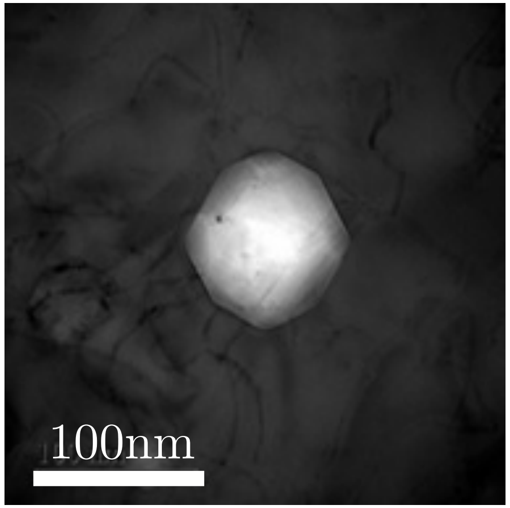
- Dislocation nucleation
- Void growth
- Very large stress required

Experimental results ?


(c) 50fs (d) 90fs

(Zhao et al., 2009)

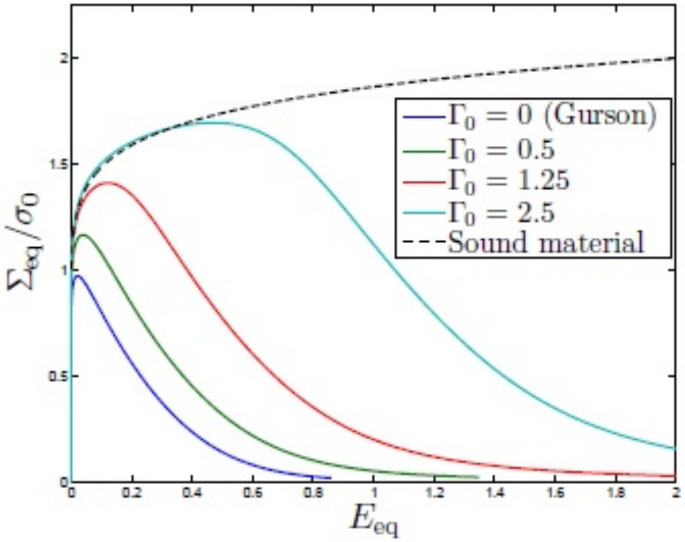
Classical ductile fracture models have no lengthscale, but physical lengthscales appear naturally at lower scales

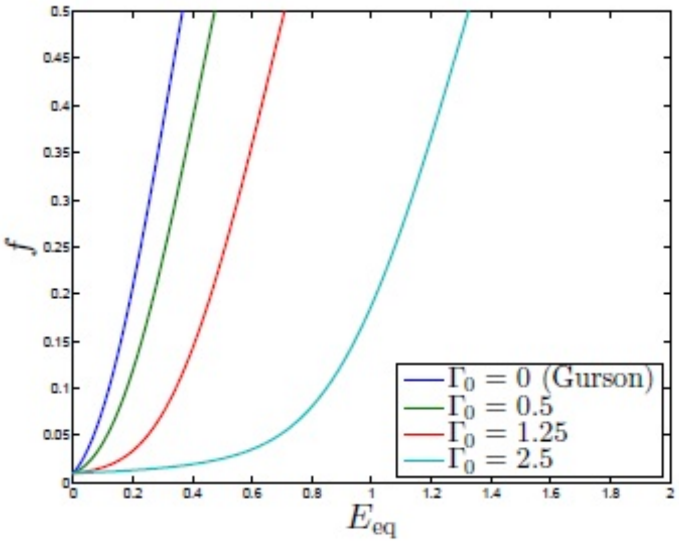


Surface tension of the void-matrix interface γ

$$\left.\begin{array}{ll} \text{Surface energy} & \Delta\mathcal{E}_\gamma \sim \gamma R \Delta R \\ \text{Plastic dissipation} & \Delta\mathcal{E}_p \sim \sigma_0 \dfrac{\Delta R}{R} R^3 \end{array}\right\} \quad \frac{\Delta\mathcal{E}_\gamma}{\Delta\mathcal{E}_p} = \boxed{\frac{\gamma}{\sigma_0 R}}$$

Hardening / delayed softening for smaller voids





(Morin et al., 2015)

Experimental results ?

Lots of things have been done, but even more to do !