Couplages thermomécaniques durant la déformation plastique de polycristaux métalliques

Eric CHARKALUK[1], Rian SEGHIR[1], Laurence BODELOT[2], Jean-françois WITZ[1], Philippe DUFRENOY[1]

[1]Laboratoire de Mécanique de Lille - CNRS UMR 8107, France
[2]Laboratoire de Mécanique des Solides - CNRS UMR 7649, France
eric.charkaluk@ec-lille.fr

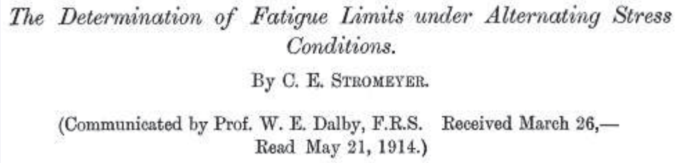
LABORATOIRE
de MECANIQUE
de LILLE
UMR CNRS 8107

E.C. LILLE
E.N.S.A.M.
U.S.T.L.

Outline

1. Motivations
2. Experiment and data treatments
3. Results and analysis
    - Multi-scale yield stress identification
    - Energy balance within polycristals
4. Conclusions and prospects

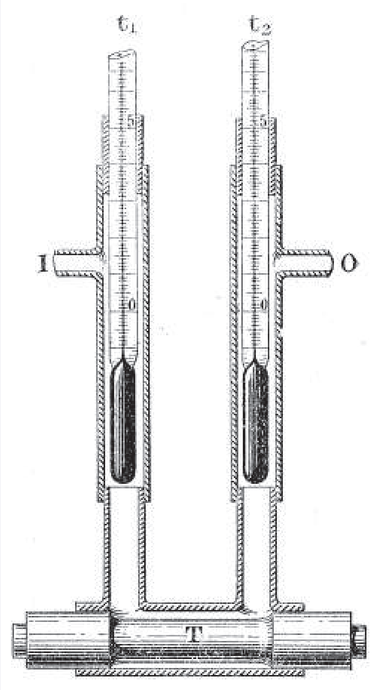
Self-heating tests



The Determination of Fatigue Limits under Alternating Stress Conditions.

By C. E. Stromeyer.

(Communicated by Prof. W. E. Dalby, F.R.S. Received March 26,—Read May 21, 1914.)



[Stromeyer, Proc. Roy. Soc., 1914]

Fatigue limit and temperature

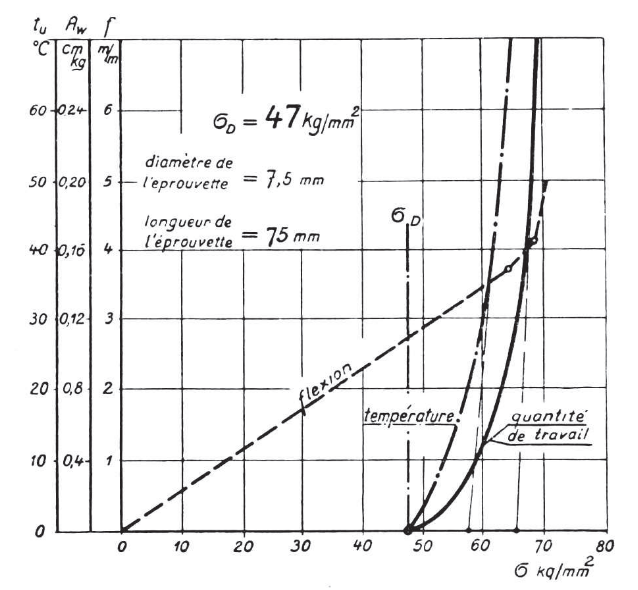
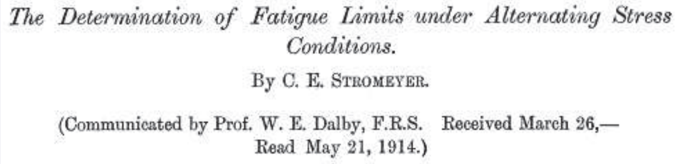


Fig. 59. — Variation de la flèche, de la température et de l'énergie absorbée en fonction de l'effort, au cours de la flexion rotative (Lehr).

[Lehr and Skiba, Mot. Tech. Zeit., 1943]

Self-heating tests



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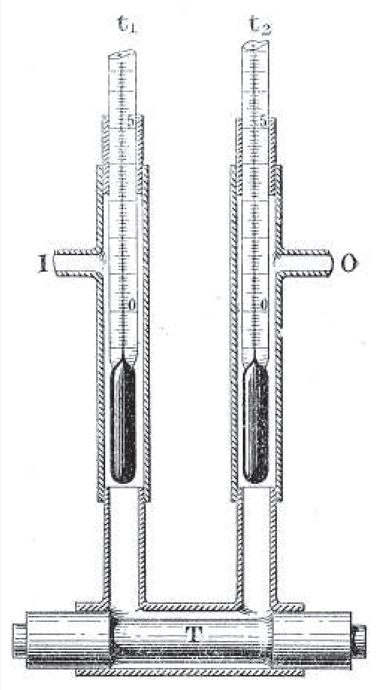
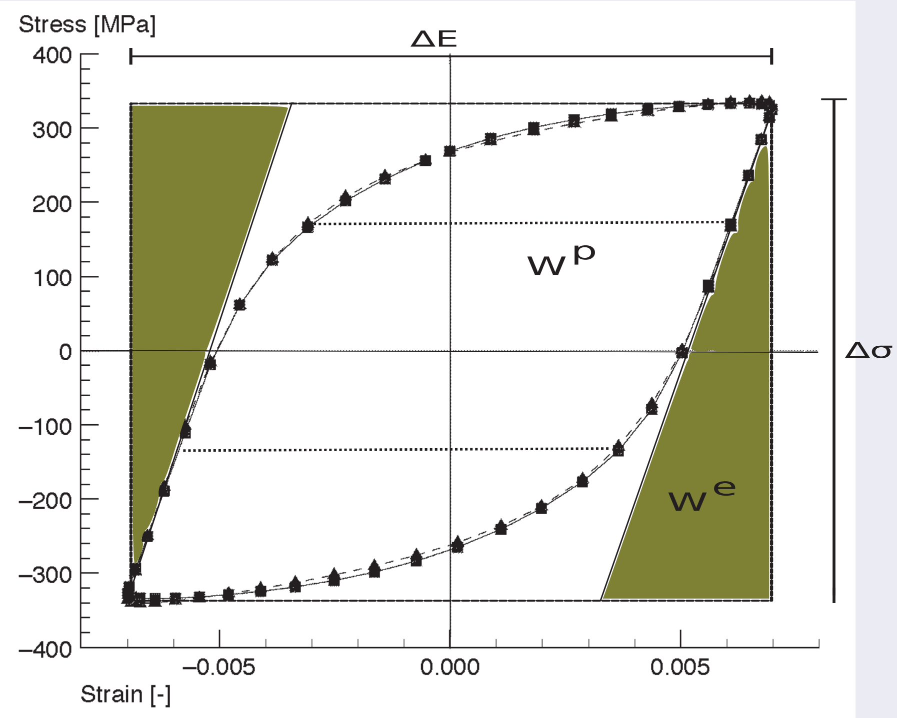


[Stromeyer, Proc. Roy. Soc., 1914]

Fatigue limit and temperature

- What are the origin of such thermal variations?
- Is there a link with shakedown concept?
- Is there a link with fatigue damage?

Cyclic loadings



A dissipative framework

- Inelastic strain energy → dissipation + storage
- Storage → Microstructural changes → Strain localization → Damage [Bever et al., Prog. Mat. Sci., 1973]

Heat coupled equation in classical plasticity

$$\rho C \frac{dT}{dt} - div(\underline{\underline{K}} \cdot \underline{grad}(T)) = \underbrace{(\underline{\underline{\sigma}} - \underline{\underline{X}}) : \dot{\underline{\underline{\varepsilon}}}_p - R\dot{p}}_{intrinsic\ dissipation} + \underbrace{T \frac{\partial \underline{\underline{\sigma}}}{\partial T} : \dot{\underline{\underline{\varepsilon}}}_e}_{thermoelastic\ coupling}$$

Calorimetry

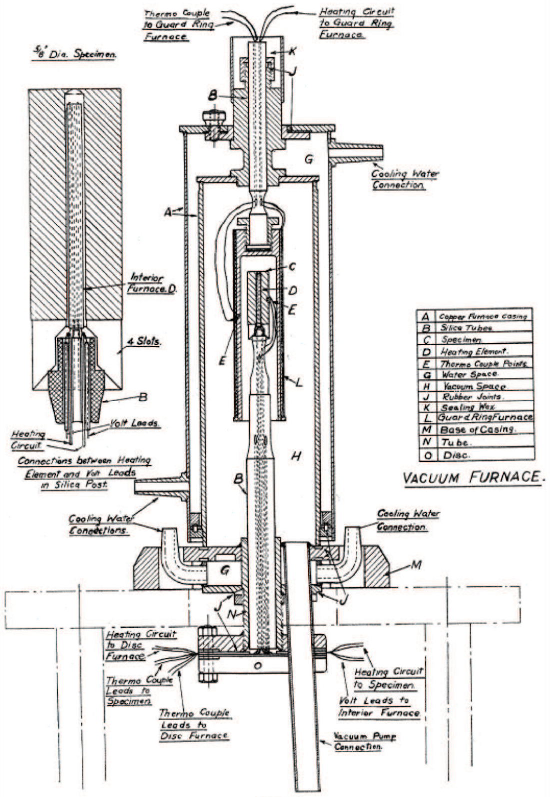


Fig. 4

[Quinney and Taylor, Proc. Roy. Soc., 1937]

$$\beta = 1 - \frac{\dot{d}}{\boldsymbol{\sigma} : \dot{\boldsymbol{\varepsilon}}^p} \subset [5, 20]\,\%$$

Infrared Thermography

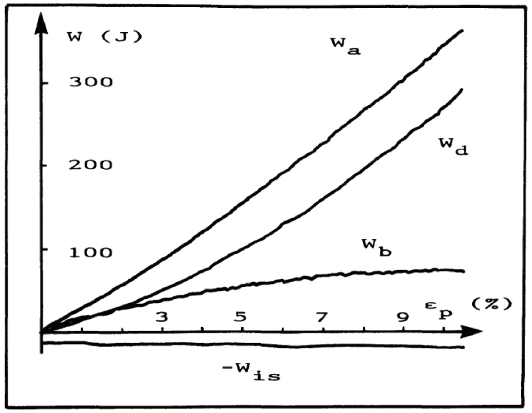


Fig. 6. — Bilan énergétique dans le cas d'un duralumin ; limitation de l'énergie bloquée.

[Energy balance in case of duralumin ; stored energy limitation.]

[Chrysochoos et al., Nucl. Engng. Design, 1989]

Classical constitutive laws are not "thermomechanically admissible", i.e. respect energy balance

Towards the microstructure

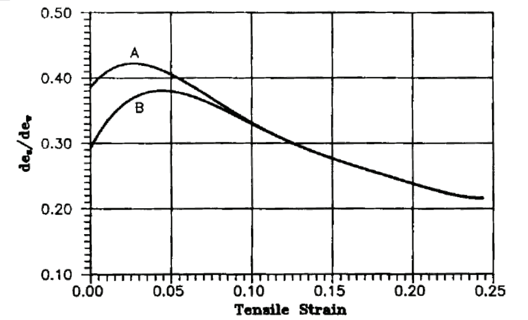
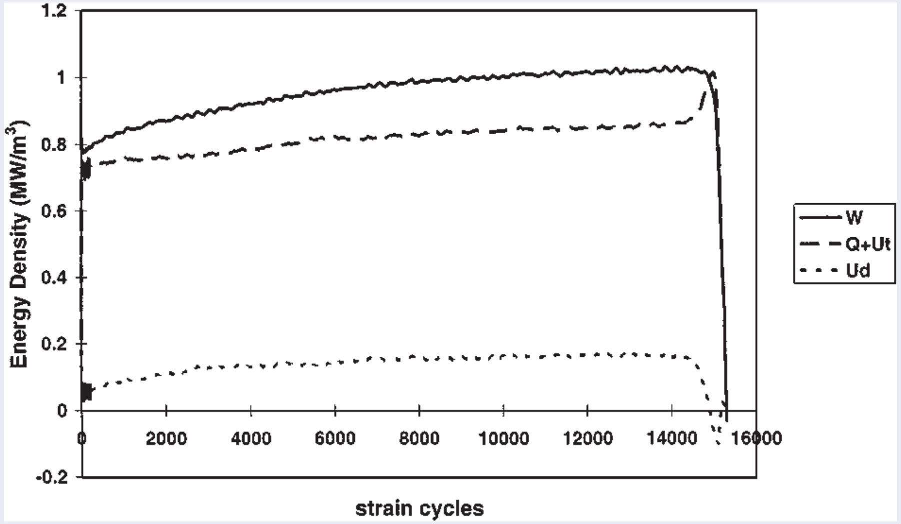


Fig. 7. Dependence of de_s/de_W vs. strain for the fine-grained (curve A) and coarse-grained (curve B) samples.

[Oliferuk et al., Mat. Sci. Eng. A, 1995]

β depends on the microstructure (grain size ...)

Macroscopic energy balance in fatigue

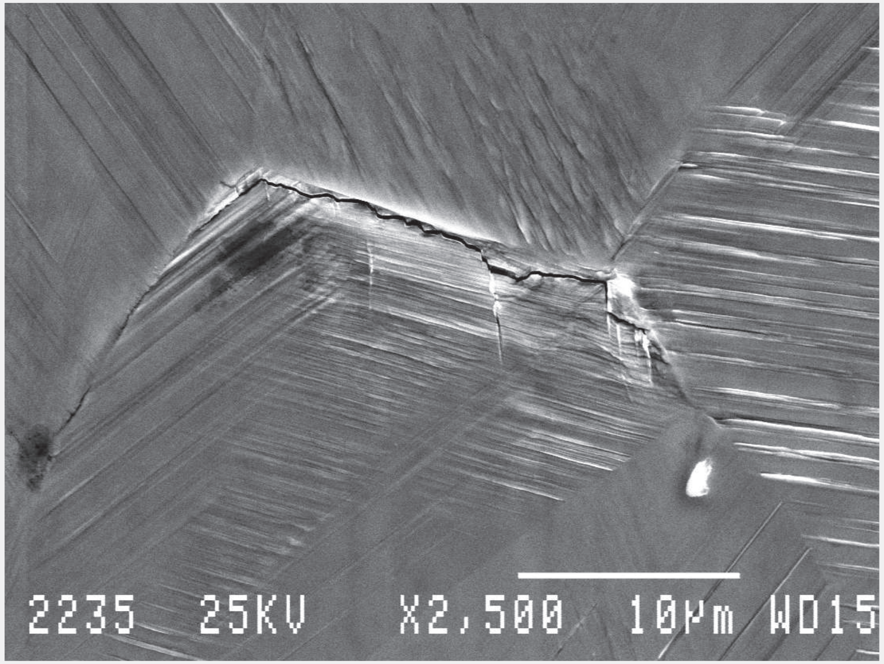


[Harvey et al., J. Mat. Sci. Lett., 2000]

Fatigue process in polycrystals

- Polycrystal: grain aggregates with boundaries
- Crack initiation: PSB, GBs, TBs, defects. . .
- Local cyclic energy variations? **How? Where? Why?**

Crack initiation in a AISI 316L stainless steel



[Sabatier, 2002]

Fatigue process in polycrystals

- Polycrystal: grain aggregates with boundaries
- Crack initiation: PSB, GBs, TBs, defects. . .
- Local cyclic energy variations? **How? Where? Why?**

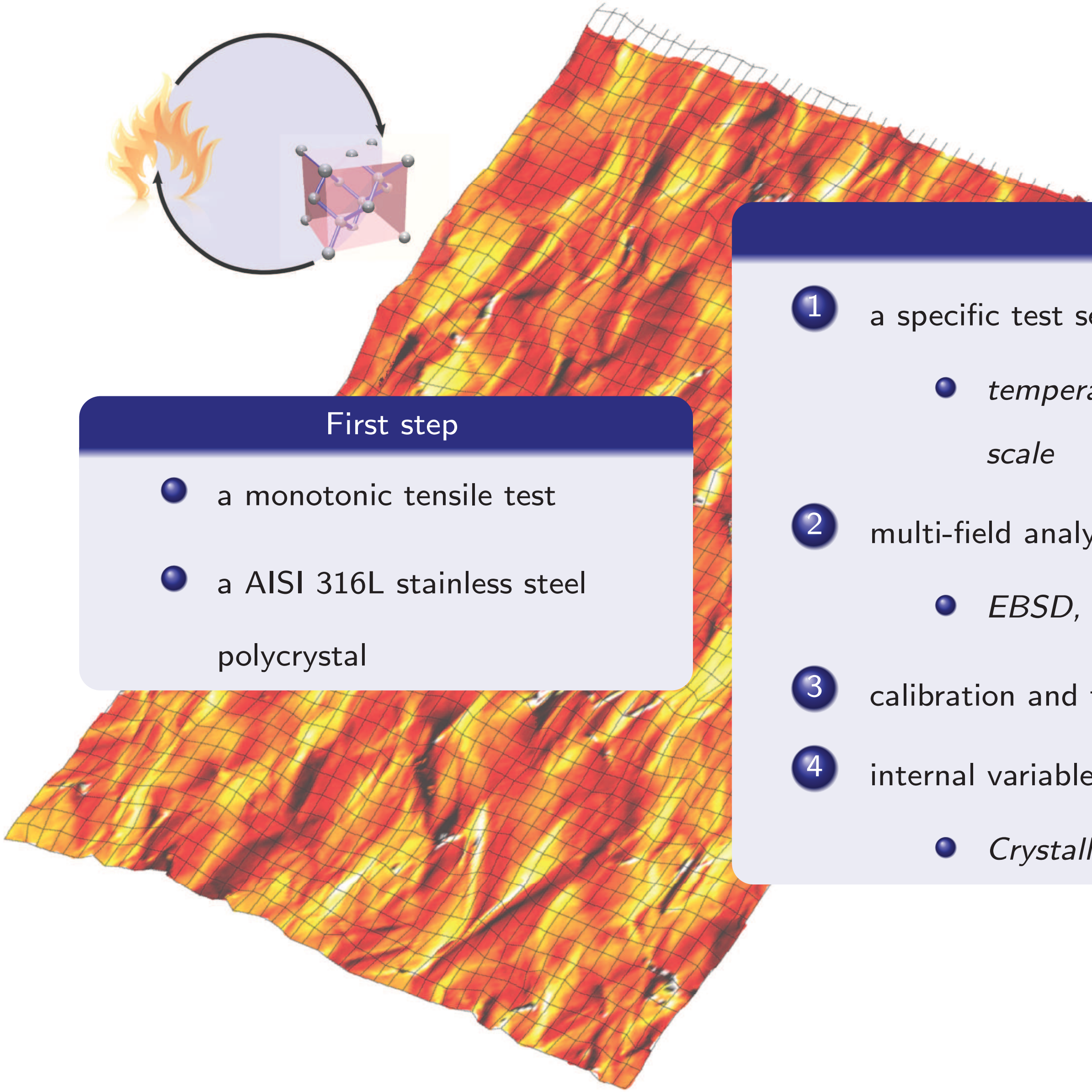
Fatigue: an energy driven process?

- Can we see fatigue as an energy storage/release process?
- Does crack initiation correspond to a stored energy limit?

[Tanaka and Mura, J. Appl. Mech., 1981]

Materials and methods

- A specific setup: ideally, **temperature**, stress and **strain** full-fields in polycrystals
- Single crystals, oligocrystals, **polycrystals**
- **Monotonic** tensile tests
- LCF tests
- HCF / VHCF tests



First step

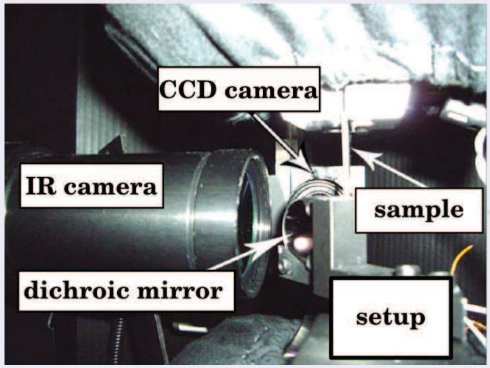
- a monotonic tensile test
- a AISI 316L stainless steel polycrystal

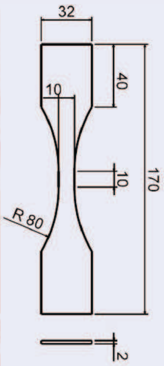
Some requirements

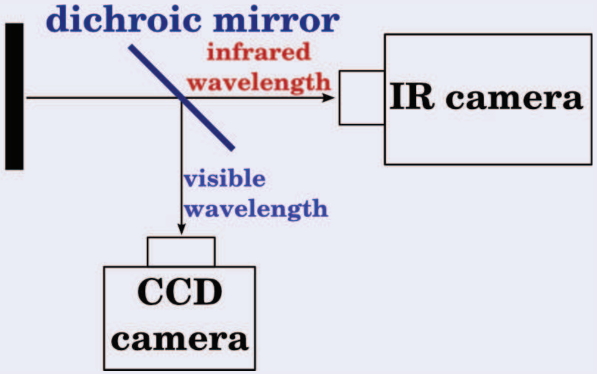
1. a specific test setup
    - *temperature and displacement fields at the grain scale*
2. multi-field analysis at the grain scale
    - *EBSD, profilometry, optical micrography*
3. calibration and treatment tools
4. internal variables
    - *Crystalline Plasticity F.E. strategy*

An original test setup

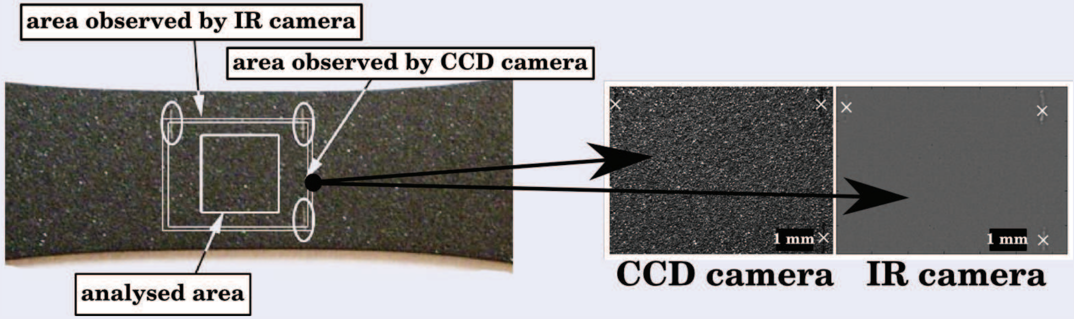
Dichroic mirror able to separate infrared and visible wavelength







Specific coating adapted to Digital Image Correlation (speckle aspect) and thermal measurements (uniform aspect)

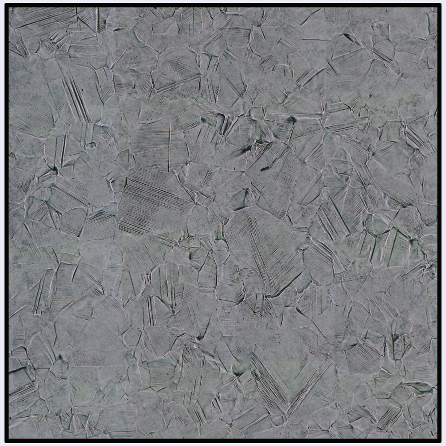


AISI 316L stainless steel heat treated for 2 hours at 1,200^{o}C and water-quenched (mean grain size $\approx 120\mu m$)

[Bodelot et al., Mat. Sci. Eng. A, 2009] [Bodelot et al., Mech. Mat., 2011]

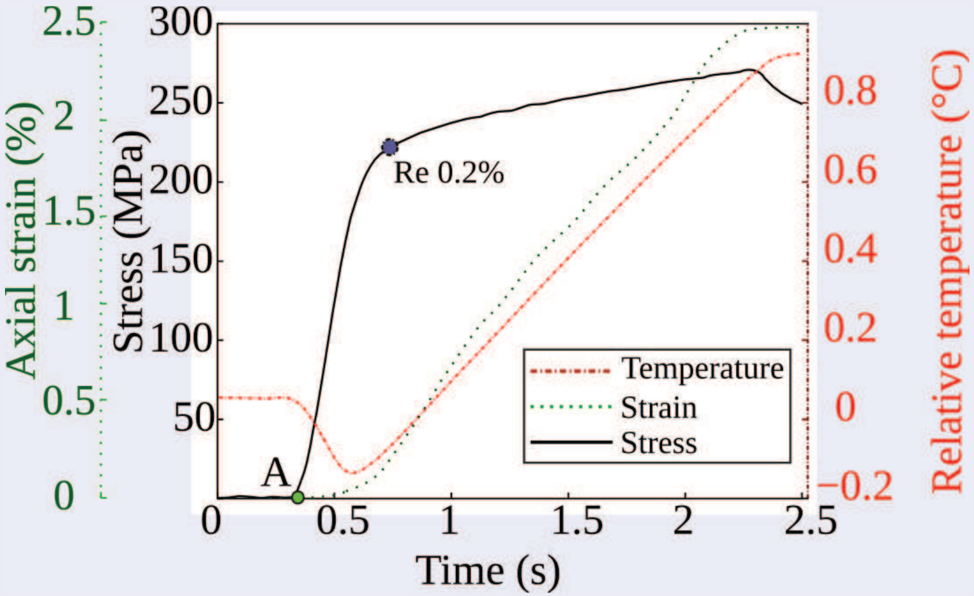
A material and a test

Microstructure: 1,776 grains on surface



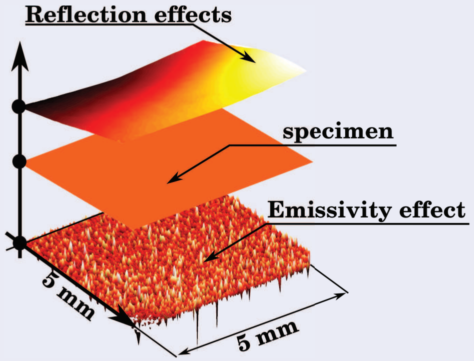
surface microstructure (5x5mm^2)

A monotonic tensile test



Tensile test at $5 \cdot 10^{-3}\ s^{-1}$

A flux-based thermal calibration

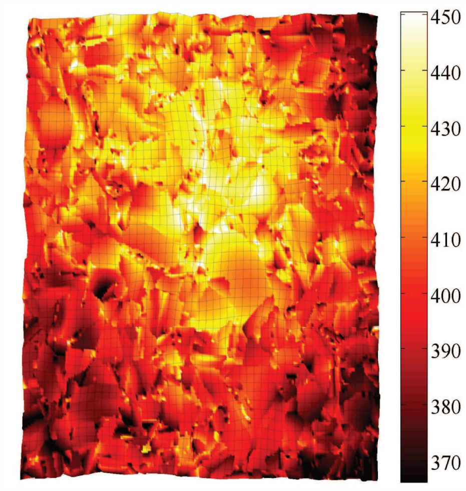


local emissivity map

from radiations to temperature

[Seghir et al., QIRT J., 2013]

A data projection



first-order discontinuities

thermal and displacement fields

[Seghir et al., Mech. Ind., 2013]

A thermoplastic simulation

internal variable estimation

[Seghir et al., C. Mat. Sc., 2012]

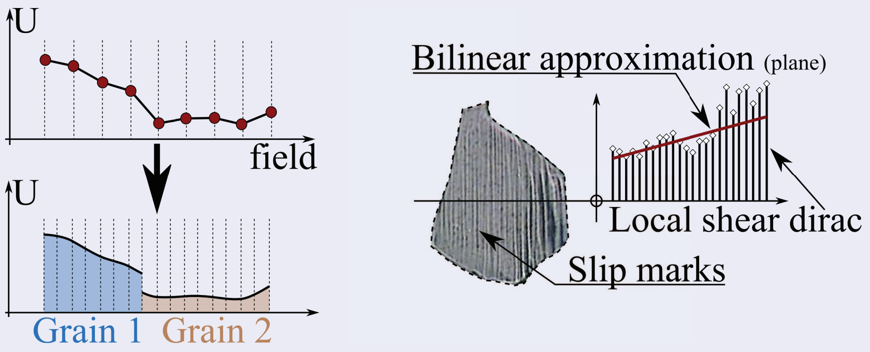
Full-fields microstructural analysis

A cristallography-based projection

- 1^{st} order discontinuity: grain boundary network
- piecewise continuous (intragranular domain)

Assumptions

- assumes discontinuities at grain boundary: *Kapitza effect, strain incompatibilities . . .*
- projection base
  - biparabolic displacement field per grain → bilinear strain field
  - biparabolic thermal field per grain → constant heat losses
  - analytic approach of intragranular domain
- additive decomposition (Field + Residue)



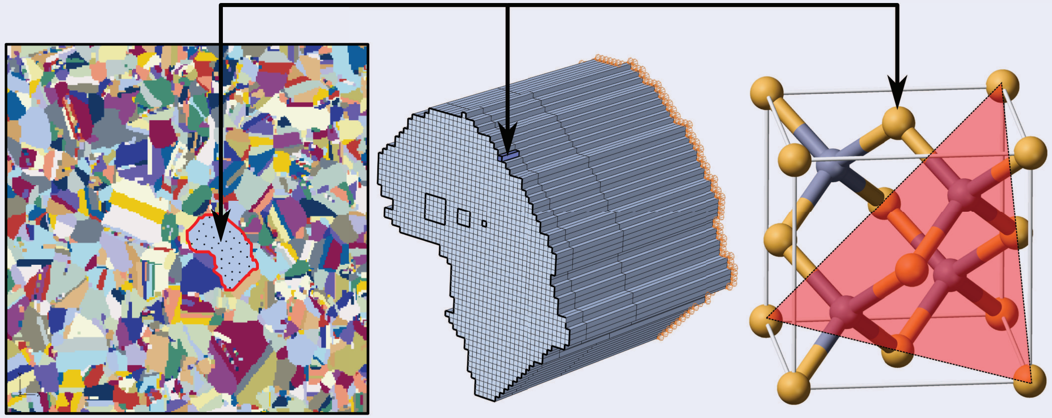
Crystal thermoplasticity framework

Originality

crystalline plasticity and thermo-coupled finite element model

[Huang, Harvard University Report, 1991]

1,776 grains || DOF $>$ 1,000,000 || 12 slip-systems CFC



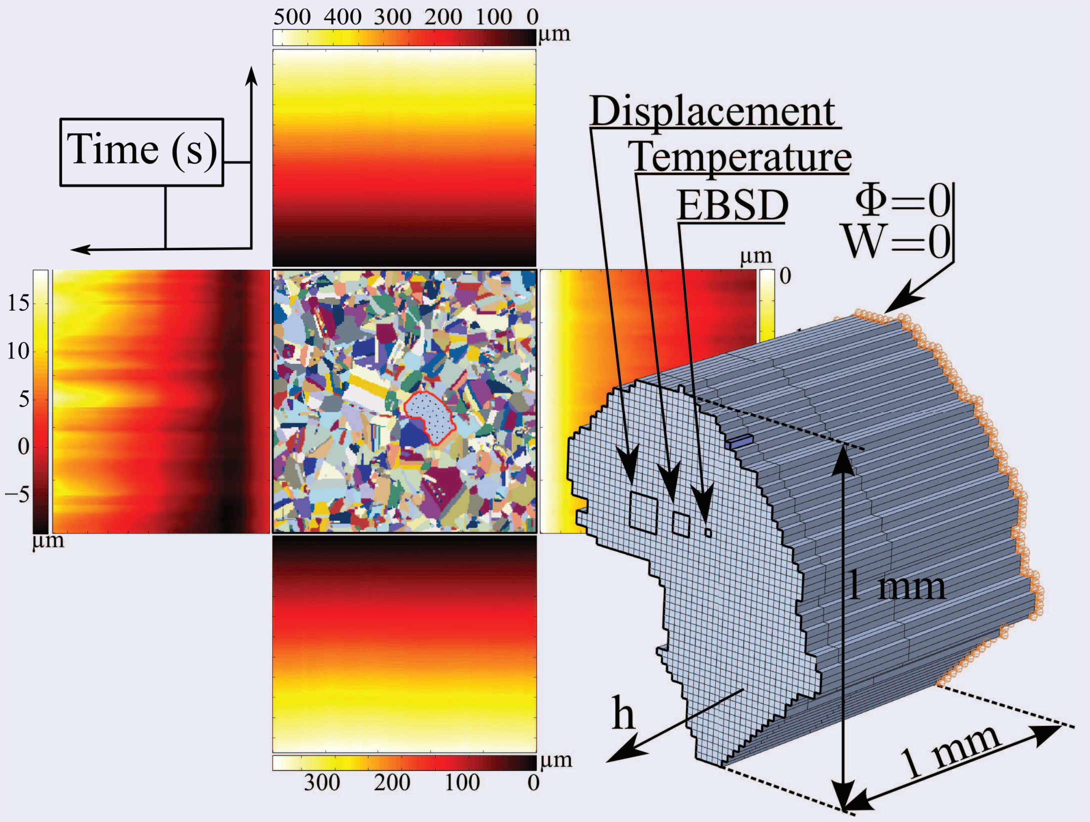
F.E.M. and constitutive law

- Abaqus/standard and Fully Coupled Thermo-Mechanical calculation
- regular mesh (C3D8TR)
- dislocation density based (SSD)
- isotropic hardening (UMat)

Crystal thermoplasticity framework

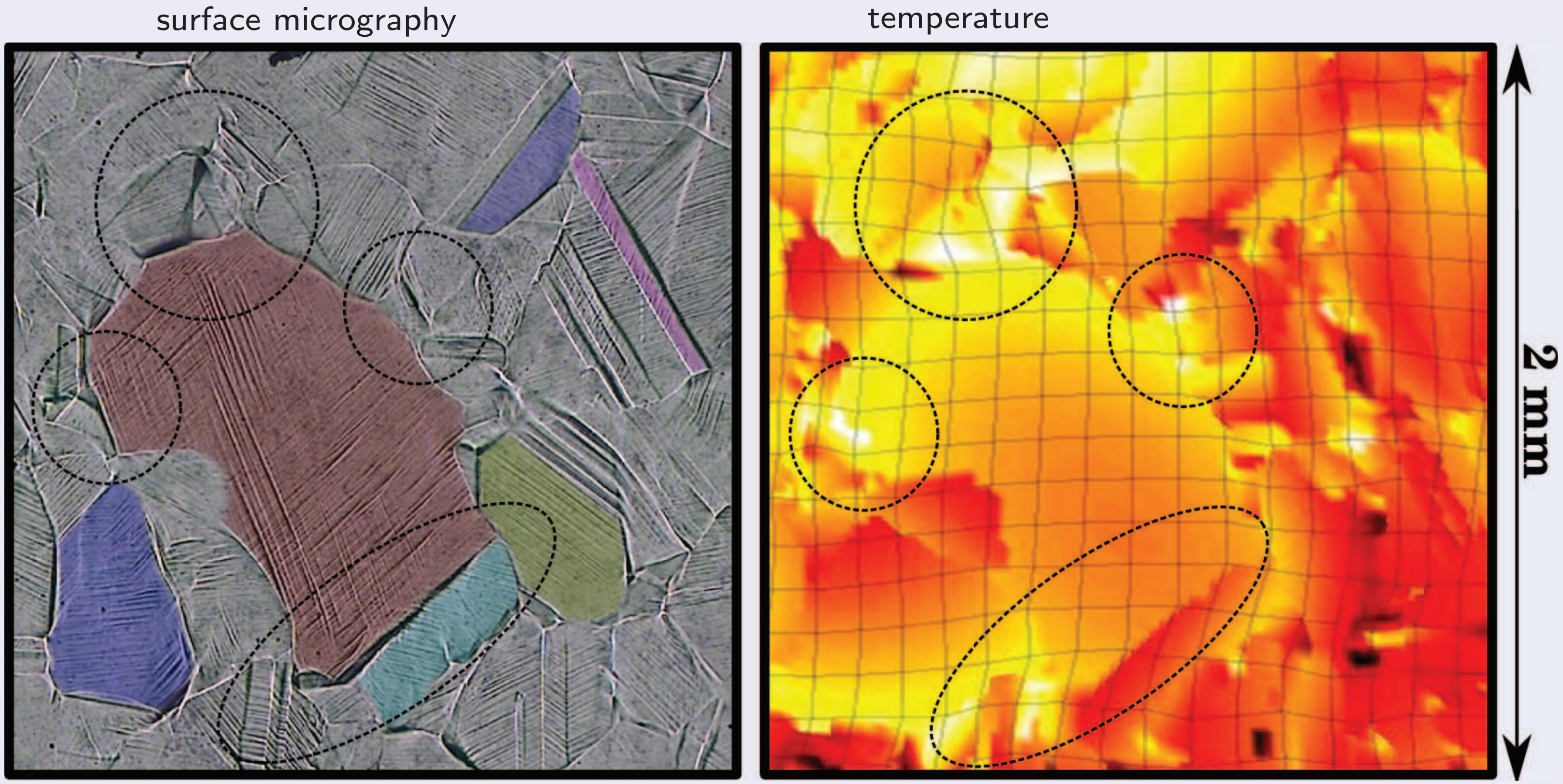
Ingredients

- U_{exp} and T_{exp} at boundary nodes
- columnar boundary conditions
- symmetry on backface
- natural surface convection



Physical discontinuities

Importance of grain and twin boundaries [Kapitza, Phys. Rev., 1941]



Fully coupled database

Material

- AISI 316L
- $\text{grain}_{Diam} \approx 120 \mu m$

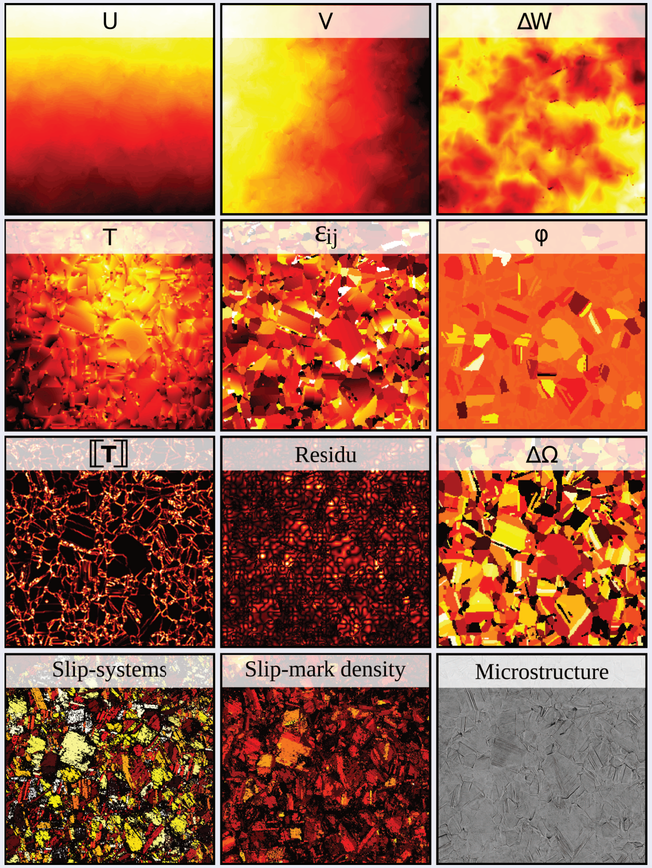
Test

- $\varepsilon \in [0 \rightarrow 2.5]\,\%$
- $T \in$ $[-0.17 \rightarrow 0.8]\ K$
- Zone: 5x5 mm^2

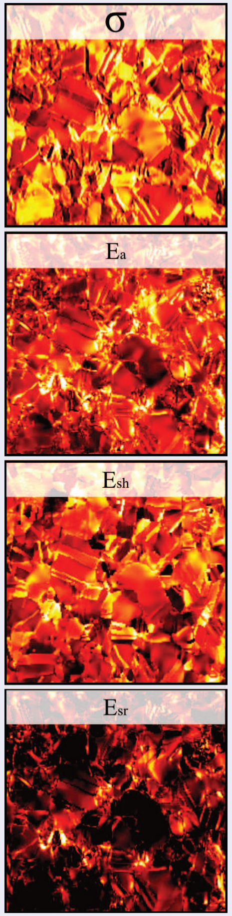
Resolutions

- **104x104 μm^2**
- IR_{freq}: 25 Hz
- **IR_{res}: 30 mK**
- $\underline{\text{U}}_{freq}$: 7 Hz
- $\underline{\text{U}}_{res}$: 4x$10^{-2}$ μm

Experimental (macroscopic scale)



Numerical (macroscopic scale)



Fully coupled database

Originality

intragranular heterogeneous datas

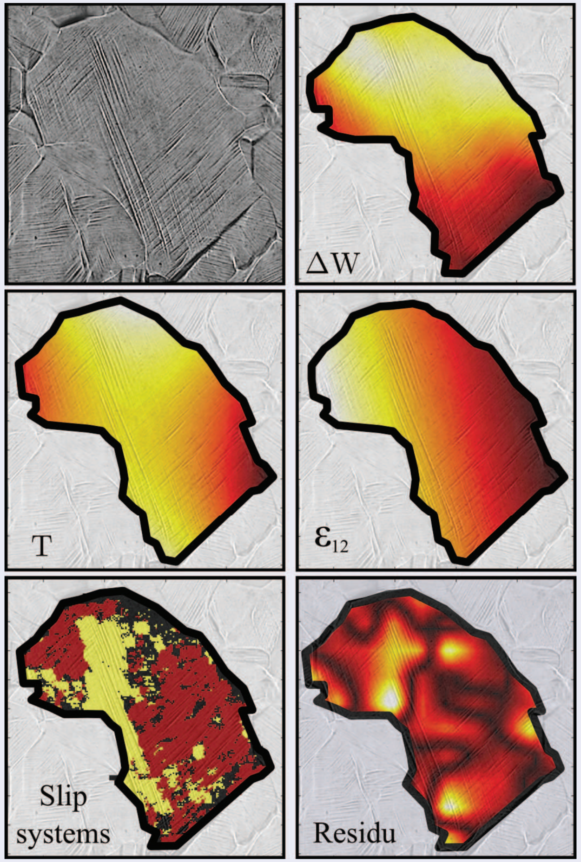
Intragranular domain

84% of grains> 104x104 μm^2

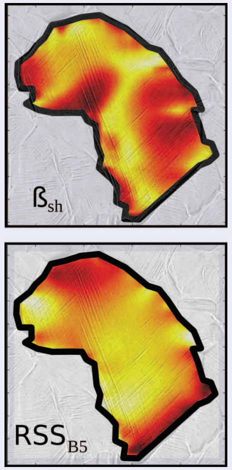
20 grains> 400x400 μm^2

2 millimetric grains

Experimental (intragranular scale)



Numerical (intragranular scale)



Multi-scale yield stress identification

from macroscopic to intragranular plasticity

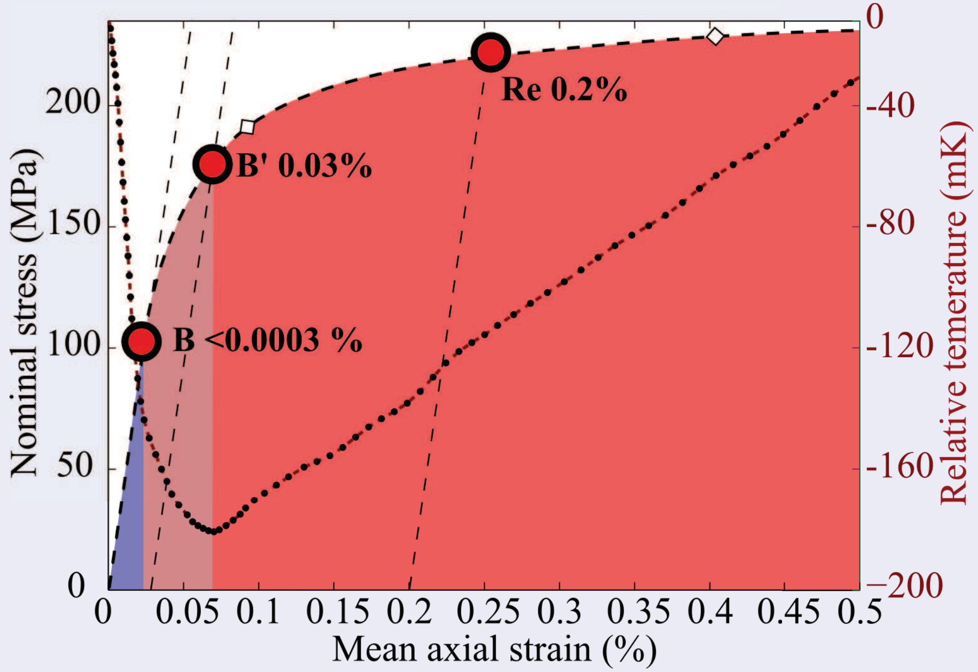
Multi-scale yield stress identification: macroscopic scale

3 thermal phases

1. linear drop: *elasticity*
2. inflection: *micro dissipation*
3. increase: *global dissipation*

[Lee, J. Mat. Sci., 1991]

Macroscopic results



Conclusion

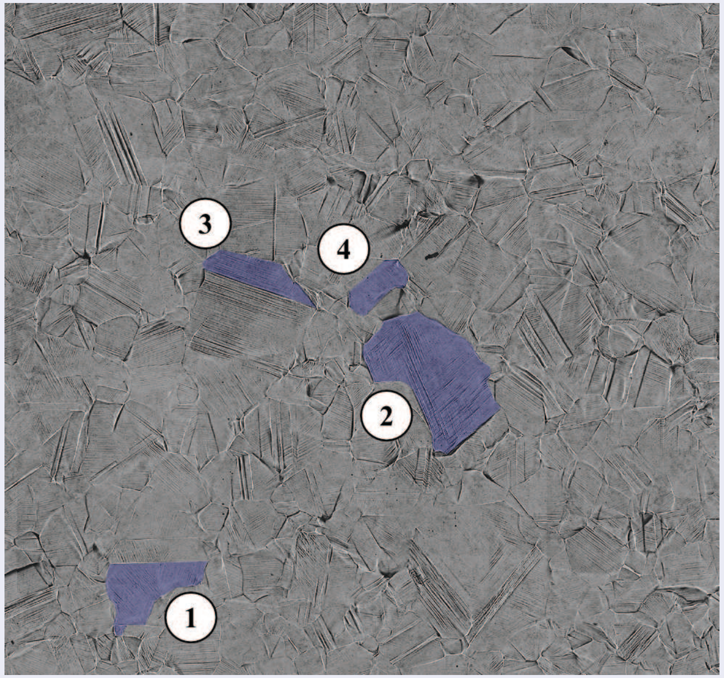
Identification of a macroscopic yield of dissipation → $\varepsilon^{p} < 10^{-4}\%$

by means of Maximum Likehood method and deviation from thermal linearity

Multi-scale yield stress identification: intragranular plasticity

Multi-scale yield stress identification: intragranular plasticity

Critical Resolved Shear Stress in individual grains

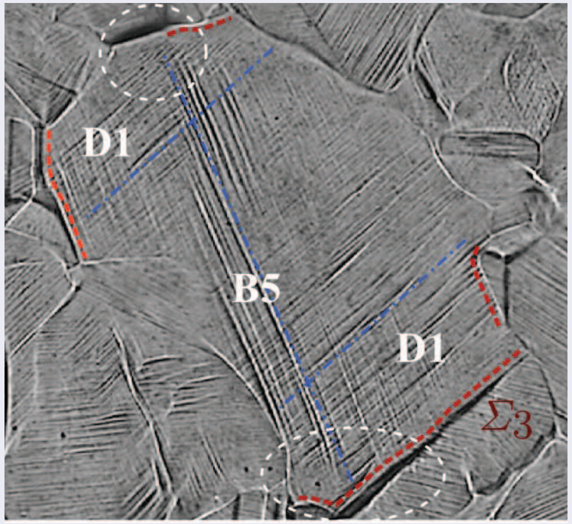


Multi-scale yield stress identification: intragranular plasticity

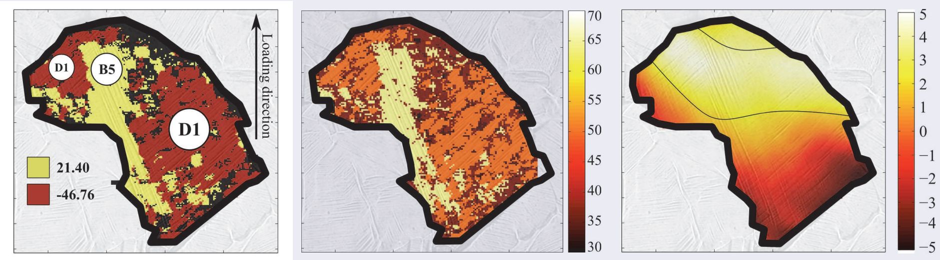
Deformation scenario

2 distinct plastic domains $D_1 \rightarrow B_5$

Micrography



Crystallographic point of view: slip-systems



Slip orientation Slip density Profilometry in µm

- significant impact of slip-systems on surface topography
- maximum Schmid factor principle: system D_1 (0.339) then B_5 (0.296)

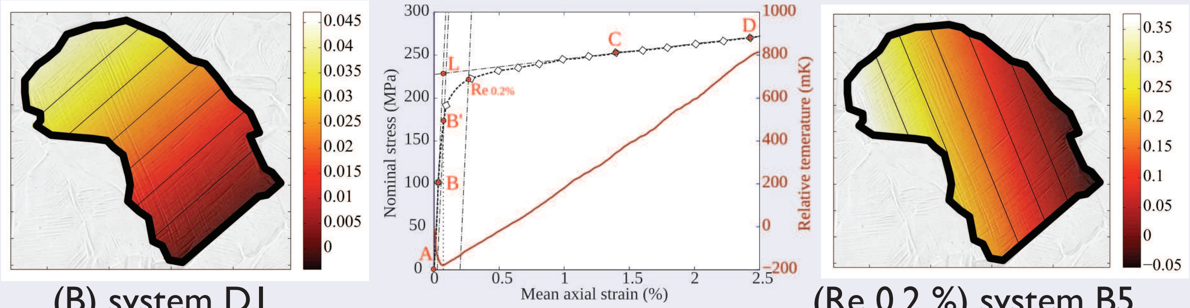
Multi-scale yield stress identification: intragranular plasticity

Deformation scenario

- $D_1 < 106$ MPa
- $191 < B_5 < 220$ MPa
- $\tau_c = 35$ MPa

$$\boldsymbol{\sigma} = \mathbb{C}_{loc} : \boldsymbol{\varepsilon}^e \rightarrow \tau^s = \boldsymbol{\sigma} : \mathbb{M}^s$$

Kinematic point of view: ε_{12}



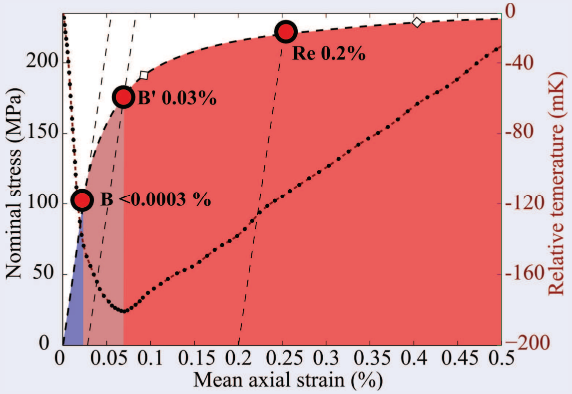
(B) system D1 (Re 0.2 %) system B5

- in-plane slip isovalues in agreement with slip-marks orientations
- in line with Schmid theory: system D_1 then B_5
- no or neglectable multiple shear

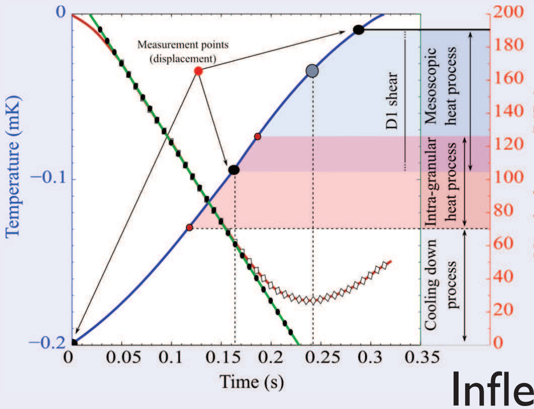
Multi-scale yield stress identification: intragranular plasticity

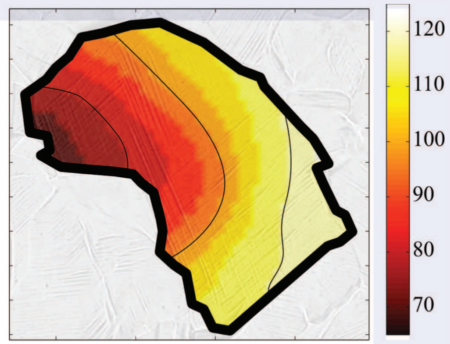
Deformation scenario

- kinematic → $\tau_c = 35$ MPa
- D_1 dissipates early
- temperature → $\tau_c = 25$ MPa



Thermal point of view: local temperature inflection





Inflection = f(nominal stress)

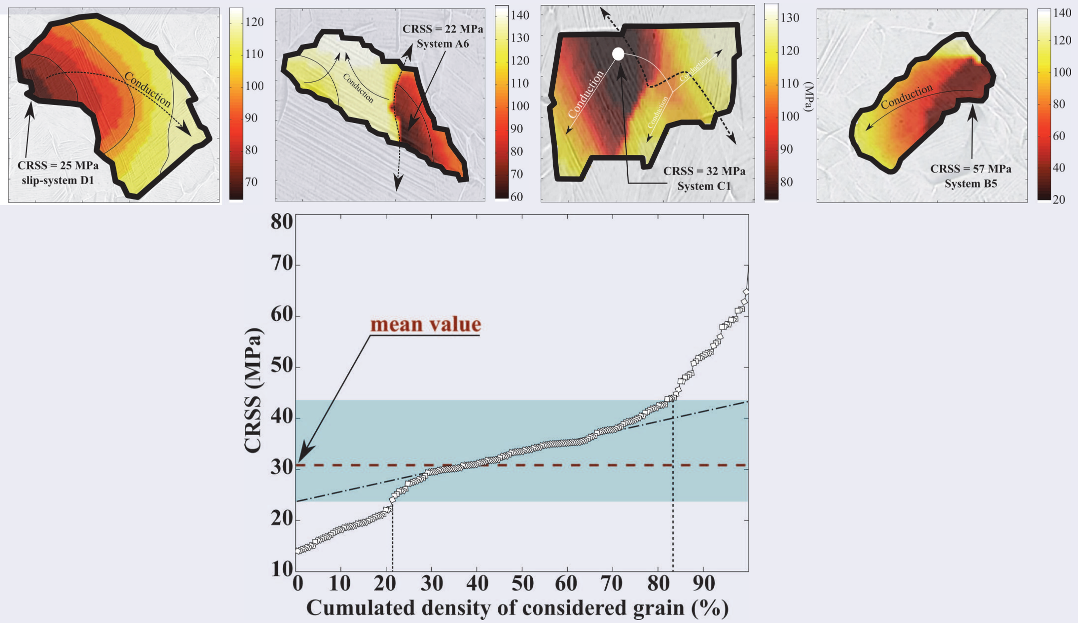
- intragranular thermal deviation from linearity at 78 MPa

Multi-scale yield stress identification: intragranular plasticity

Deformation scenario

- 2 distinct plastic domains $D_1 \rightarrow B_5$
- kinematic $\rightarrow \tau_c = 35$ MPa
- temperature $\rightarrow \tau_c = 25$ MPa
- generalization:
  - grain diameter $> 104 \mu m$
  - early inflection (165 grains)

Statistical point of view: 165 grains



Conclusion

CRSS = 31 MPa ±7 MPa within the polycrystal

in line with [Feaugas, Adv. Eng. Mater., 2009] within AISI 316L single crystal

Energy balance within polycristal

Intra- and intergranular stored energy

Energy balance within polycristals

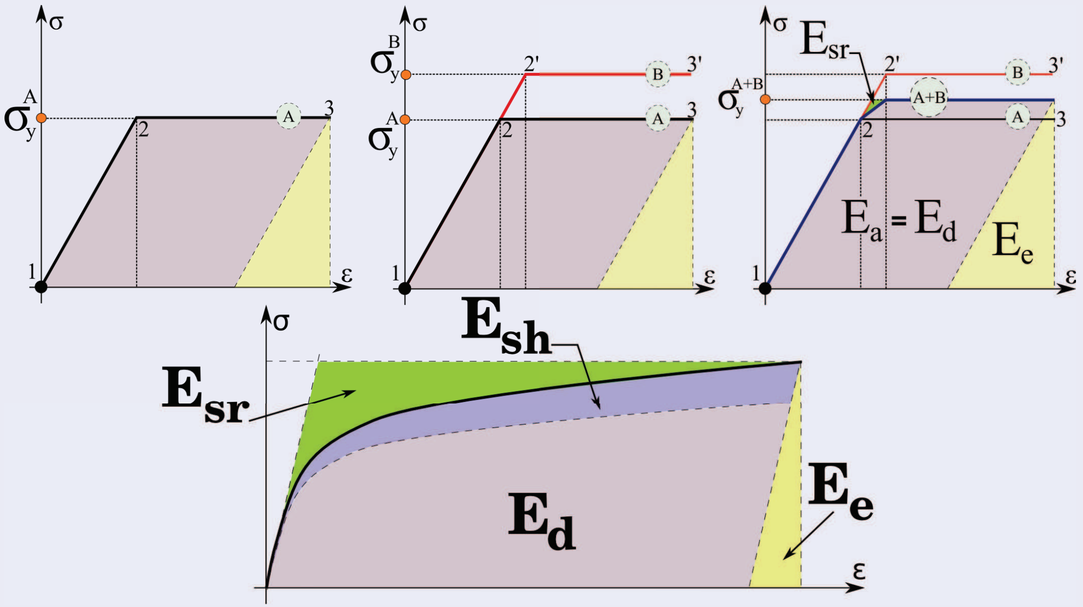
Storage mechanisms in polycrystals

1. E_{sr} → stored elastic energy due to internal stresses field resulting from incompatibilities
2. E_{sh} → stored energy due to the hardening process (dislocations)

Measurements

1. $E_s = E_{sh} + E_{sr}$ → macroscopic energy balance
2. E_{sr} → stress-strain curve
3. E_{sh} → constitutive law

Principle: elastic perfectly plastic bi-crystal



Polycrystals with local hardening

Energy balance within polycristal: macroscopic scale

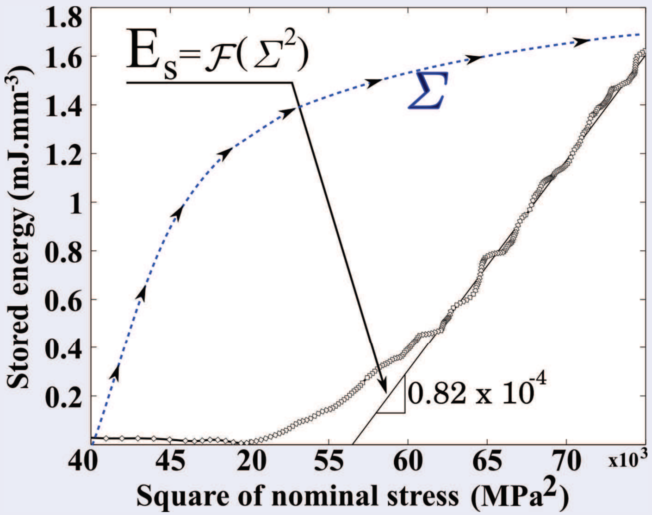
Theory: storage within dislocations only

$$E_s = \frac{m^2 \alpha_s}{\alpha^2 \mu} \Sigma^2 \approx 0.8\text{x}10^{-4} \Sigma^2$$

[Schmid and Boas, 1950] [Bailey and Hirsch, 1960] [Williams, 1964] [Bever et al., 1973]

- m: Schmid factor
- α: a constant ≈ 0.3
- α_s: a constant $\in [1.8 - 2.1]$
- μ: the shear modulus

Relation between stored energy and nominal stress

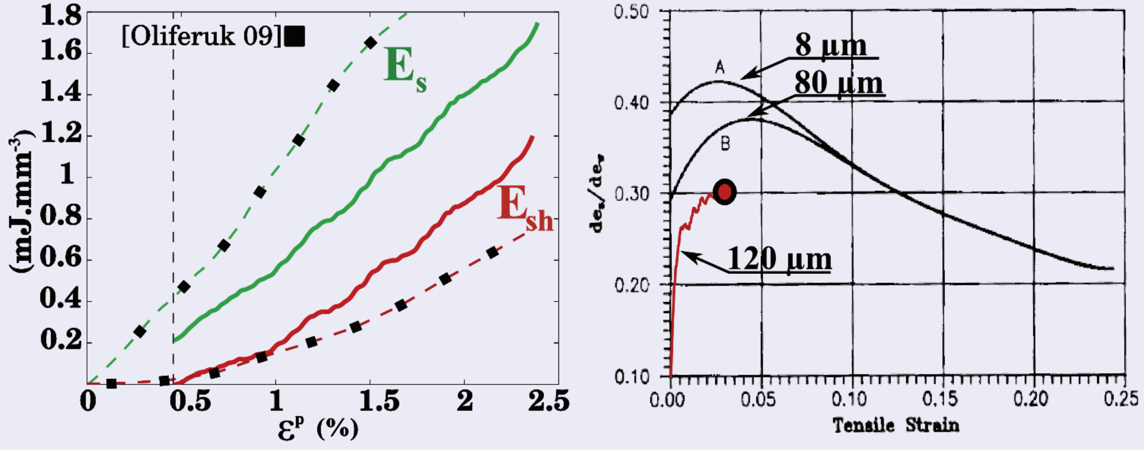


Conclusion

linear hardening mainly due to dislocation

Energy balance within polycristal: macroscopic scale

Macroscopic storage



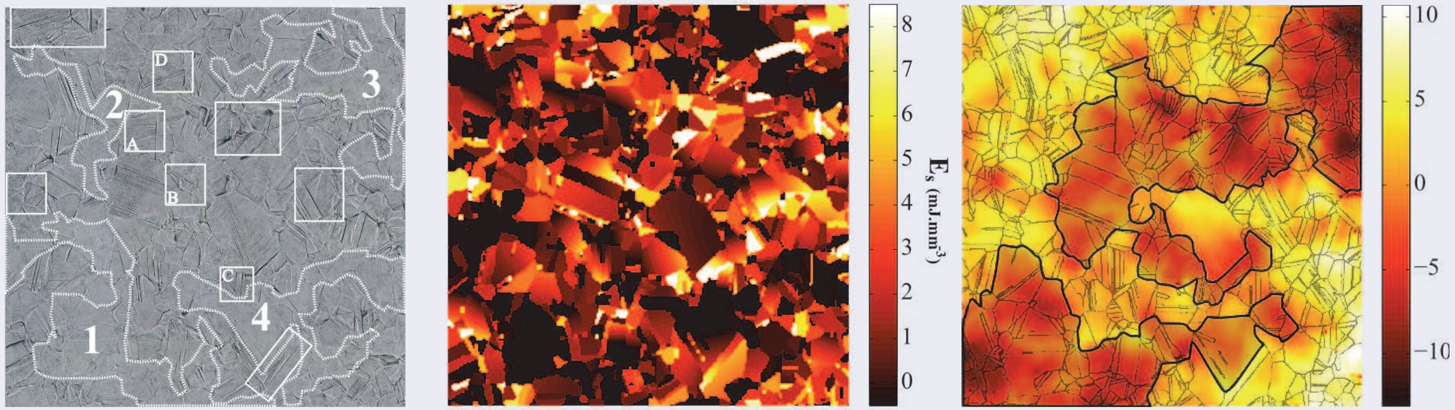
[Oliferuk et al., Eur. J. Mech. A/sol., 2009] & [Oliferuk et al., Mat. Sci. Eng. A, 1994]

Observations

- confirmation: grain size $\nearrow$ β^* $\searrow$ (early plasticity)
- observation at 2.5% of plastic strain:
  - grain size ($\approx 20\mu m$): storage $\rightarrow$ "internal stresses" 77% $\rightarrow$ "hardening" 23%
  - grain size ($\approx 120\mu m$): storage $\rightarrow$ "internal stresses" 31% $\rightarrow$ "hardening" 69%

Energy balance within polycristal: stored energy field

Experimental estimation of stored energy



Micrography

E_s in $(mJ.mm^{-3})$

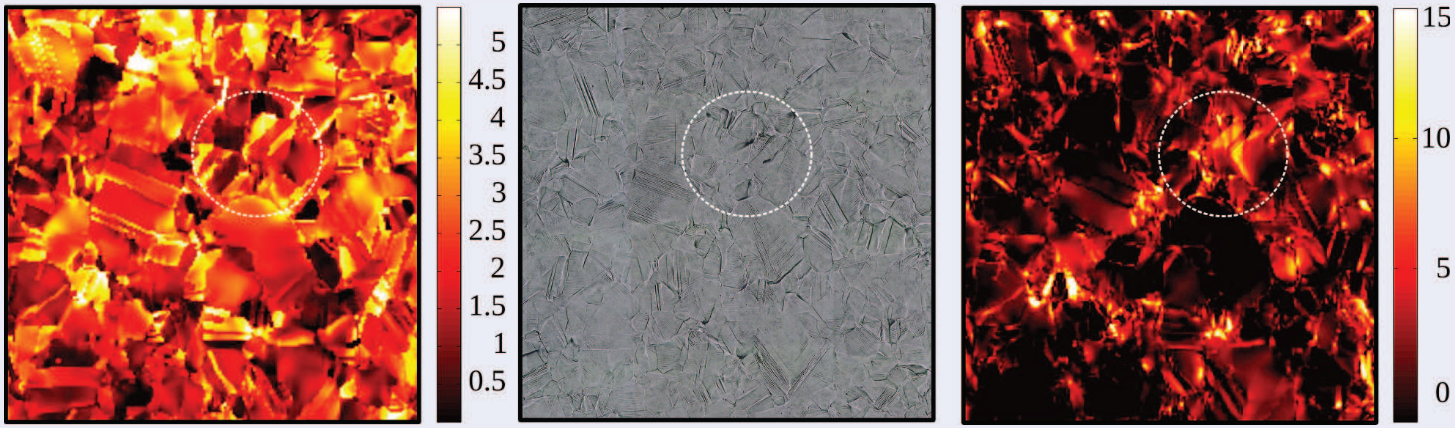
Profilometry

Observations

- E_s: some intense vs. very low levels
- some qualitative relations with slip bands density: to be statistically improved

Energy balance within polycristal: stored energy field

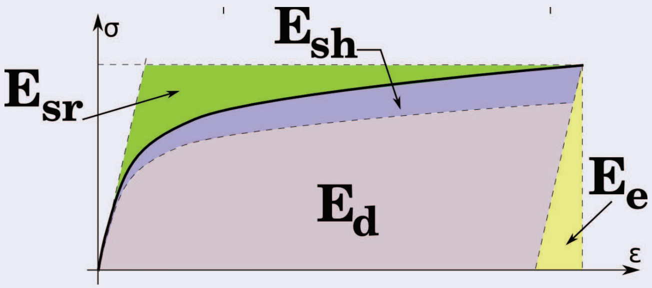
Numerical estimation of stored energies



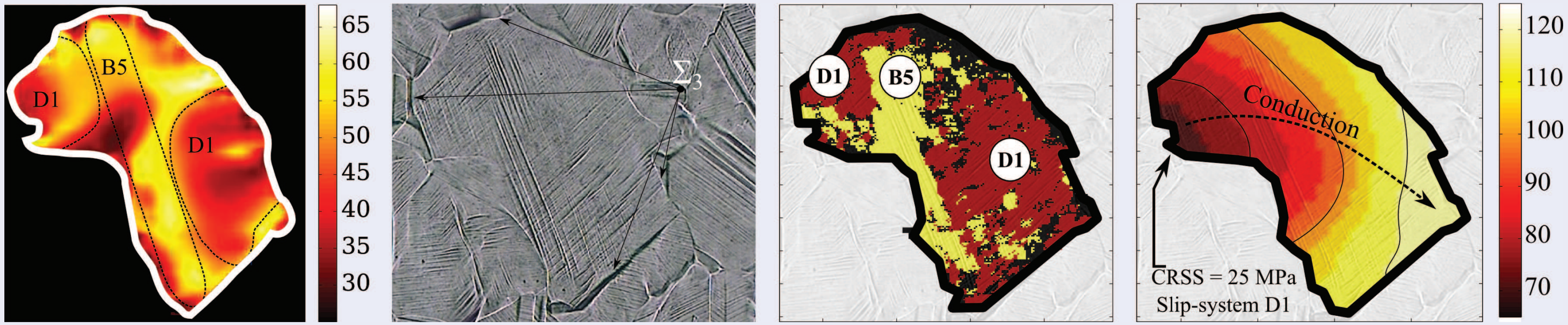
E_{sh} in $(mJ.mm^{-3})$ Micrography E_{sr} in $(mJ.mm^{-3})$

Observations

- E_{sr} structural intense effect
- E_{sh} intragranular plasticity effect



Energy balance within polycristal: intragranular stored energy


numerical β_{sh} in %
surface micrography
slip-systems

thermal threshold propagation function of the nominal stress ↑

Conclusions

- **numerical results locally in line with experiment (millimetric grain)**
- **strong localization of β_{sh}^{num}**
- **local level far from classical global ones (Taylor)**
- **interest of the local factor β_{sh} (localization indicator?)**

Conclusions

1. Multifields granular analysis on metallic polycrystal
   → surface temperature
   → strain tensor on surface
   → crystallographic orientations and grain geometry
   → slip bands intensity and orientation
   → profilometry . . .
2. First steps on granular experimental and numerical thermomechanical analysis

Prospects

1. Single crystals under monotonic and cyclic loadings
2. Role of the physical discontinuities (GBs, TBs, PSB . . .)
3. Energy balance at the grain scale in fatigue?

Thank you for your attention

eric.charkaluk@ec-lille.fr