Ecole nationale Supérieure des Mines de Saint-Etienne (Centre SMS)
CNRS UMR 5146 "Laboratoire Georges Friedel"

COUPLING MECHANICS AND RECRYSTALLIZATION: DYNAMIC RECRYSTALLIZATION

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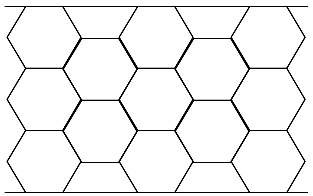
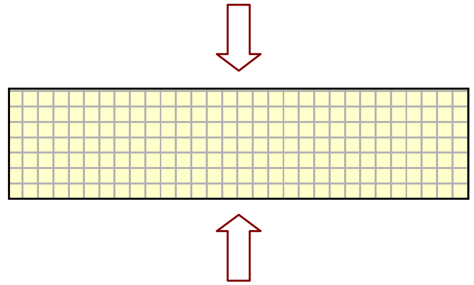
Outline

1. Introduction

What does REcrystallization mean?



initial crystallized state

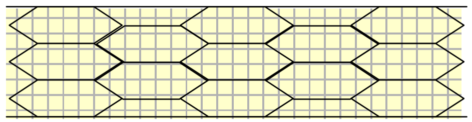


former interpretation

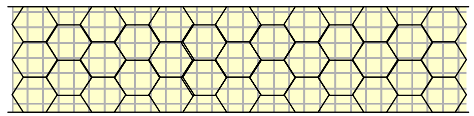
mechanical working ⇒ amorphous state

[Kalisher, 1881-1882]

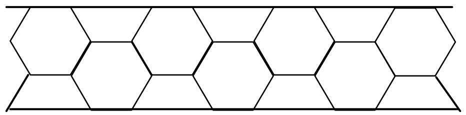
modern interpretation



cold working: deformed initial grains
high dislocation density



hot working: dynamically recrystallized
grains low dislocation density



annealing: statically or post-dynamically
recrystallized grains: no dislocations

- Do metals recrystallize during hot working? [Stüwe, 1968]

  ***Answer*: YES, definitively**

- Dynamic recrystallization–Scientific curiosity or industrial tool? [Jonas, 1994]

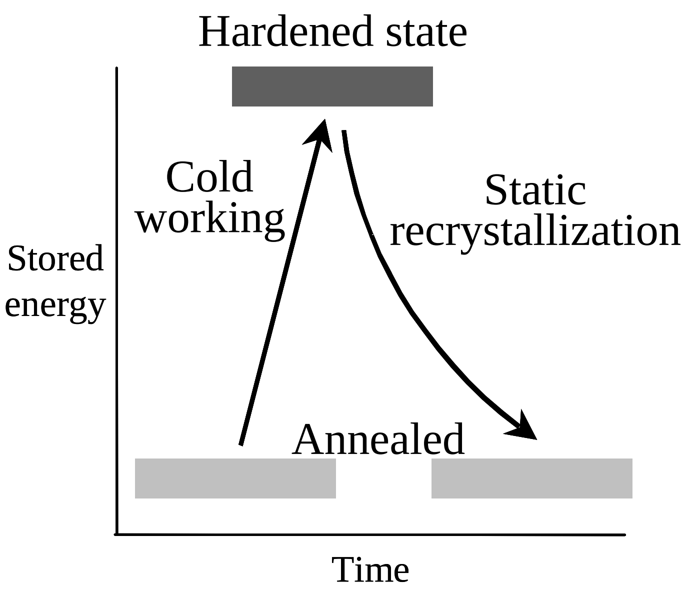
  ***Answer*: BOTH !**

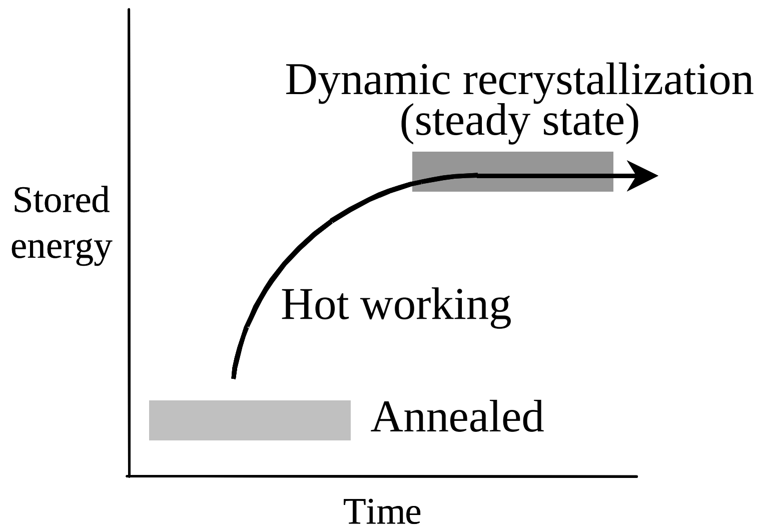
  "discontinuous" DRX (DDRX) takes place by <u>nucleation and growth of new grains</u>

- Is there any form of DRX in ferritic steels or aluminium alloys? [Rossard, 1960]

  ***Answer*: YES, "continuous" DRX (CDRX) occurs by <u>generation of new grain boundaries</u>**

Static vs. dynamic recrystallization



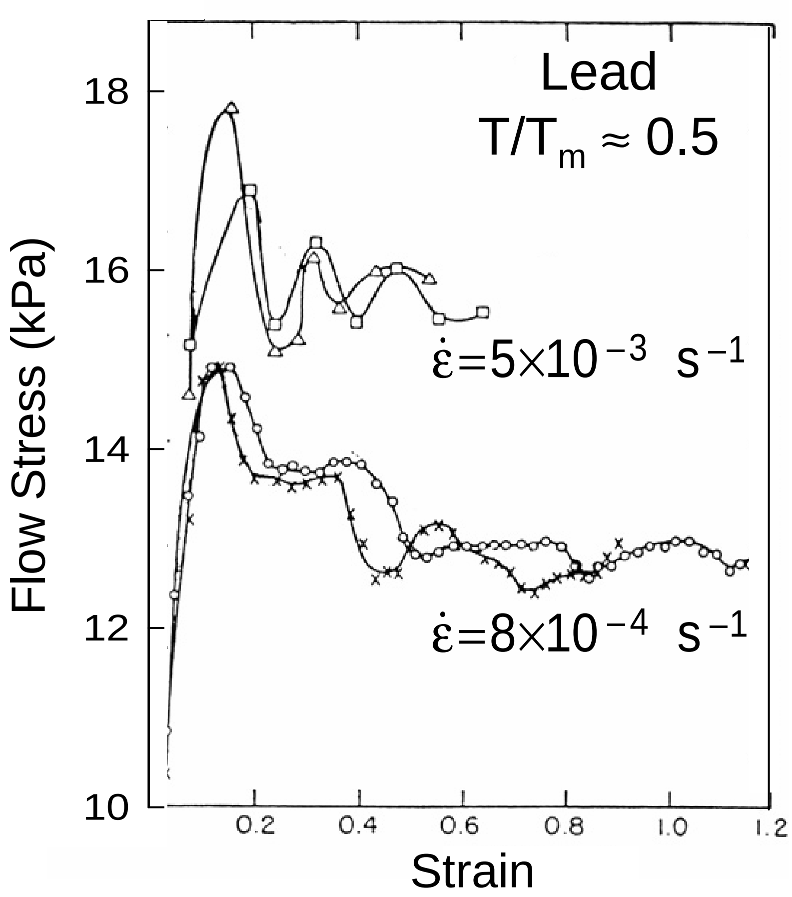


- static recrystallization
⇔ phase transformation

- dynamic recrystallization
⇔ generation of a dissipative structure

2. Basic knowledge: What is DRX?

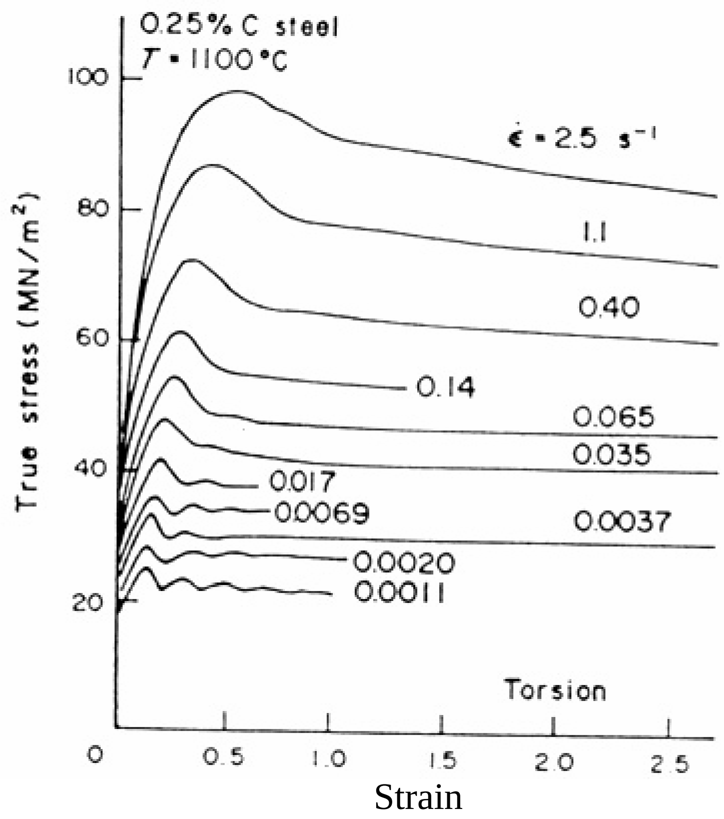
DDRX



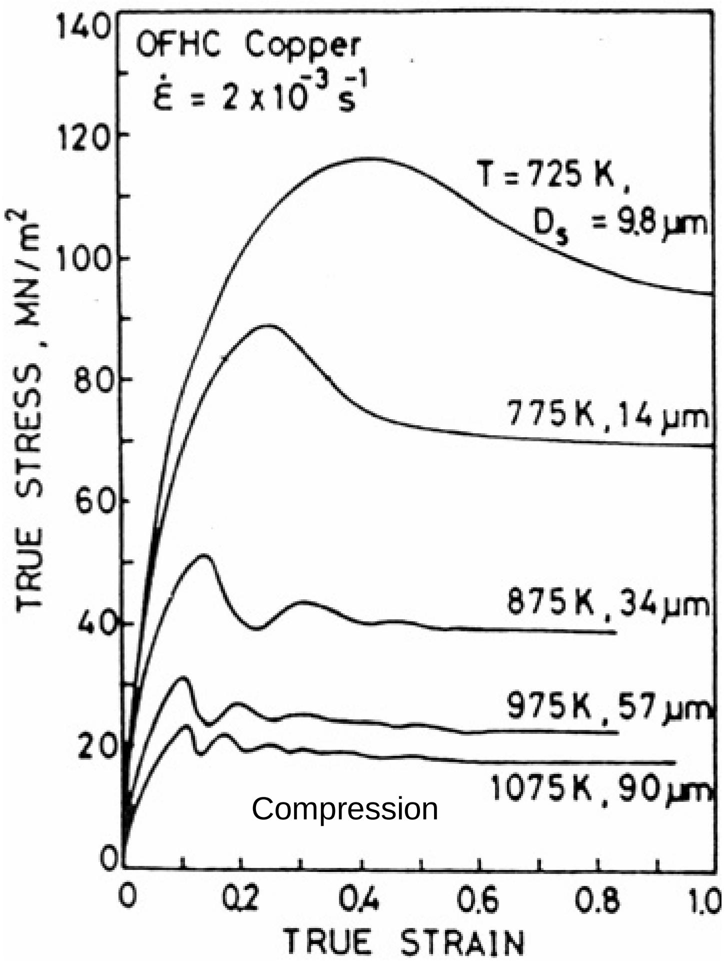
Dynamic recrystallization in lead [Thomsen *et al.*, 1954]:

- oscillating stress-strain curves

DDRX



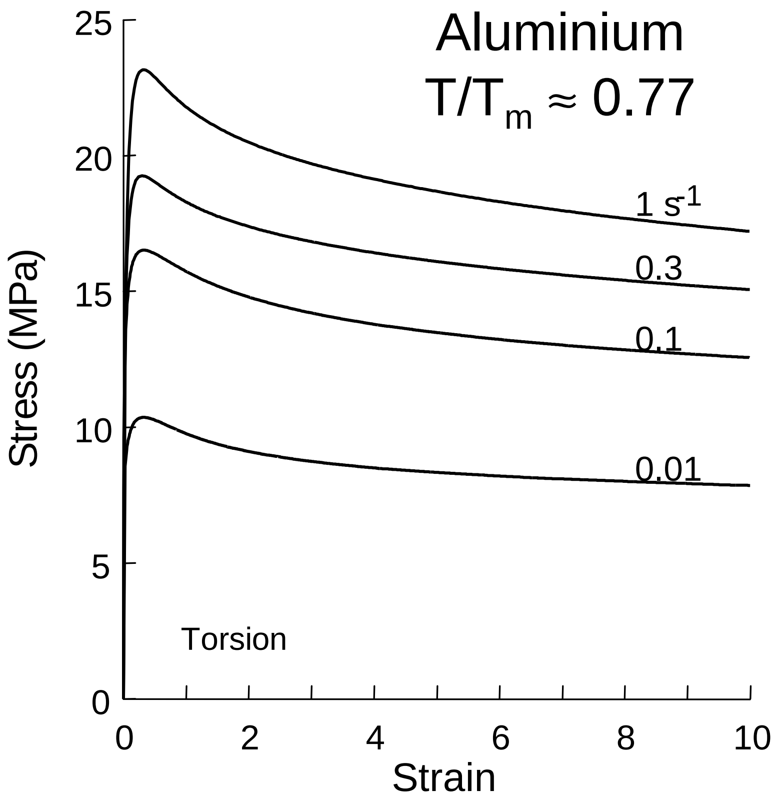
[Rossard and Blain, 1959]



[Blaz *et al.*, 1983]

- steady reached at $\varepsilon \approx 1$
- *multiple peak* and *single peak* curves at low and large flow stresses, respectively

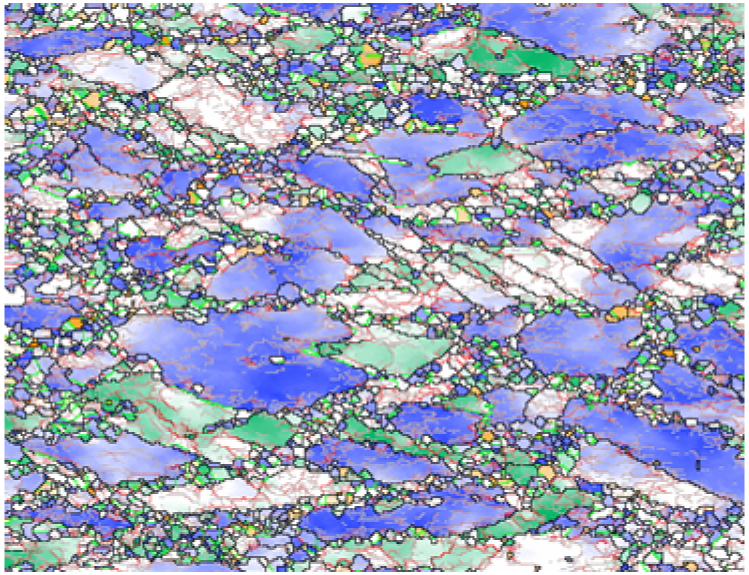
CDRX



[Chovet, 2000]

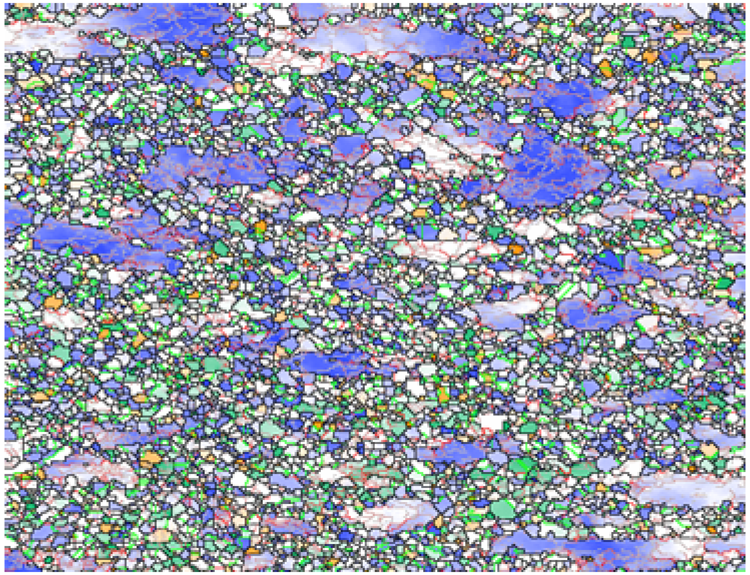
- no oscillations
- steady state *not yet* reached at $\varepsilon = 10$

DDRX



100 µm

$\varepsilon = 0{,}7$



$\varepsilon = 1$

uniaxial compression (vertical axis) – Alloy 718 (Ni-Cr-Fe)

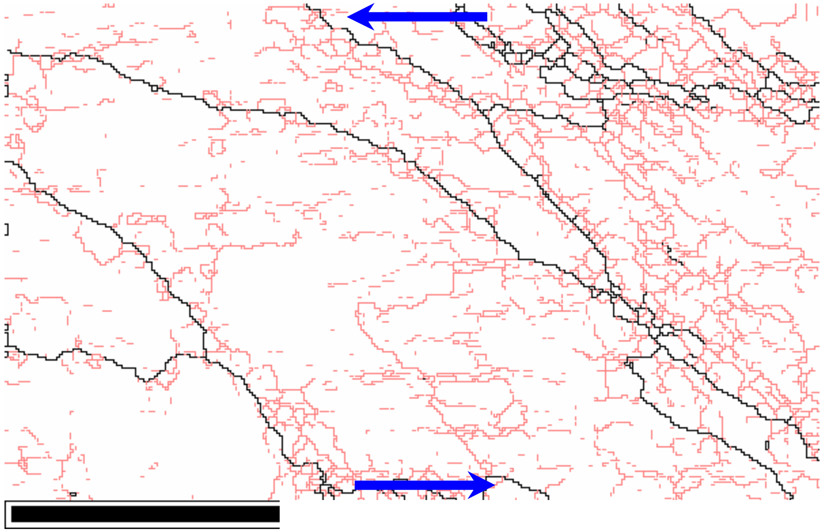
980 °C, 0.01 s^{-1}

EBSD orientation maps [Thomas, 2002]

- necklace DDRX (associated with single peak flow curves)

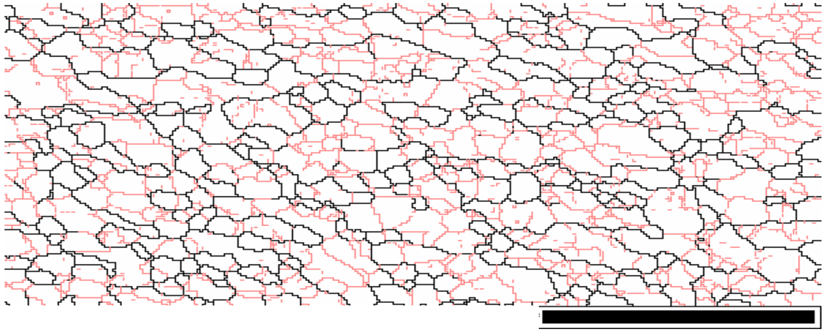
CDRX

black = grain boundaries
red = subgrain boundaries



100 µm

$\varepsilon = 1$



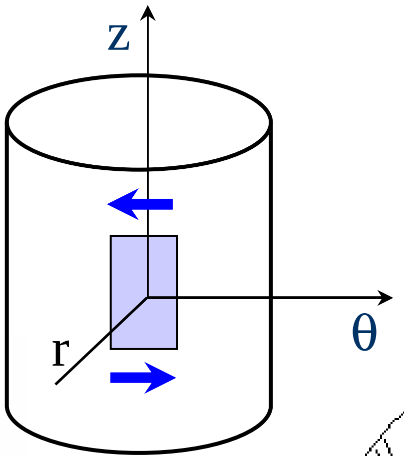
$\varepsilon = 50$

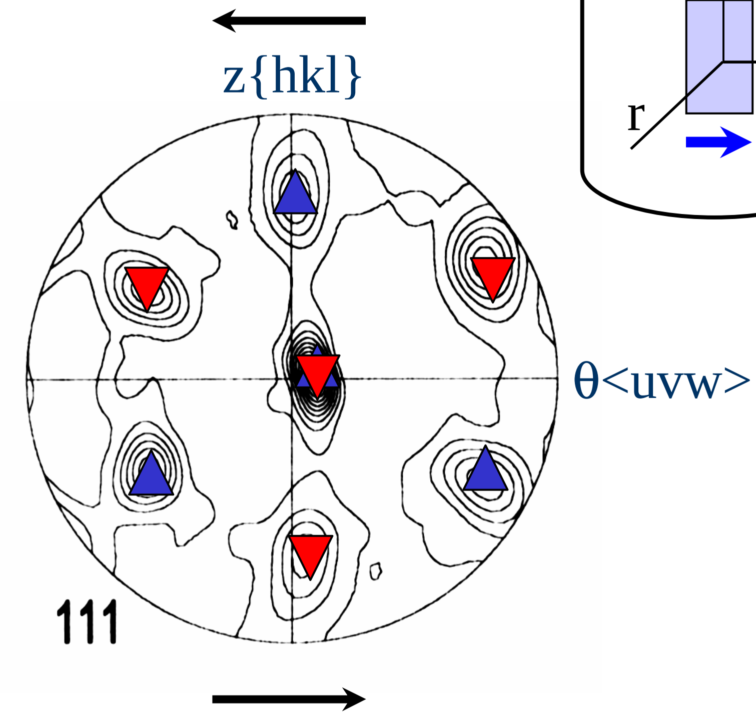
torsion (simple shear) – Al-Mg-Si alloy
400 °C, 0.1 s^{-1}
EBSD misorientation maps [Chovet, 2000]

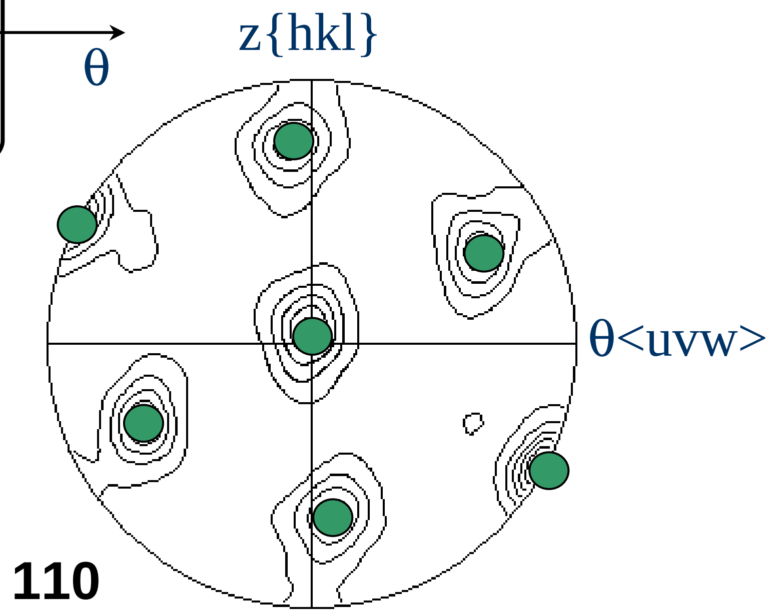
- "geometric DRX" at low / moderate strains
- "cristallite" microstructure

- DDRX leads to weak textures (random nucleation)
- CDRX generates modified deformation textures at large strains

CDRX





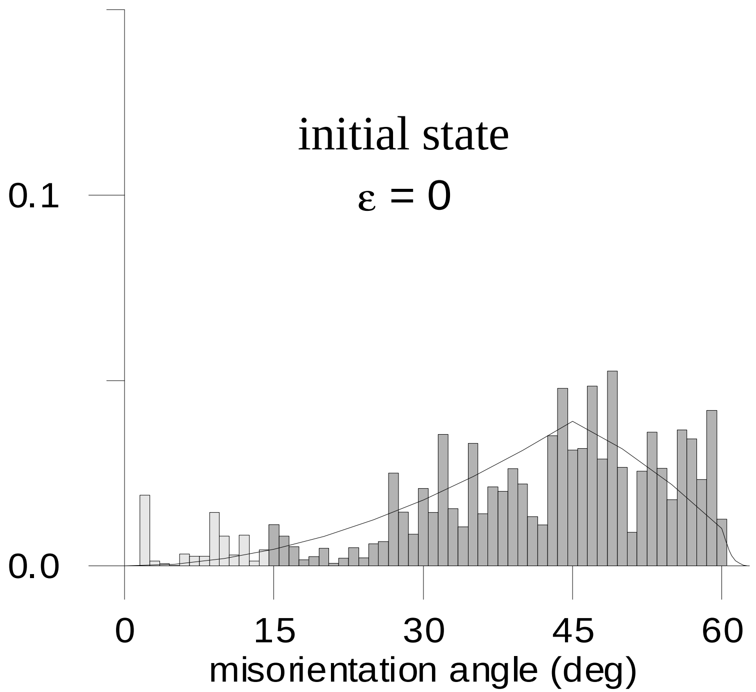


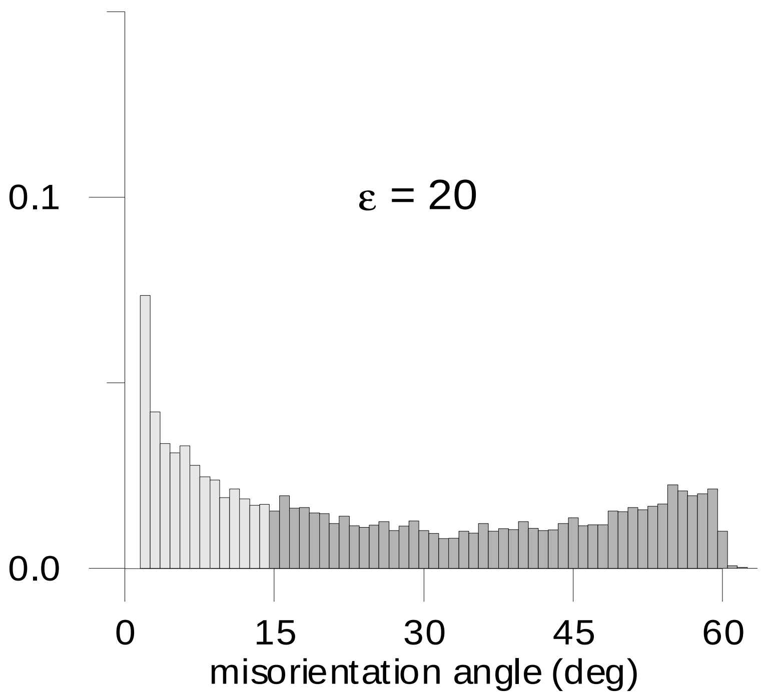
- FCC structure: $B/\bar{B}\ \{112\}\langle 1\bar{1}0\rangle$
  twin-symmetric texture component
  (Al-Mg-Si aluminium alloy, ε = 20)

- BCC structure: D2$\{112\}<\bar{1}\bar{1}1>$
  self-symmetric texture component
  (ferritic steel, ε = 100) [Lim *et al.*, 2009]

CDRX

(Correlated) misorientation angle distributions
(Al-Mg-Si aluminium alloy, 400 °C, 0.1 s–1)





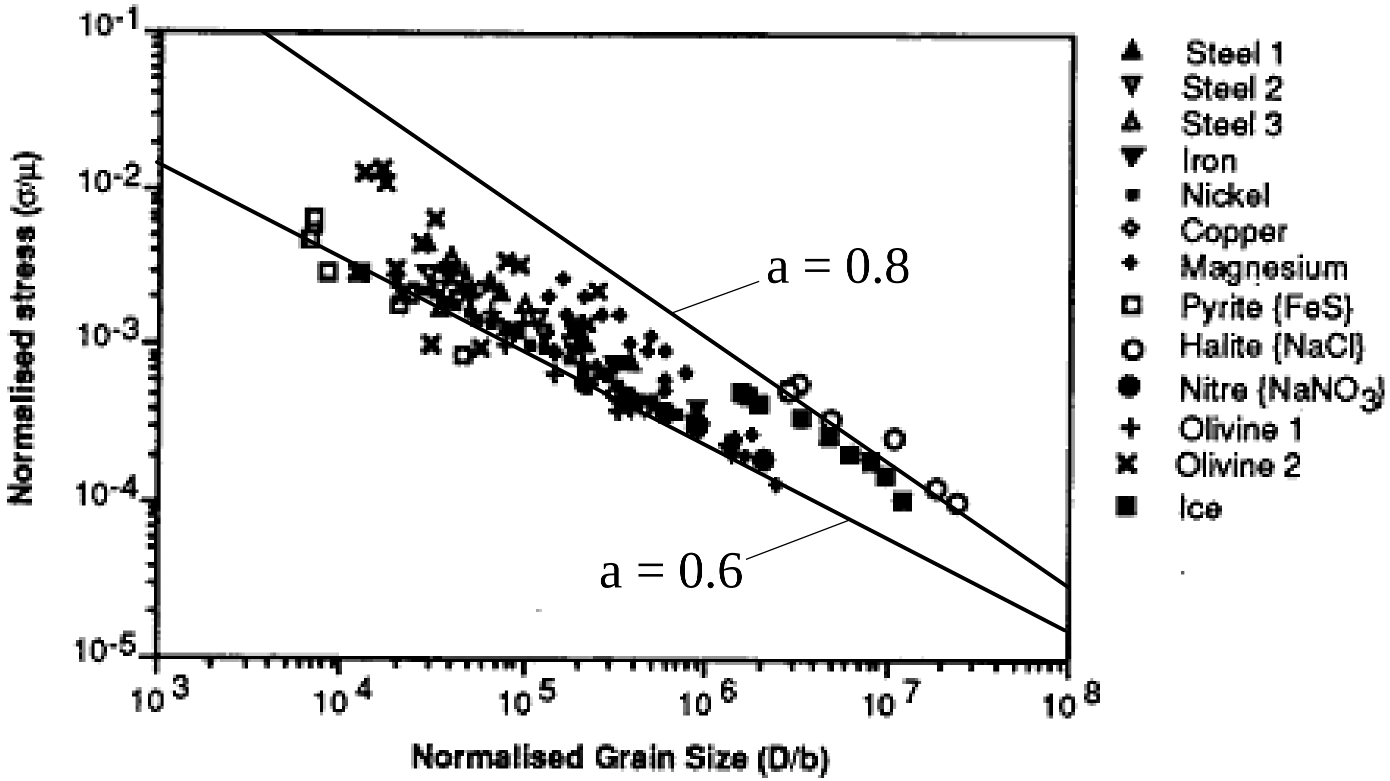
• Mackenzie distribution (random orientations and positions)

• crystallite structure distribution

DDRX and CDRX

Derby relationship

- Universal correlation between steady state flow stress σ_s and average grain / crystallite size D_s



$$\sigma_s = \frac{A}{D_s^{\,a}} \quad \text{where} \quad 0.6 \le a \le 0.8$$

3.Modeling DDRX

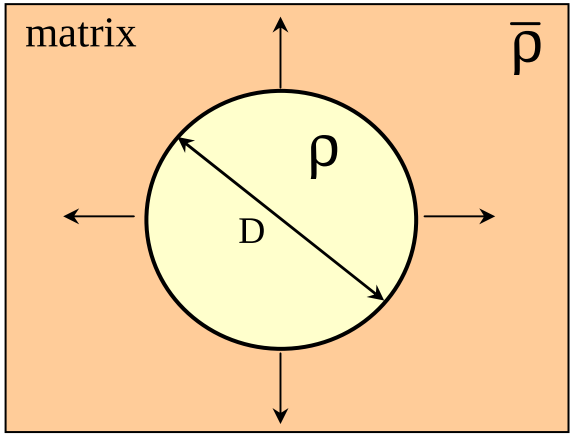
Literature data

- Stüwe & Ortner (1974)	analytical
- Sandström & Lagneborg (1975)	semi-analytical
- Rollett et al. (1992)	
- Luton & Peczak (1992)	Monte-Carlo
- Peczak (1995)	
- Kaptsan *et al.* (1992)	semi-analytical
- Goetz & Seetharaman (1998)	cellular automaton
- Zhaoyang Jin *et al.* (2012)	*id*
- Solas, Baudin *et al.* (2008)	*id*
- Busso (1997)	analytical
- Gao *et al.* (1999)	analytical
- Montheillet (1999)	semi-analytical
- Montheillet, Lurdos & Damamme (2009)	*id*
- Logé *et al.* (2011)	*id*
- Cram *et al.* (2012)	*id*
- Favre *et al.* (2012)	*id*
- Gourdet & Montheillet (2003)	semi-analytical (CDRX)

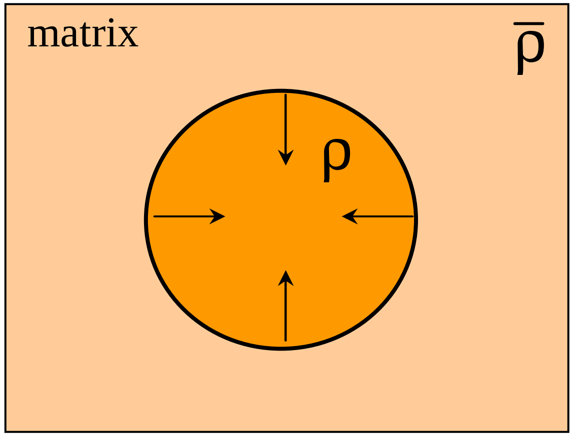
DDRX model

A set of interacting spherical grains is considered
(*average field* approach)

• Grain growth / shrinkage



$\rho < \bar{\rho}$: growth



$\rho > \bar{\rho}$: shrinkage

$$\frac{dD}{dt} = 2M\tau(\bar{\rho} - \rho)$$

M grain boundary mobility
τ line energy of dislocations

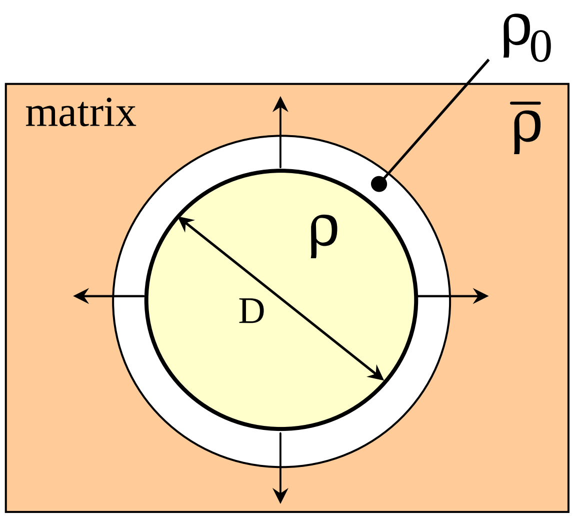
$V \propto \sum D_i^3$ remains constant $\Leftrightarrow$ $\bar{\rho} = \sum \rho_i D_i^2 / \sum D_i^2$

- Strain hardening and dynamic recovery

$$\frac{d\rho}{dt} = (h - r\rho)\dot{\varepsilon} - 3\frac{\rho - \rho_0}{D}\frac{dD}{dt} \quad \text{if} \quad \rho \leq \bar{\rho} \qquad \text{(growth)}$$

YLJ BMIS

$$\frac{d\rho}{dt} = (h - r\rho)\dot{\varepsilon} \quad \text{if} \quad \rho \geq \bar{\rho} \qquad \text{(shrinkage)}$$



YLJ: Yoshie-Laasraoui-Jonas equation

BMIS: *Boundary Migration Induced Softening*

- Grain nucleation

$$\frac{dN^+}{dt} = k_N \, \bar{\rho}^p \sum D_i^2$$

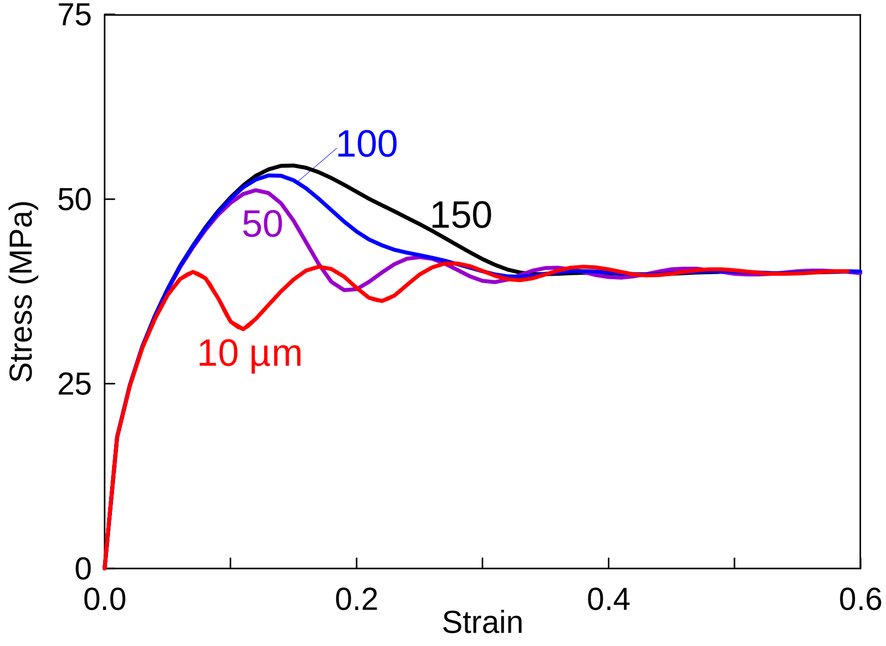
$\sum D_i^2$: nucleation at grain boundaries (necklace DRX)

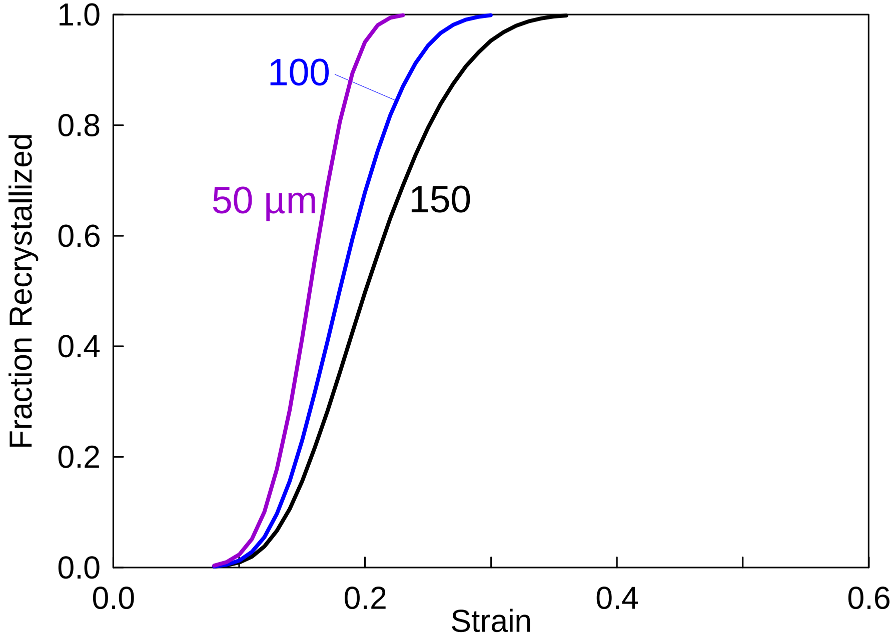
k_N nucleation parameter

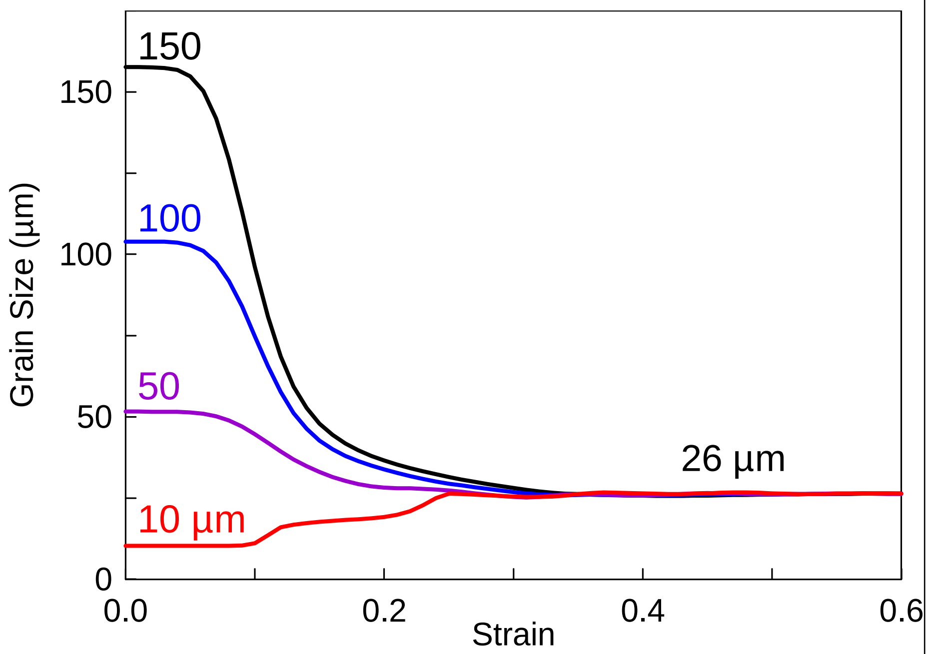
$p \approx 3$

- a nucleus is generated whenever N^+ has increased by one unit

Some predictions of the DDRX model (data from 304L steel)







• Closed form equations for steady state using a power law for strain hardening and dynamic recovery, and neglecting boundary migration induced softening (BMIS)

$$\frac{d\rho}{dt} = \frac{H^{\nu+1}}{\rho^{\nu}}\dot{\varepsilon} \quad \text{where } \nu \geq 0 \quad \text{leads to}$$

wherefrom

$$\sigma_s = \alpha\mu b\left(\frac{M\tau}{k_N}\frac{C(\nu)}{D_s^{\,3}}\right)^{1/[2(p-1)]}$$

$\Leftrightarrow$ Derby relationship $\quad \sigma_s = \dfrac{A}{D_s^{\,a}}$

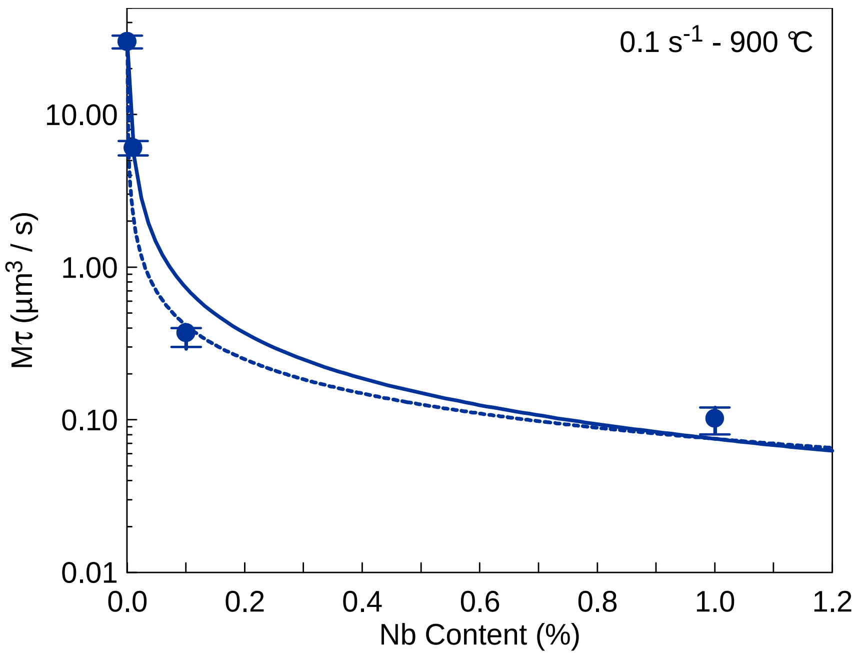
$$a = \frac{3}{2(p-1)} \qquad a = 0.75 \Rightarrow p = 3$$

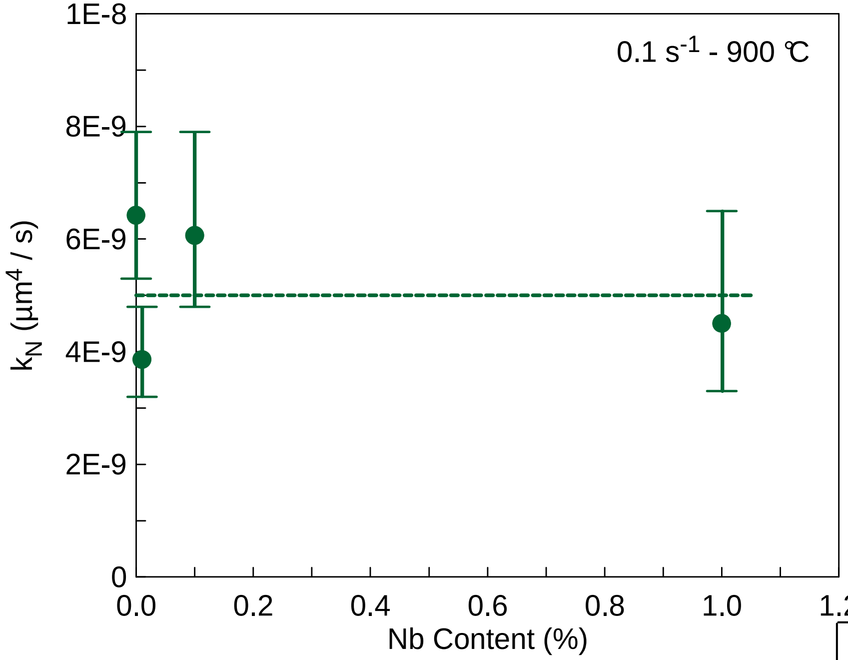
- Estimation of $M\tau$ and k_N from H, ν, σ_s, and D_s

$$M\tau = C_3(\nu) H^{\nu+1} \dot{\varepsilon} \frac{D_s}{(\sigma_s/\alpha\mu b)^{2(\nu+2)}}$$

$$k_N = C_4(\nu) \frac{H^{\nu+1} \dot{\varepsilon}}{(\sigma_s/\alpha\mu b)^{2(p+\nu+1)} D_s{}^2}$$

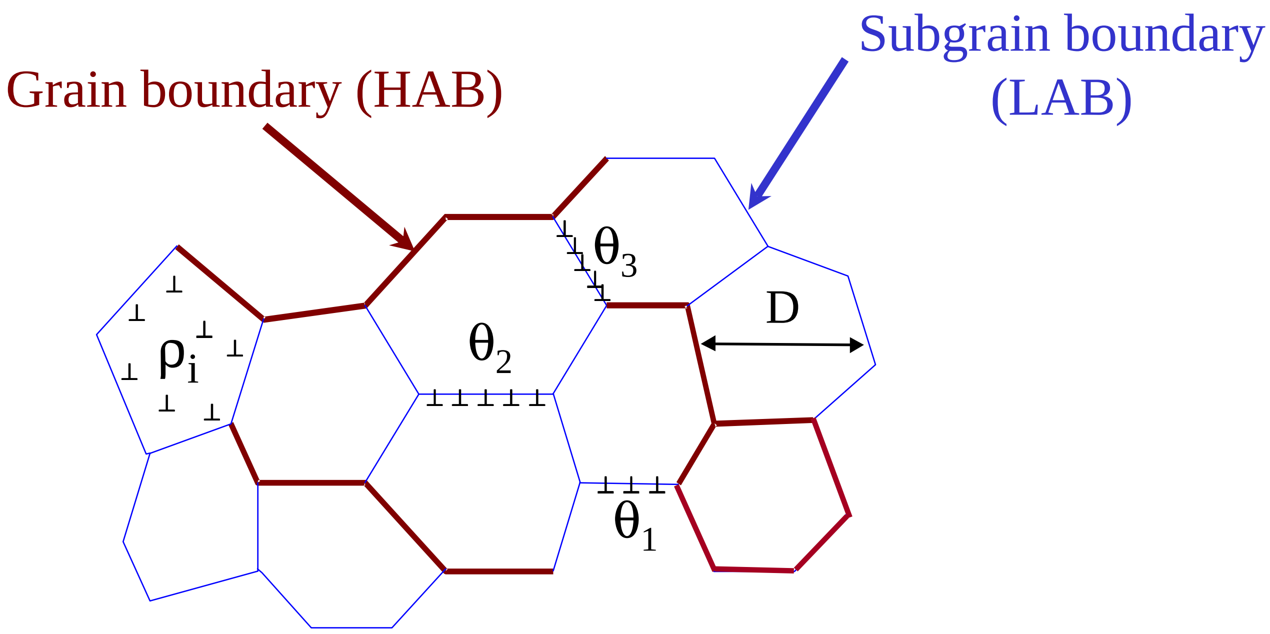
- Example of nickel-niobium alloys [Piot *et al.*, 2009]





CDRX model

Evolving interfaces are considered



Crystallite microstructure [Gourdet and Montheillet, 2003]

- The model involves three internal variables:

ρ_i	dislocation density inside the crystallites
D	average size of the crystallites
$\varphi(\theta)\, d\theta$	the fraction of subgrain boundaries with misorientation between θ and $\theta + d\theta$

- Strain hardening and dynamic recovery: *see DDRX*
- Generation of low angle boundaries from dislocations : dS^+/dt
- LAB misorientation rate of increase:

$$\frac{d\theta}{dt} = A\, r \rho_i D\, \dot{\varepsilon}$$

when $\theta > \theta_c$, LAB $\rightarrow$ HAB

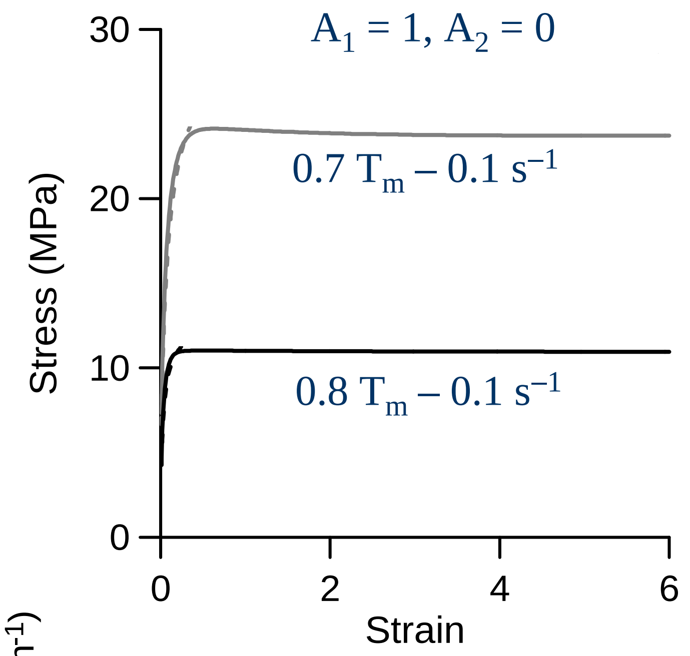
- Annihilation of boundaries by the movement of high angle boundaries : dS^-/dt

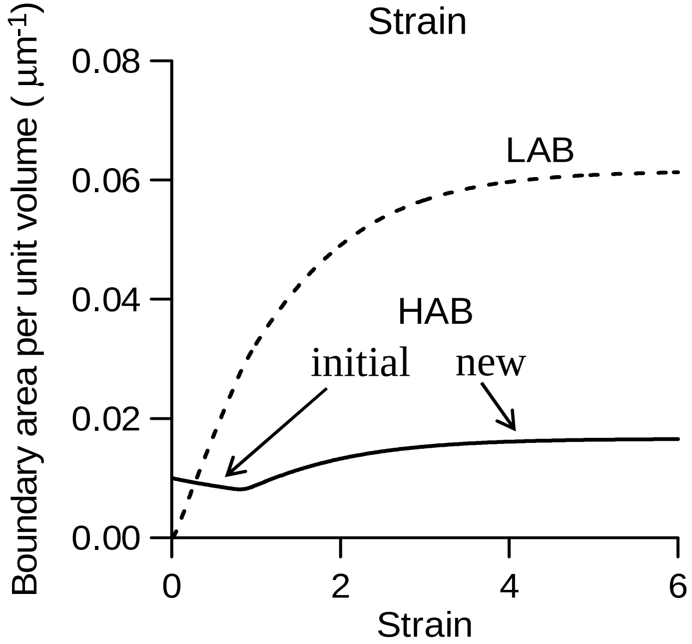
Finally $$\frac{dS}{dt} = \frac{dS^+}{dt} - \frac{dS^-}{dt}$$ and $D = \kappa / S$

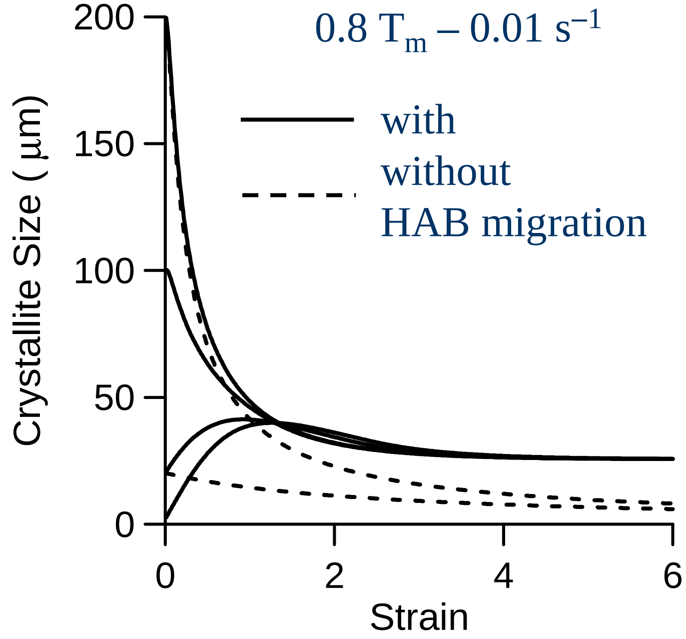
κ shape factor

Flow stress: $$\sigma = Gb\left(A_1\sqrt{\rho_i} + A_2\sqrt{\rho_{LAB}}\right)$$

Some predictions of the CDRX model (data from aluminium)



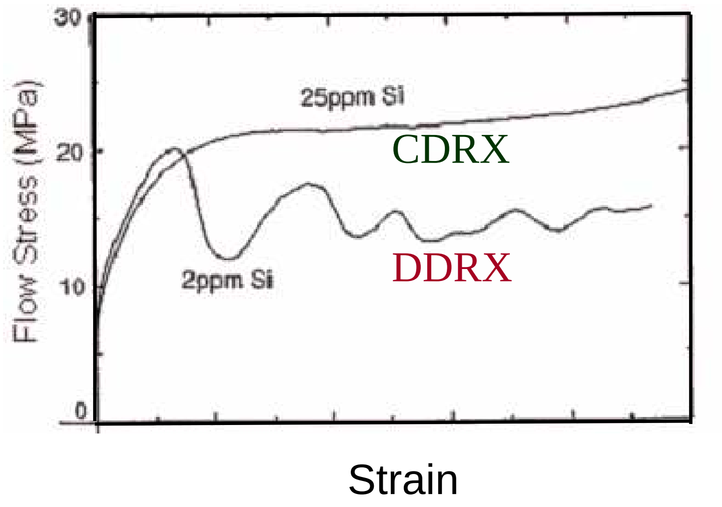




4. Challenges and perspectives

- Basic research:

  - Understanding and modeling the steady states (dissipative structures)
  - Transitions from CDRX to DDRX by increasing temperature, strain rate, or purity → unified predictive model



aluminium single crystals uniaxial compression along the <111> axis, 260 °C, 1.67 x 10^{-3} s^{-1}

[Tanaka et al., 1999]

  - Coupling DRX and precipitation / dissolution, phase transformations
  - Globularization / dynamic recrystallization of lamellar (Widmanstätten) microstructures

- Industrial challenges:

  - Implementation of "metallurgical routines" in the finite element metal forming codes
  - Controlled forging of titanium and zirconium alloys (aeronautic and nuclear applications)

Example of forging schedule for a titanium alloy