Severe Plastic Deformation

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Aussois 22-25 octobre 2012

Content

- For Introduction: Keywords and objectives
- Strain modes in SPD
- Strain hardening
- Microstructure features
- Texture evolution
- A model of grain refinement
- Effect of strain path on grain refinement and texture
- Strong points and future key issues

Keywords and objectives

Keywords:

SPD: Severe Plastic Deformation,   Hyperdéformation

UFG: Ultra Fine Grain

BNM: Bulk Nanostructured Materials

NanoSPD: Nanostructured Materials by SPD

NanoSPD6: Metz, 2014, June 30-July 4

Objectives:

To apply SPD for reducing the grain size.

Modern SPD techniques: obtain large strains without changing the shape!

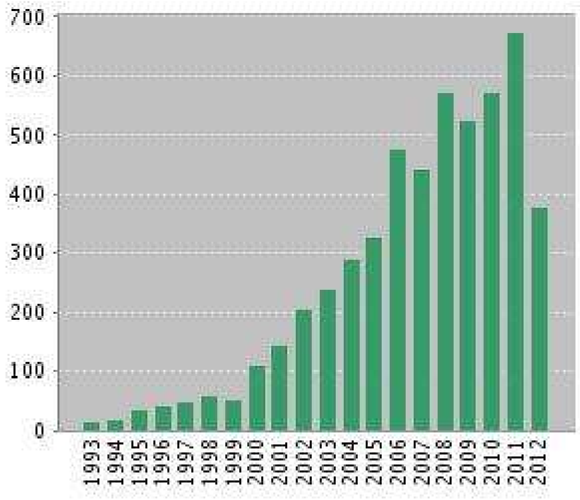
SPD transforms the microstructure, introduces very large amount of new GB.

→ Grain boundary engineering

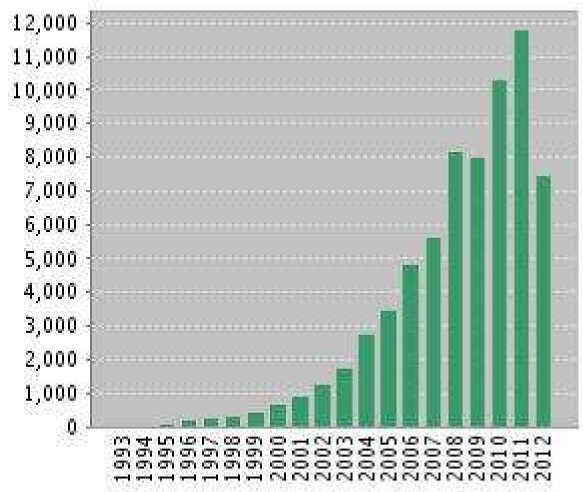
→ Explore the properties between nano and conventional grain structures, in the UFG regime.

Publication activity in SPD

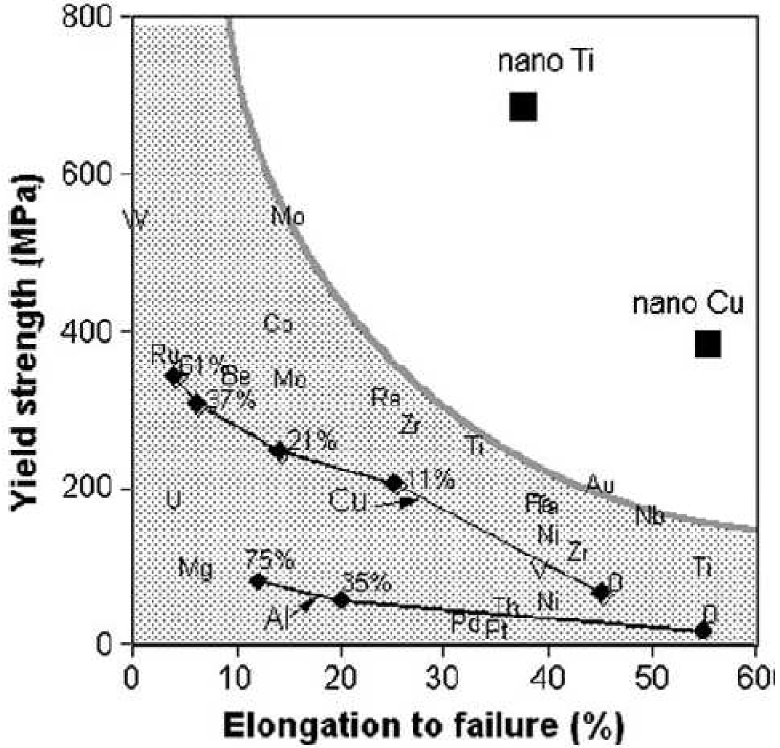
Number of publications



Number of citations

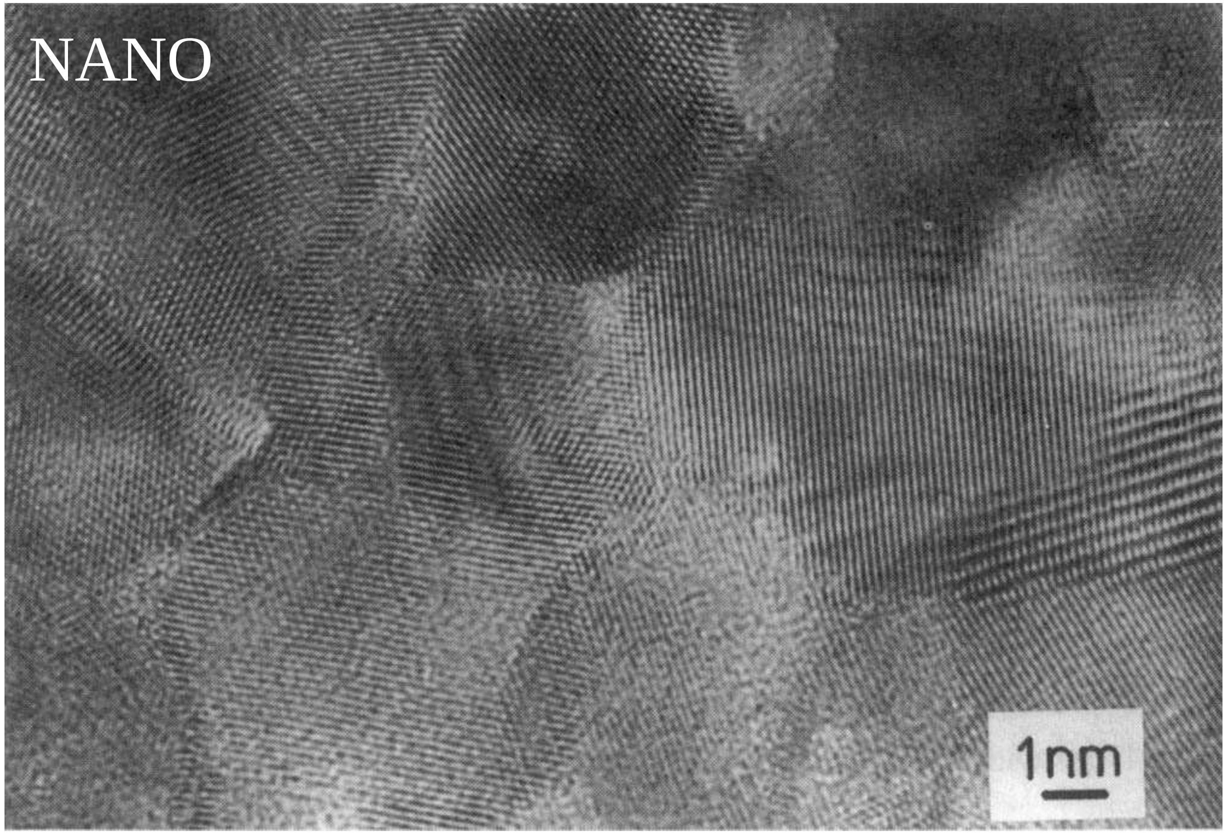


Paradox of strength vs ductility



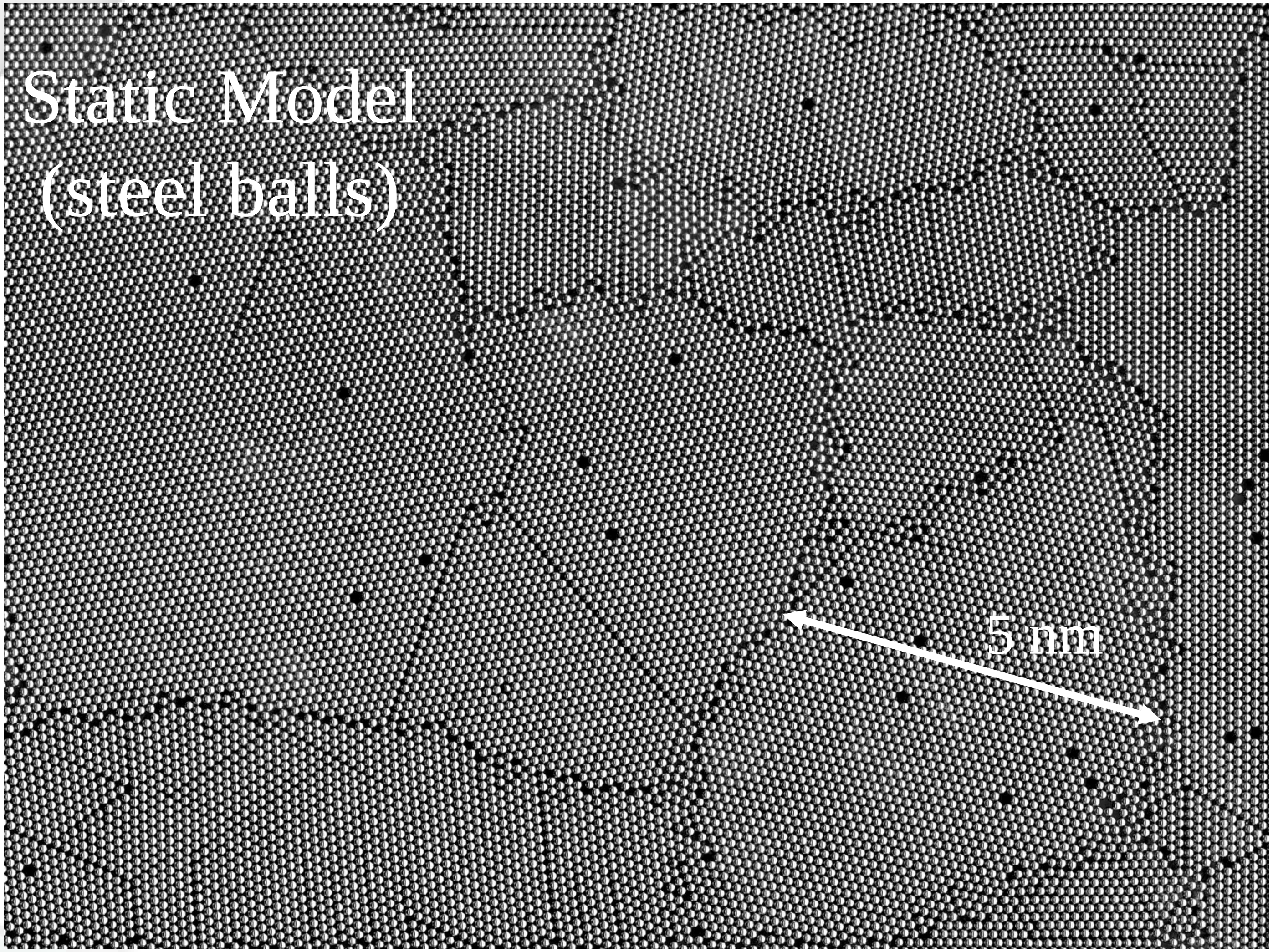
The paradox of strength vs ductility; the nano-Ti and nano-Cu has superior properties

RZ Valiev, IV Alexandrov, TC Lowe, et al., J Mater Res 17 (2002) 5



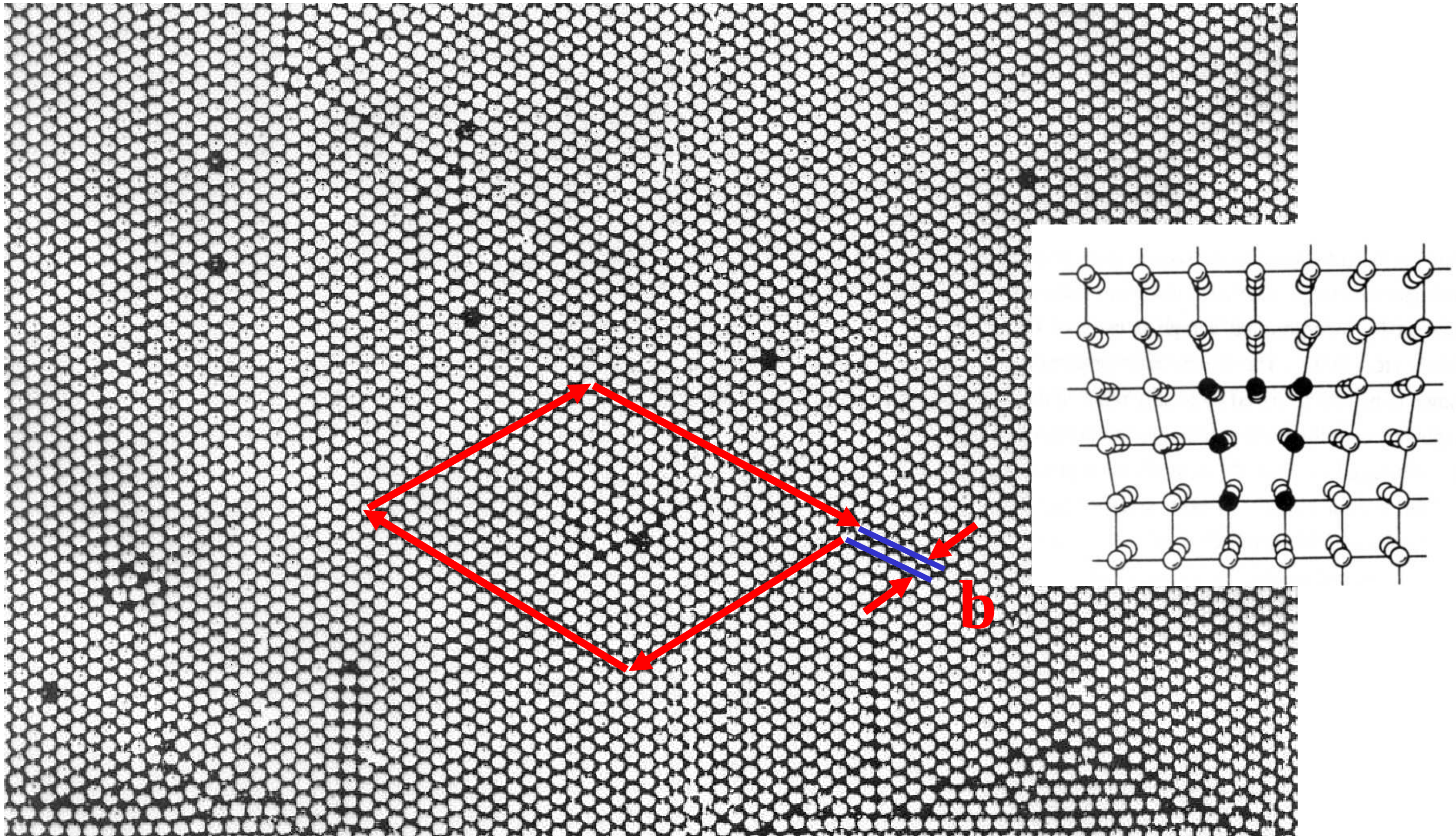
Palladium, HREM

For microstructure teaching



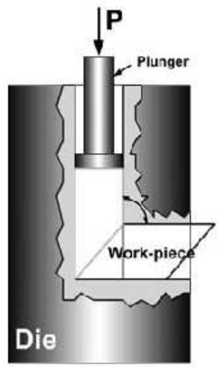
Model for plastic deformation of nanocrystals

For microstructure teaching -dislocation

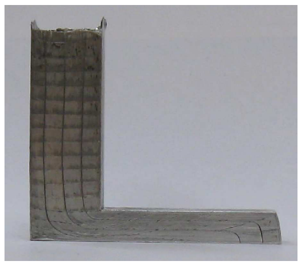


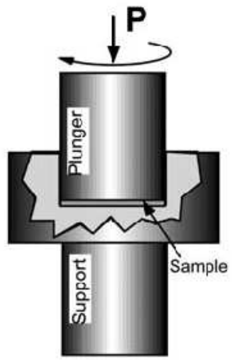
SPD processes

ECAP (ECAE), NECAP, ARB, HPT, HPTT

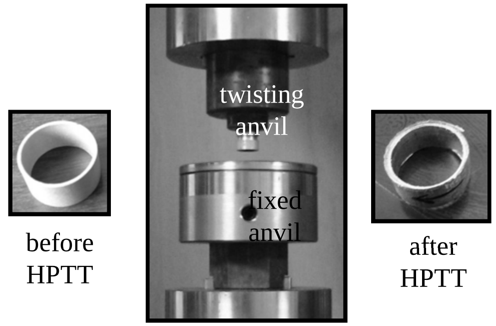


Equal Channel Angular Extrusion

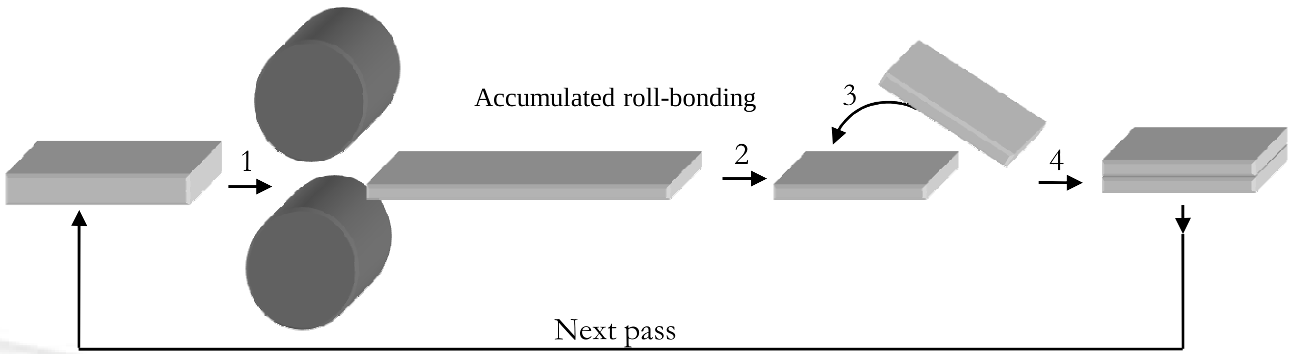

Non-Equal Channel Angular Extrusion



High pressure torsion

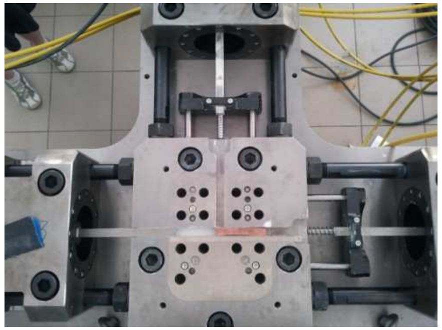


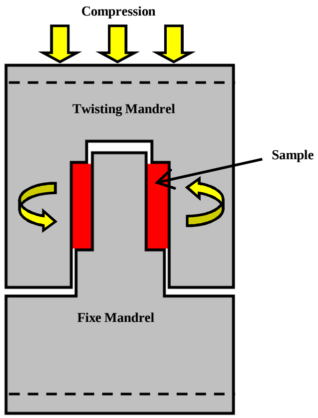
High Pressure Tube Twisting



SPD in LEM3, Metz

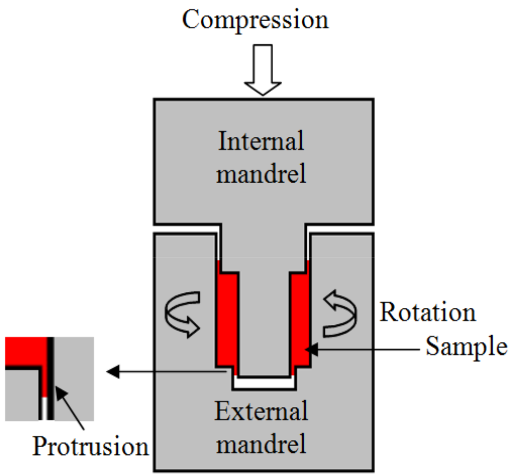
ECAE

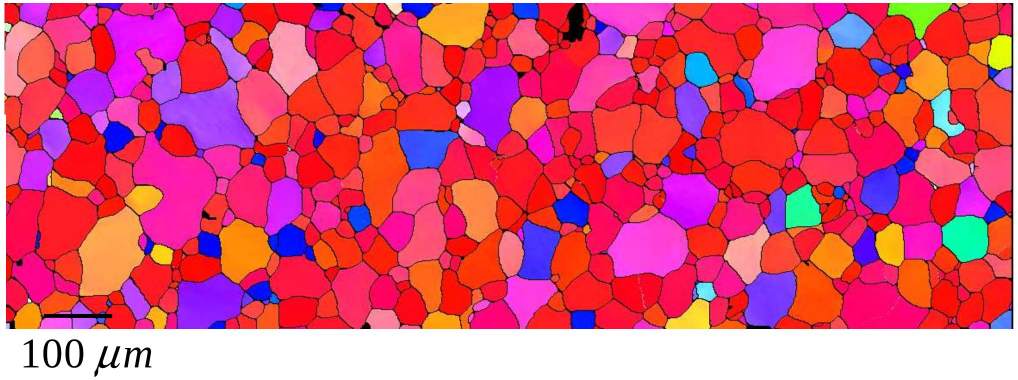




HPTT

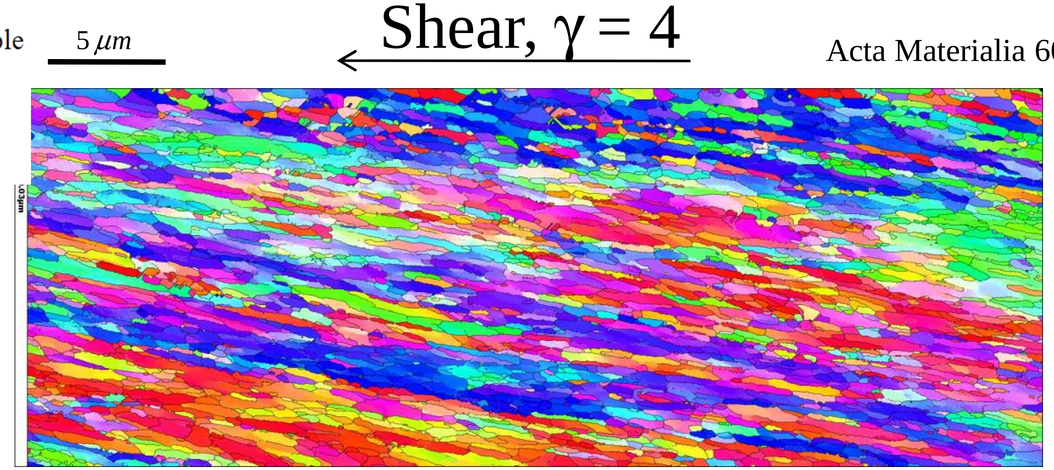
Experimental evidence for grain fragmentation in SPD





Shear, $\gamma = 4$

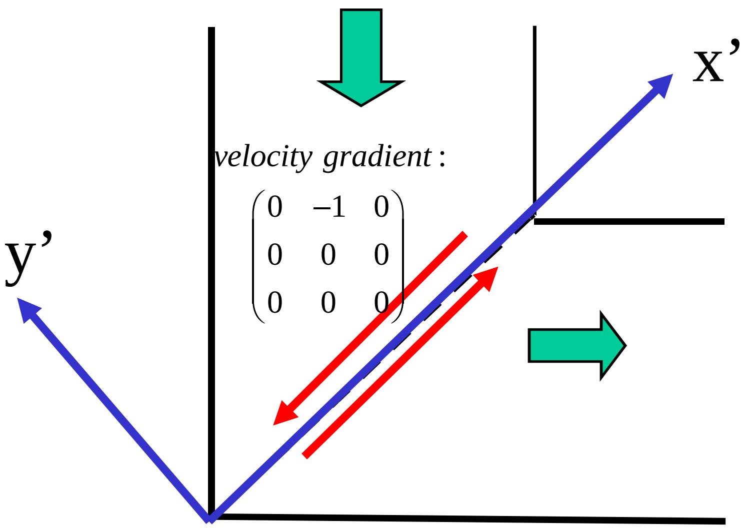
Acta Materialia 60 (2012), pp. 4393-4408

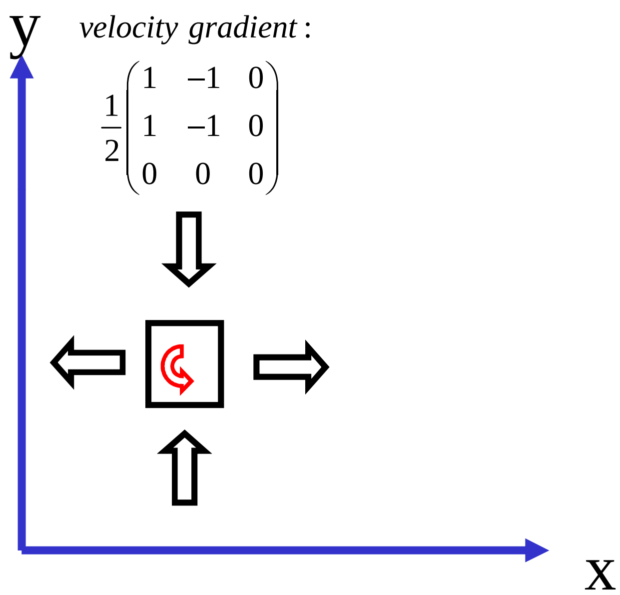


Al, CP, defomed by HPTT – Arzaghi, thesis

The strain mode in SPD

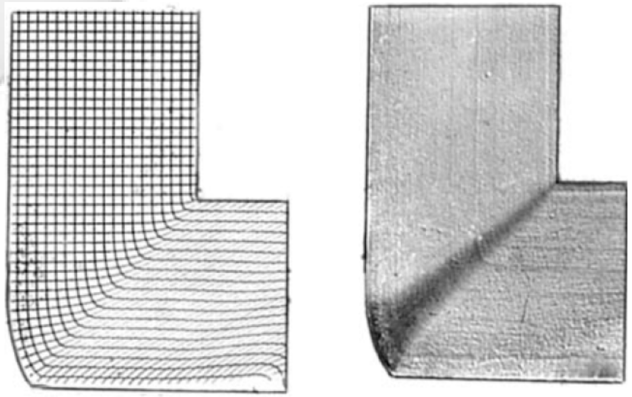
Strain field in ECAE
(simple shear model)



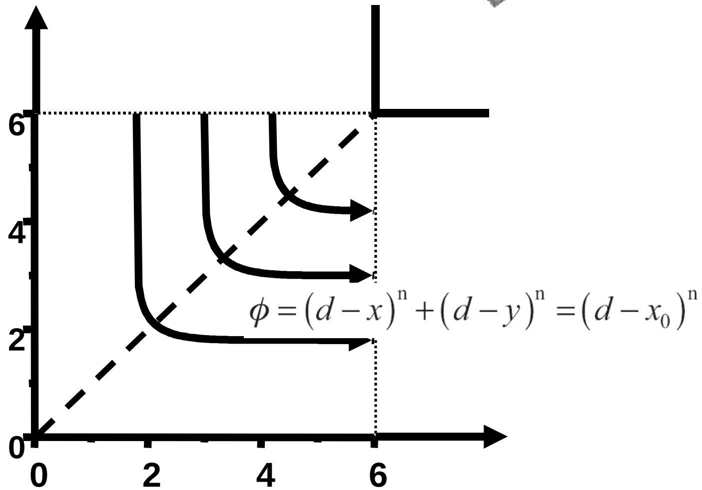


Deformation state:
compression, tension
+ rigid body rotation

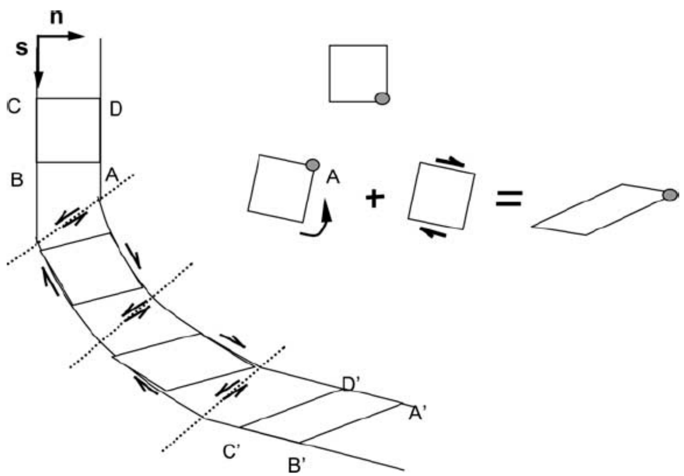
Experiment, Segal, 1999



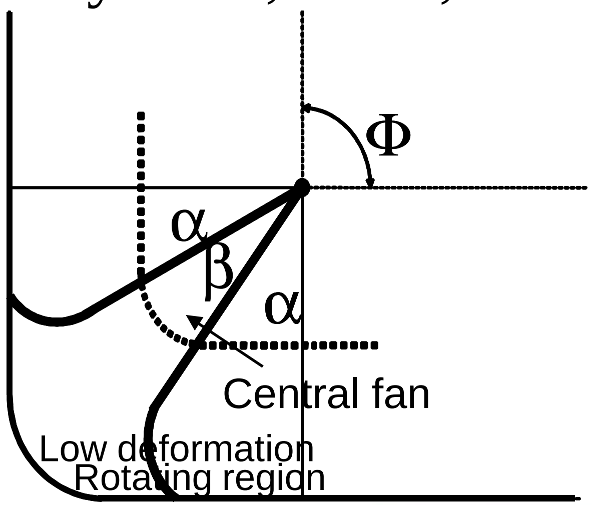
Toth, 2003



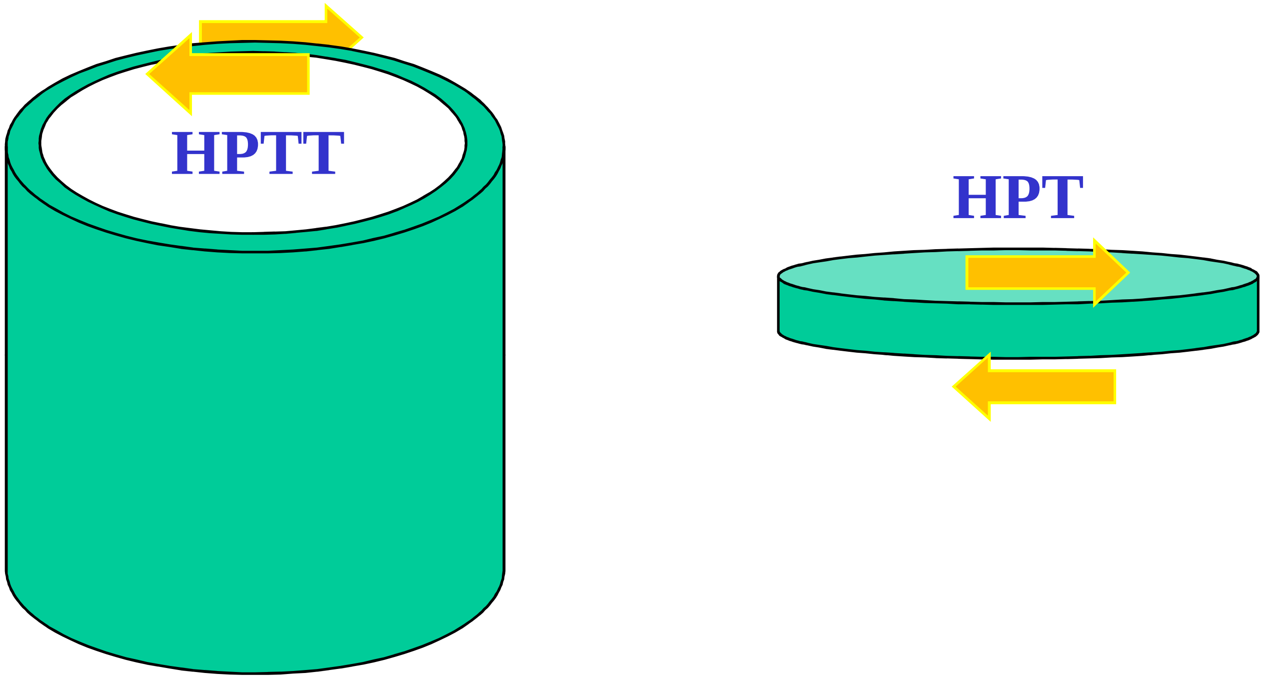
Gholinia, Bate, Prangnell, 2002



Beyerlein, Tome, 2004

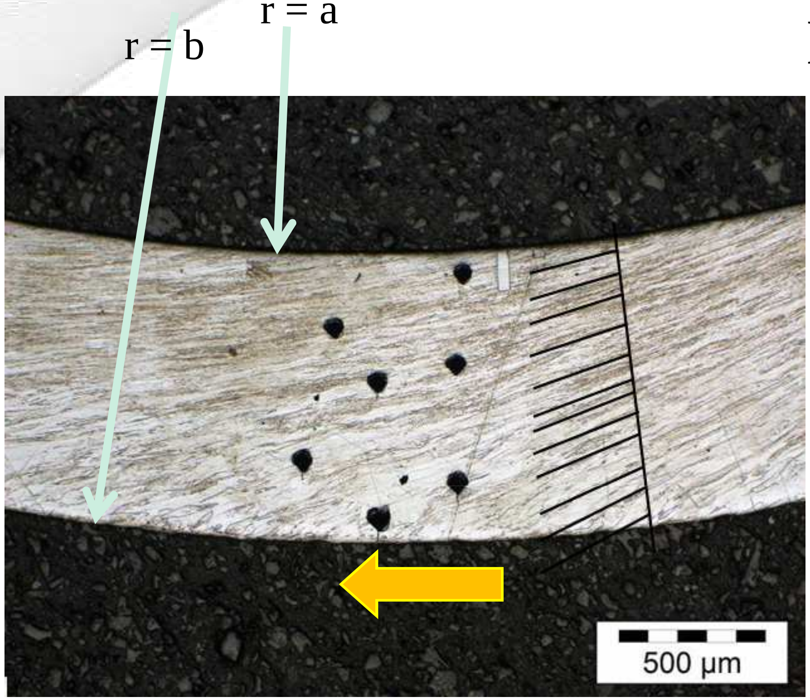


Strain mode in HPTT et HPT

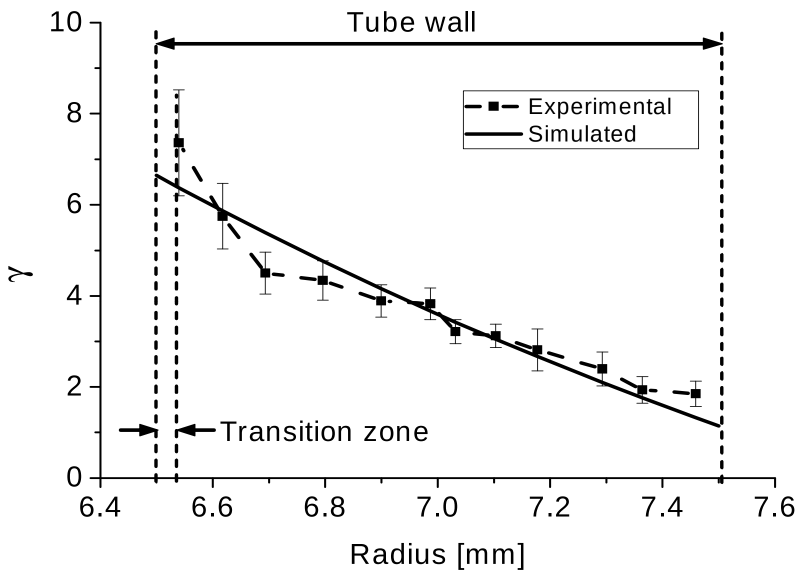


Strain heterogeneity in HPTT

IF steel



Local strain



Average strain:

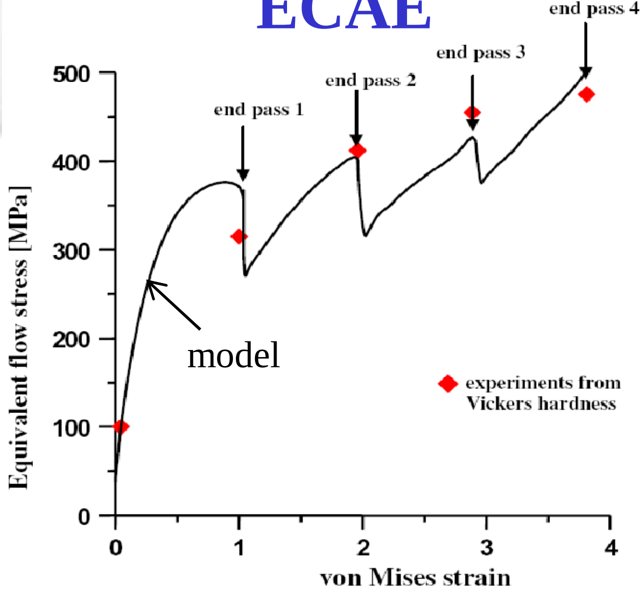
$$\theta = \int_a^b \frac{\gamma(r)}{r} dr \qquad \bar{\gamma} = \frac{\theta}{\ln(b/a)}$$

Pougis et al. Scripta Materialia, 66 (2012) 773-776

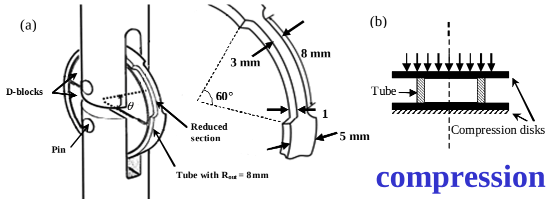
Strain hardening in SPD

L. Toth, Computational Materials Science 32 (2005) 568–576

ECAE



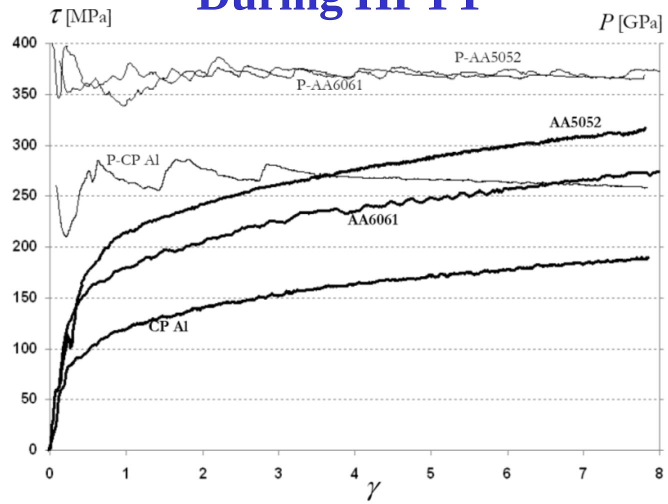
Ring-hoop tensile test



compression

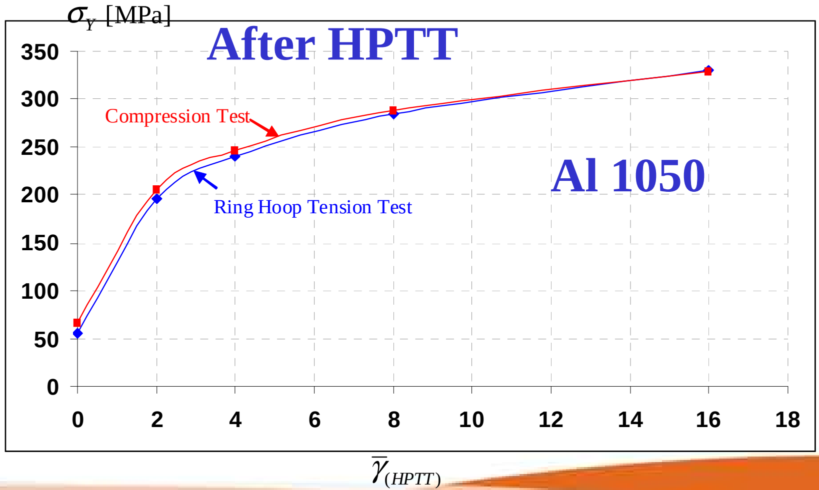
Arzaghi et al. Acta Materialia 60 (2012), pp. 4393-4408

During HPTT



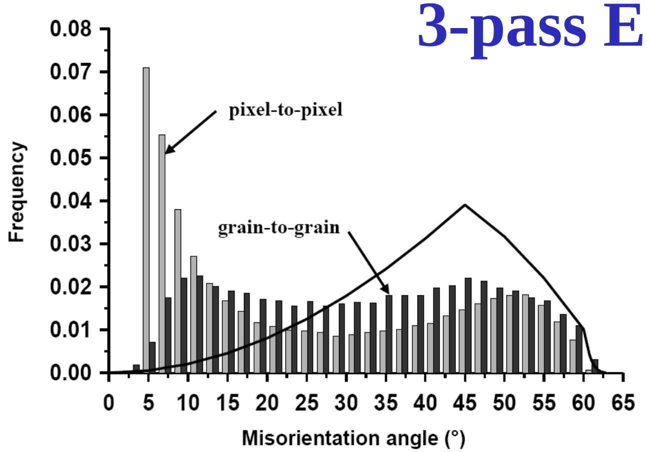
$$\overline{\tau} = \frac{T \ln(b/a)}{(b^2 - a^2)\pi h}$$

After HPTT

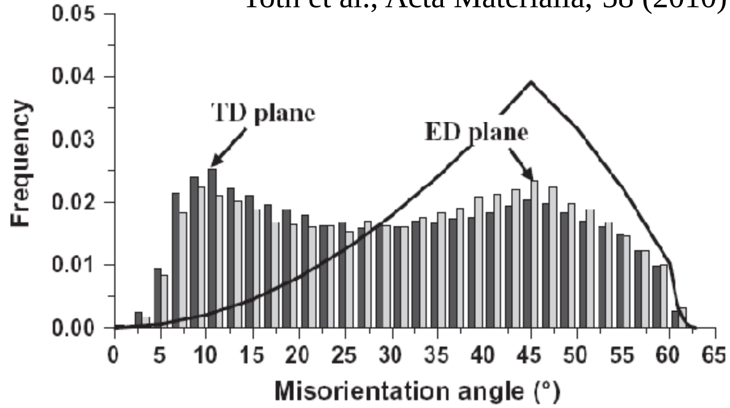


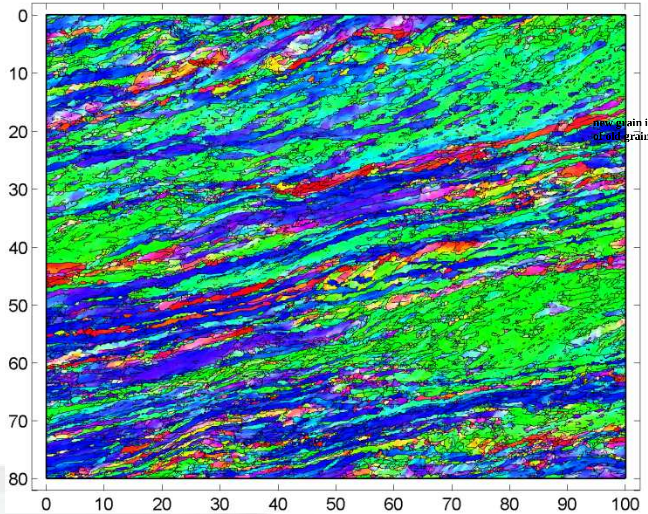
Microstructure features

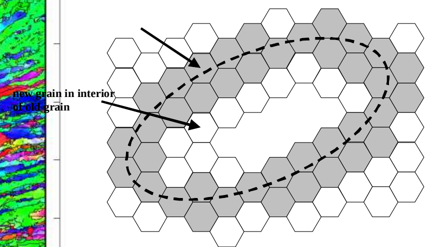
3-pass ECAE Cu



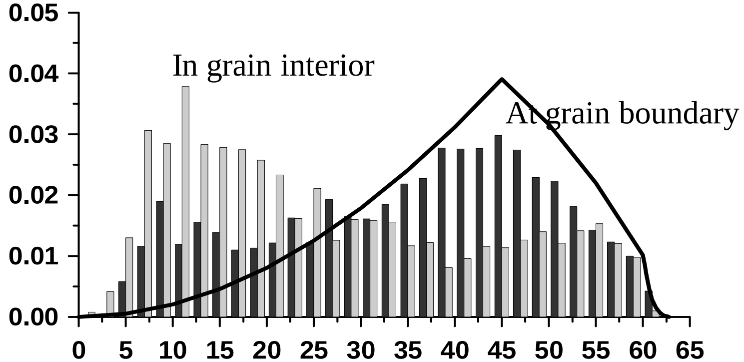
Toth et al., Acta Materialia, 58 (2010) 6706-6716





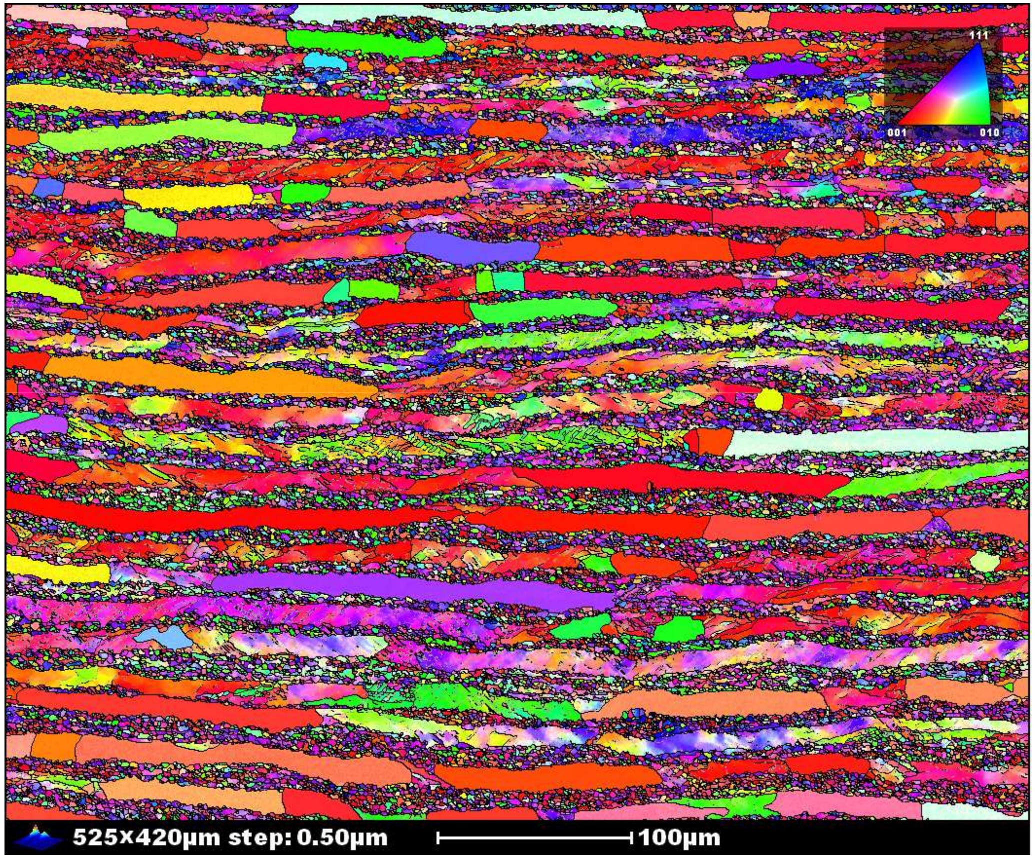


$$\upsilon_{total}(\theta) = f_{\text{int}}\upsilon_{\text{int}}(\theta) + f_{OBG}\upsilon_{OBG}(\theta)$$



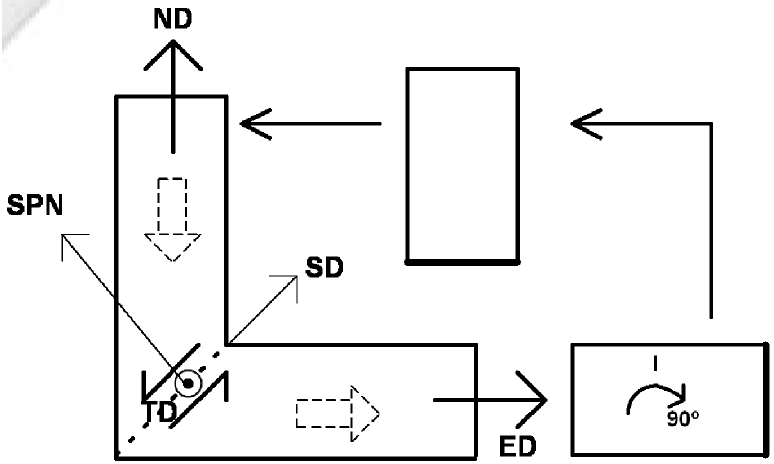
Microstructure in ARB

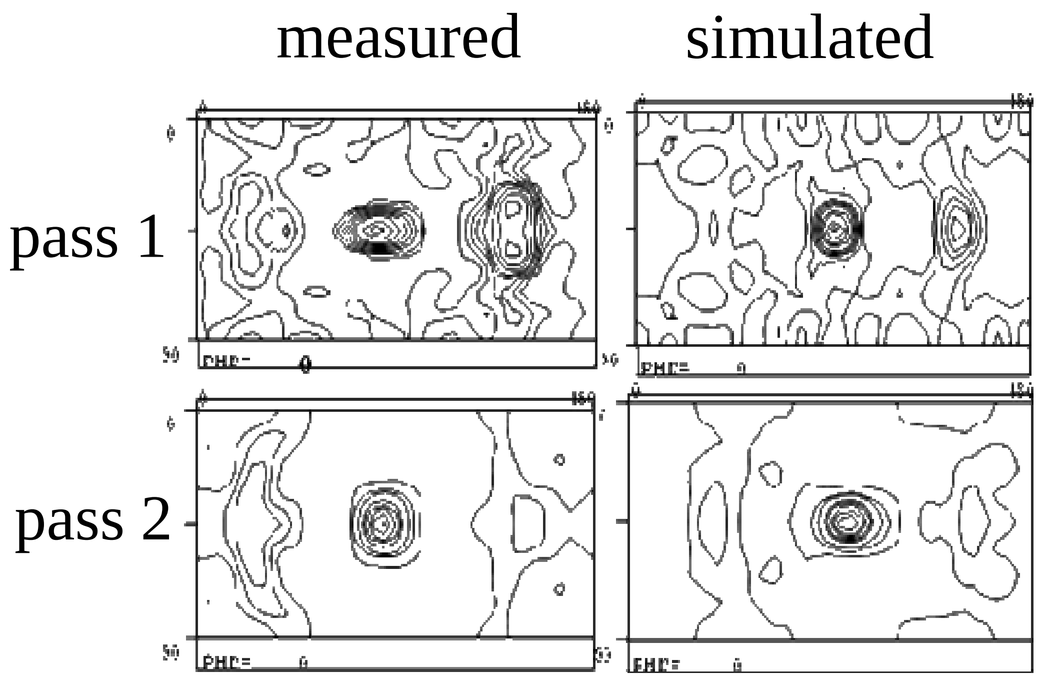
Al pure +
Al 1050



B. Beausir, T.U. Dresden

Texture evolution





ECAE, Route A, Copper

A new quantitative grain fragmentation model

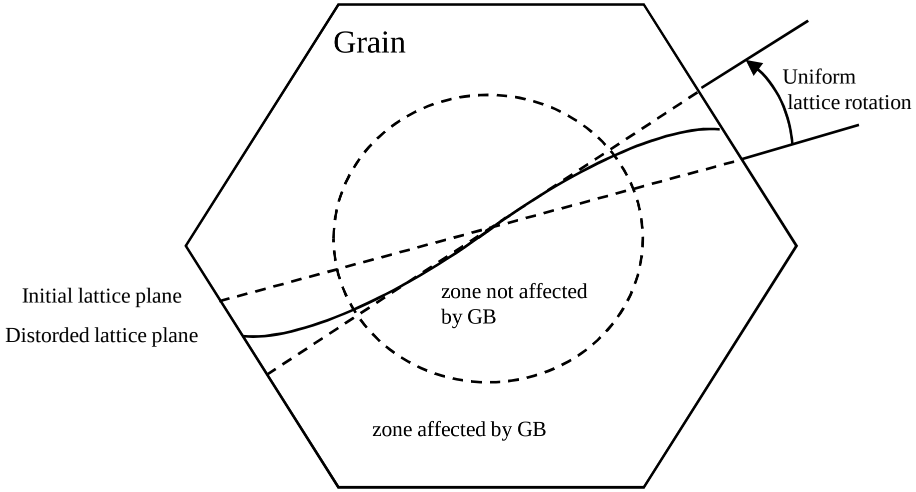
László S. Toth, Yuri Estrin, Rimma Lapovok, Chengfan Gu
Acta Materialia 58 (2010) 1782-1794

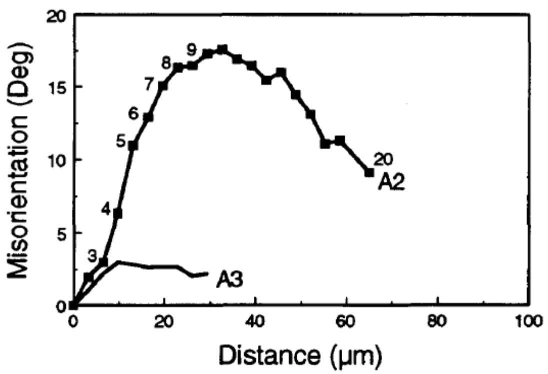
A new model is proposed for grain fragmentation that is based on lattice curvature. The lattice curvature is produced by the grain boundaries where lattice rotation is slowed down.

The new model predicts:

- **Grain size evolution and distribution**
- **Misorientation distribution of grains**
- **Misorientation of cell walls**
- **Texture development**
- **Strain hardening**

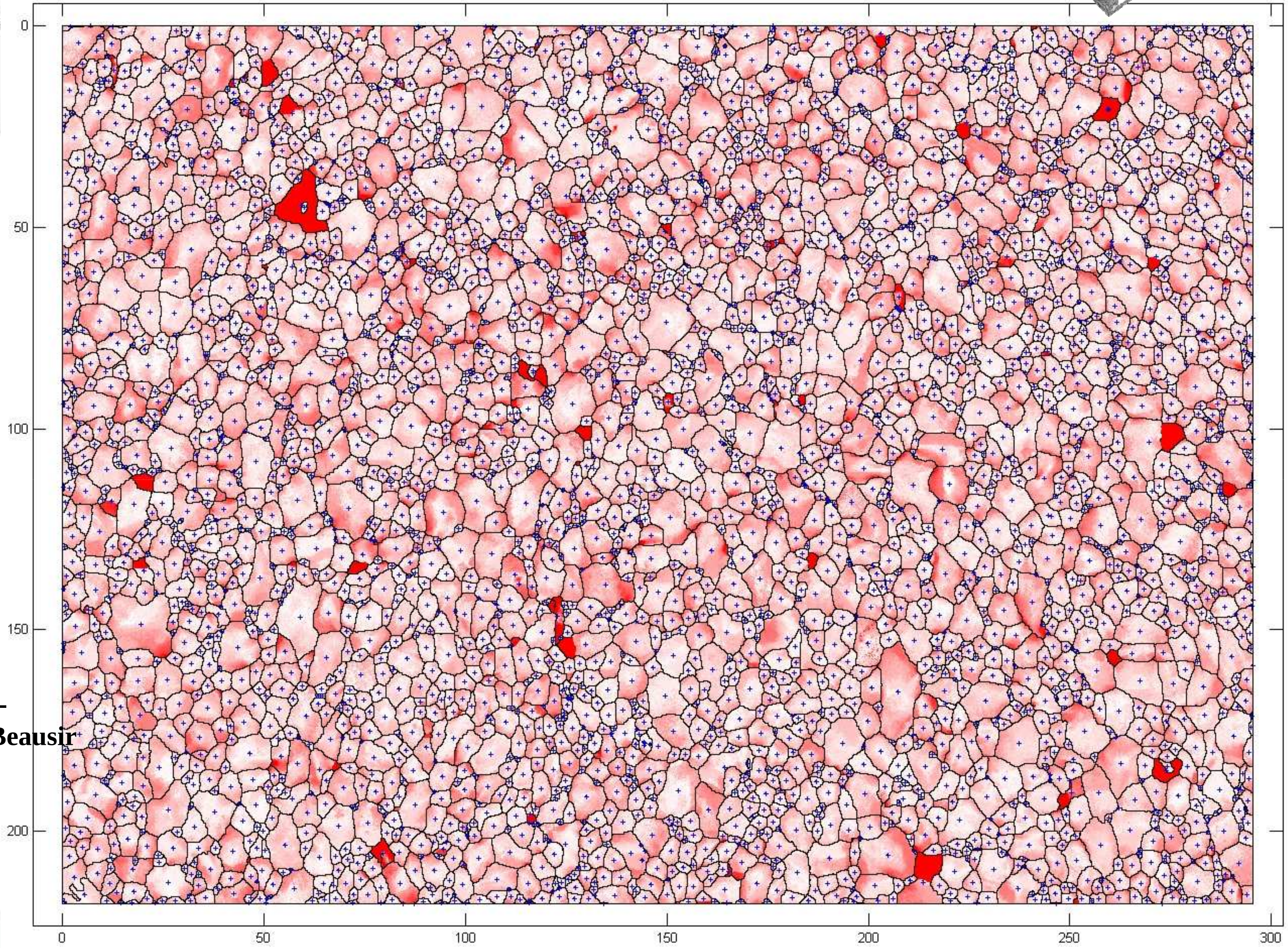
Lattice curvature in a grain





Al-Si alloy, Skjervold, 1995

Experimental evidence



Ti rolled to 2% - Fundenberger-Beausir

Lattice curvature in experiments

C.F. Gu, L.S. Tóth, B. Beausir, *Scripta Materialia*, 2012.

$$\rho_{GND} = \frac{1}{b}\sqrt{\alpha_{ij}\alpha_{ij}}$$

α_{ij} : Nye's dislocation density tensor

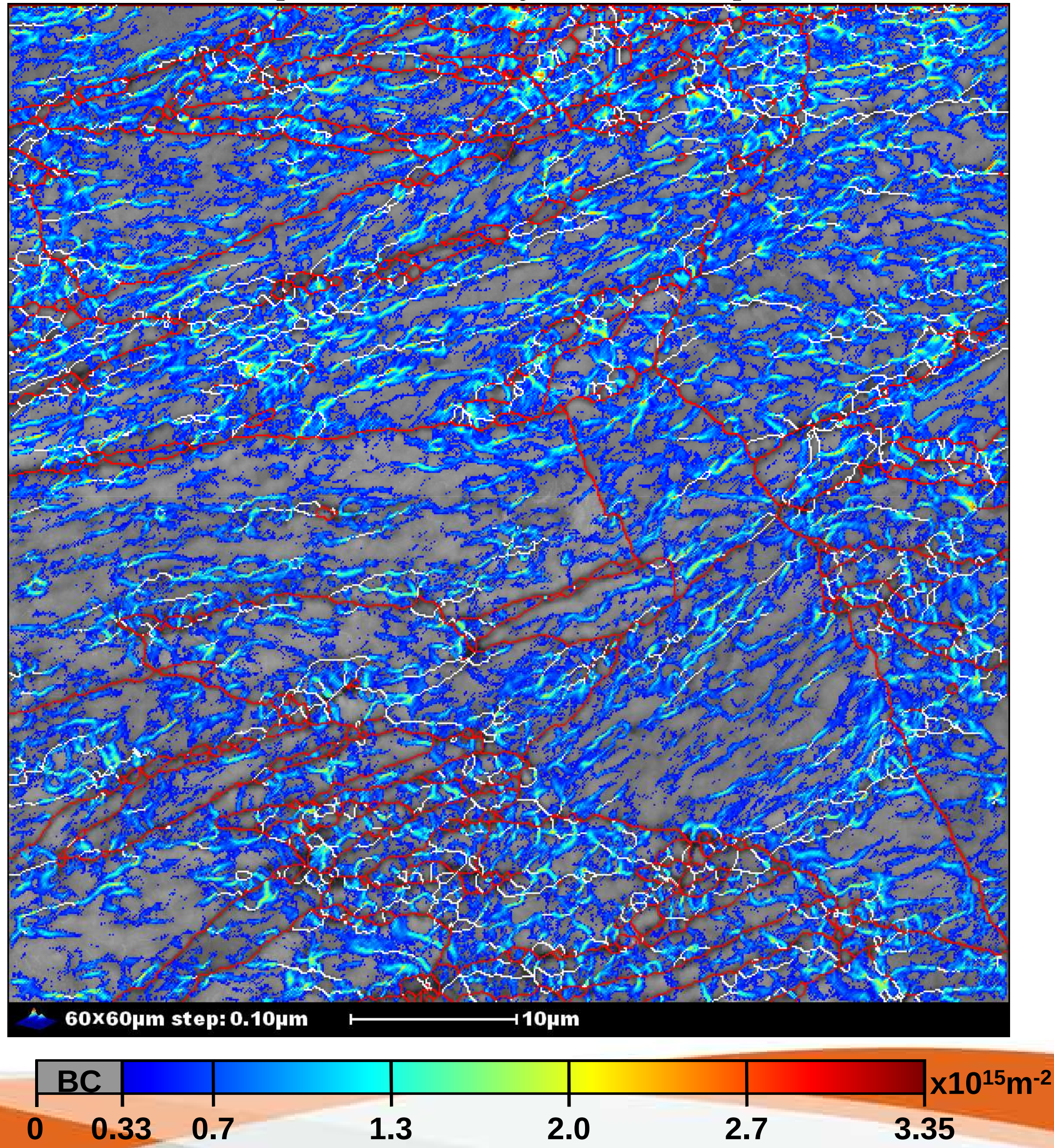
$$\rho_{GND}^{(2D)} = \frac{1}{b}\sqrt{\alpha_{12}^2 + \alpha_{13}^2 + \alpha_{21}^2 + \alpha_{23}^2 + \alpha_{33}^2}$$

Assuming isotropy:

$$\rho_{GND}^{(3D)} = 3\rho_{GND}^{(2D)} \Big/ \sqrt{5}$$

$$\rho_{GND}^{(3D)} = 4.38 \times 10^{14}\,\mathrm{m}^{-2}$$

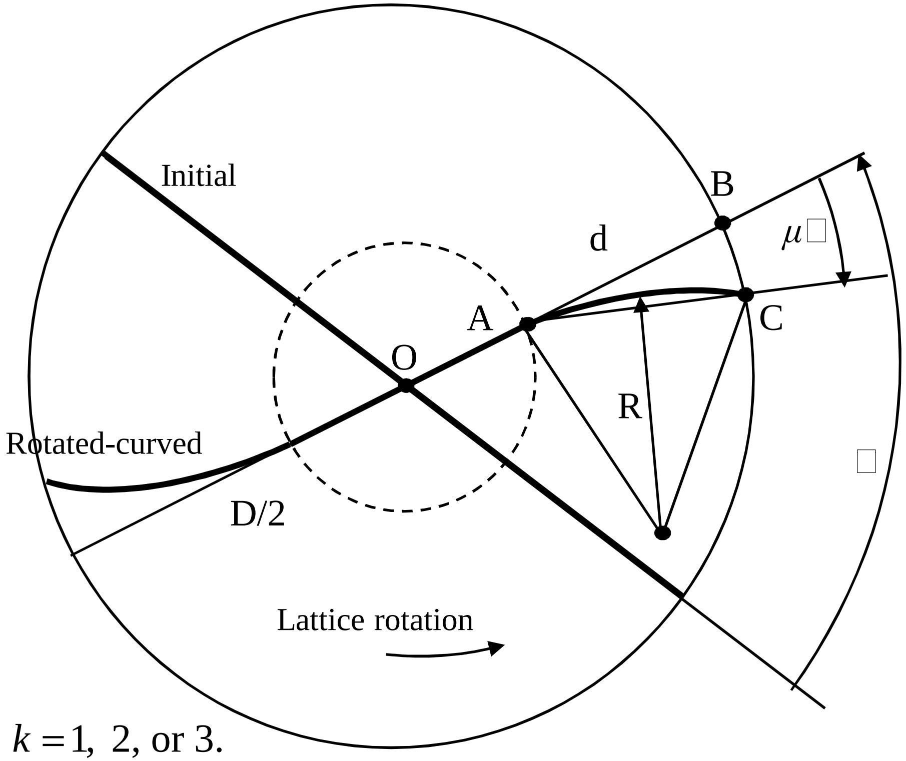
EBSD map of GND density, Cu ECAP 1 pass



Lattice curvature in a grain

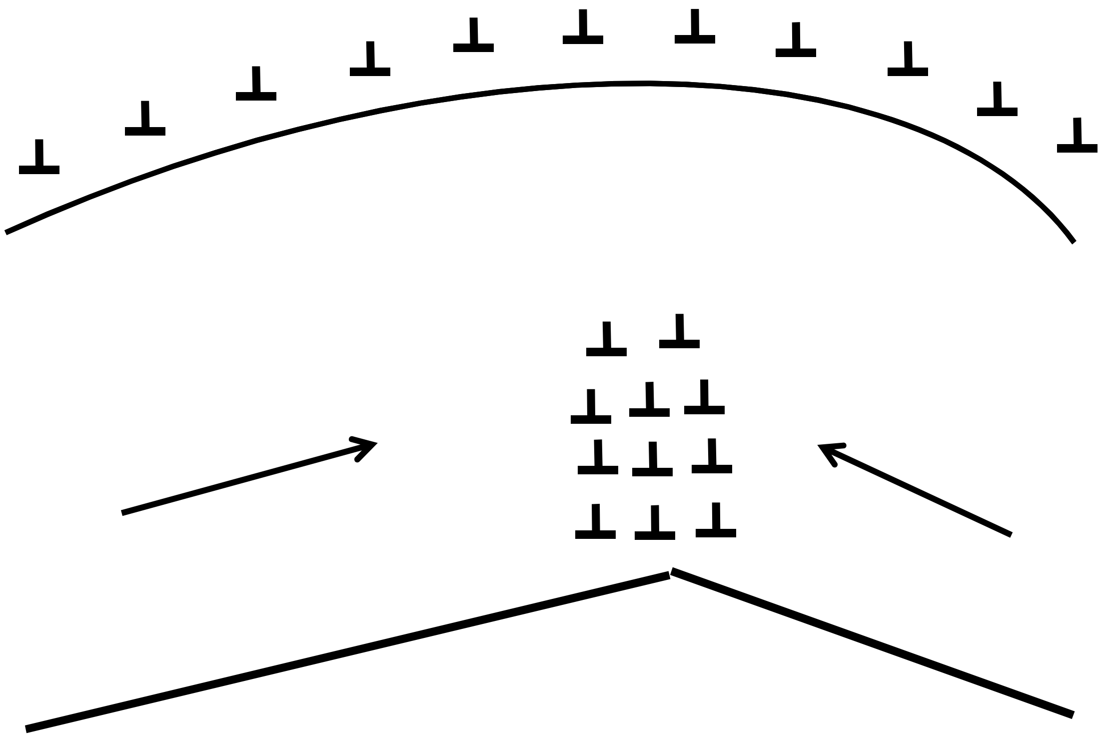
Curvature-induced dislocation density:

$$\kappa = \frac{1}{R} = \rho_{CID} b$$



$$\rho_{CID} = k \frac{12\sin(\mu\Omega)}{bD\left[-\cos(\mu\Omega)+\sqrt{\cos^2(\mu\Omega)+8}\right]}, \quad k = 1,\ 2, \text{ or } 3.$$

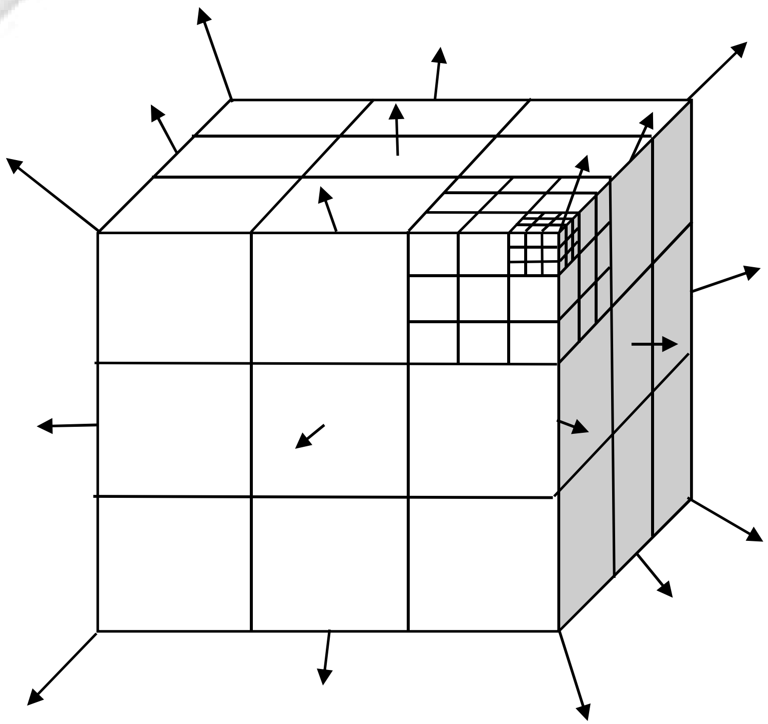
Grain fragmentation procedure

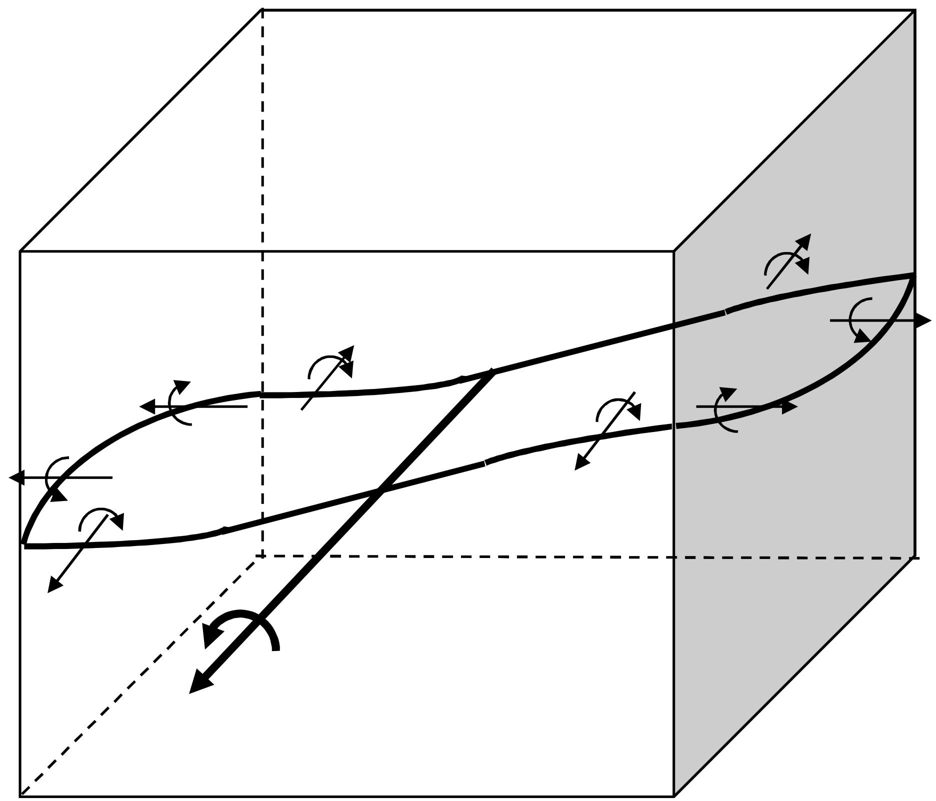


Grain fragmentation

Sugbrain rotations:

$$\dot{\underline{\Omega}}_{SG} = \dot{\underline{\Omega}}_{G} + \dot{\underline{\Omega}}_{SG}^{GB}$$





Application to ECAP of copper

Taylor model, μ=0.5, 500 initial grains → 6 million grains

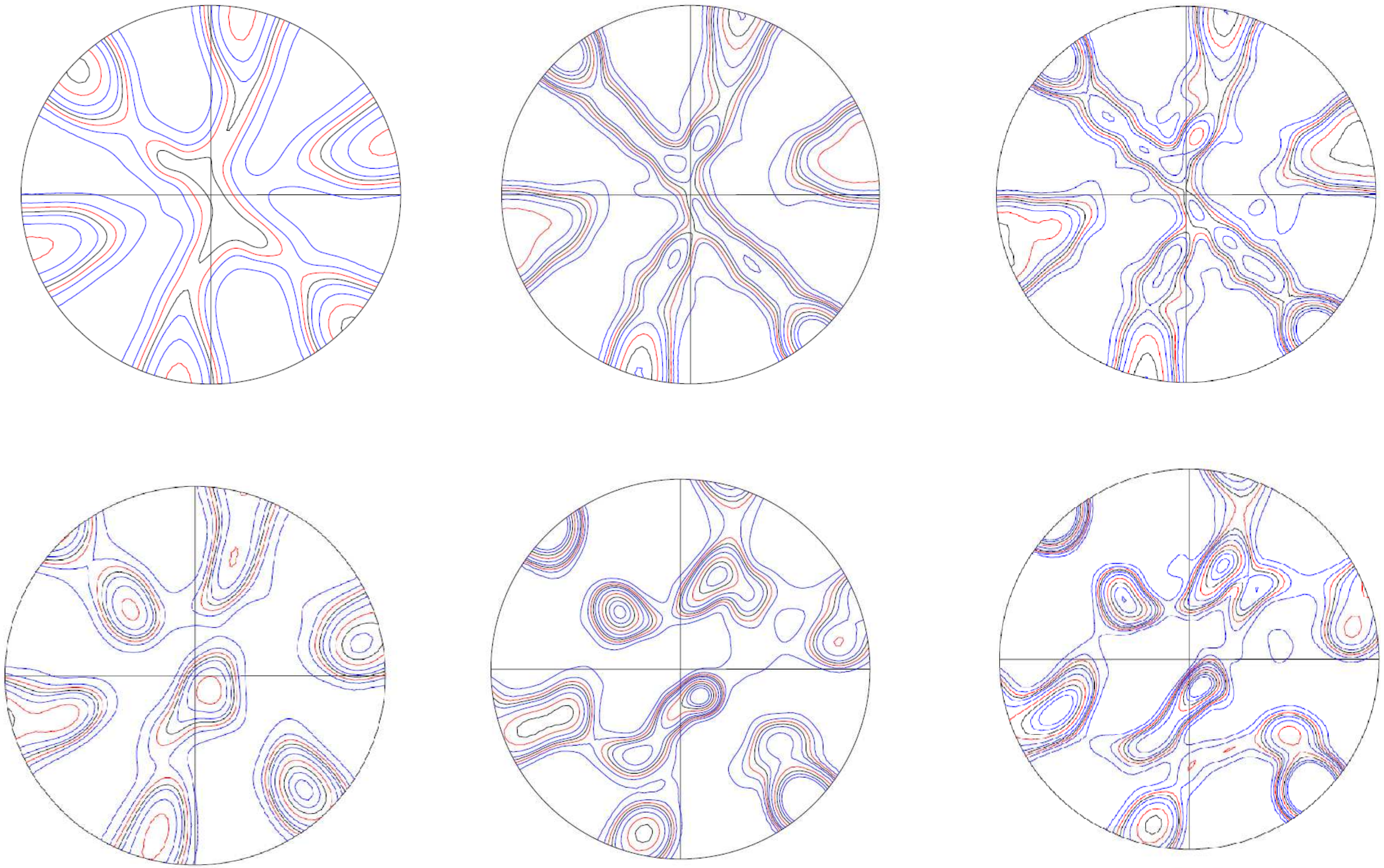
Measured:

Simulated with grain refinement:

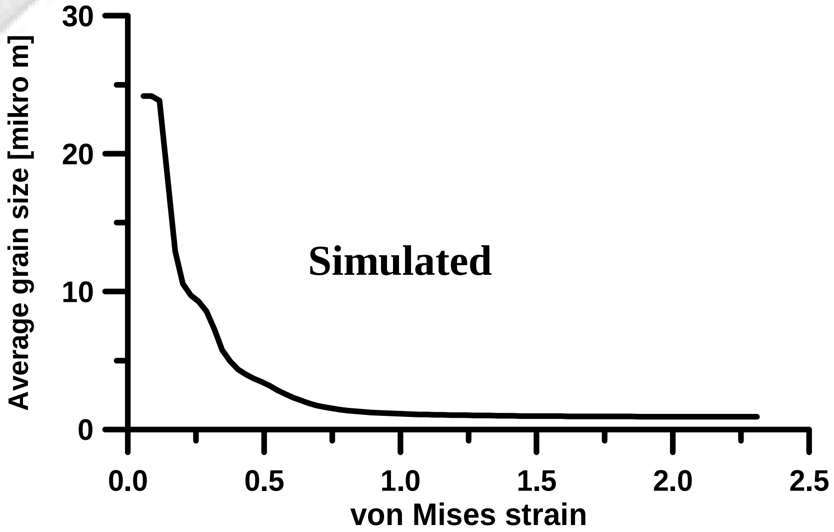
Simulated without grain refinement:

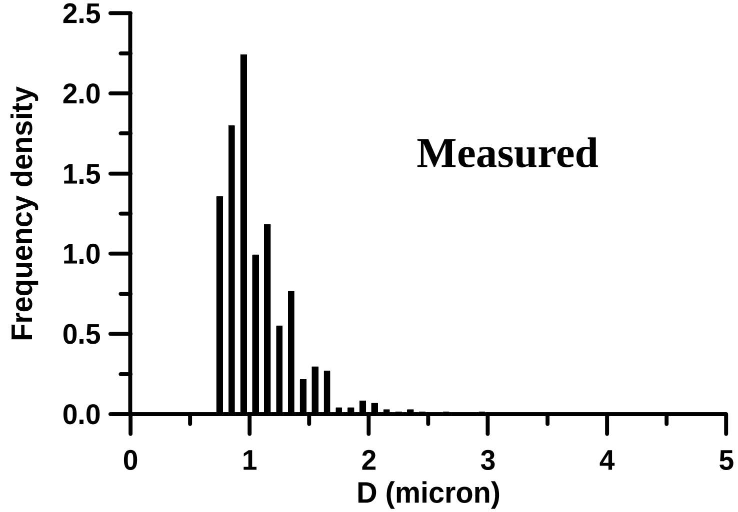
Passs-1

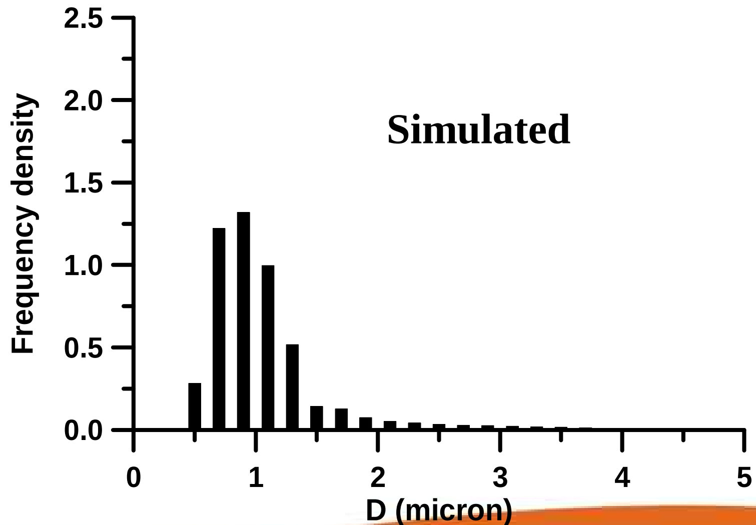
Passs-2, Route Bc



Grain size


Average grain size [mikro m]
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
von Mises strain
Simulated

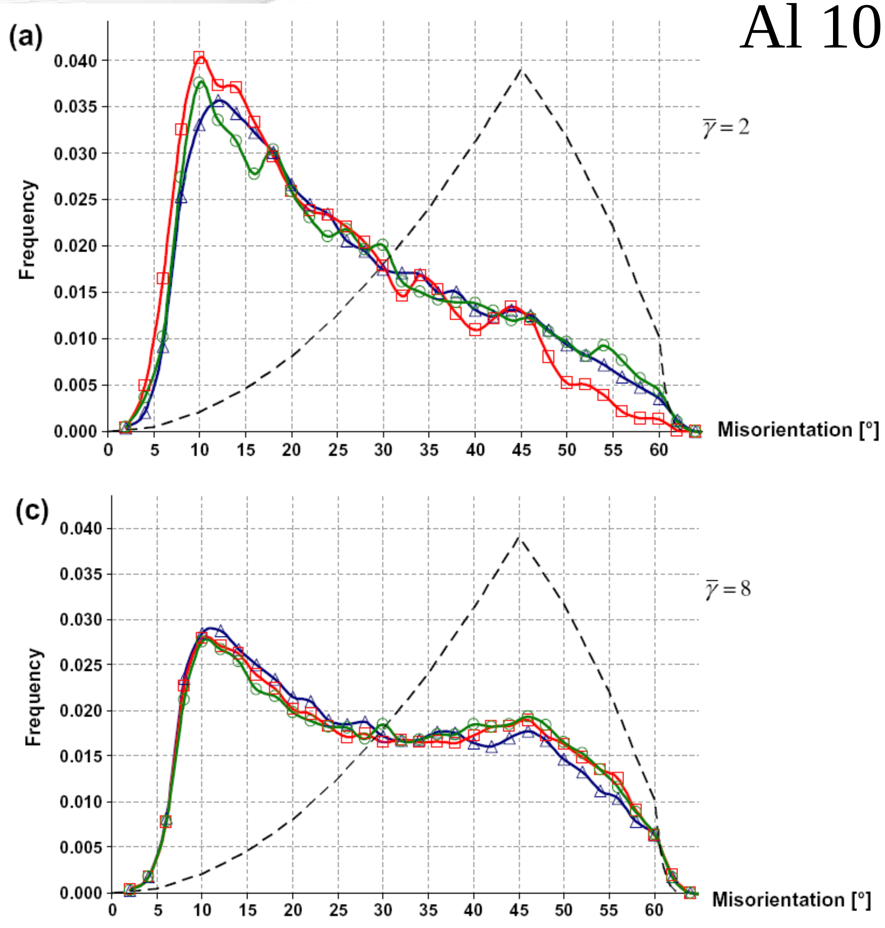

Frequency density
2.5
2.0
1.5
1.0
0.5
0.0
0
1
2
3
4
5
D (micron)
Measured


Frequency density
2.5
2.0
1.5
1.0
0.5
0.0
0
1
2
3
4
5
D (micron)
Simulated

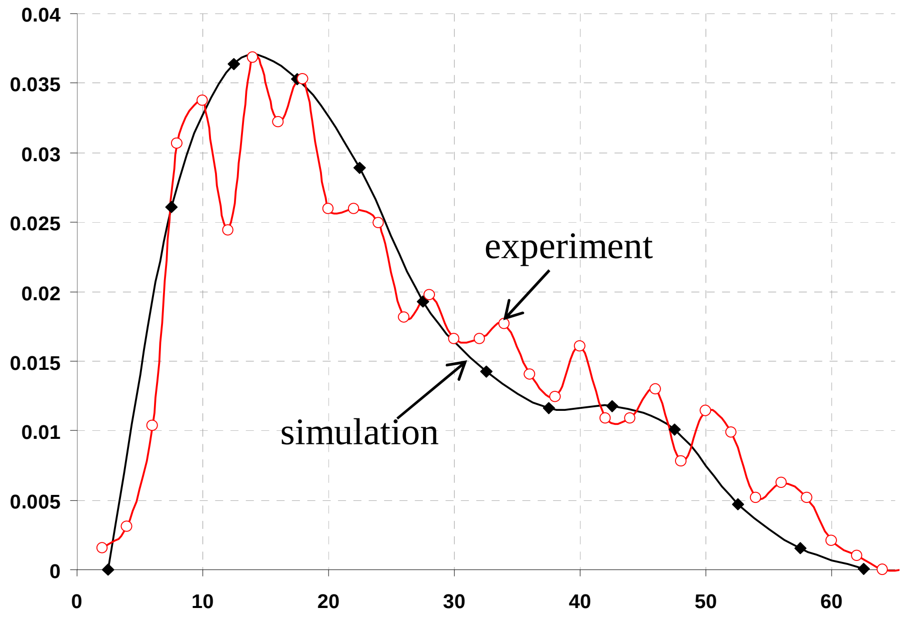
Misorientation distribution (NNMD)

Arzaghi et al. Acta Materialia 60 (2012), pp. 4393-4408

Al 1050 HPTT



M. Arzaghi, Ph.D. thesis, Metz, France, 2010



Next-grain misorientation distribution
Al 1050 HPTT, shear = 4

The dislocation-cell based hardening model

Y. Estrin, L.S. Toth, A. Molinari, Y. Bréchet, *Acta materialia*, 46, 5509-5522, 1998, cited 182 times
L.S. Toth, A. Molinari, Y. Estrin, *J. Eng. Mat. Techn.* 124, 71-77, 2002, cited 70 times.

Cell wall:

$$\dot{\rho}_{ws} = (1-\xi_1)\frac{6\beta^*\dot{\gamma}_r(1-f)^{2/3}}{bdf} + (1-\xi_2)\frac{\sqrt{3}\beta^*\dot{\gamma}_r(1-f)\sqrt{\rho_{ws}+\rho_{wg}}}{fb} - k_0\left(\frac{\dot{\gamma}_w}{\dot{\gamma}_0}\right)^{-1/n}\dot{\gamma}_r\rho_{ws}$$

$$\dot{\rho}_{wg} = \xi_1\frac{6\beta^*\dot{\gamma}_r(1-f)^{2/3}}{bdf} + \xi_2\frac{\sqrt{3}\beta^*\dot{\gamma}_r(1-f)\sqrt{\rho_{ws}+\rho_{wg}}}{fb}$$

slip from the cells

FR sources for dislocations coming from the cell

annihilation (cross slip)

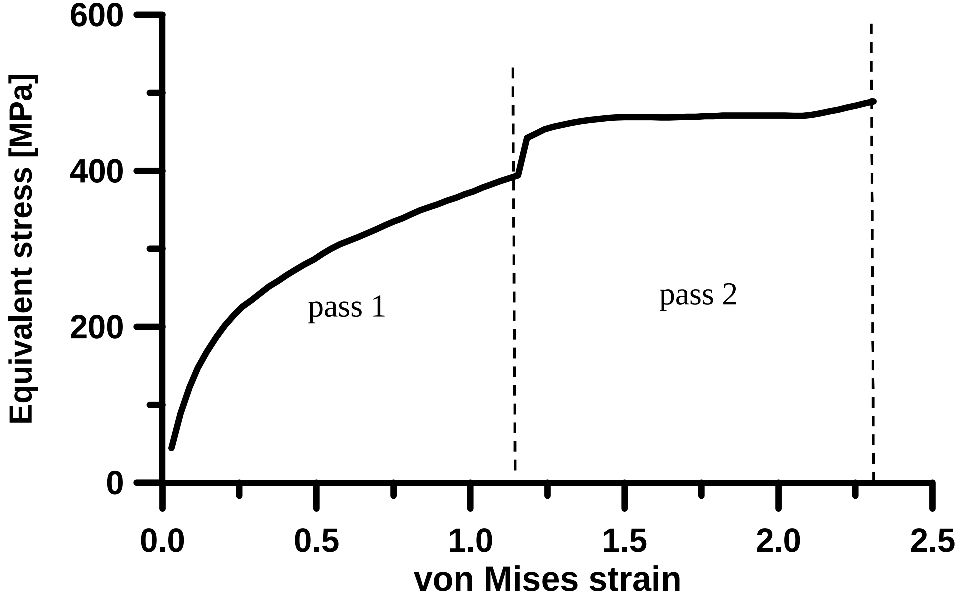
Cell interior:

$$\dot{\rho}_c = \alpha^*\frac{1}{\sqrt{3}}\frac{\sqrt{\rho_w}}{b}\dot{\gamma}_w - \beta^*\frac{6\dot{\gamma}_c}{bd(1-f)^{1/3}} - k_0\left(\frac{\dot{\gamma}_c}{\dot{\gamma}_0}\right)^{-1/n}\dot{\gamma}_c\rho_c$$

by FR sources from the walls

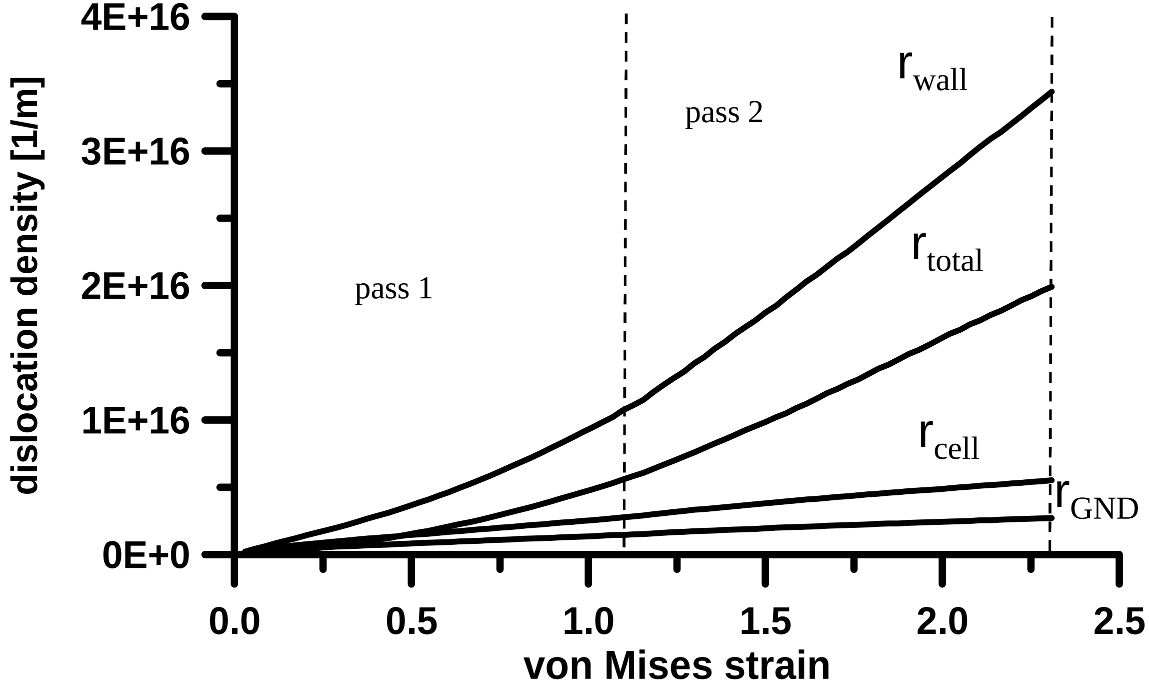
flux to the walls

Hardening

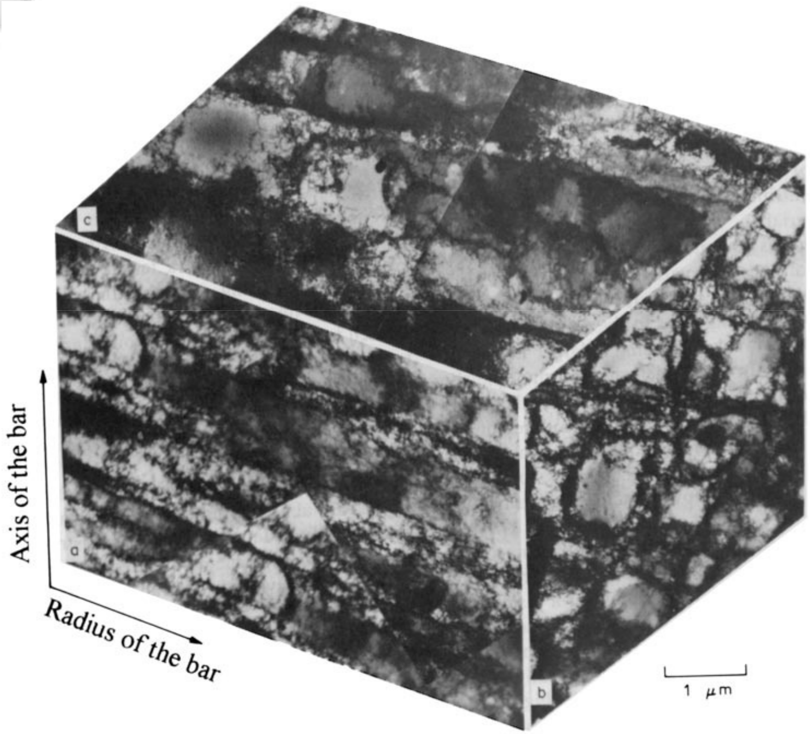


Predicted strain hardening curve

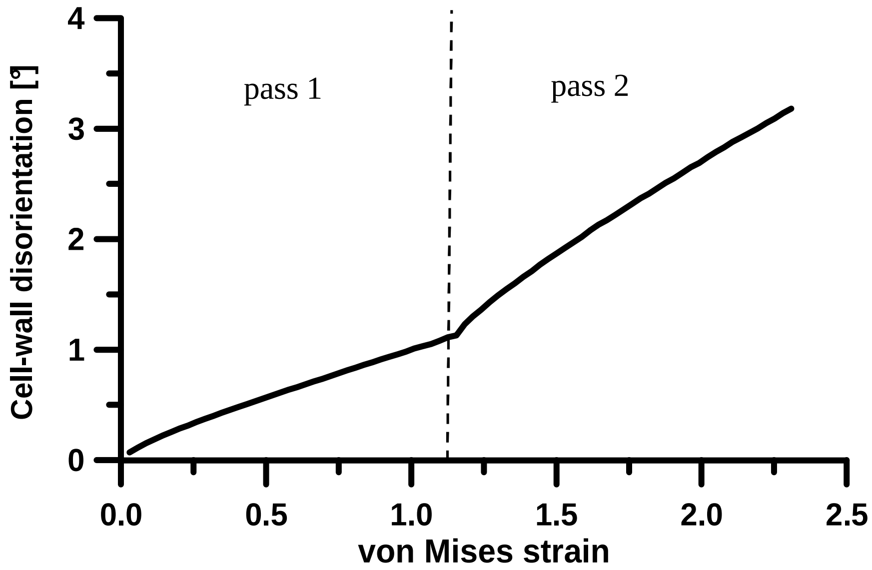
Dislocation densities



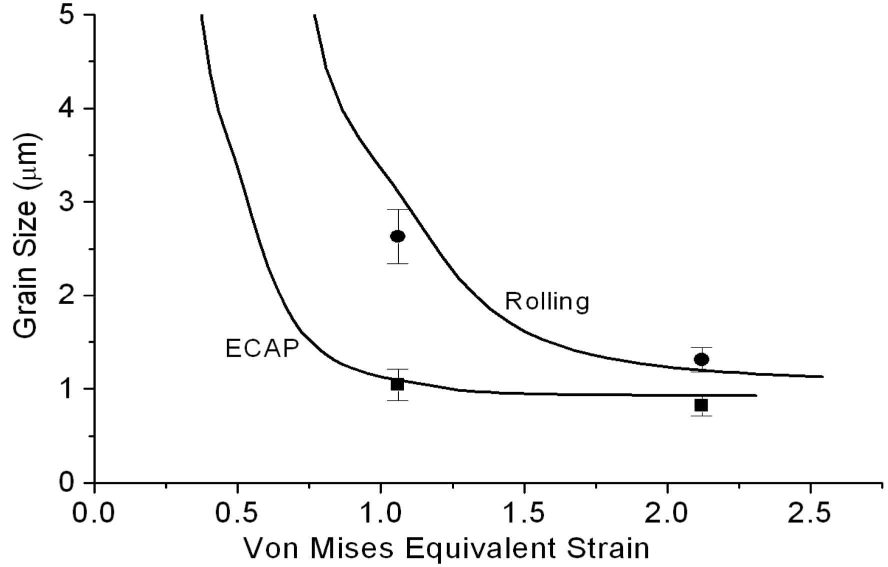
Cell-wall misorientation



$$\theta = bd\rho_{wg}$$



Strain path effect on grain refinement



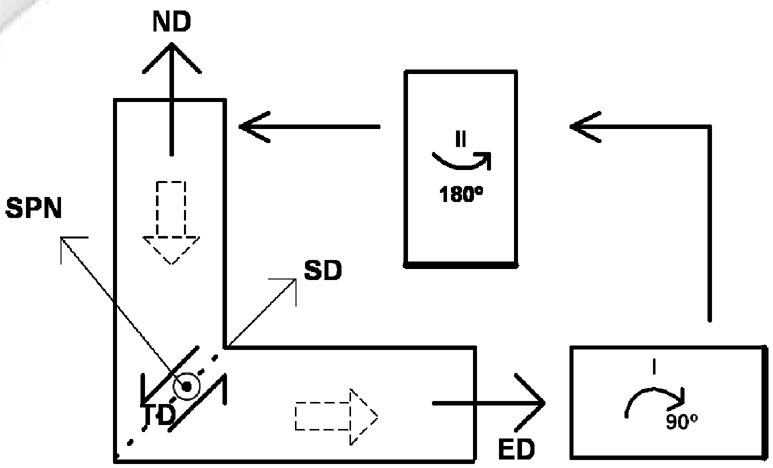
Simulated (continuous lines) and experimental (symbols) development of average grain size obtained in ECAE and rolling

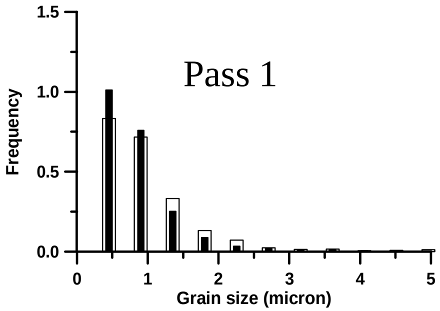
C.F. Gu, L.S. Toth, M. Arzaghi, C.H.J. Davies, *Scripta Materialia*, 64 (2011) 284–287

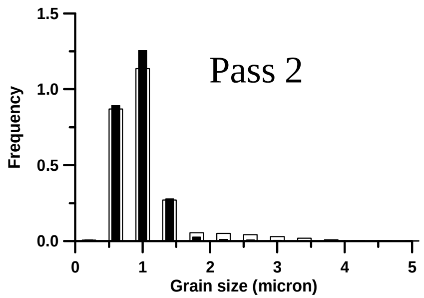
Strain reversal effect on texture and grain refinement

C.F. Gu and L.S. Tóth,
Acta Materialia, 59 (2011) 5749-5757

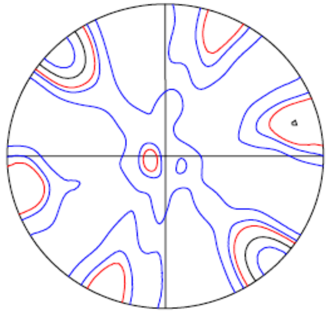
Route C ECAE



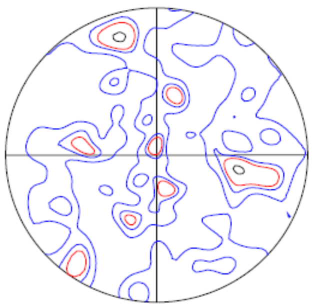




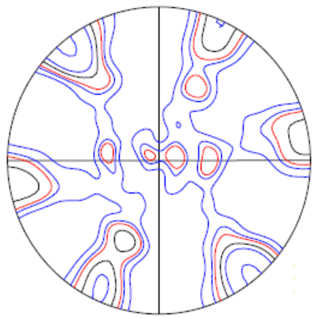
Grain size



Route C two-pass measured texture



Simulated texture by traditional VPSC model



Simulated texture by the new grain refinement model

C.F. Gu, L.S. Toth, C.H.J. Davies,
Scripta Materialia, 65 (2011), 167-170

Strong points and future key issues

Strong points:

- SPD deformation techniques can produce ultra fine grain microstructures with enhanced mechanical properties in bulk form.
- Grain sizes are in the range of sub-micron, in between the minimum grain sizes by DRX et nano-structures, readily feasible
- BNM materials are excellent candidates for biomechanics applications and micro-parts.

Future keys issues:

- Up-scaling from laboratory to industrial processes.
- Mastering of microstructure variations → grand potential in metallurgy
- Understanding the grain subdivision process

Fundamental publications in SPD

Bulk nanostructured materials from severe plastic deformation, Valiev, RZ; Islamgaliev, RK; Alexandrov, IV, PROGRESS IN MATERIALS SCIENCE 45, **2000**, 103-189, **2622** citations

Principles of equal-channel angular pressing as a processing tool for grain refinement, Valiev, Ruslan Z.; Langdon, Terence G. PROGRESS IN MATERIALS SCIENCE 51 **2006** 881-981, **972** citations

STRUCTURE AND PROPERTIES OF ULTRAFINE-GRAINED MATERIALS PRODUCED BY SEVERE PLASTIC-DEFORMATION, VALIEV, RZ; KORZNIKOV, AV; MULYUKOV, RR, MATERIALS SCIENCE AND ENGINEERING 168 **1993** 141-148, **779** citations

Ultra-fine grained bulk aluminum produced by accumulative roll-bonding (ARB) process, Saito, Y; Tsuji, N; Utsunomiya, H; et al. SCRIPTA MATERIALIA 39 **1998** 1221-1227, **462** citations

Producing bulk ultrafine-grained materials by severe plastic deformation, Valiev, RZ; Estrin, Y; Horita, Z; et al., JOM 58 **2006** 33-39, **407** citations

Nanostructuring of metals by severe plastic deformation for advanced properties, Valiev, R, NATURE MATERIALS 3 **2004** 511-516, **355** citations

Analysis of texture evolution in equal channel angular extrusion of copper using a new flow field, Toth, LS; Massion, RA; Germain, L; et al., ACTA MATERIALIA 52 **2004** 1885-1898, **109** citations

Texture evolution in equal-channel angular extrusion, Beyerlein, Irene J.; Toth, Laszlo S., PROGRESS IN MATERIALS SCIENCE 54 **2009**, 427-510, **60** citations

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