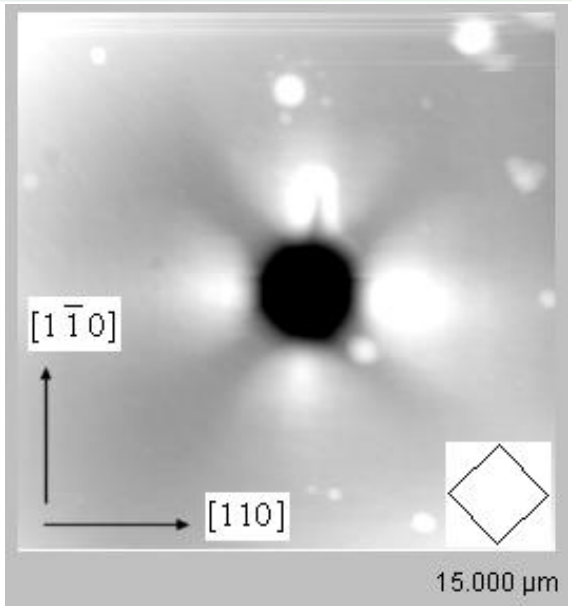
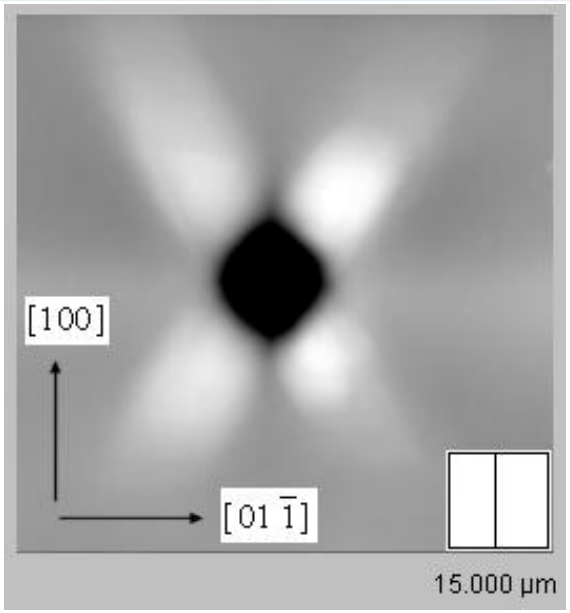
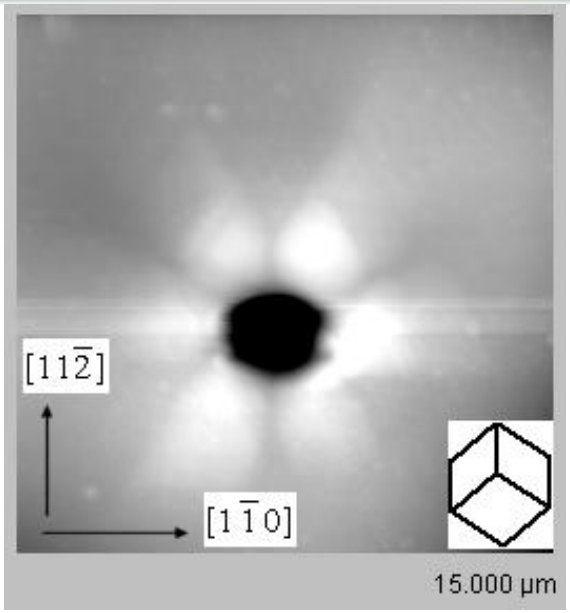
Nanoindentation – orientation dependence, Cu single crystals

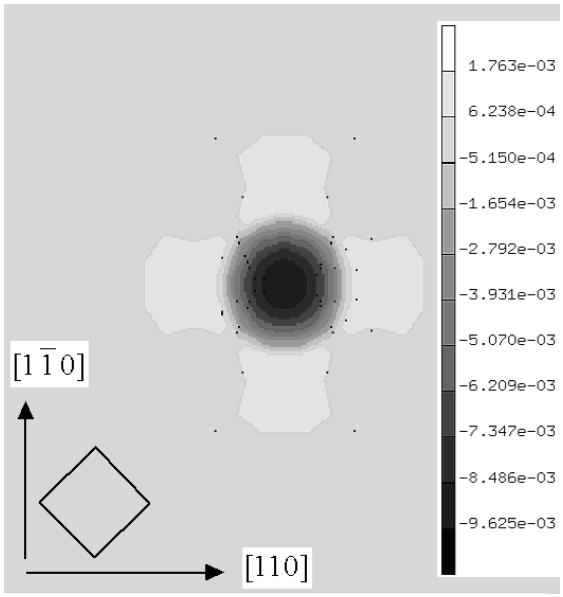
experiment

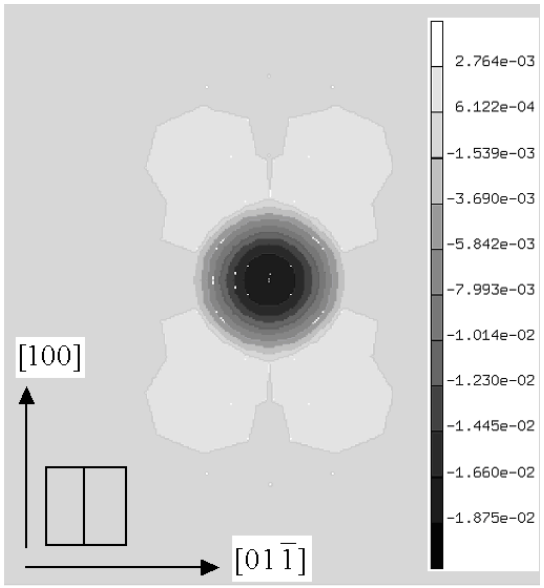


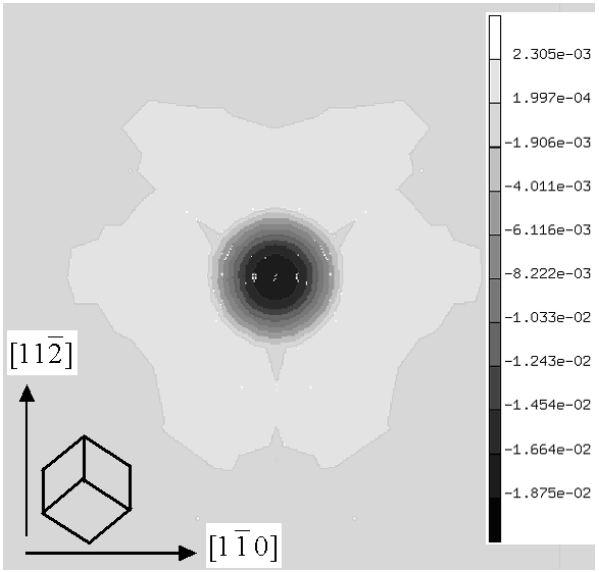




simulation

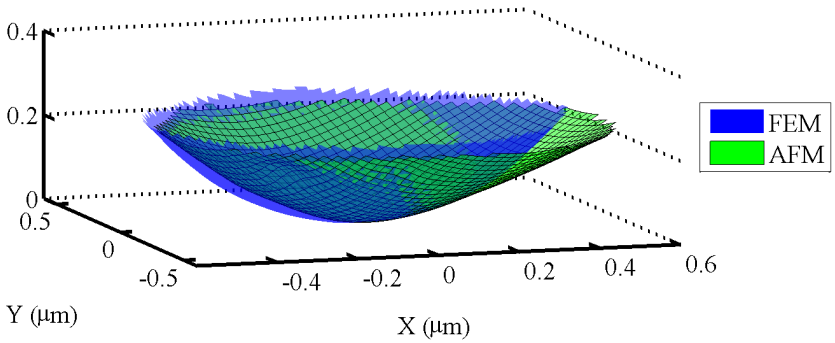






Zaafarani et al. Acta Mat. 54 (2006) 1707; Wang et al. Acta Mat. 52 (2004) 2229

Plastic anisotropy of γ-TiAl: Simulated pile-up profiles

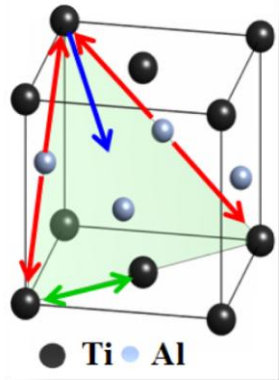


[110]

from 51 orientations
approx. resol. 9°

[111]

Pile-up IPF
High symmetry orientations



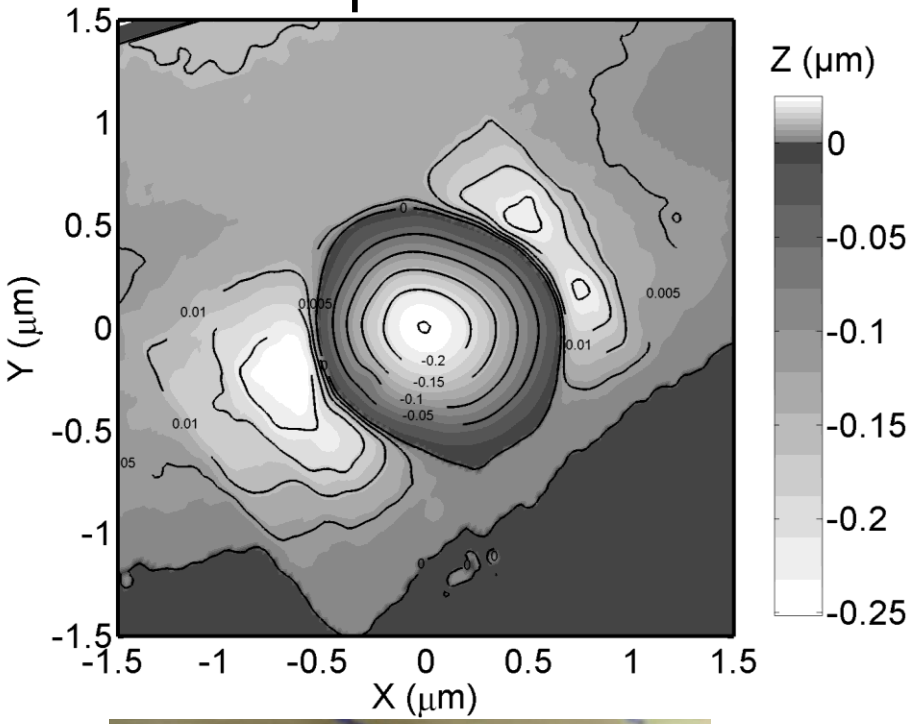
[001]

[101]

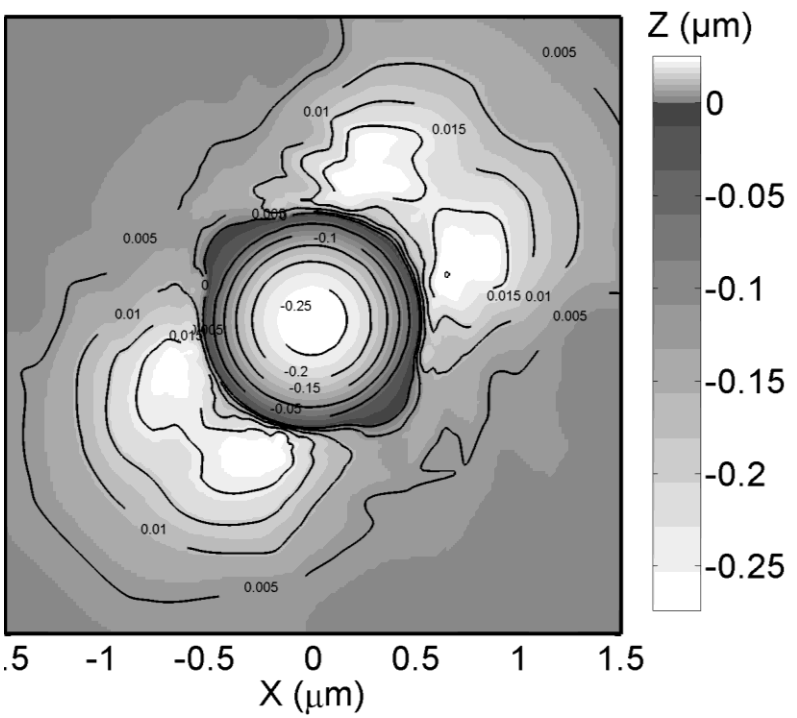
[100]

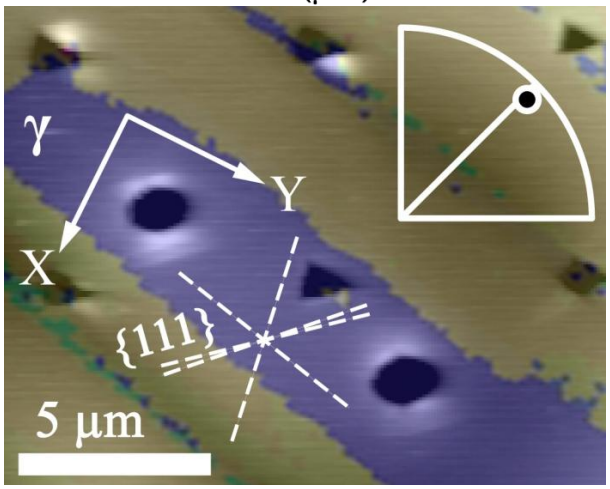
γ-TiAl: comparison of AFM with CPFEM topography

Experiment

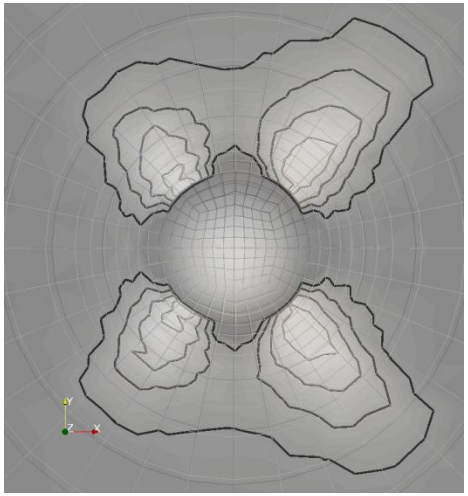


Simulation

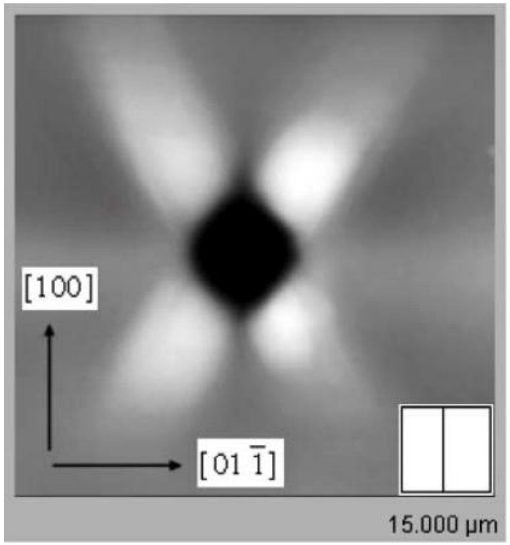




Relative strengths of slip systems

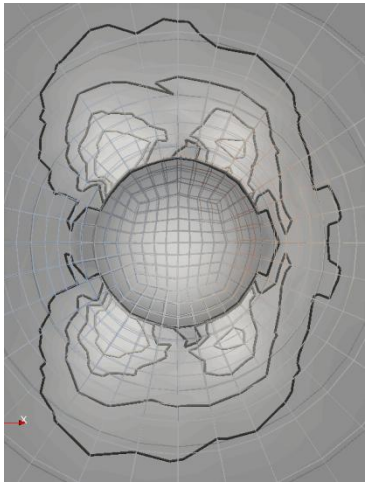


$\tau_c^O/\tau_c^S < 1$ (Ti-50Al)



$\tau_c^O/\tau_c^S \approx 1$

Cu, Al, Au, Ag,…

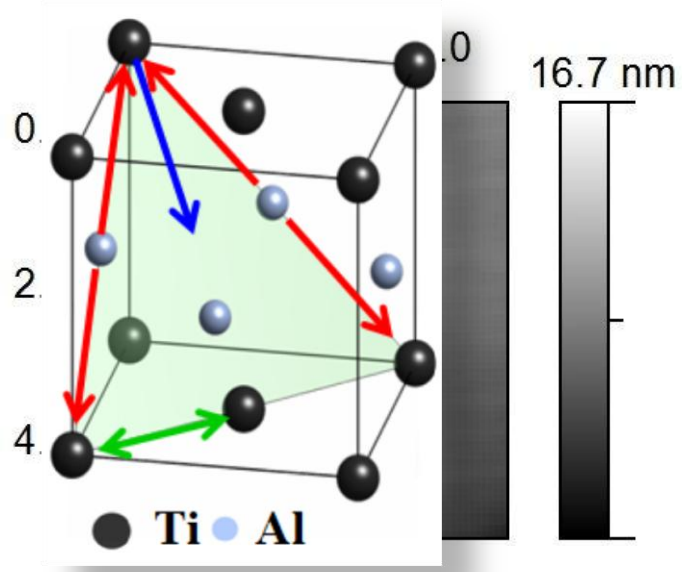


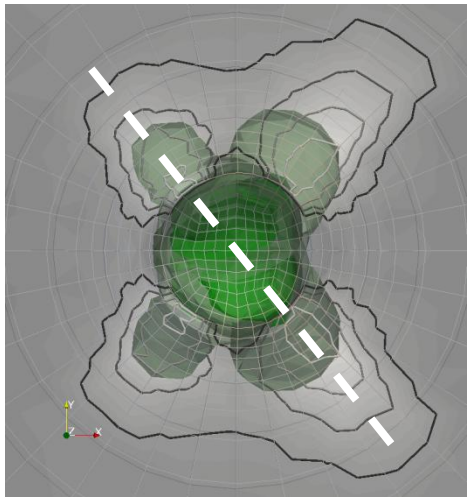
$\tau_c^O/\tau_c^S > 1$

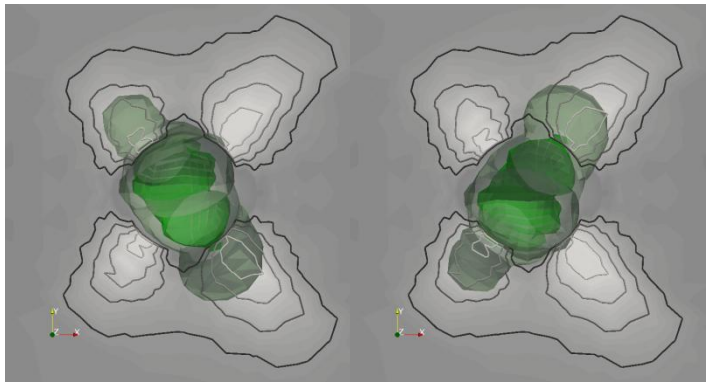
Predicted for Ti-55Al

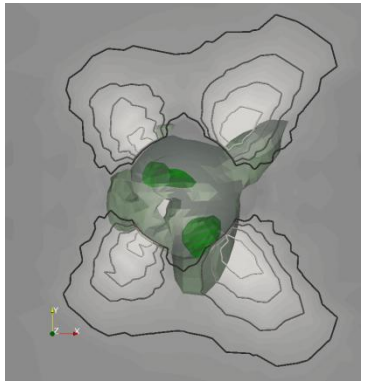
[101] indentation indicates relative strengths of ordinary and super dislocation glide in TiAl

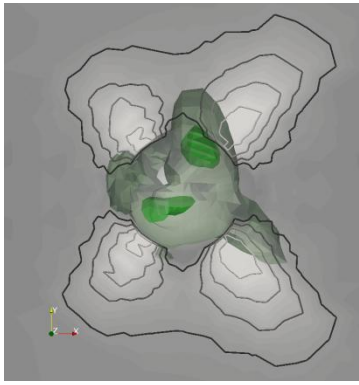
[101] indentation in γ-TiAl

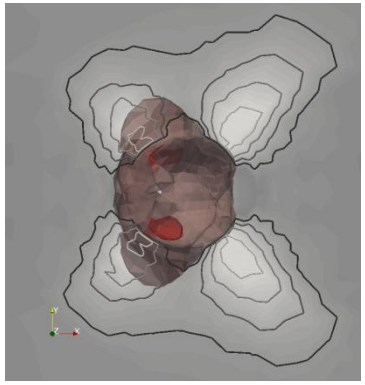


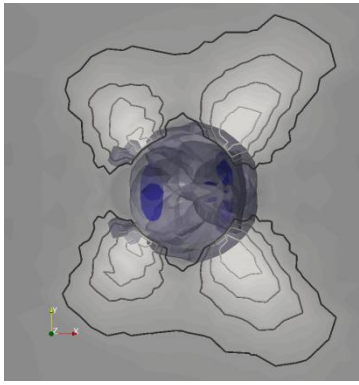


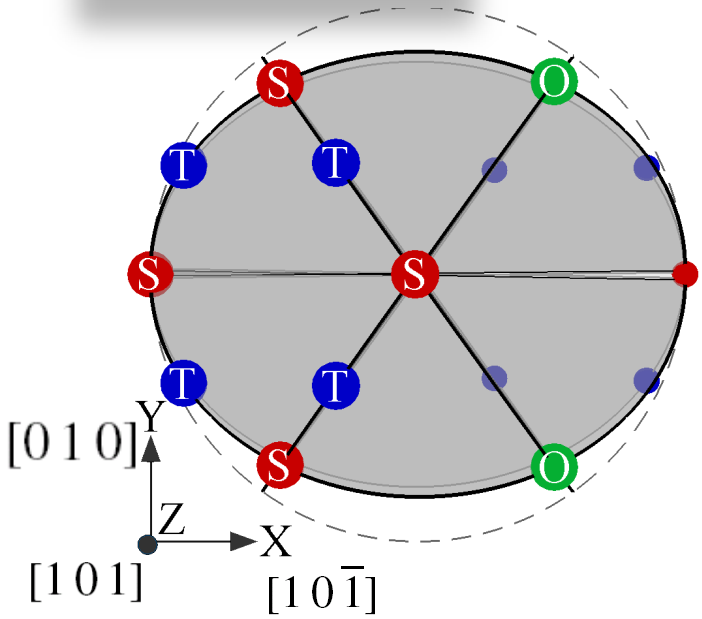


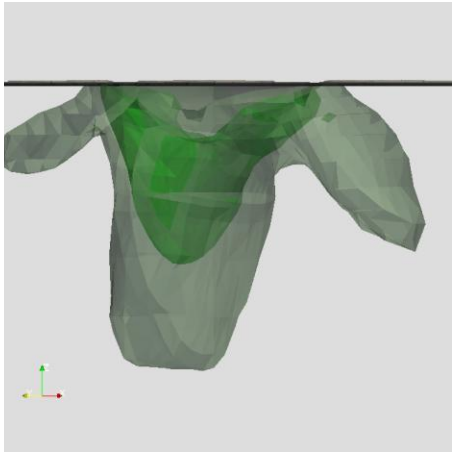






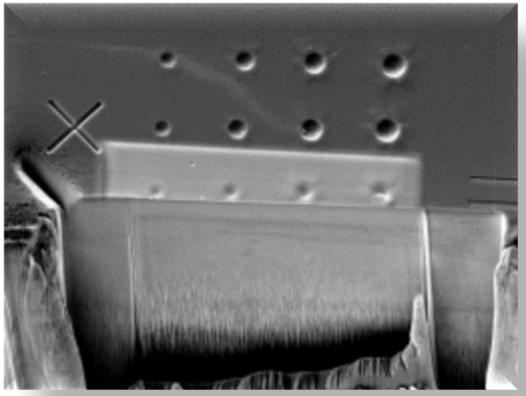


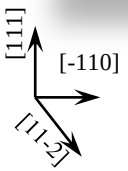


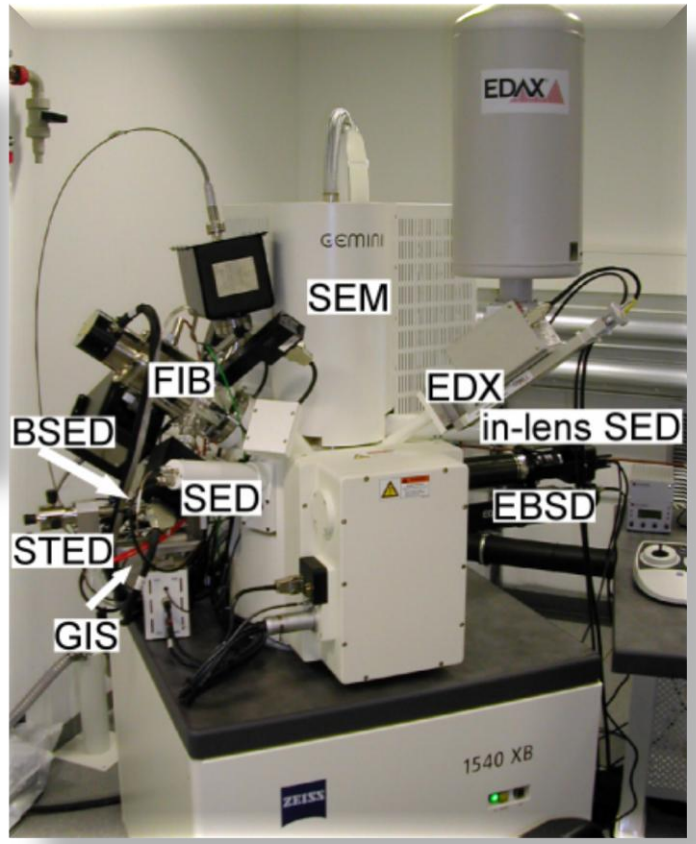


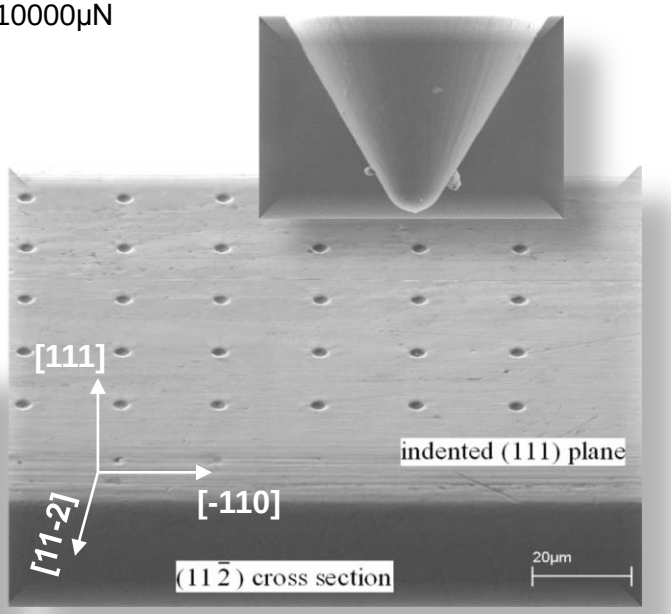
3D microstructure analysis

Cu, 60° conical, tip radius 1µm, loading rate 1.82mN/s, loads: 4000µN, 6000µN, 8000µN, 10000µN





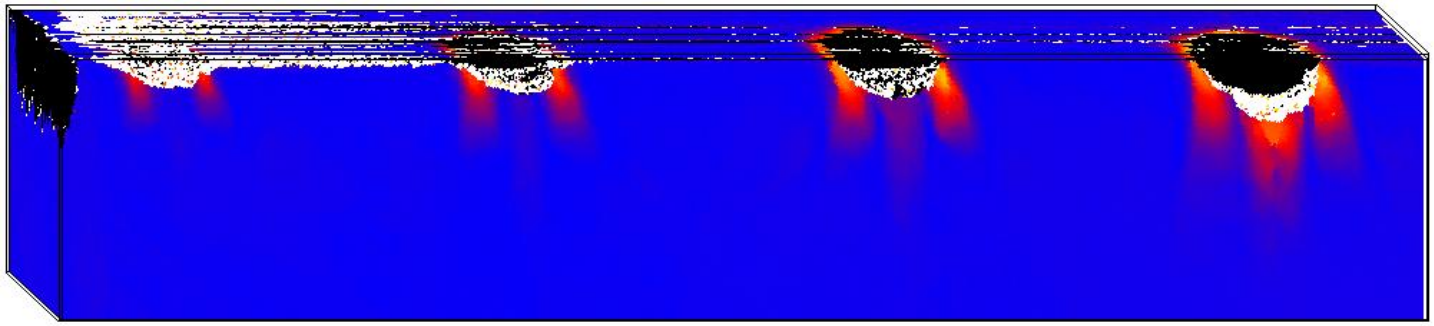


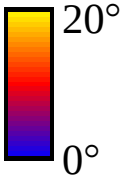


Zaafarani et al. Acta Mat. 54 (2006) 1707; Wang et al. Acta Mat. 52 (2004) 2229

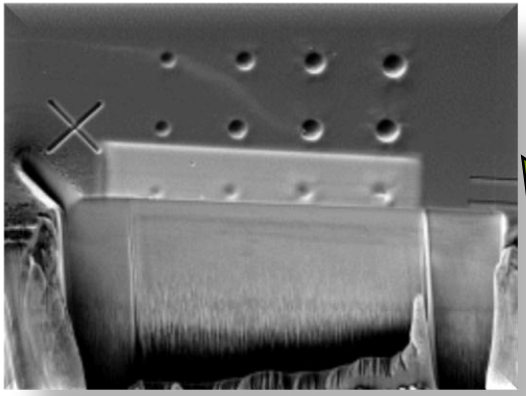
Indentation (smaller is stronger): 3D EBSD and CPFEM

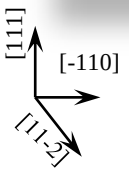
Cu, 60° conical, tip radius 1µm, loading rate 1.82mN/s, loads: 4000µN, 6000µN, 8000µN, 10000µN

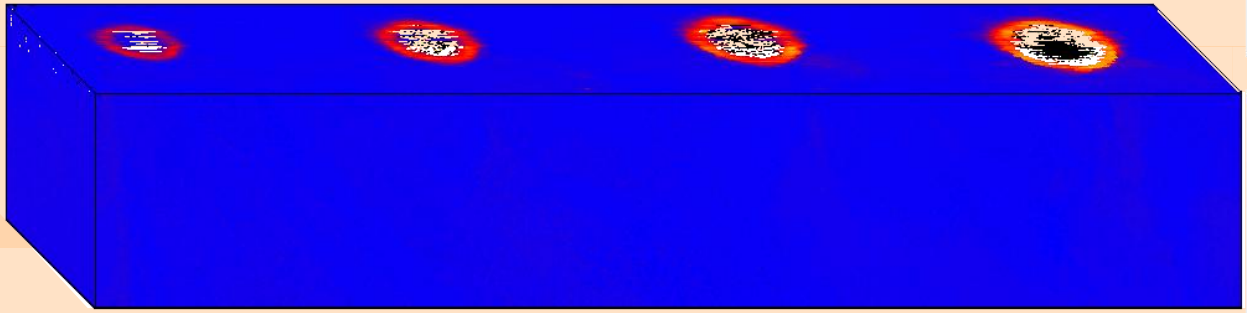




Misorientation angle



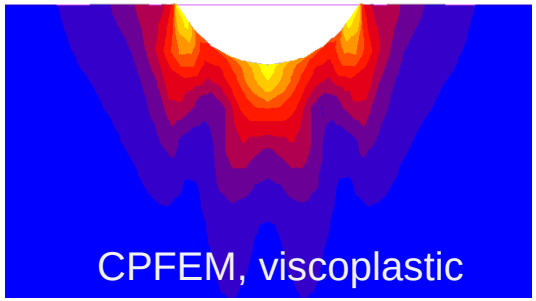


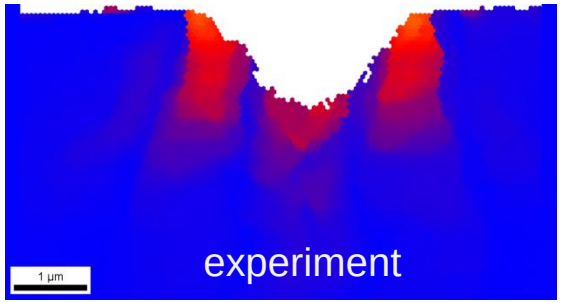


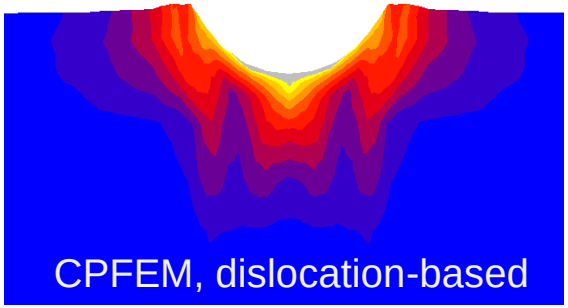
Zaafarani et al. Acta Mat. 54 (2006) 1707; Wang et al. Acta Mat. 52 (2004) 2229

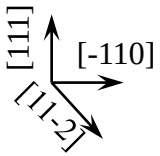
Comparison, crystal rotations (absolute, about [11-2] axis)

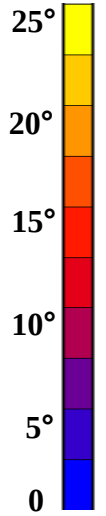
Absolute rotations



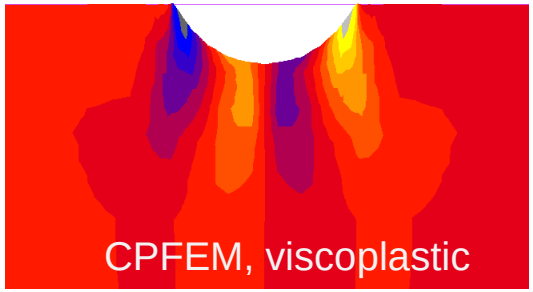


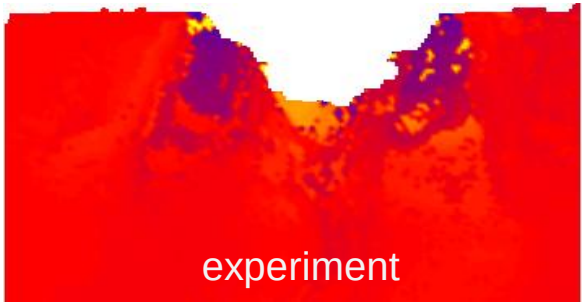


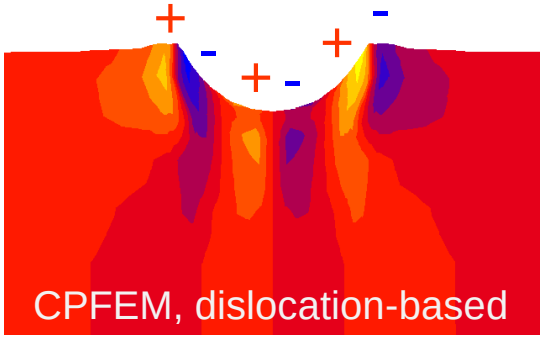


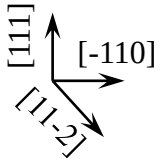


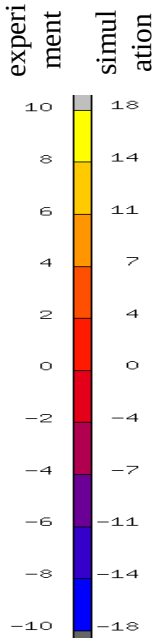
<11-2> rotations



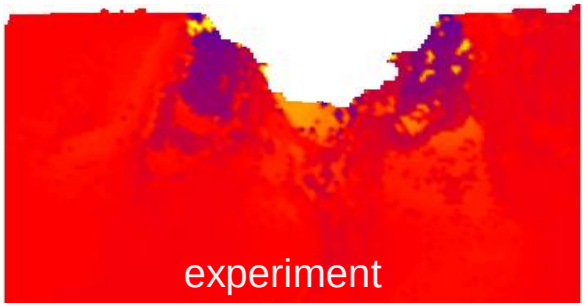


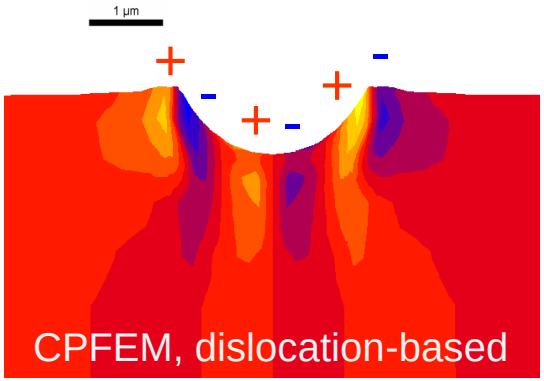


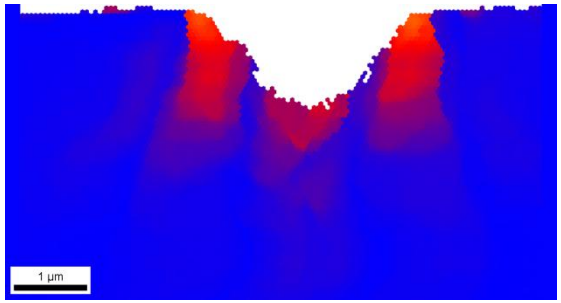


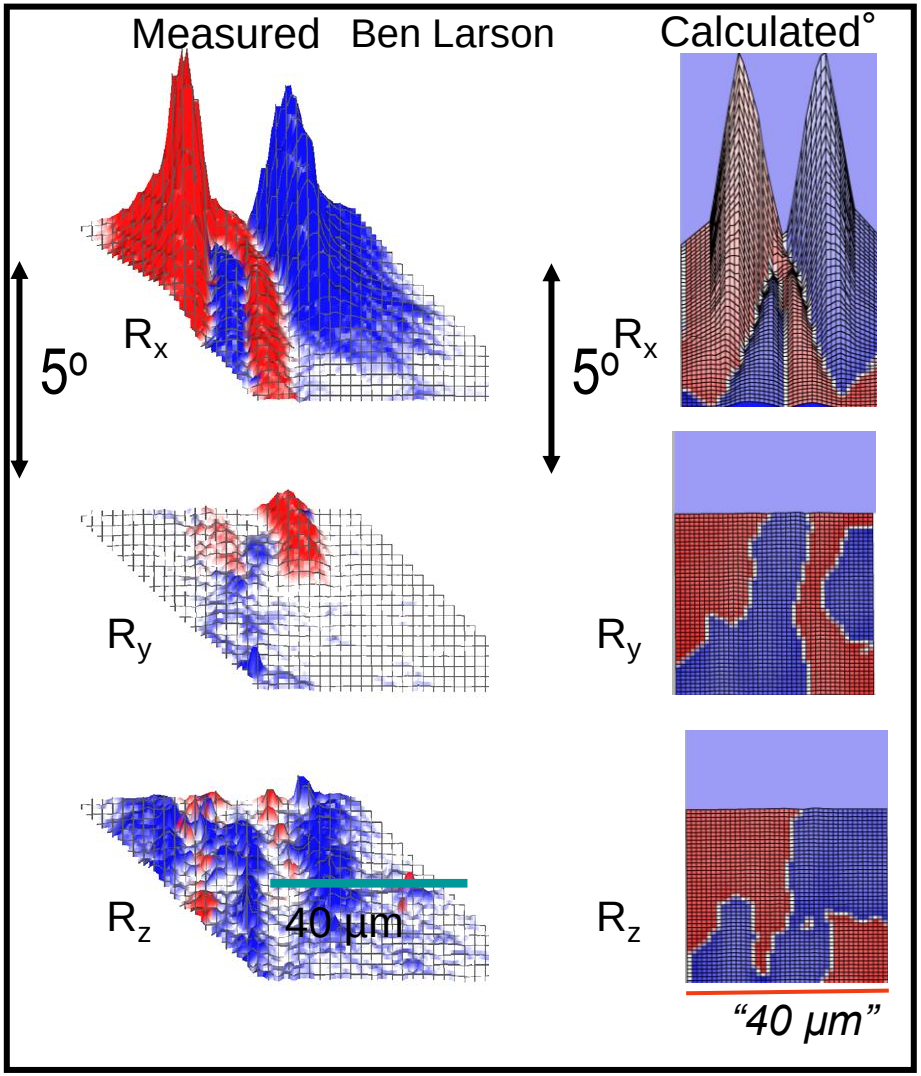


Comparison between crystal rotation about [11-2]



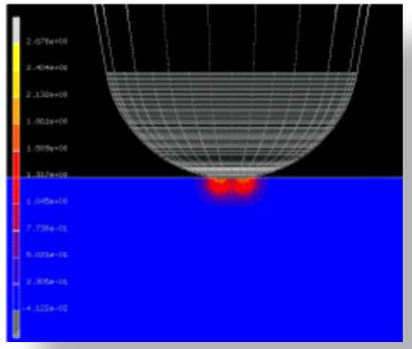


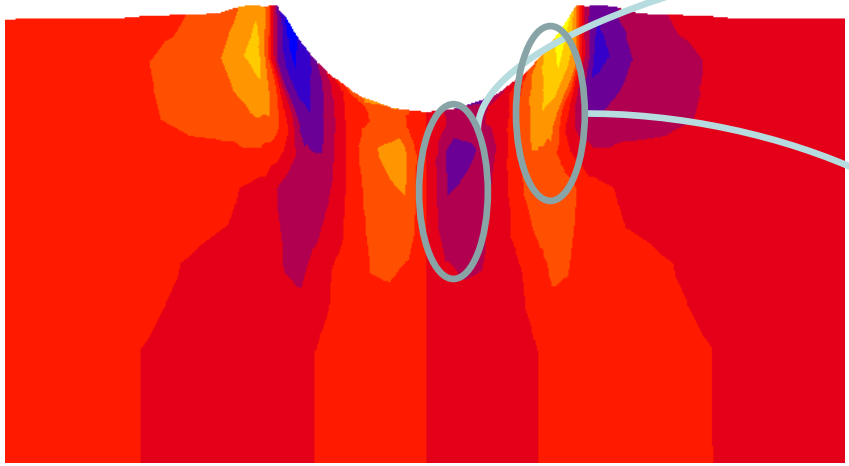


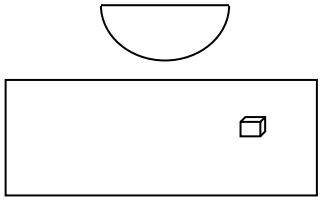


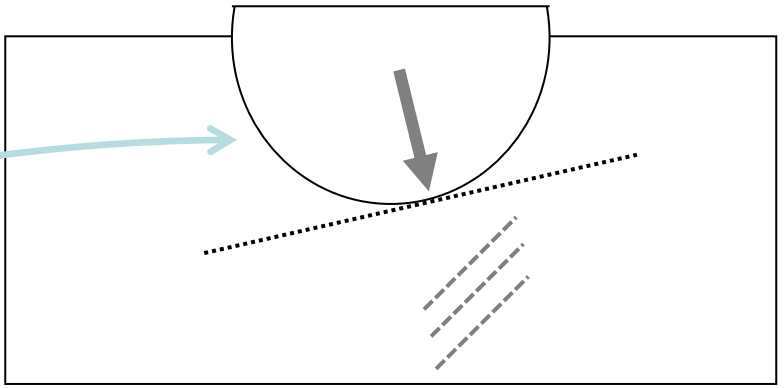
see also: Ben Larson, Bill Clegg, Alan Needleman

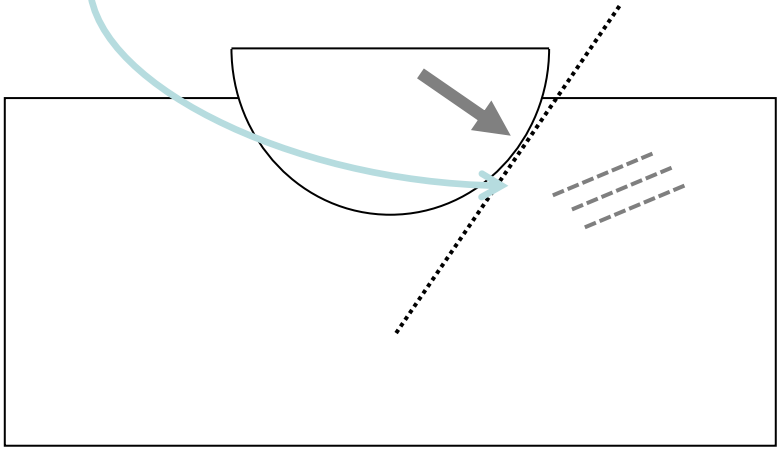
Rotations about [11-2] axis, simplify, strain path



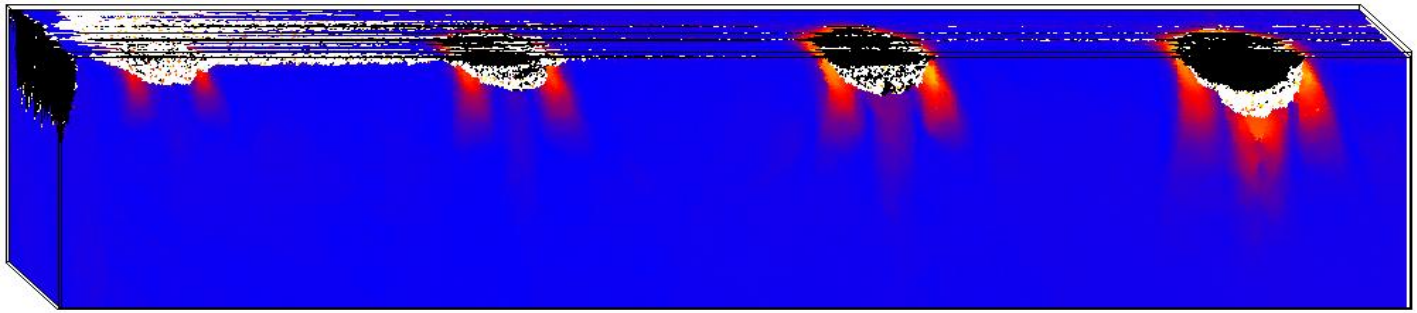


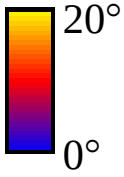






From local misorientations to GNDs



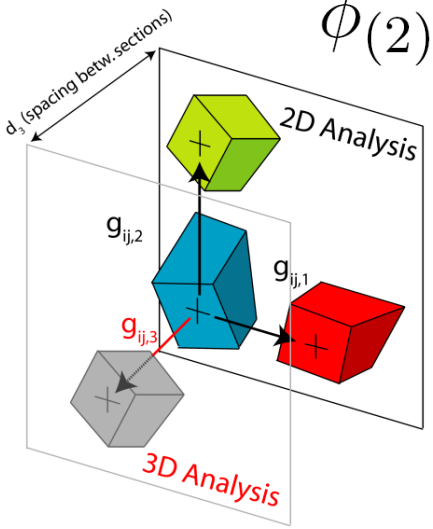


misorientation angle

$$\triangle\phi = \phi_{(2)}\ \phi_{(1)}^{-1}$$ misorientation

$$|\triangle\phi| = min\{cos^{-1}\{tr[(O_i^{cry}\phi_{(1)})\phi_{(2)}^{T}O_j^{cry}]\}\} \quad i = 1\ldots24,\ j = 1\ldots24$$

$$\phi_{(2)} - \phi_{(1)} = (\triangle\phi - I)\phi_{(1)}$$ orientation difference



$$g_{ij,k} = \frac{\phi_{(2)ij} - \phi_{(1)ij}}{d_k}$$

orientation gradient
(spacing d from EBSD scan)

From local misorientations to GNDs

$$\alpha = \nabla \times \beta^{el}$$

$$\alpha_{pi} = e_{pkj} \left(\epsilon^{el}_{ij,k} + g_{ij,k} \right)$$

$$\alpha_{pi} = e_{pkj} \, g_{ij,k}$$

dislocation tensor (GND)

J. F. Nye. Some geometrical relations in dislocated crystals. Acta Metall. 1:153, 1953.
E. Kröner. Kontinuumstheorie der Versetzungen und Eigenspannungen (in German). Springer, Berlin, 1958.
E. Kröner. Physics of defects, chapter Continuum theory of defects, p.217. North-Holland Publishing, Amsterdam, Netherlands, 1981.

From local misorientations to GNDs

Slip and line directions of dislocations for GNDs in a FCC crystal

$\sqrt{2}\,\hat{\mathbf{b}}$:	$\bar{1}10$	$10\bar{1}$	$0\bar{1}1$	$\bar{1}\bar{1}0$	101	$01\bar{1}$	110	$\bar{1}01$	$0\bar{1}\bar{1}$	$1\bar{1}0$	$\bar{1}0\bar{1}$	011	110	101	011	$\bar{1}10$	$10\bar{1}$	$0\bar{1}1$
$\sqrt{6}\,\hat{\mathbf{t}}$:	$\bar{1}\bar{1}2$	$\bar{1}2\bar{1}$	$2\bar{1}\bar{1}$	$\bar{1}1\bar{2}$	$\bar{1}\bar{2}1$	211	$1\bar{1}\bar{2}$	121	$\bar{2}\bar{1}1$	112	$1\bar{2}\bar{1}$	$\bar{2}1\bar{1}$	110	101	011	$\bar{1}10$	$10\bar{1}$	$0\bar{1}1$

$$\mathbf{B} = \mathbf{b}(\hat{\mathbf{t}} \cdot \mathbf{r}) = (\mathbf{b} \otimes \hat{\mathbf{t}})\mathbf{r}$$

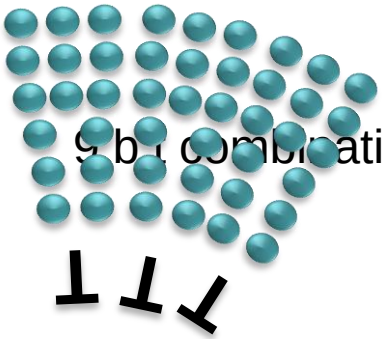
Frank loop thro

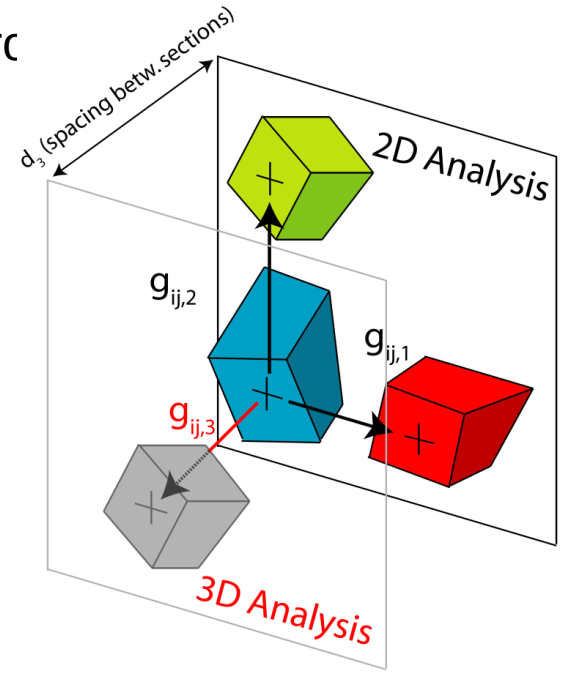
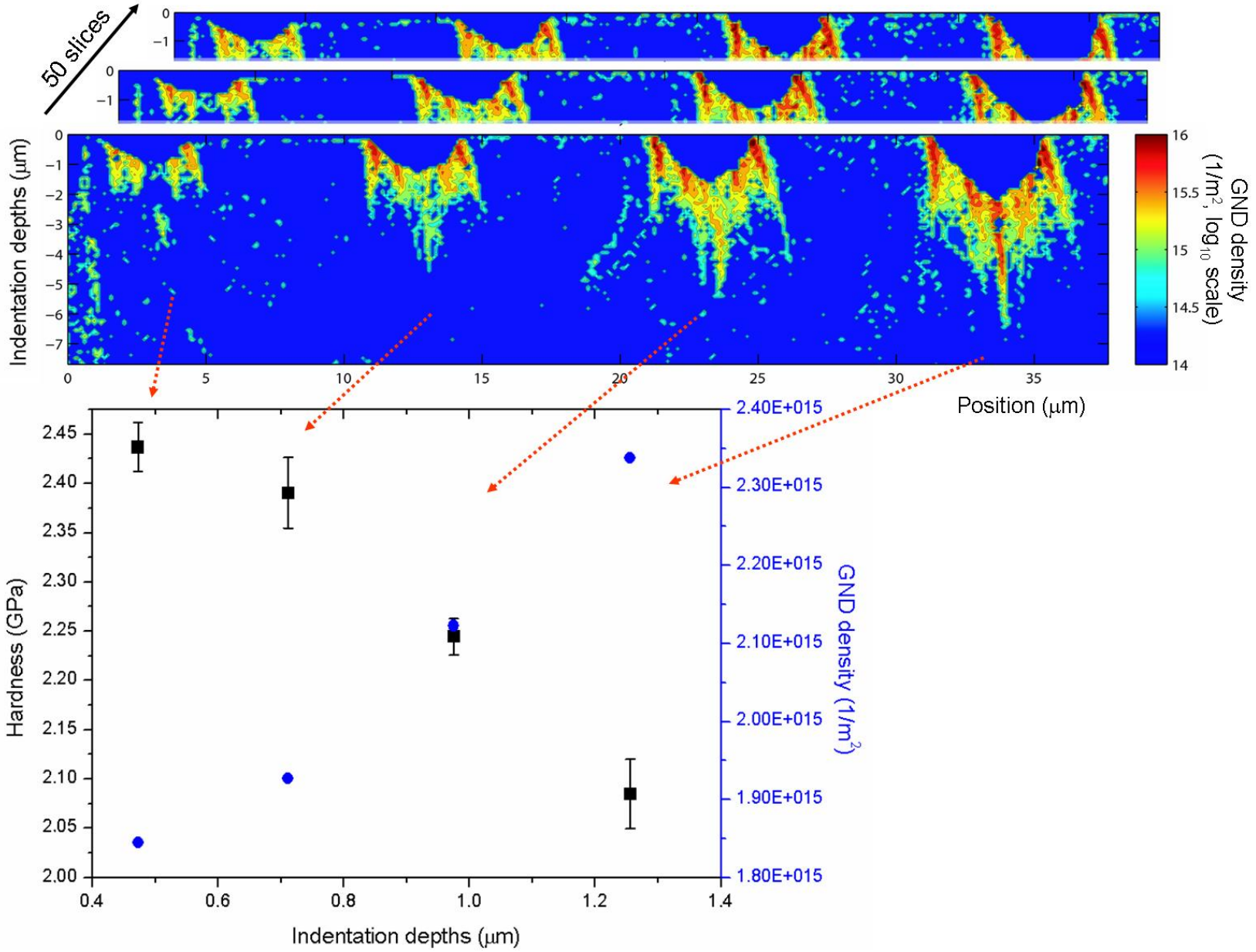
$$\alpha_{ij} = \sum_{a=1}^{18} \rho_{gnd}^{a}\, b_i^a t_j^a$$

18 b,t combinations

$$\alpha_{ij} = \sum_{a=1}^{9} \rho_{gnd}^{a}\, b_i^a t_j^a$$

9 b,t combinations





Extract geometrically necessary dislocations