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AND TECHNOLOGY

Pomiar odkształceń sieci krystalicznej w materiałach dwufazowych poddanych obciążeniu zewnętrznemu

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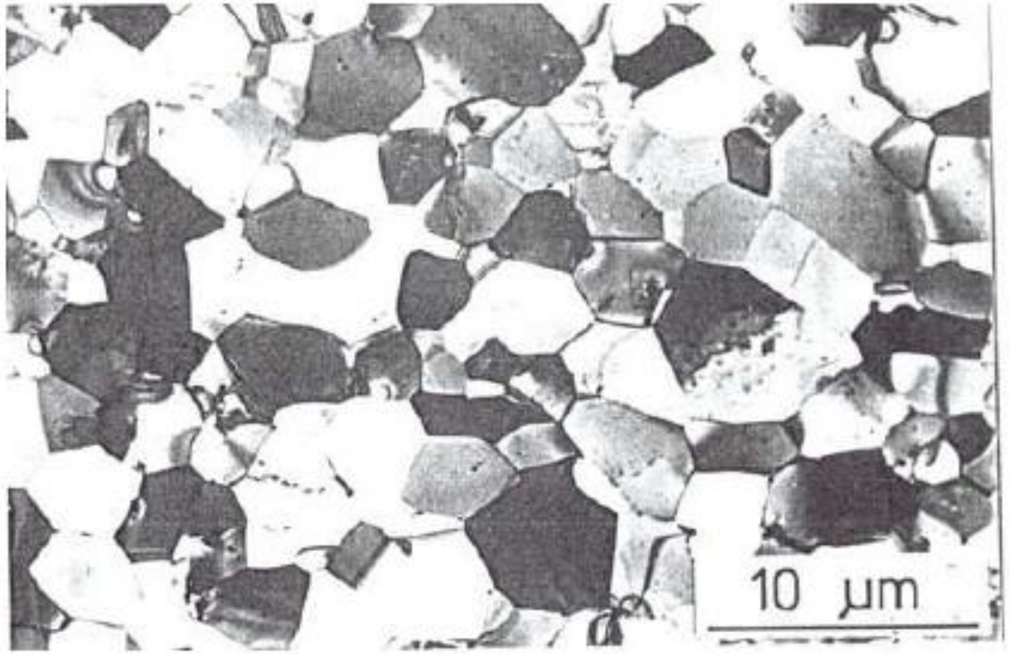
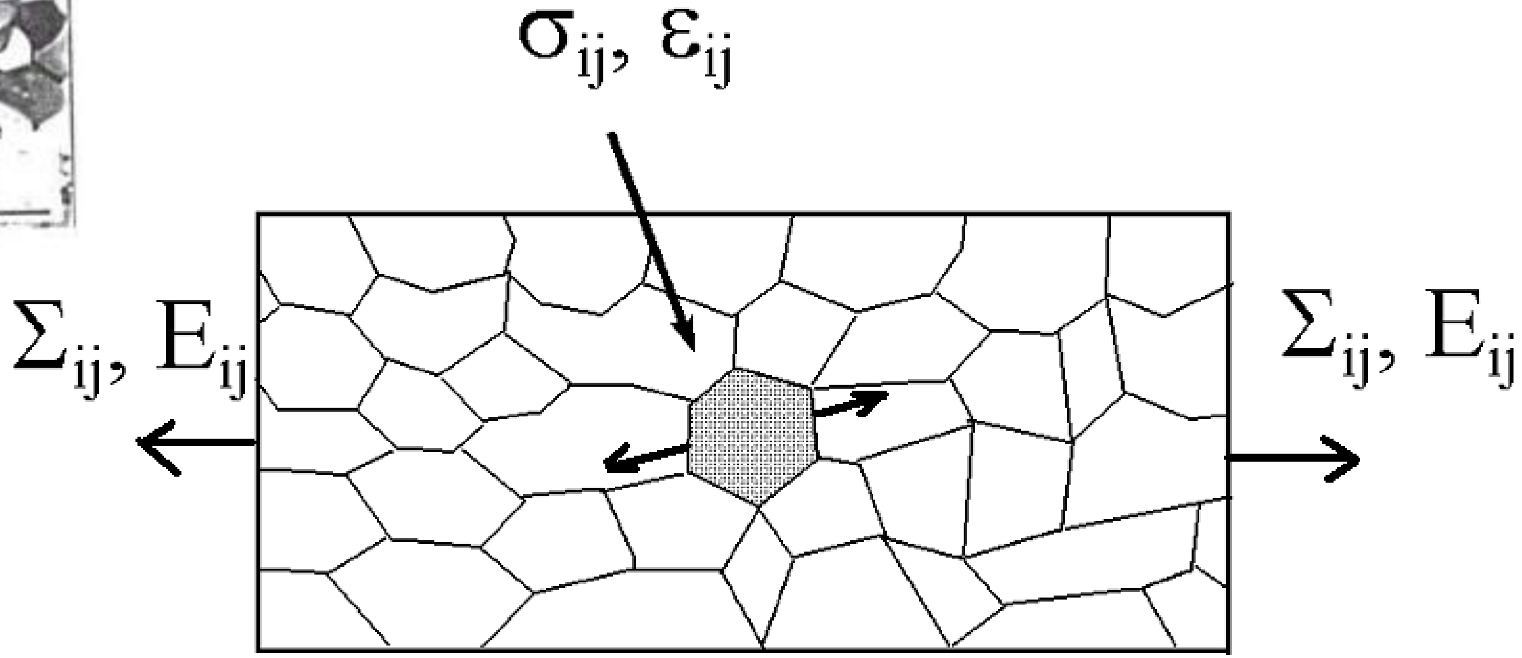
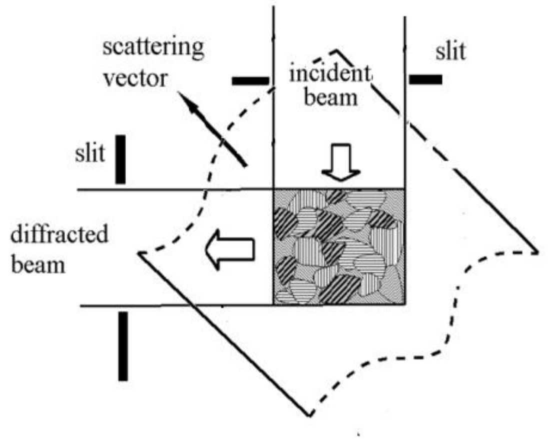
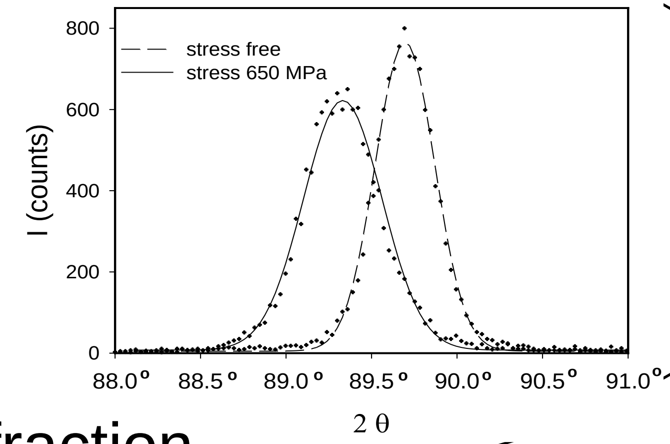
Mechanical properties of polycrystalline material at grain scale



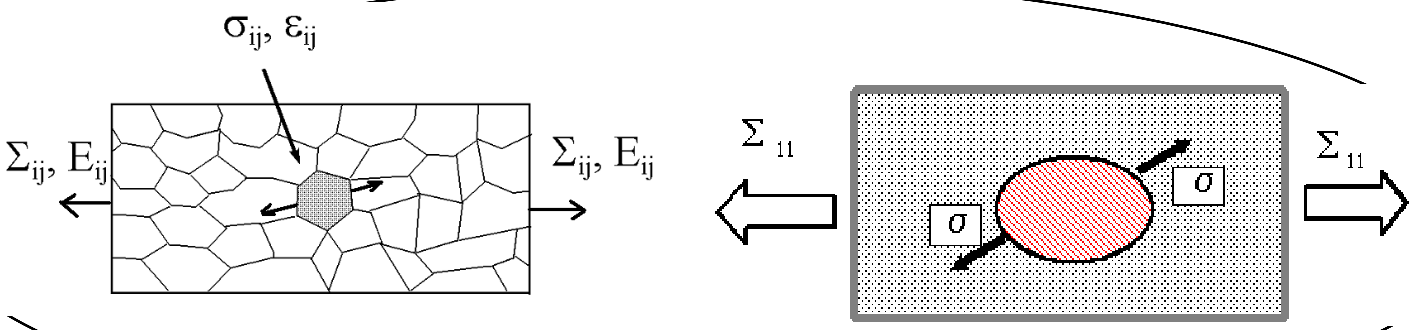


Mechanical properties of polycrystalline material at grain scale





Diffraction



Elastic-plastic model

Lattice strains:

$$< \varepsilon >_{hkl} = \frac{< d >_{hkl} - d^{0}_{hkl}}{d^{0}_{hkl}}$$

$$n\lambda = 2 < d >_{\{hkl\}} \sin\theta$$

Scale transition model:

$$\dot{\varepsilon}^{g}_{ij} = A^{g}_{ijkl} \dot{E}_{kl}$$

$$\dot{\sigma}^{g}_{ij} = B^{g}_{ijkl} \dot{\Sigma}_{kl}$$

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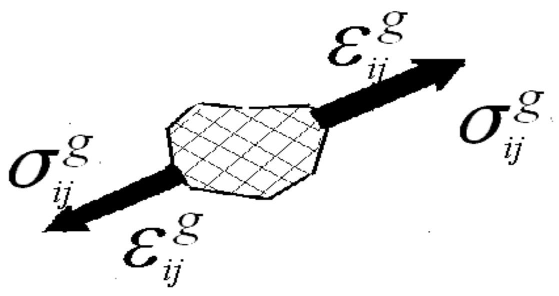
Self-consistent model

Grain scale:



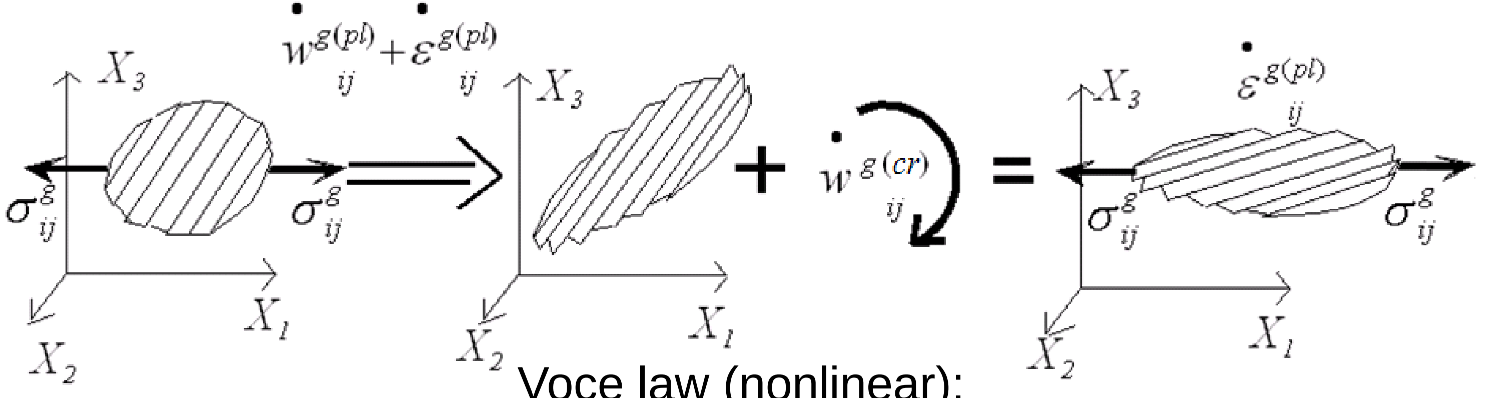
elastic deformation: $\varepsilon_{ij}^{g(el)}$

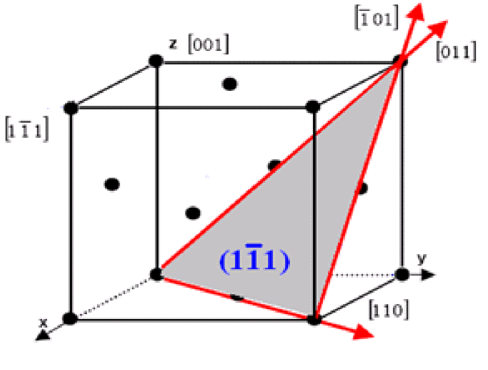
$$\sigma_{ij}^{g} = c_{ijkl}^{g}\,\varepsilon_{kl}^{g(el)}$$

elastic-plastic deformation: $\varepsilon_{ij}^{g} = \varepsilon_{ij}^{g(el)} + \varepsilon_{ij}^{g(pl)}$

lattice rotation : $w_{ij}^{g(cr)}$

$$\sigma_{[uvw](hkl)} = \tau_c$$





fcc: {111}<110>

Voce law (nonlinear):

$$\tau_c^{gr} = \tau_0 + \left(\tau_1 + \theta_1 \xi^{gr}\right)\left[1 - \exp\left(-\frac{\theta_0}{\tau_1}\xi^{gr}\right)\right]$$

$$\dot{\sigma}_{ij}^{g} = l_{ijkl}^{g}\,\dot{\varepsilon}_{kl}^{g}$$

Self-consistent model

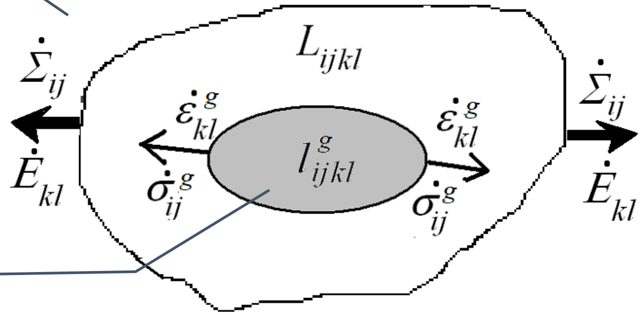
Scale transition:

*** Homogenisation and localisation (self-consistent, Taylor….):**

$$\underline{\dot{\Sigma}} = \underline{\underline{L}} : \underline{\dot{E}}$$

$$\underline{\dot{\sigma}}^g = \underline{\underline{l}}^g : \underline{\dot{\varepsilon}}^g$$

Eshelby's inclusion

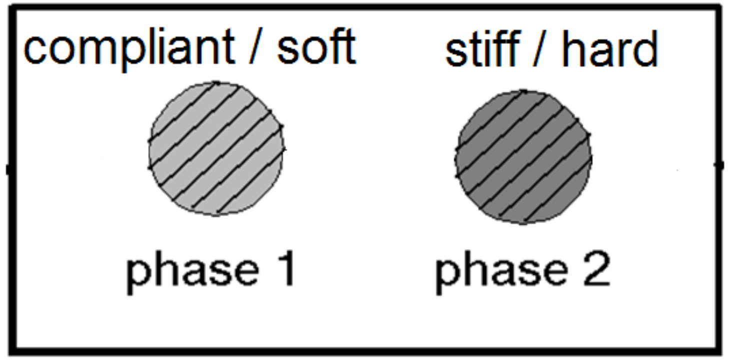


$$\underline{\dot{\varepsilon}}^g = \underline{\underline{A}}^g : \underline{\dot{E}}$$

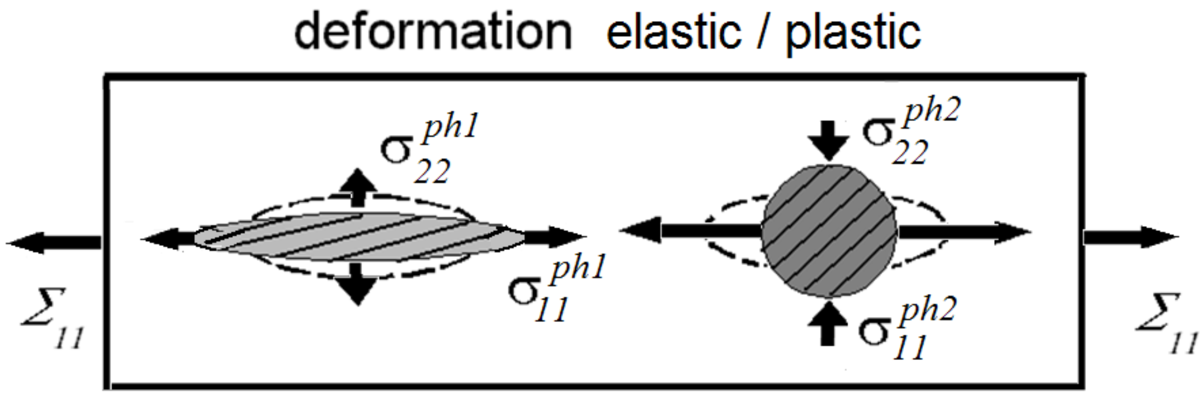
Self-consistent model

Stress/strain localisation:

(Eshelby type model)



two phases



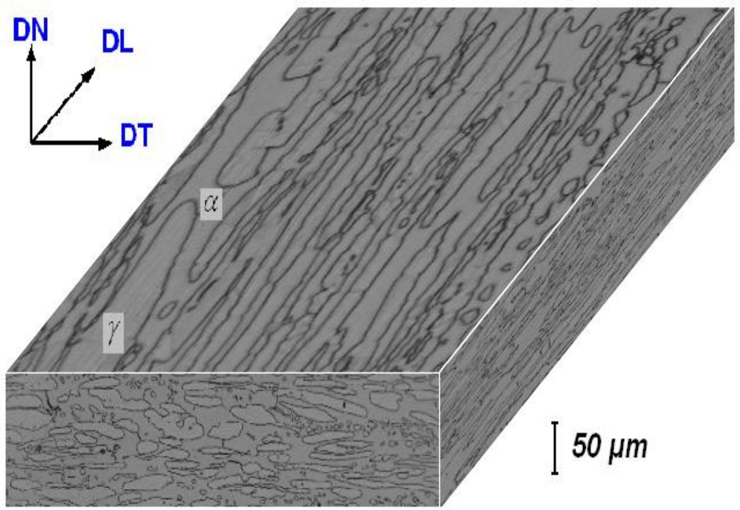
$$\dot{\varepsilon}_{ij}^{g} = A_{ijkl}^{g}\,\dot{E}_{kl} \qquad \dot{\sigma}_{ij}^{g} = B_{ijkl}^{g}\,\dot{\Sigma}_{kl}$$

Lipinski, P. & Berveiller, M. (1989). ***Int. J. Plast.* 5**, 149–172.

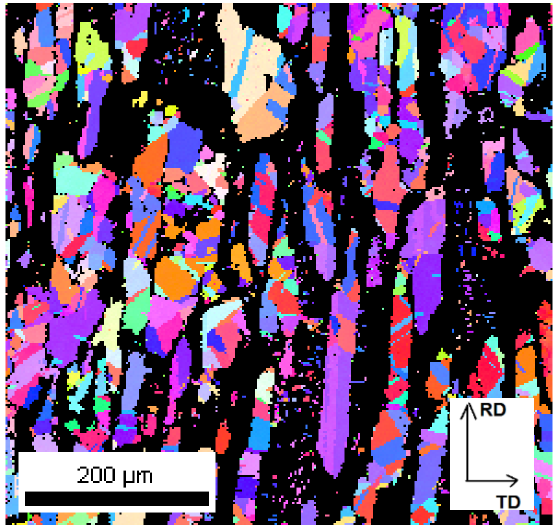
Time of Flight
in-situ tests

Material: stainless duplex steel (aged)

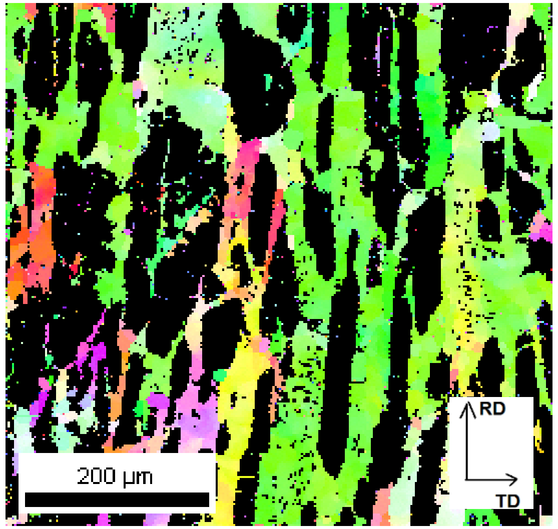
50% austenite (γ) and 50% ferrite (γ)



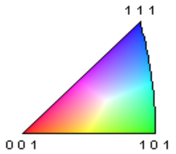
EBSD



austenite

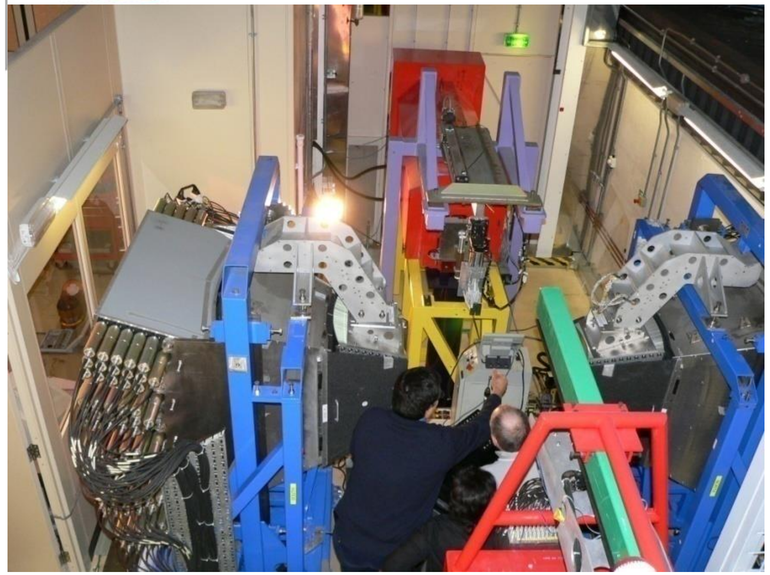


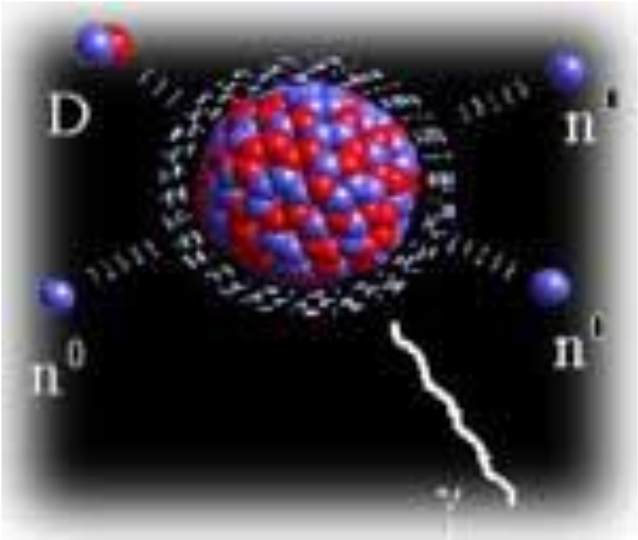
ferrite



Euronorm	C	Mn	Cr	Ni	Mo	Cu	S	N
X2 Cr Ni Mo 22.5.3	0,015	1,6	22,4	5,4	2,9	0,12	0,001	**0,17**

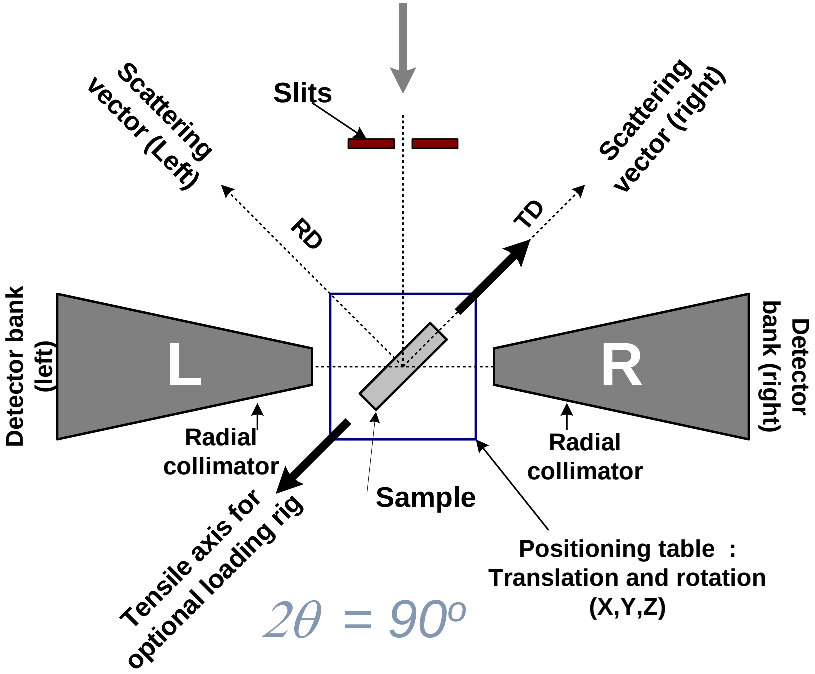
Duplex steel - ISIS, Rutherford Appleton Lab., UK

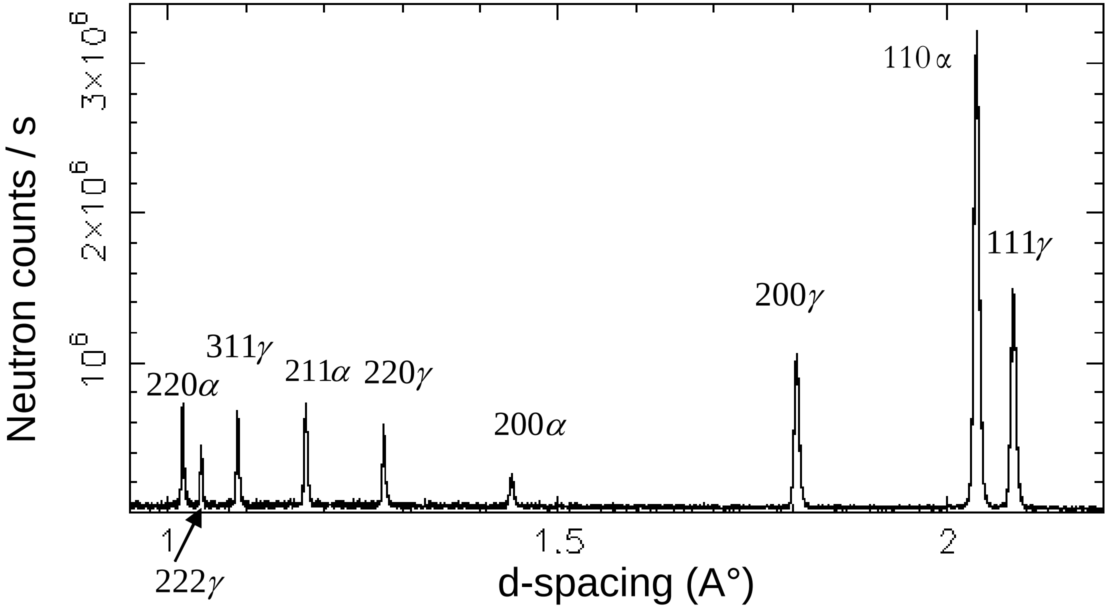




Spallation source
TOF
(time of flight)

$$d_{hkl} = \frac{ht}{2\sin\theta \; m_n L}$$

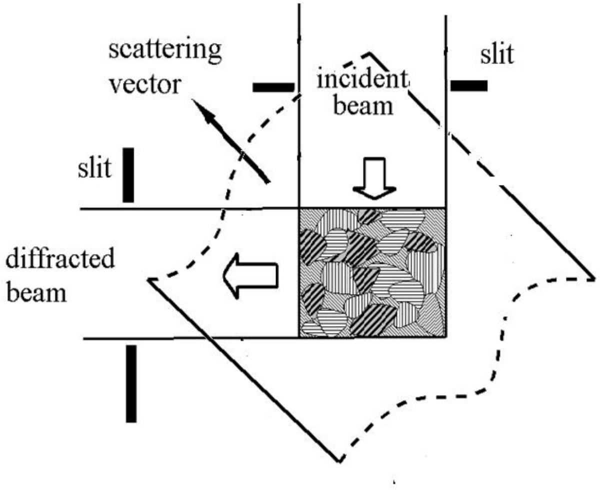




Duplex steel - ISIS, Rutherford Appleton Lab., UK

Spallation source TOF (time of flight)

-„in situ” tensile test

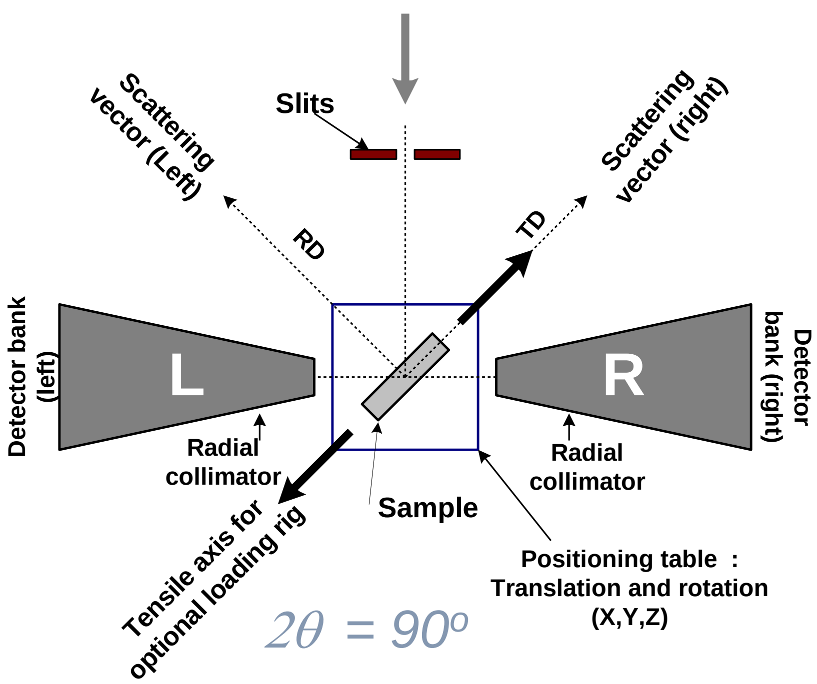


$$n\lambda = 2d_{hkl}\sin\theta$$

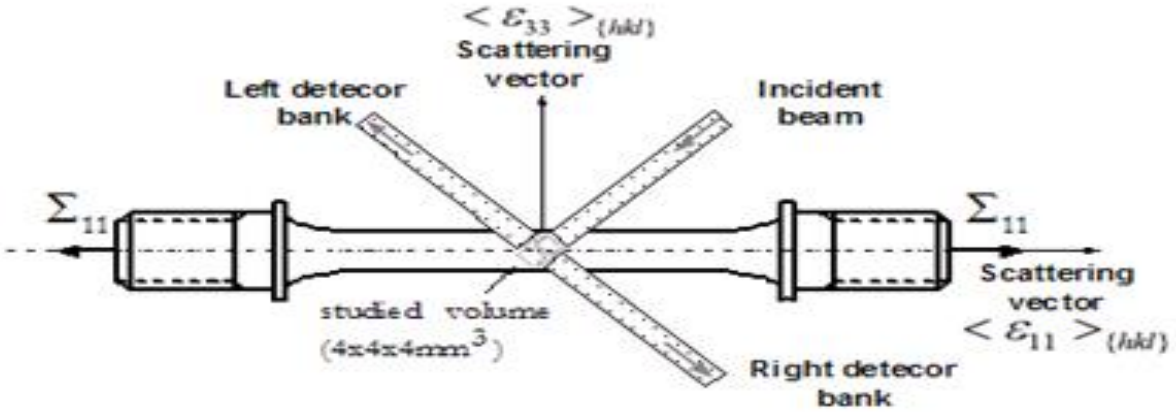
$$\lambda = \frac{h}{m_n v} = \frac{ht}{m_n L}$$

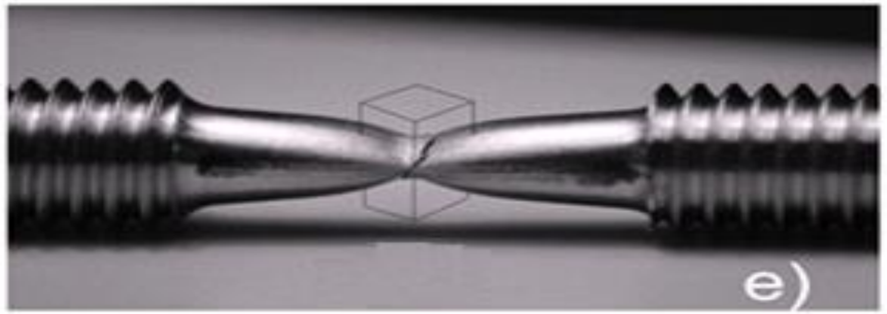
Lattice strains:

$$<\varepsilon>_{hkl} = \frac{<d>_{hkl} - d^{0}_{hkl}}{d^{0}_{hkl}}$$



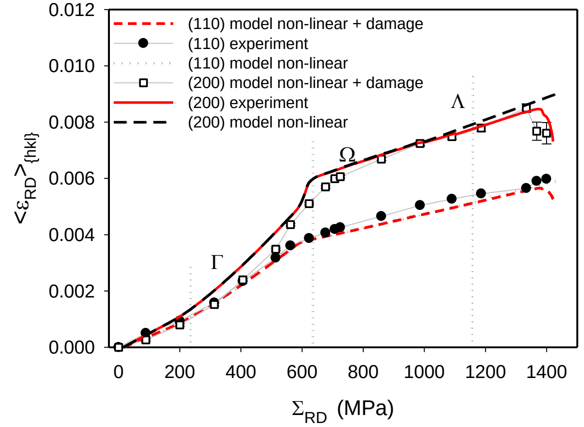
$2\theta = 90^o$



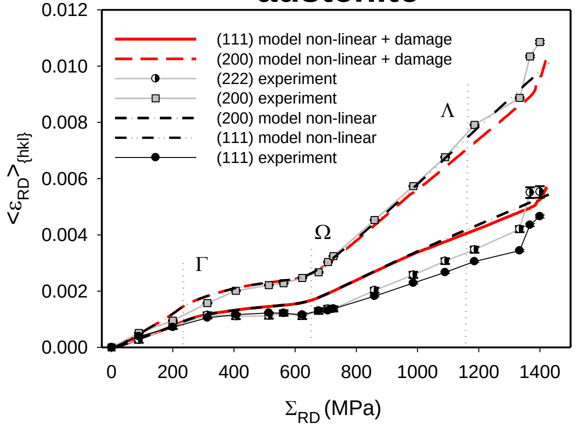


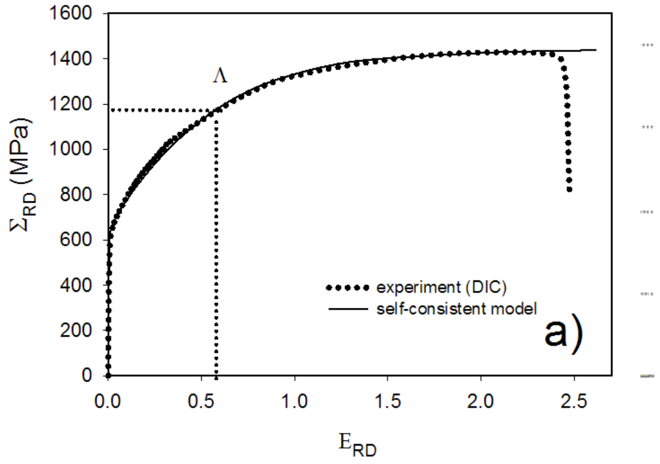
DUPLEX STEEL – ISIS results

ferrite



austenite





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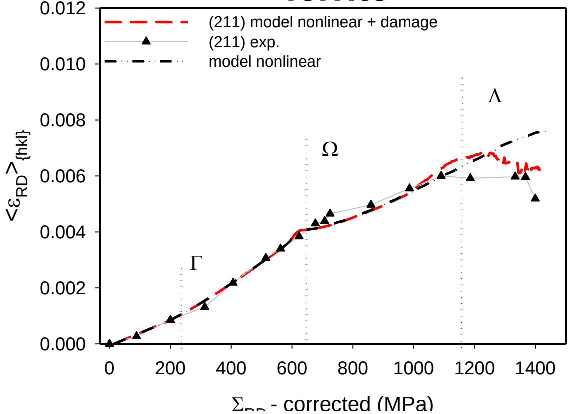
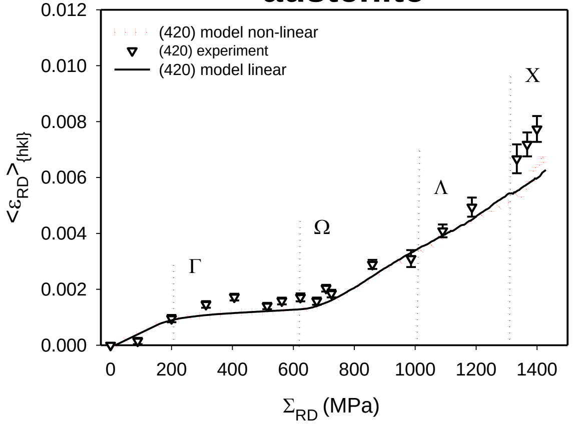
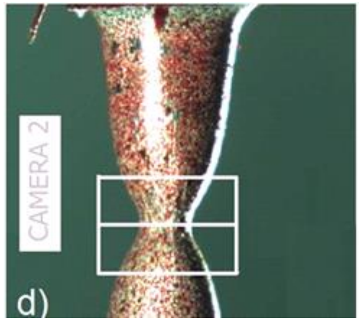


austenite

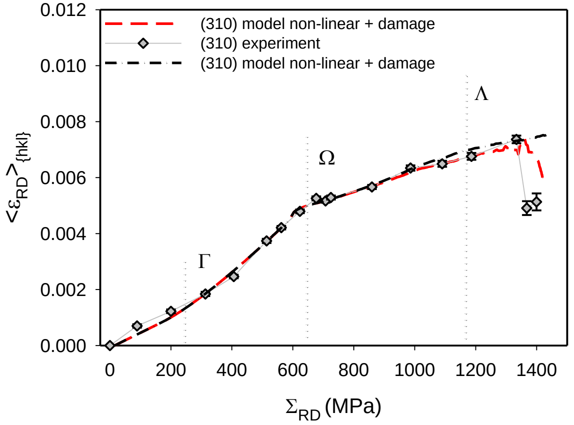




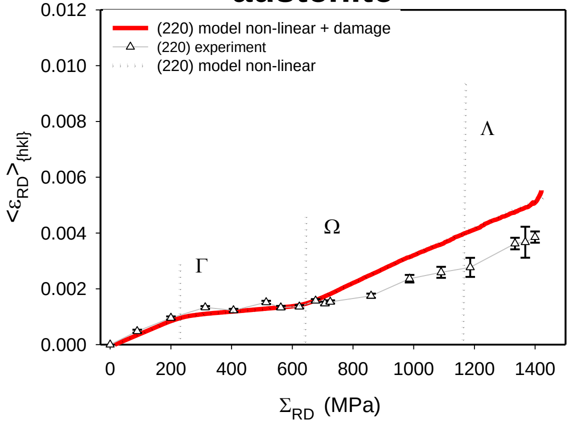
DIC

Digital Image Corelation

ferrite



austenite

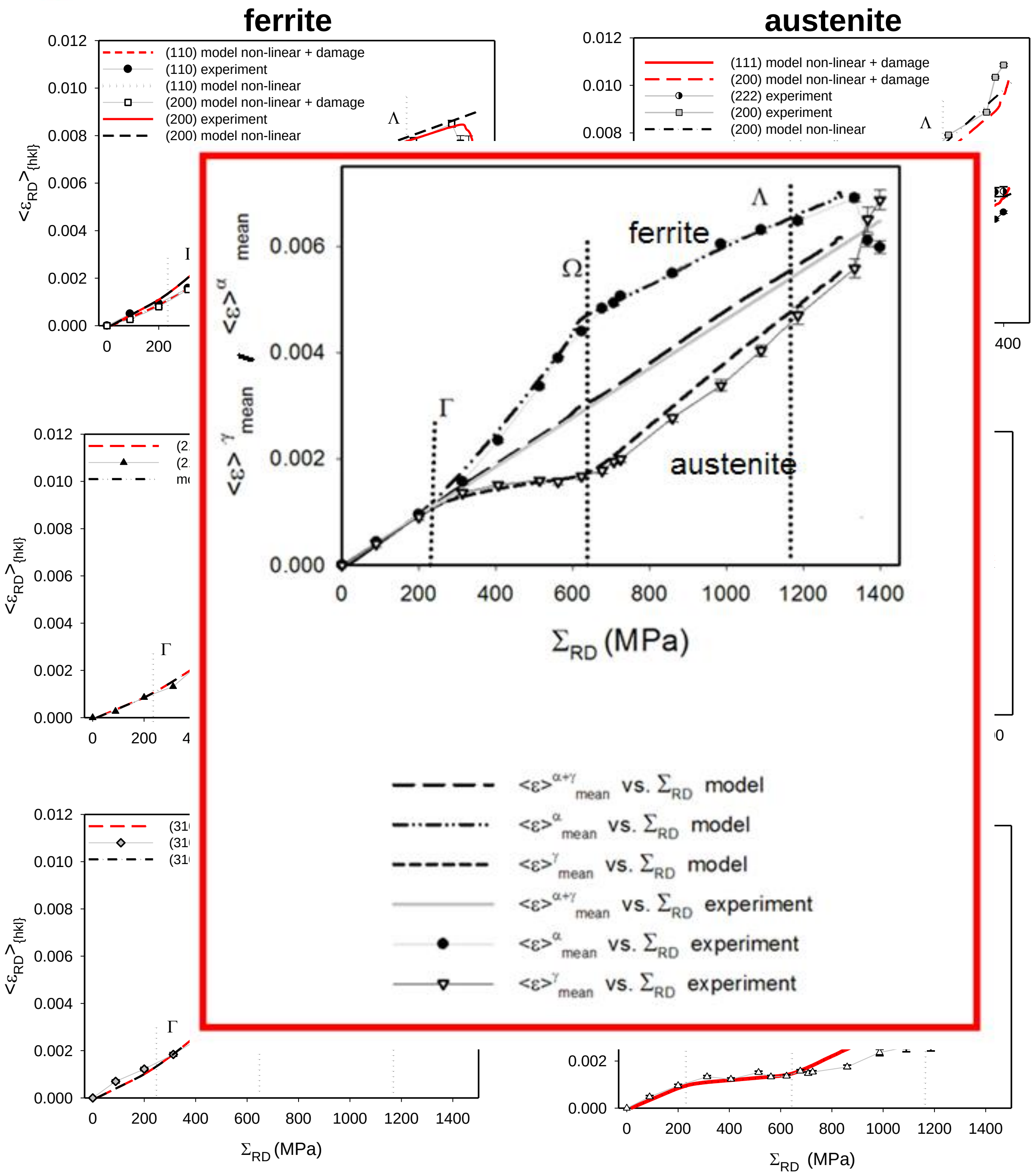


$$<\varepsilon>_{hkl} = \frac{<d>_{hkl} - d^{0}_{hkl}}{d^{0}_{hkl}}$$

d^{0}_{hkl} **before loading**

$<d>_{hkl}$ **under applied load**

DUPLEX STEEL – mechanical behaviour of phases



Voce law:

$$\tau^{gr} = \tau_0^{\alpha} + \left(\tau_1^{\alpha} + \theta_1^{\alpha}\xi^{gr}\right)\left[1 - \exp\left(-\frac{\theta_0^{\alpha}}{\tau_1^{\alpha}}\xi^{gr}\right)\right]$$

$$\tau^{gr} = \tau_0^{\gamma} + \left(\tau_1^{\gamma} + \theta_1^{\gamma}\xi^{gr}\right)\left[1 - \exp\left(-\frac{\theta_0^{\alpha}}{\tau_1^{\alpha}}\xi^{gr}\right)\right]$$

The parameters of plastic deformation (MPa)

Material		UR45N (quenched)	UR45N (aged)
$\tau_0^{(ph)}$ (MPa)	Austenite	140	140
	Ferrite	220	350
$\theta_0^{(ph)}$ (MPa)	Austenite	225	225
	Ferrite	110	110
$\tau_1^{(ph)}$ (MPa)	Austenite	Not adjusted	280
	Ferrite		140
$\theta_1^{(ph)}$ (MPa)	Austenite		0.3
	Ferrite		0.1

AGH

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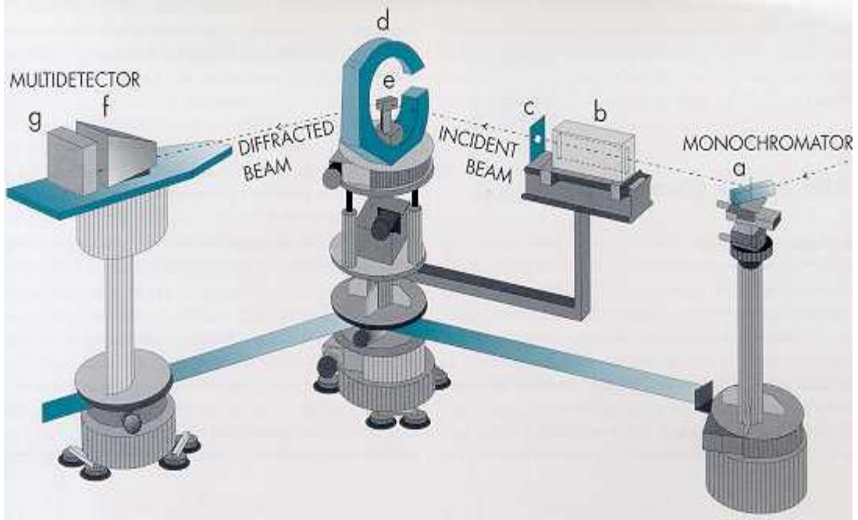
INICJATYWA DOSKONAŁOŚCI

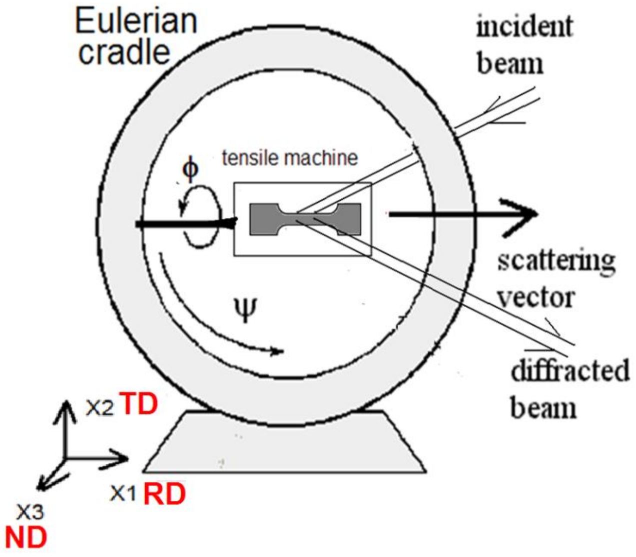
Crystallite Group Method (in situ):

- **Angular dispersion + Eulerian cradle**
- **ToF**

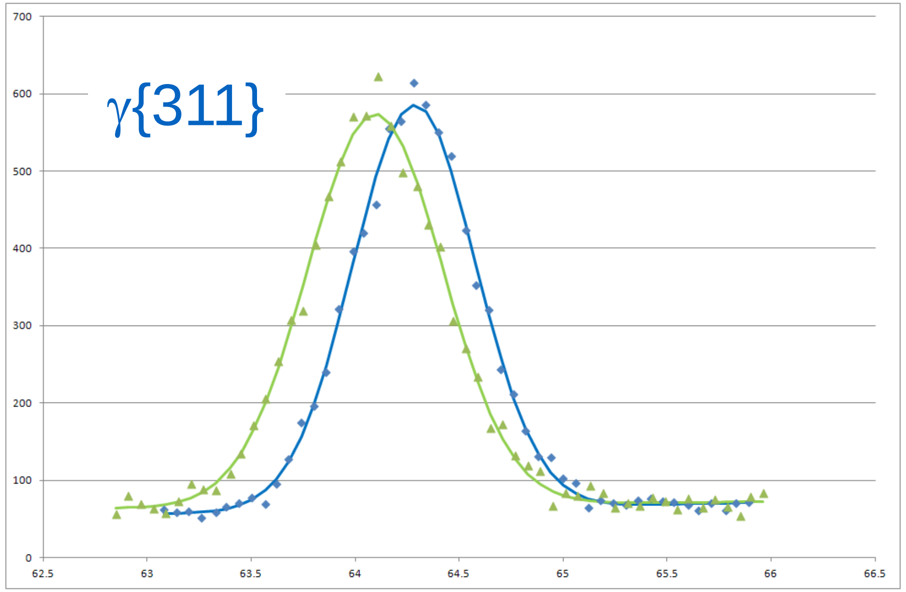
DUPLEX STEEL – in situ tensile test

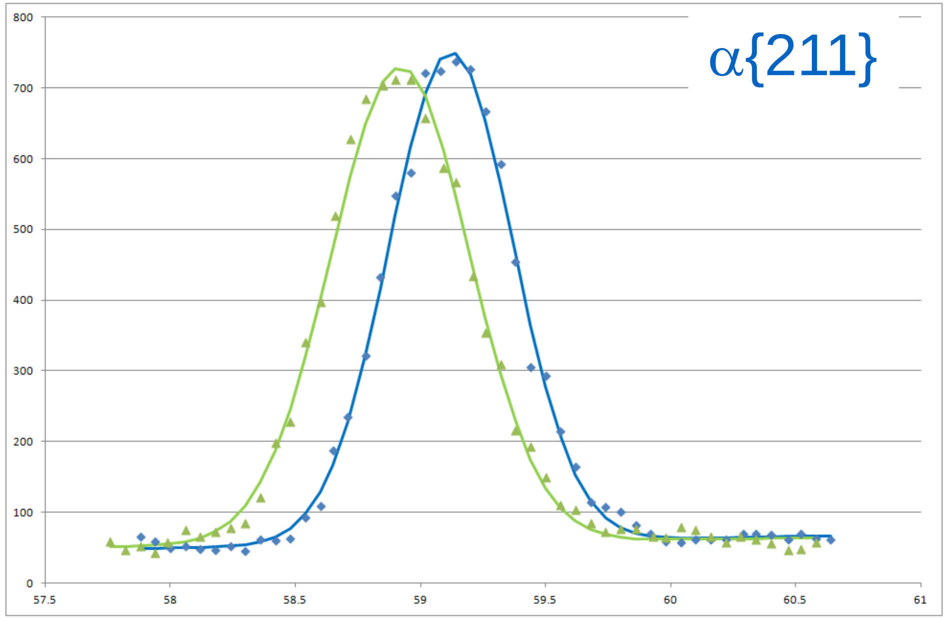
(LLB, Saclay, 6T1, neutrons - 2θ dispersion, λ= 1.159 A)





$$n\lambda = 2d_{hkl}\sin\theta$$

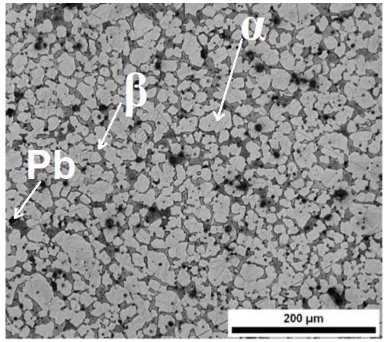




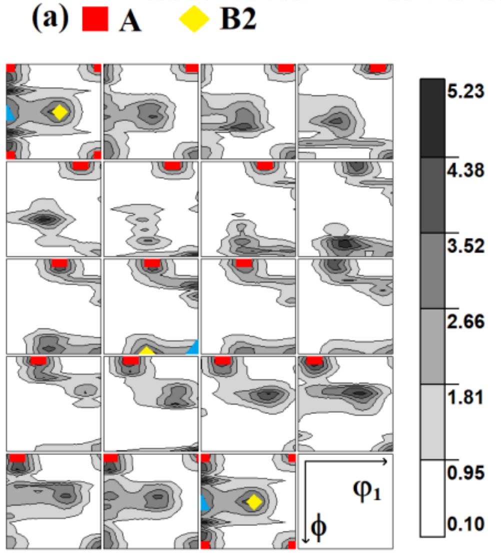
Studied materials

Two-phase brass alloy ($CuZn39Pb3$):

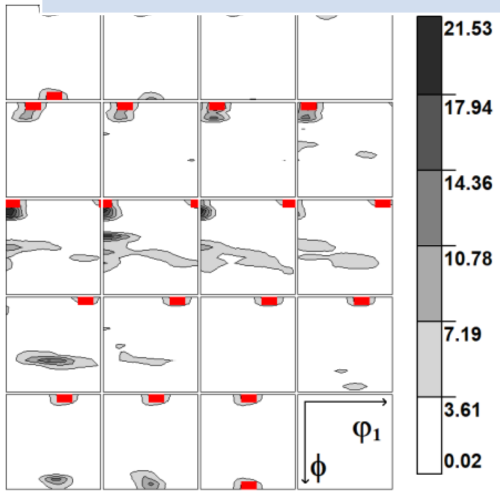
Cu	Pb	Ni	Fe	Sn	Al	Zn	other
57-59 [%]	2,5-3,5 [%]	0,30 [%]	0,50 [%]	0,30 [%]	0,005 [%]	balance	0,2 [%]



Fi[...]
m[...]



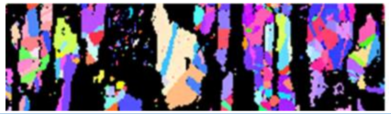
α (fcc, ~65%)

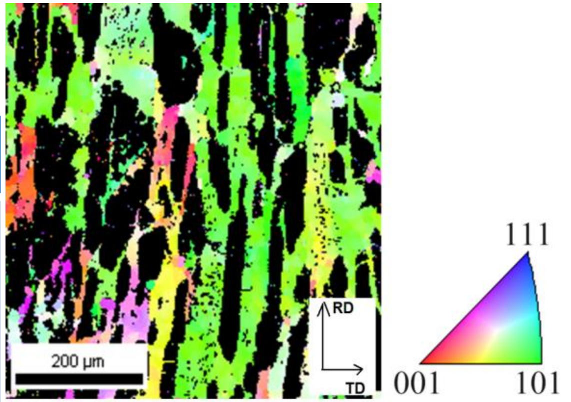


β (bcc, ~35%)

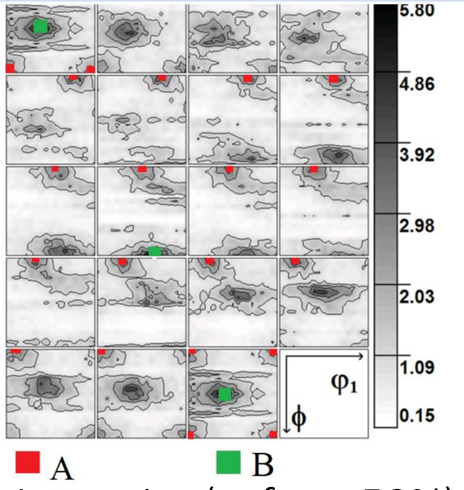
Austeno-ferritic duplex stainless steel (UR45N):

Cr	Ni	Mo	Mn	N	Cu	C	S	Fe
22,4 [%]	5,4 [%]	2,9 [%]	1,6 [%]	0,17 [%]	0,12 [%]	0,015 [%]	0,001 [%]	balance

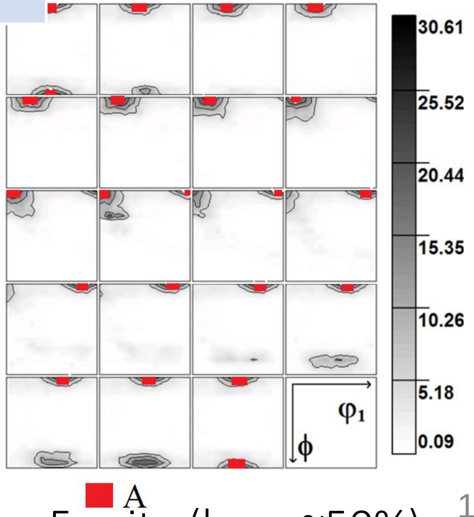




Brass	Duplex steel
Hot rolled, annealed	continuous casting, hot rolling, heat treated at 1050°C, annealed at 400°C



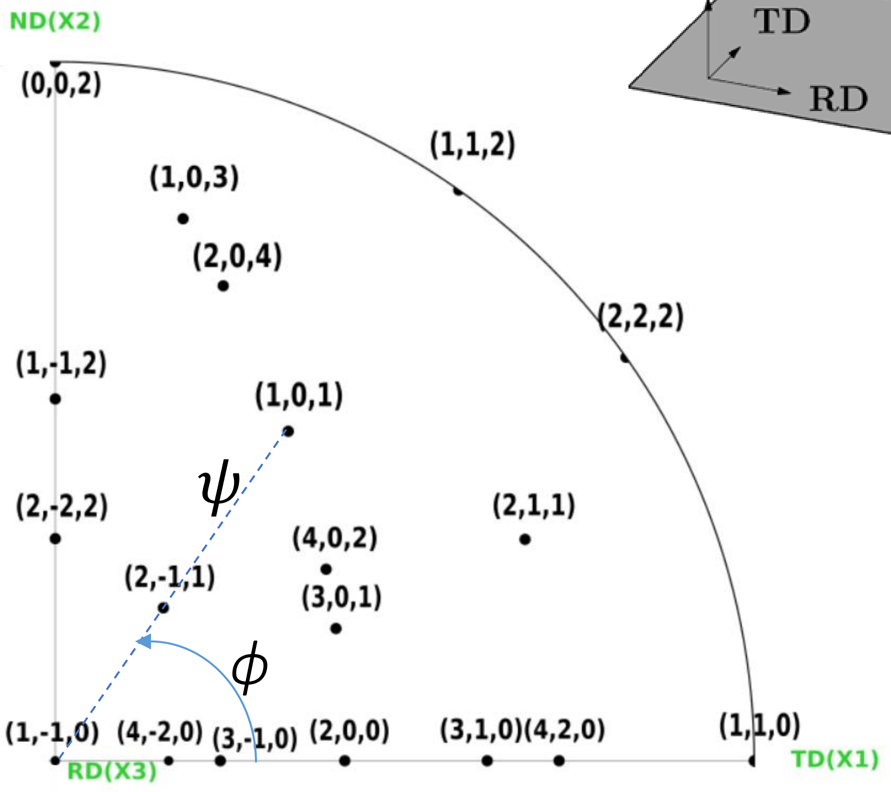
Austenite (γ, fcc, ~50%)



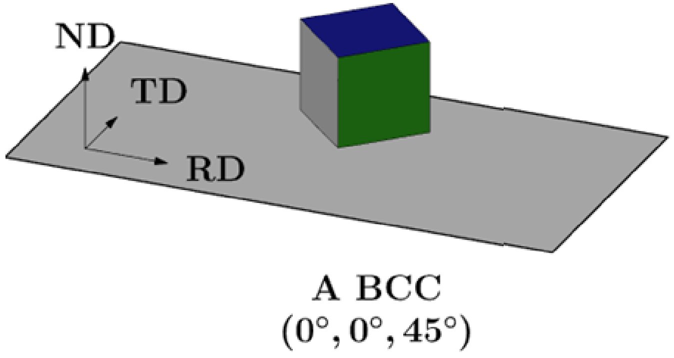
Ferrite (bcc , ~50%)

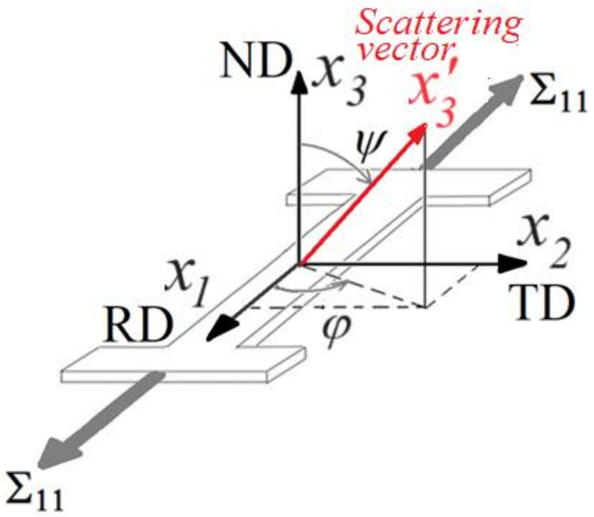
Crystalite Group Method

Analysis of a group of grains with similar orientations – such groups can be determined using the poles $P(\psi,\phi)_{\{hkl\}}$ in the pole figure.



Poles for A_{BCC} grain orientation.





$$\langle \varepsilon(\psi,\phi)\rangle_{\{hkl\}} = \frac{d^{\Sigma}_{\{hkl\}} - d^{\Sigma=0}_{\{hkl\}}}{d^{\Sigma=0}_{\{hkl\}}}$$

$$\langle \varepsilon(\psi,\phi)\rangle_{\{hkl\}} = a_{3k}a_{3l}s_{klij}\sigma^{CR}_{ij}$$

where:

$\langle \varepsilon(\psi,\phi)\rangle_{\{hkl\}}$ – lattice strain for $P(\psi,\phi)_{\{hkl\}}$ pole,

σ^{CR}_{ij} – stress tensor for the grain group,

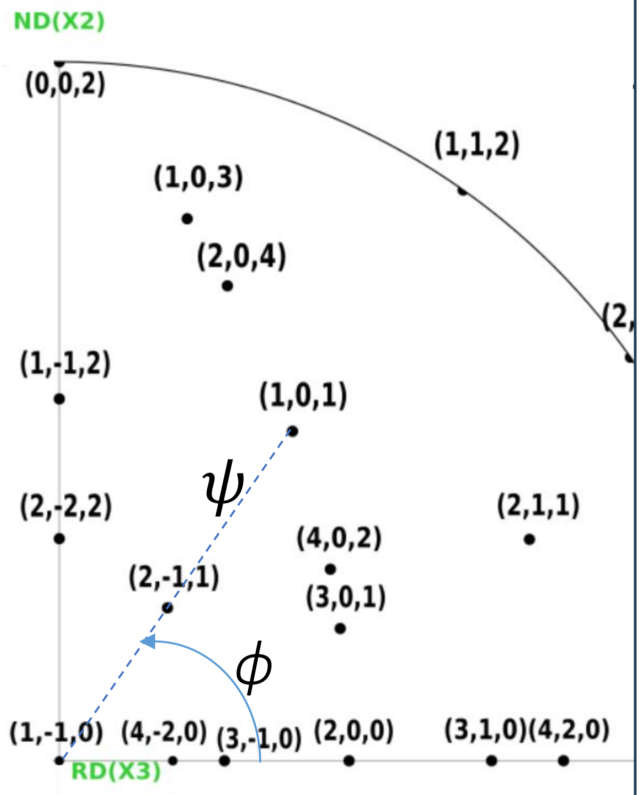
s_{klij} – crystallite elastic constants,

a_{3k}, a_{3l} – components of the transformation matrix.

Crystalite Group Method

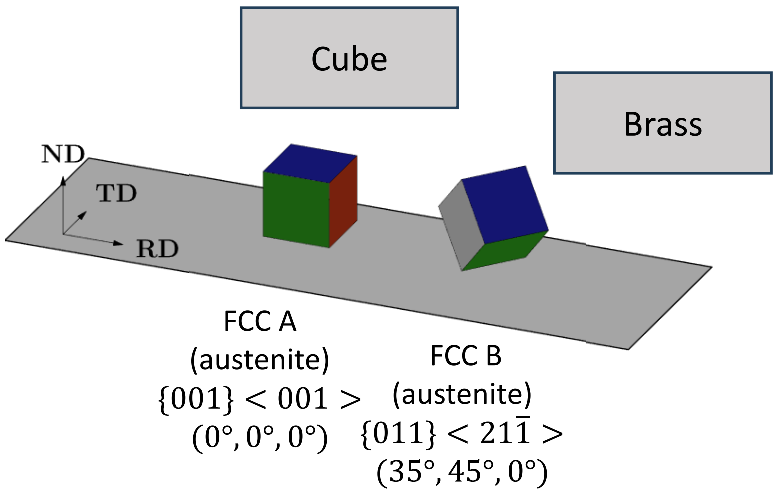
$$\langle \varepsilon(\psi,\phi)\rangle_{\{hkl\}} = a_{3k}a_{3l}s_{klij}\sigma_{ij}^{CR}$$

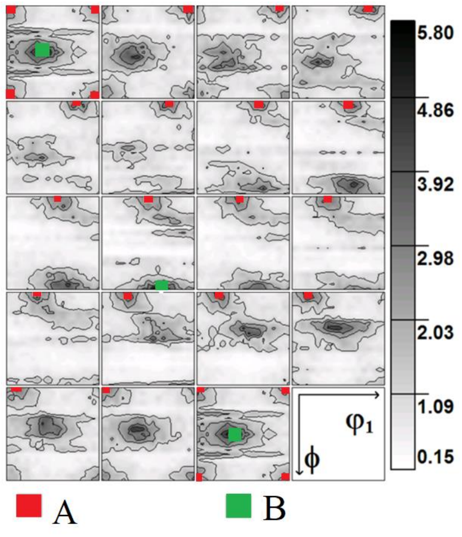
Selection of orientations
poles.



Poles for A_{BCC} grain orientation.

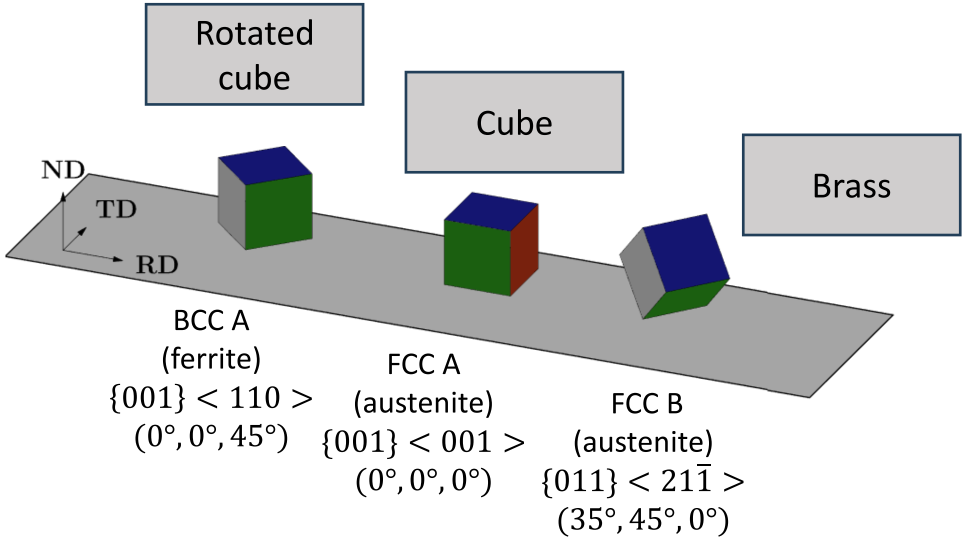
Shared poles (for preffered orientations) have to be excluded. Orientations selection should be tested to check if CGM works properly for given texture.

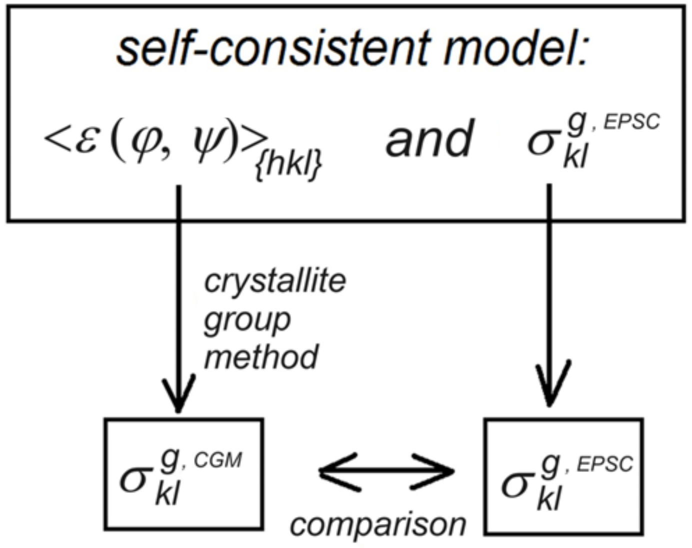


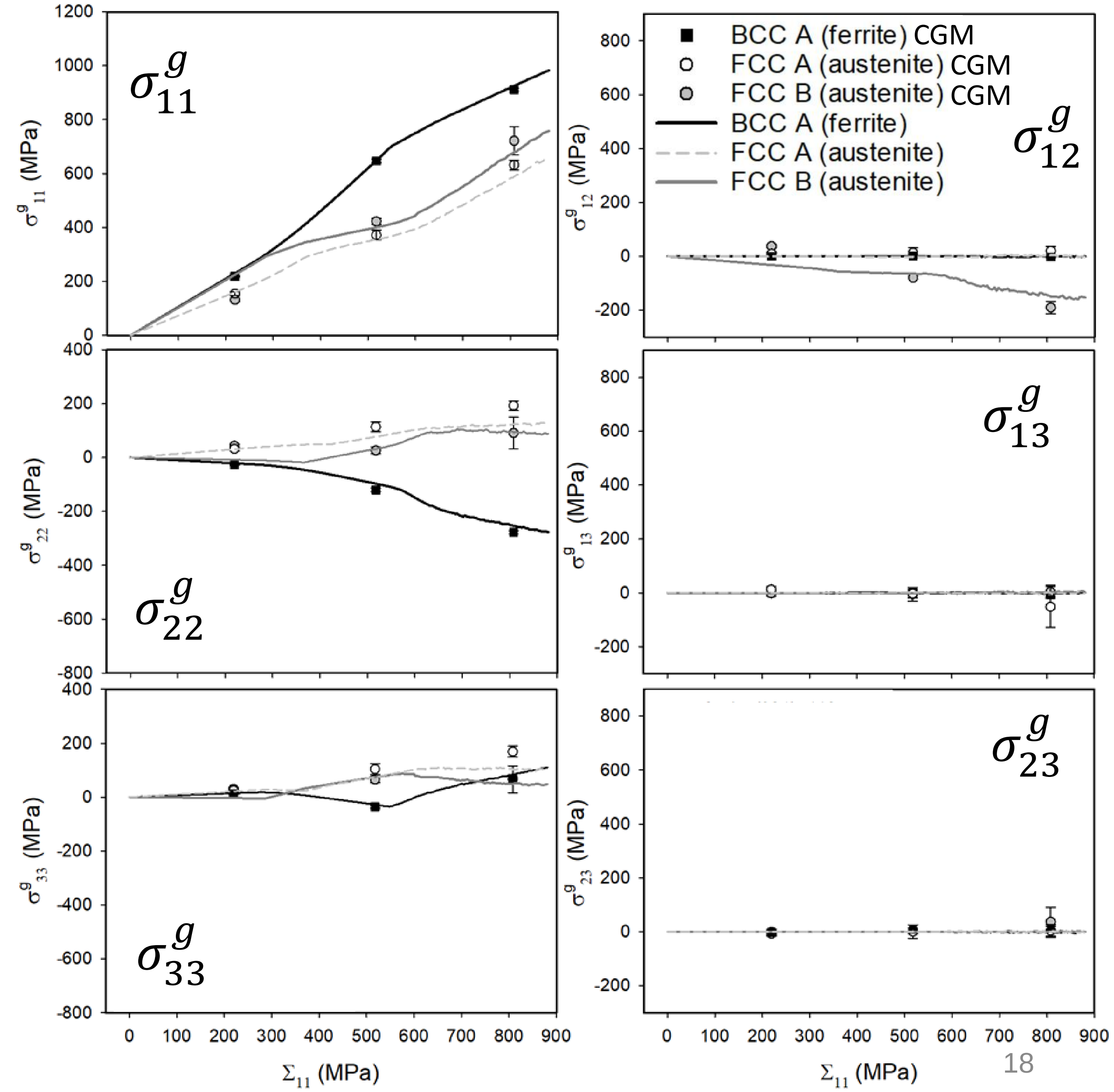


Austenite (γ, fcc, ~50%)

Crystalite Group Method (CGM) test (duplex steel)





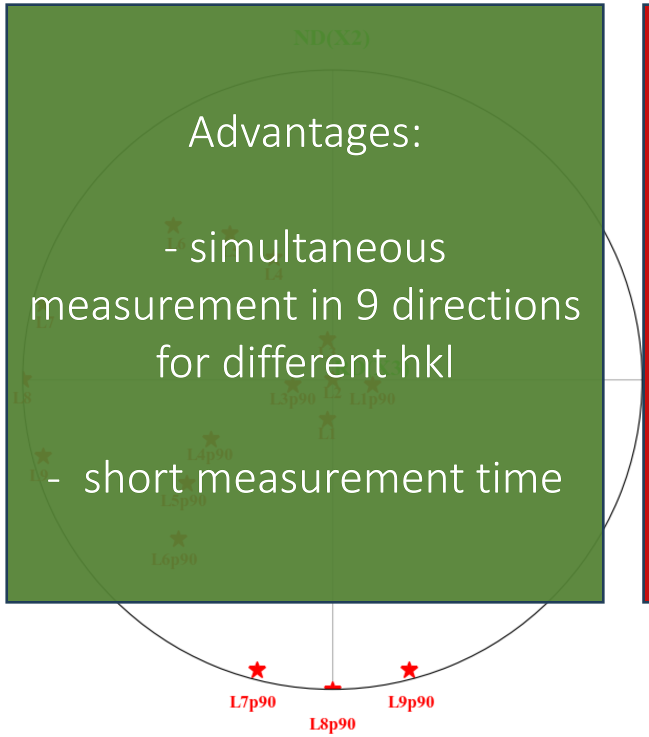


Measurments Setups

Two-phase Brass - Time of Flight (ToF)

EPSILON-MDS (JINR, Dubna) diffractometer: 9 detectors, perpendicular to the primary beam

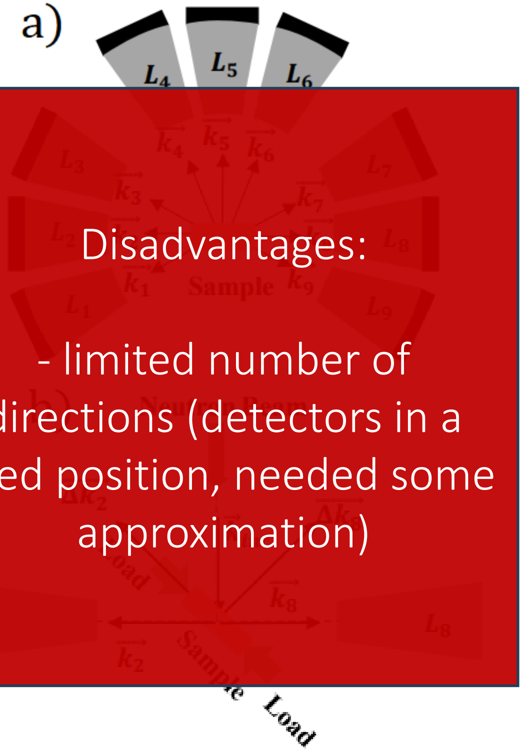
$$d_{hkl} = \frac{ht}{2\sin\theta \; m_n L} \qquad 2\theta = 90°$$



Advantages:

- simultaneous measurement in 9 directions for different hkl
- short measurement time

Poles corresponding to the orientations of the scattering vectors of detectors L1–L9 presented in the sample system X.



Disadvantages:

- limited number of directions (detectors in a fixed position, needed some approximation)

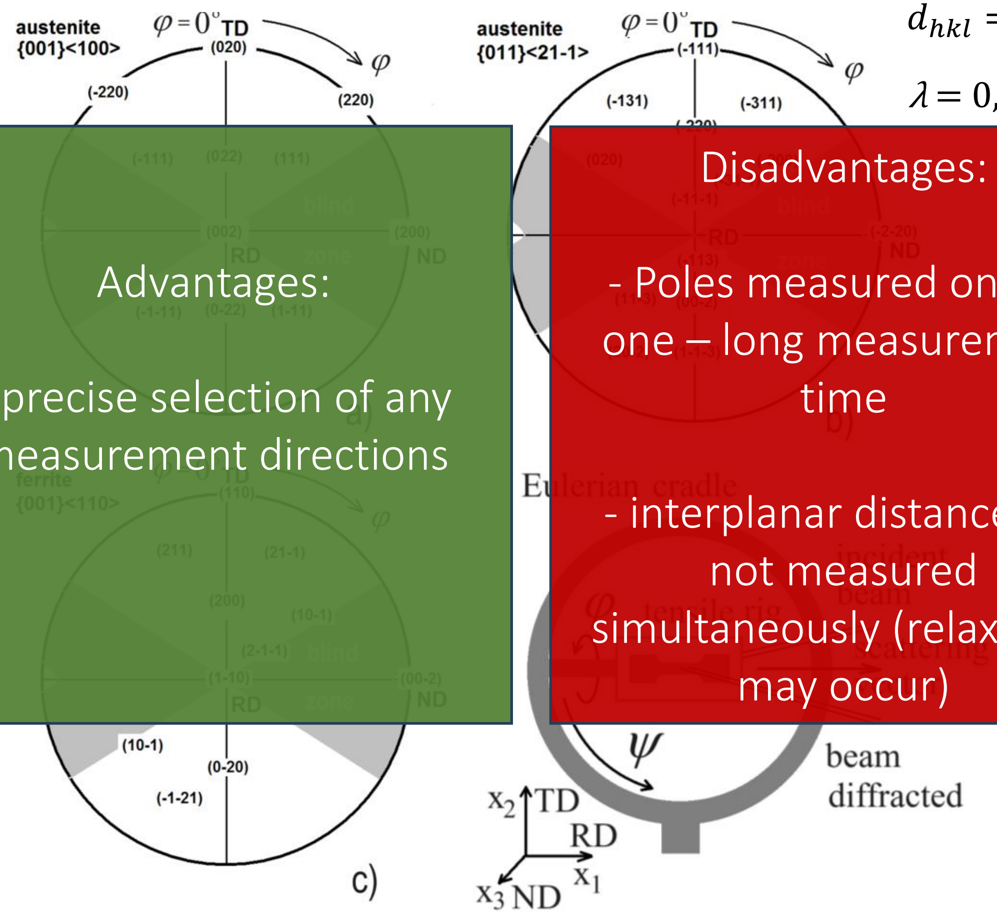
Arrangement of detectors in the EPSILON-MDS diffractometer, a) front view, showing the directions of diffracted beams, b) top view, showing two example scattering vectors $\overrightarrow{\Delta k_2}$ and $\overrightarrow{\Delta k_8}$.

Duplex steel - angular dispersion

6T1 (LLB, Saclay) diffractometer: 1 detector, Eulerian cradle;
Currently measurements done in TKSN400 (NPI, Prague)

$$d_{hkl} = \frac{\lambda}{2\sin\theta}$$

$$\lambda = 0{,}1159 \text{ nm}$$



Advantages:

- precise selection of any measurement directions

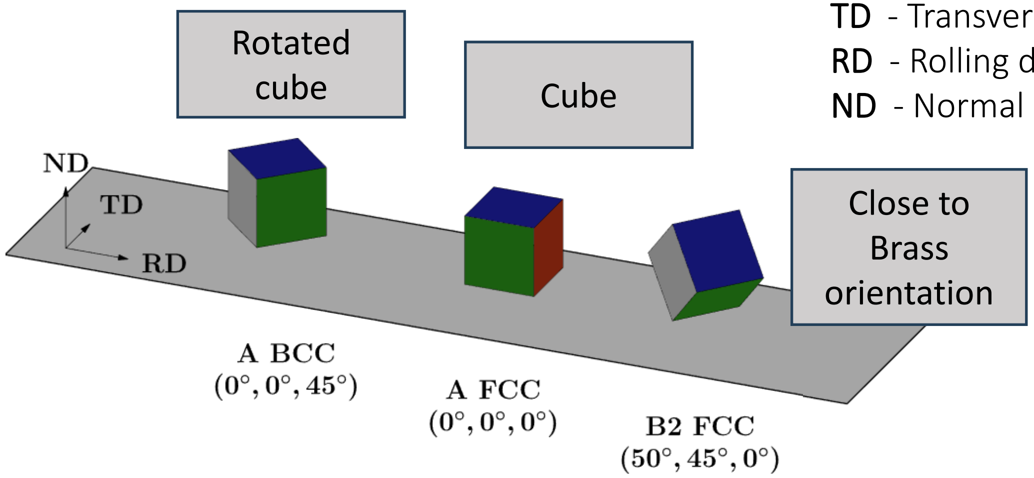
Disadvantages:

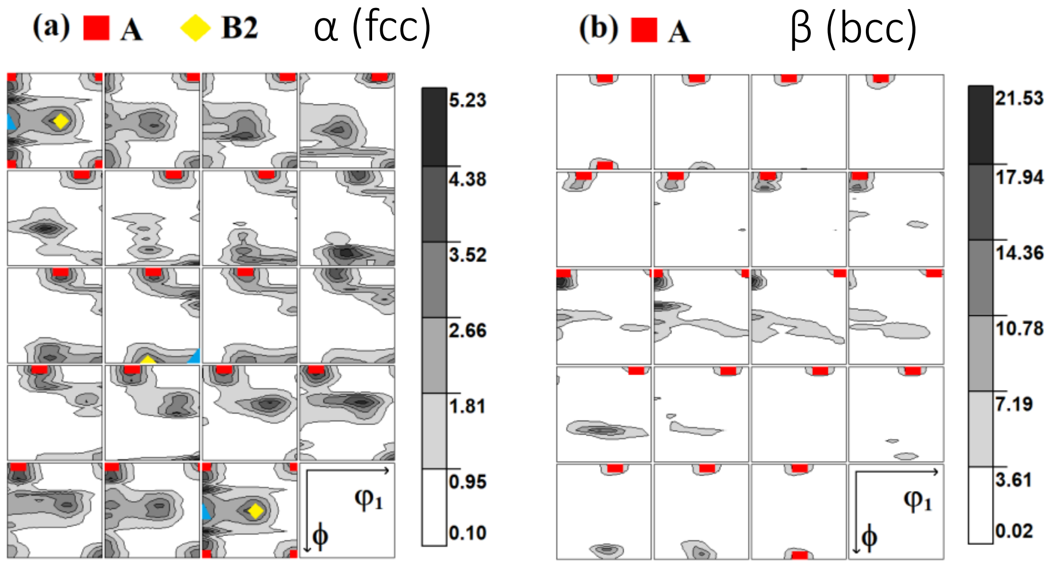
- Poles measured one by one – long measurement time
- interplanar distances are not measured simultaneously (relaxation may occur)

Poles corresponding to a, b) two preferred orientations in austenite and c) one orientation in ferritic phase. Orientation of the tensile rig (with the sample) rotated in Eulerian cradle is defined by ϕ and ψ angles (d).

Brass - Pole Figures Analysis (ToF, CGM)

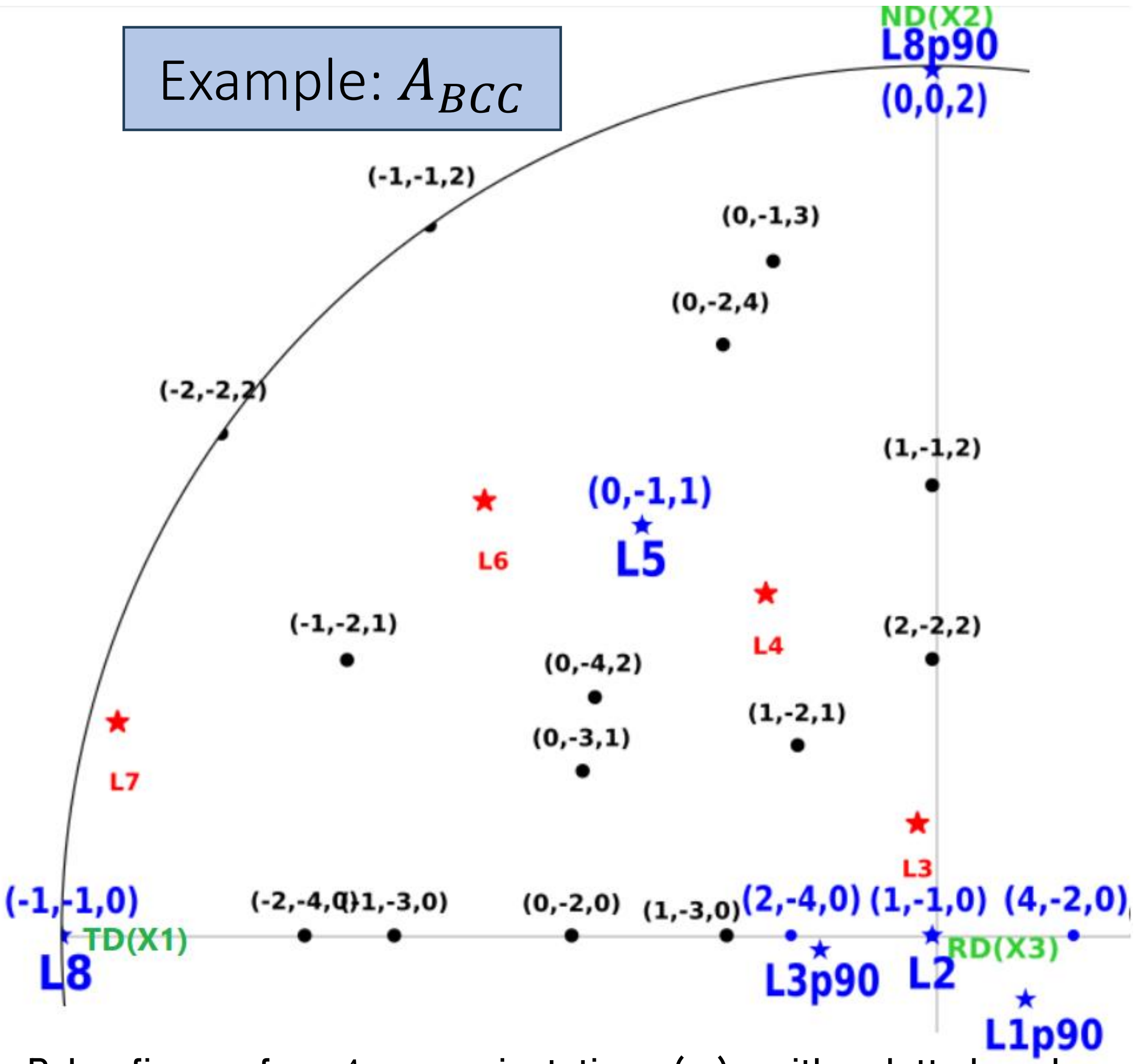
TD - Transverse direction
RD - Rolling direction
ND - Normal direction





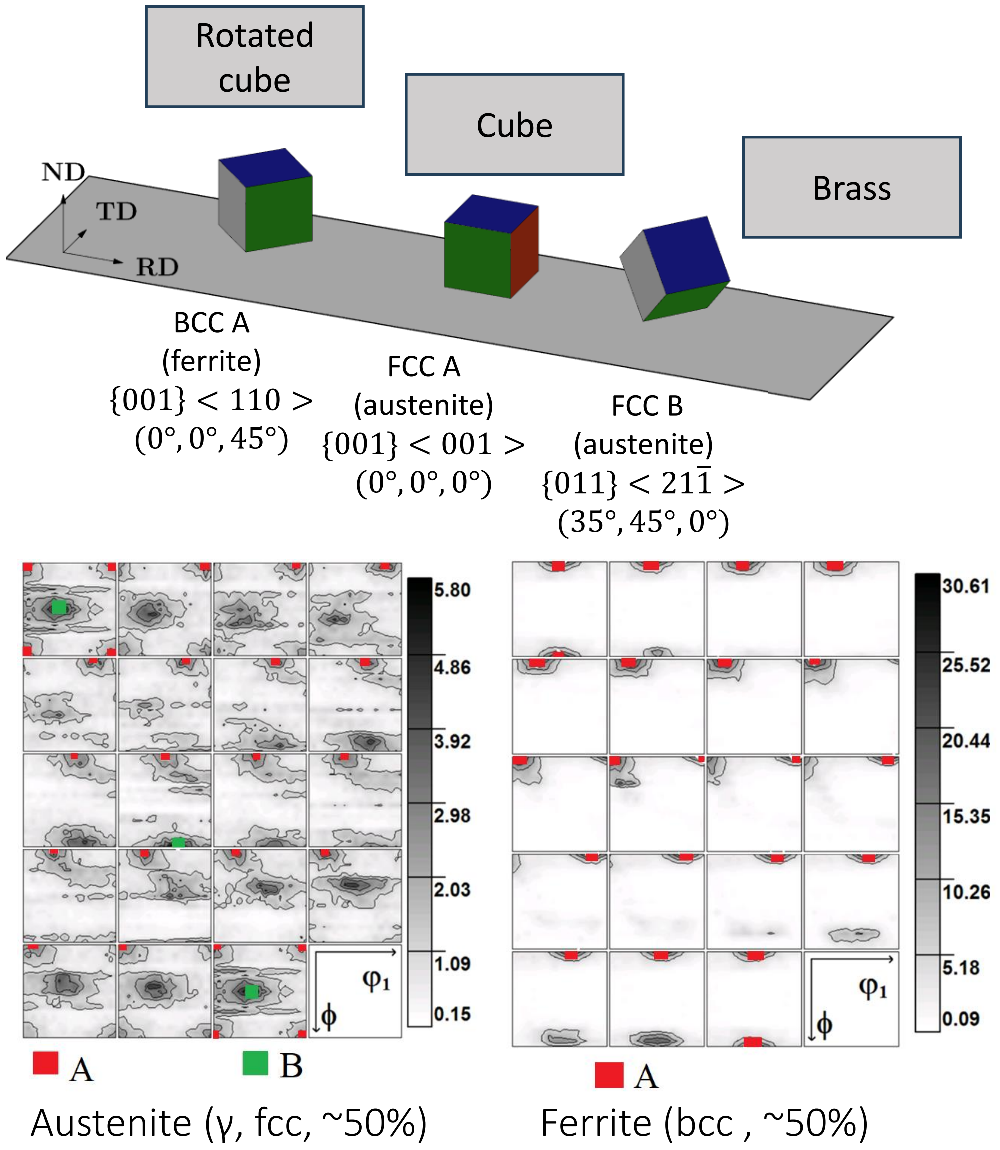
Orientations analyzed for Brass sample.

Example: A_{BCC}

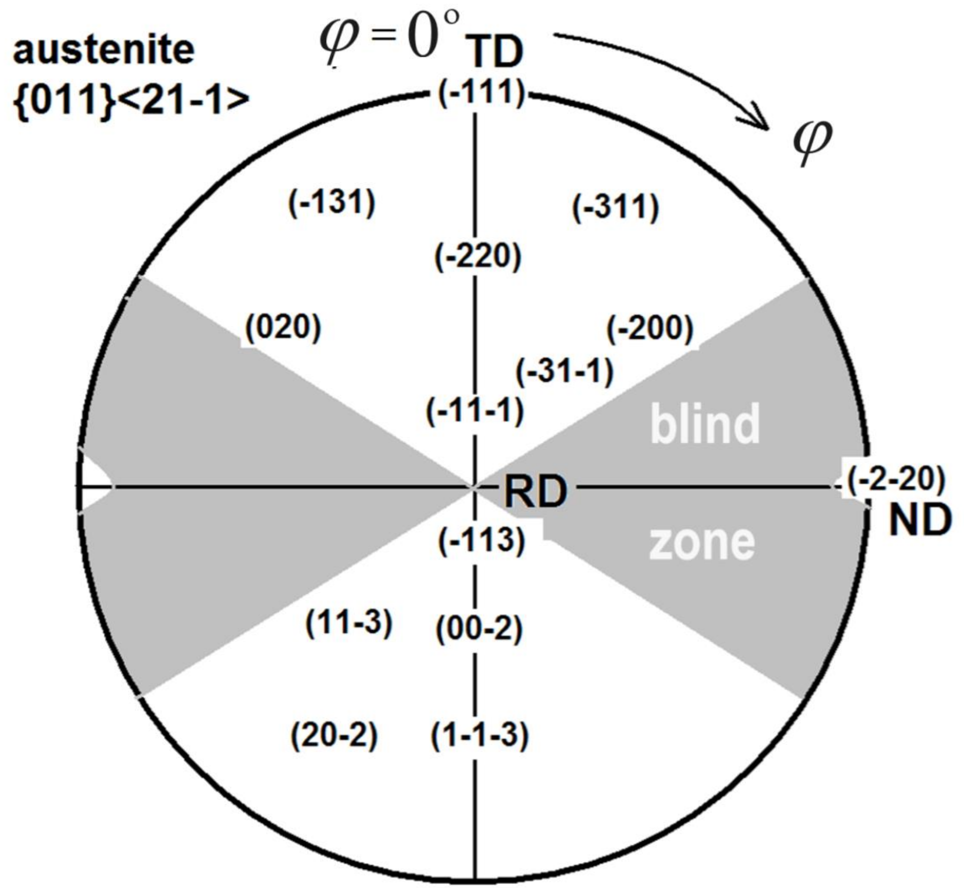


Pole figure for A_{BCC} orientation (●) with plotted poles corresponding to the scattering vectors orientations for detectors L1–L9 (★). Reflex-detector pairs are marked in blue.

Duplex steel - Pole Figures Analysis (angular dispertion, CGM)



Orientations analyzed for duplex steel.

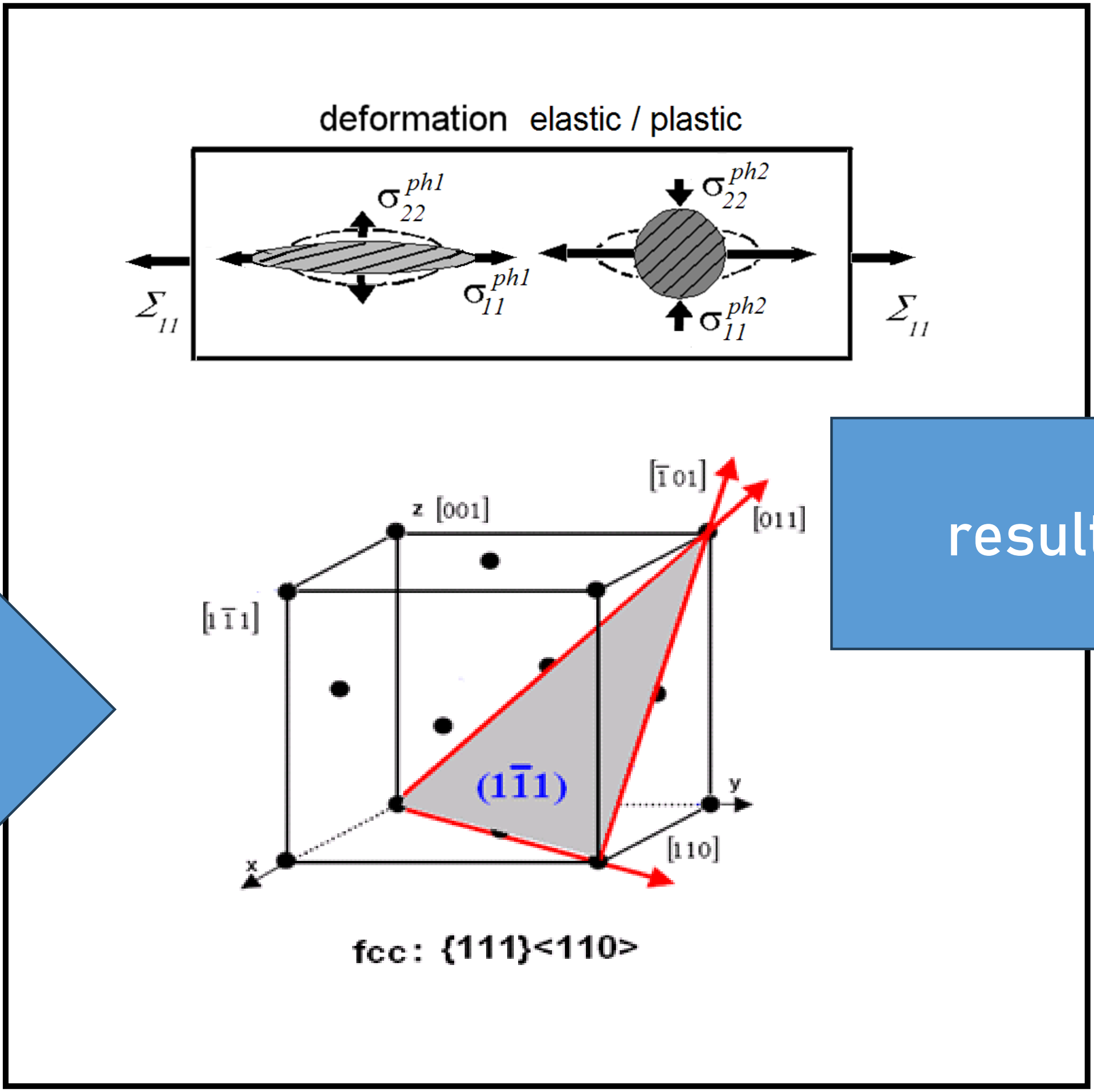


Pole figure for B_{FCC} orientation with plotted poles corresponding to the scattering vectors orientations set using Eulerian cradle.

Self-consistent model used for prediction of elasto-plastic deformation

Can we determine such parameters as CRSS directly from diffraction?

parameters

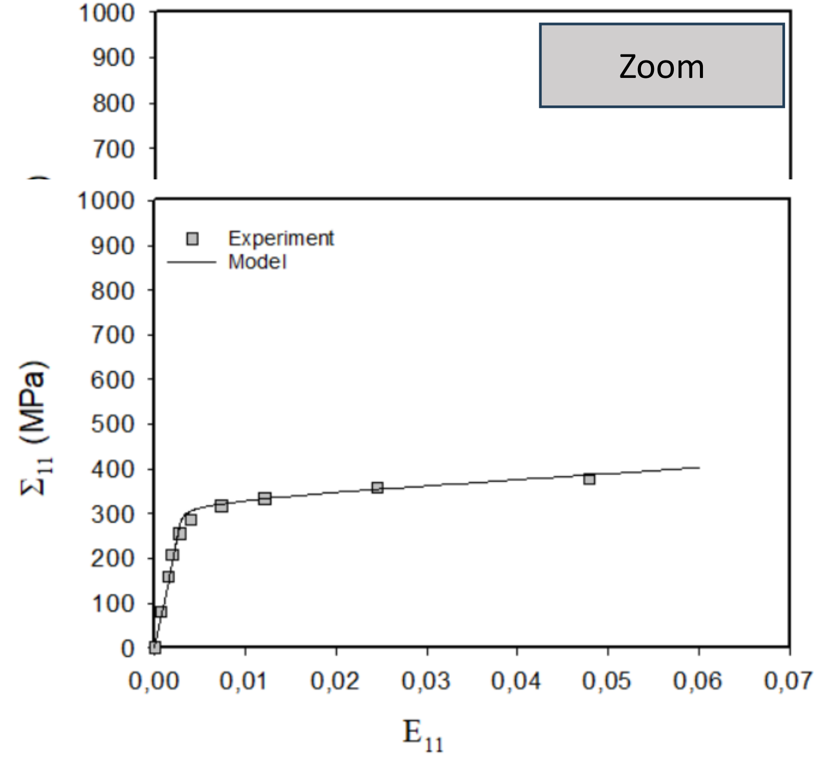


results

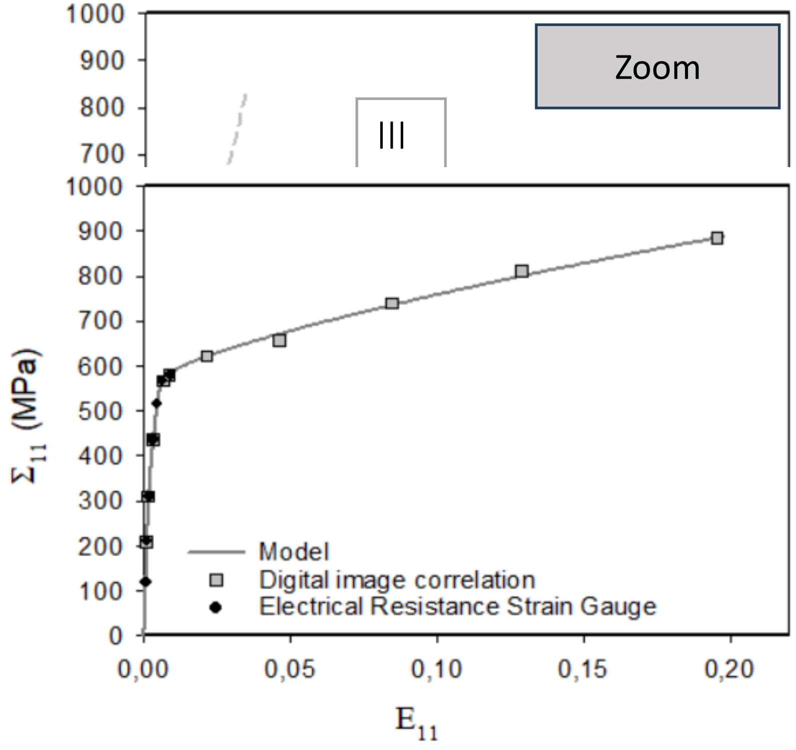
Macroscopic curves

Measurements performed after relaxation

Brass (compression):



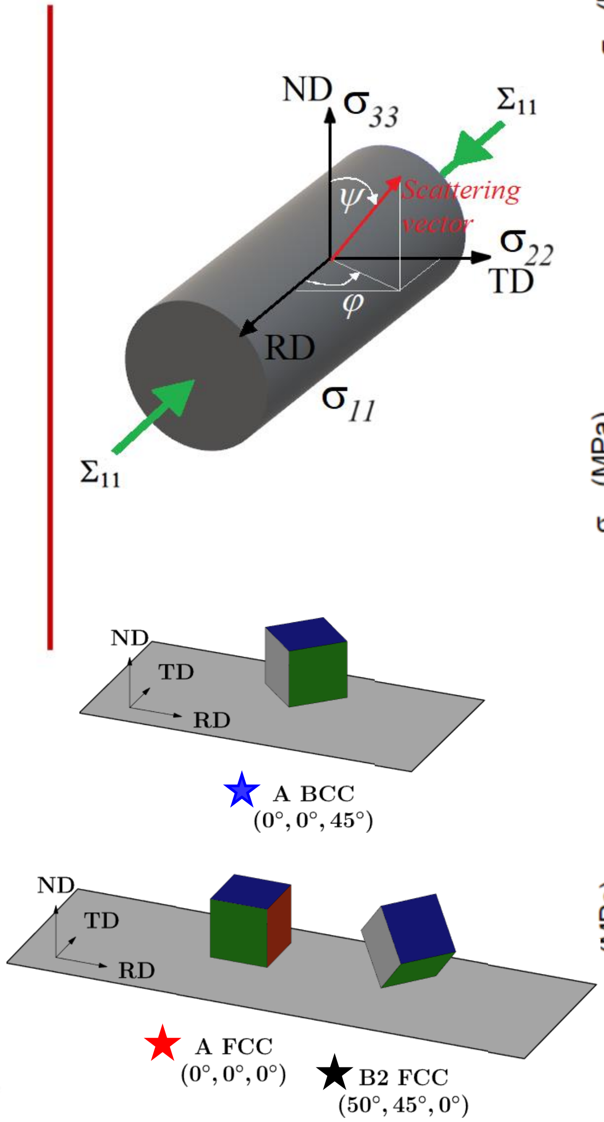
Duplex steel (tension):

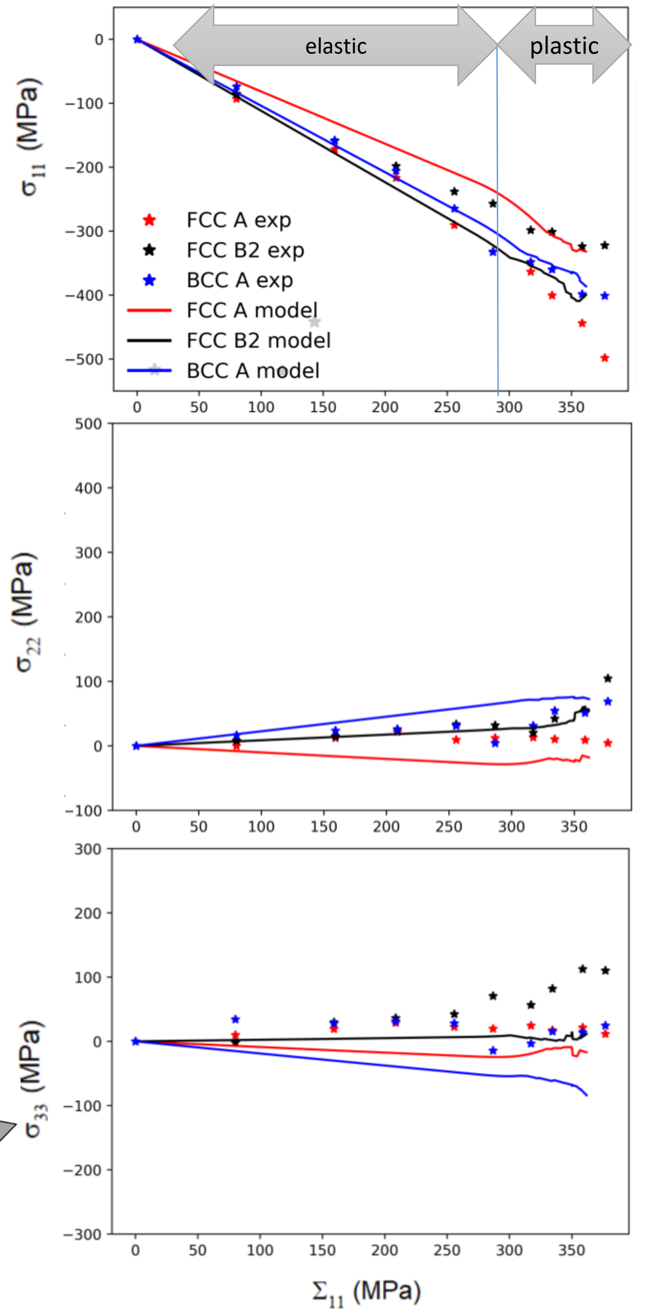


Normal stresses (CGM)

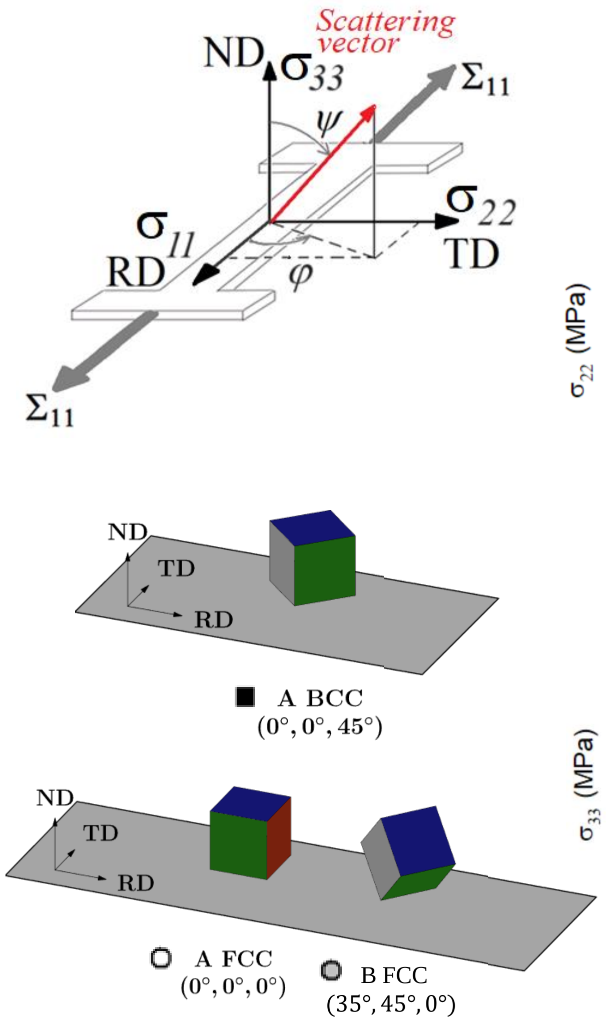
$$\langle \varepsilon(\psi,\phi)\rangle_{\{hkl\}} = a_{3k}a_{3l}s_{klij}\sigma_{ij}^{CR}$$

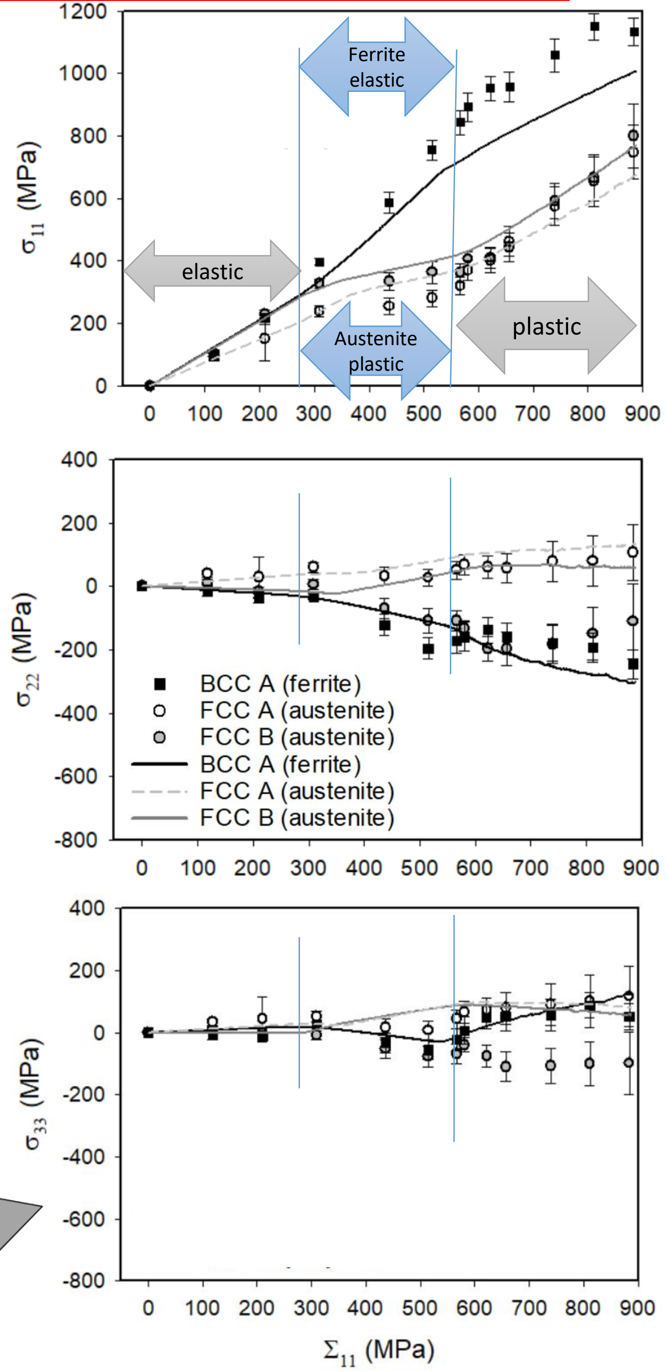
Brass:





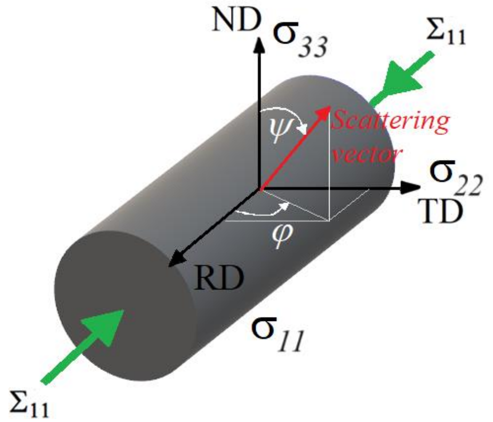
Duplex steel:

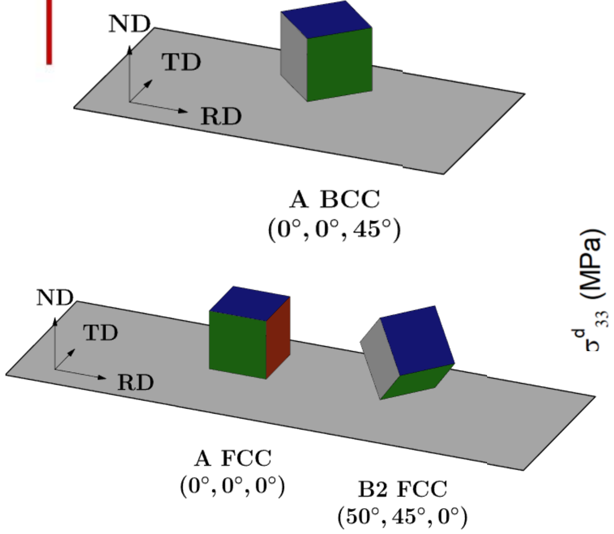


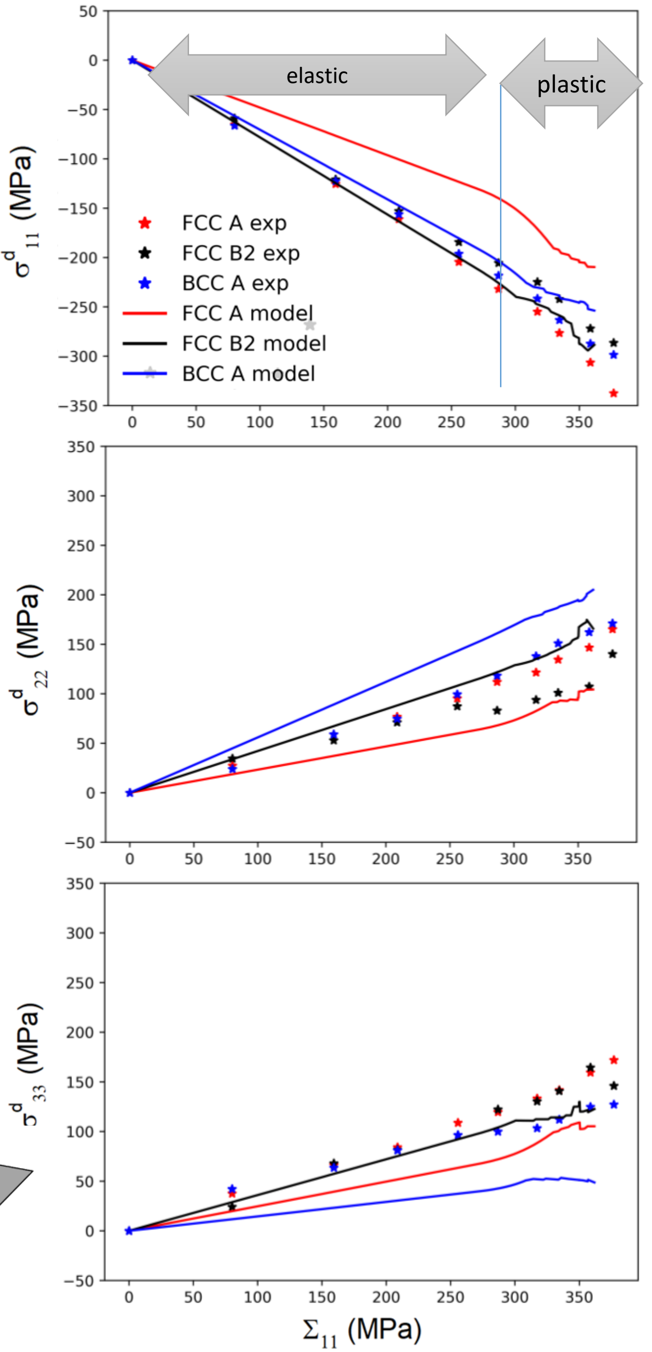


Deviatoric stresses

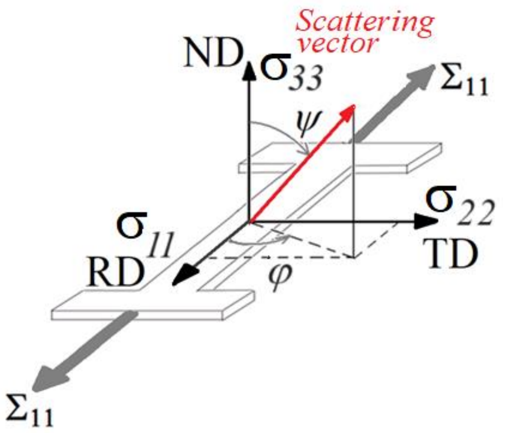
Brass:

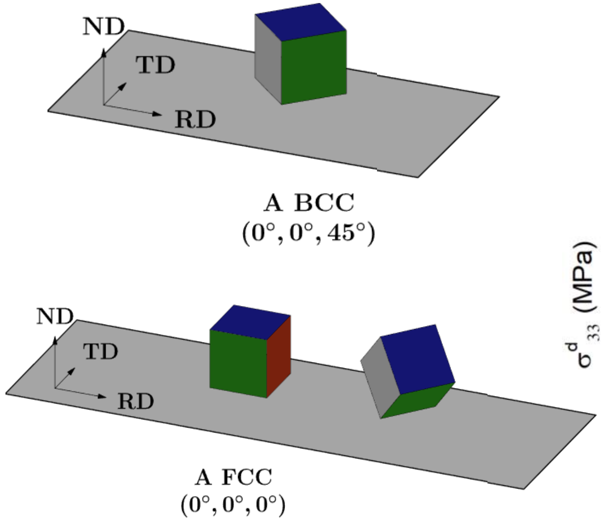


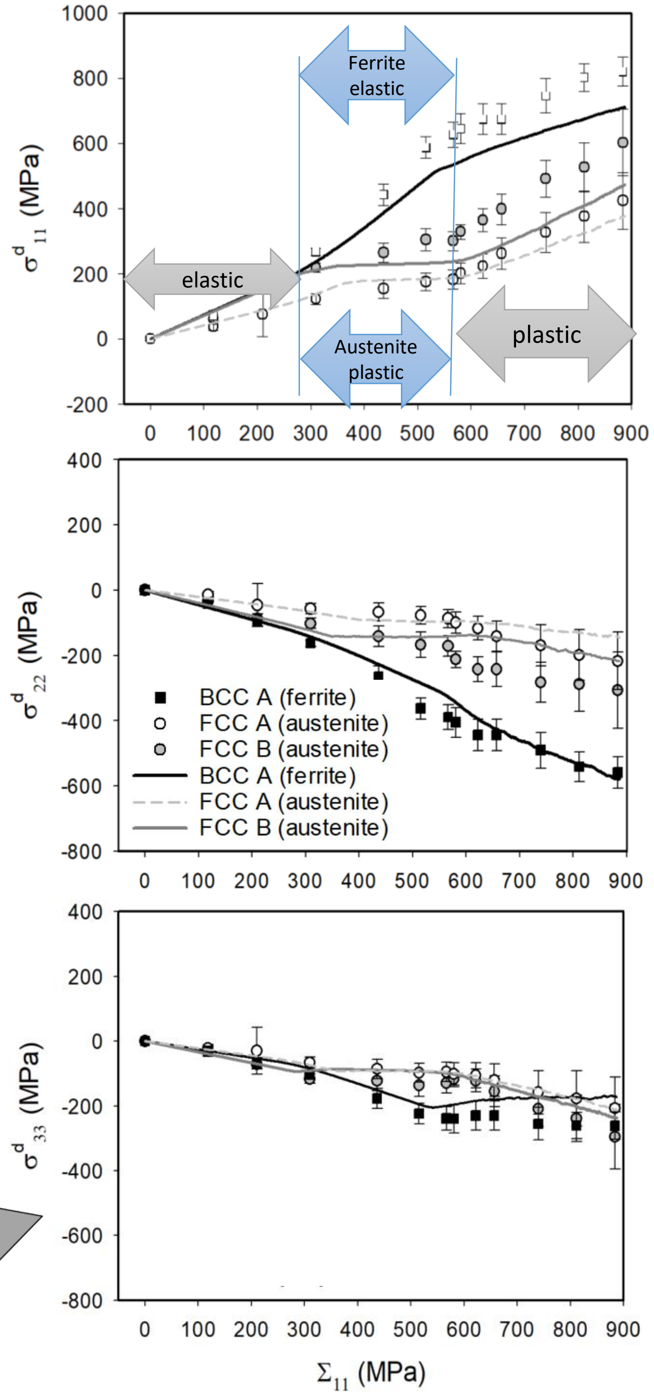




Duplex steel:







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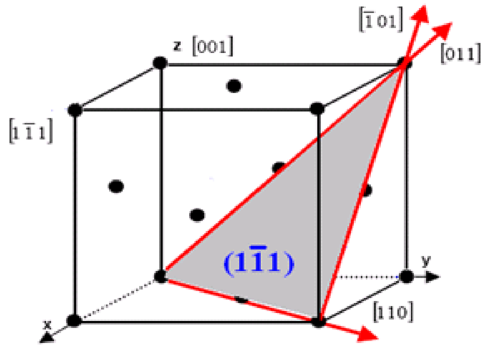
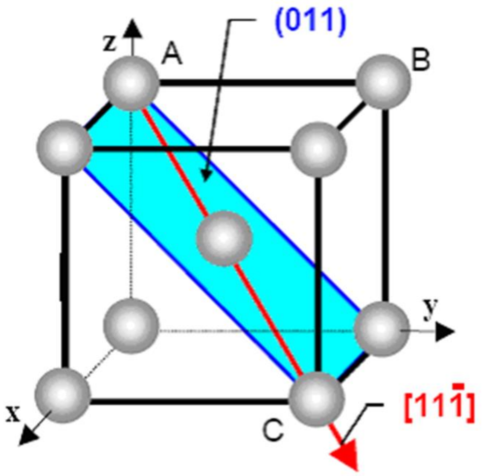
Resolved Shear Stresses (RSS) + CRSS

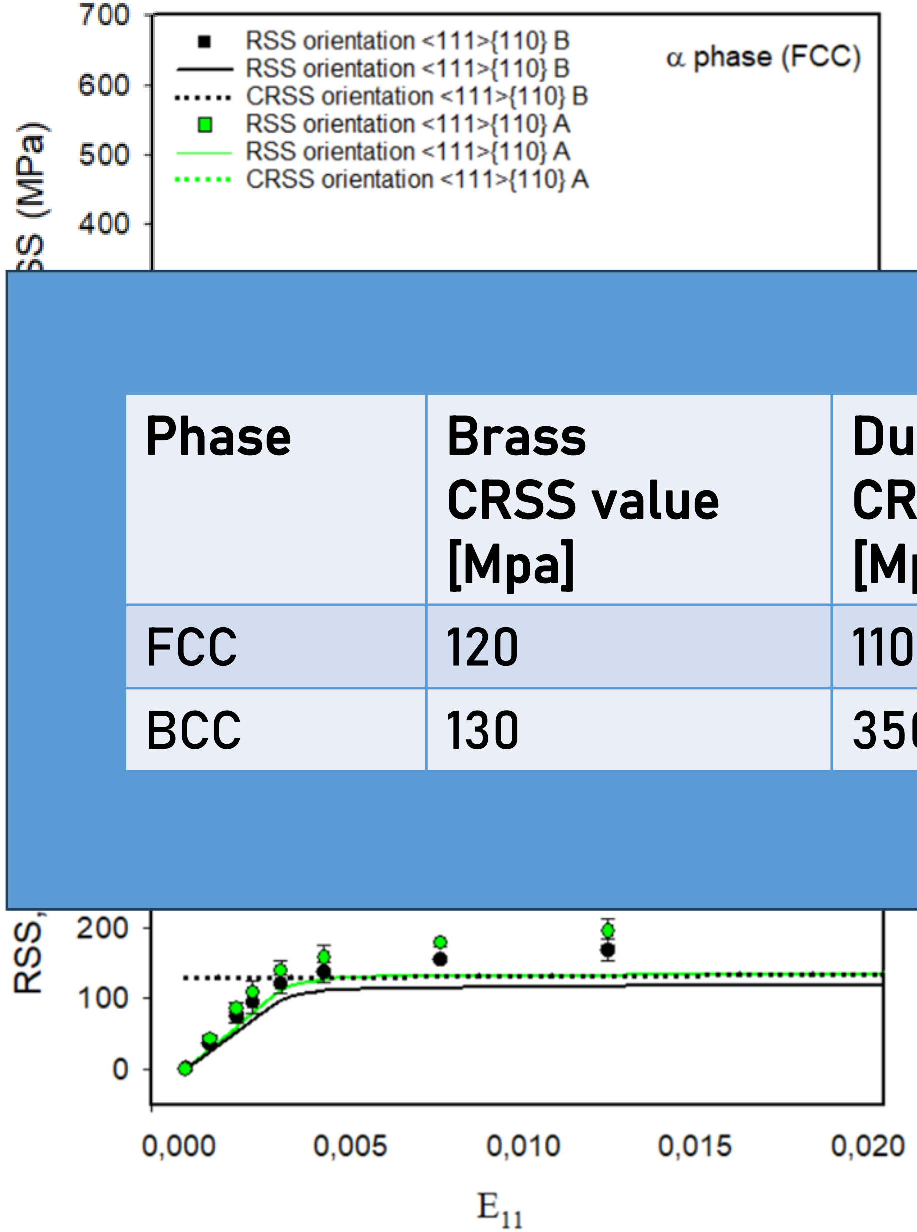


fcc: {111}<110>

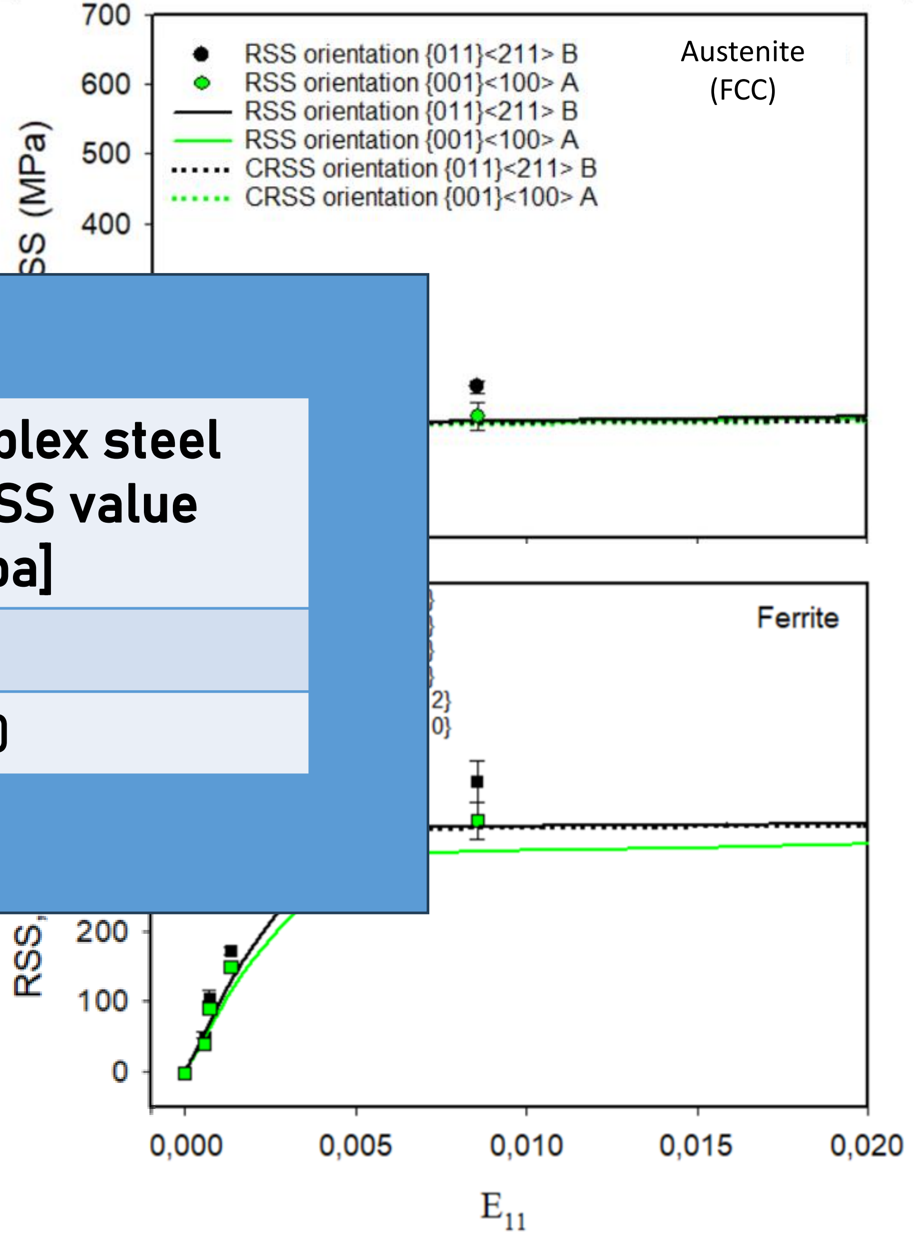


bcc: <111>{110}

Brass:



Duplex steel:



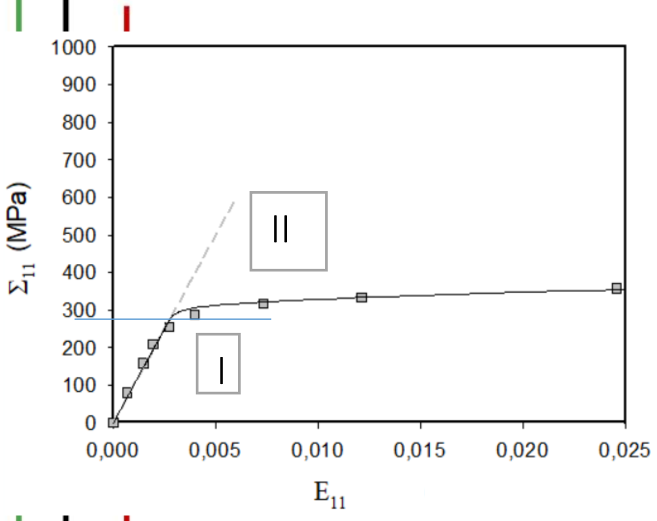
Phase	Brass CRSS value [Mpa]	Duplex steel CRSS value [Mpa]
FCC	120	110
BCC	130	350

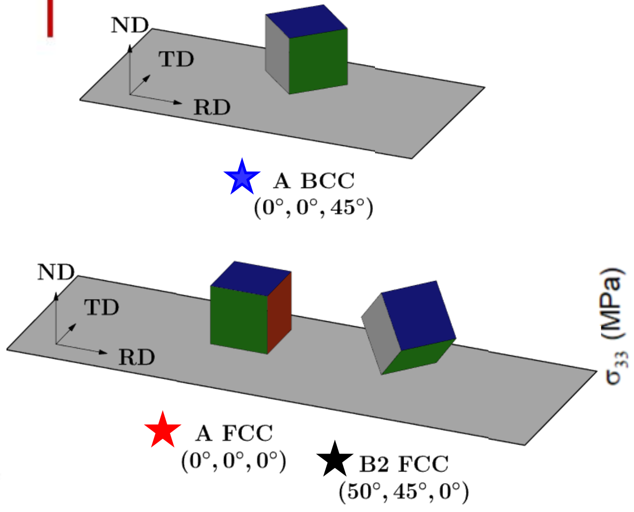
fcc

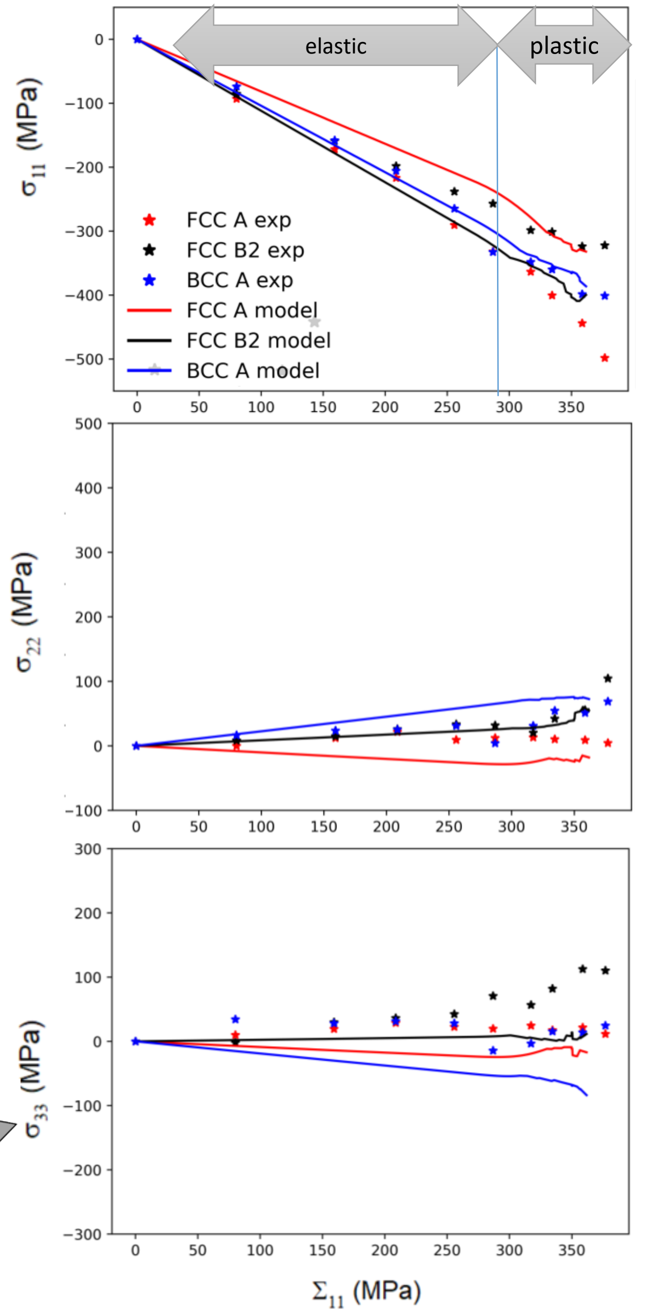
bcc

Results (CGM + model)

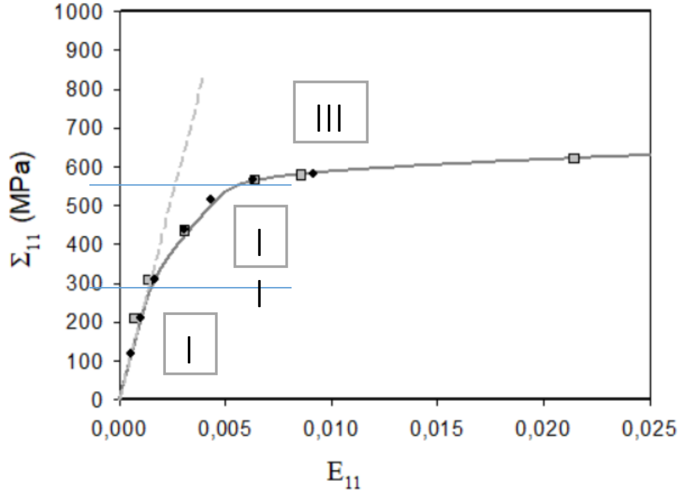
Brass:

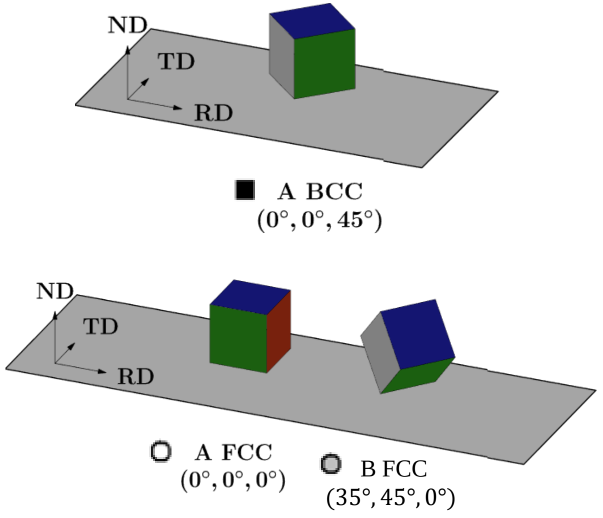


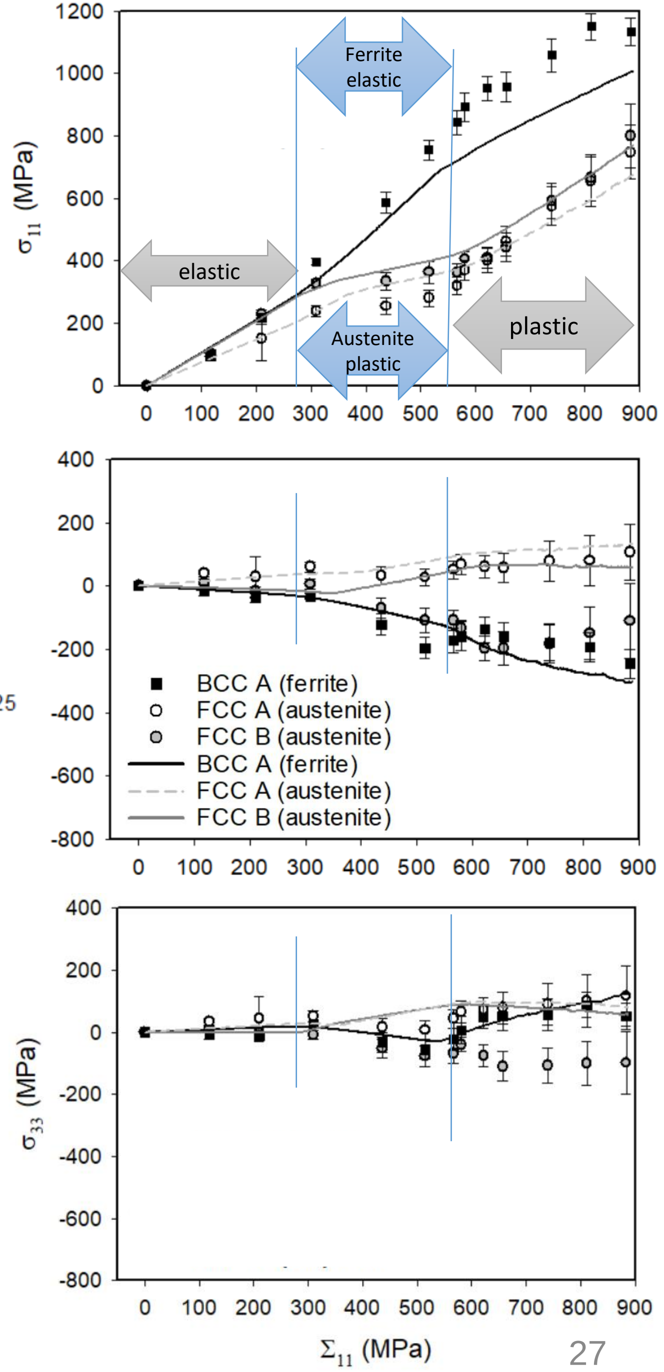




Duplex steel:







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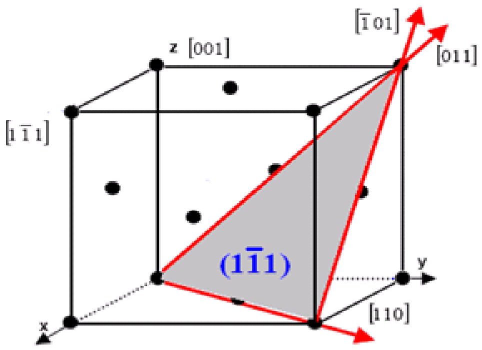
Resolved Shear Stresses (RSS) + CRSS



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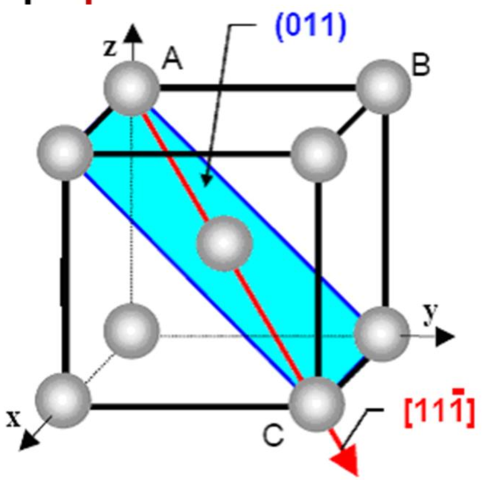

bcc: <111>{110}

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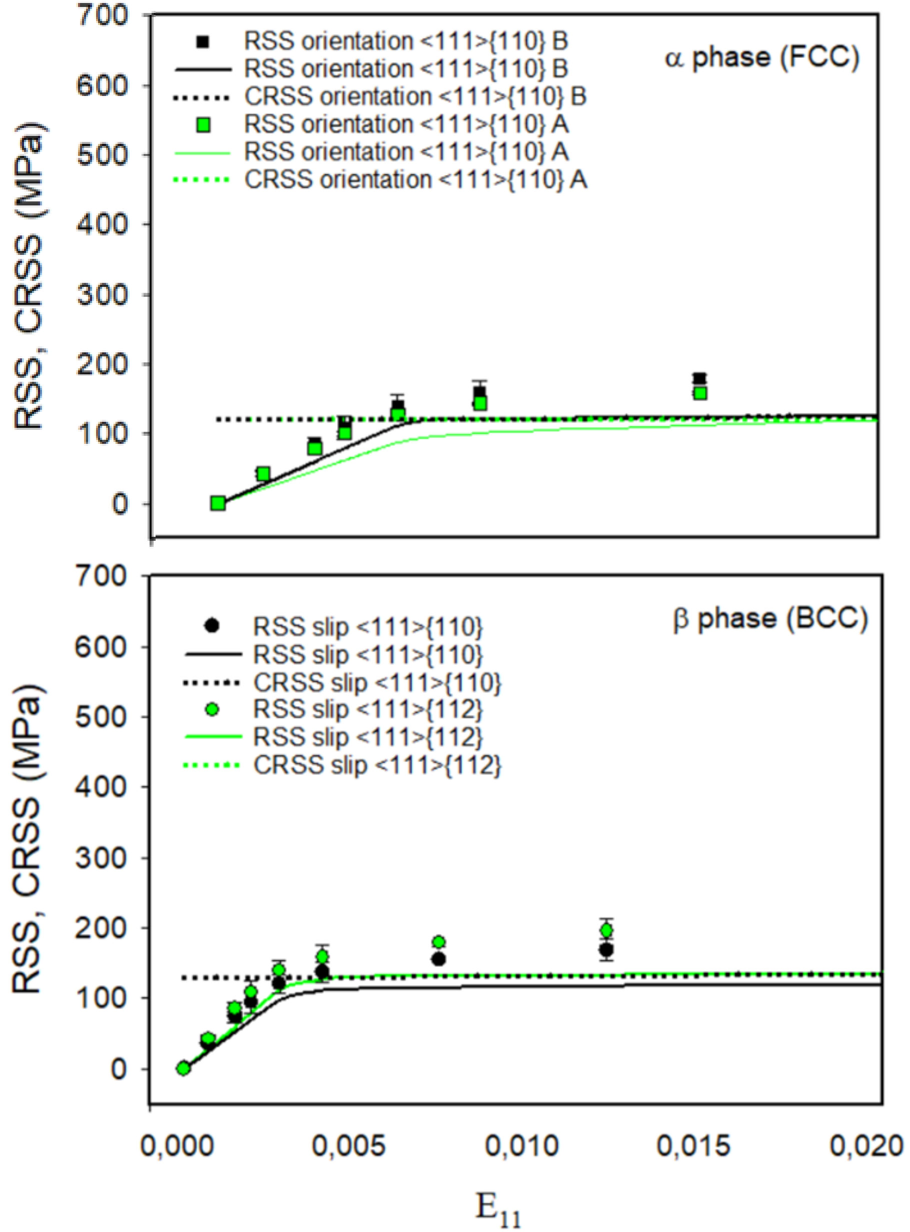
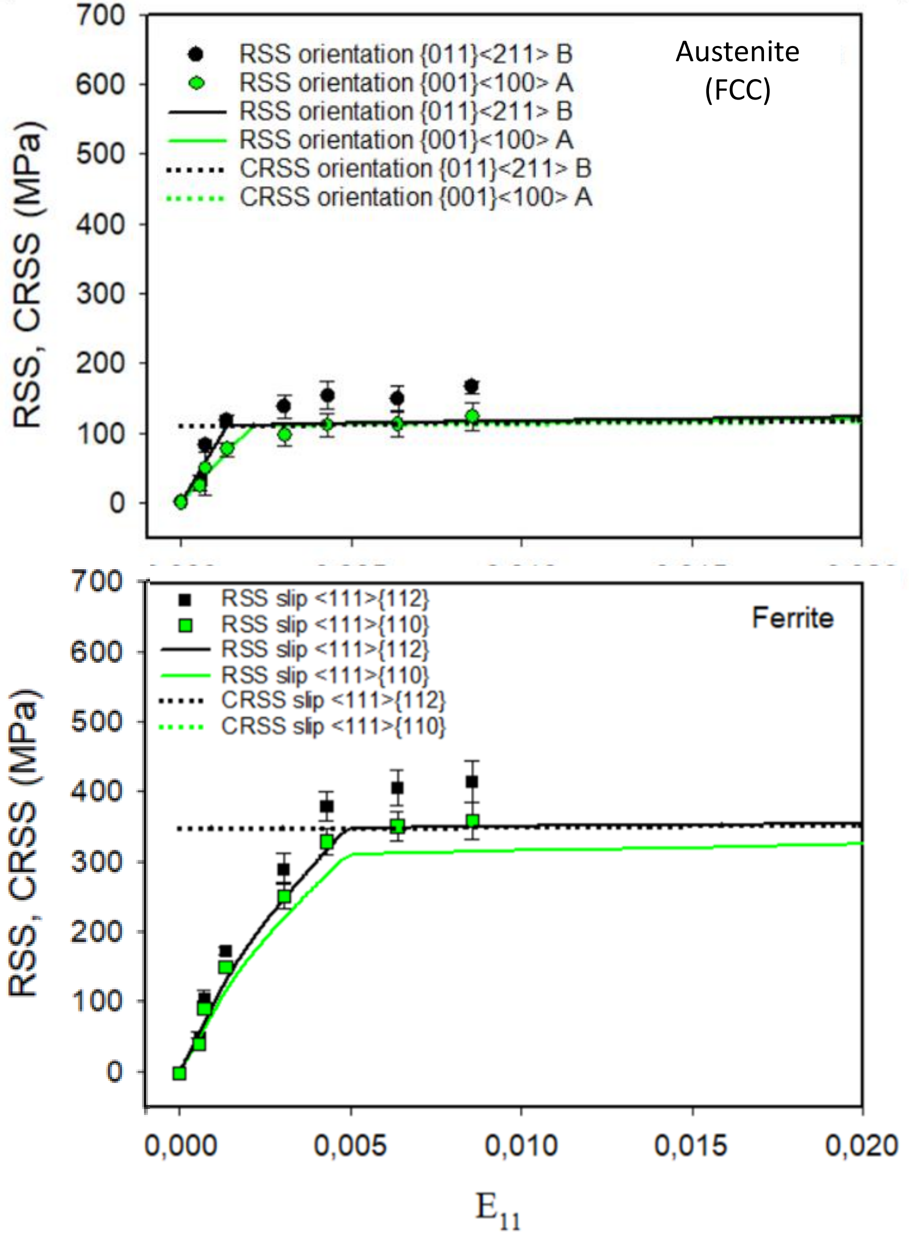


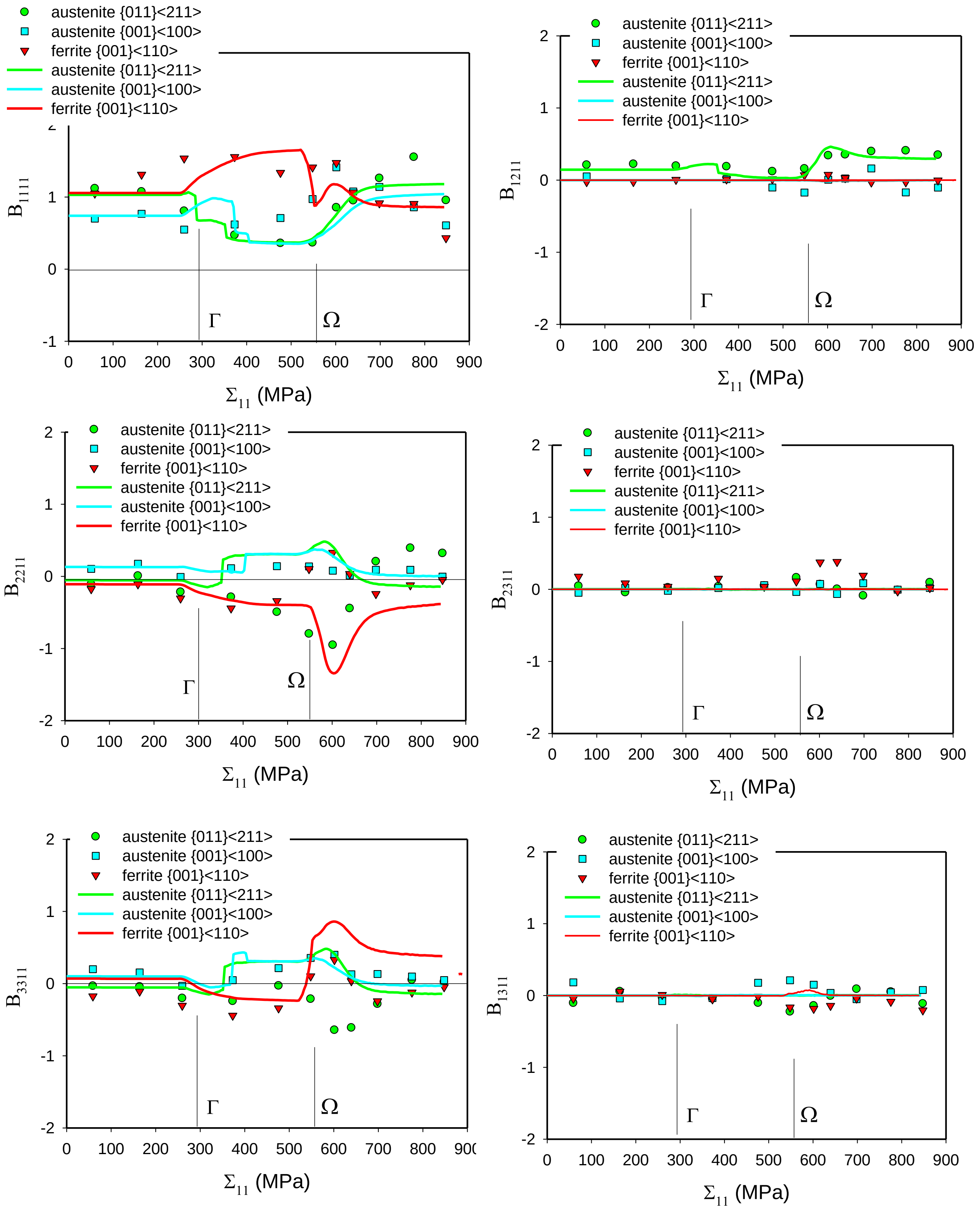
Duplex steel:

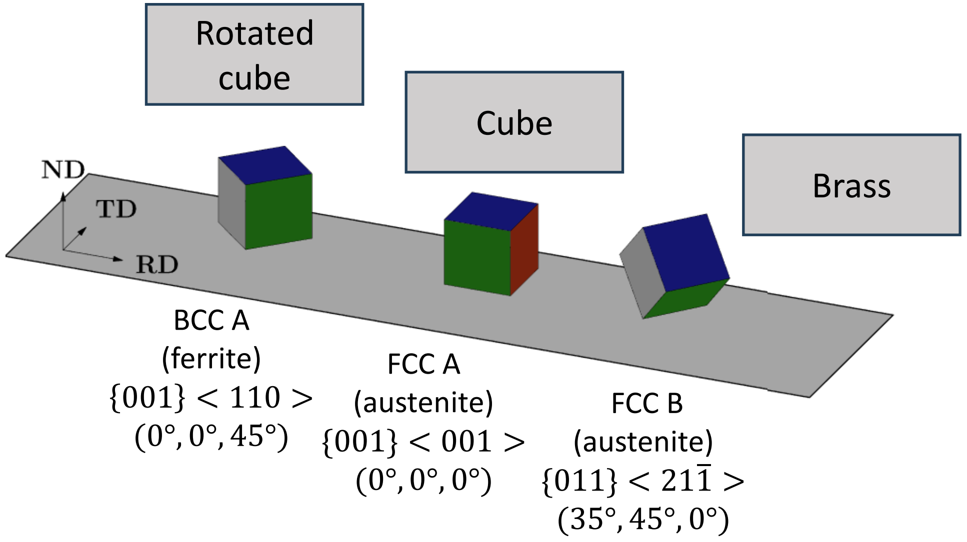


fcc

bcc

Stress concentration tensor – duplex steel

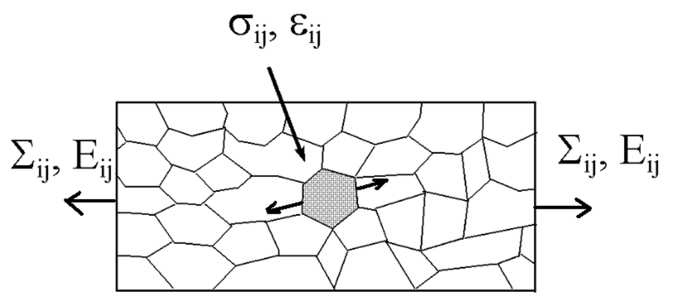




Scale transition :

$$\dot{\varepsilon}_{ij}^{g} = A_{ijkl}^{g}\,\dot{E}_{kl}$$

$$\dot{\sigma}_{ij}^{g} = B_{ijkl}^{g}\,\dot{\Sigma}_{kl}$$



$\overline{B}_{ijkl}$ model → lines

B_{ijkl} experiment → points

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SUMMARY:

1) Elastoplastic deformation in individual phases was studied using diffraction and crystallographic models.

2) Agreement between the results from neutron diffraction and model was obtained.

3) Grain interaction model can be verified using diffraction data.

4) Evolution of stress localization tensor characterizes elastic-plastic transition.

5) Stress tensor for particular groups of grains can be measured using CGM (crystallite group method).

6) Critical resolved stresses (CRSS) can be determined using CGM.

Thank you for your attention