AKADEMIA GÓRNICZO-HUTNICZA
IM. STANISŁAWA STASZICA
W KRAKOWIE

Badanie mechanizmów plastyczności w steksturowanym stopie magnezu AZ31 przy użyciu dyfrakcji neutronowej

Plastic deformation study in textured AZ31 magnesium alloy using neutron diffraction

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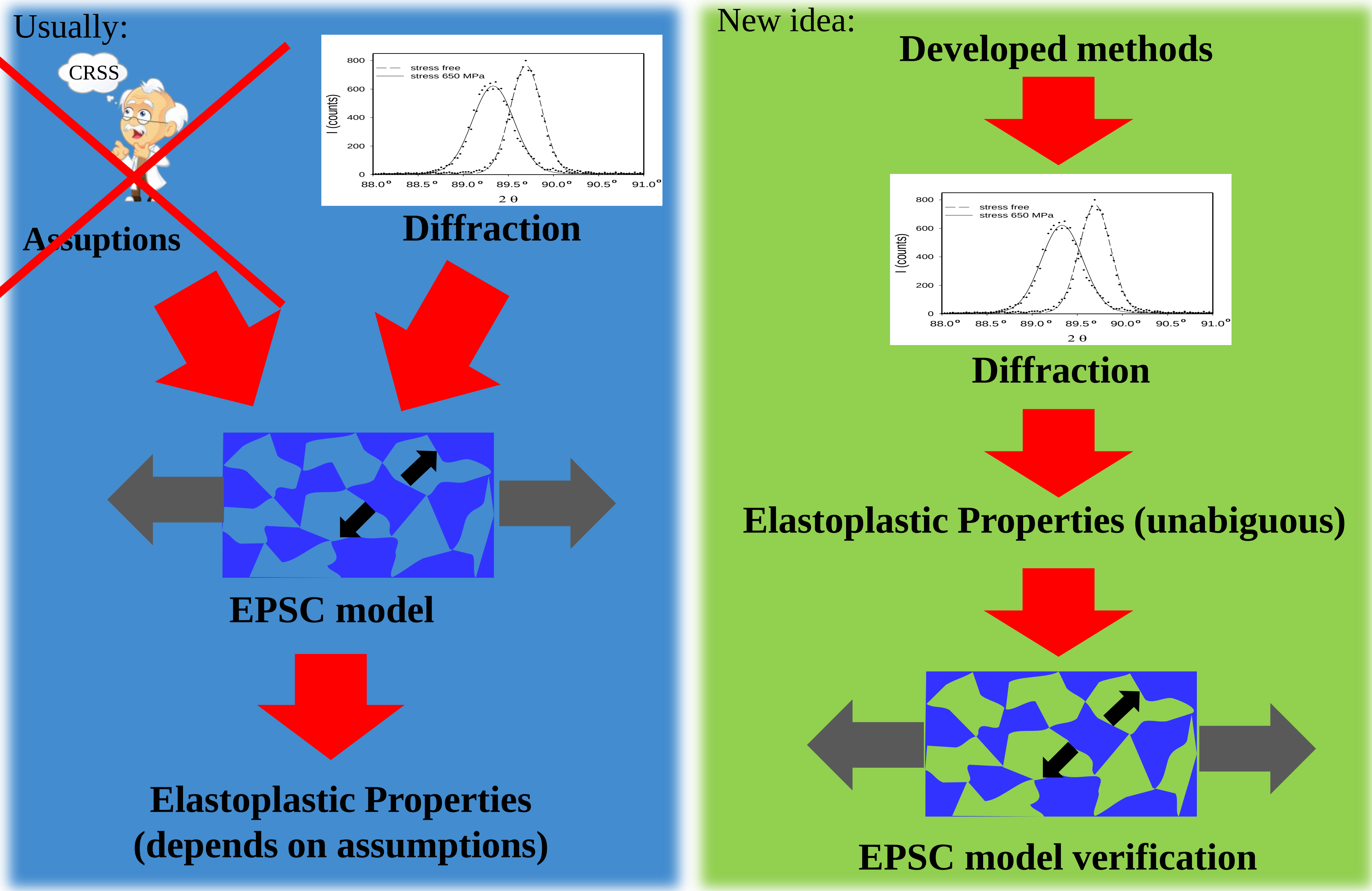
Agenda

1. Aim of the study
2. Material characterisation
3. Crystallite group method
4. Stress localisation
5. Direct measurement of CRSS
6. Cycling load & detwinning

Aims of the study



Aims of the study

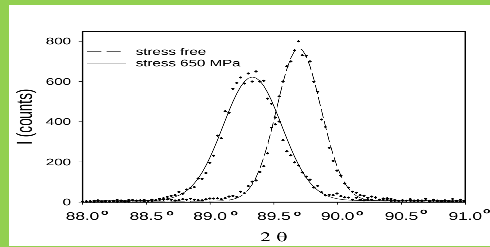
Usually:

How to get Elastic properties directly from experiment?

(depends on assumptions)

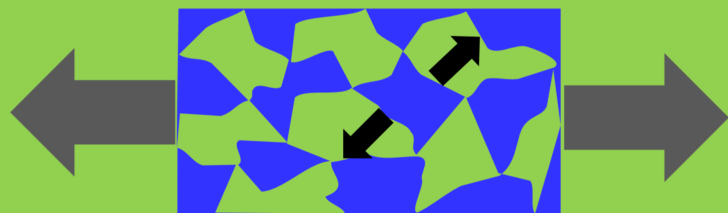
New idea:

Developed methods



Diffraction

Elastoplastic Properties (unabiguous)



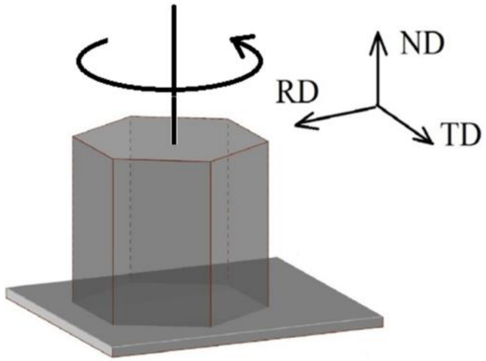
EPSC model verification

Grain stresses – textured Mg alloy

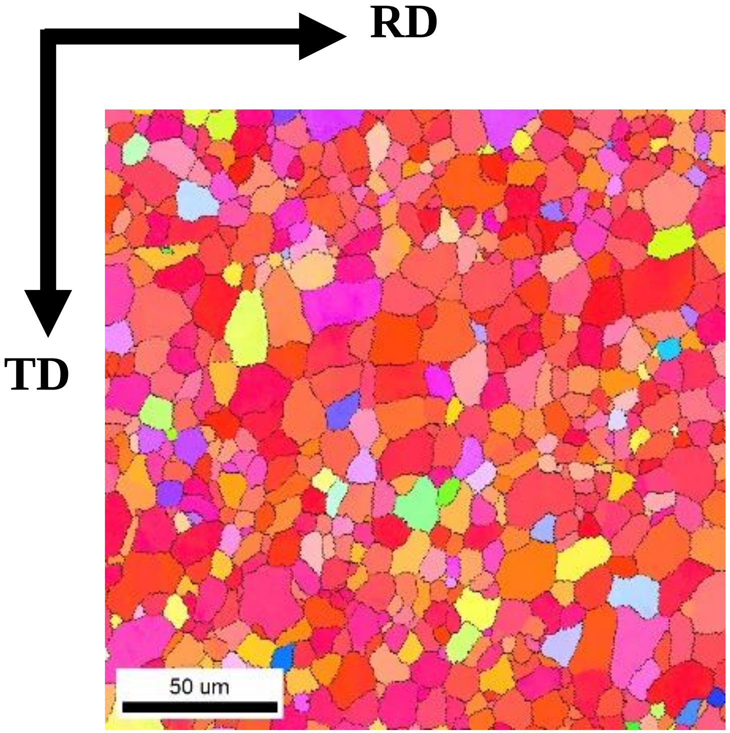
Material characterization Mg alloy (AZ31) – hot rolled

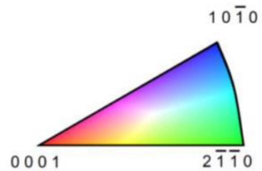
	Al	Zn	Mn	Cu	Mg
wt%	2,5-3,5	0,7-1,3	0,2-1,0	0,05	94,15-96,55

Fibre texture



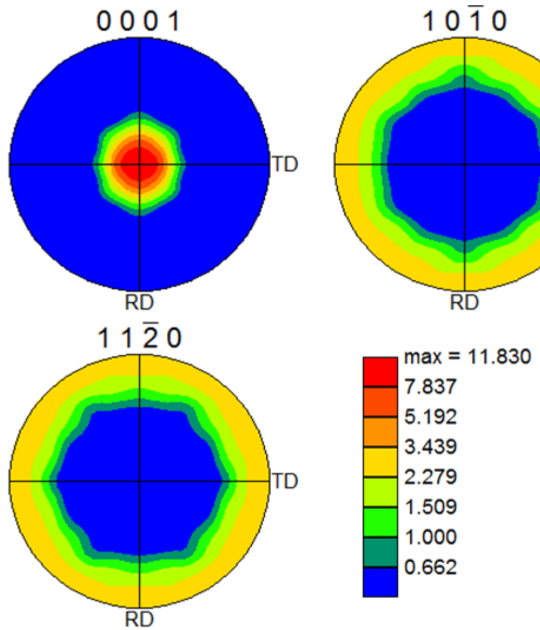
$\{0001\}\langle 10\bar{1}0\rangle$



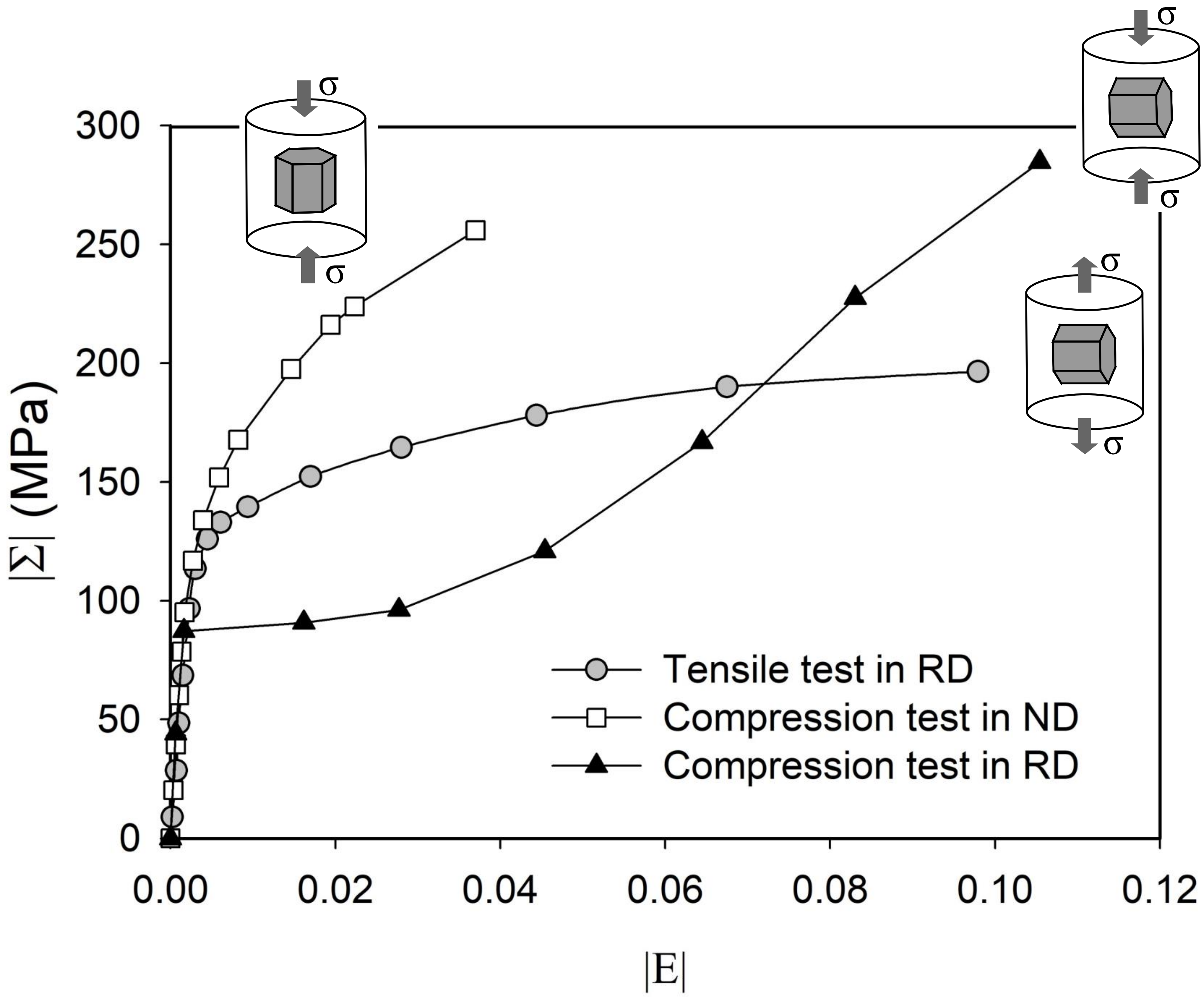


Orientation map from EBSD

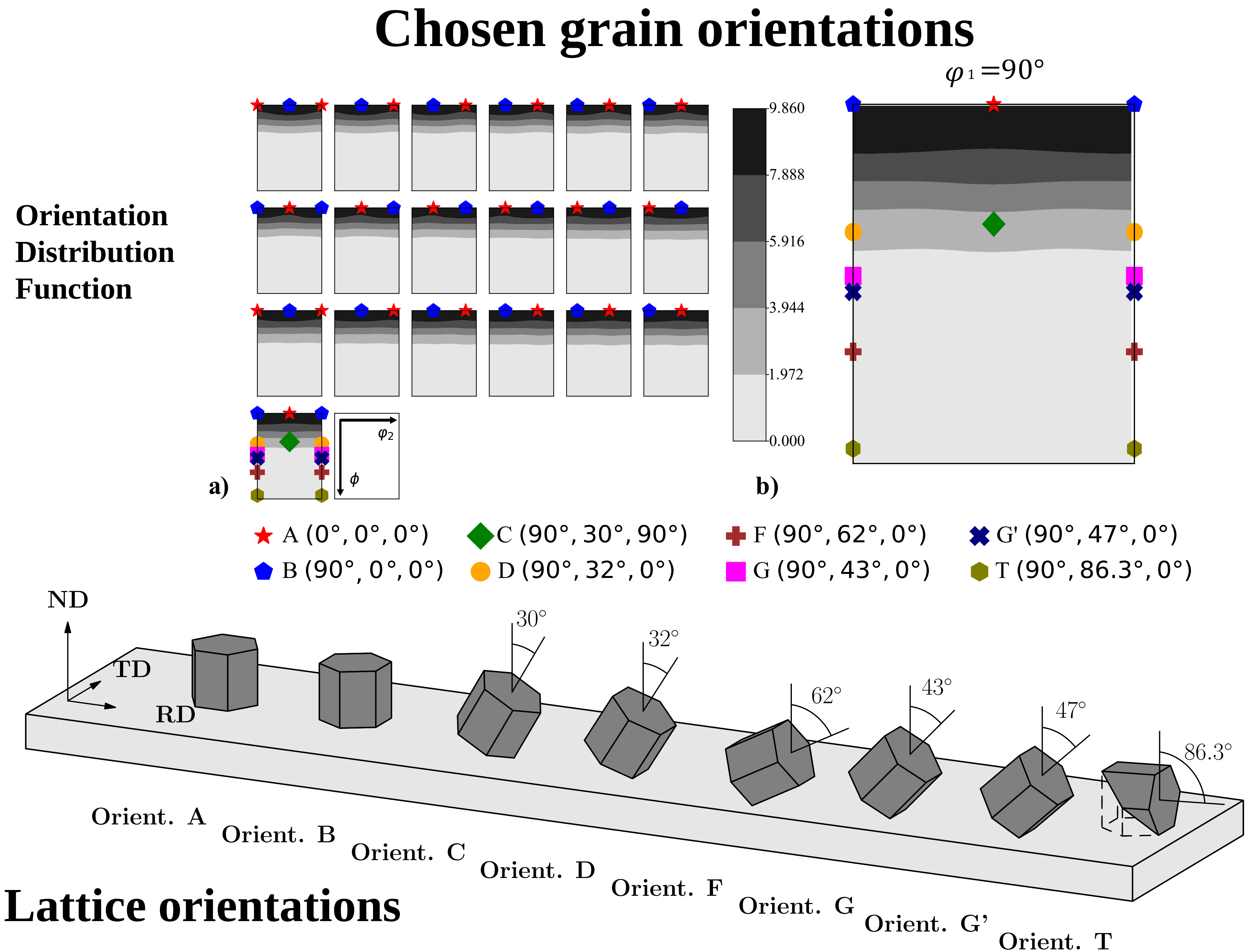
Crystallographic texture



Mg alloy (AZ31) – anisotropy

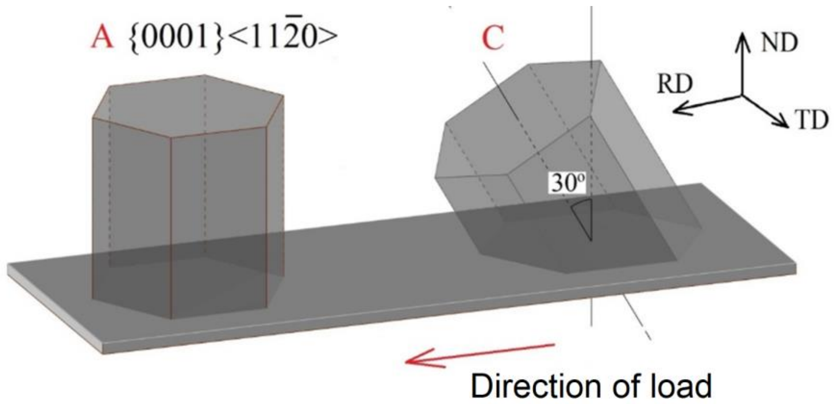


Crystallite Group Method



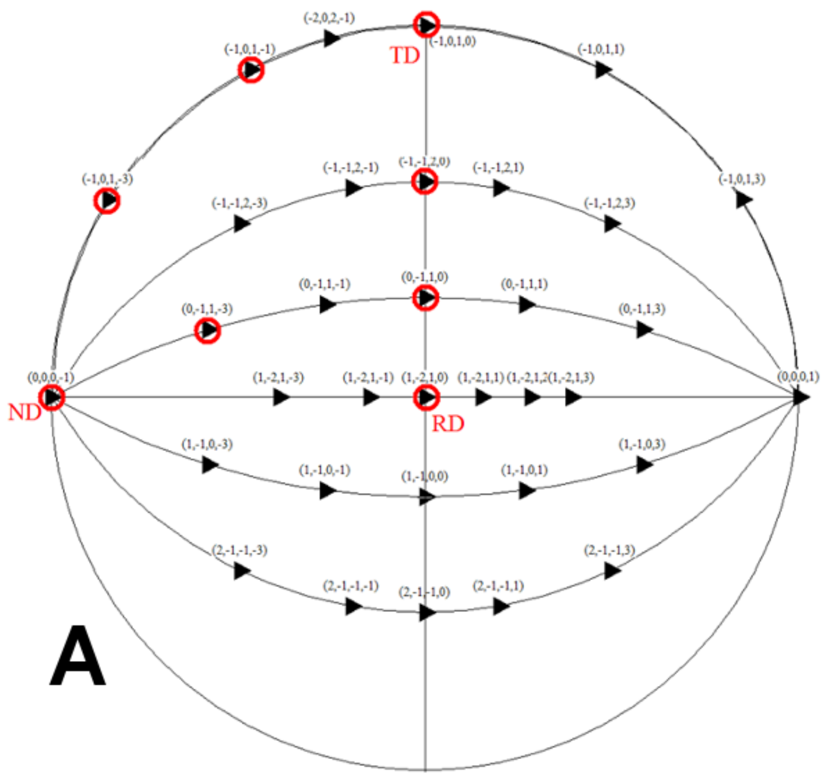
Chosen grain orientations
Orientation Distribution Function
φ_1=90°
9.860
7.888
5.916
3.944
1.972
0.000
φ_2
ϕ
a)
b)
A (0°, 0°, 0°)
B (90°, 0°, 0°)
C (90°, 30°, 90°)
D (90°, 32°, 0°)
F (90°, 62°, 0°)
G (90°, 43°, 0°)
G' (90°, 47°, 0°)
T (90°, 86.3°, 0°)
ND
TD
RD
30°
32°
62°
43°
47°
86.3°
Orient. A
Orient. B
Orient. C
Orient. D
Orient. F
Orient. G
Orient. G'
Orient. T
Lattice orientations

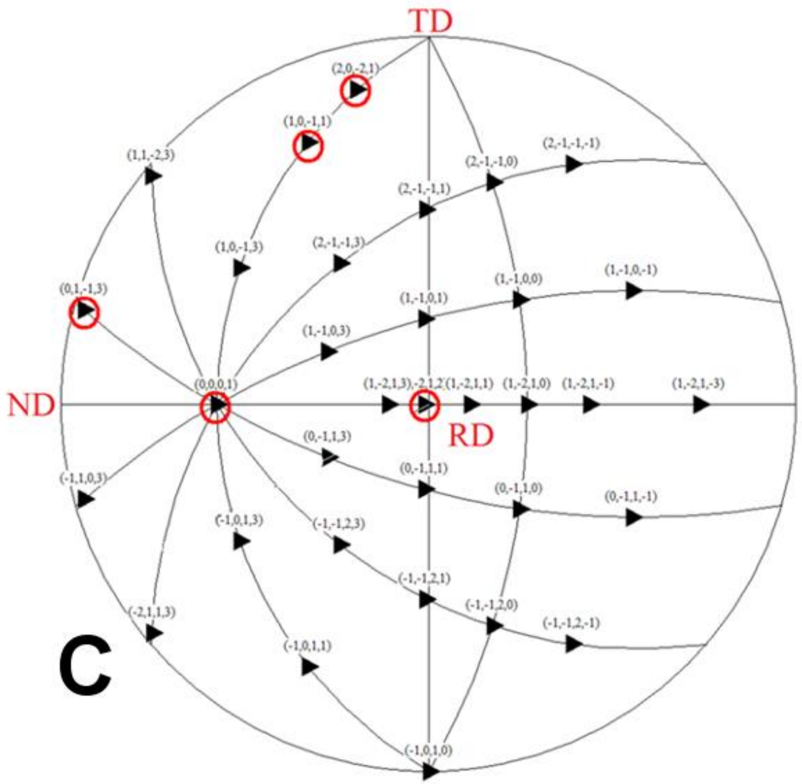
Crystallite group method



Least squares fitting

$$< \varepsilon\,(\psi,\varphi) >_{\{hkl\}} = < \gamma_{3i}\gamma_{3j} s^{g}_{33ij} >_{\{hkl\}} \sigma^{g}_{ij}$$

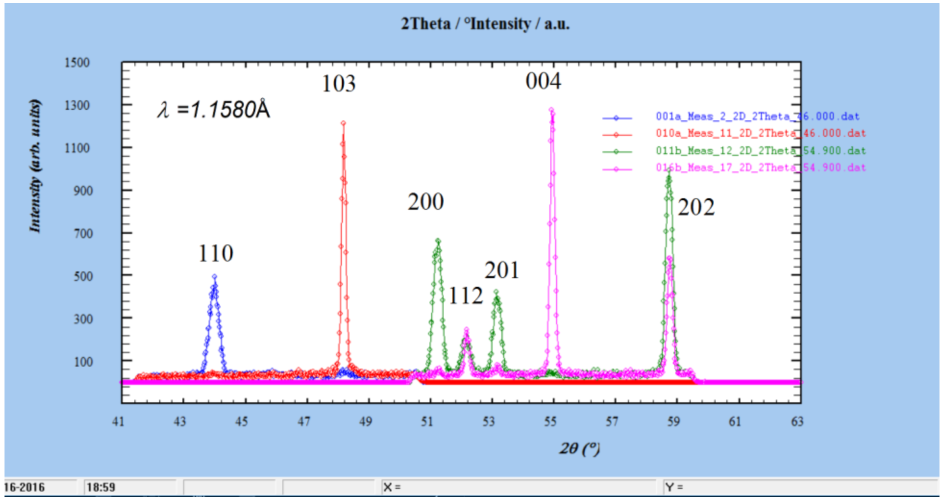




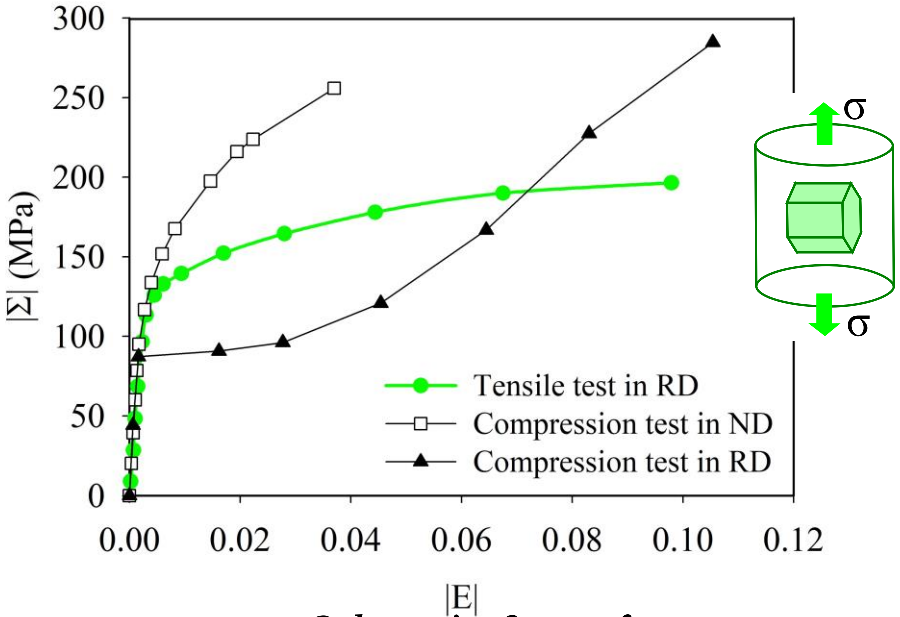
Monotonic load experiments for Mg alloy

Experiment at HK9, NPI, Řež/Prague
tensile in RD (RDT)

Monochromatic wavelength: λ=1.158 Å

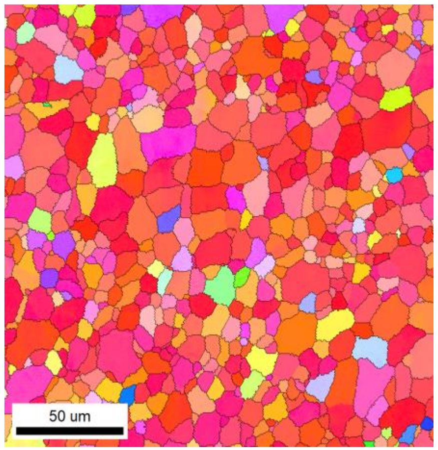


$$2d_{hkl}\sin\theta = n\lambda$$



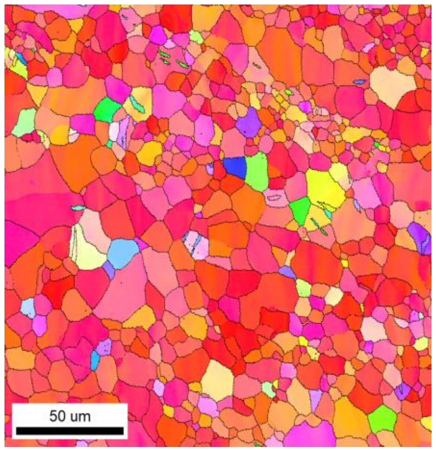
$$2d_{hkl}\sin\theta = n\lambda$$

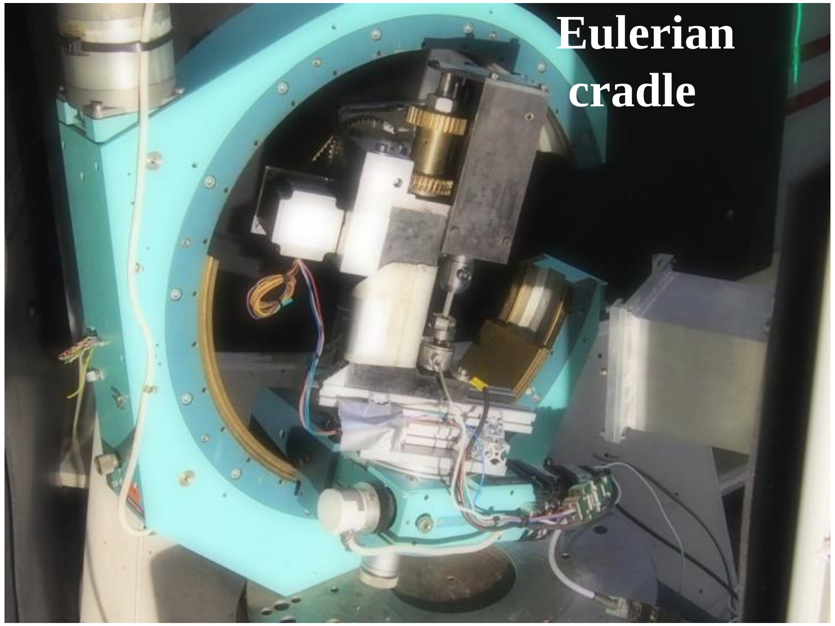
Initial state



RDT

ε = 2%

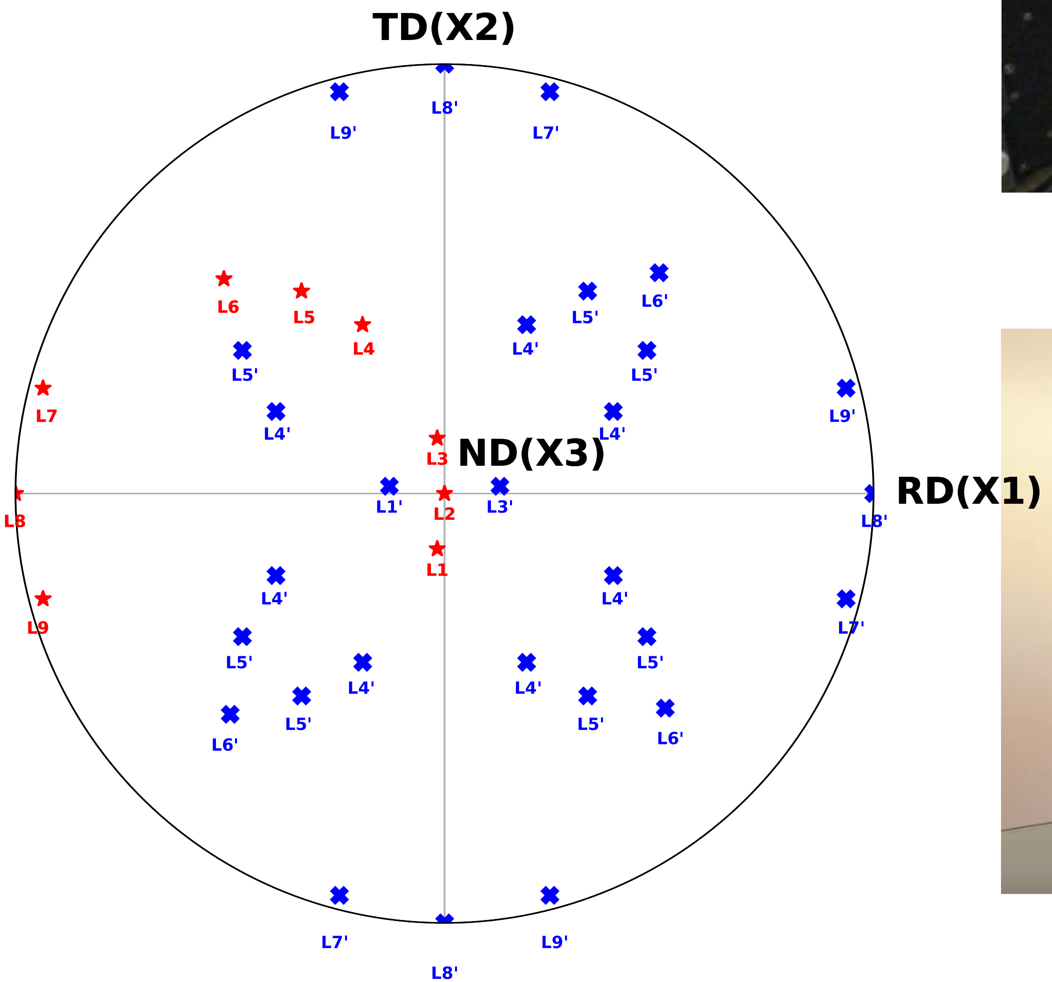


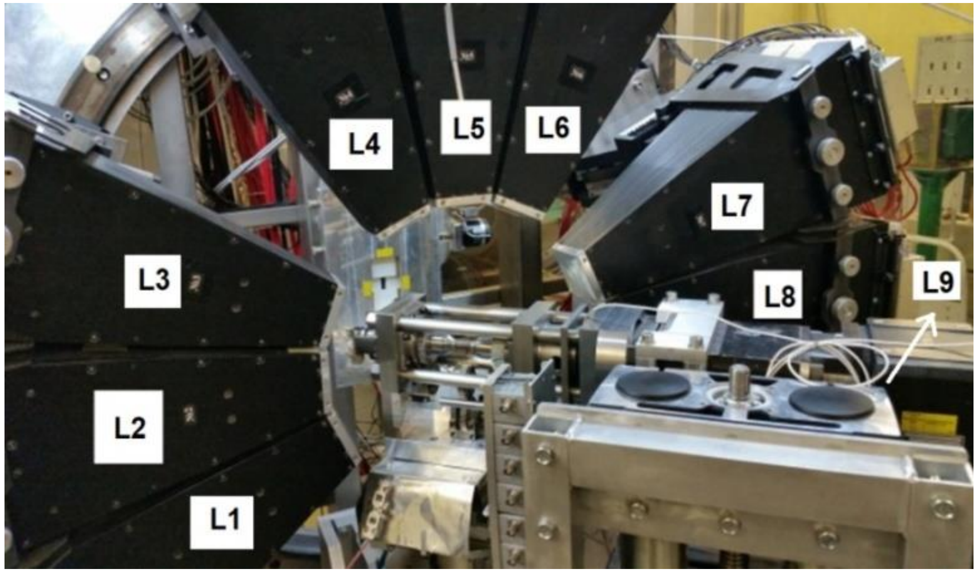


TOF diffraction in JINR Dubna, Russia (NDC and RDC)

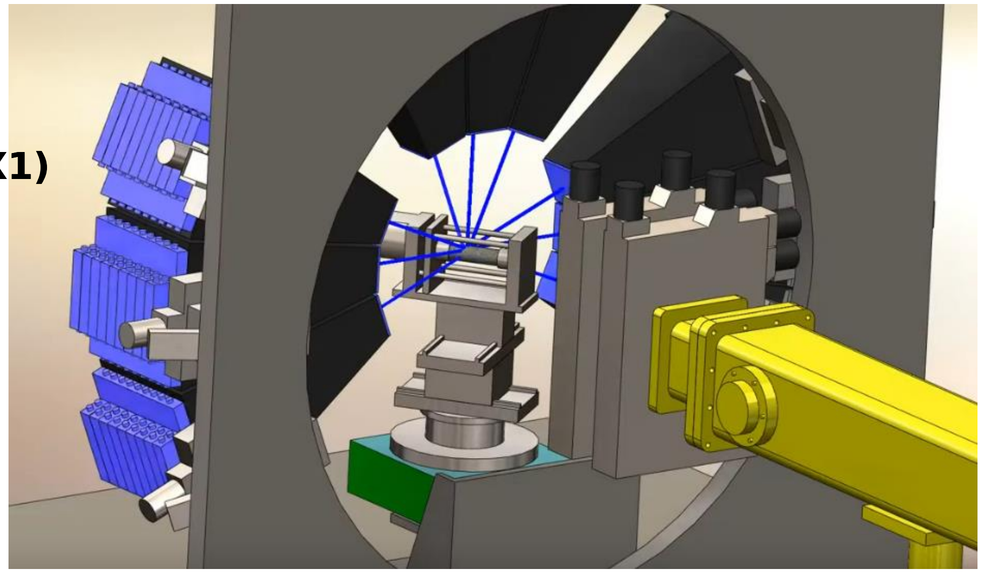
Time of Flight: $$d_{hkl} = \frac{hT}{2mL\sin\theta}$$

$$2\theta = 90°$$





EPSILON - MDS diffractometer



Orient. D

TOF diffraction in JINR Dubna, Russia (NDC and RDC)

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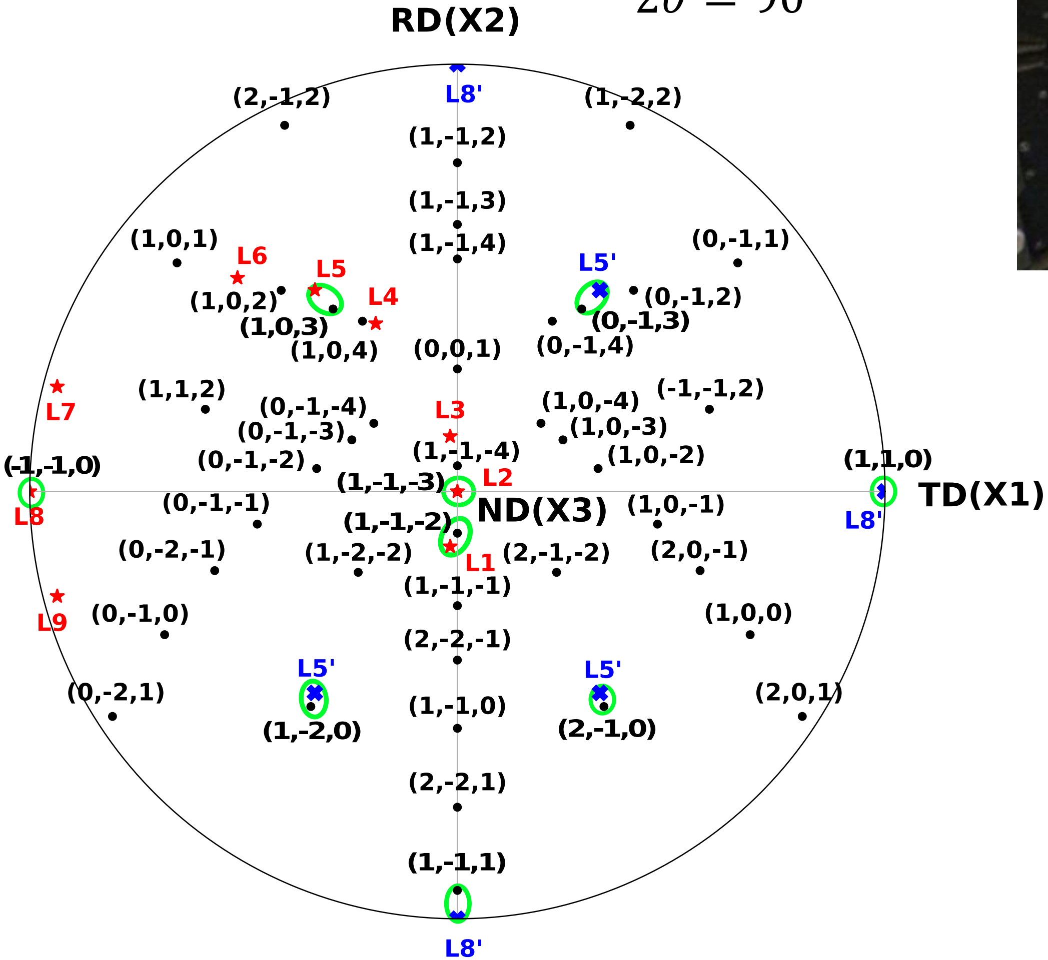
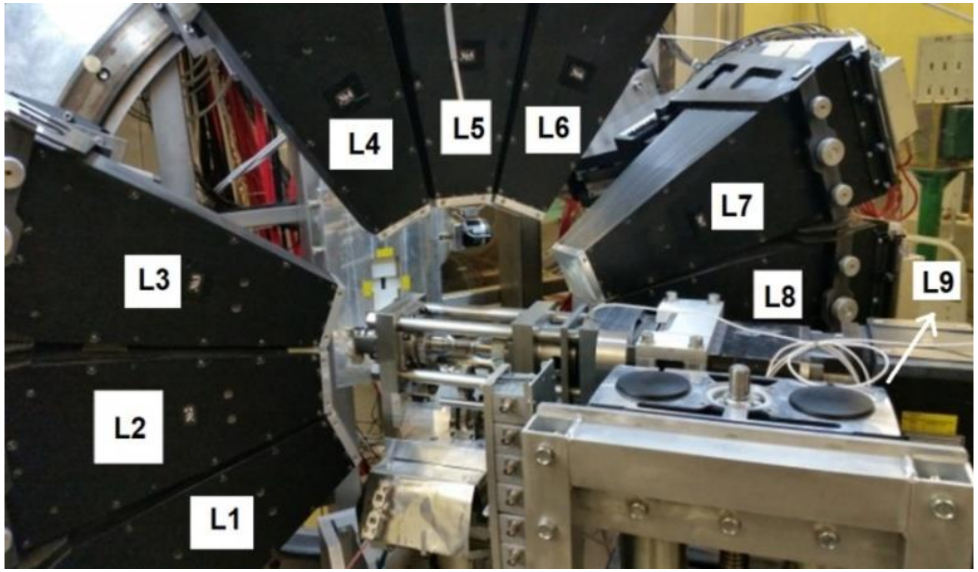
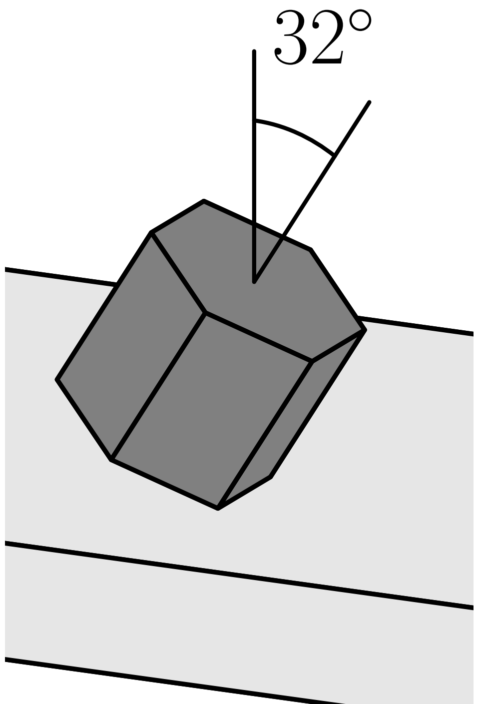
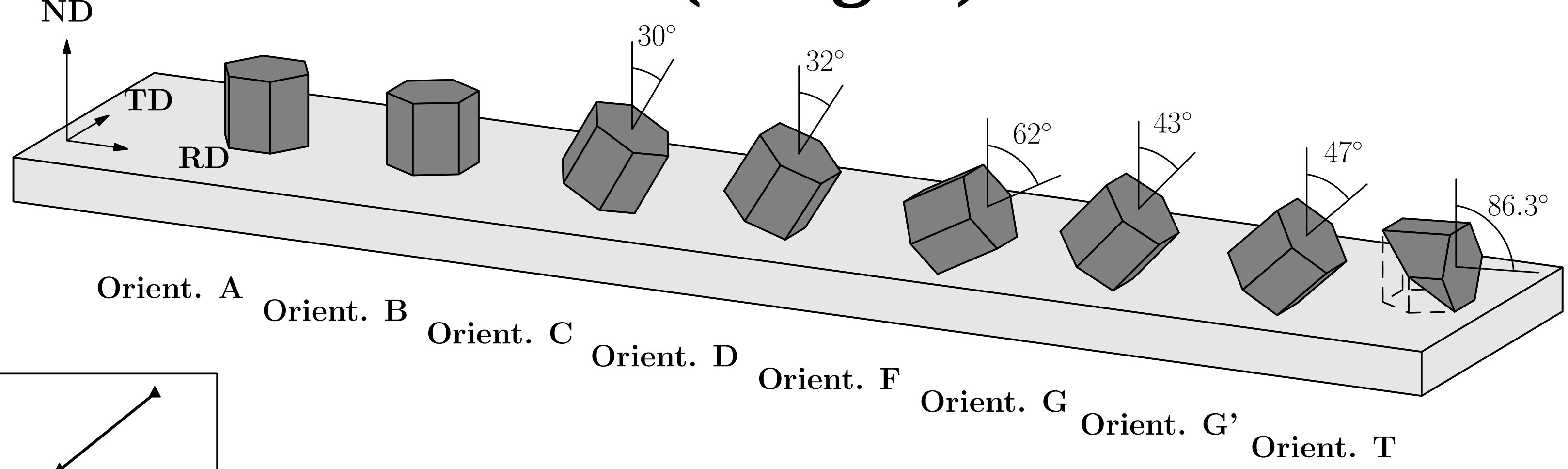


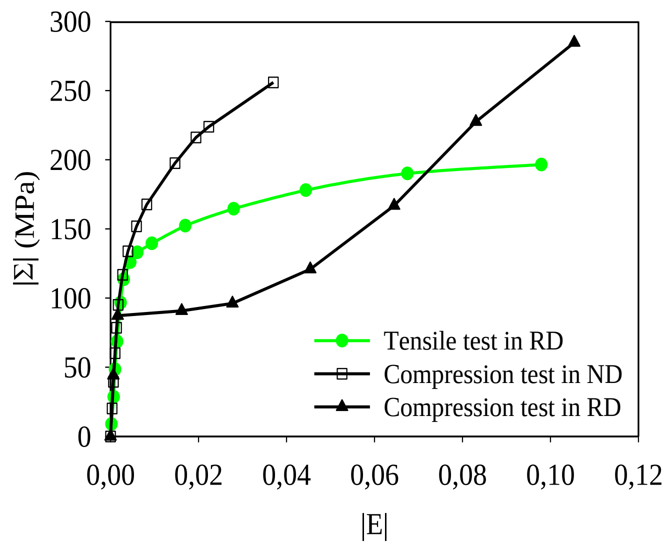


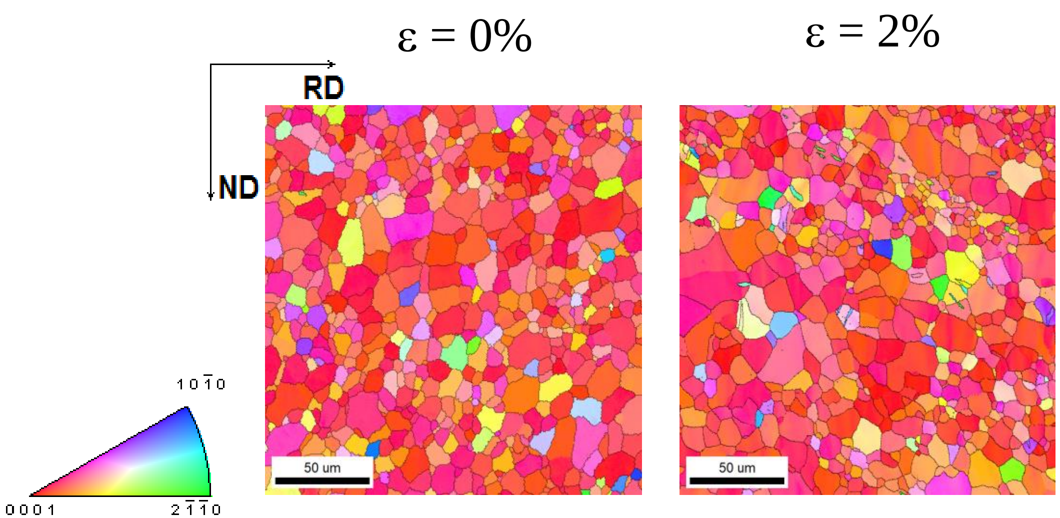


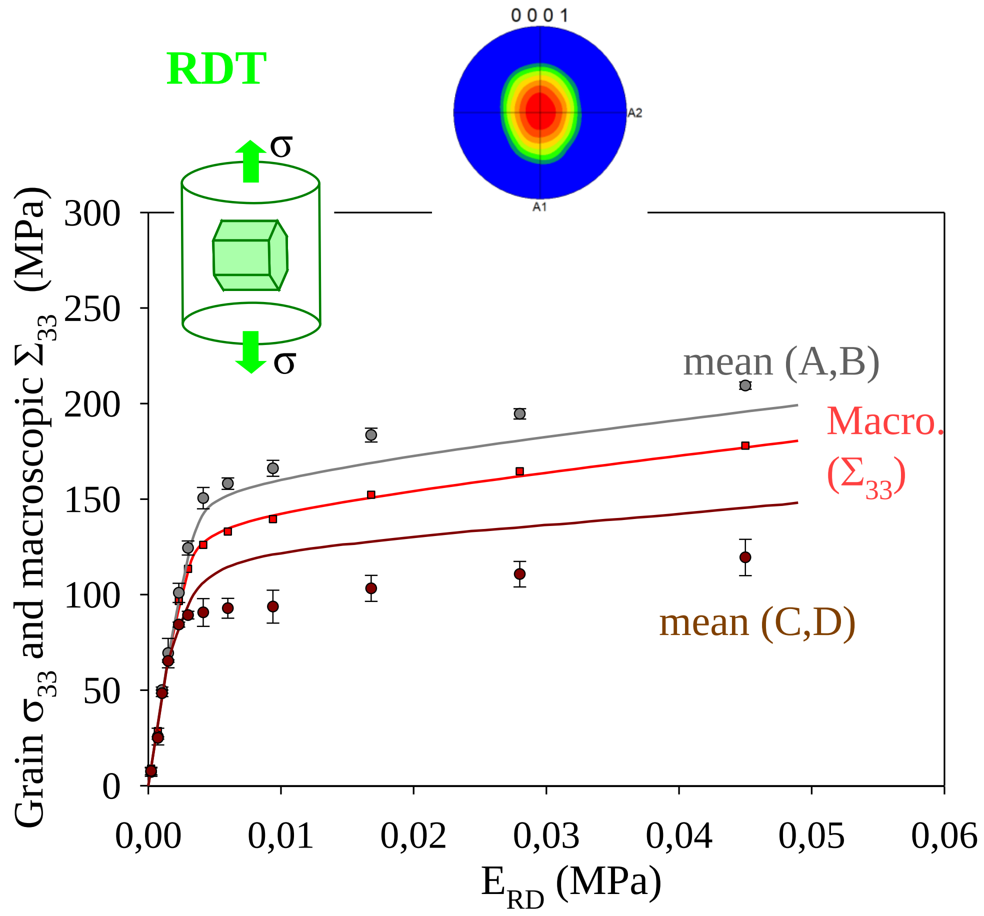
Orient. D

Stress localisation (Prague)

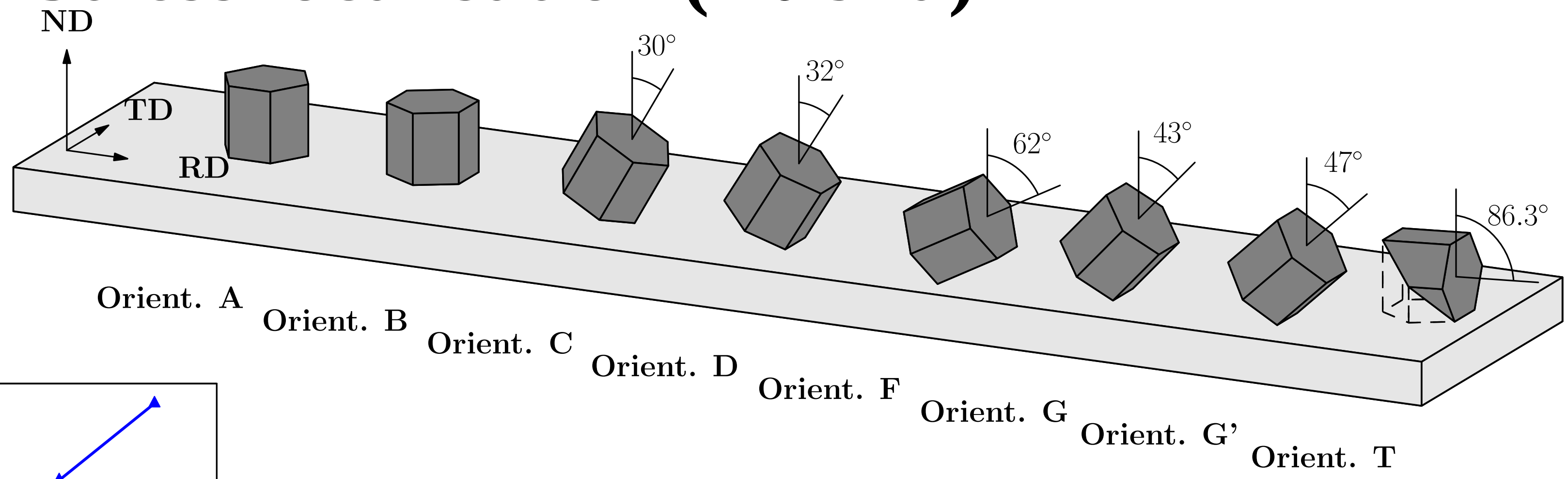


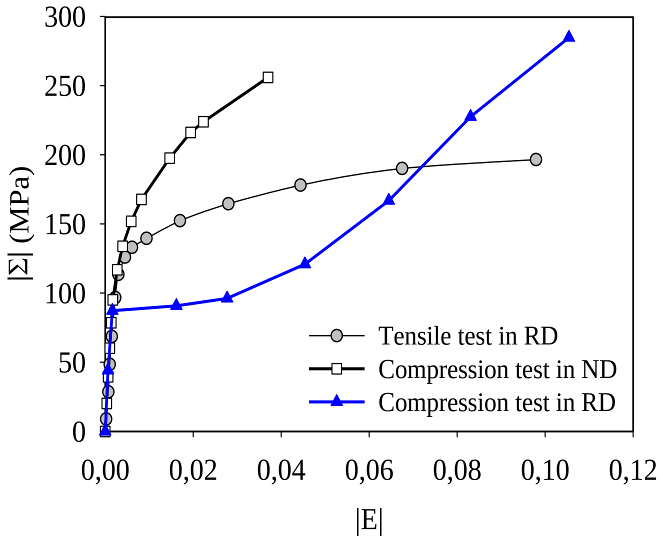


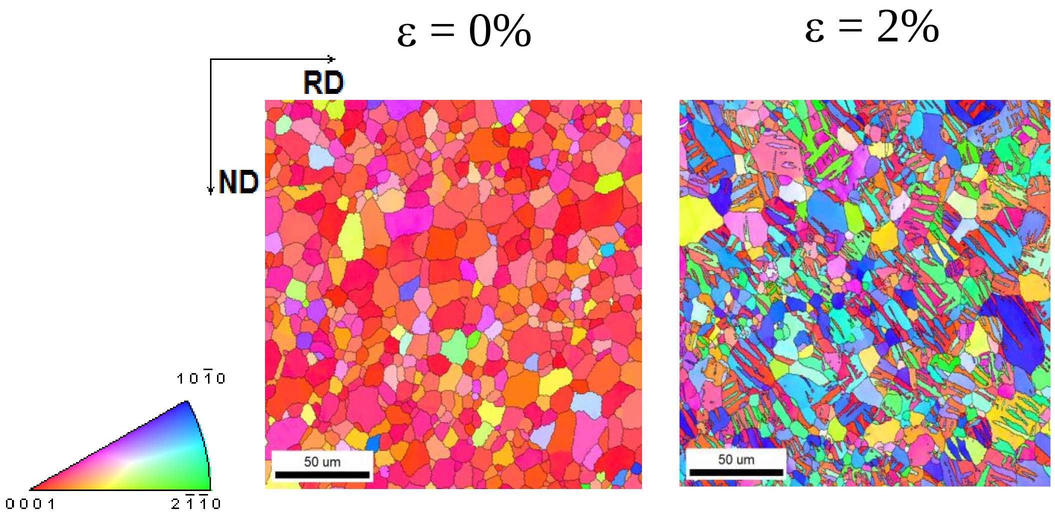


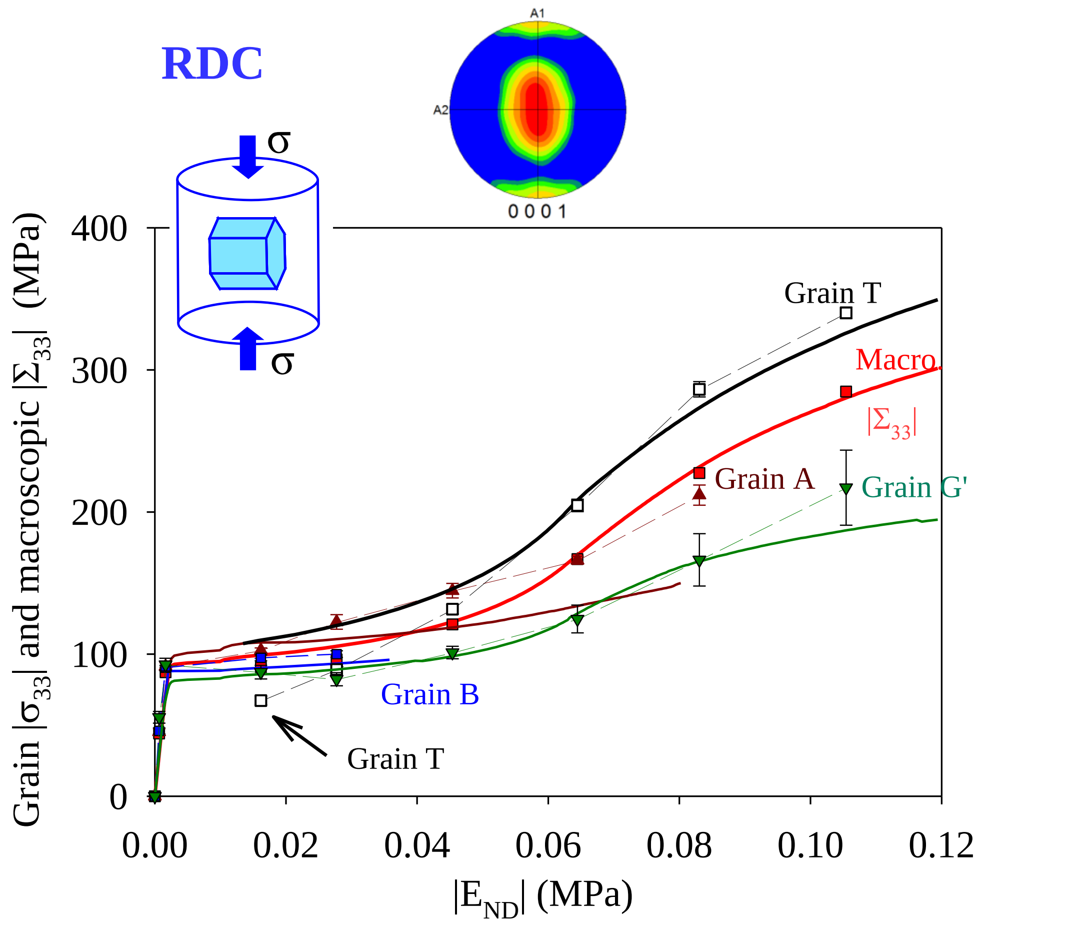


Stress localisation (Dubna)



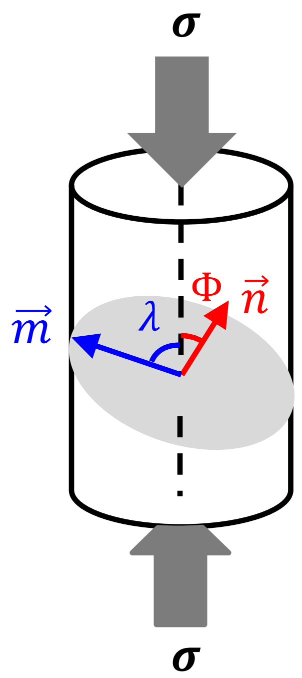






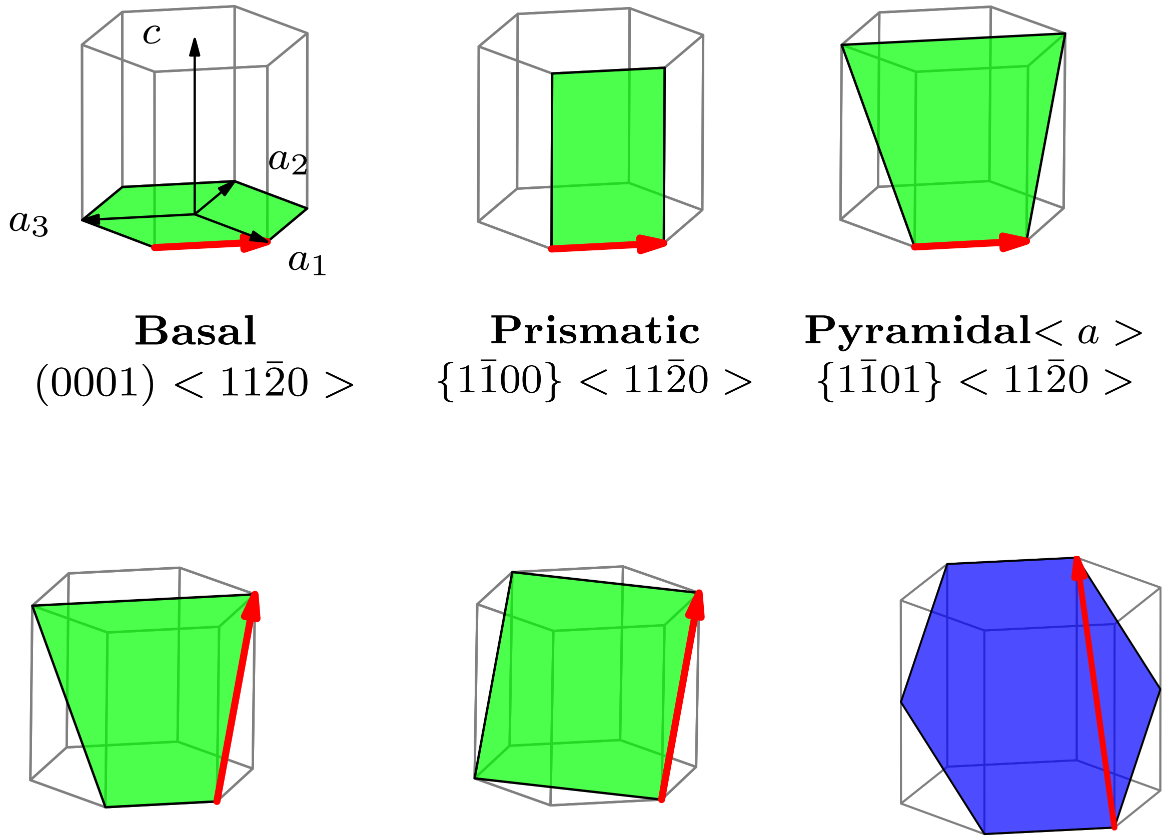
Plastic deformation mechanisms in Mg alloy

Resolved shear stress in Mg AZ31 alloy



Resolved shear stress (RSS):

$$\tau = \vec{n}\,\boldsymbol{\sigma}\,\vec{m}$$



Basal $(0001) < 11\bar{2}0 >$

Prismatic $\{1\bar{1}00\} < 11\bar{2}0 >$

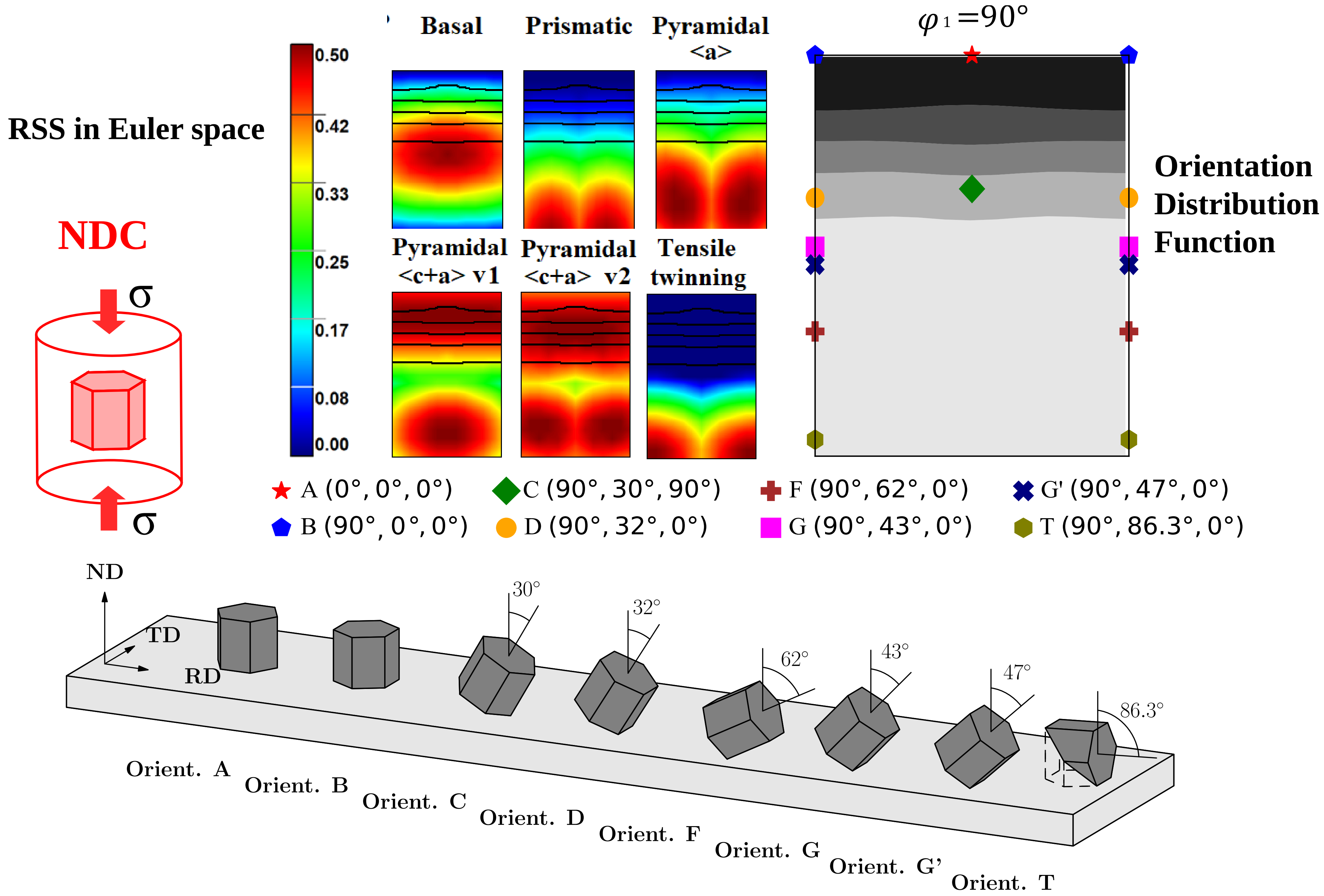
Pyramidal $< a >$ $\{1\bar{1}01\} < 11\bar{2}0 >$

First order pyramidal $< c + a >$ $\{1\bar{1}01\} < \bar{1}2\bar{1}3 >$

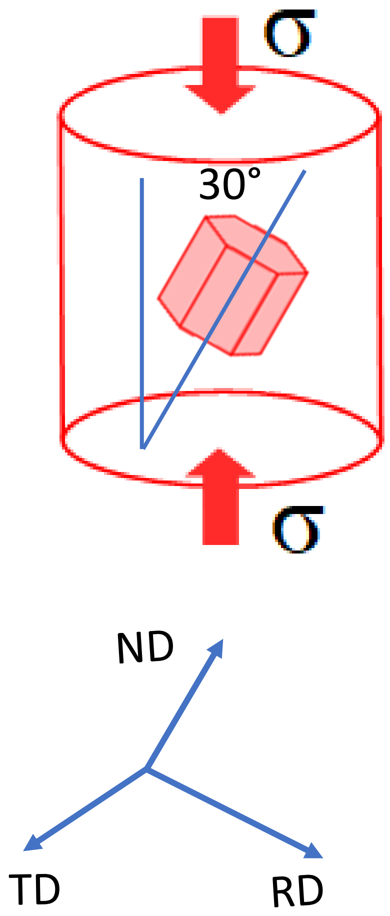
Second order pyramidal $< c + a >$ $\{1\bar{2}12\} < \bar{1}2\bar{1}3 >$

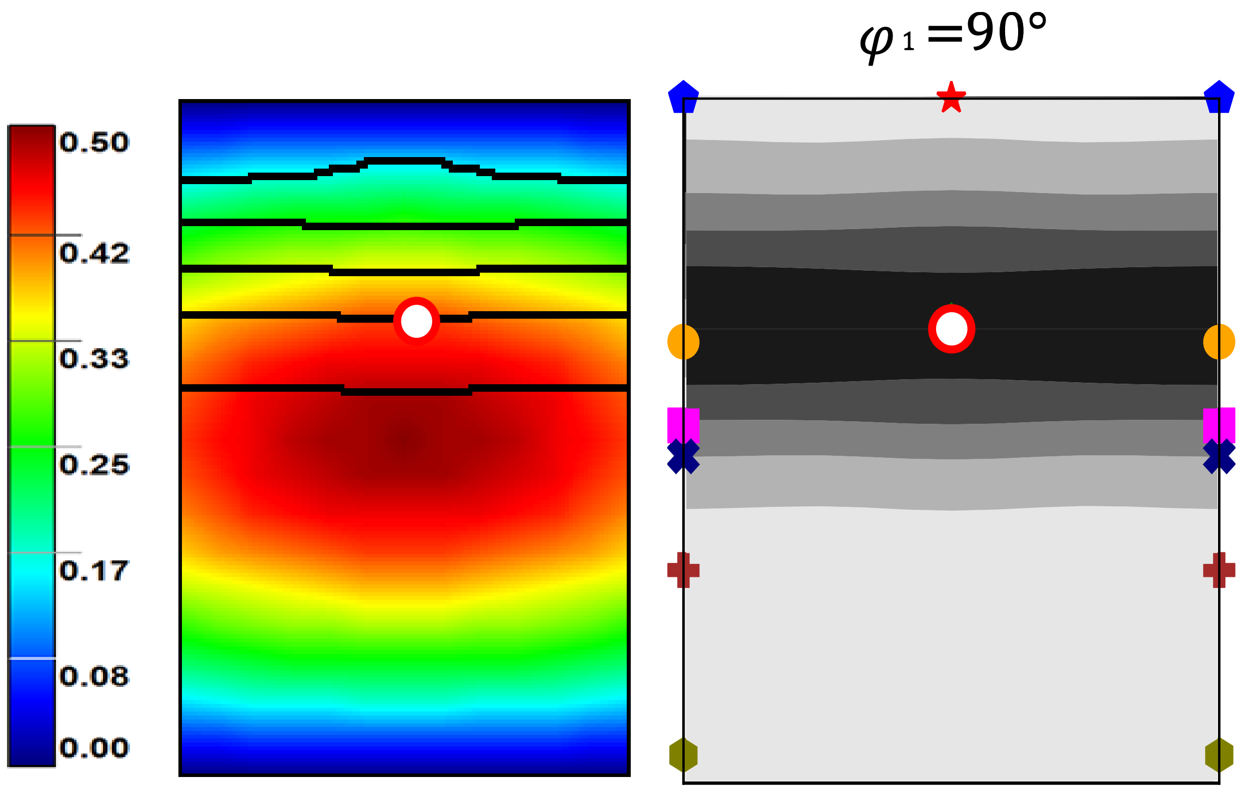
First order tensile twin $\{10\bar{1}2\} < \bar{1}011 >$

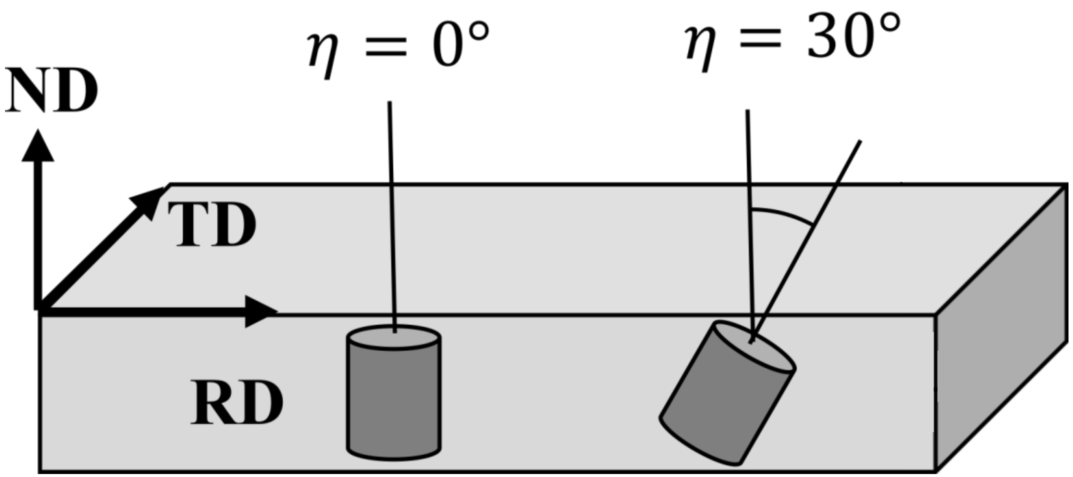
Resolved shear stress in Mg AZ31 alloy



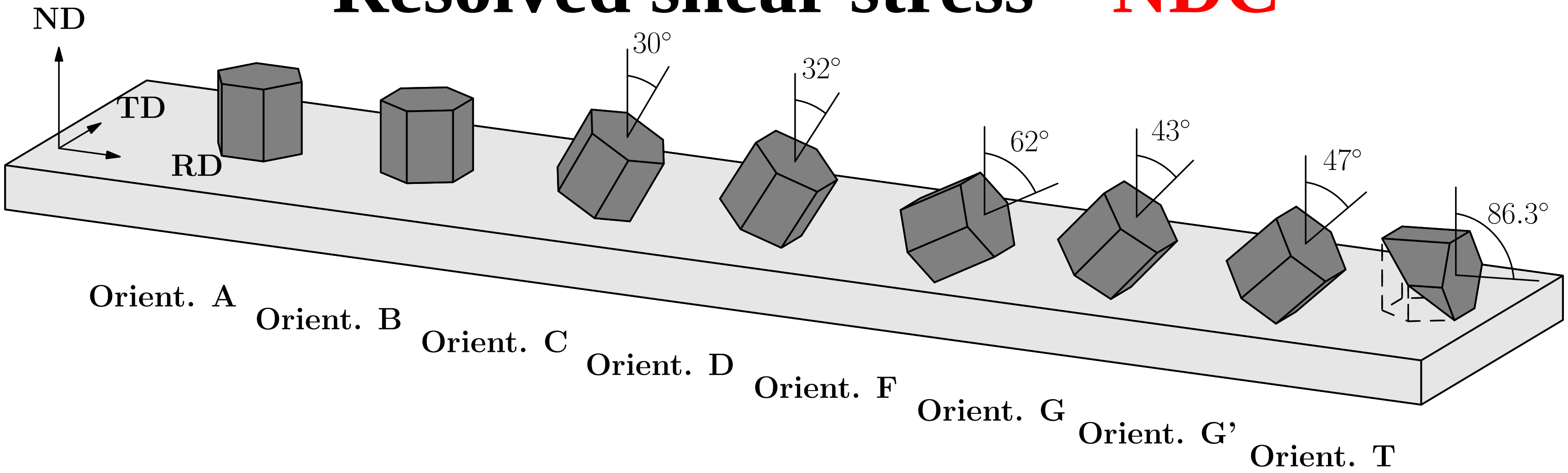
Basal confirmation (Mg30)

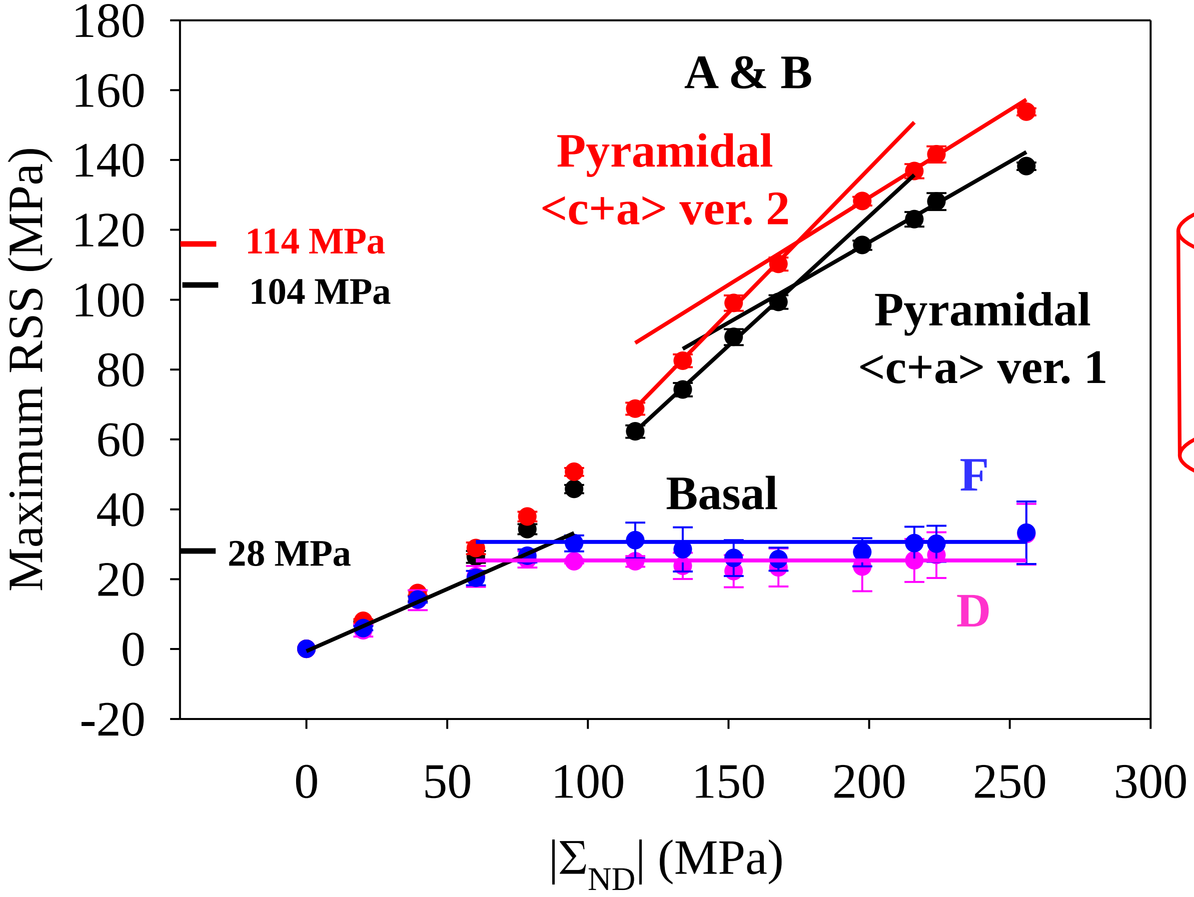


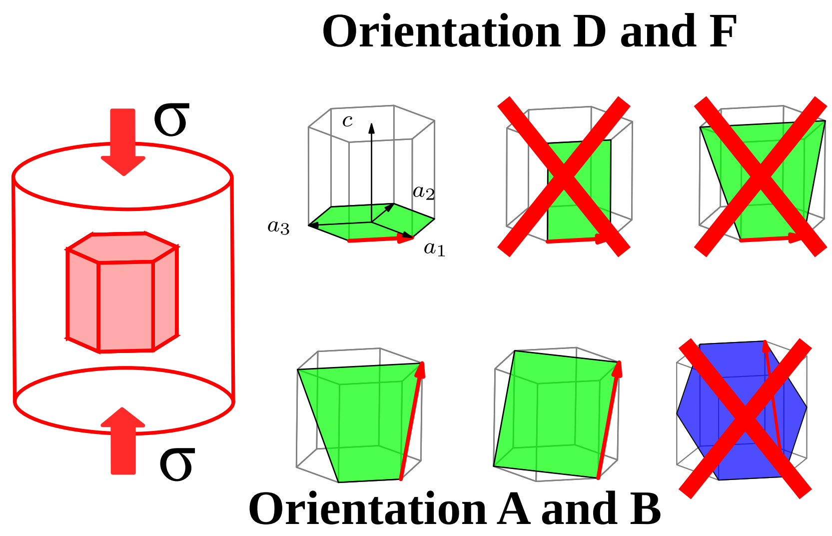




Resolved shear stress – NDC







CRSS:

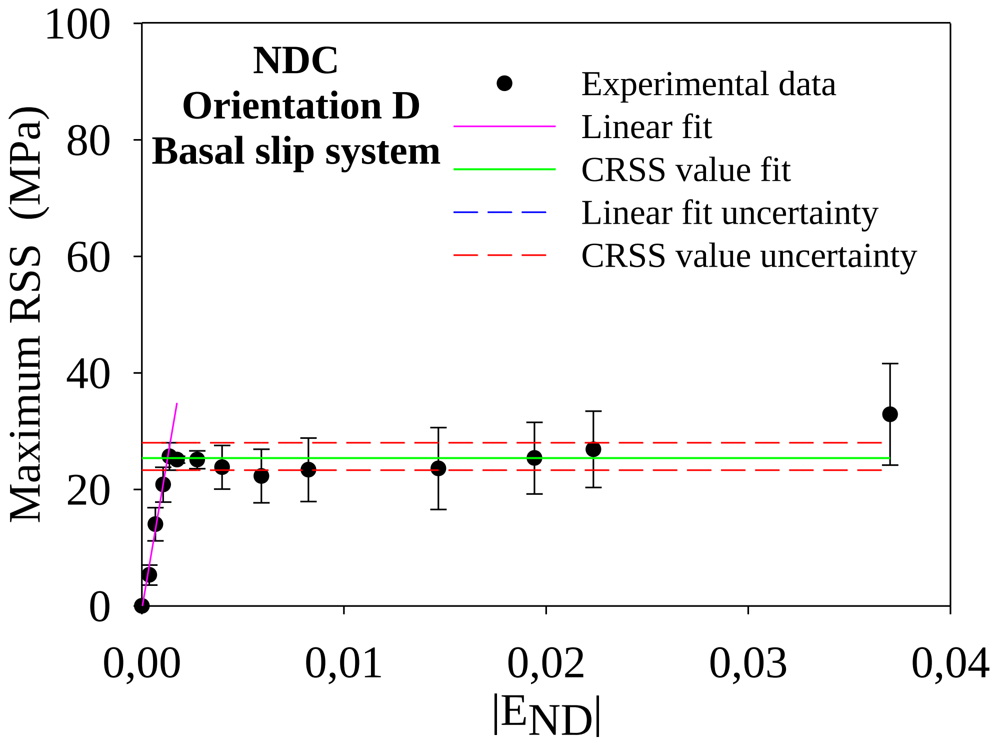
Pyramidal <c+a> v1 104 MPa

Pyramidal <c+a> v2 114 MPa

Basal 28 MPa

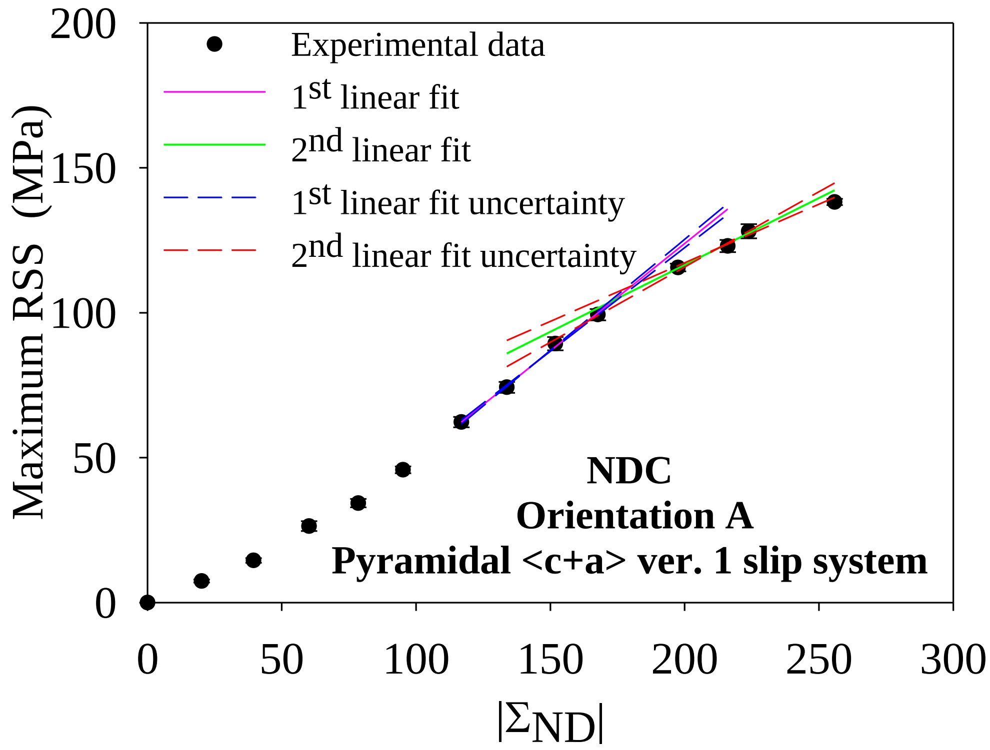
CRSS uncertainty

Linear + constant



Uncertainty based on points uncertainty

Linear + linear



Uncertainty based on linear regression

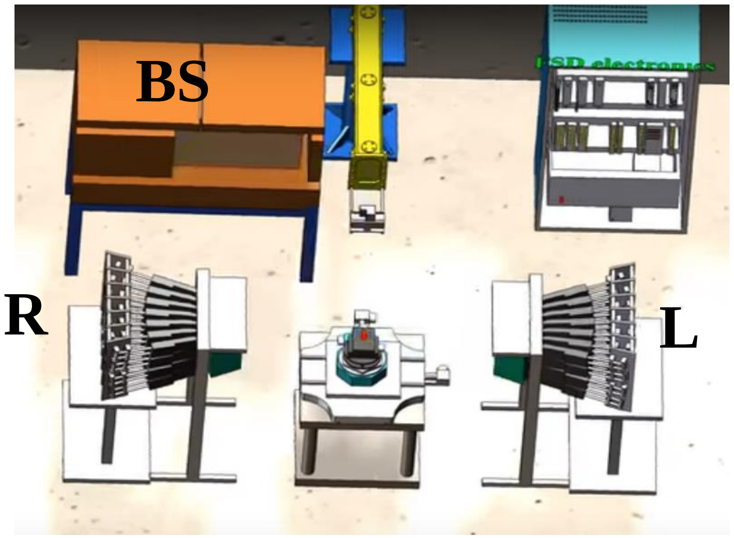
CRSS from experiments comparison

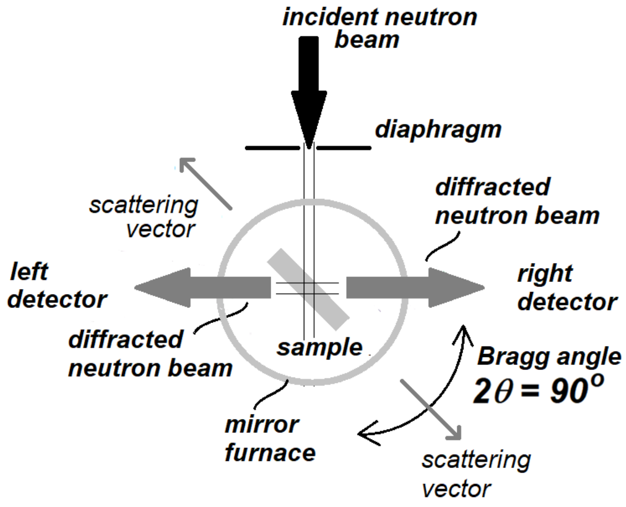
Slip systems	Miller-Bravais indices	τ_0 (MPa)		
		Rez RDT	Dubna NDC, RDC	Rez NDC, RDC, Mg30
Basal <a>	$\{0001\}\langle 11\bar{2}0\rangle$	35	28.0 (3.1)	24.0(3.0)
Prismatic <a>	$\{1\bar{1}00\}\langle 11\bar{2}0\rangle$	>62	67.7 (7.9)	-----
Pyramidal <a>	$\{1\bar{1}01\}\langle 11\bar{2}0\rangle$	>62	59.7 (6.9)	-----
Pyramidal <c+a> v1	$\{\bar{1}011\}\langle 11\bar{2}3\rangle$		104.4 (5.6)	117(10)
Pyramidal <c+a> v1 (in twin)			130 (108 – 145)	120.5(8.2)
Pyramidal <c+a> v2	$\{11\bar{2}\bar{2}\}\langle 11\bar{2}3\rangle$		116.6 (3.5)	130(12)
Pyramidal <c+a> v2 (In twin)			144 (120 – 161)	134.3(9.1)
Twinning	$\{10\bar{1}2\}\langle\bar{1}011\rangle$		49.1 (2.5)	45.5(1.6)

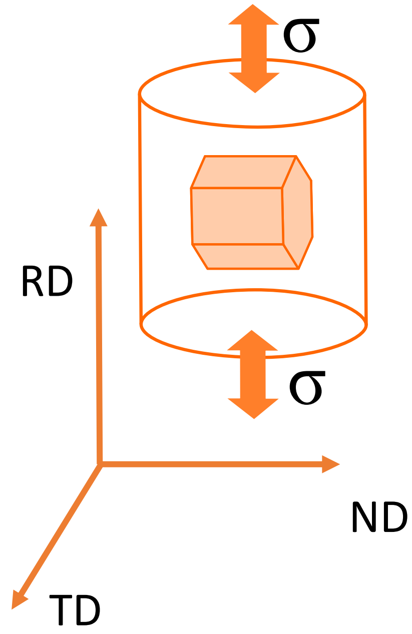
Cycling load

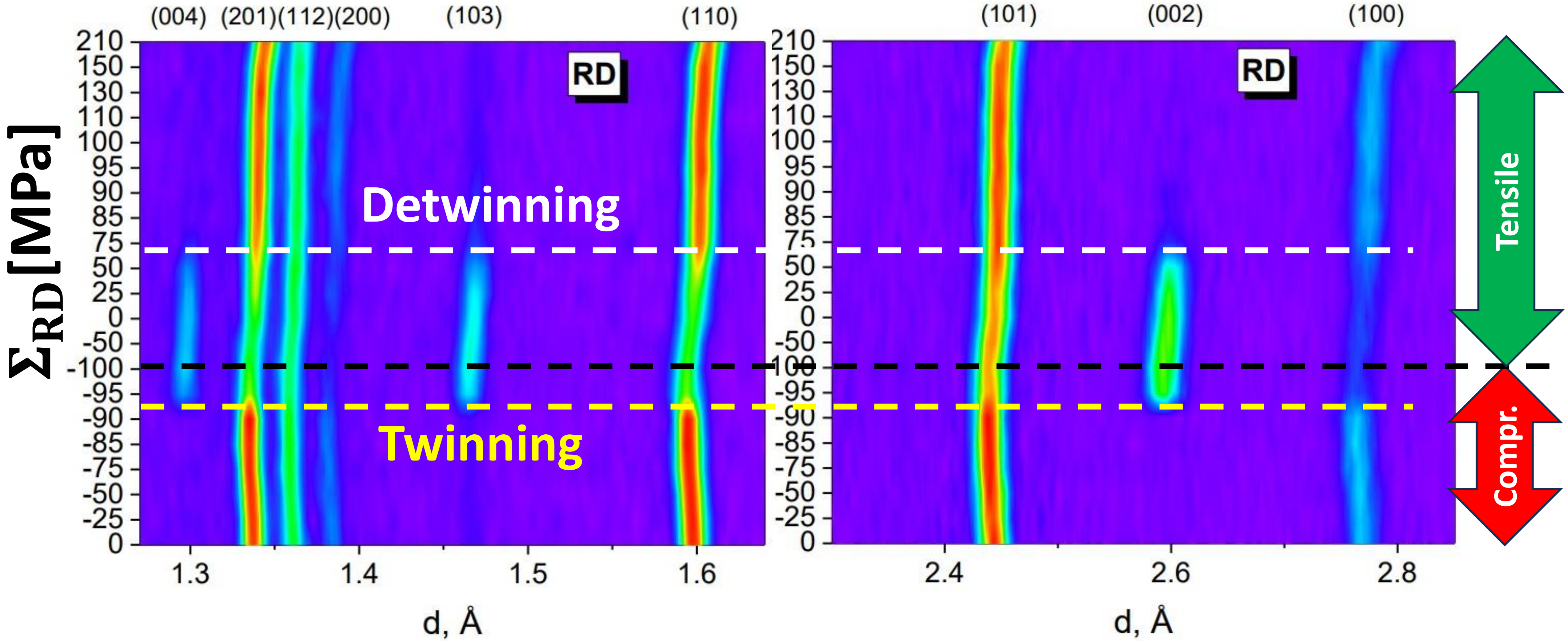
twinning and detwinning

Cycling load at FSD, Dubna

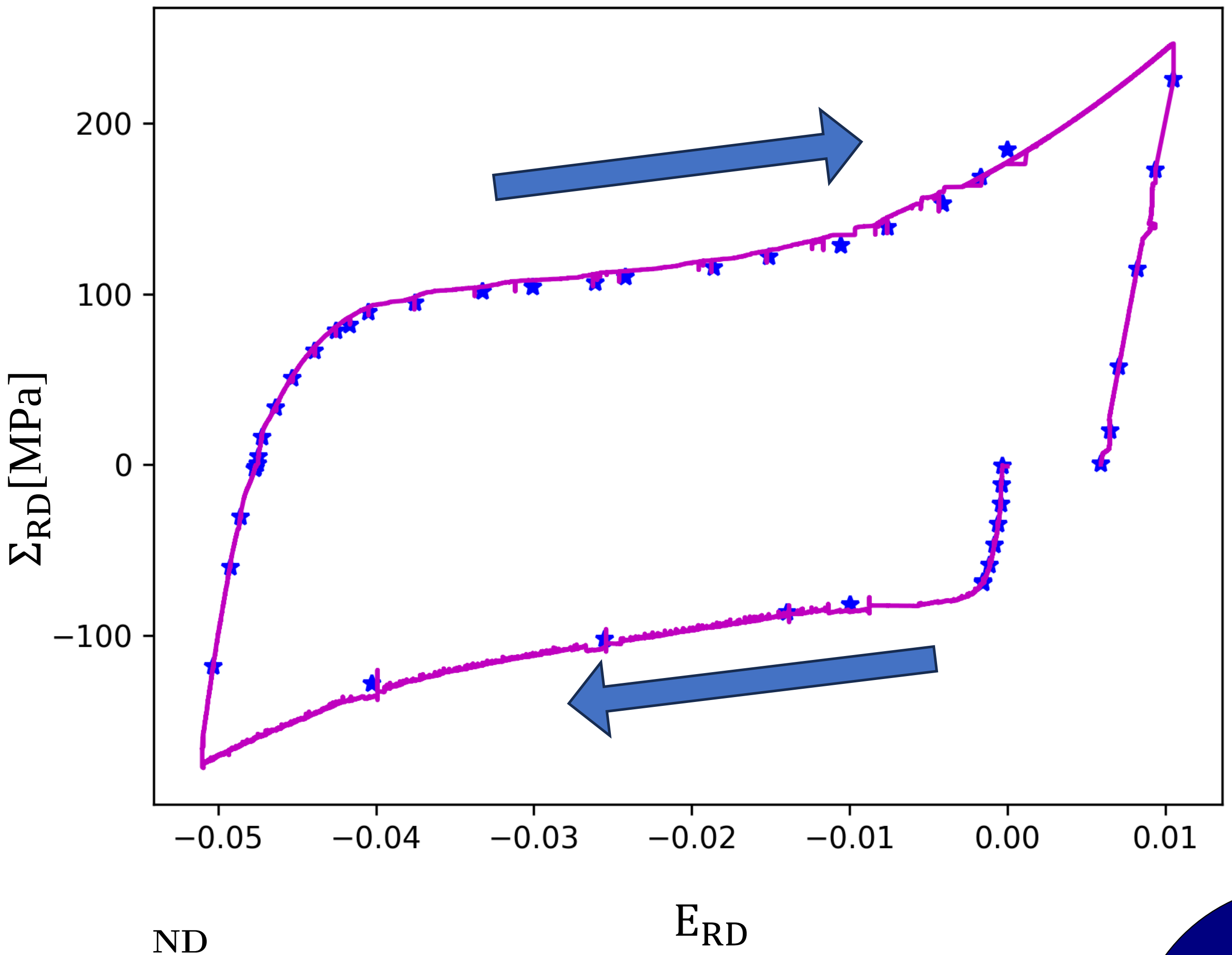


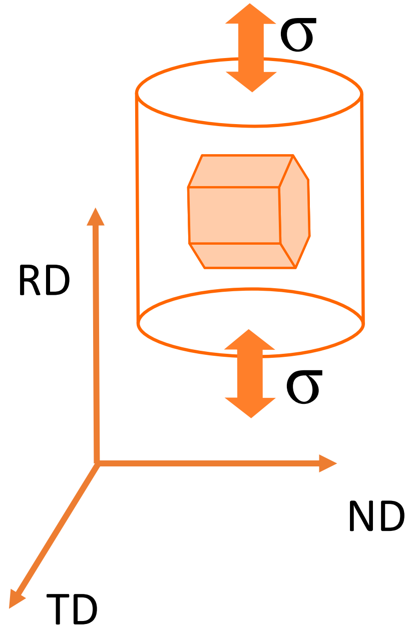


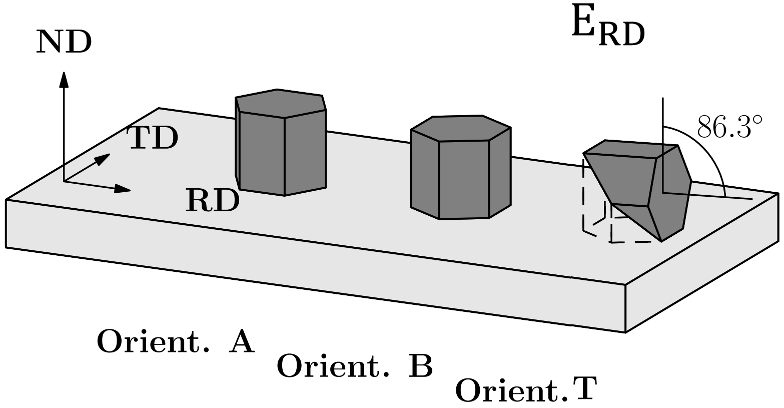




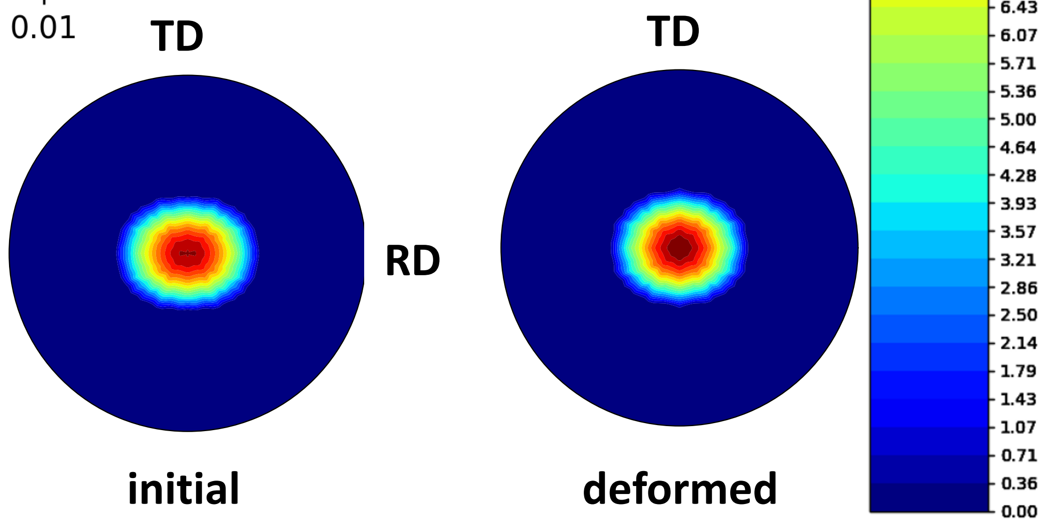
Cycling load at HK9, NPI, Řež/Prague





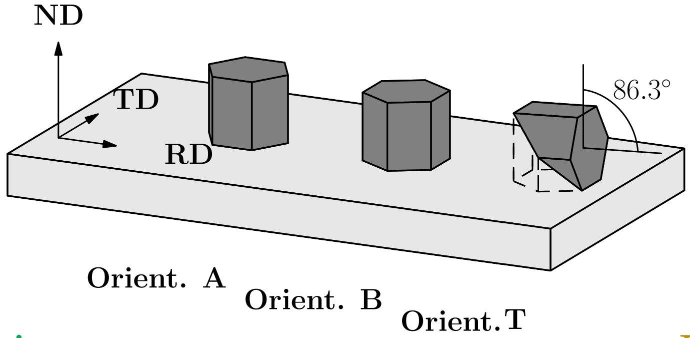


00.2 texture

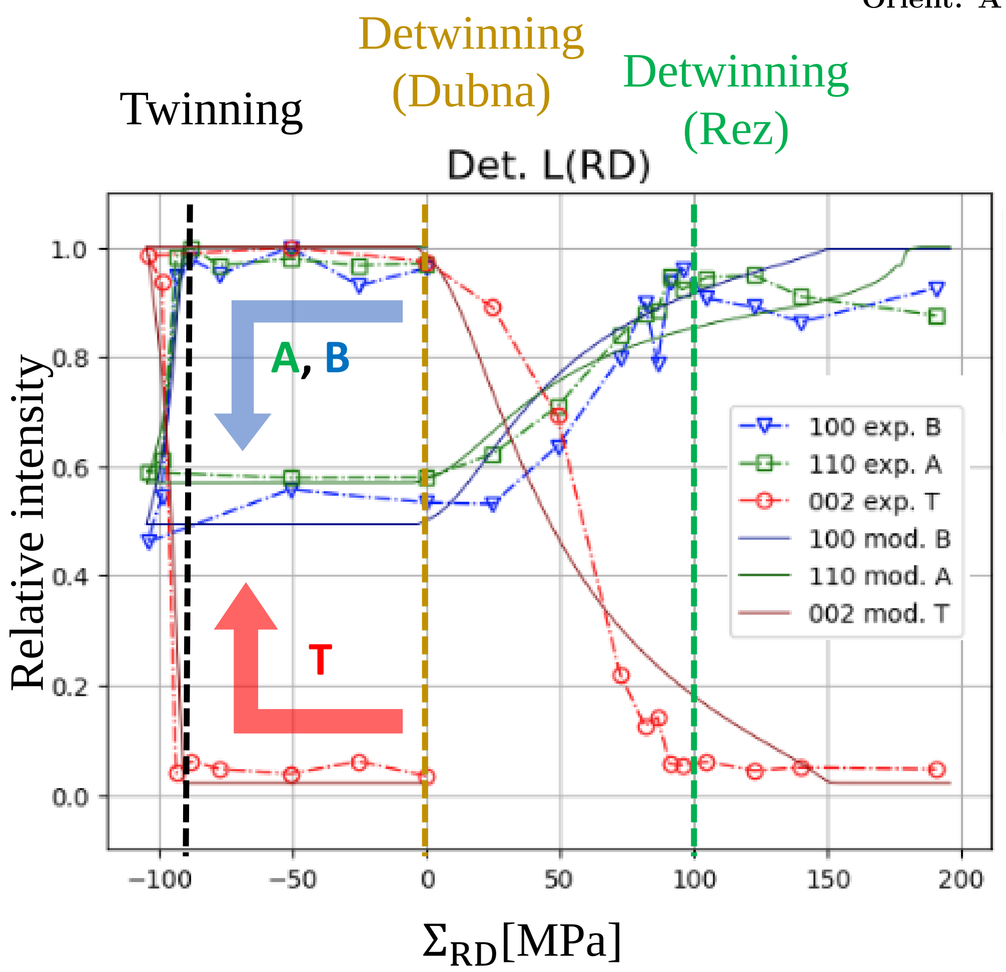


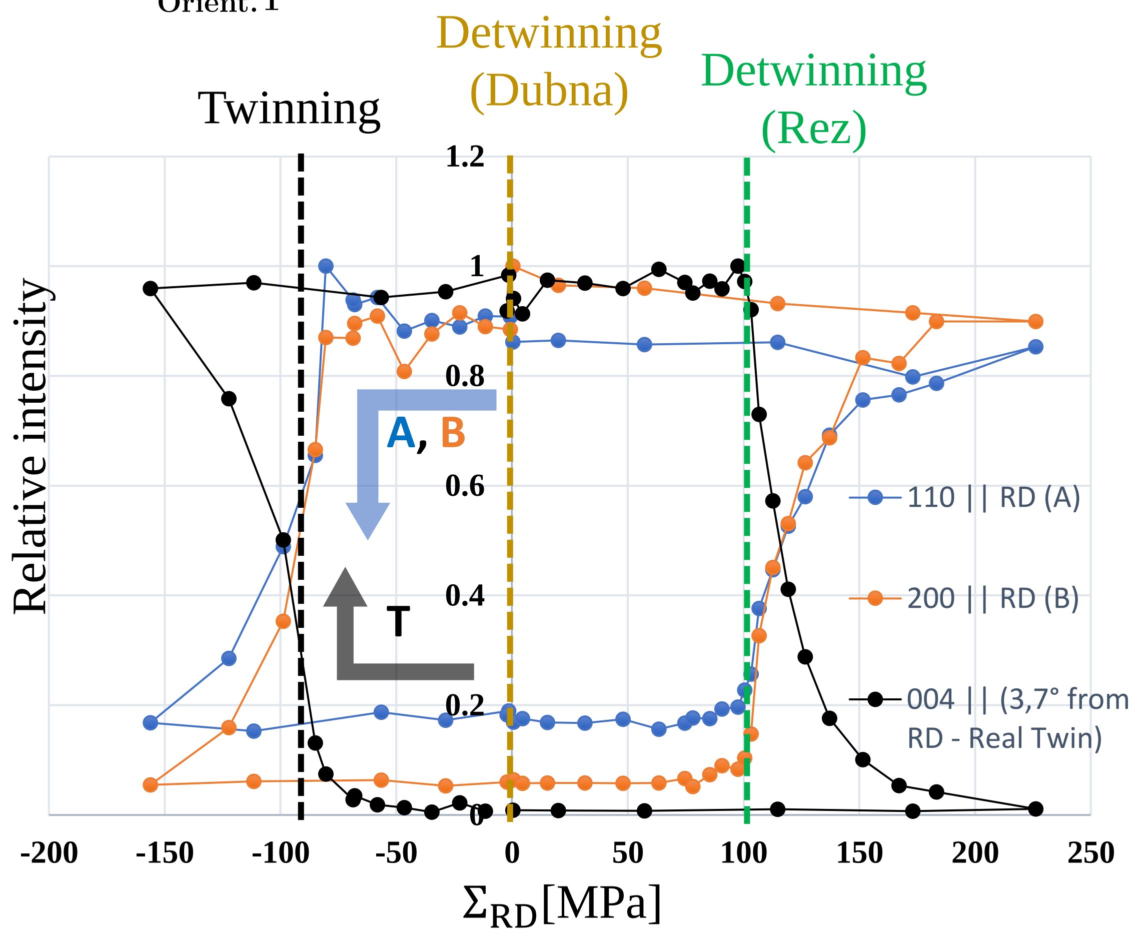
Twinning and detwinning during cycle loading

Dubna

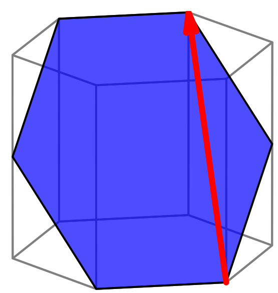


Řež/Prague

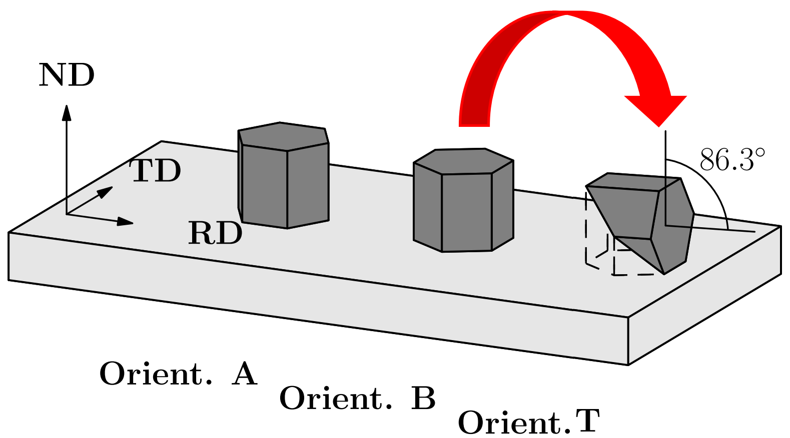


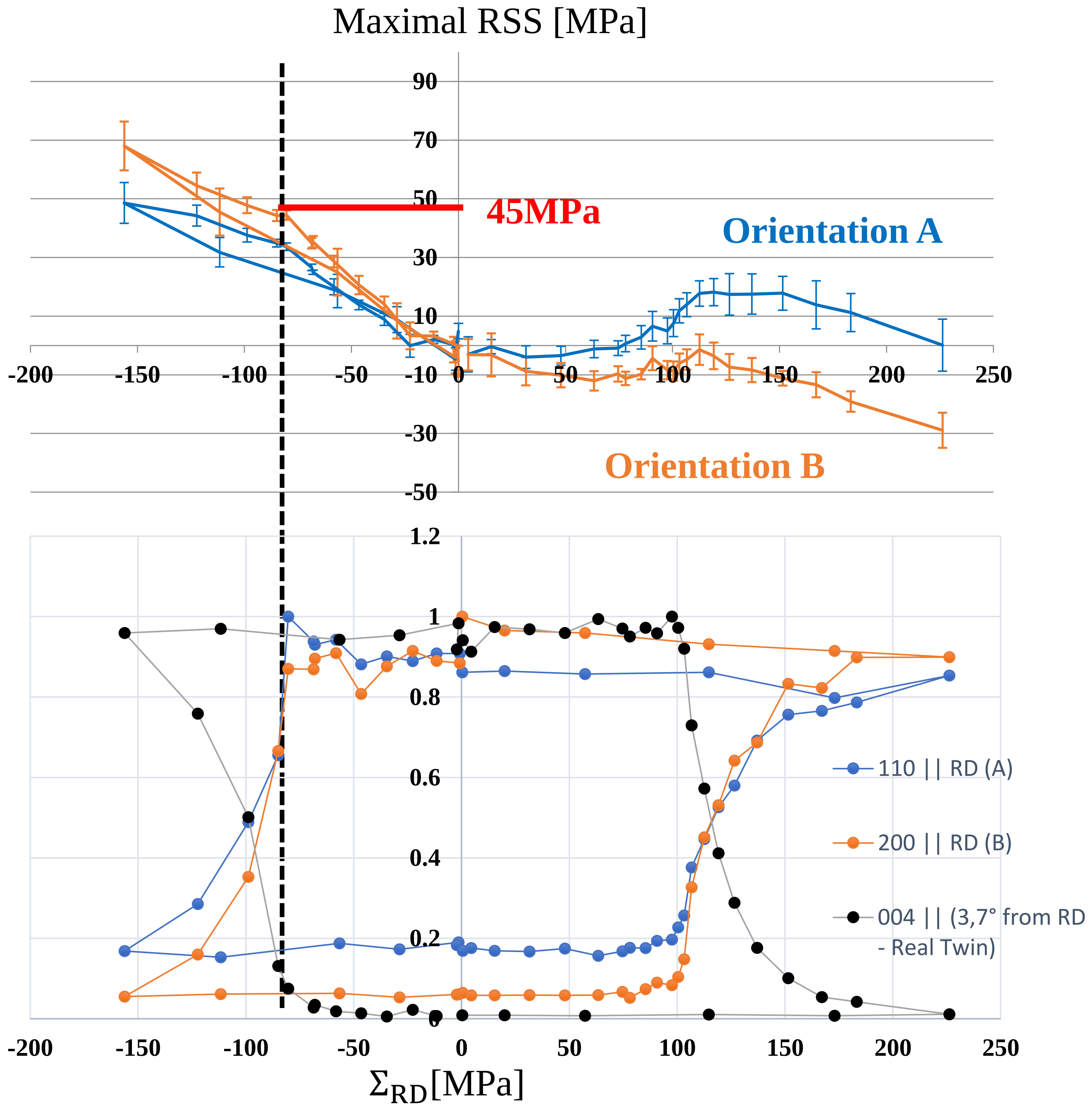


Twinning during compression phase

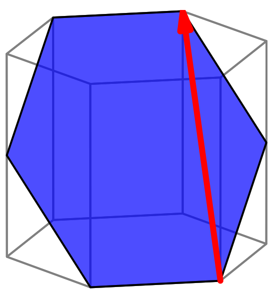


First order tensile twin
$\{10\bar{1}2\} < \bar{1}011 >$

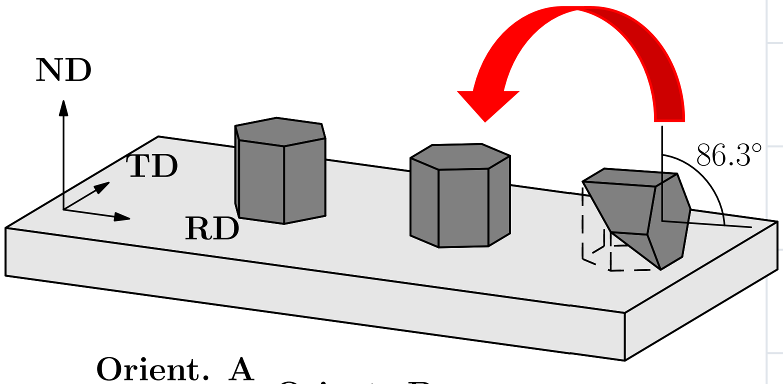


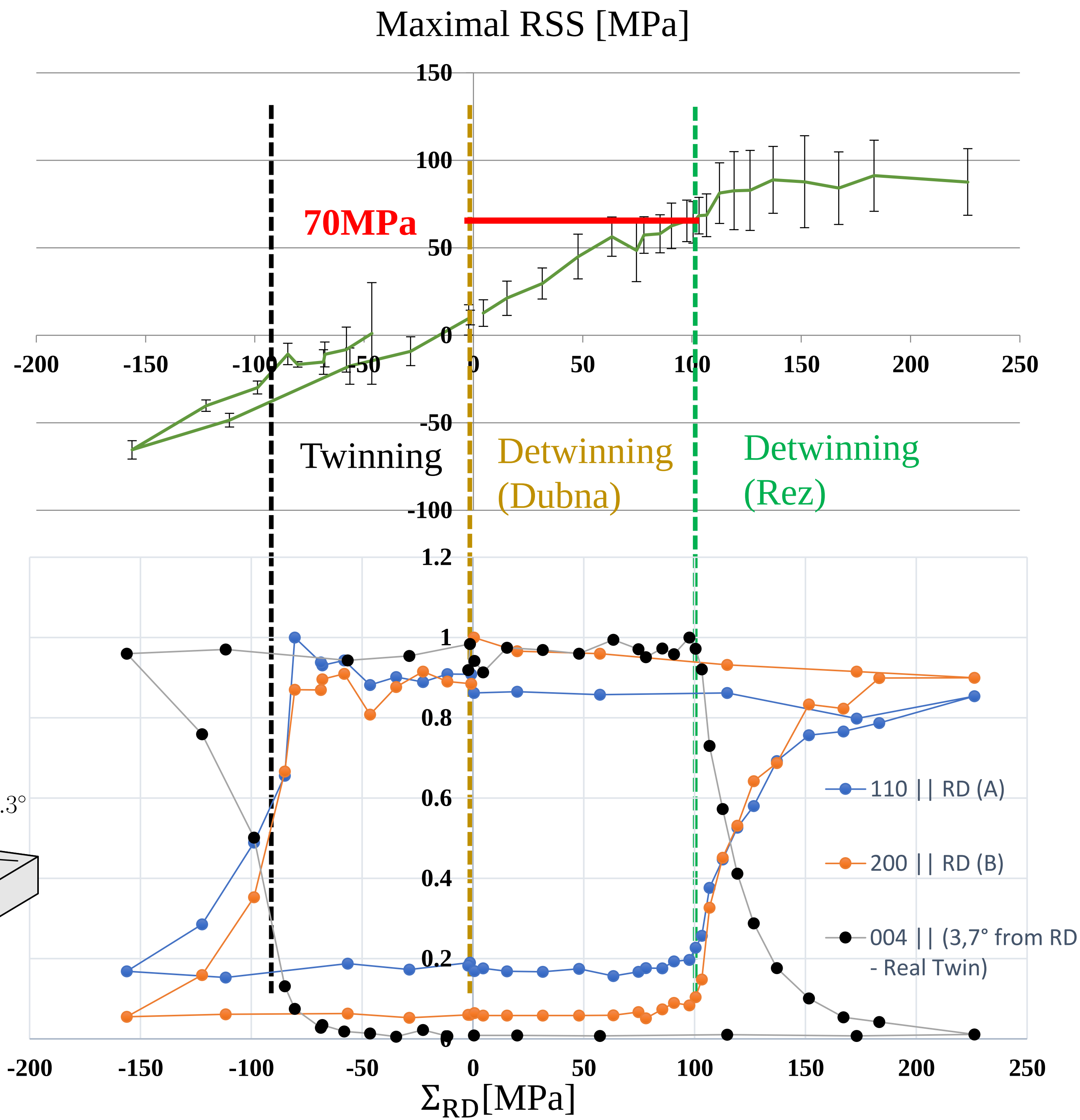


Detwinning during tensile phase



First order
tensile twin
$\{10\bar{1}2\} < \bar{1}011 >$





Conclusions

1. **Diffraction methods for deformation study was developed**
2. **For textured Mg AZ31 alloy stresses on different crystallite groups were determined directly from experiment**
3. **Elastic-plastic deformation was described at grain scale in textured magnesium**
4. **The CRSS values are unabiguously determined directly from experiment with uncertainties (model assumptions not used)**
5. **For the first time detwinning CRSS value was measured using neutron diffraction**

Acknowledgements

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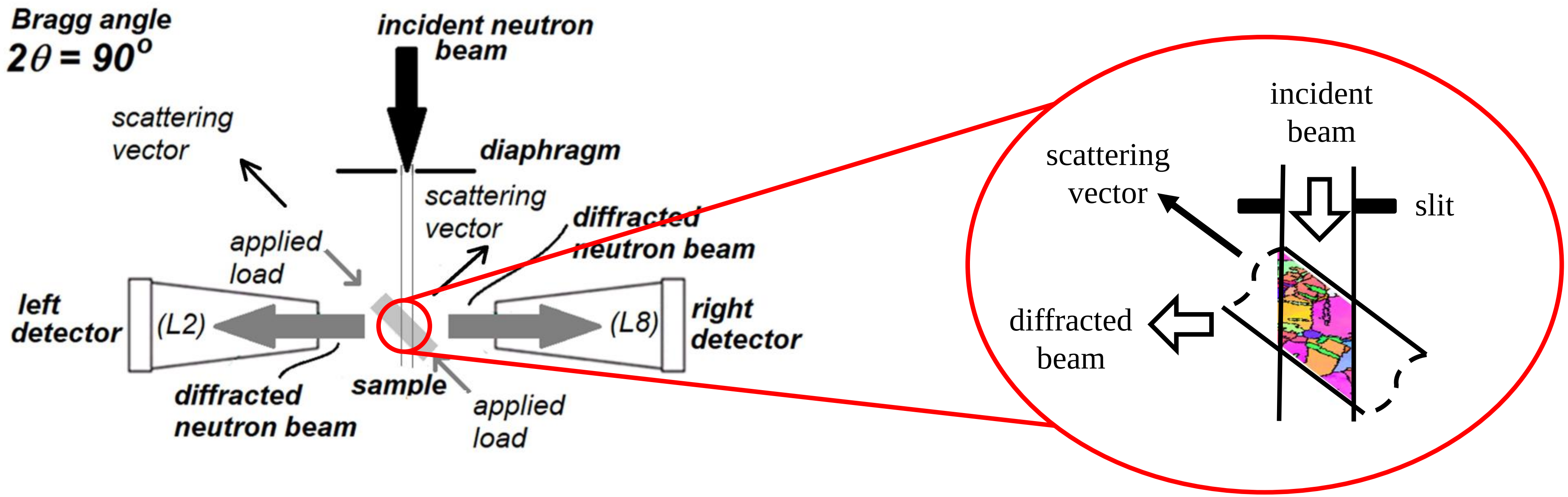
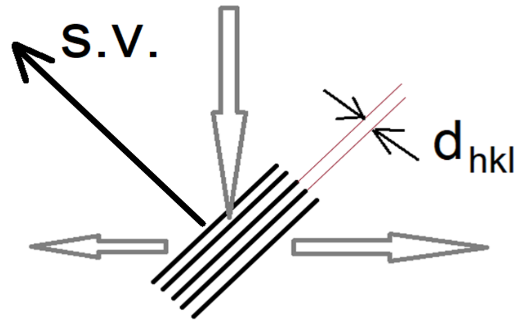
Thank you for your attention!

Backup slides

Stress/strain measurement using diffraction

In situ diffraction measurement under applied loads

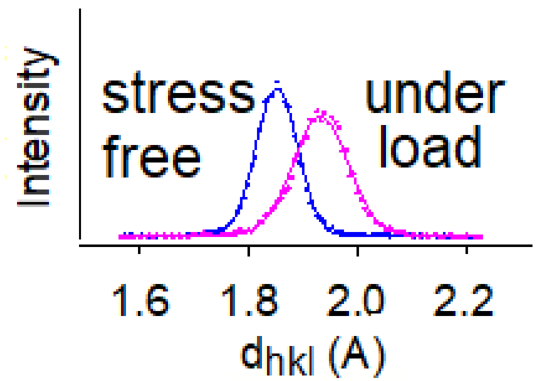




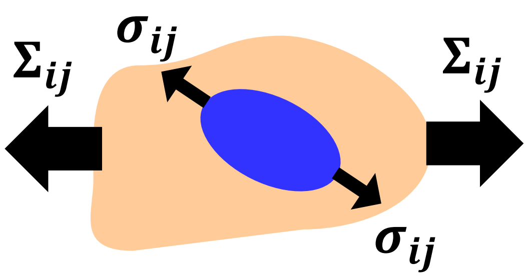
$$n\lambda = 2d_{hkl}\sin\theta$$

Relative lattice strain for loads:

$$\varepsilon_{hkl} = \frac{d_{hkl} - d_{hkl}^{initial}}{d_{hkl}^{initial}}$$

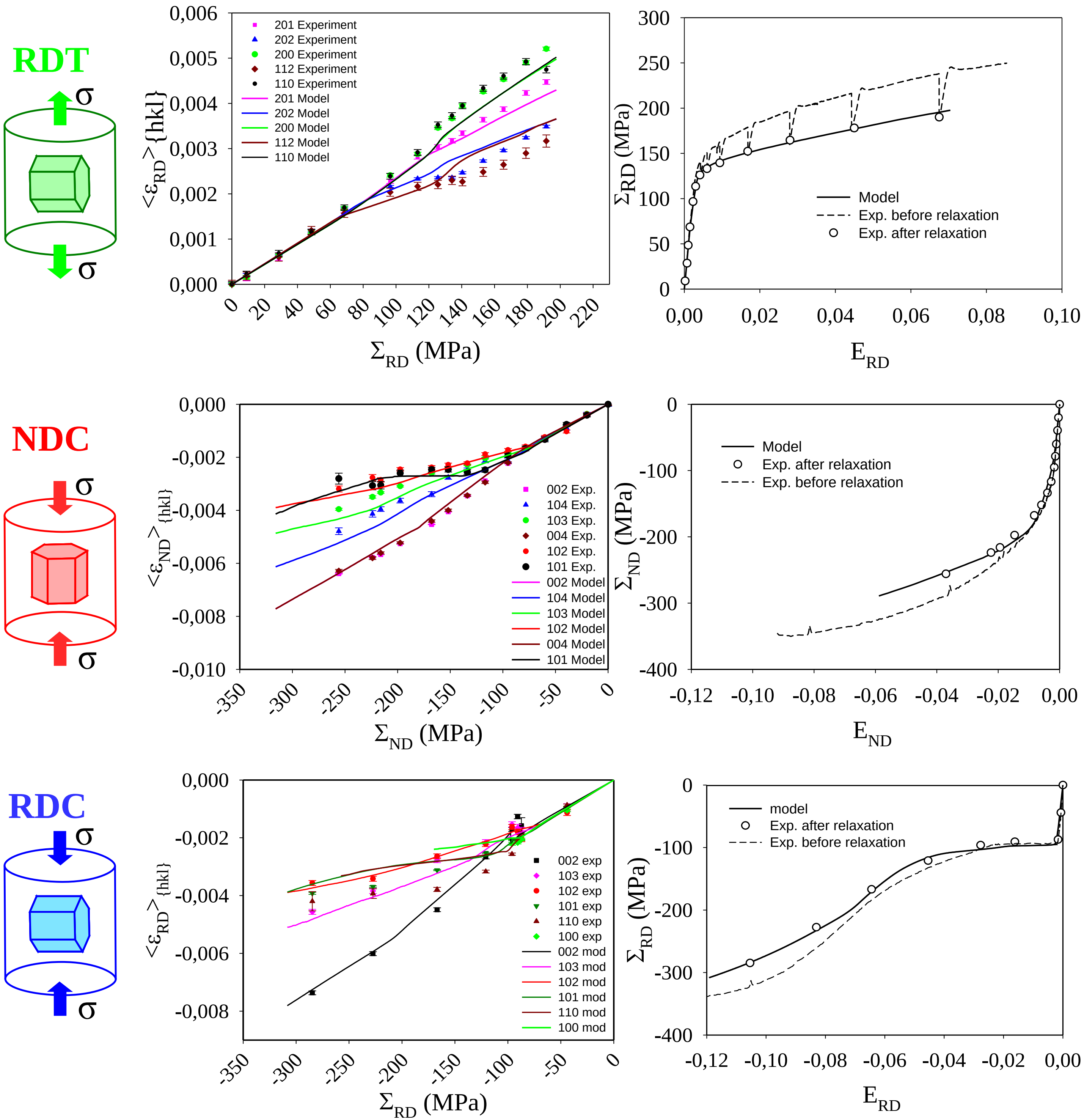


EPSC model with experimental parameters

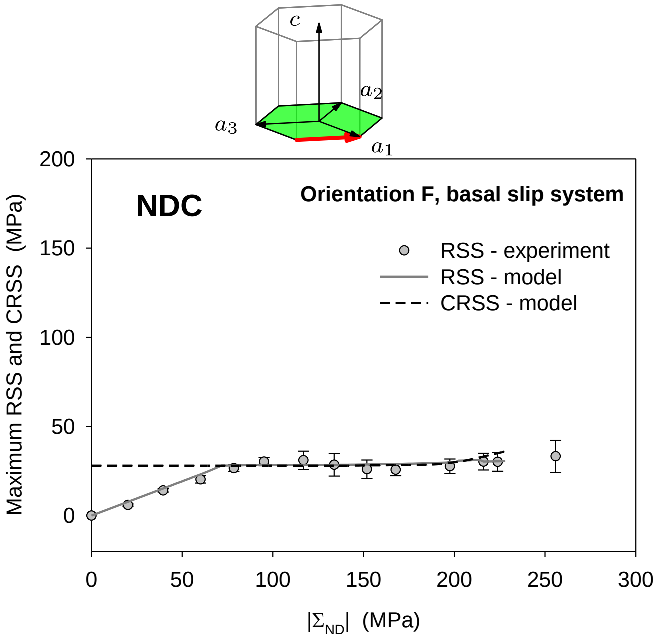


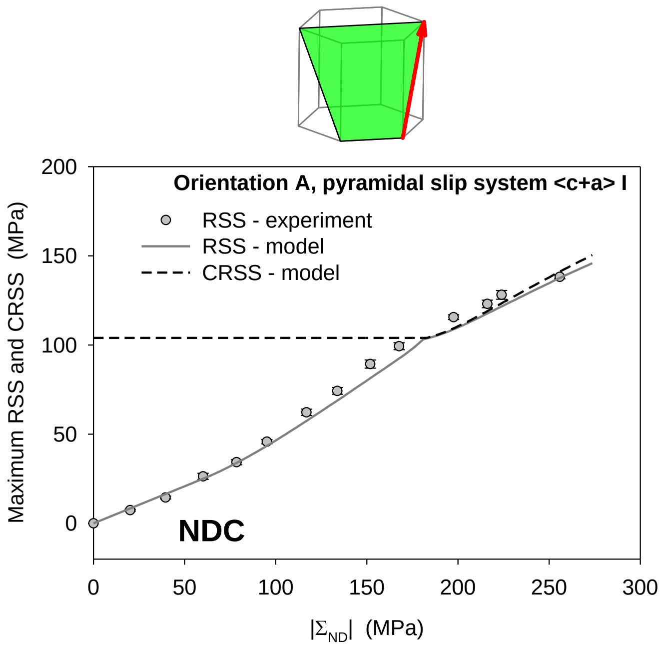
The values CRSS were directly determined from experiment and applied to verify model.

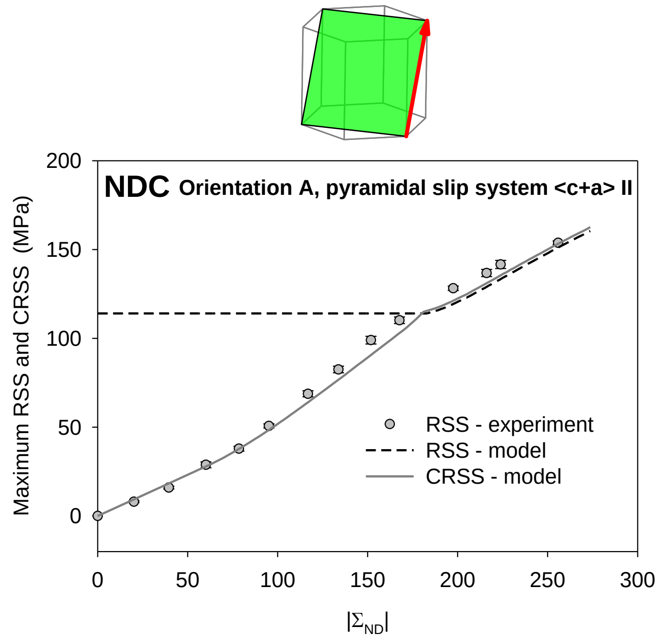
The Voce-law was used to determine hardening parameters.

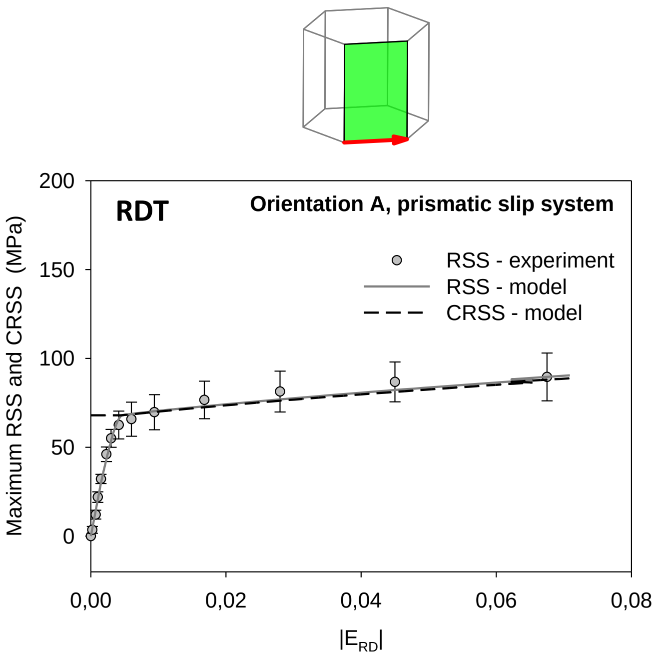


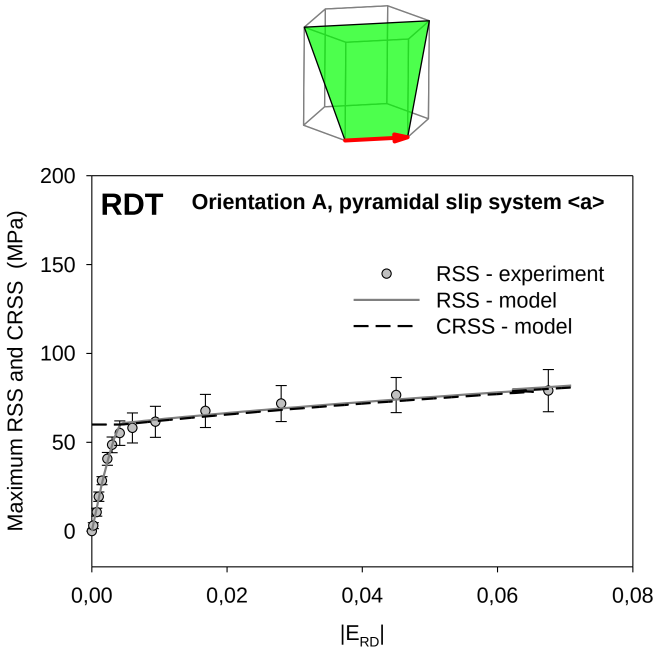
Maximum RSS and CRSS - model confirmation

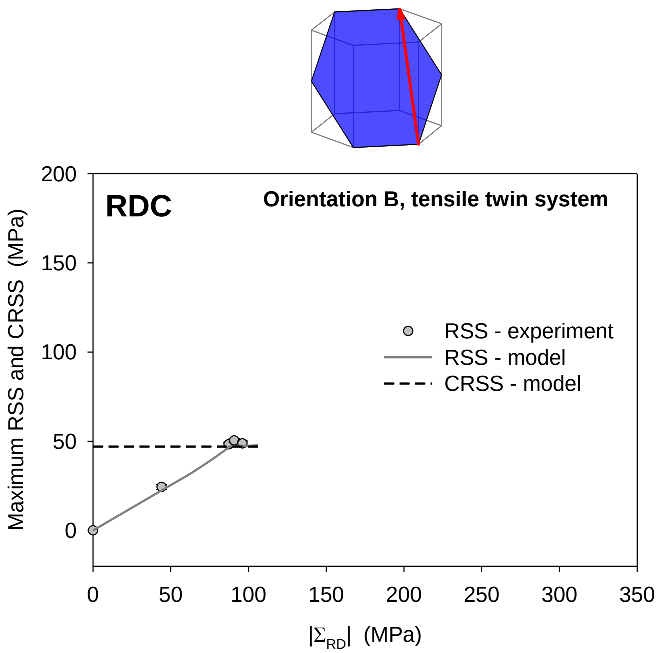




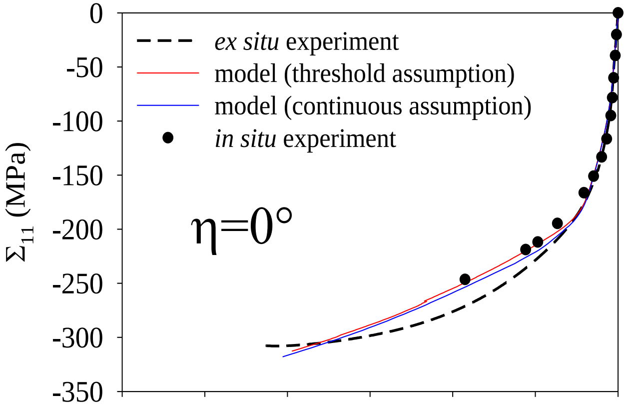


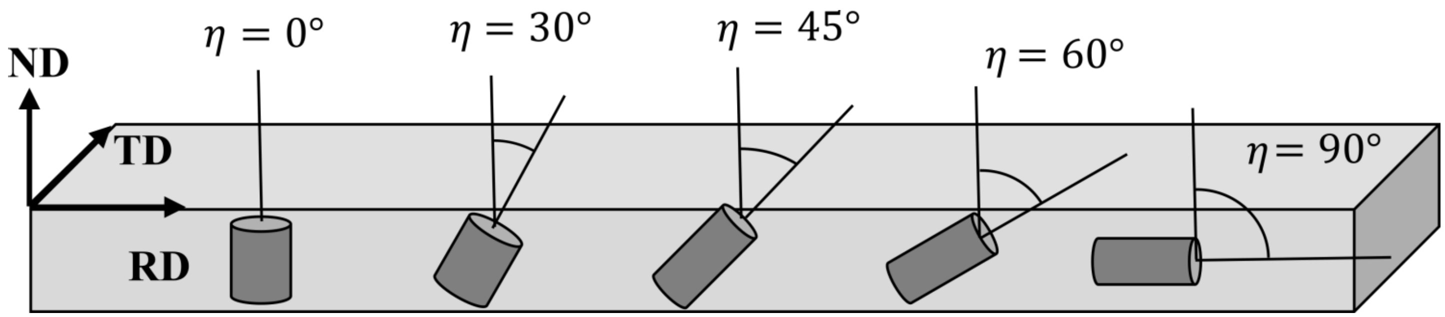


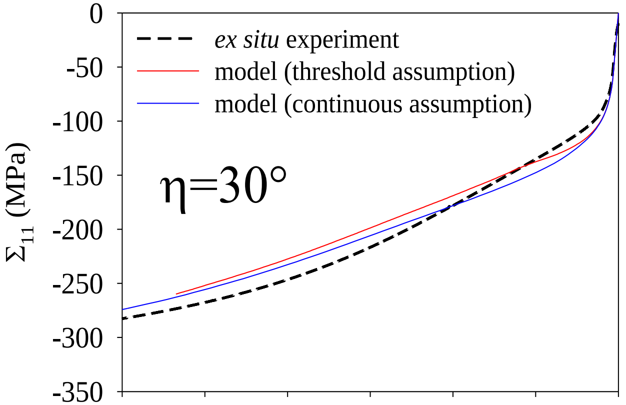


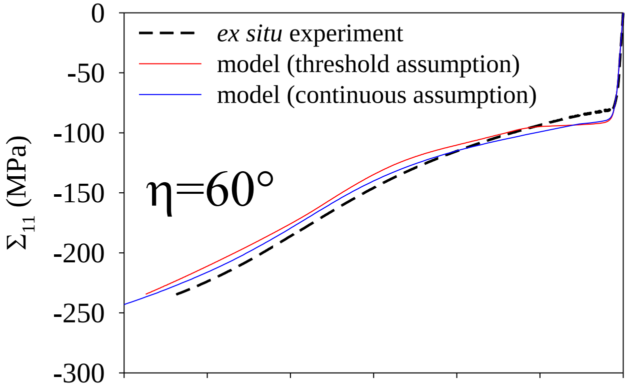


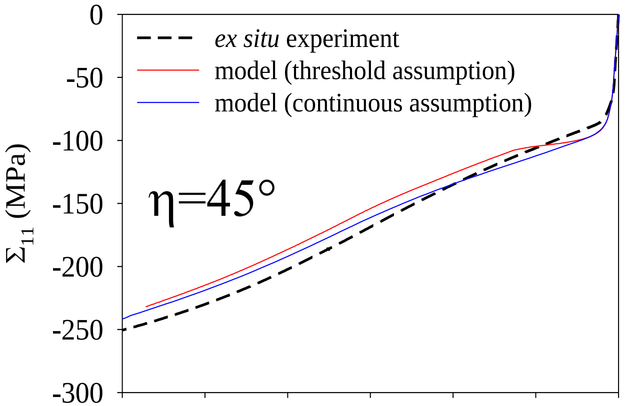
Model vs ex-situ compression

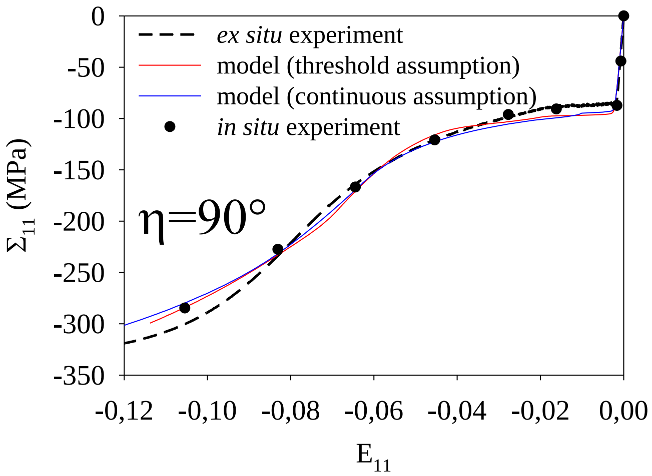








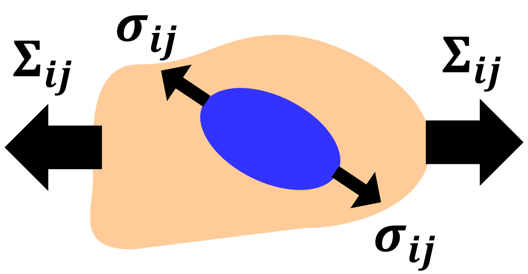




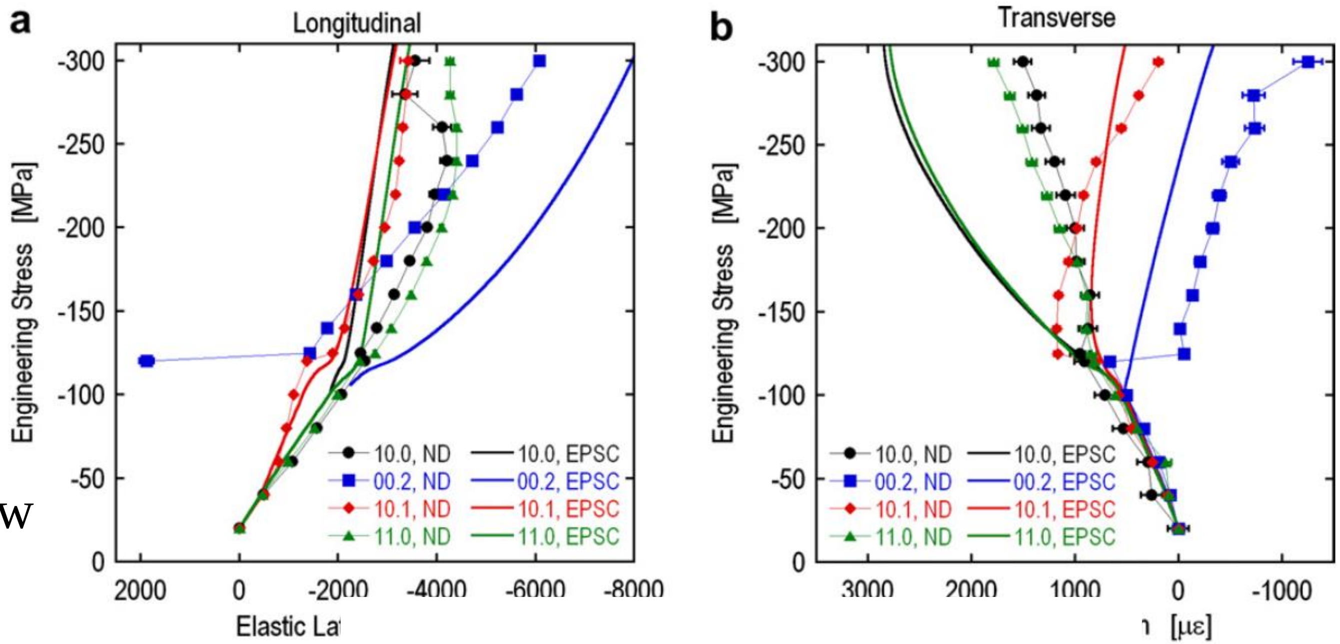
Ex-situ compression tests were carried out for samples cut at different angles between ND and cylinder axis. The results were compared with model prediction. Two model assumptions were verified – continuous and trheshold.

Previous model results…

B. Clausen et al. / Acta Materialia 56 (2008) 2456-2468



EPSC model with the Voce-law fitted to experimental data obtained in 2 directions.



Macroscopic Stress-Strain Curves

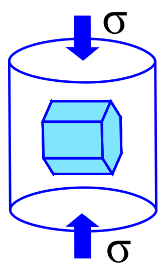


Table 1
CRSS and hardening parameters used for the two assumptions

Assumption	Initial twin fraction	Deformation system	τ_0 (MPa)	τ_1 (MPa)	θ_0 (MPa)	θ_0 (MPa)
Continuity	N/A	Basal	12	20	40	0
		Prism	60	20	40	0
		Pyramidal	100	117	2500	0
		Tensile twin	54	0	0	0
Fixed initial fraction	3%	Basal	12	20	240	0
		Prism	60	20	240	0
		Pyramidal	100	117	2000	0
		Tensile twin	60	0	0	0

0 -2 -4 -6 -8 -10
Engineering Strain [%]

2 detectors

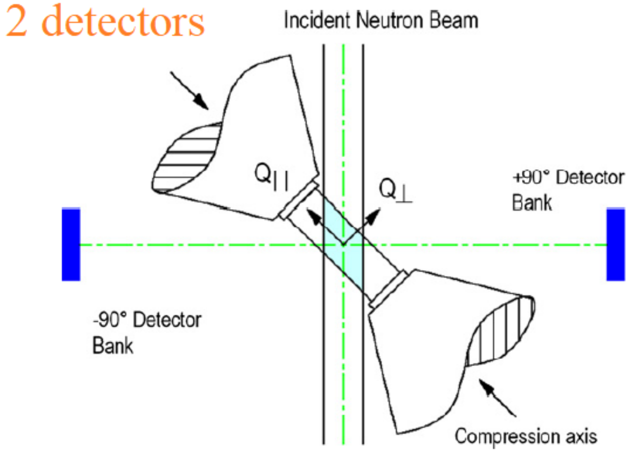


Fig. 3. Schematic of the in situ compression set-up of the SMARTS instrument.

Comparison with literature

Model + diffraction

H. Wang et al. / International Journal of Solids and Structures 47 (2010) 2905–2917

Table 1
List of material constants for various self-consistent models.

Model	Mode	τ_0
Affine	Basal	9
	Prismatic	79
	Pyramidal	100
	Tensile twin	47
Secant	Basal	13
	Prismatic	73
	Pyramidal	110
	Tensile twin	31
m^{eff} ($m^{eff} = 0.1$)	Basal	17
	Prismatic	77
	Pyramidal	148
	Tensile twin	33
Tangent	Basal	21
	Prismatic	90
	Pyramidal	145
	Tensile twin	38

Direct method

Slip system	CRSS from experiment τ_0 (MPa)
Basal	28.0 (3.1)
Prismatic <a>	67.7 (7.9)
Pyramidal<a>	59.7 (6.9)
Pyramidal <a+c> ver. 1	104.4 (5.6)
Pyramidal <a+c> ver. 2	116.6 (3.5)
First order tensile twin	49.1 (2.5)