Self-consistent crystal plasticity framework as constitutive description for sheet metals

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MATERIALS SCIENCE AND ENGINEERING

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Acknowledgements

Prof. Barlat @**POSTECH**

Drs. Iadicola, Creuziger, Gnäupel-Herold, Foecke @**NIST**

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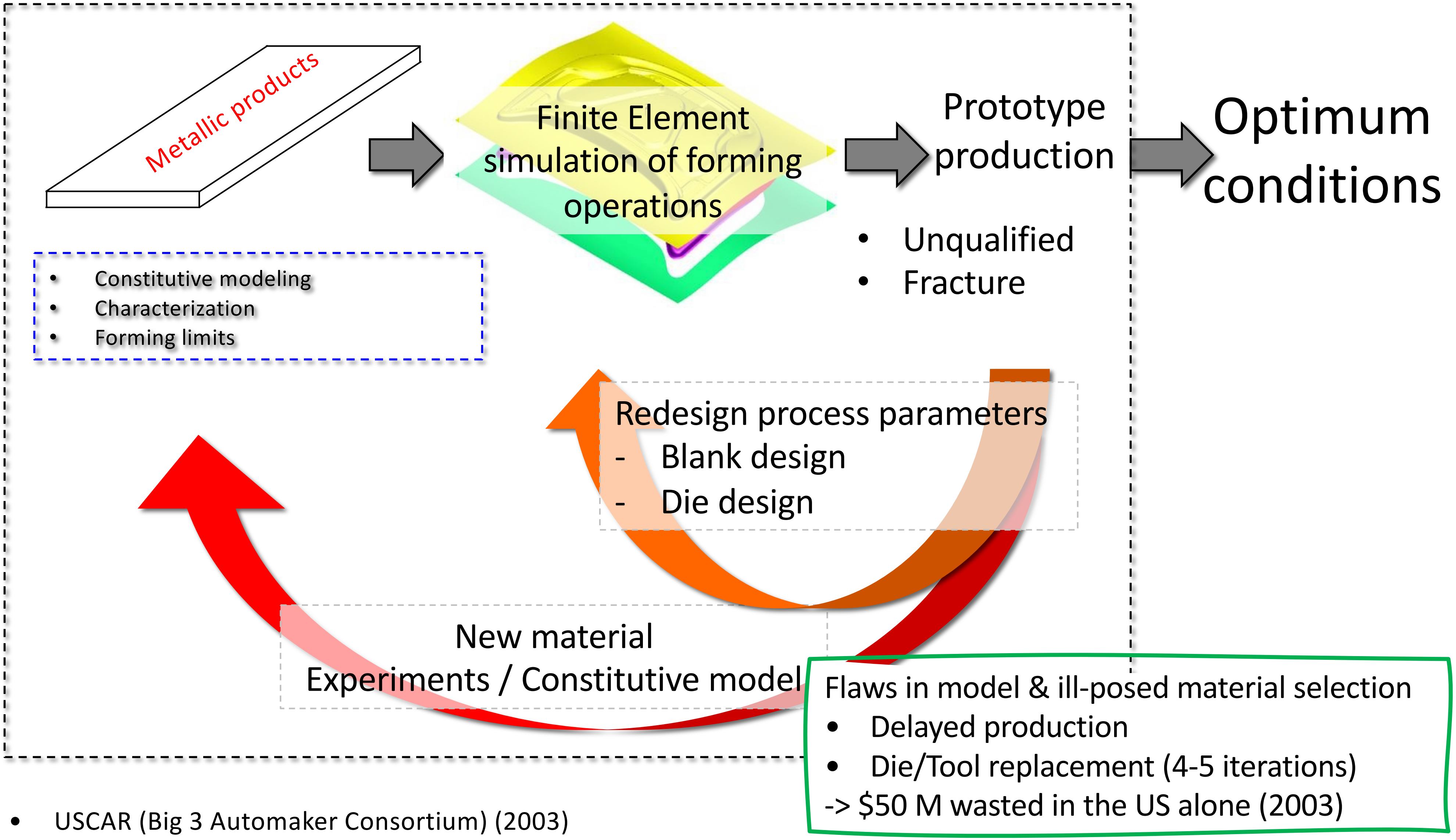
Outlines

- Research motivation
- Short lecture on mean-field crystal plasticity (VPSC)
- Applications
  - Formability prediction using VPSC
  - Multiaxial flow stress measurement using XRD
  - VPSC and HAH
  - New EVPSC model development
- Summary
- Application to TRIP steel

Research Motivation



- USCAR (Big 3 Automaker Consortium) (2003)
- Innovation in Sheet Metal Forming: Workshop Summary Report (2015)

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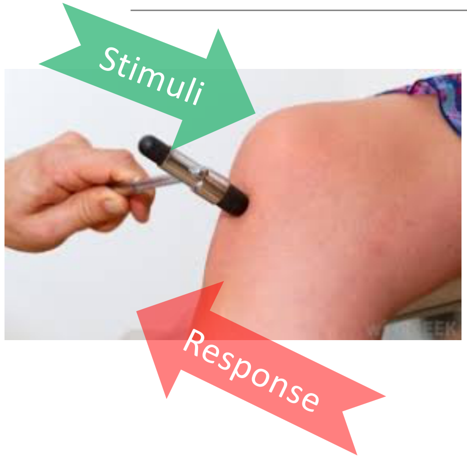
VPSC in a nutshell

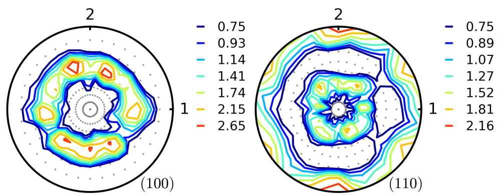


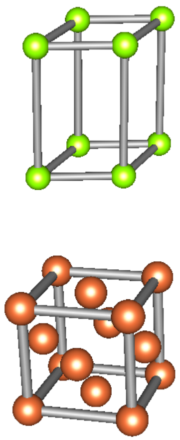
Material Model	Constitutive model	Visco-Plastic model
$\boldsymbol{y} = \boldsymbol{a}\boldsymbol{x}$	$\boldsymbol{\sigma} = \mathbb{C}\boldsymbol{\varepsilon}$	$\boldsymbol{\sigma} = \mathbb{C}^{vp}\dot{\boldsymbol{\varepsilon}}$
Material Property	Moduli	Visco-Plastic Moduli

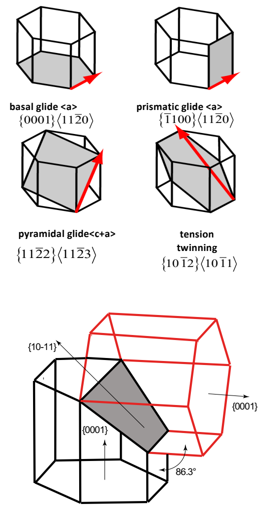
$$\dot{\boldsymbol{\varepsilon}} = \frac{d\boldsymbol{\varepsilon}}{dt}$$

In VP **crystal plasticity**:

$$\mathbb{C}^{vp} = \text{func}\,(\text{ Texture (ODF), Crystal structure, Slip/Twin, Dislocation density (CRSS), ... })$$

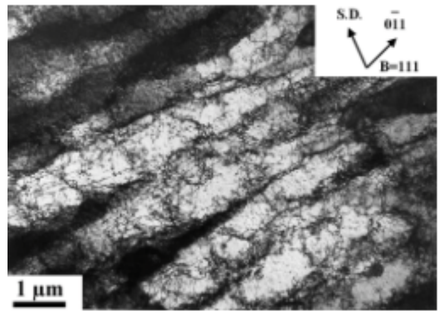






$$\tau = \mu\alpha\sqrt{\rho}$$

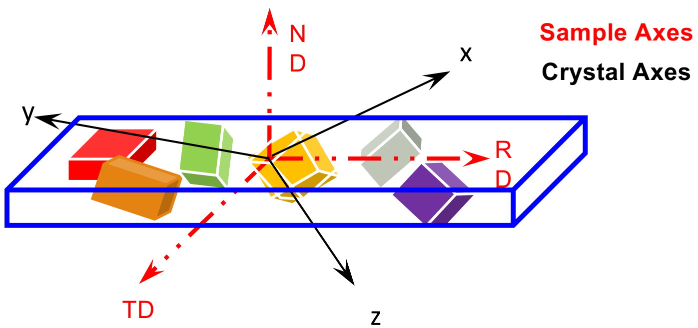
ρ: dislocation density



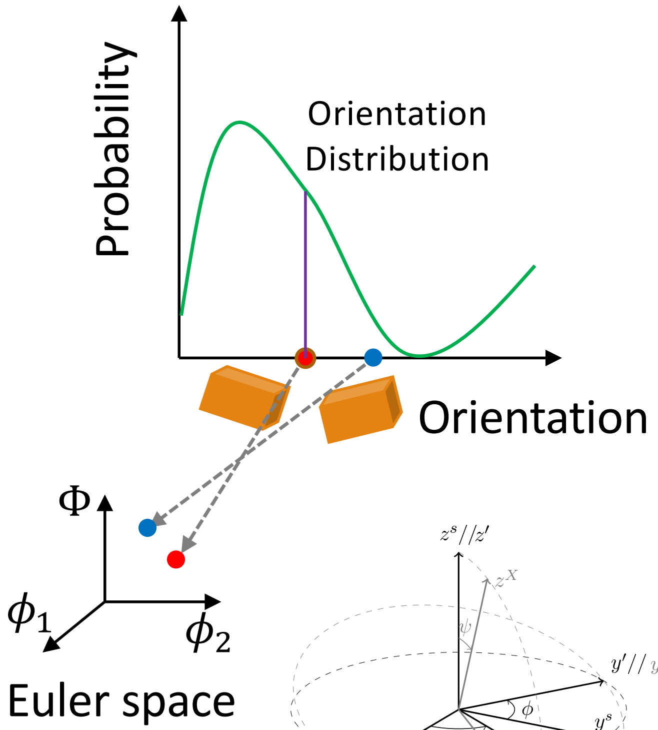
Statistical representation of polycrystal

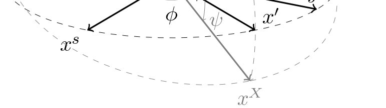
Visco-Plastic model

$$\boldsymbol{\sigma} = \mathbb{C}^{vp}\,\dot{\boldsymbol{\varepsilon}}$$

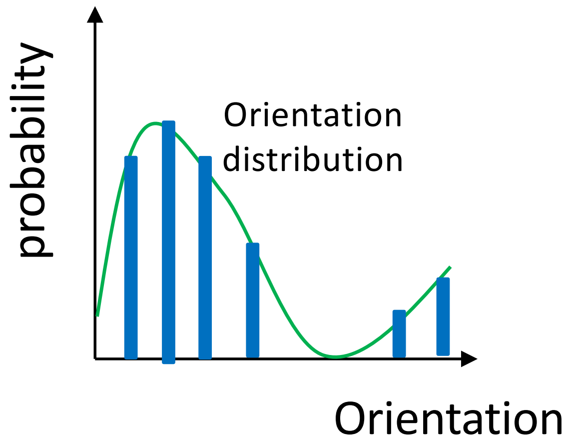


Each grain (crystal) is anisotropic.

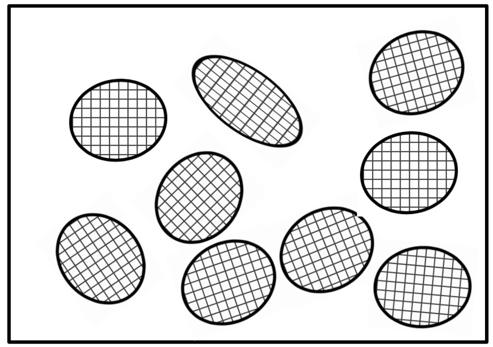




Discrete sampling

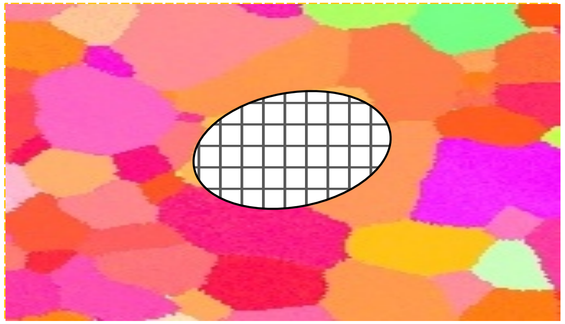


Discrete sampling to represent polycrystal

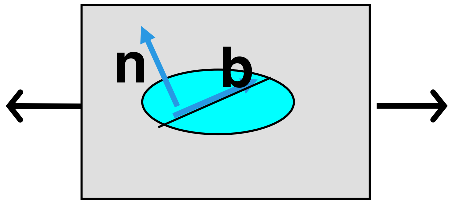


Visco-Plastic Self-Consistent (VPSC) Polycrystal Model

Homogenization



Eshelby's inclusion problem



Polycrystal constitutive law

$$\boldsymbol{\sigma} = \mathbb{C}^{vp}\,\dot{\boldsymbol{\varepsilon}}$$

Single crystal constitutive law

Strain (rate) of individual grain

$$\dot{\boldsymbol{\varepsilon}} = \dot{\gamma}_0 \sum_s \mathbf{m}^s \left(\frac{\mathbf{m}^s : \boldsymbol{\sigma}}{\tau_c^s}\right)^n$$

Stress of individual grains

Schmid tensor (~Schmid factor) of individual slip system (s)

CRSS, Strain-hardening

$$\tau^s = \tau_0^s + (\tau_1^s + \theta_1^s \Gamma)\left\{1 - \exp\left(\Gamma\left|\frac{\theta_0^s}{\tau_1^s}\right|\right)\right\}$$

$\tau = \alpha\mu b\sqrt{\rho}$ ρ: dislocation density

Okay, you have learned VPSC

I have been giving lectures and talks on VPSC often in

- Korean community of crystallographic texture (금속재료학회 집합조직 분과위원회)

So if you are interested in VPSC (and the mean field crystal plasticity in general) …

- From now on, we'll be exploring what is possible by using VPSC.
- These examples are very limited as I am going to provide you with what I have done.
- Yet, you might be able to enjoy the versatility of VPSC model in general.

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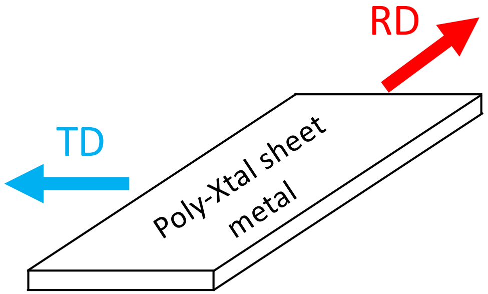
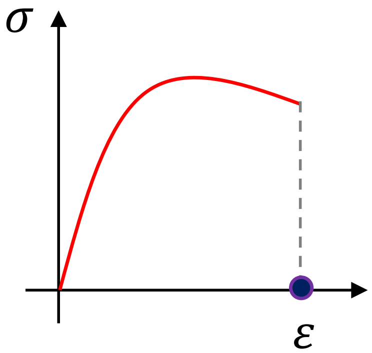
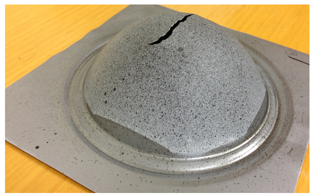
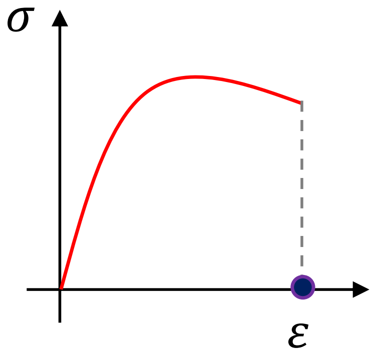
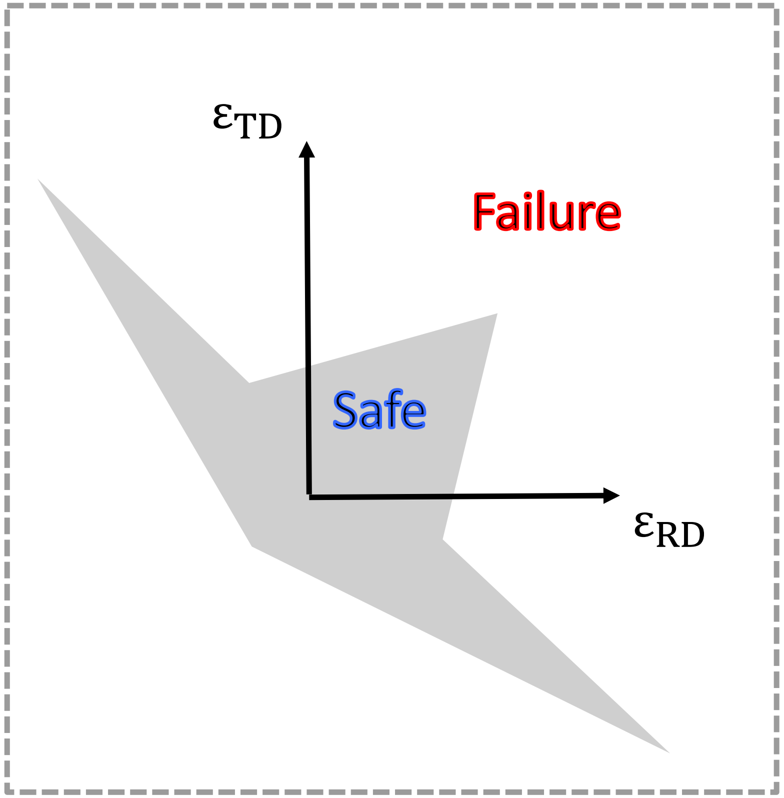
Forming limit diagram (FLD)



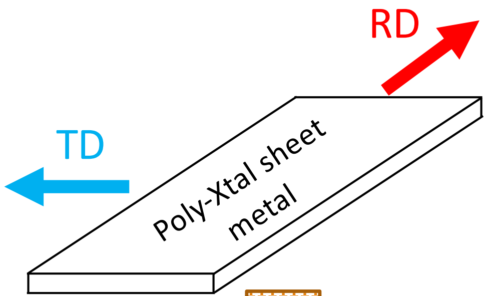


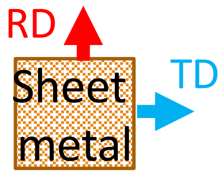


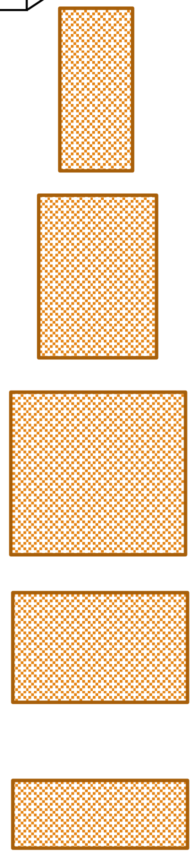




Measurement of FLD is expensive and difficult







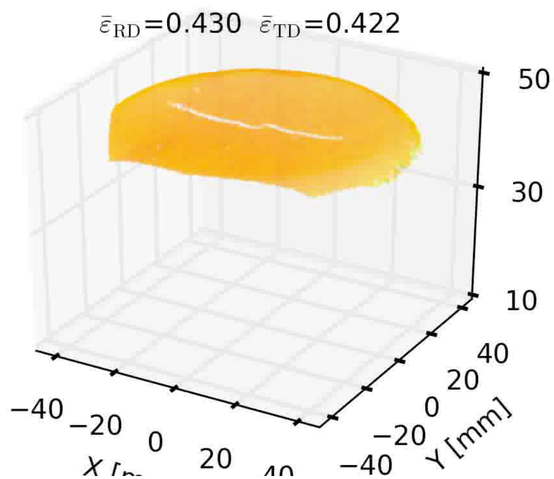
RD uniaxial tension
($\sigma_{RD} > 0$, σ_{TD}=0)

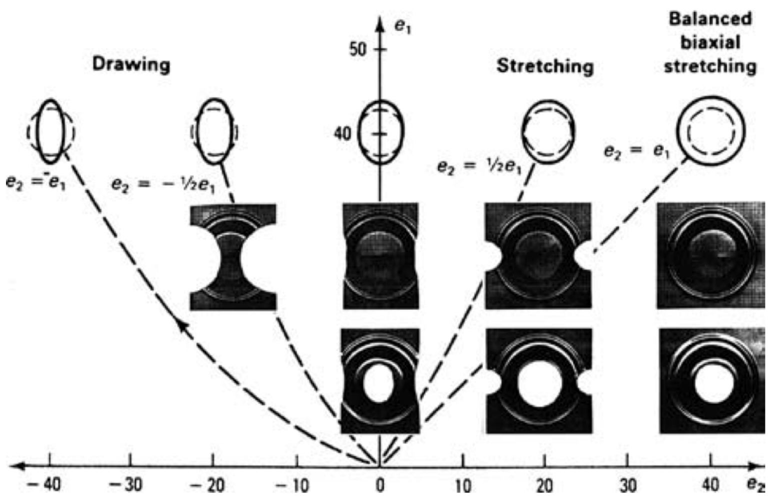
Plane-strain RD
$\sigma_{RD} \approx 2\sigma_{TD} > 0$

Equi-biaxial stress
($\sigma_{RD} = \sigma_{TD}$)

Plane-strain TD
$\sigma_{TD} \approx 2\sigma_{RD} > 0$

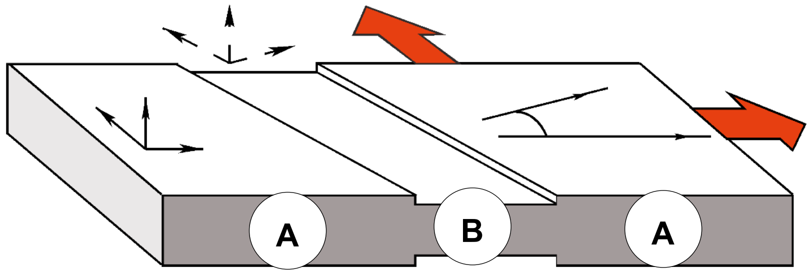
TD uniaxial tension
($\sigma_{TD} > 0, \sigma_{RD} = 0$)





FLD predictive models found in the literature

Solution we focus: predictive models using Marciniak-Kuczyński approach

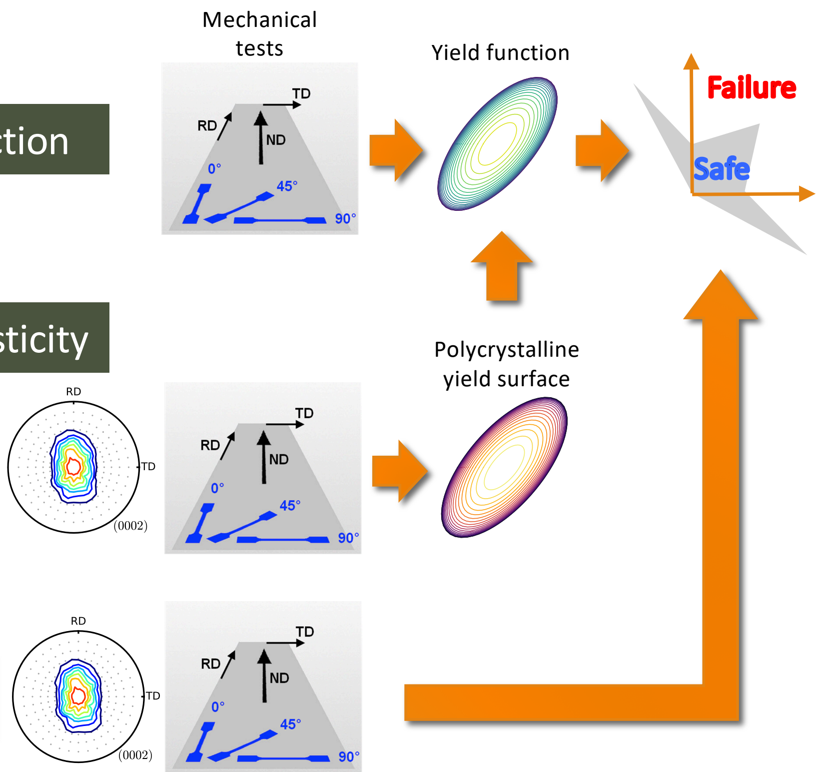


MK with yield function

MK with crystal plasticity

Indirect approach

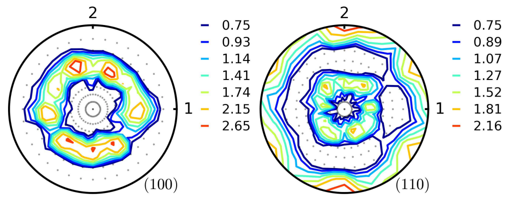
Direct approach



Computational time

- MK with yield function is the fastest
- Direct crystal plasticity model is the slowest.

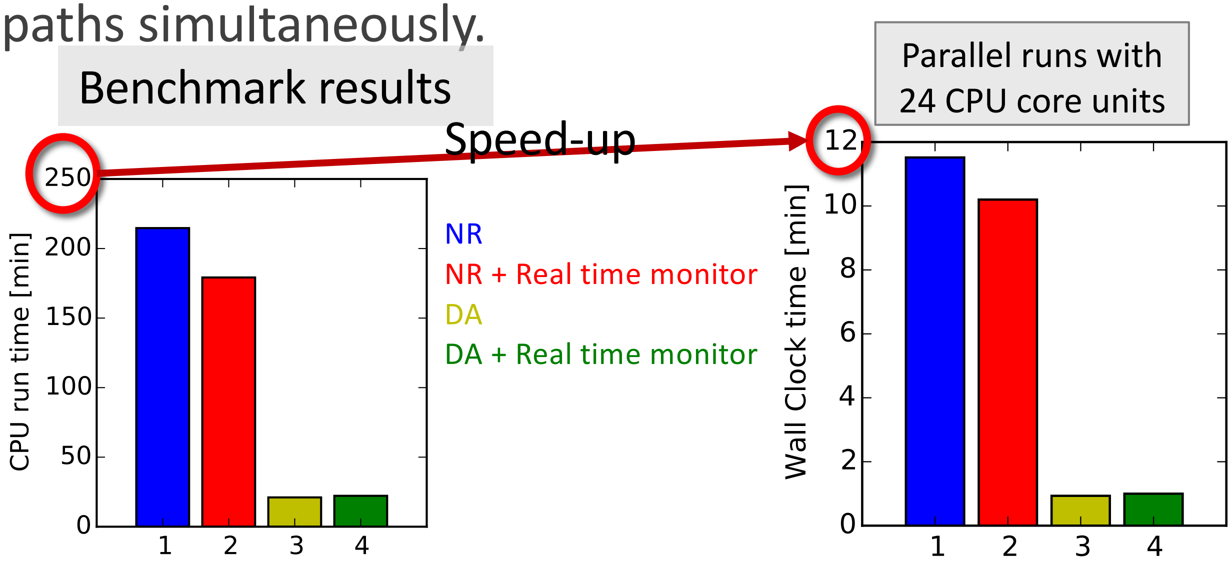
Crystal plasticity accounts for microstructural features

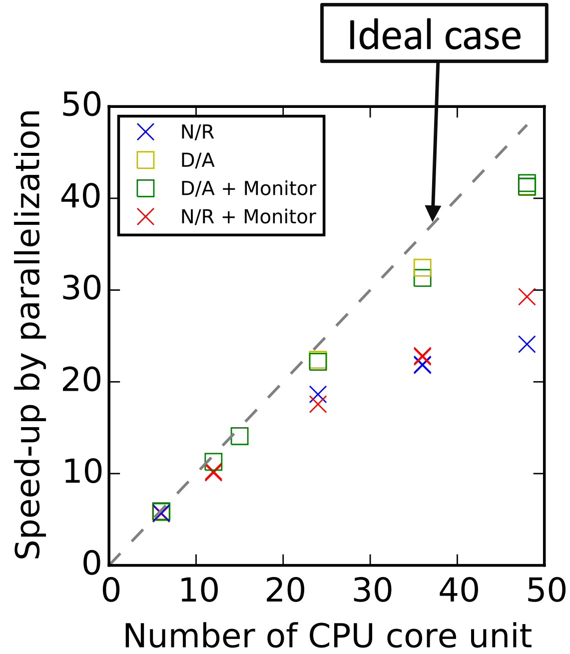


Computational Speed

- Computationally efficient FLD calculations with crystal plasticity (VPSC)
- We use python™ to wrap the VPSC code so that we can run VPSC-FLD at many strain paths simultaneously.

Benchmark results





NR method:
Hutchinson and Neale (1978)
Wu et al. (1998)
Signorelli et al. (2009)
==========================
DA method:
Schwindt et al. (2015)

+

Multi-threaded parallel run powered by python™

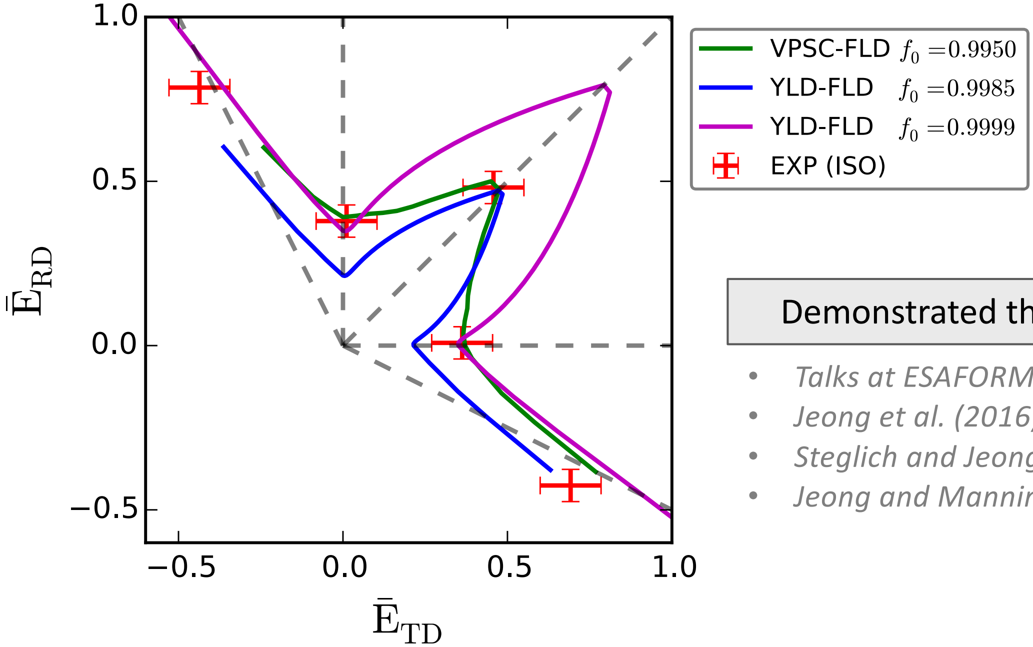
Jeong et al. MSMSE (2016)

Steglich and Jeong IJMS (2016)

*Benchmark simulations were conducted using IF steel polycrystal aggregate with 100 grains

Predictive accuracy on IF steel

* VPSC-FLD: Forming Limit Diagram predictive tool based on VPSC code
* YLD-FLD: Forming Limit Diagram by YLD2000-2D & isotropic hardening



Demonstrated that VPSC-FLD works well

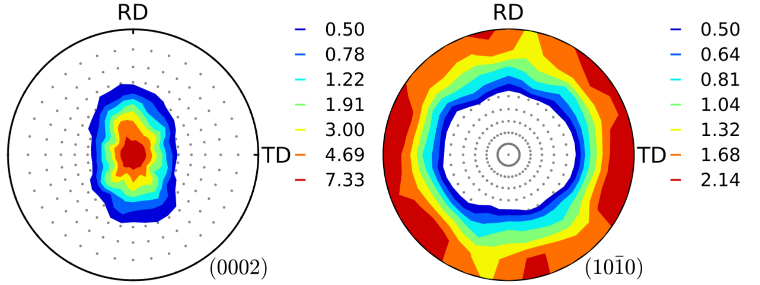
- *Talks at ESAFORM (2015) and NADDRG (2015)*
- *Jeong et al. (2016) MSMSE*
- *Steglich and Jeong (2017) IJMS*
- *Jeong and Manninen (2019) MMI*

More examples of VPSC-FLD for magnesium alloys AZ31 and ZE10

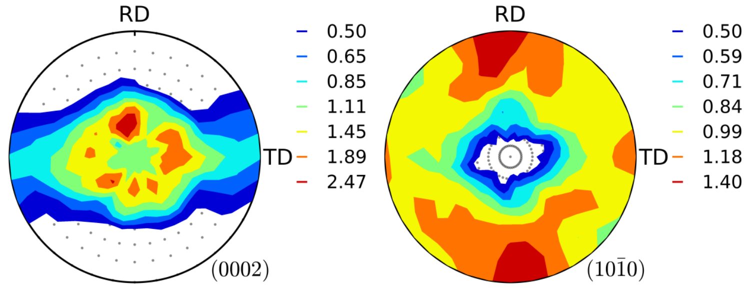
Model calibration (AZ31 and ZE10 Mg alloys)

Initial crystallographic texture

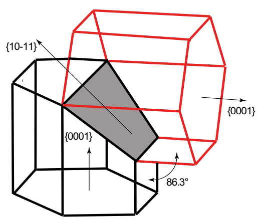
AZ31 alloy

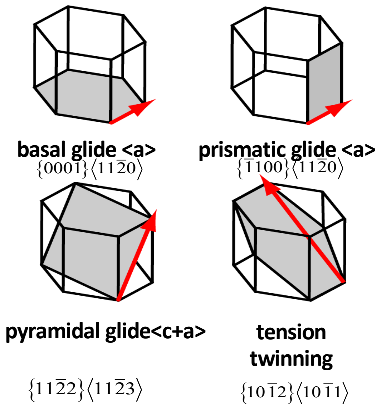


ZE10 alloy



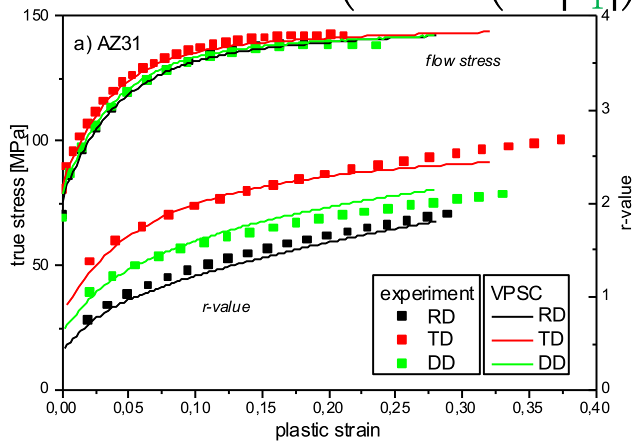
Plastic accommodation mechanism (slip/twin systems)



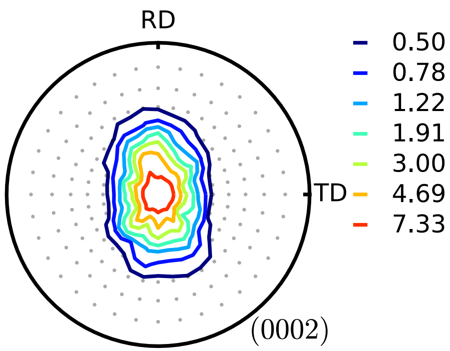


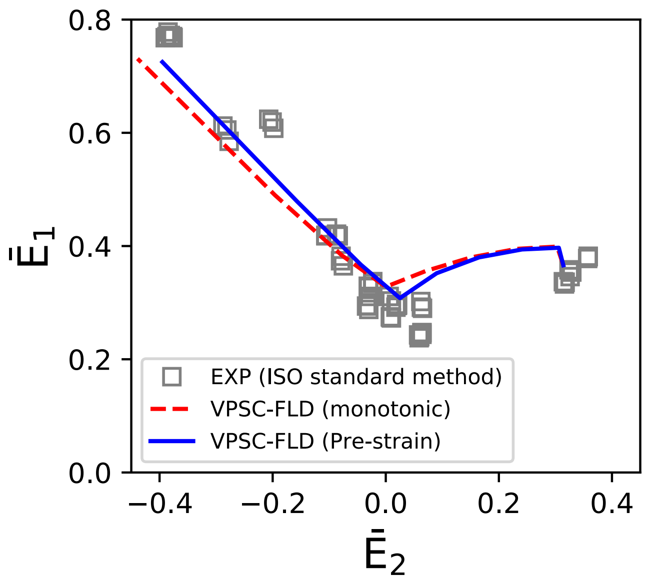
Parameter identification

$$\tau_c^s = \tau_0^s + (\tau_1^s + \theta_1^s\Gamma)\left(1 - \exp\left(-\Gamma\left|\frac{\theta_0^s}{\tau_1^s}\right|\right)\right)$$

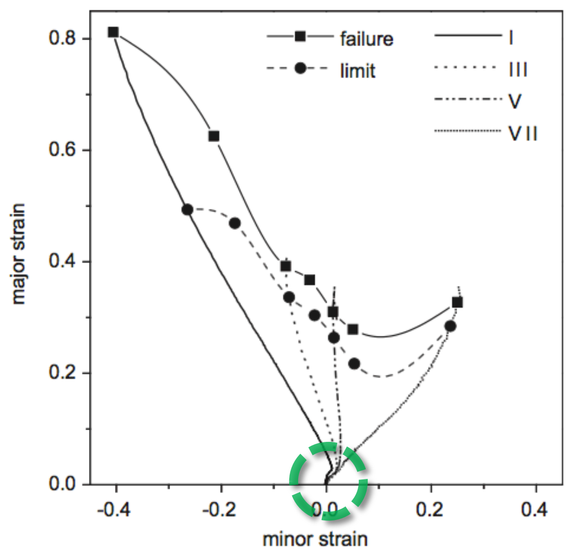


VPSC-FLD application for AZ31





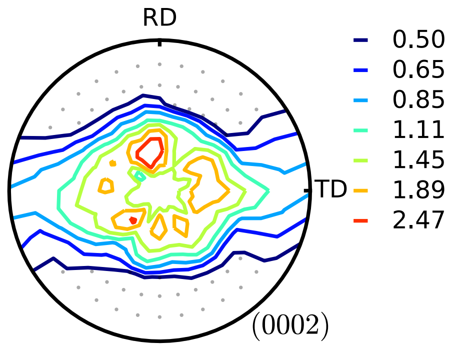
Mekonen et al. (2013)

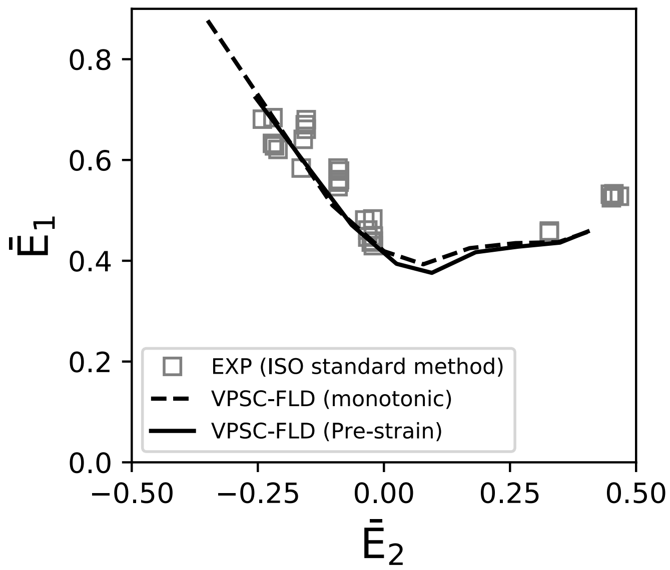


Experimental strain paths during Nakajima tests are **not strictly monotonic**!

Initially 2.5% biaxial followed by monotonic strain paths (pre-strain case)

VPSC-FLD application for ZE10



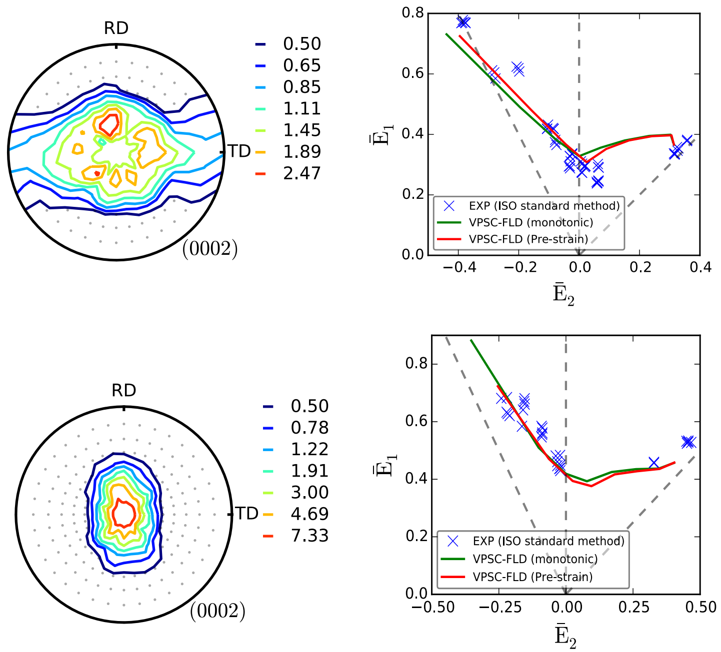


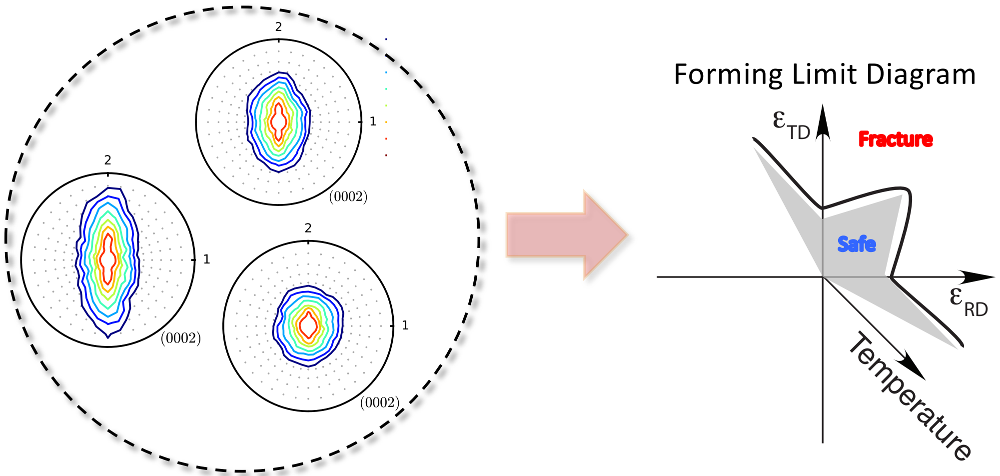
- The effect of pre-strain is well captured by VPSC-FLD
  - AZ31 was more sensitive to the non-linearity in strain paths induced by Nakajima spherical punch.
  - ZE10 was less sensitive.

Effect of initial crystallographic texture: approach

Formability of AZ31 and ZE10 at 200°C
Compared predictions with Exp. data

Ways to tweak initial texture of Mg
•Tilt of basal pole
•Initial twinning (TD compression)

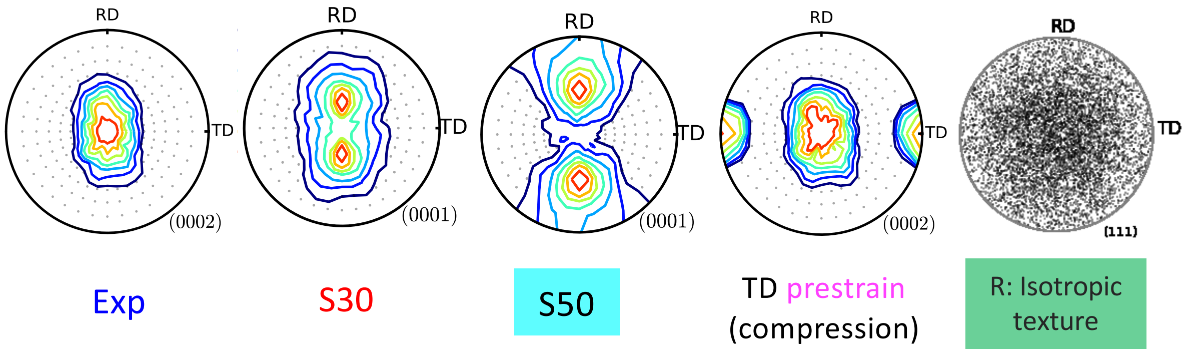


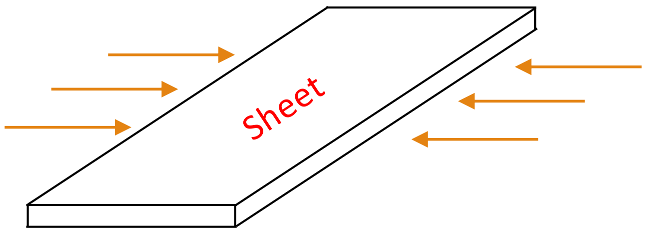


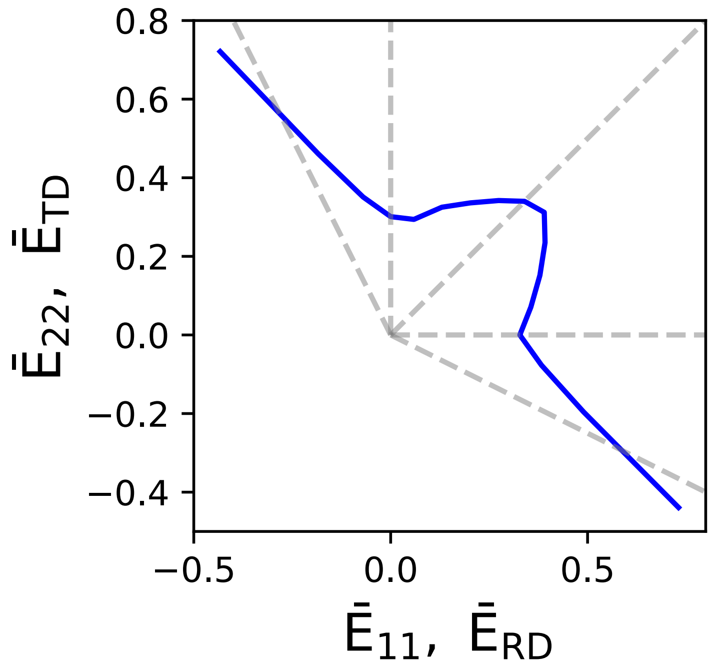
*Optimal crystallographic texture can be suggested based on VPSC-FLD predictions

Effect of initial crystallographic texture: AZ31

Pool of initial textures for AZ31







Initial crystallographic texture of AZ31 significantly affects the FLD

- Increase in the degree of basal pole separation expands the safe region (both RD)
- Isotropic texture (texture-free) case improves the FLD along all strain paths.

D. Steglich, ***Y. Jeong*** (IJMS, 2016)

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Multiaxial measurement

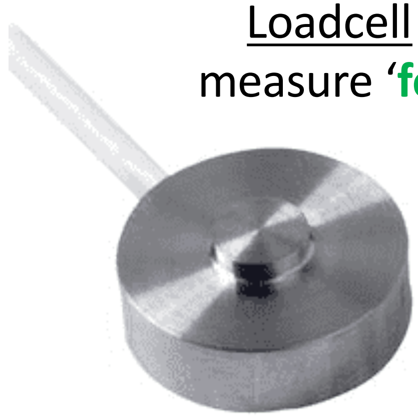
Constitutive model

$$\boldsymbol{\sigma} = \mathbb{C}\boldsymbol{\varepsilon}$$

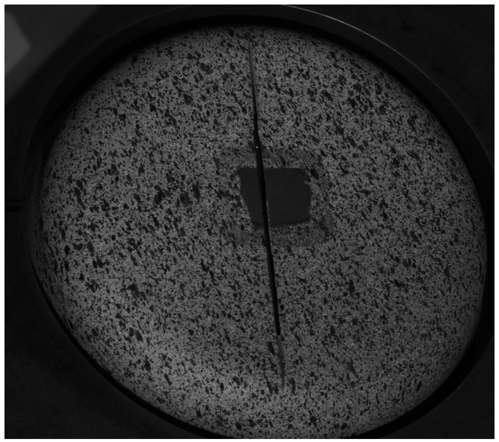
Need to validate $\mathbb{C}$ and the entire model by experimentally measuring both ($\boldsymbol{\varepsilon}$,$\boldsymbol{\sigma}$) pairs in various stress/strain conditions.

$$\boldsymbol{\sigma} = \frac{\boldsymbol{F}}{\boldsymbol{A}}$$

Loadcell to measure '**force**'

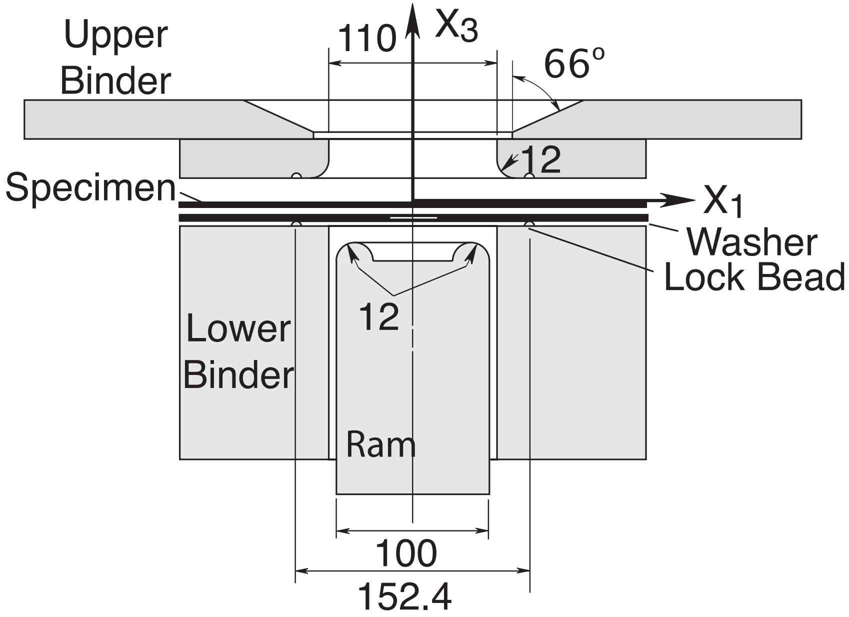


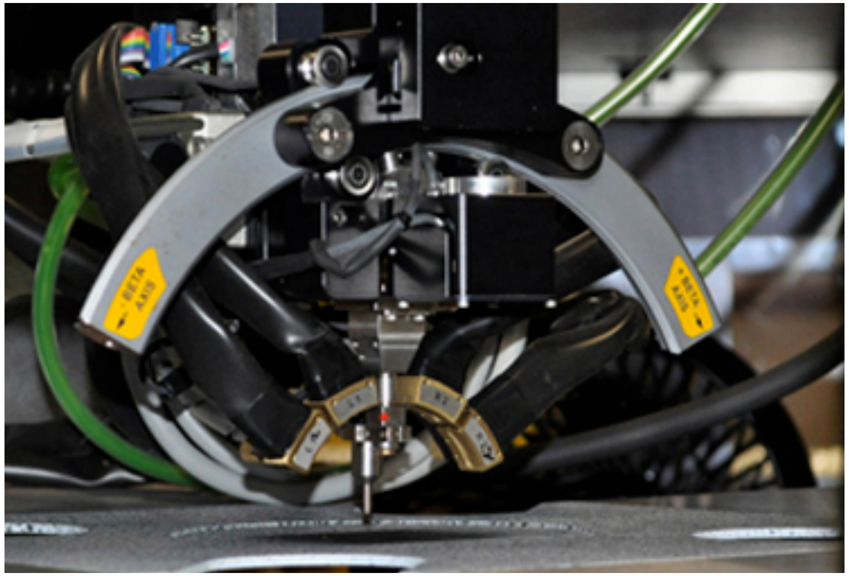
Yet, it is difficult to measure the guage area $\boldsymbol{A}$

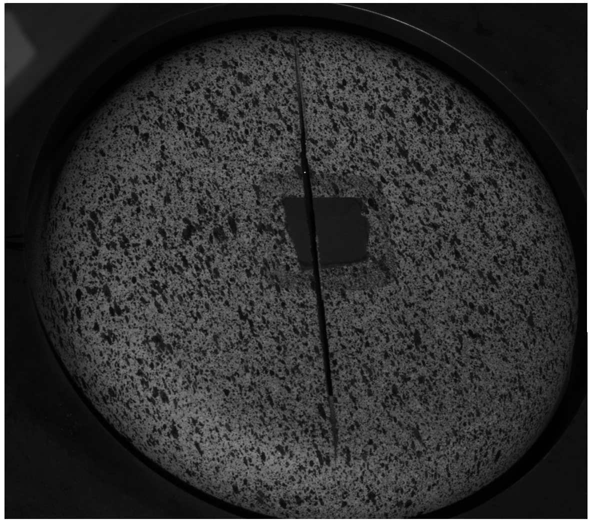


2D stereo digital camera system

Augmented Marciniak tooling

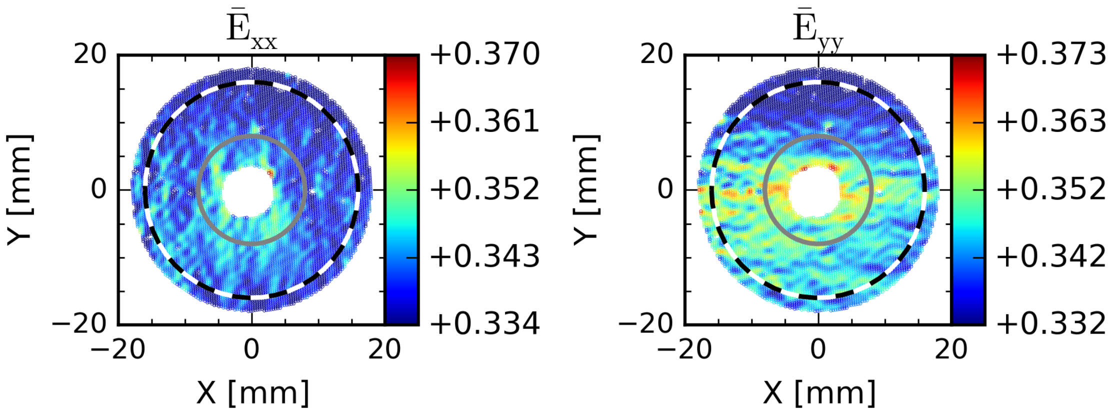




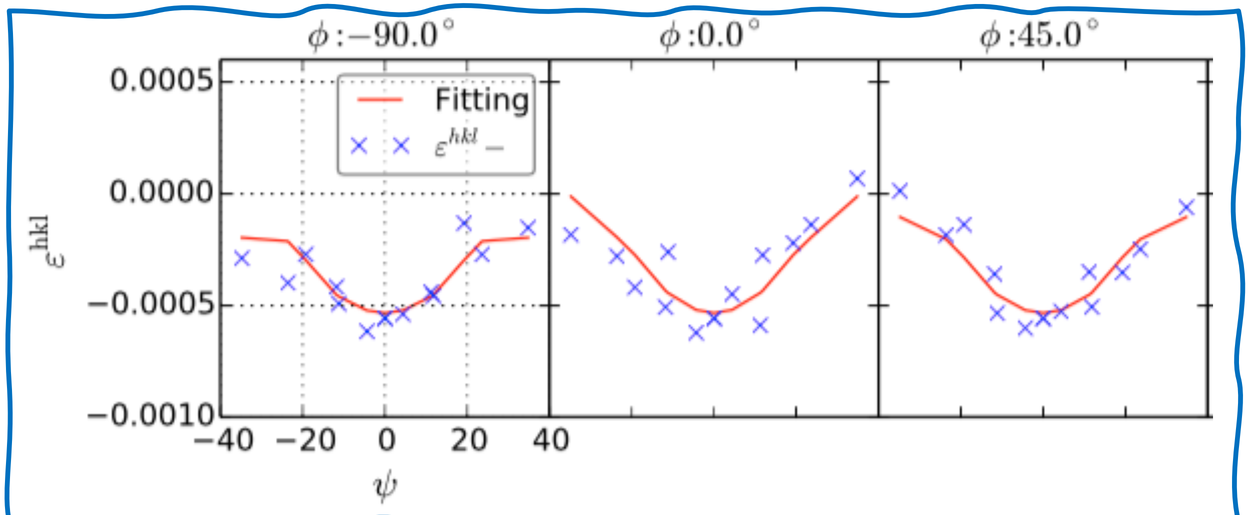


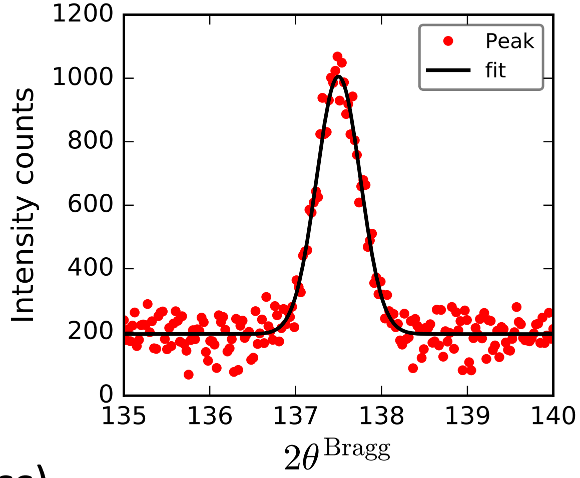
2D stereo digital camera system

Multiaxial strain and stress data from DIC and XRD



2D stereo digital camera system



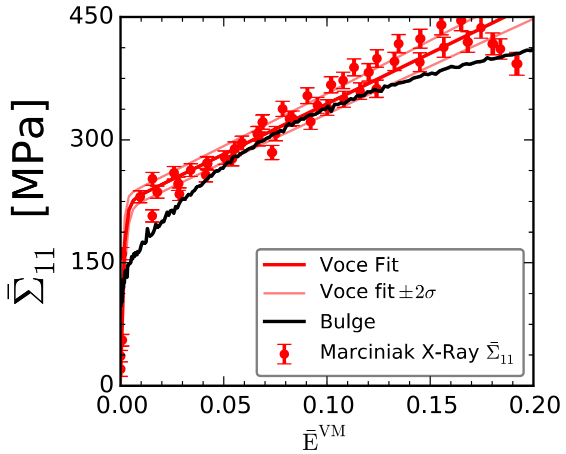


Multiaxial stress state calculated using in-house code (**DiffStress**)

https://github.com/usnistgov/DiffStress

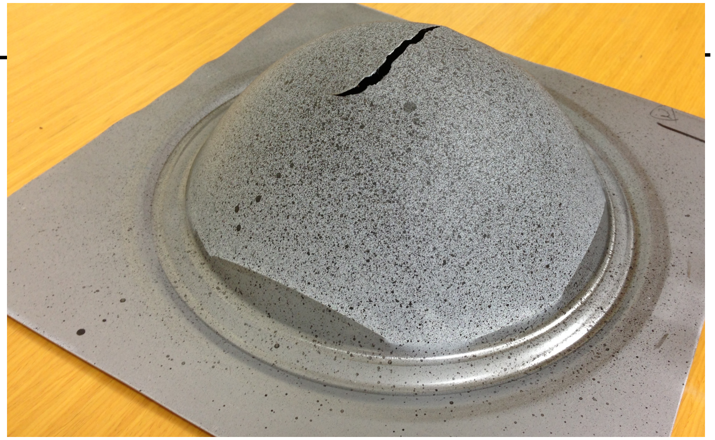
Multiaxial stress-strain measurements using X-ray

Multiaxial constitutive data for interstitial-free steel



- The first case known, where X-ray / DIC method were successfully used for multiaxial experiments.
- Enhanced amount of measureable deformation was realized
  - (cruciform: ~7% -> 20%)
- Comparison with hydraulic Bulge test

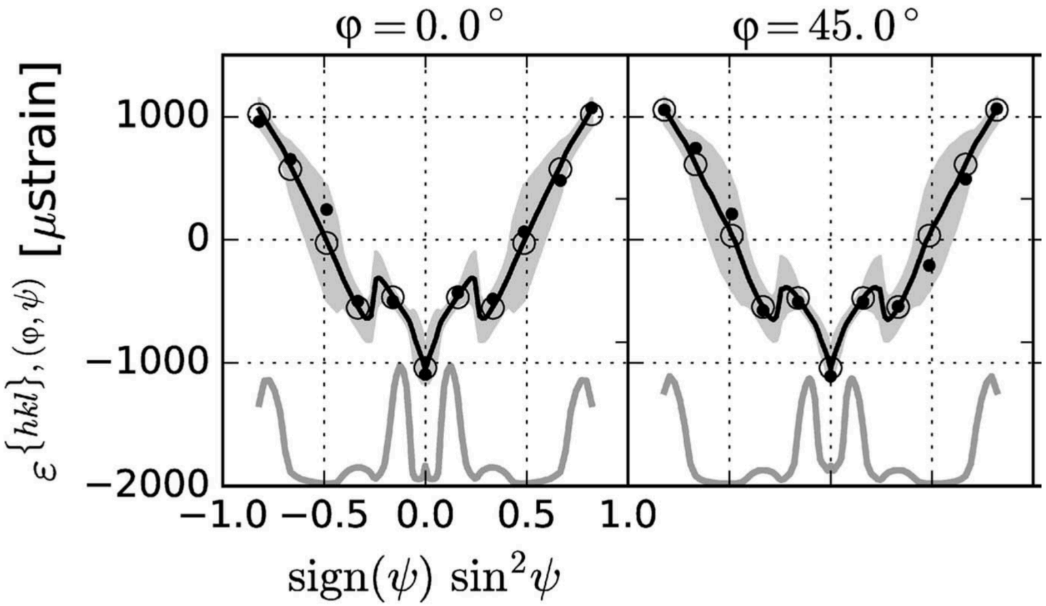
- Strain measured at the bulged top
- Flow stress estimated by monitoring oil pressure
- Unreliable data at the early stage of measurements.

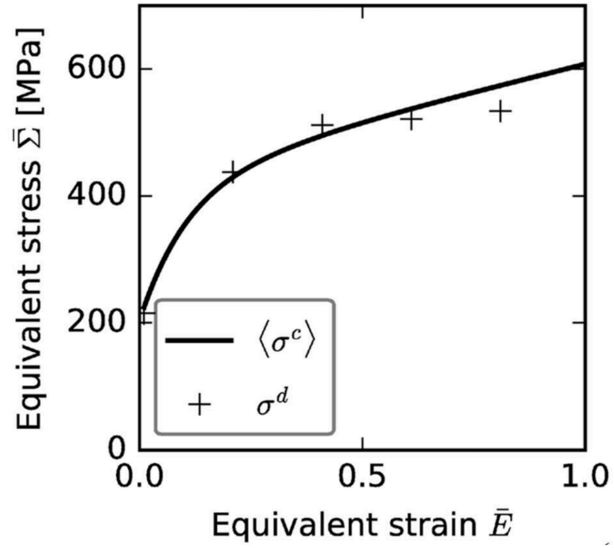


Y. Jeong et al., International Journal of Plasticity (2015)

Uncertainty estimation

Monte Carlo experiments applied to X-ray diffraction-based stress measurement using EVPSC

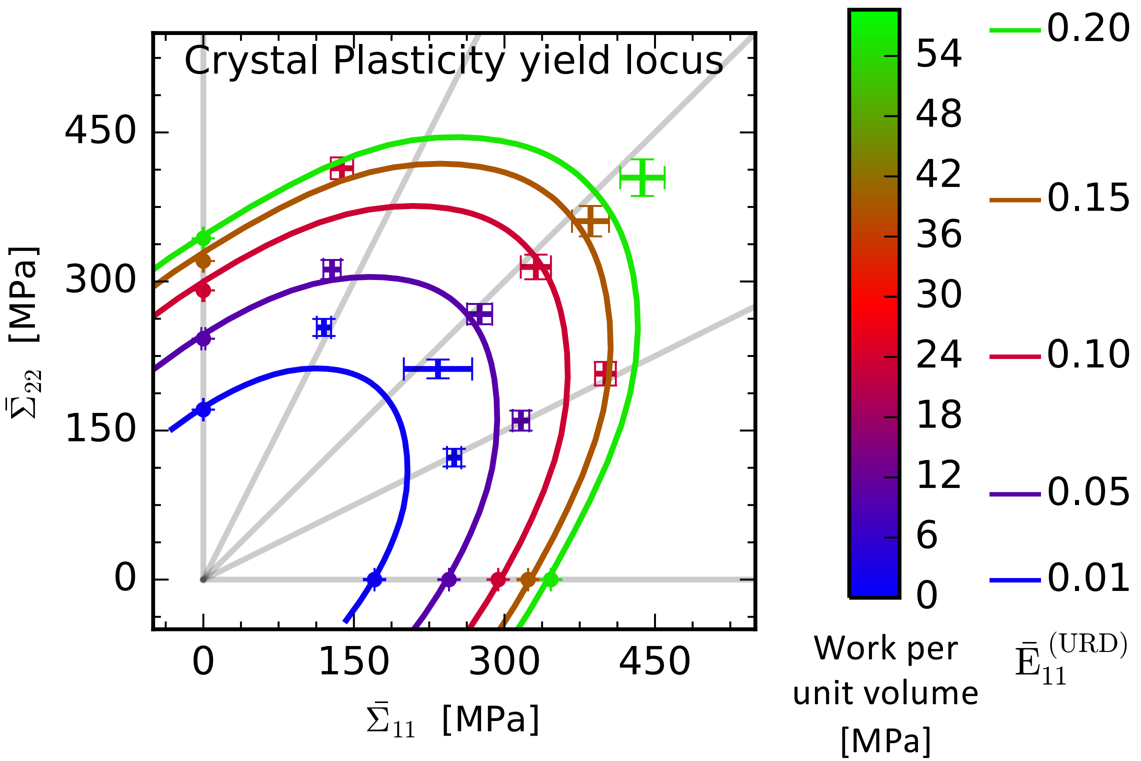




Optimized experimental conditions (less time without loss of accuracy)

Y. Jeong et al., Journal of Applied Crystallography (2016)

Multiaxial constitutive data at large plastic deformation



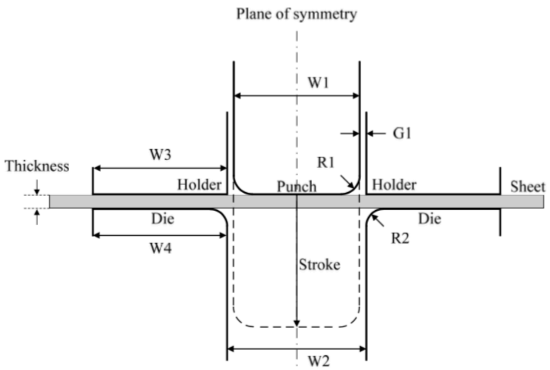
** Demonstrated that the experimental approach using X-ray is able to determine anisotropic hardening for the IF steel with 'anisotropic' diffraction strains.

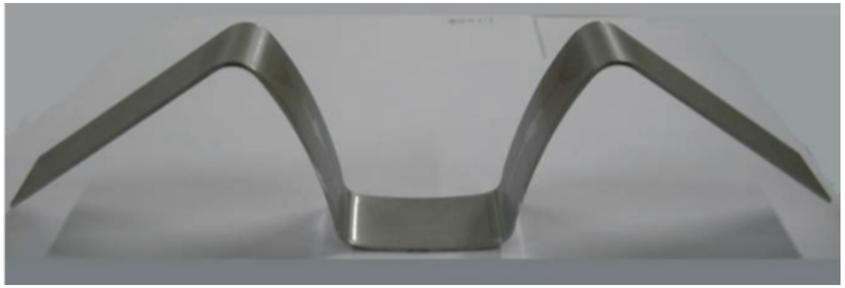
<u>Y. Jeong</u> et al., Acta Materialia (2016)

Outlines

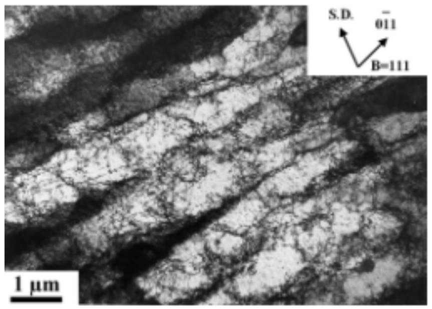
- Research motivation
- Short lecture on mean-field crystal plasticity (VPSC)
- Applications
  - Formability prediction using VPSC
  - Multiaxial flow stress measurement using XRD
  - VPSC and HAH
  - New EVPSC model development
- Summary

Multiscale modelling for springback





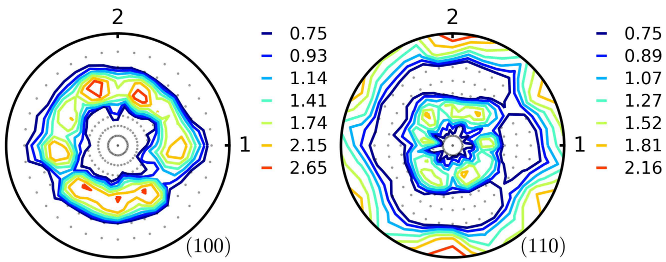
Dislocation cell structure



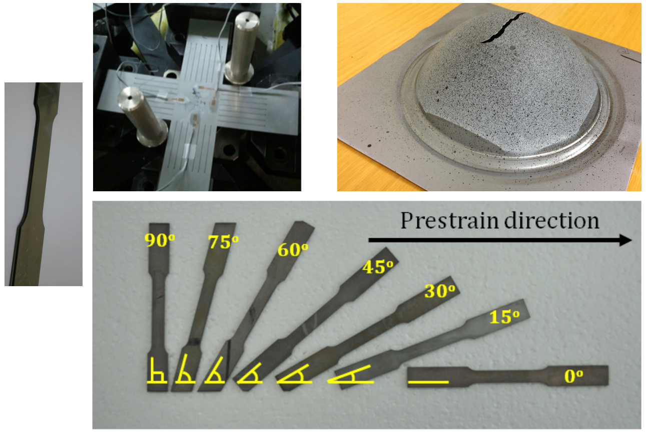
Micromechanical models (dislocation structure formation/ annihilation)

$$\tau_{\mathrm{B}}^{i} = \tau_{d}^{i}\left[1 - f_{\mathrm{B}}^{i}\left(\frac{\rho_{\mathrm{rev}}^{i,-(+)}}{\rho_{\mathrm{total}}}\right)\right] \quad \text{if} \quad \dot{\gamma}^{i,+(-)} > 0,$$

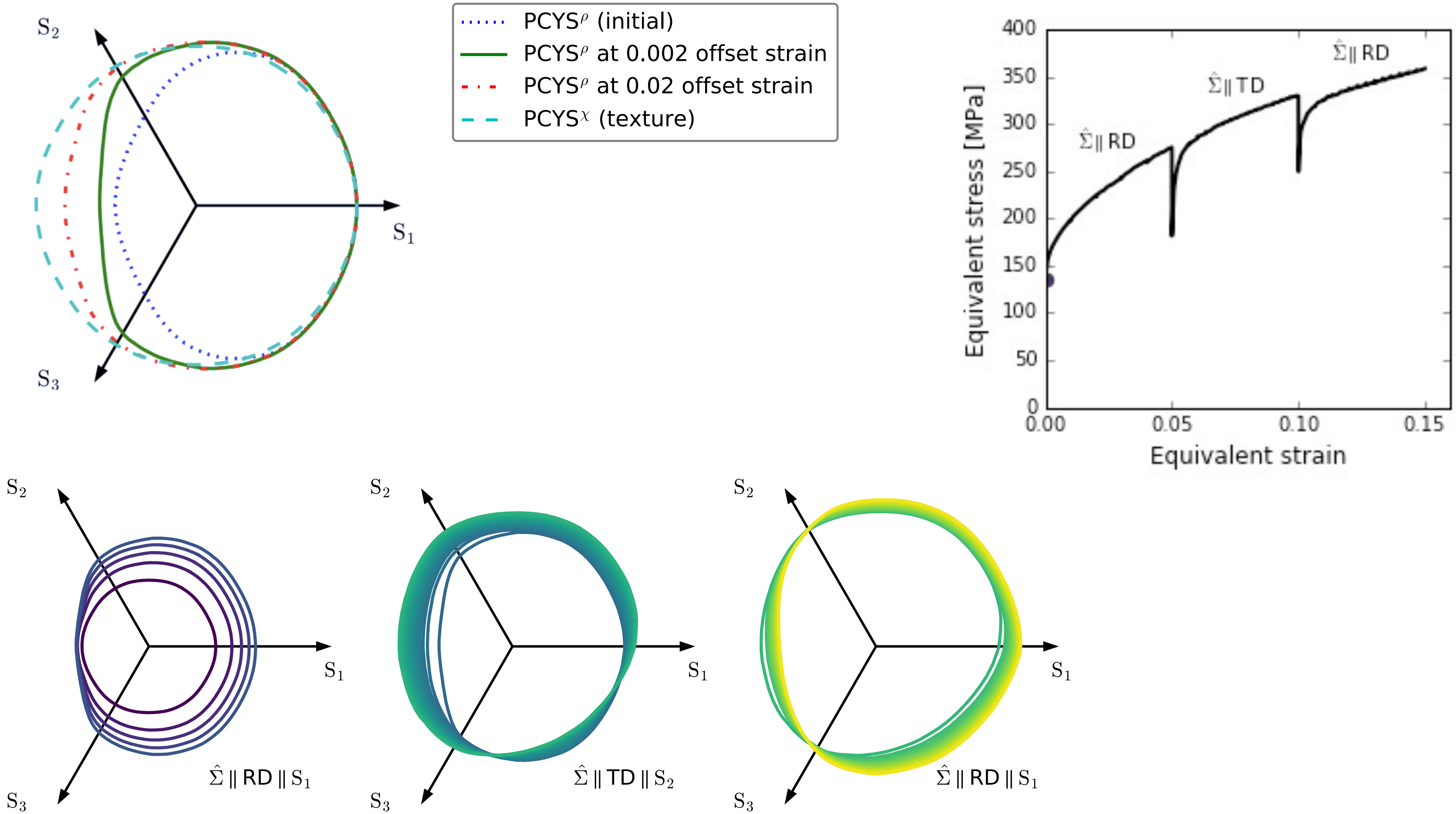
Crystallographic texture evolution



Conduct virtual experiments for complex loading paths



VPSC (micro) and HAH (macro)



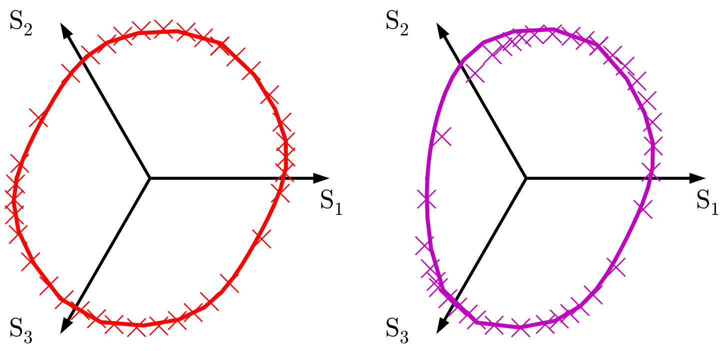
<u>Y. Jeong</u> et al., International Journal of Plasticity (2017)

Validating Empirical Rule of HAH

Yield surface (pi-plane)

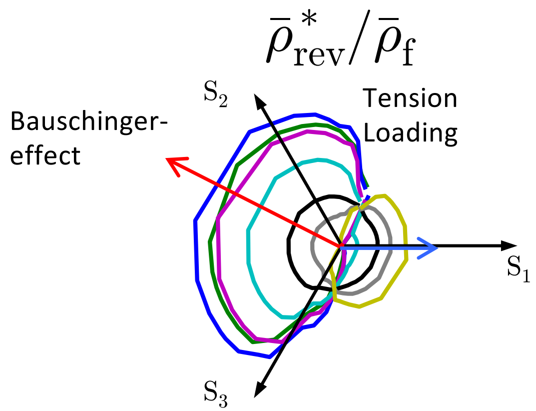
Crosses: Current micro crystal plasticity model

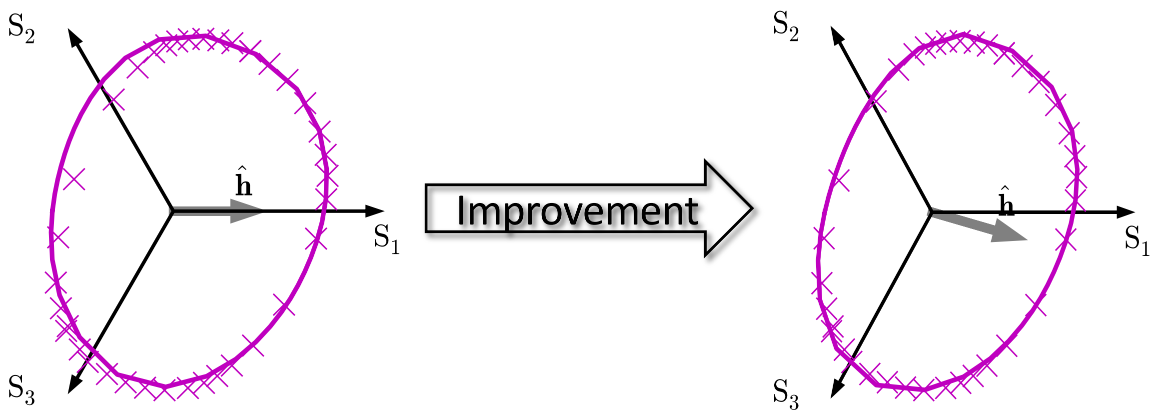
Line: Macro phenomenological model



initial   0.09 strain

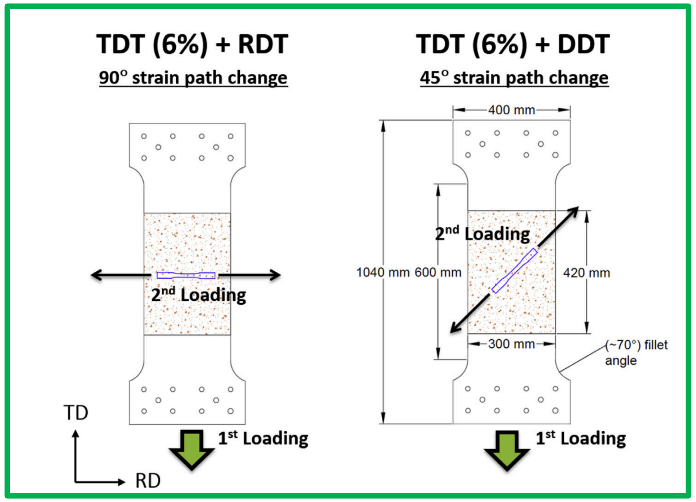
Back-stress surface

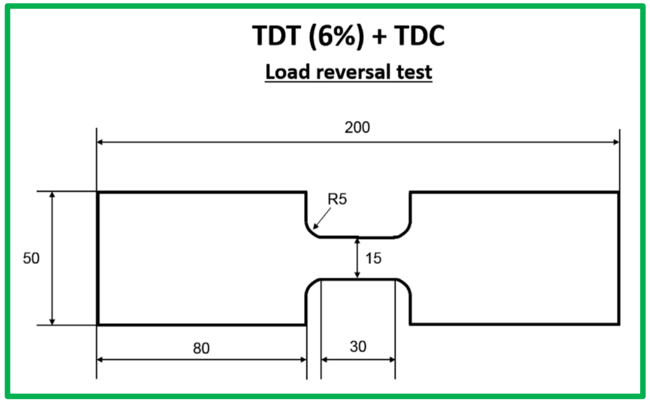


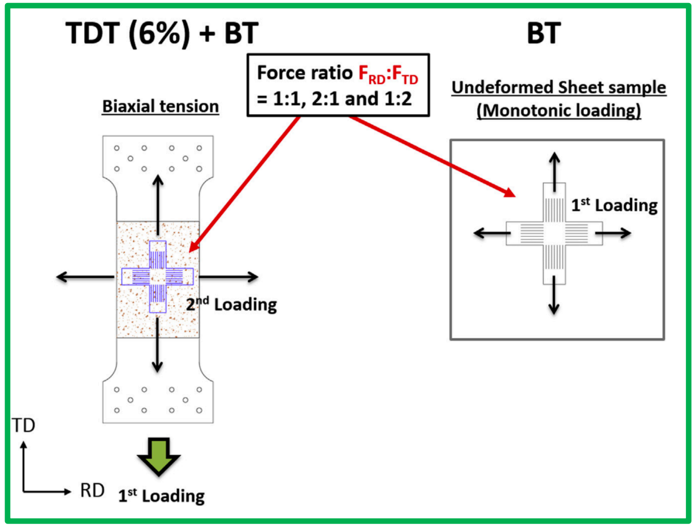


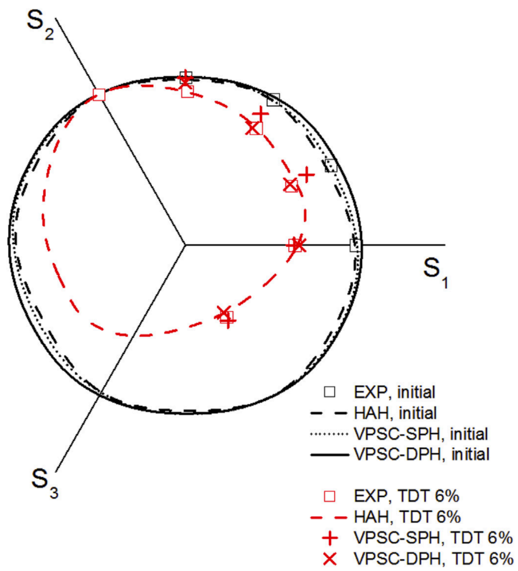
- ***Y. Jeong,*** F. Barlat, C. Tome (ESAFORM 2016)

VPSC, HAH and Dual phase steels









H. Kim, F. Barlat, Y. Lee, S. Zaman, C. S. Lee, ***Y. Jeong****, International Journal of Plasticity (2018)

Outlines

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- ❑ Applications
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New elasto-visco-plastic crystal plasticity model

Visco-Plastic model

$$\boldsymbol{\sigma} = \mathbb{C}^{vp} \dot{\boldsymbol{\varepsilon}}^{vp}$$

$$\dot{\boldsymbol{\varepsilon}}^{vp} = \mathbb{M}^{vp} \boldsymbol{\sigma}$$

Note: $\mathbb{M}^{vp} = (\mathbb{C}^{vp})^{-1}$

Elasticity model

$$\dot{\boldsymbol{\varepsilon}}^{el} = \mathbb{M}^{el} \dot{\boldsymbol{\sigma}}$$

$$\dot{\boldsymbol{\varepsilon}} = \dot{\boldsymbol{\varepsilon}}^{vp} + \dot{\boldsymbol{\varepsilon}}^{el}$$

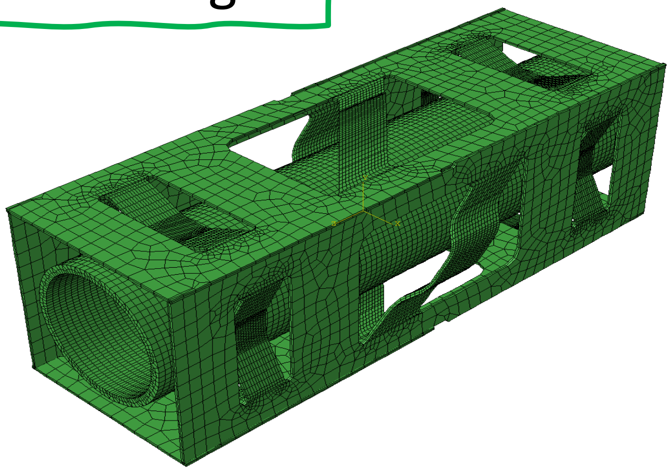
Elasto-Visco-Plastic model

$$\mathbb{M}^{el} \dot{\boldsymbol{\sigma}} + \mathbb{M}^{vp} \boldsymbol{\sigma} = \dot{\boldsymbol{\varepsilon}}$$

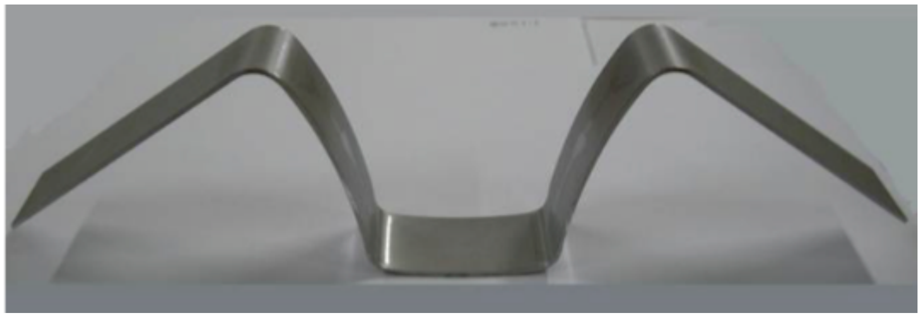
- EPSC (P.A. Turner, C.N. Tomé, Acta metall mater **42 (1994)** 4143-53)
- EVPSC (H. Wang, P.D. Wu, C.N. Tomé, Y. Huang, J Mech Phys Solids **58** (**2010**) 594-612)

Research Motivations

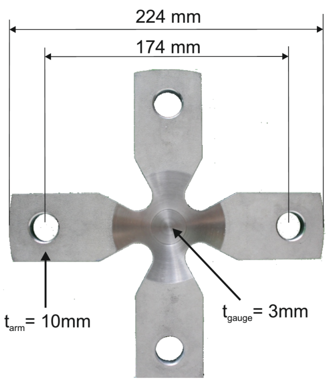
Reactor clad tube and grid

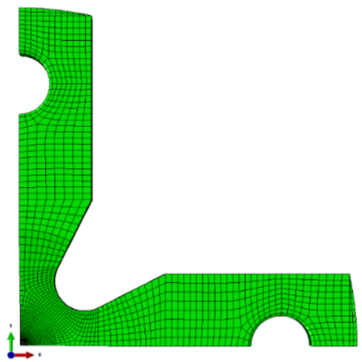


Springback



Cruciform biaxial specimen





Our new model (VPSC+)

- New EVPSC (called VPSC+) – perturbed strain term addition.

$$\left(\dot{\boldsymbol{\varepsilon}}^{vp} - \bar{\dot{\boldsymbol{\varepsilon}}}^{vp}\right) = -\widetilde{\mathbb{M}}^{vp} : (\boldsymbol{\sigma} - \bar{\boldsymbol{\sigma}})$$

$$\left(\dot{\boldsymbol{\varepsilon}}^{el} - \bar{\dot{\boldsymbol{\varepsilon}}}^{el}\right) = -\widetilde{\mathbb{M}}^{el} : (\dot{\boldsymbol{\sigma}} - \bar{\dot{\boldsymbol{\sigma}}})$$

The sum as a visco-plastic law with an eigen-strain-rate '***perturbing***' the interaction equation:

$$\left(\dot{\boldsymbol{\varepsilon}}^{vp} - \bar{\dot{\boldsymbol{\varepsilon}}}^{vp} + \dot{\boldsymbol{\varepsilon}}^{tr}\right) = -\widetilde{\mathbb{M}}^{vp} : (\boldsymbol{\sigma} - \bar{\boldsymbol{\sigma}})$$

the eigen-strain-rate is $\dot{\boldsymbol{\varepsilon}}^{tr} = \left(\dot{\boldsymbol{\varepsilon}}^{el} - \bar{\dot{\boldsymbol{\varepsilon}}}^{el}\right) + \widetilde{\mathbb{M}}^{el} : (\dot{\boldsymbol{\sigma}} - \bar{\dot{\boldsymbol{\sigma}}})$

$$= \left(\mathbb{M}^{el} + \widetilde{\mathbb{M}}^{el}\right) : \dot{\boldsymbol{\sigma}} - \left(\bar{\mathbb{M}}^{el} - \widetilde{\mathbb{M}}^{el}\right) : \bar{\dot{\boldsymbol{\sigma}}}$$

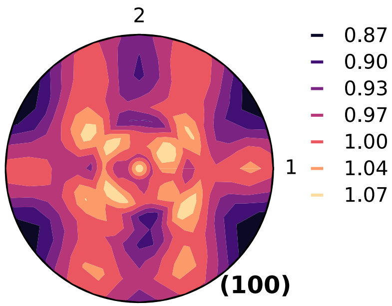
$$\dot{\boldsymbol{\sigma}} \approx \frac{\boldsymbol{\sigma} - \boldsymbol{\sigma}_{prev}}{\Delta t} \qquad \bar{\dot{\boldsymbol{\sigma}}} \approx \frac{\bar{\boldsymbol{\sigma}} - \bar{\boldsymbol{\sigma}}_{prev}}{\Delta t}$$

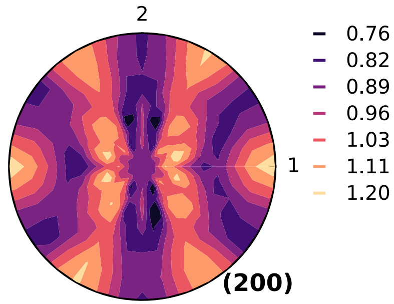
- ***Y. Jeong*** and C. N. Tomé (submitted)

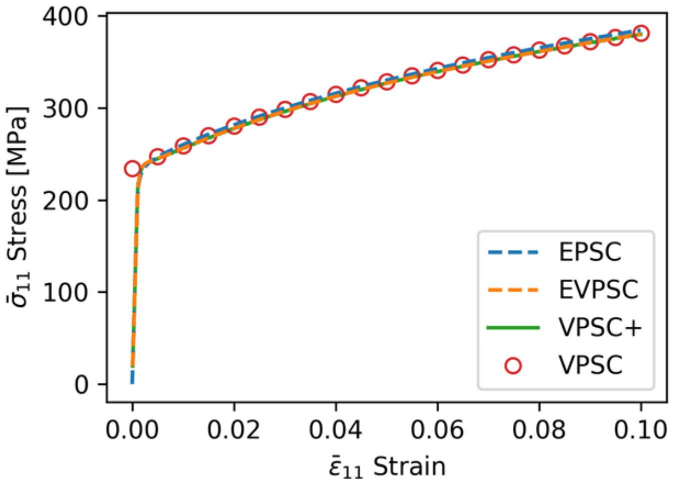
VPSC+ results are compared with other similar models and experiments

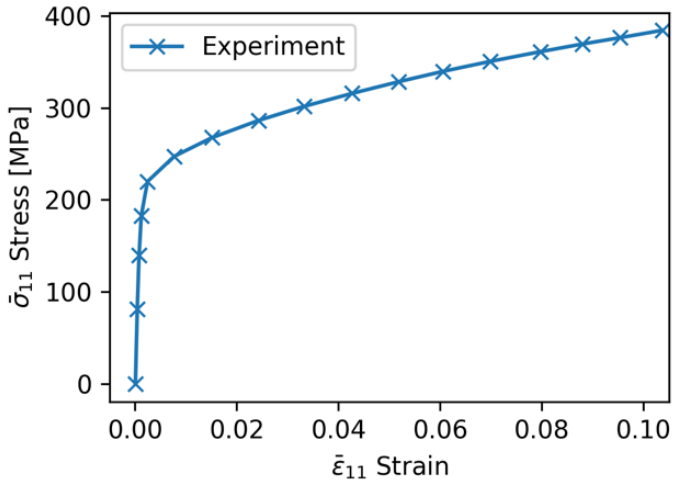
Application to 316L stainless steel

Initial texture

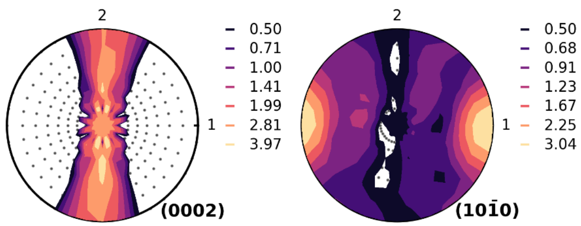


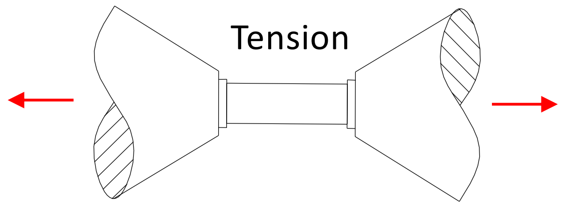


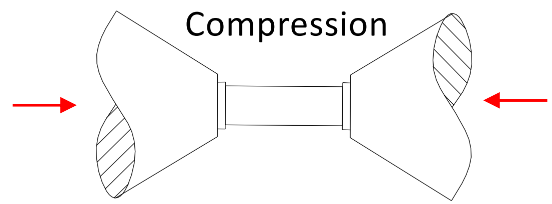


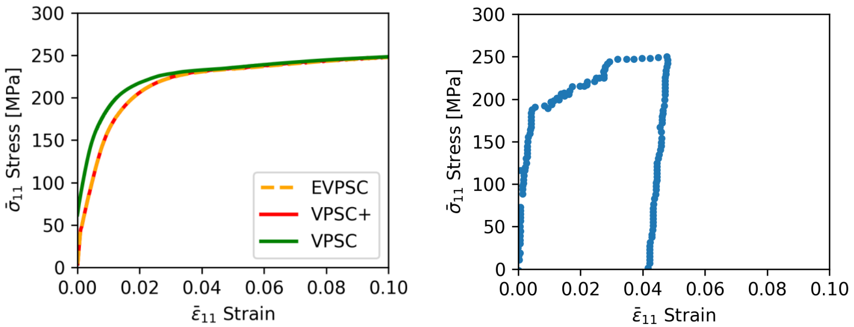


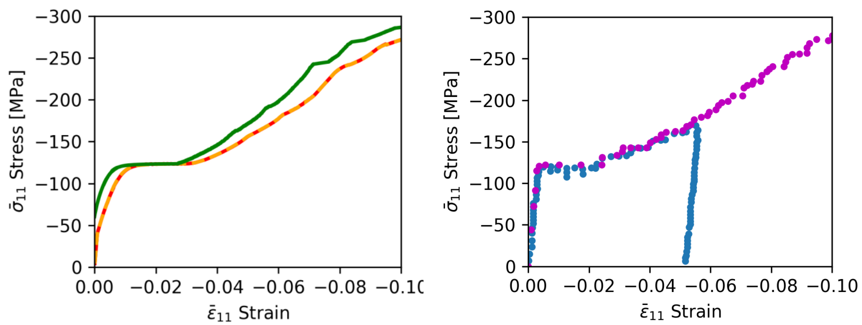
AZ31; uniaxial tension and compression; flow stress-strain curves

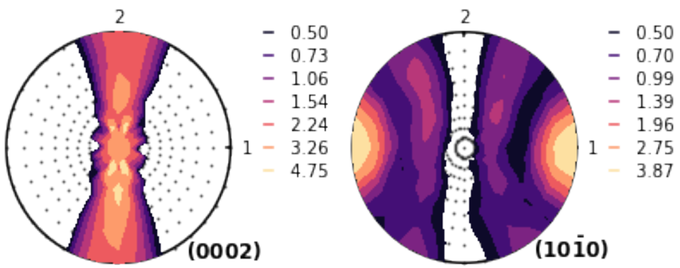


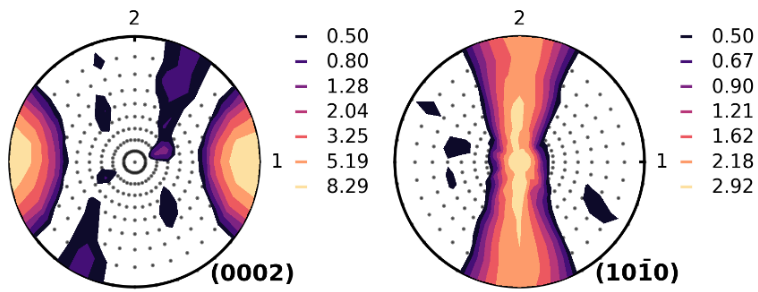




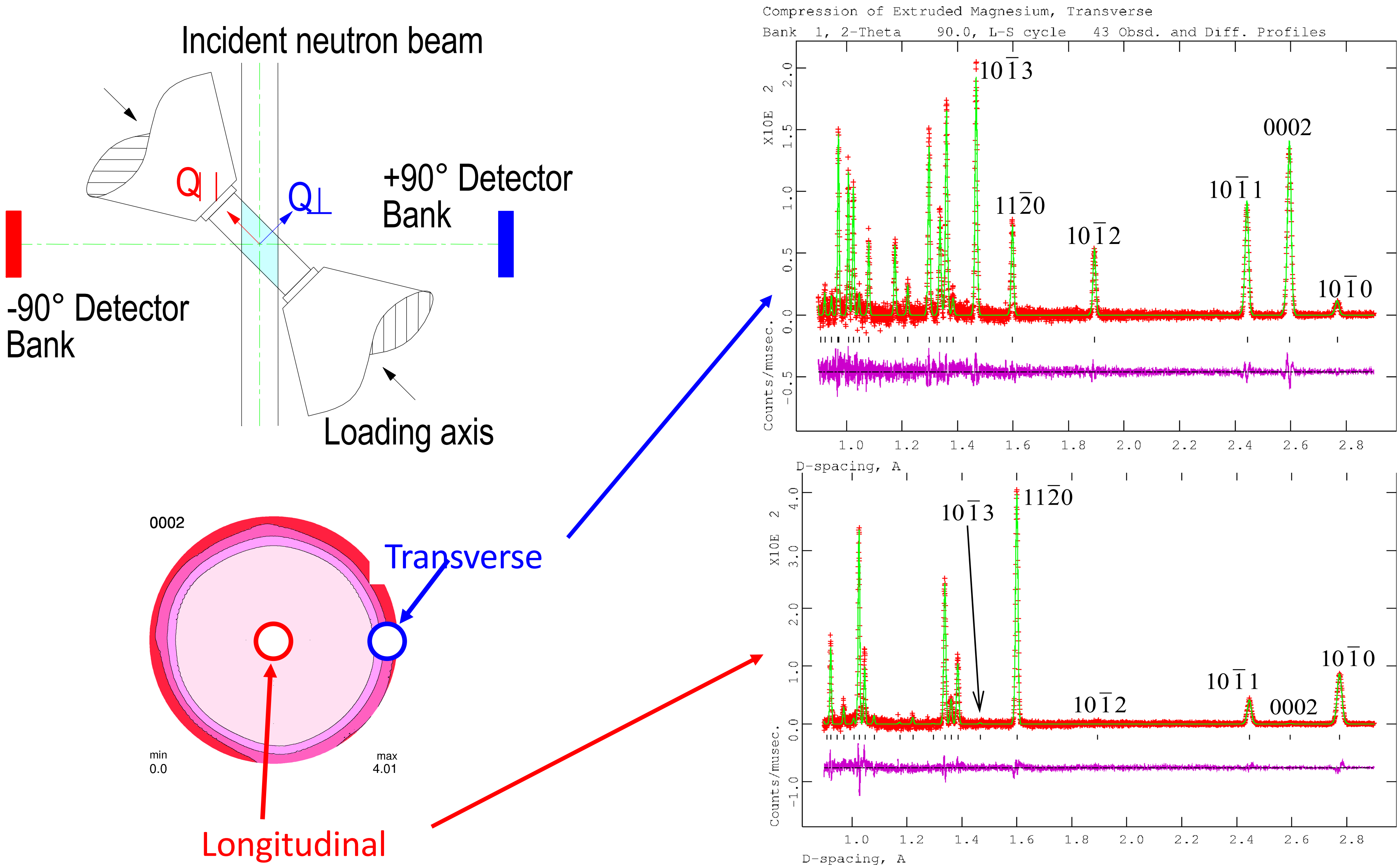




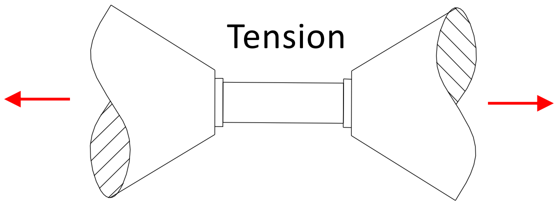


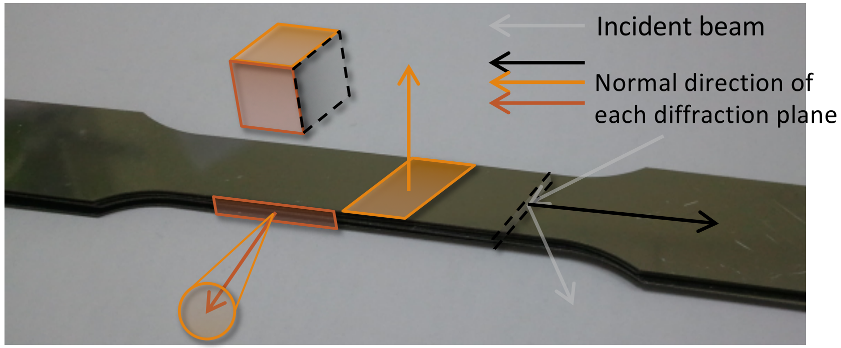


Scattering Vectors, Texture, Diffraction Profiles

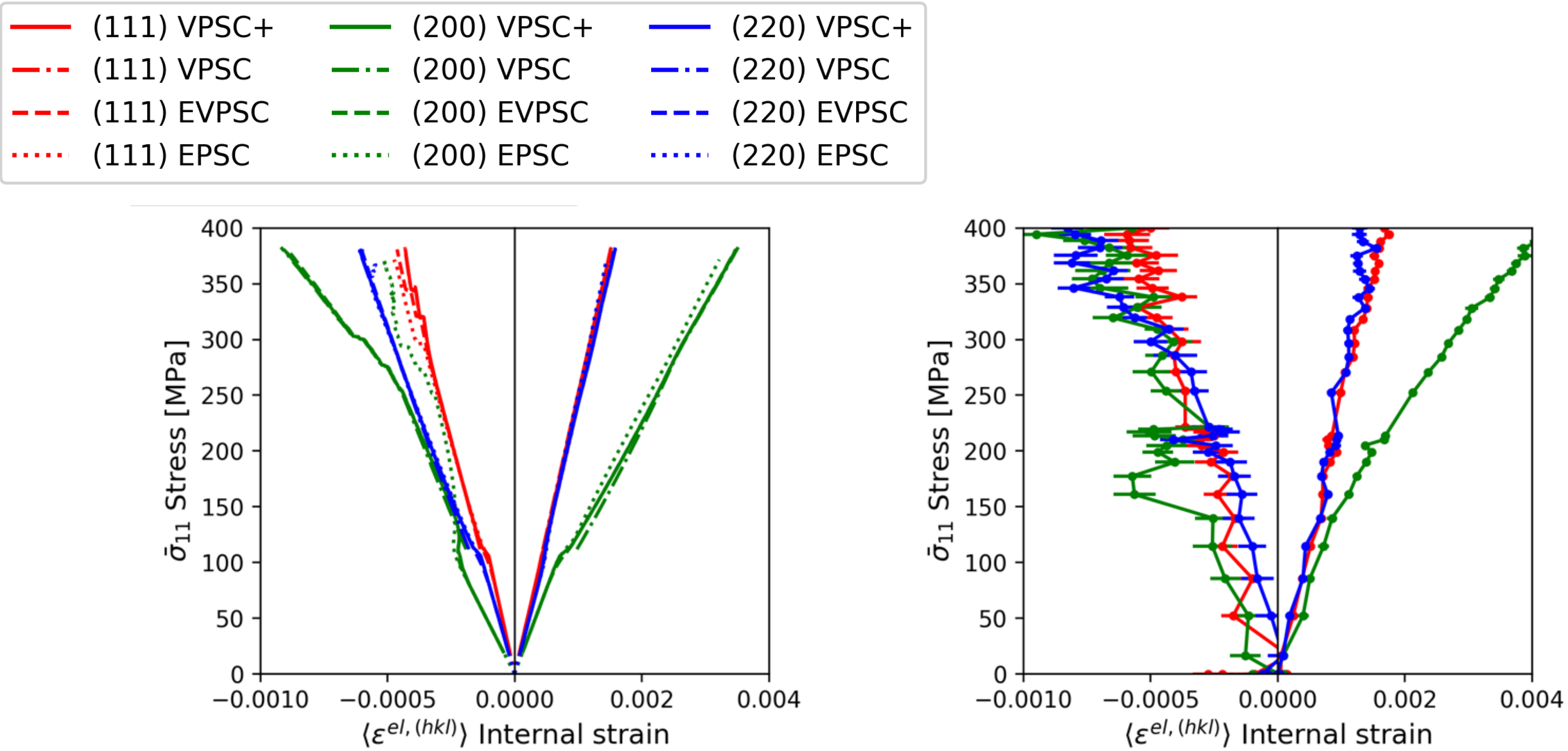


Internal strain evolution (316L)

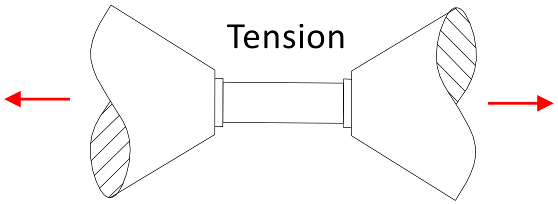


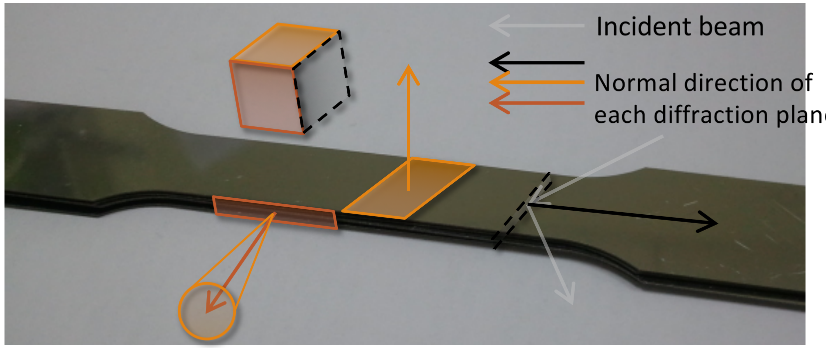


Schematic illustration on in-situ diffraction uniaxial test

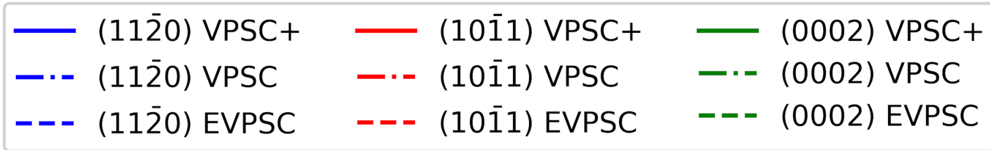


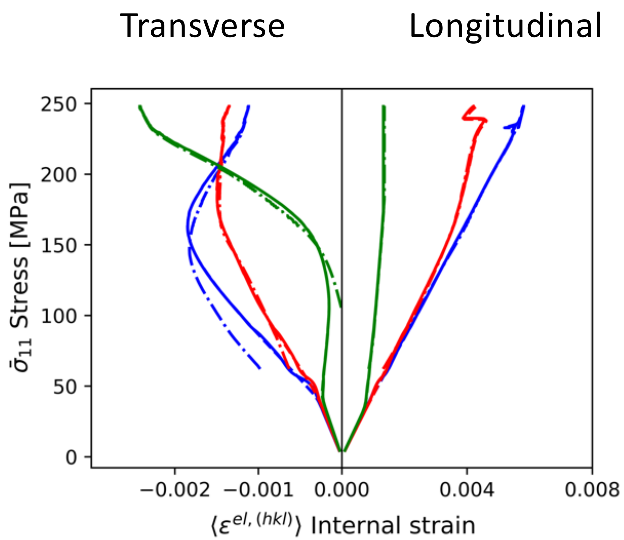
Internal strain evolution (AZ31 - tension)

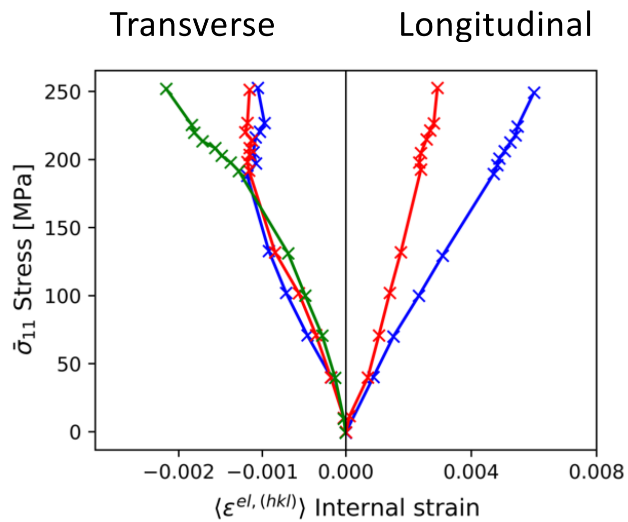




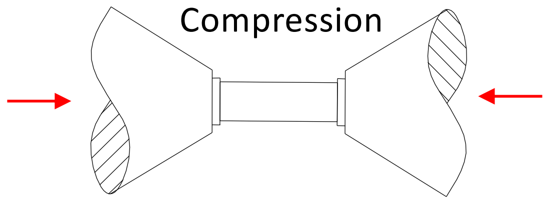
Schematic illustration on in-situ diffraction uniaxial test

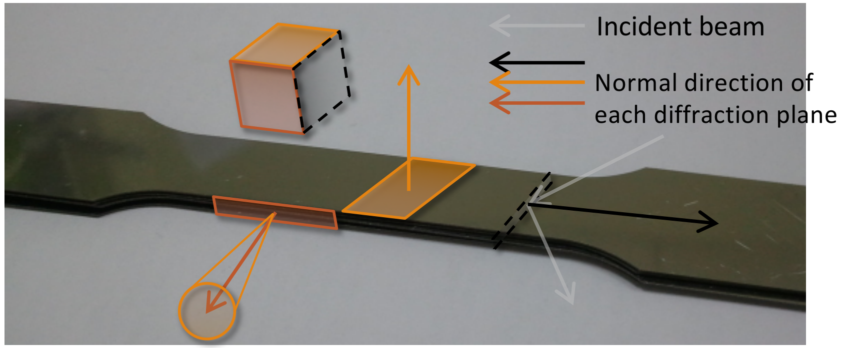




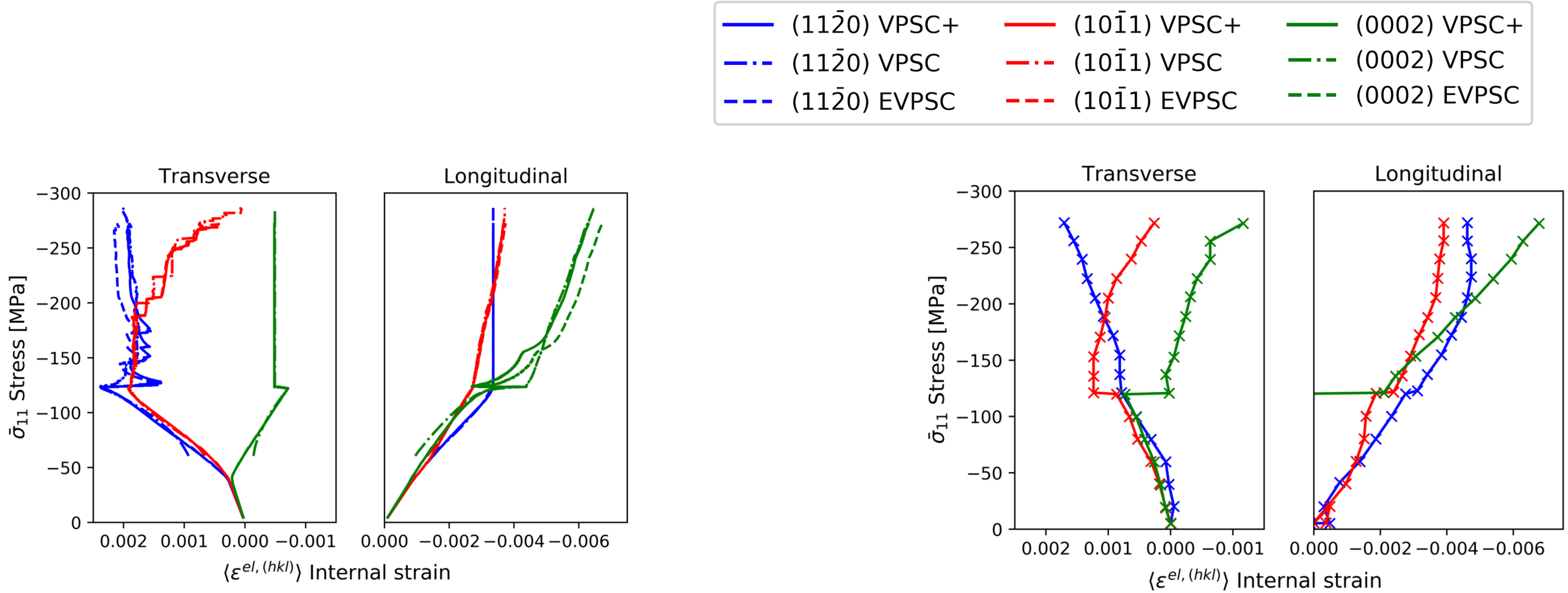


Internal strain evolution (AZ31 - compression)

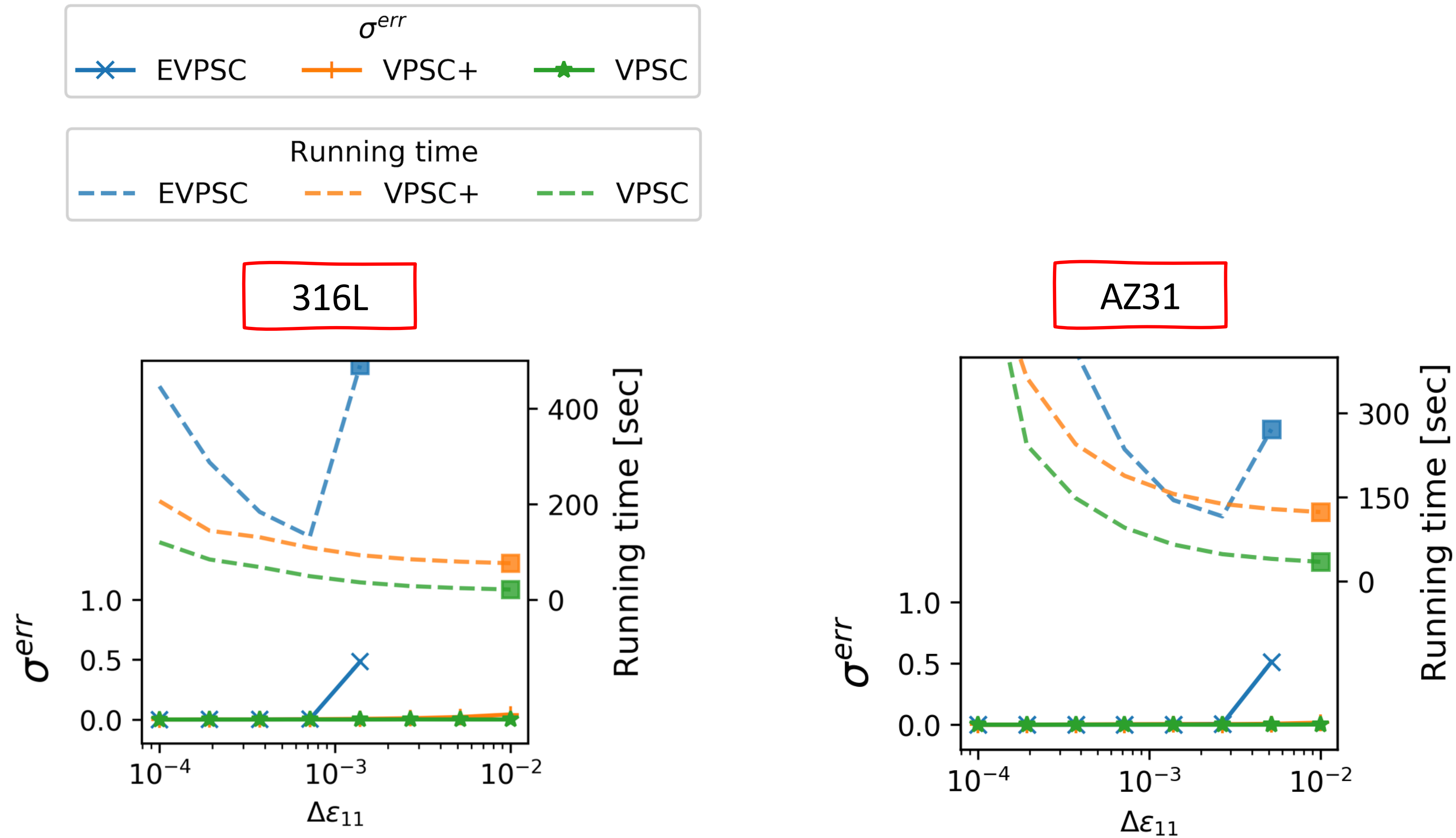




Schematic illustration on in-situ diffraction uniaxial test



Computational performance

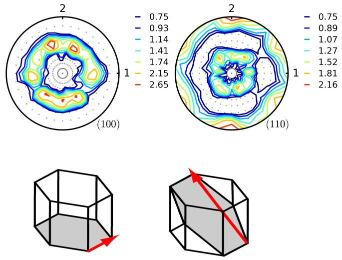


- Y. Jeong and C. N. Tomé (submitted)

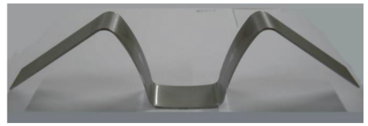
Summary

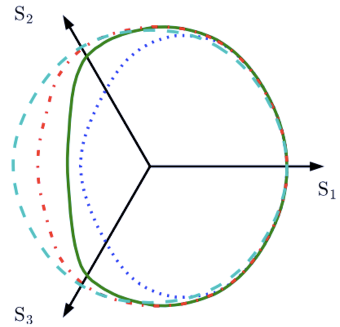
Visco-Plastic model

$$\boldsymbol{\sigma} = \mathbb{C}^{vp}\dot{\boldsymbol{\varepsilon}}$$

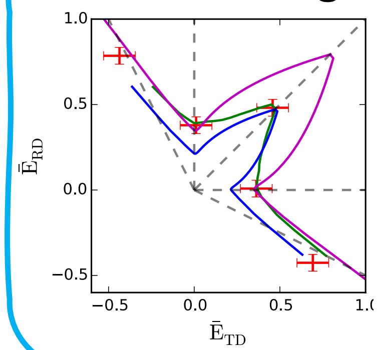


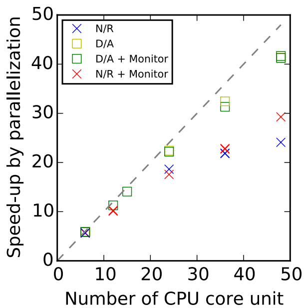
Multiscale modelling





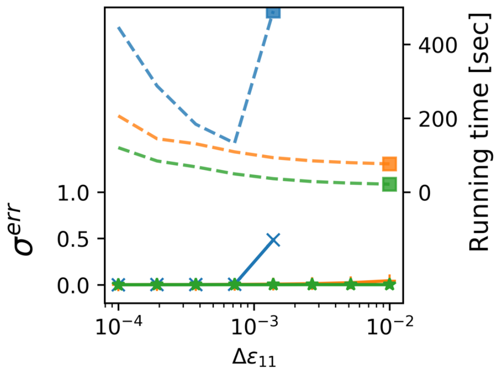
Forming limit diagram



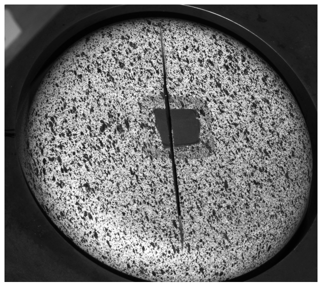


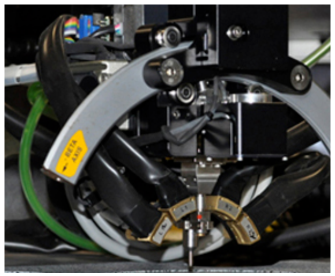
New Elasto-Visco-Plastic model

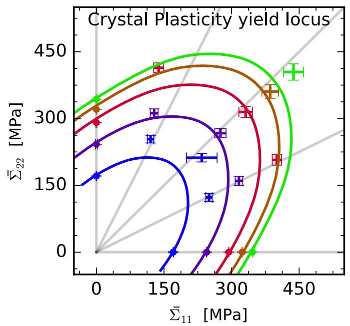
$$\mathbb{M}^{el}\dot{\boldsymbol{\sigma}} + \mathbb{M}^{vp}\boldsymbol{\sigma} = \dot{\boldsymbol{\varepsilon}}$$



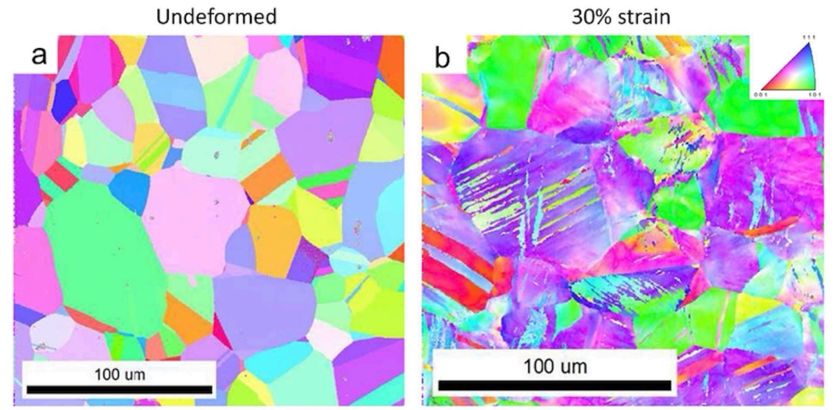
Multiaxial Experiments

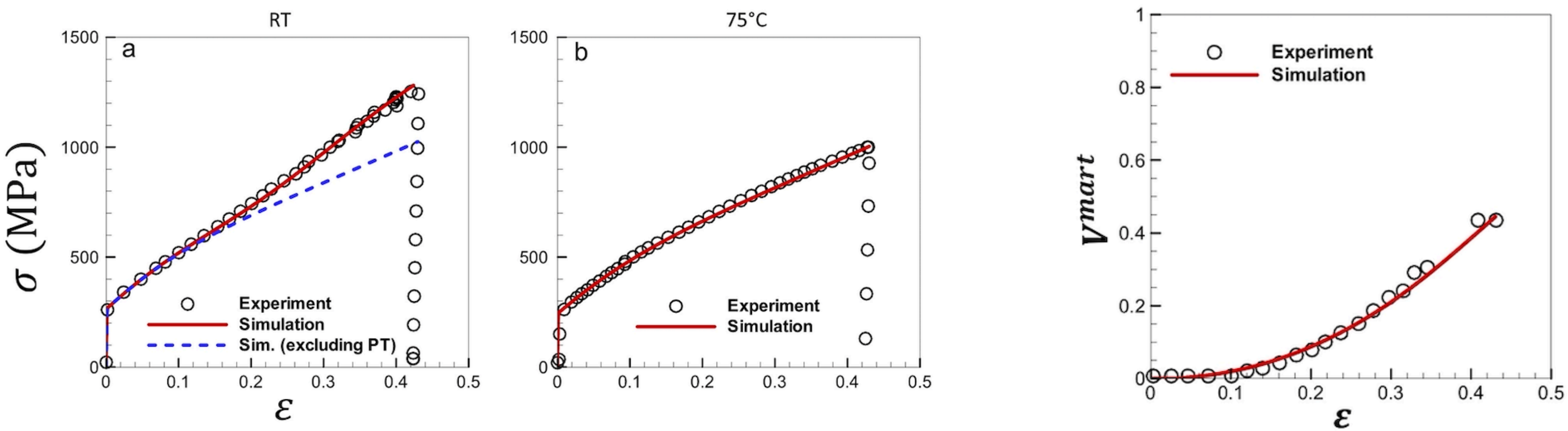






TRIP steel (304 Stainless steel)





Texture prediction and lattice strain