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STATISTICAL CRYSTAL PLASTICITY MODELS AND THEIR IMPLEMENTATION IN FE MODELS FOR PLASTIC FORMING

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M2i Conference, December 10th 2019

(Presented by Leo Kestens, UGent, TUDelft)

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Jurij Sidor	

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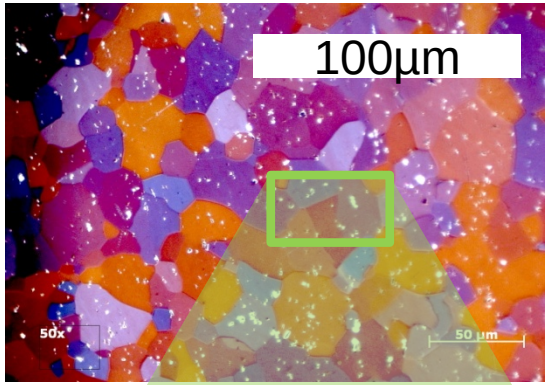
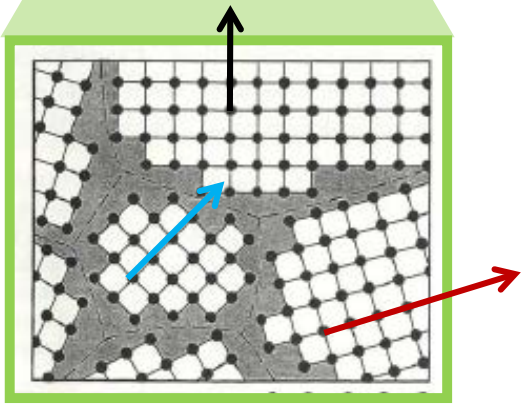
Outline

- Introduction
- Statistical crystal plasticity models
- FE coupled with statistical CP models
- Conclusions and perspectives

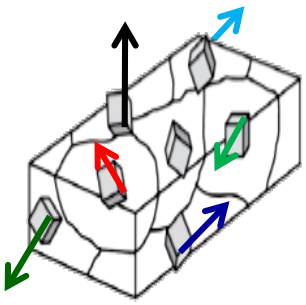
Crystallographic Texture

Polycrystalline Microstructure

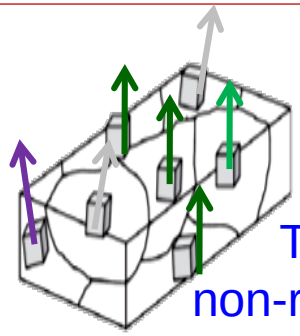




Lattice orientations

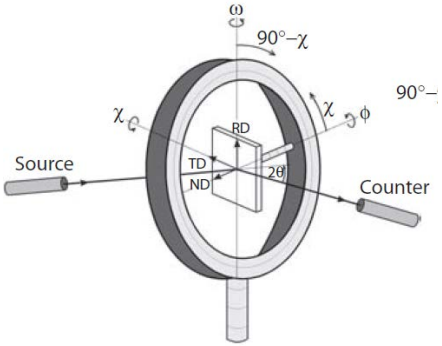


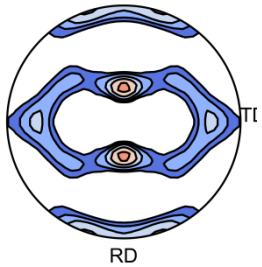
random orientations

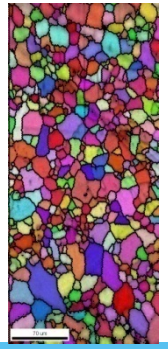


Texture: non-random distribution of orientations

Measurement: X-Ray Diffraction (Pole figures) or EBSD







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Scales in Plastic Forming Process Simulations

***Engineering scale:* work-piece**

FE model

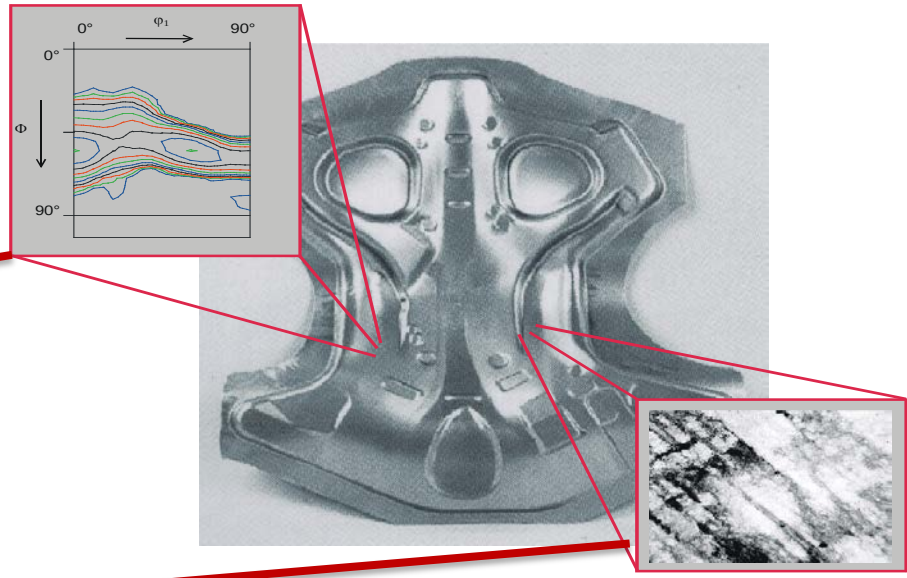
Macroscopic scale: Integration point
multicrystal with ~ 5000 grains

Meso-Macro Model

Mesoscopic scale: Grain or inclusion
Cluster with 1 or 2 grains

Microscopic work hardening law

Microscopic scale: Dislocation densities, cell (block) boundaries
Distribution of dislocations, substructure



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Scales in Plastic Forming Process Simulations

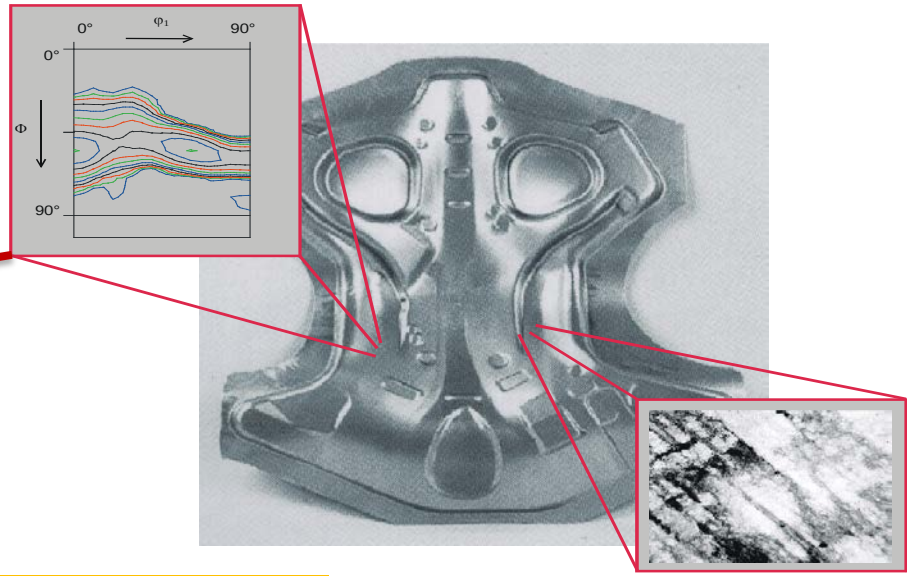
***Engineering scale:* work-piece**

FE model

Macroscopic scale: Constitutive Model
multicrystal with ~ 5000 grains

Meso-Macro Model

Mesoscopic scale: Crystal Plasticity Model
Cluster with 1 or 2 grains



Hierarchical multi-scale modelling!

Microscopic scale:
Distribution of dislocations, substructure

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Outline

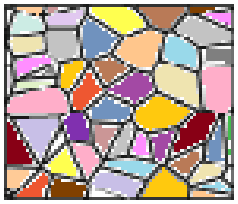
- Introduction
- Statistical crystal plasticity models
- FE coupled with statistical CP models
- Conclusions and perspectives

Crystal Plasticity Models

- **Homogenization/statistical models**
  - (FC) Taylor
  - RC Taylor
  - LAMEL
  - ALAMEL
  - Self-Consistent (VPSC, EPSC, …)
  - Grain InterAction (GIA)
  - …
- **Full-field/RVE models**
  - Crystal Plasticity Finite Element (CP FEM)
  - Crystal Plasticity Fast Fourier Transform (CP FFT)
  - …

100s -1000s microstructural units

A single RVE



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Crystal Plasticity Models

- **Homogenization/statistical models**
  - (FC) Taylor
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  - …
- **Full-field/RVE models**
  - Crystal Plasticity Finite Element (CP FEM)
  - Crystal Plasticity Fast Fourier Transform (CP FFT)
  - …

Grain interaction neglected

Grain interaction modeled

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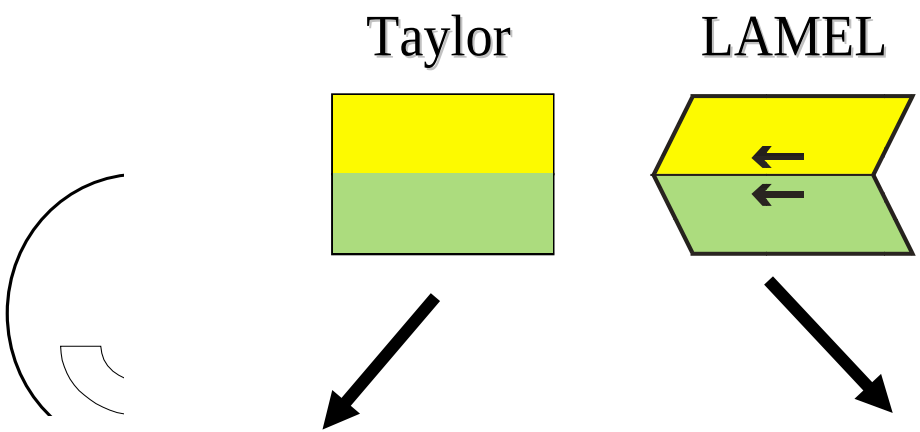
Statistical crystal plasticity models

- set of crystal orientations
- each crystal orientation has a certain volume fraction, chosen such that the entire set is statistically representative for the polycrystalline material, as far as the overall texture is concerned



Model Assumptions:

All grains have the same plastic deformation

The model operates on stacks of 2 grains (with the same volume)
Mutually compensating, shear-type deviations from the Taylor theory are allowed.

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Statistical crystal plasticity models - Taylor

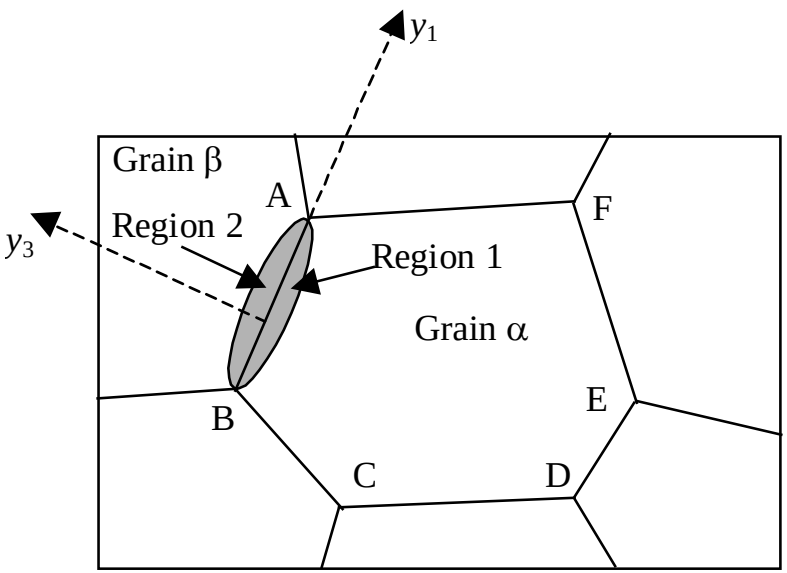
– **Assessment of the Full Constraints Taylor Model :**
  - Stress equilibrium at grain boundaries is NOT guaranteed
  - Heterogeneity of plastic strain is underestimated
  - Plastic flow stress is overestimated
  - Predicted deformation textures: qualitatively correct, not quantitatively
  - Fairly general model (not restricted to particular materials or deformation modes)

Statistical crystal plasticity models - ALAMEL

Advanced Lamel Model (ALAMEL)

strain gradient/Interaction Model

schematic representation
of microstructure: 2-grain clusters



– It is assumed that at the grain boundaries (in Region 1 and Region 2), the slips activities are
  - different in both regions (*different lattice orientations!*)
  - stress equilibrium is achieved at the boundary
  - geometrical compatibility exists at the boundary ⇒ co-operative shear

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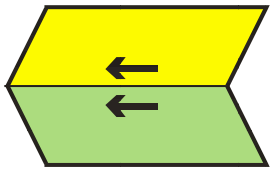
Statistical crystal plasticity models - ALAMEL

- **Assessment of ADVANCED LAMEL model:**
  - Taylor ambiguity does normally NOT occur.
  - Physical justification possible for ALL microstructures and ALL strain modes.
  - In principle generally applicable.
  - All cases of co-operative slip should be recognised and taken into account.
  - Statistical model based on stress equilibrium and strain compatibility along grain boundaries.
  - Predictions of rolling textures *(quantitative assessment)*:
    - good for steel, slightly less than LAMEL model or GIA model
    - very good for aluminium, same quality level as CPFEM models (Crystal Plasticity Finite Element Models, applied to a 3D microstructure)
  - Model is still experimental: validation/refinement must be continued.



Co-operative slip

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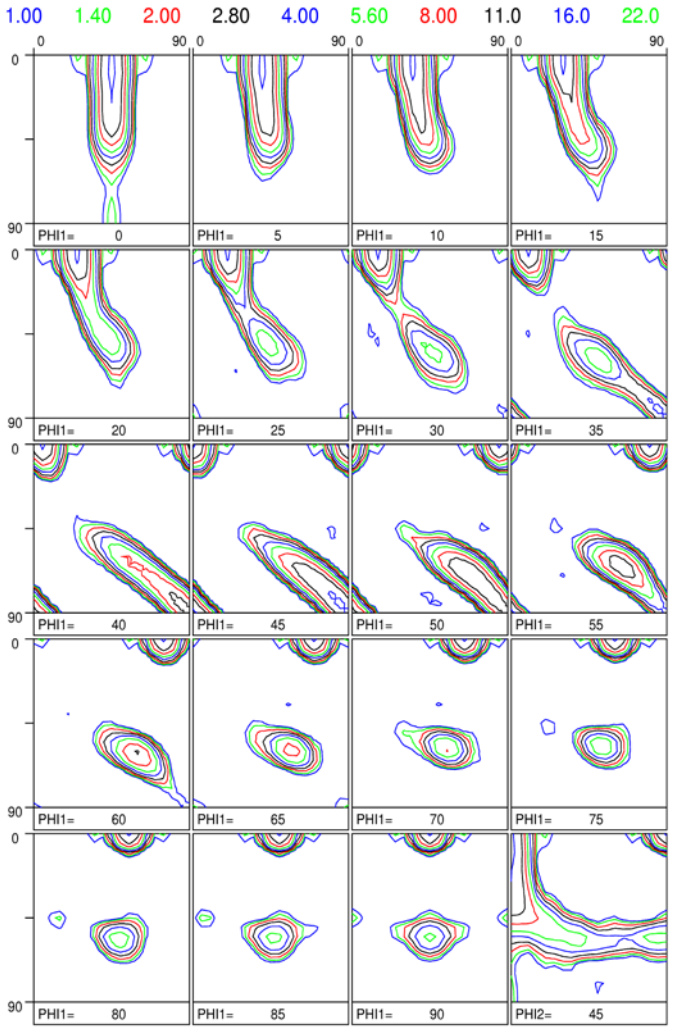
Statistical crystal plasticity models – texture evolution predictions

- ODF for IF Steel:
  - Measured by X-ray diffraction + data deconvolution procedure
  - Other methods:
    - Neutron diffraction
    - OIM scan
  - sections of constant φ_1
    - + φ_2=45° section



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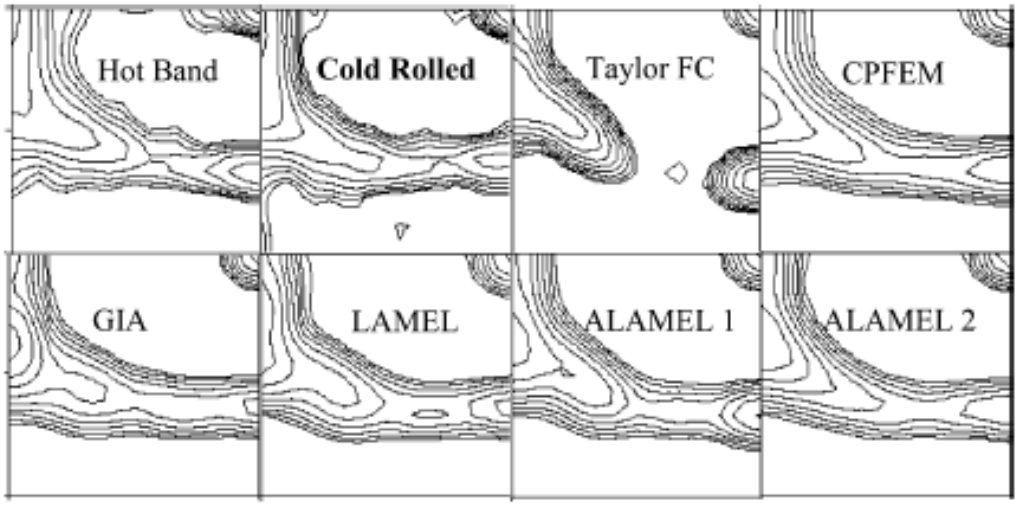
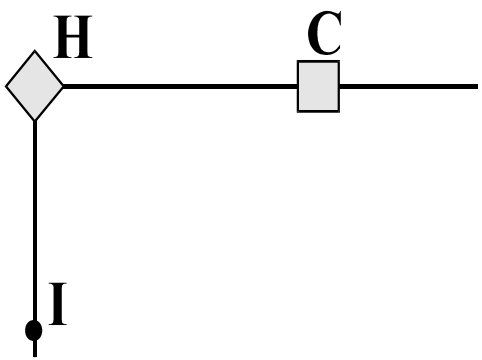
Statistical crystal plasticity models – texture evolution predictions

Example of Results: Simulation of Cold rolling texture, IF steel





φ_2=45° sections of the ODF of 8 textures of IF steel: hot band texture, texture after 70% cold rolling reduction, simulated textures according to 6 models. CPFEM by Bate (1999). ALAMEL 1: starting from equiaxed grains; ALAMEL 2: starting from elongated grains (as if the grains of the hot rolled microstructure already had 40% rolling reduction) and using additional {123}<111> slip systems.
Levels: 1; 1.4; 2; 2.8; 4; 5.6; 8; 11; 16; 22.

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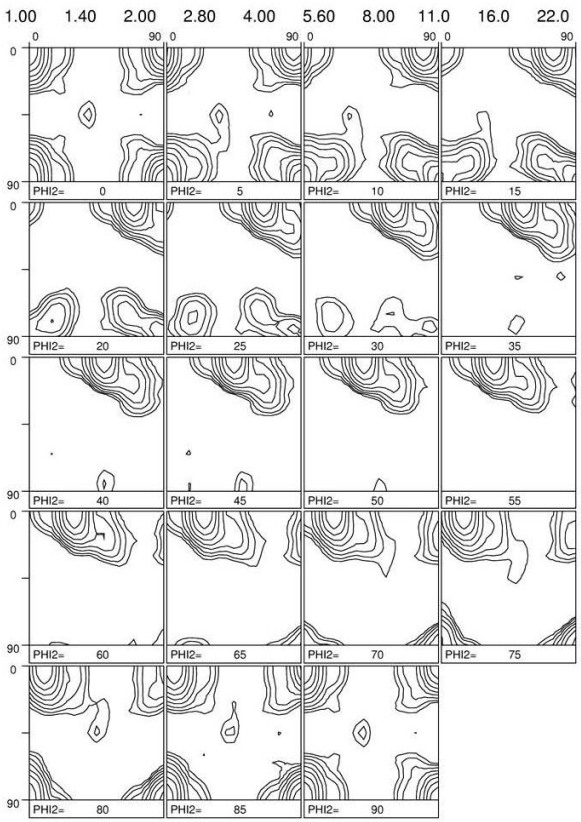
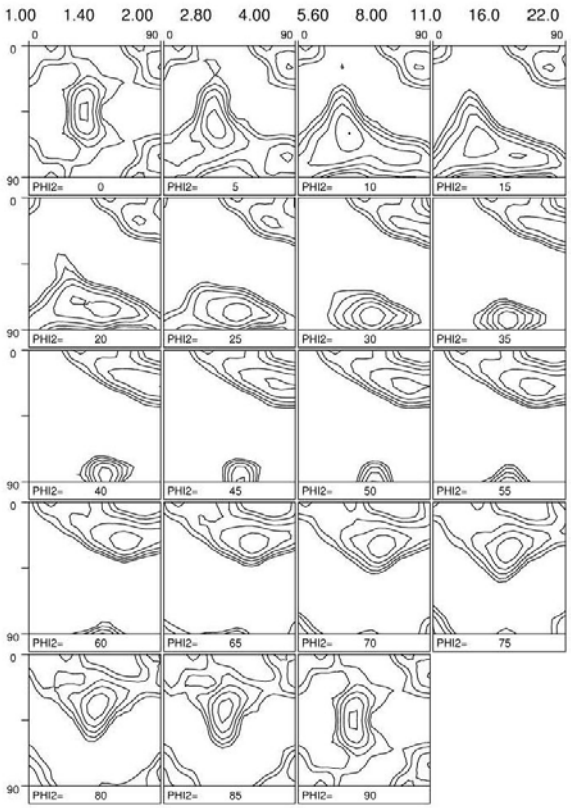
Statistical crystal plasticity models – texture evolution predictions

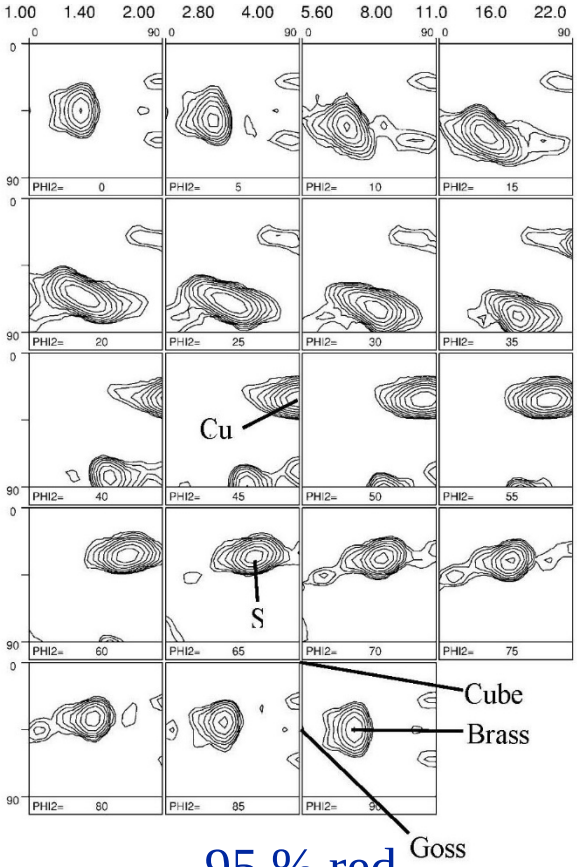
AA 1200 φ_2=constant sections



Hot rolled



Cold rolled: 40 % red.



95 % red.

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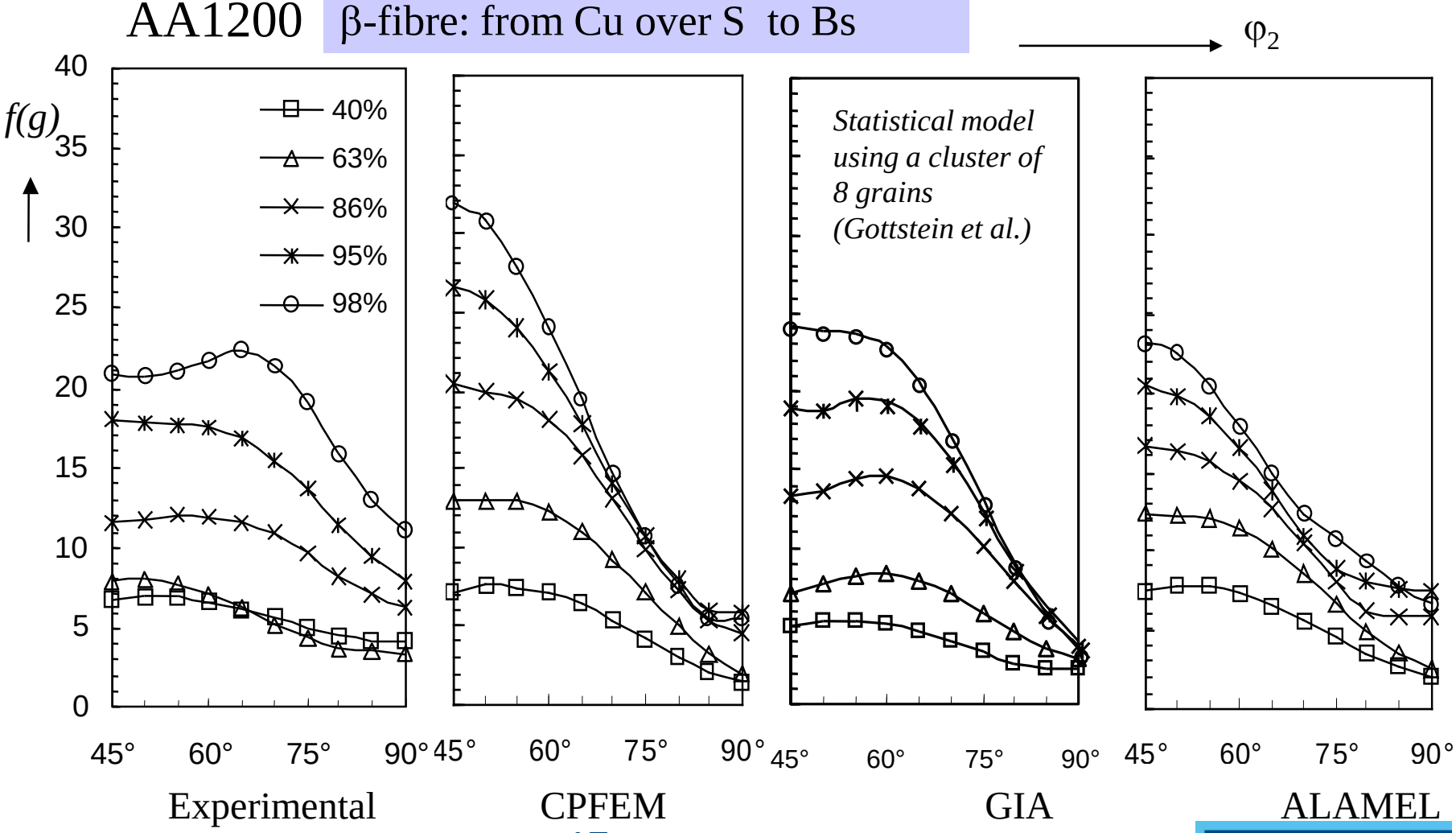
Statistical crystal plasticity models – texture evolution predictions

AA1200 β-fibre: from Cu over S to Bs



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Application:

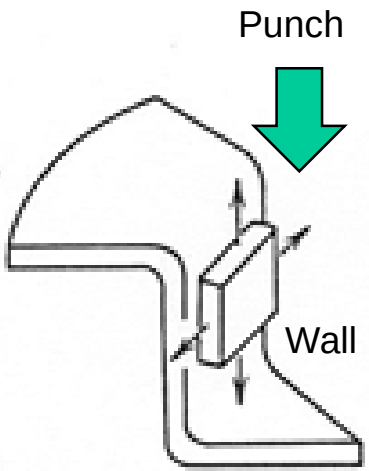
Asymmetric rolling for texture optimization of aluminium sheet

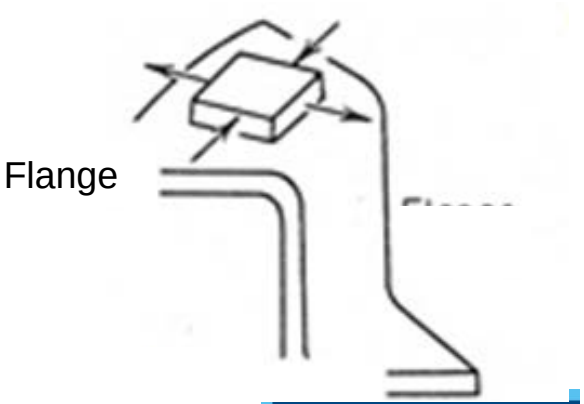
Shore et al., Int. J. Mater. Form. (2018) 11:297-309

Deep drawability

- Complex concept, used in sheet metal forming
- Very conventional approach here:
  - Cup drawing test: a cylindrical punch pushes a circular blank through a cylindrical die.
  - Measurement of limiting deep drawing (LDR): maximum ratio between blank to punch radius for which the cup drawing operation does not fail

- Punch applies a vertical force to the bottom of the cup.
- Failure occurs when the cup wall cannot transfer this force to the flange where the deformation takes place.

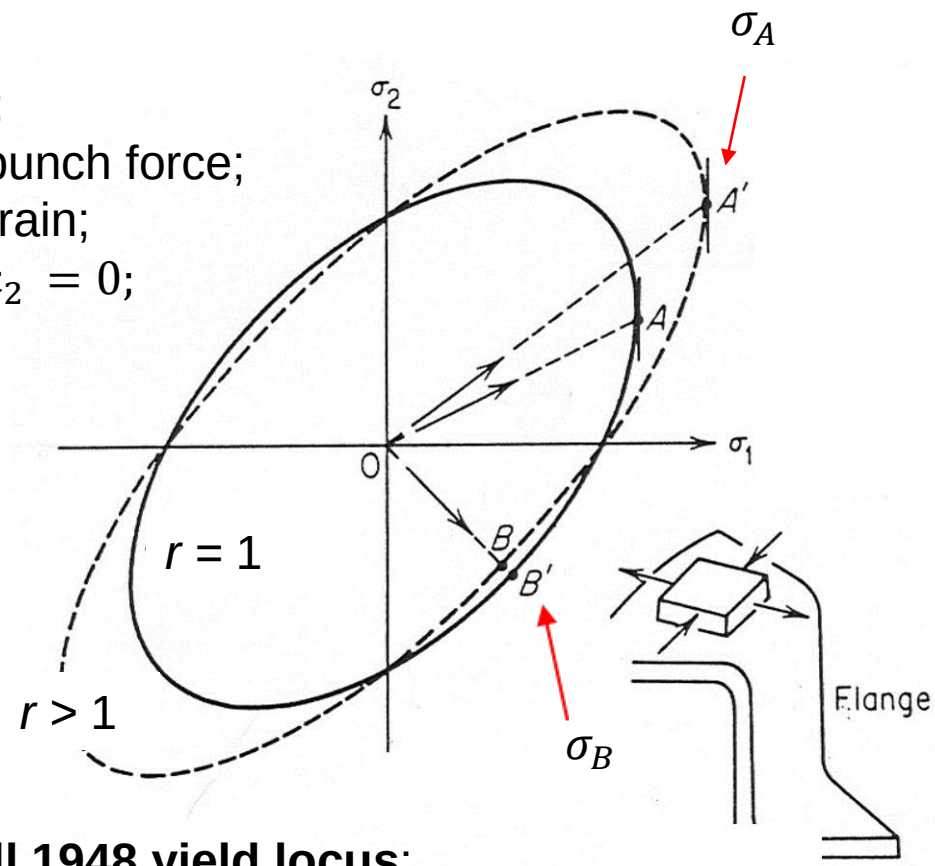




Deep drawability

Cup wall:
σ_A *should be as high as possible*:
vertical tensile stress to transfer punch force;
punch prevents circumferential strain;
circumferential tensile stress for $\varepsilon_2 = 0$;

Cup flange:
σ_B *should be as low as possible;*
compression stress in
circumferential direction;



Hill 1948 yield locus:
The larger *r*, the larger the ratio between
σ_A and σ_B , which will increase LDR.

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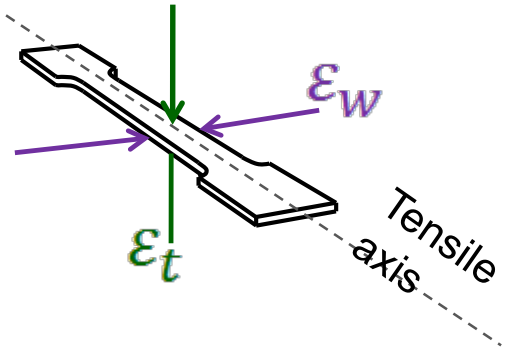
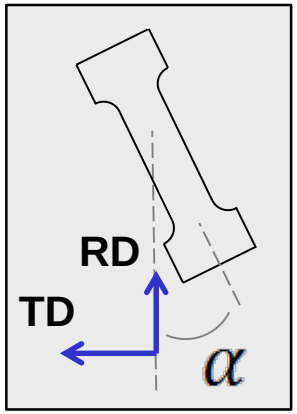
r and *q* values





$$r_\alpha = \frac{\varepsilon_w}{\varepsilon_t}$$

$$\bar{r} = {}^1/_4\,(r_0 + 2r_{45} + r_{90})$$

Shape of yield locus is correlated with material parameters *r* and *q*.

Ideally, users of aluminium sheet would like to have the same quality as for steel sheet. That would be:
1.5 to 2.5 for *r,* or 0.6 to 0.71 for *q*.

Note on *r*. It is 1 for an isotropic material. But it can be 0 as well as ∞ for extremely anisotropic materials. Note that from a physical point of view, the range 0-1 is equivalent to the range 1-∞. Better is to use the contraction ratio *q*:

$$q = -\frac{\varepsilon_w}{\varepsilon_\ell} = \frac{r}{r+1}$$

r=0, 1 and ∞ correspond to *q*=0, 0.5 and 1, respectively.

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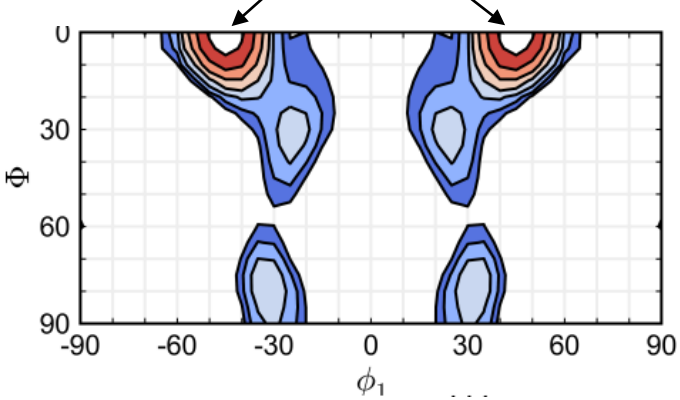
Textures and *r* or *q* values

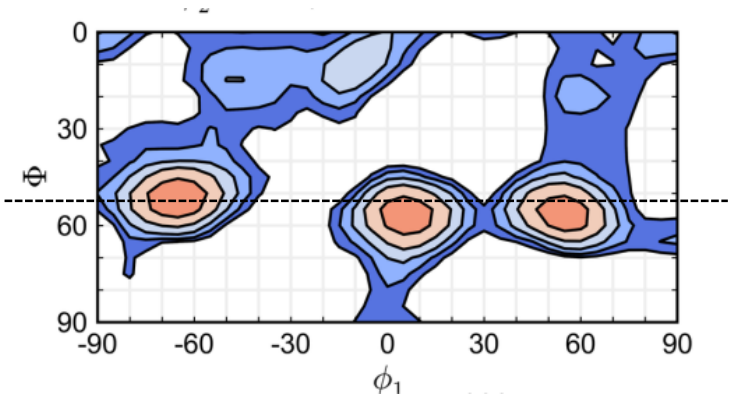
Bad for *r*

Good for *r*

Cube

ODF sections:
$\varphi_2 = 45°$





γ-fibre

(001) Plane // Rolling Plane

Typical for cold rolled and annealed Al alloys

(111) Plane // Rolling Plane

Typical for cold rolled and annealed steels

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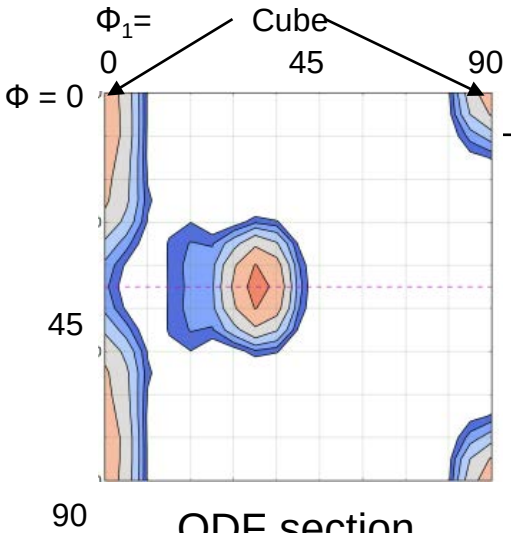
Texture and plastic anisotropy

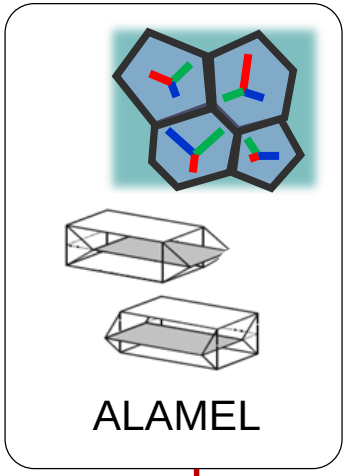
Statistical Representation: Orientation Distribution Function (ODF), 3 Euler angles (φ_1,Φ,φ_2)

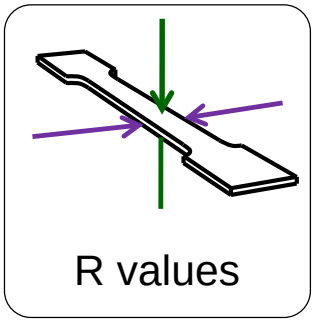


ODF section
φ_2 = 0°

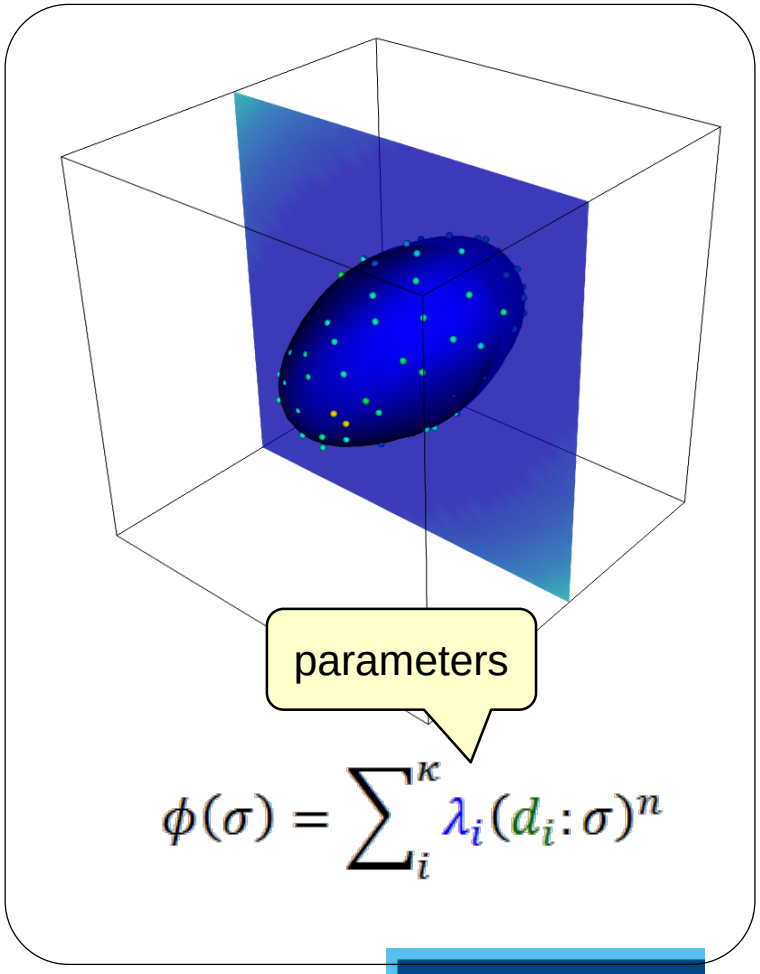
Al: plagued by “Cube” texture
Very bad r values!

Crystal Plasticity (CP) model





Continuum Plasticity model (“Facet” plastic potential)



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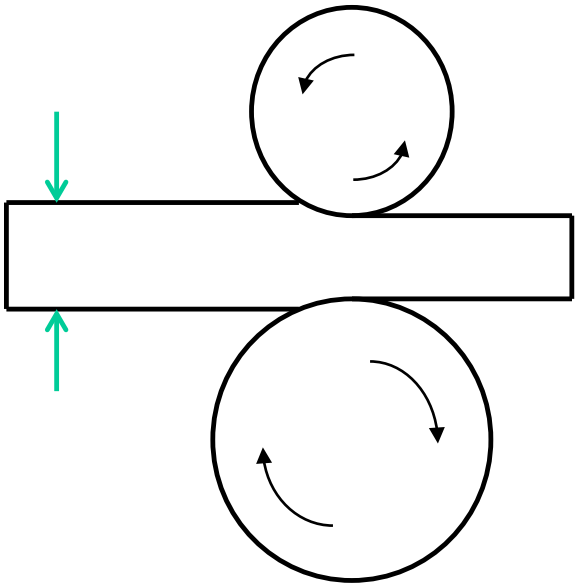
Adding shear to the rolling deformation by Asymmetric Rolling

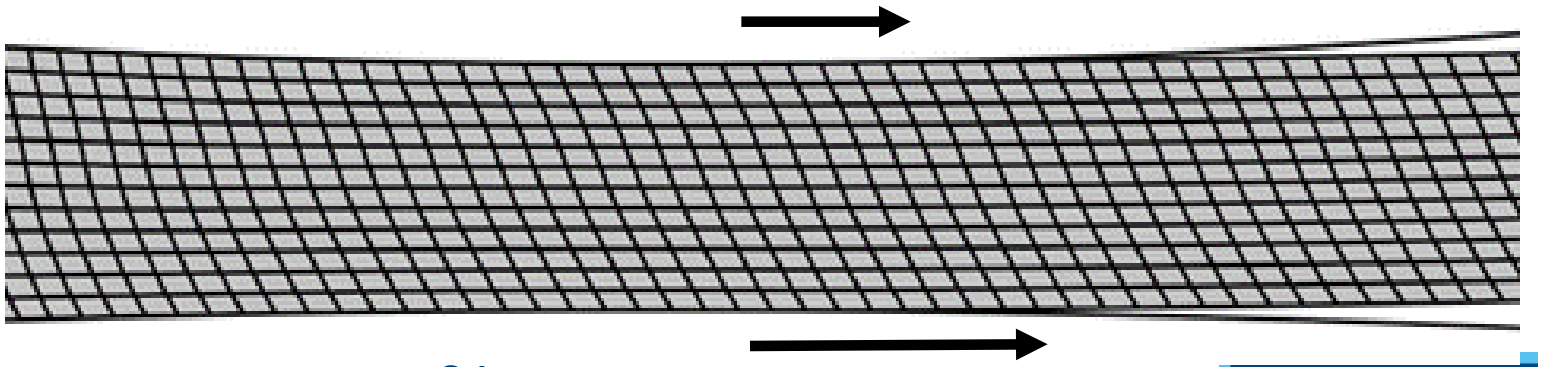
Principle:

A-symmetric rolling is achieved by differentiating the speeds of rolls of an identical diameter, or by using **different-diameter rolls with equal angular speeds**

(*A. Kawałek, Czestochowa University of Technology*)



Result: Additional shear



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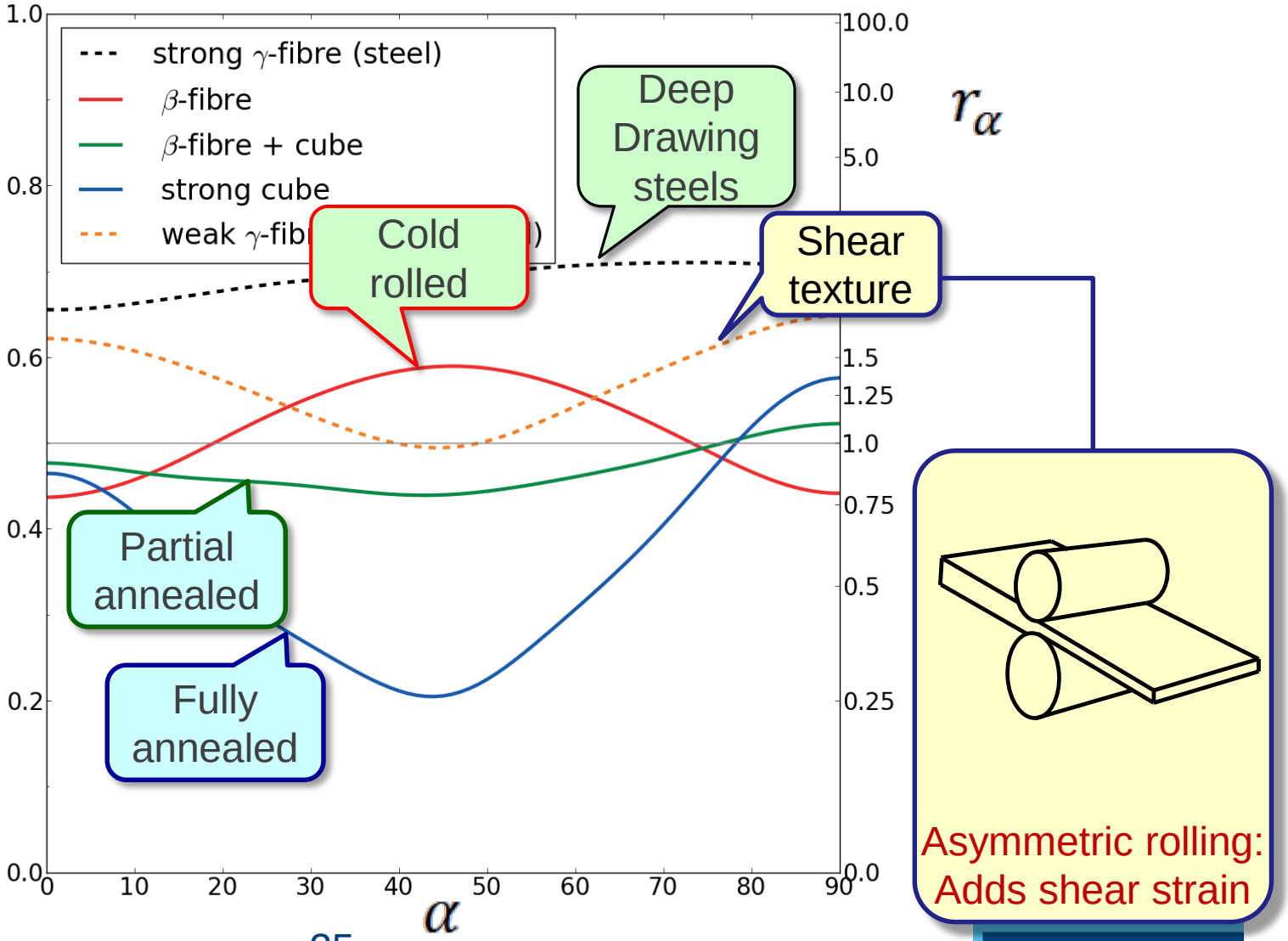
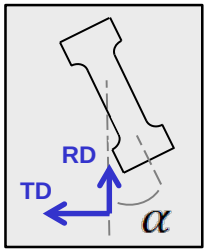
Low *r* values in Aluminium

$$q_\alpha = \frac{r_\alpha}{(1 + r_\alpha)}$$





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Questions

1. What configurations of ASR are interesting for improving formability?
2. What type of microstructural (texture) gradients can be expected?
3. What would the effects of such gradients be?

Length scale terminology used in HMS model

- *Each "integration point" is a different set of N crystallites each with its own texture.*
- *A local meso-macro model serves as "constitutive model"*
- *5000 is our standard choice of N*

***Engineering scale:* car body part**

FE model

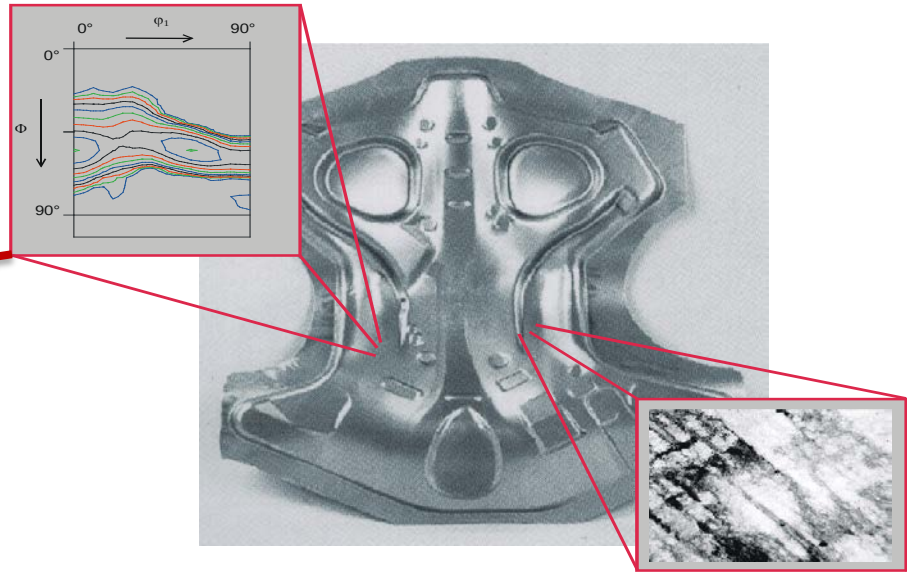
Texture + anisotropy (Facet model)

Macro-scale:
multicrystal with ~ 5000 grains

Single Integration point

Meso-Macro Model

Meso-scale:
Cluster with 1 or 2 grains



Substructure

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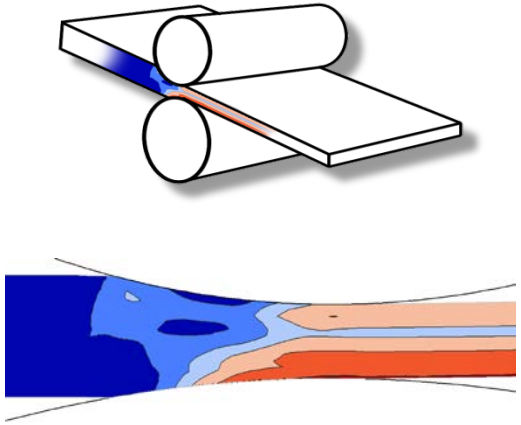
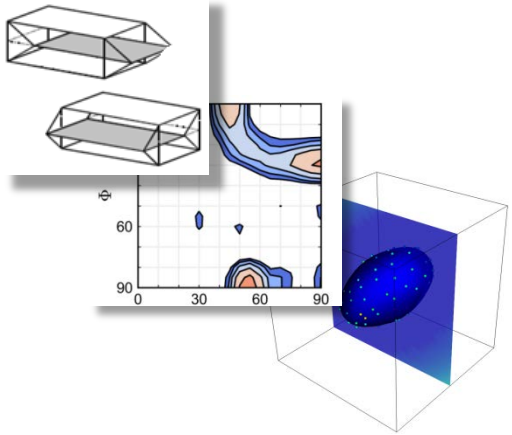
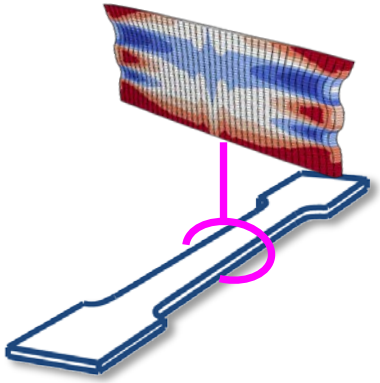
Simulation process







FEM

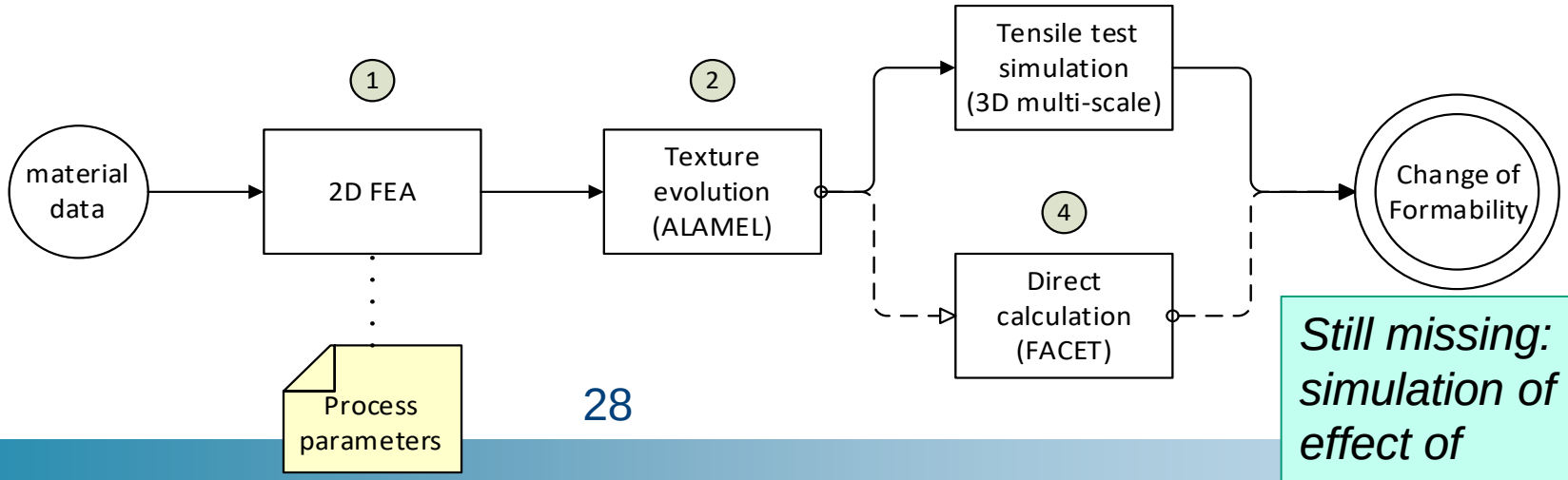
Engineering scale

Crystal Plasticity

Meso/macro scale

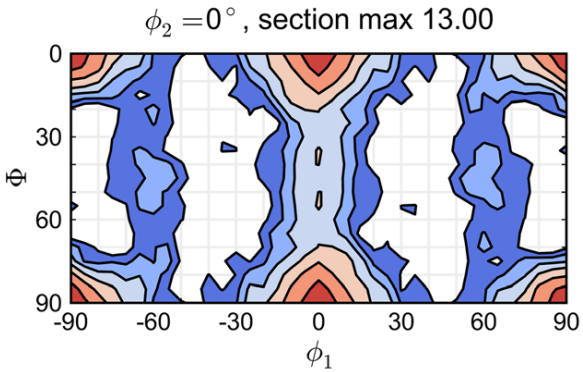
Multi-scale Model

all 3 scales



Still missing: simulation of effect of annealing

Hot rolling texture (homogenous)



Roll radius to sheet thickness ratio $\frac{r_{top}}{t_{in}}$:

10, 20, 30

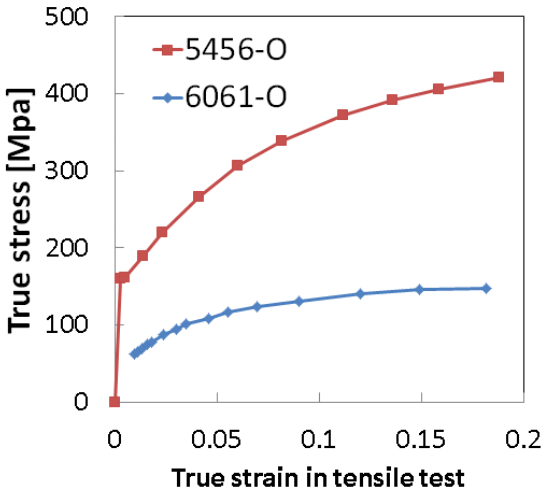
Roll ratio $r_r = \frac{r_{bot}}{r_{top}}$:

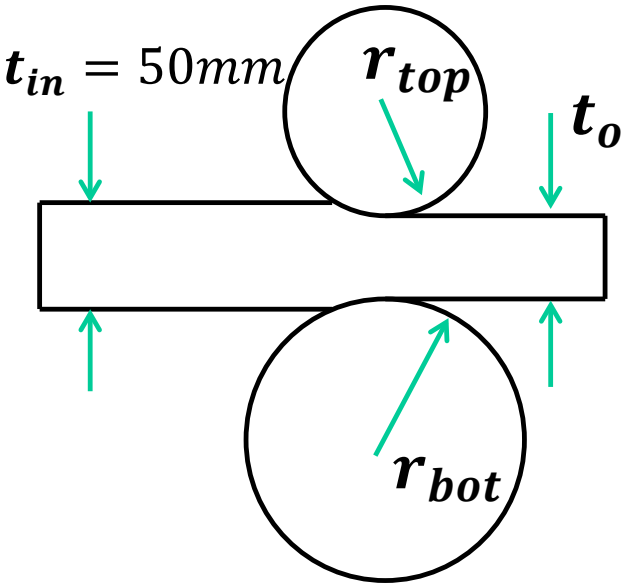
1.0, 1.25, 1.5, 1.75

Material

Swift K parameter

[2.70e8, 6.92e8]





Reduction % :

10, 20, 30, 40

Geometry

Contact

Friction μ

[.02, .05, .1, .2]

Max contact shear stress ratio $\frac{\tau_c}{\tau_Y}$

[0.5, 1.0, 10.0]

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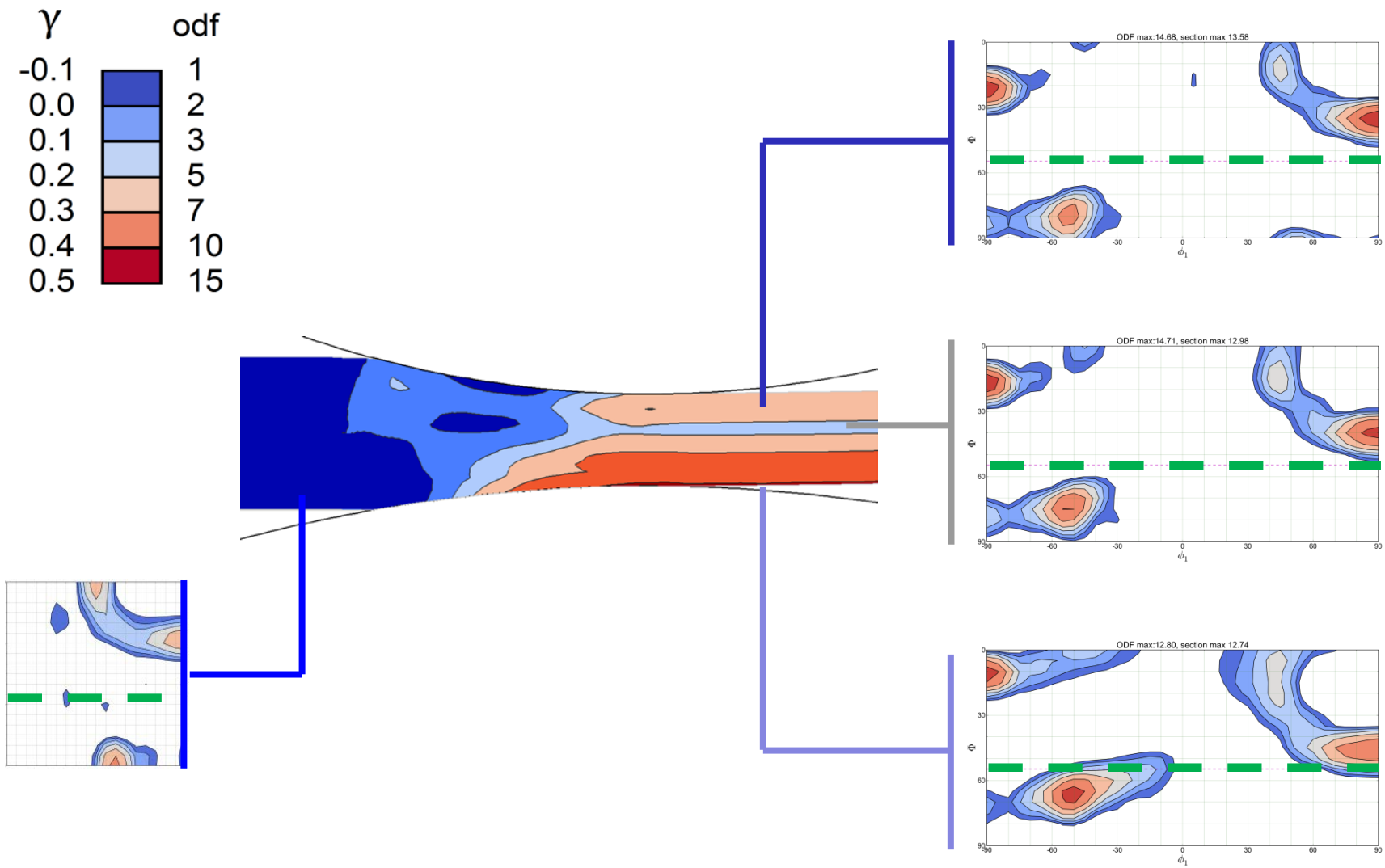
Shear Strain & Texture Gradients



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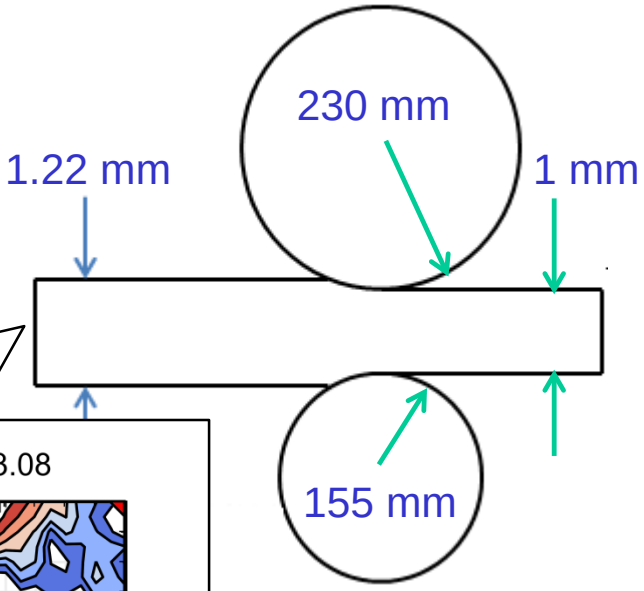
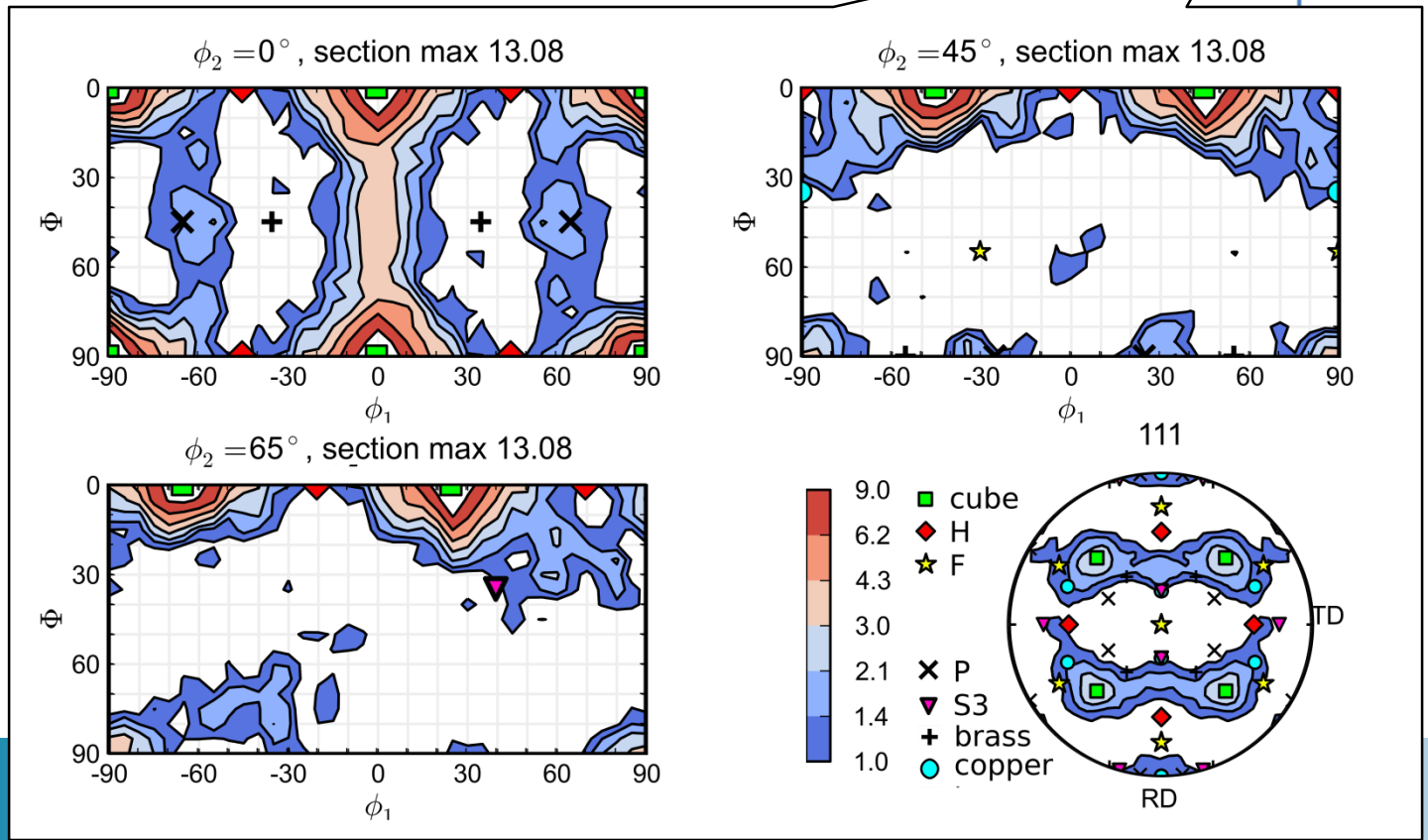
Validating Texture Prediction

Asymmetric Rolling Experiment
Pass reduction = 18%
Roll ratio = 1.5
Ratio smaller roll radius/sheet thickness = 127





Mid-plane texture BEFORE rolling

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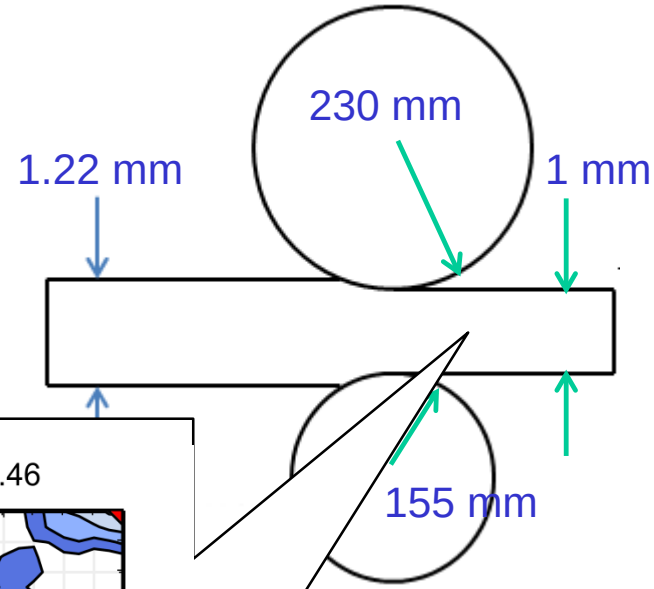
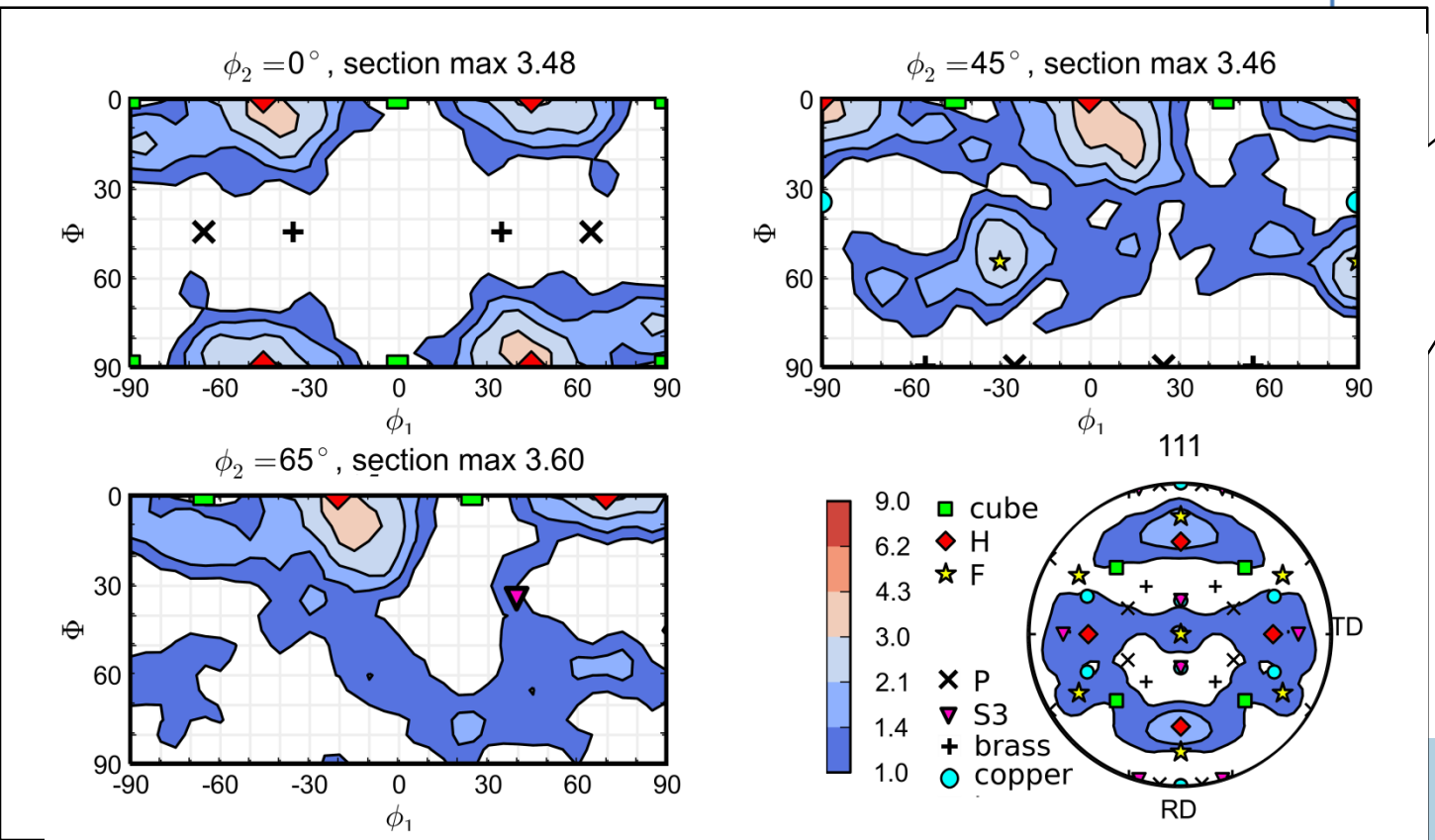
Experimental Deformed Texture

Asymmetric Rolling Experiment
Pass reduction = 18%
Roll ratio = 1.5
Ratio smaller roll radius/sheet thickness = 127





Mid-plane texture AFTER rolling

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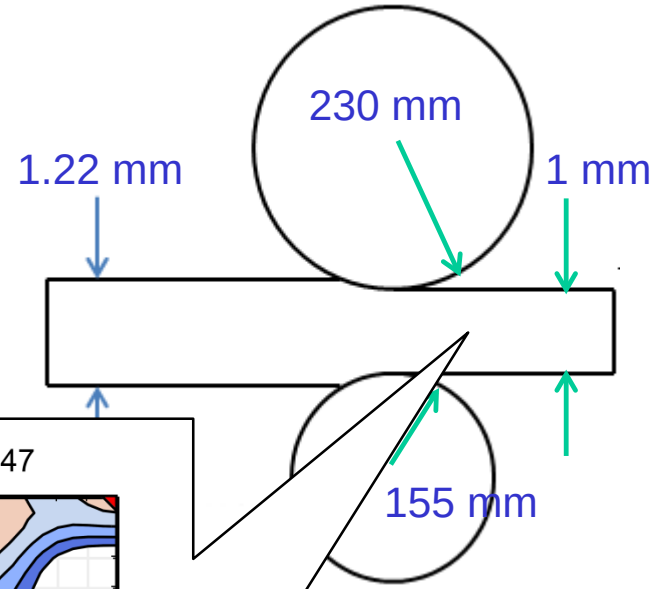
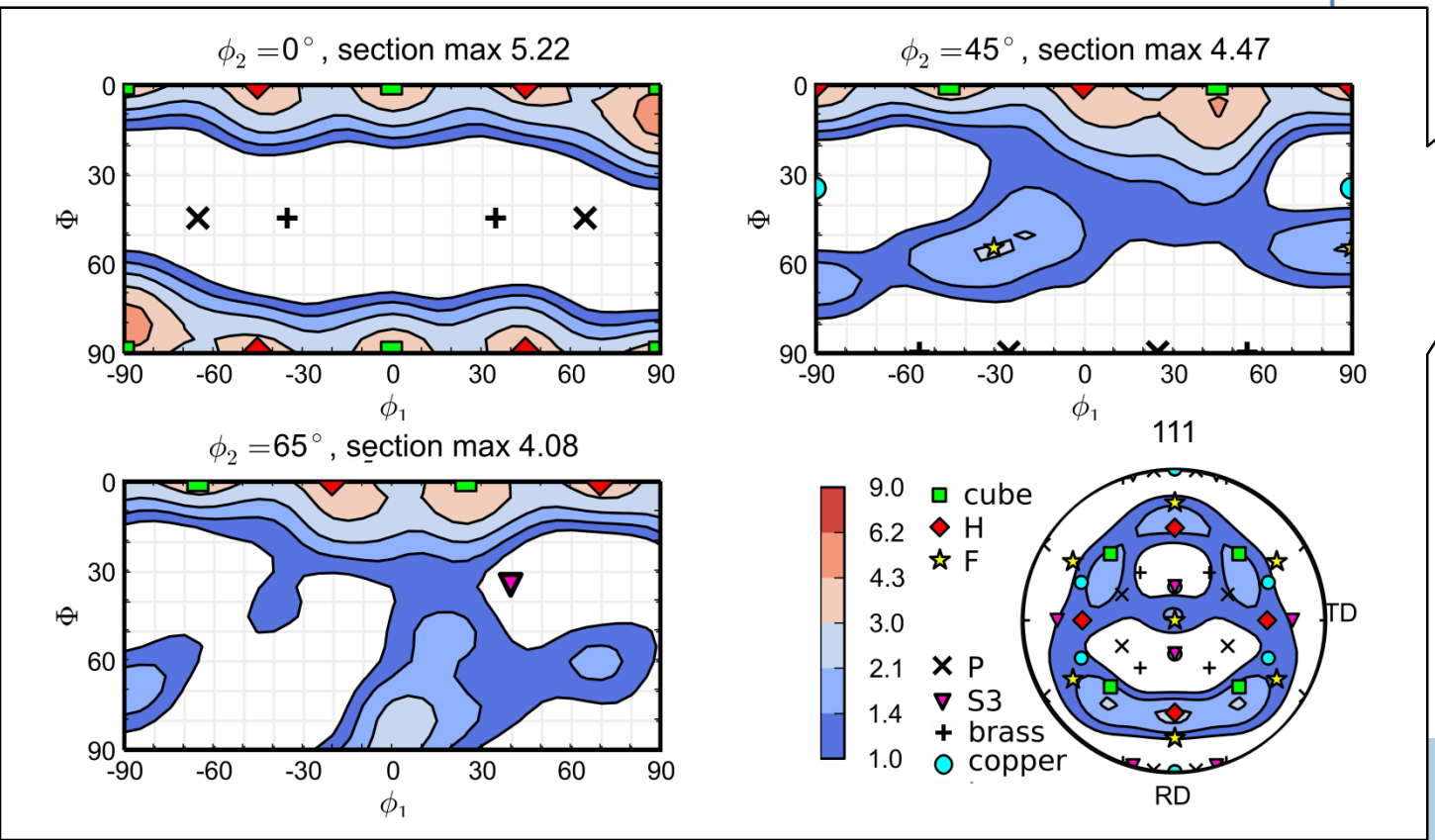
Simulated Deformed Texture

Asymmetric Rolling Simulation
Pass reduction = 18%
Roll ratio = 1.5
Ratio sheet thickness/smaller roll radius = 127
Friction μ = 0.35





SIMULATED Mid-plane texture AFTER rolling

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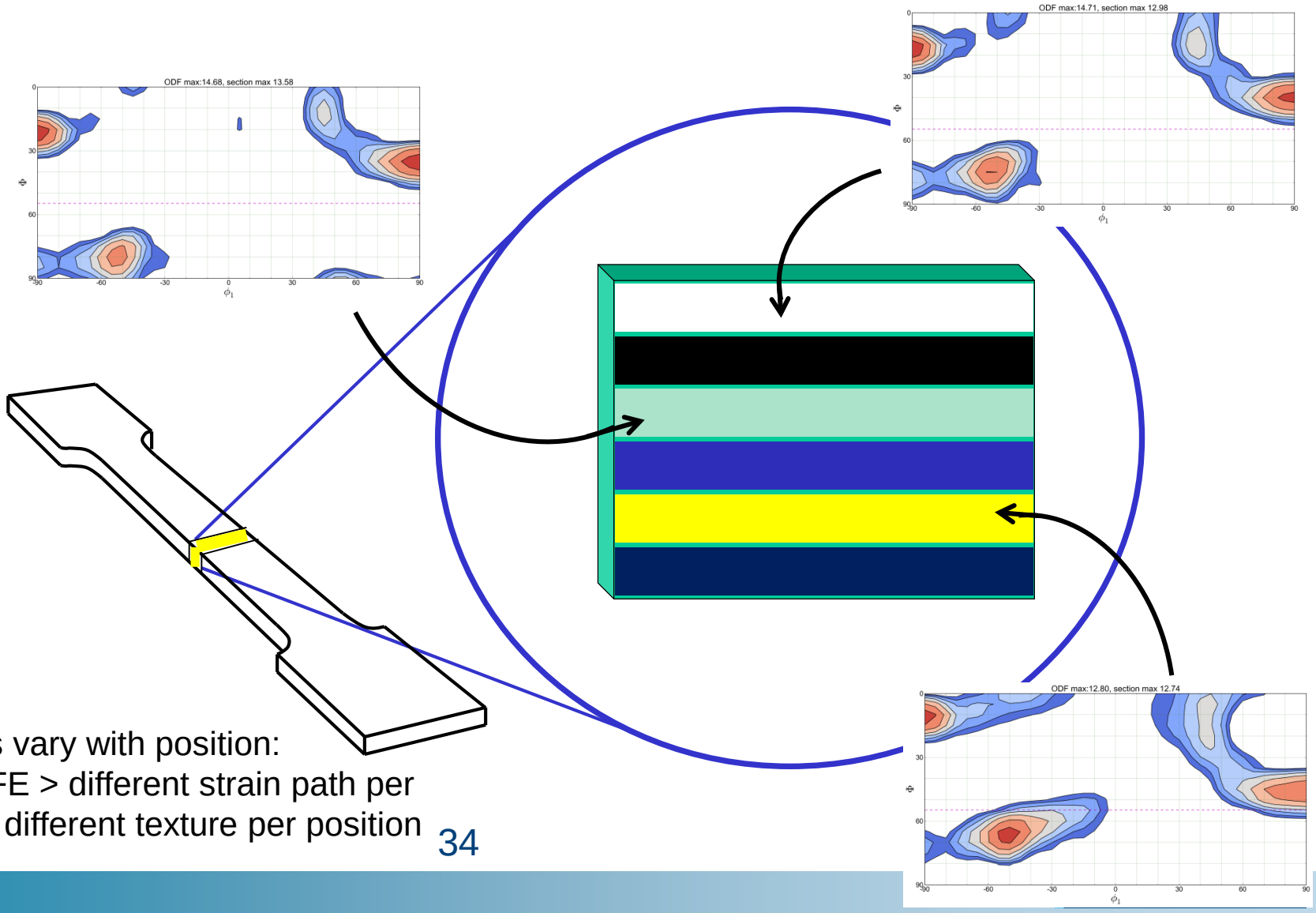
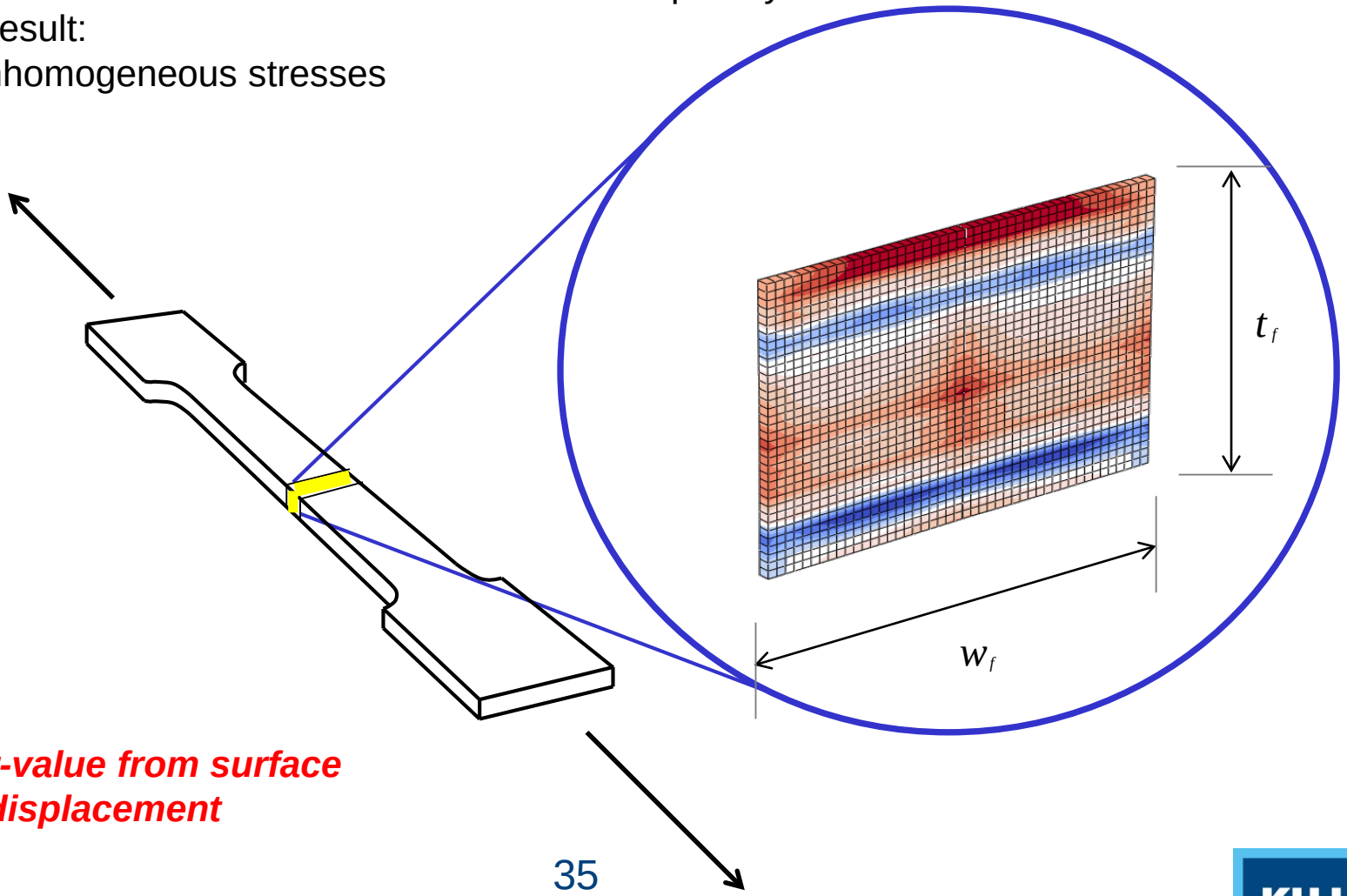
Formability Test: 3D multi-scale model



Properties vary with position:
Isotropic FE > different strain path per position > different texture per position

Formability Test: 3D multi-scale model

3D HMS model uses the different textures per layer
Result:
Inhomogeneous stresses



r-value from surface displacement

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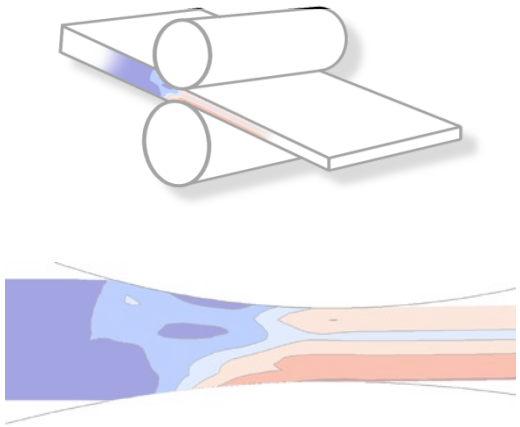
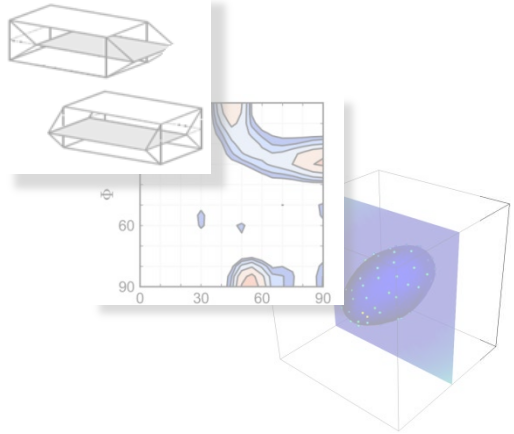
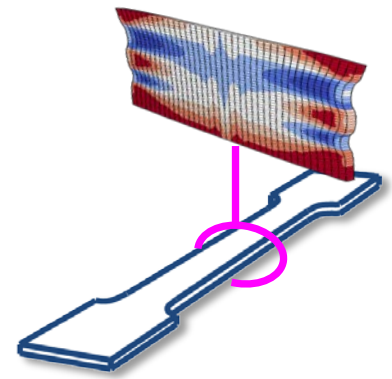
Simulation Process



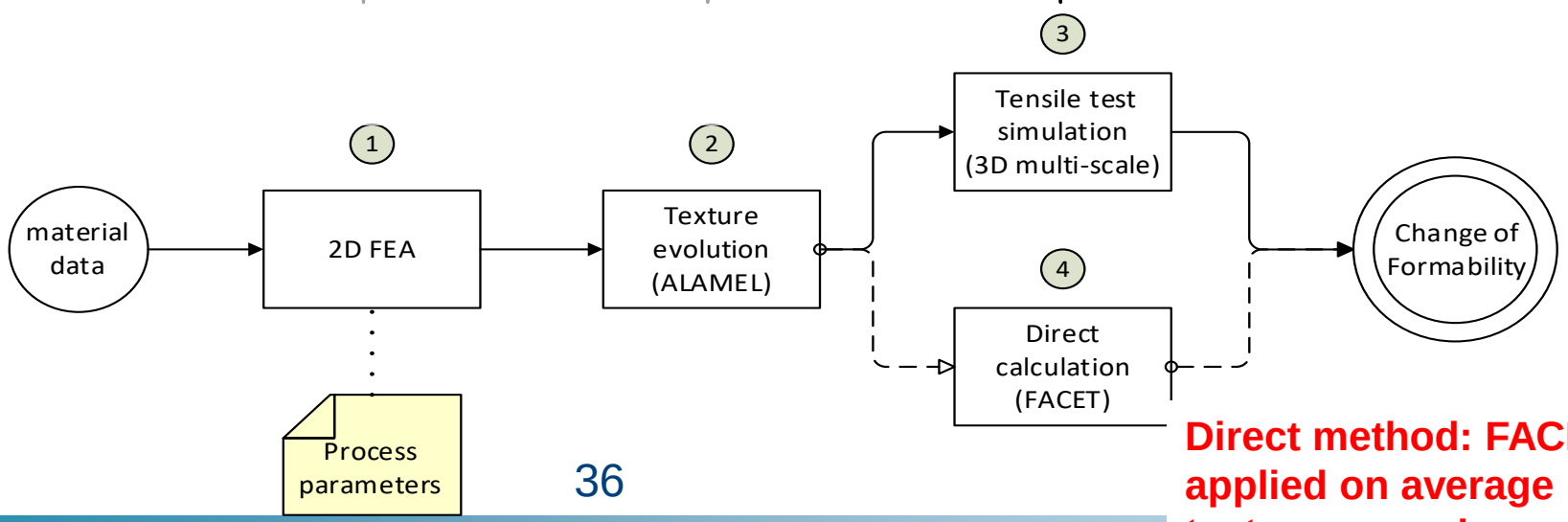




FEM

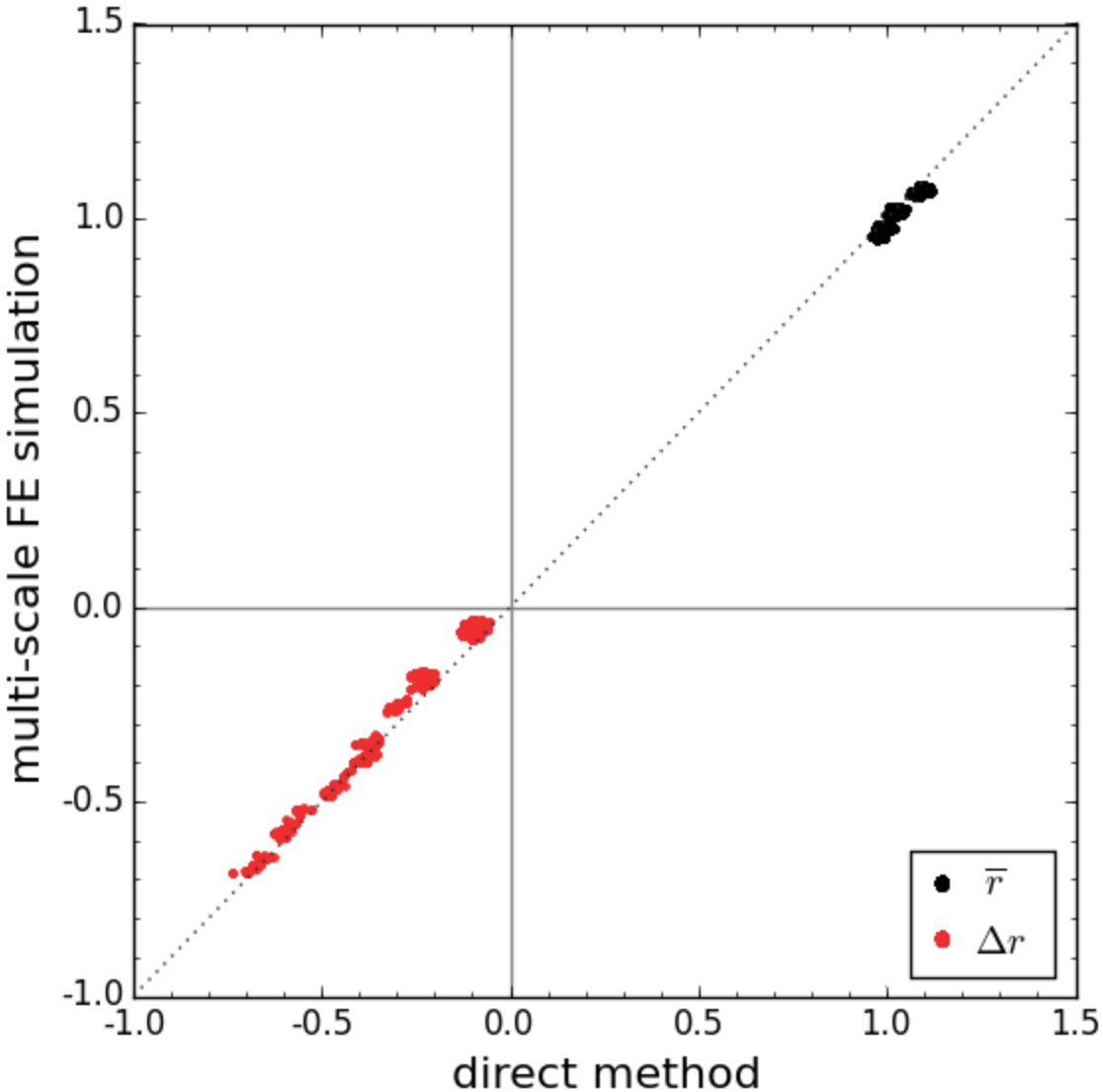
Crystal Plasticity

Multi-scale Model



Direct method: FACET applied on average texture → *r* value

Comparing Methods Step 3/4



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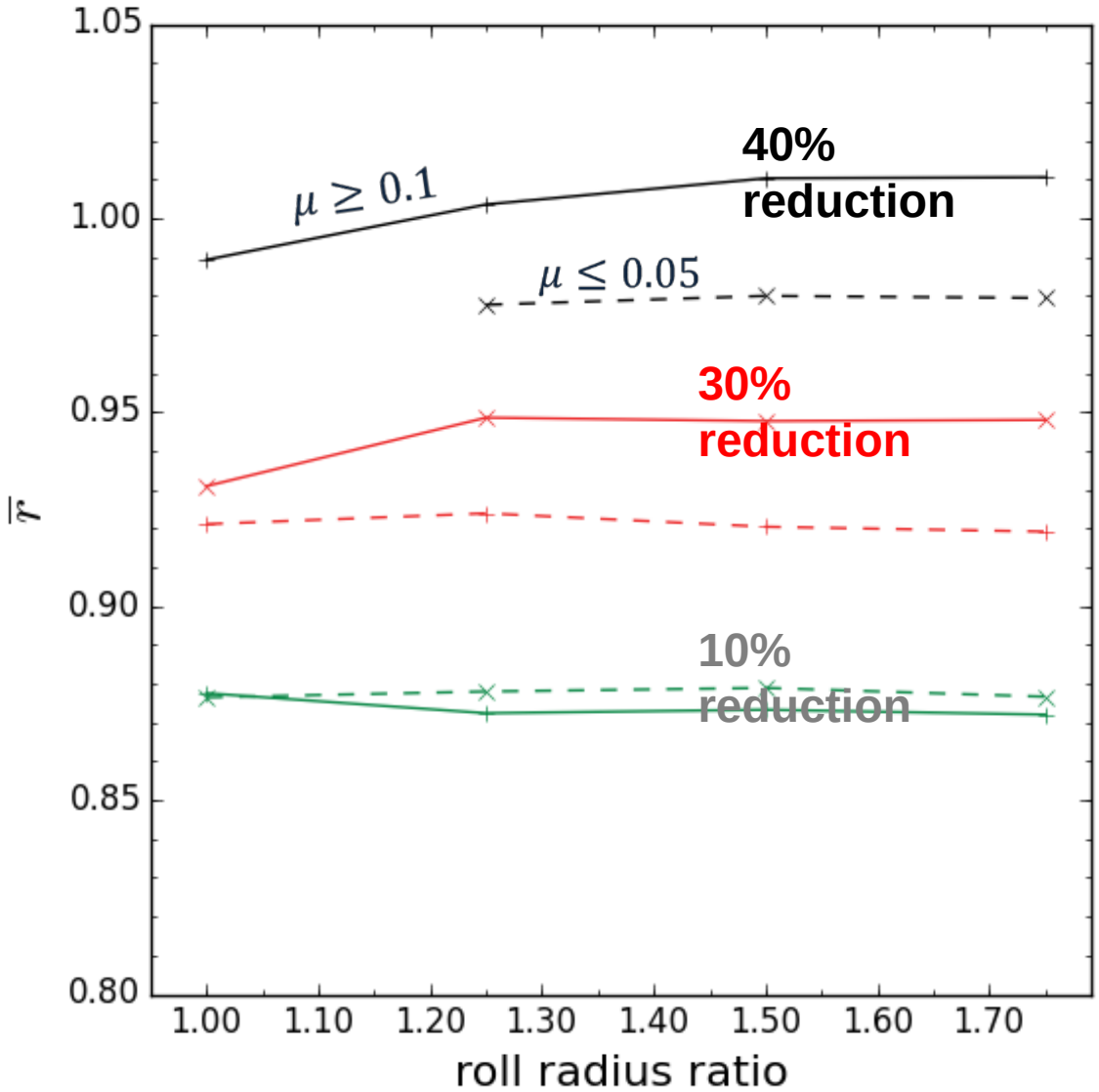
Deformation texture: best *r* values



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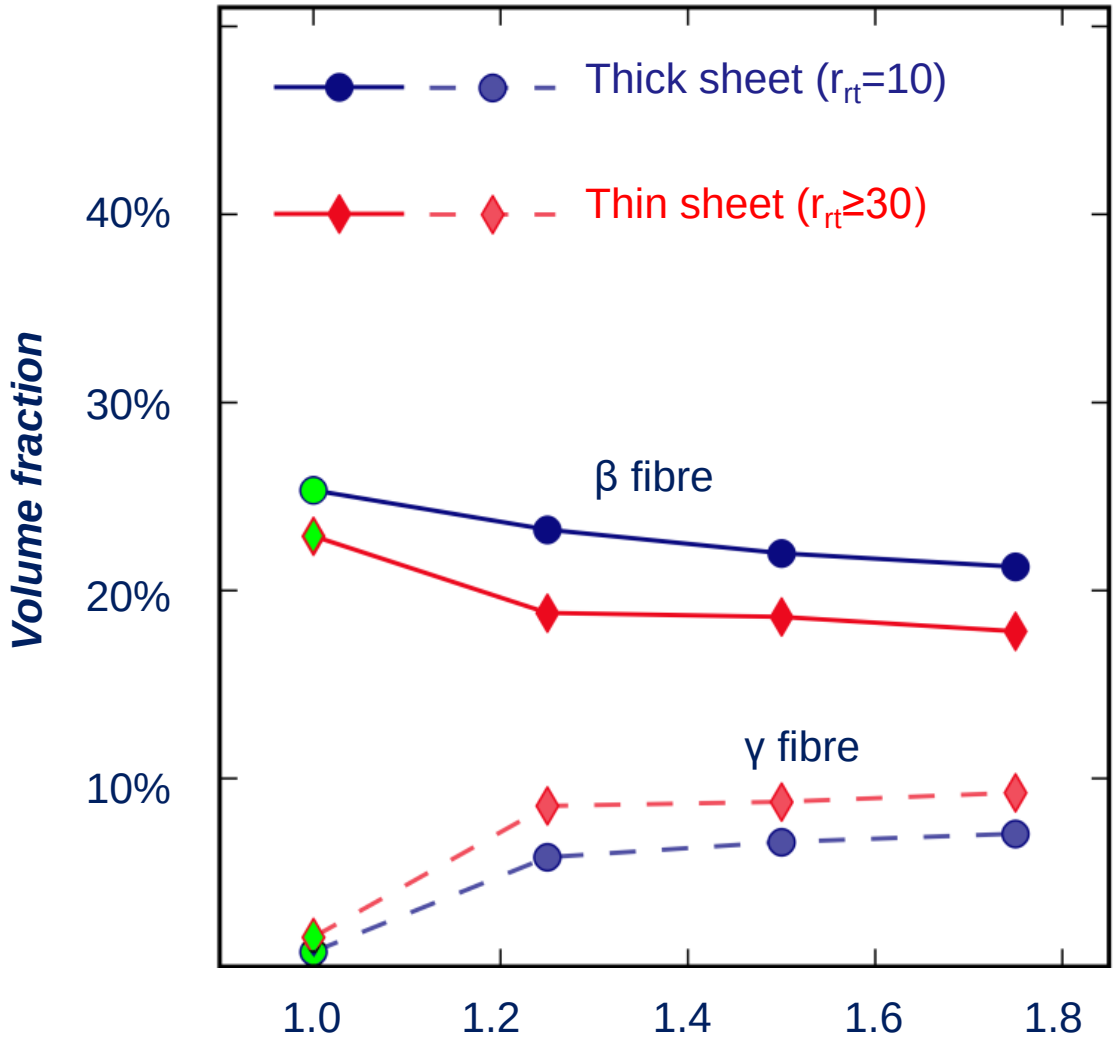
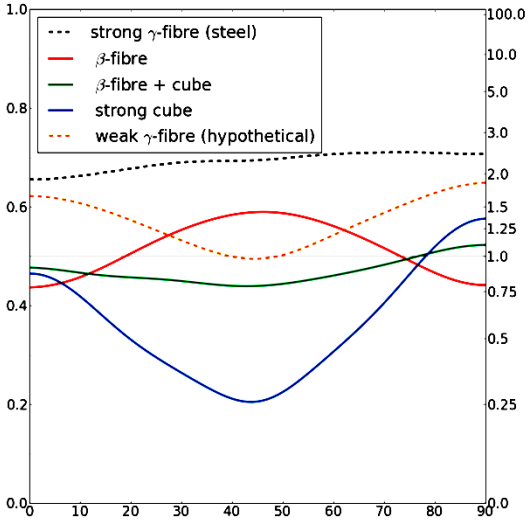
β-fibre vs. γ-fibre





Roll ratio *(asymmetry)*

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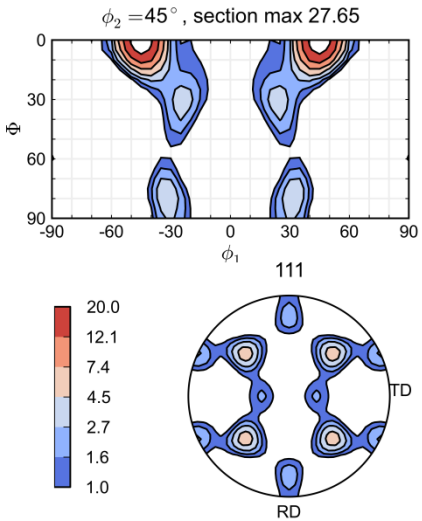
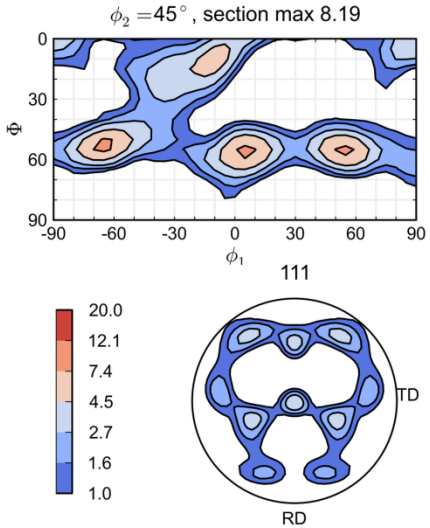
γ-fibre: stable under recrystallization

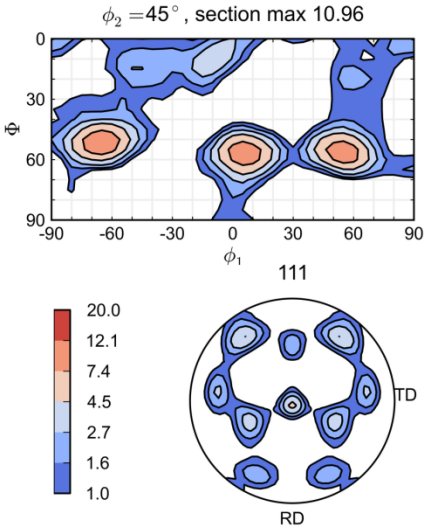
Initial texture, annealed (cube)



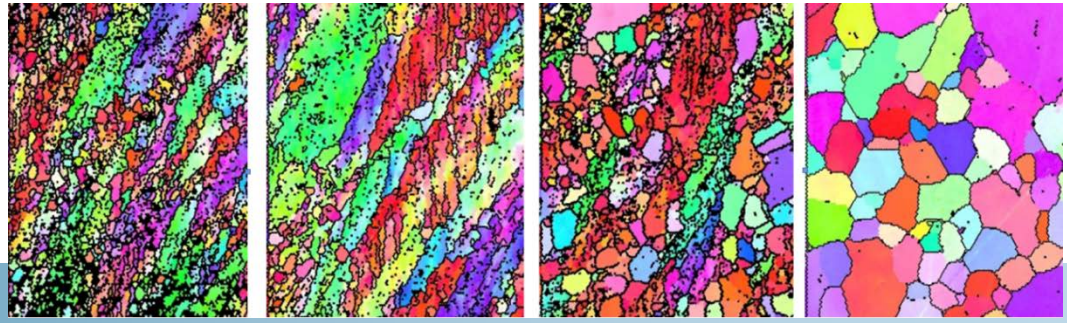
Experimental Shear texture (γ-fibre)



Annealed texture (γ-fibre)



Increasing anneal duration 5s-15s @ 500°C



Conclusions of ASR study

- *r* values after deformation by ASR predicted to be mainly controlled by the reduction
- ASR can produce a strong γ-fibre, with industrially feasible process conditions (i.e. lubricated rolling)
- The γ-fibre volume fraction increases with:
  - reduction
  - friction
  - ratio of roll radius to sheet thickness (i.e. use thin sheets or large rolls)
- Increasing asymmetry also increases γ-fibre volume fraction, but the effect levels off
- Heterogeneity:
  - increased by asymmetry
  - decreased by larger ratios of roll radius to sheet thickness

Conclusions and Perspectives

- For single-phase steels and aluminium alloys:
  accurate & computationally efficient models
  - Statistical CP (Alamel)
    for prediction of texture and plastic anisotropy
  - Hierarchical Multi-Scale Modelling of Plastic Forming Processes
    for full-field prediction of texture and anisotropy evolution

- On-going and future research:
  - For dual-phase materials:
    - require computationally demanding full-field CP models
    - coupling of such models with HMS requires compromises
    - development of statistical CP models?
  - For materials anisotropic hardening
    - not only for multi-phase materials (cf. IF-steels)