SALZGITTER MANNESMANN FORSCHUNG
Ein Unternehmen der Salzgitter Gruppe

Simulation of Deformation Texture with MTEX

Dr. M. Witte

Chemnitz, 10th February 2017

Overview

SALZGITTER MANNESMANN FORSCHUNG
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- Salzgitter Mannesmann Forschung GmbH
  - Company Overview
- Introduction
  - Taylor Model
- Plane strain deformation
  - FCC & BCC
  - Comparison with experiments
  - Effect of shear strains
- Tensile deformation
- Case study: In-situ measurement of recrystallization
- Summary

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Introduction - Salzgitter Mannesmann Forschung

SALZGITTER MANNESMANN FORSCHUNG
Ein Unternehmen der Salzgitter Gruppe

- **One of Europe's leading research institutes in the steel sector**
- Central **research company for steel activities in the Salzgitter Group**

Salzgitter AG

BU Strip steel	BU Plate/ section steel	BU Mannesmann	BU Trading	BU Technology

- **Two powerful locations with close thematic ties and cooperation**
- **Direct connection to Salzgitter AG/CEO**

SZMF is responsible for ensuring the innovation capability and innovation performance in the business units of strip steel, plate/section steel and Mannesmann

Introduction - Salzgitter Mannesmann Forschung

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SALZGITTER AG Stahl und Technologie | EUROPIPE | 219 VDM Elements | vallourec | ...

BU Strip Steel	BU Plate / Section Steel	BU Mannesmann

Markets

- OEM
- Automobile Component Supplier
- Trading and Steel Service-Center
- Cold Roller and Tube Manufacturer
- Construction Industry (Roof/Wall)

Markets

- Line Pipe
- Power Plants
- Automobile Industry
- Machinery and Plant Engineering
- Contruction Industry (Beams and Pilings)

Introduction - SZMF: Concentrated expertise

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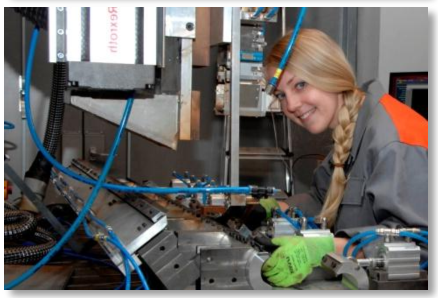
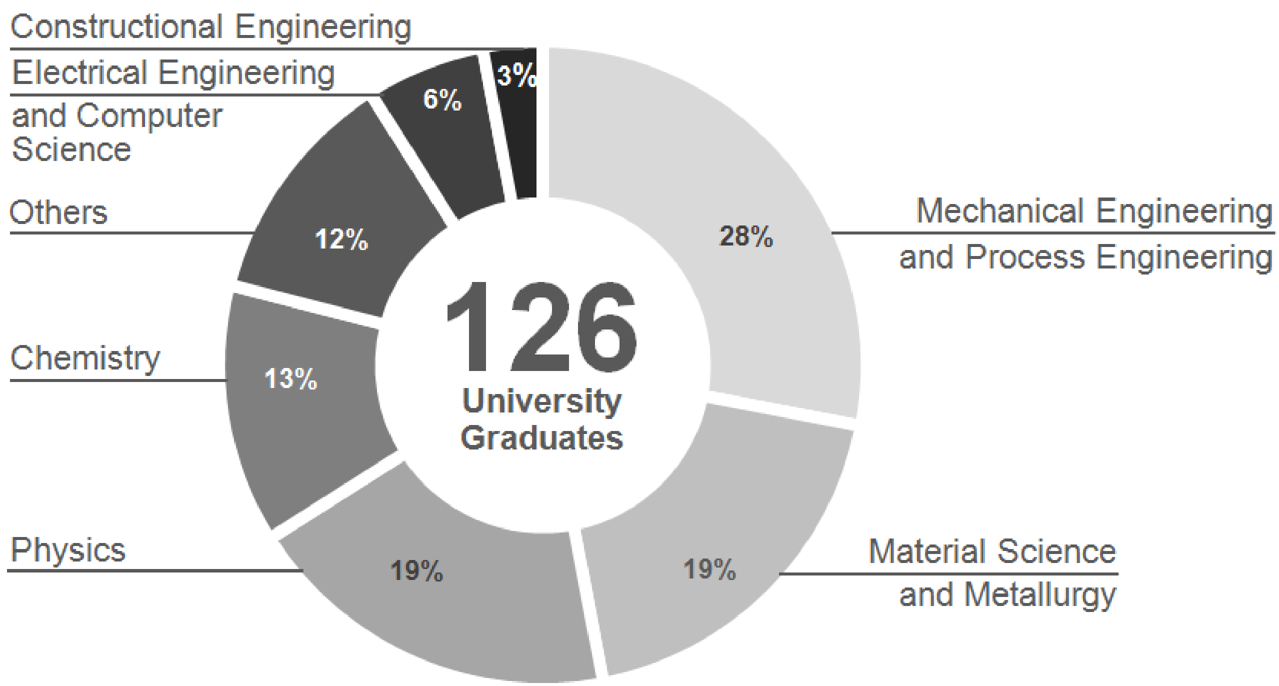
300 employees develop the future of all aspects of steel materials – around 130 members of staff in Salzgitter and 170 in Duisburg



Scientific disciplines



Update 2015-01

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Motivation

- Texture influences mechanical properties, especially plastic anisotropy.
- Mayor influences on texture development are plastic deformation, recrystallization, phase transformation and grain growth.

- Understanding of the effect of process parameters on texture development:
  - Optimization
  - Less experiments
  - Design of mechanical properties

- Understanding of texture development allows to determine process history of material:
  - Optimization
  - Characterization
  - Determine failures during processing

Taylor Model

- Von Mises stated, that **at least five slip systems** are necessary for an arbitrary plastic deformation of a crystal [1].
- The shear stress that acts on a dislocation in a certain slip system depends on the Schmid factor [2]:

$$\tau = \sigma m \otimes n$$

- Acc. to Taylor, the combination of five slip systems is activated which leads to the **lowest total amount of slip** (otherwise voids would form between the crystallites) [3]:

$$A^{(m)} = \tau_0 \sum_{n=n_1}^{n=n_5} \left|\gamma_n^{(m)}\right| = \min$$

- This **model is purely geometric**. For a more exact description of texture development material properties like work hardening, grain size, temperature etc. have to be considered.

[1] R. V. Mises, *J. Appl. Math. Mech.,* (**1928**) 161–185.
[2] E. Schmid, W. Boas, Kristallplastizität mit besonderer Berücksichtigung der Metalle, volume 17, J. Springer, **1935**.
[3] G. I. Taylor, *J. Inst. Metals* 62 (**1938**) 307

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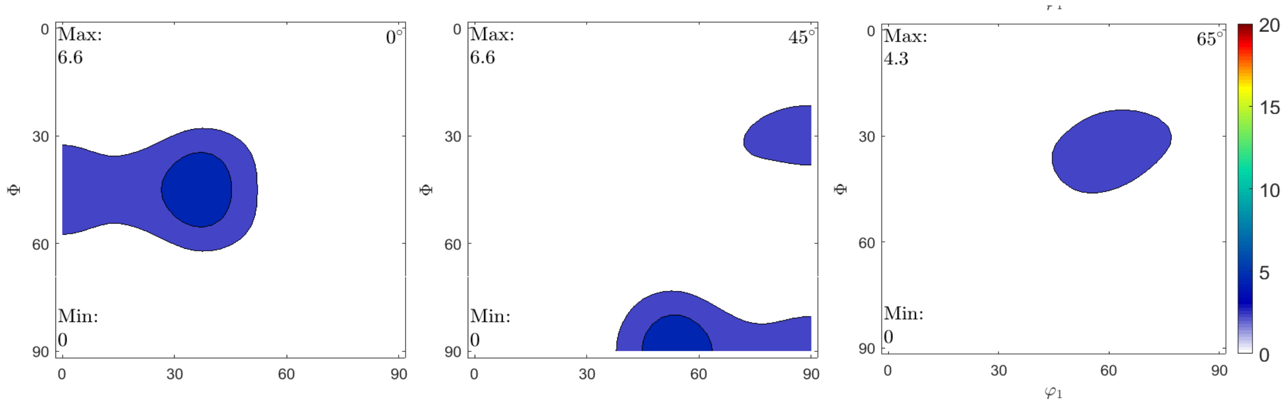
Plane strain deformation

- Rolling reduction of 10% of initial thickness in each step

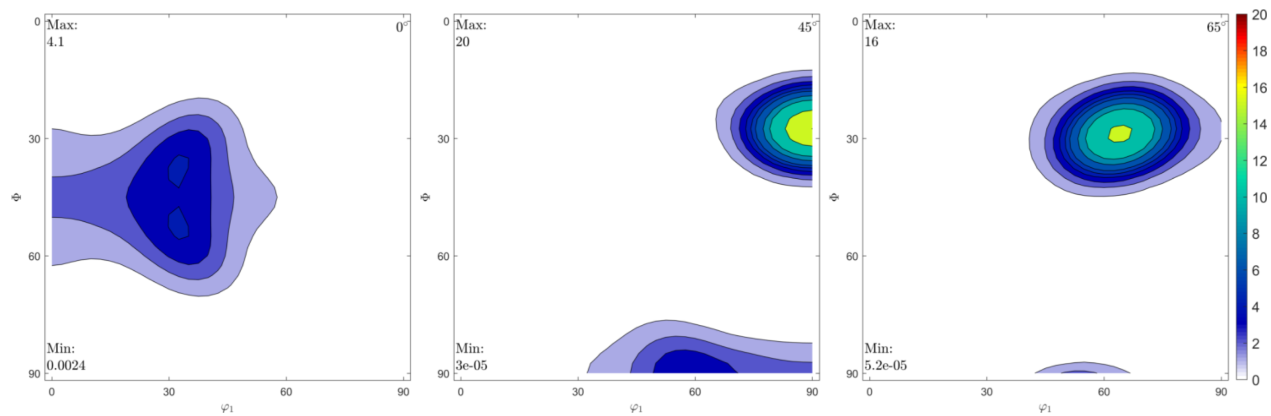
```
% rolling reduction
roll = 1:-0.1:0.1;

for i=1:9
    step(i) = roll(i+1)/roll(i);
end

% strain for each reduction
 eps = -log(step);

% slip systems
sS = symmetrise(slipSystem.bcc(CS));

for s = 1:length(eps)
        % strain tensor
        epsilon = eps(s) * tensor.diag([1 0 -1],'name','strain');

        numIter = 50; progress(0,numIter);

        for sas=1:numIter
                % compute the Taylor factors and the orientation gradients
                 [M,~,mori] = calcTaylor(inv(ori) * epsilon ./ numIter, sS.symmetrise);

                % rotate the individual orientations
                ori = ori .* mori; progress(sas,numIter);
        end
end
```

Plane strain deformation – FCC

Experimental texture
Hot rolled High-Mn steel



Simulated texture
Reduction ~70%

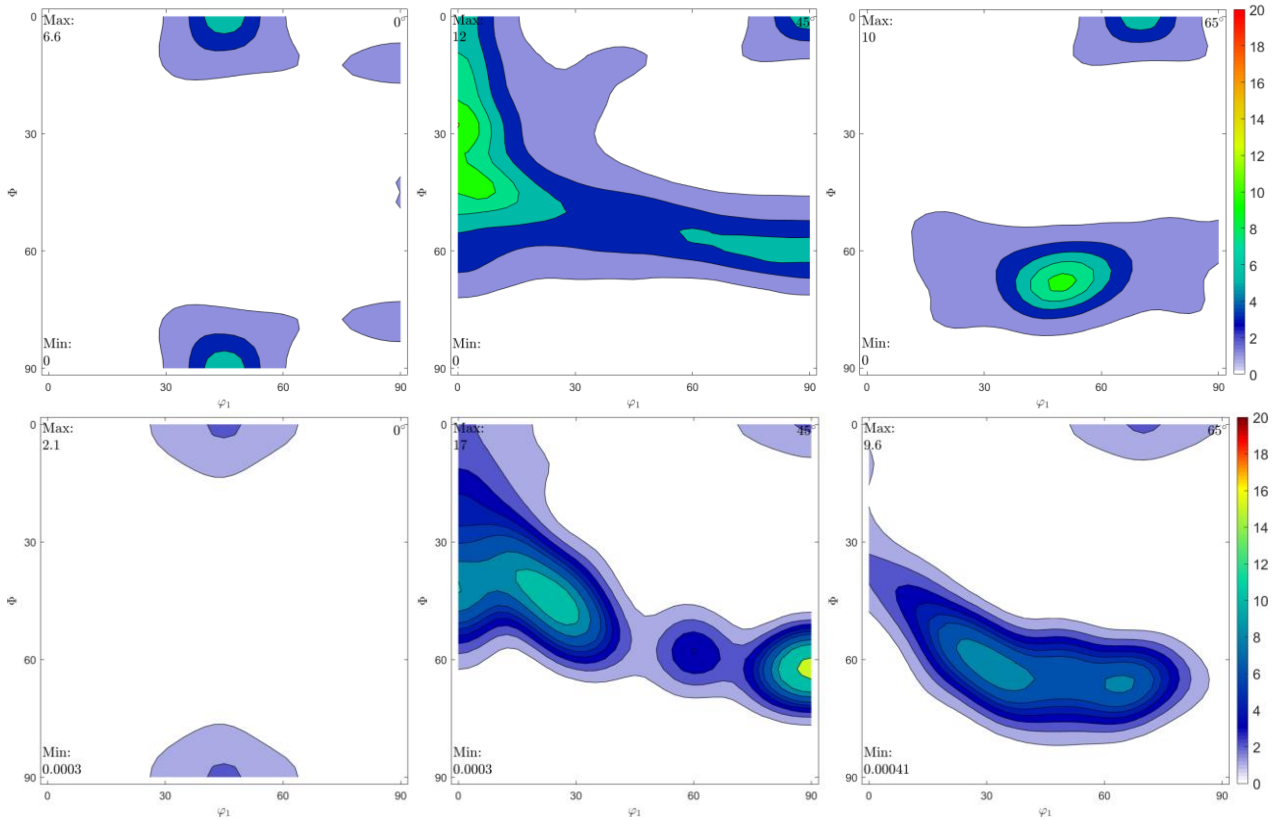


- Main texture features (β-fiber) are correctly simulated.
- Real deformation conditions are not taken into account.

Plane strain deformation – BCC

<u>Experimental texture</u>
Cold rolled IF steel,
Reduction ~70%

<u>Simulated texture</u>
Reduction ~70%

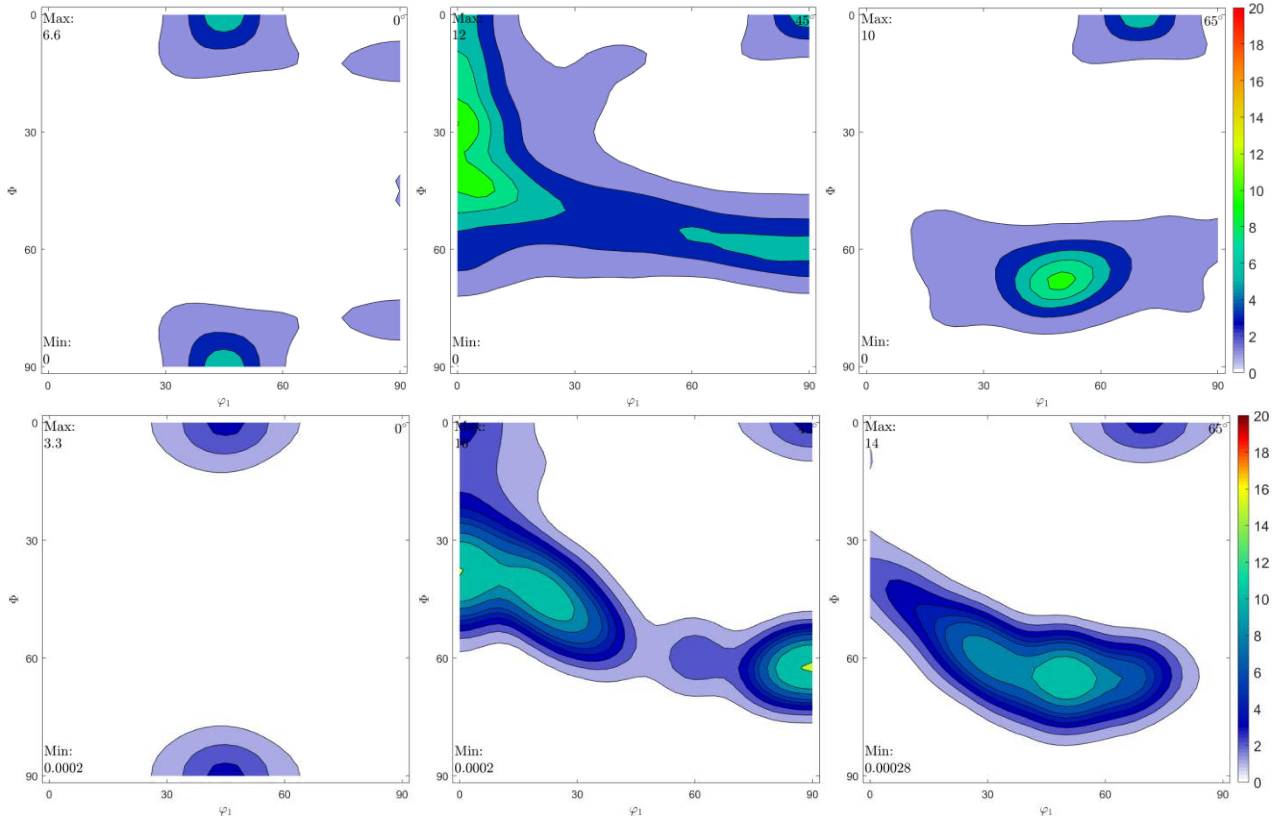


- Main texture features (α- & γ-fiber) are correctly simulated.
- Real deformation conditions are not taken into account.

Plane strain deformation – BCC

<u>Experimental texture</u>
Cold rolled IF steel,
Reduction ~70%

<u>Simulated texture</u>
With **original rolling schedule**
(5 passes)



- Better agreement with original rolling schedule.
- Time for one simulation step ~60 min → Speed up possible?

Plane strain deformation – BCC

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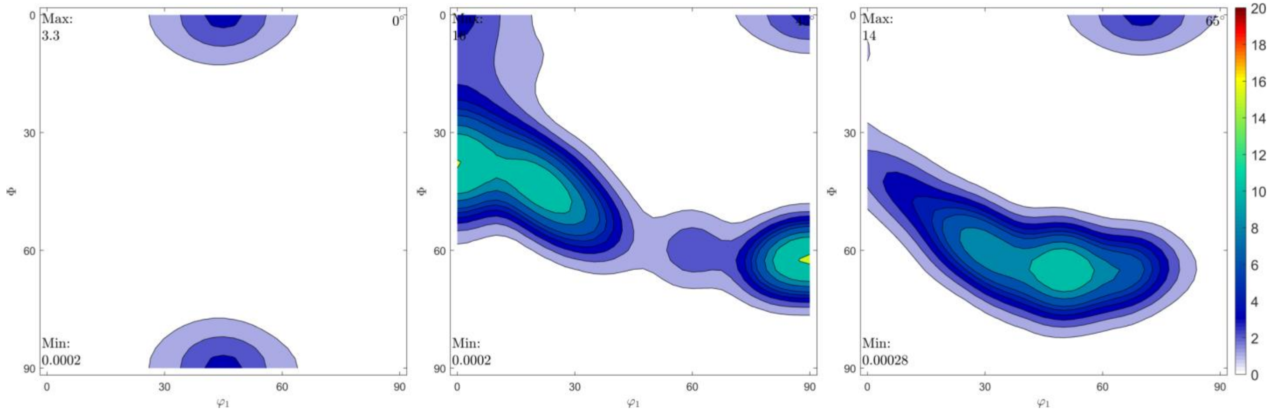
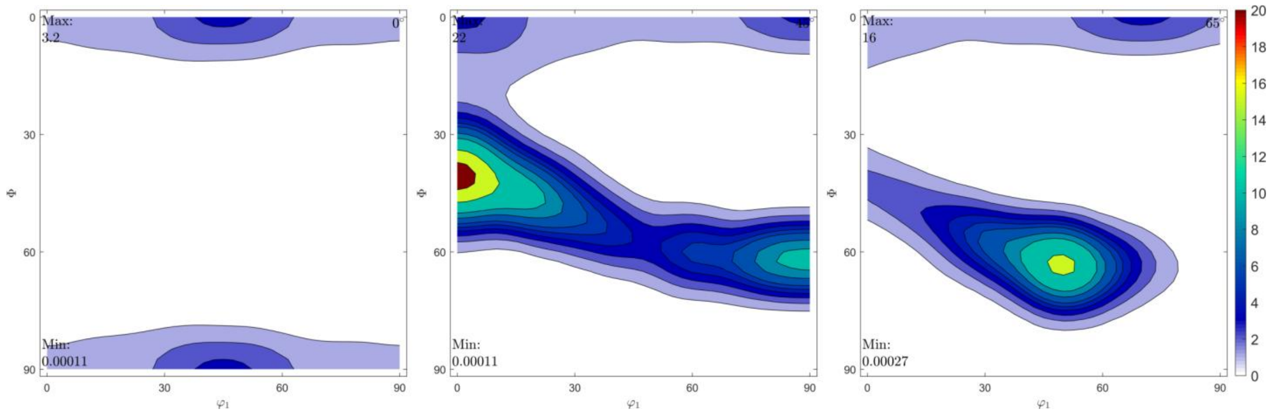
Simulated texture
With **original rolling schedule**
5 simulation steps
(for 5 rolling stands)



Simulated texture
Whole deformation in one step



- Simulated deformation step size has strong effect on result.
- How to determine the optimal deformation step size? (Except trail and error)

Plane strain deformation: Engler Shake

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[4] O. Engler, *Adv. Eng. Mat.*, 4 (**2002**) 181–186:

- According to FEM simulations **random shear strains** occur during rolling.
- Taking these shear strains into account leads to a **better agreement** of simulated and measured rolling textures.
- The strain tensor then takes the form:

$$\underline{\underline{\epsilon}} = \begin{pmatrix} \epsilon & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -\epsilon \end{pmatrix} \Rightarrow \underline{\underline{\epsilon}} = \epsilon \cdot \begin{pmatrix} 1 \pm 0.1 & \pm 0.3 \ldots 0.15 & \pm 0.6 \ldots 0.75 \\ \pm 0.3 \ldots 0.15 & 2 \cdot \pm 0.1 & \pm 0.4 \\ \pm 0.6 \ldots 0.75 & \pm 0.4 & -1 \pm 0.1 \end{pmatrix}$$

Plane strain deformation – BCC – Engler Shake

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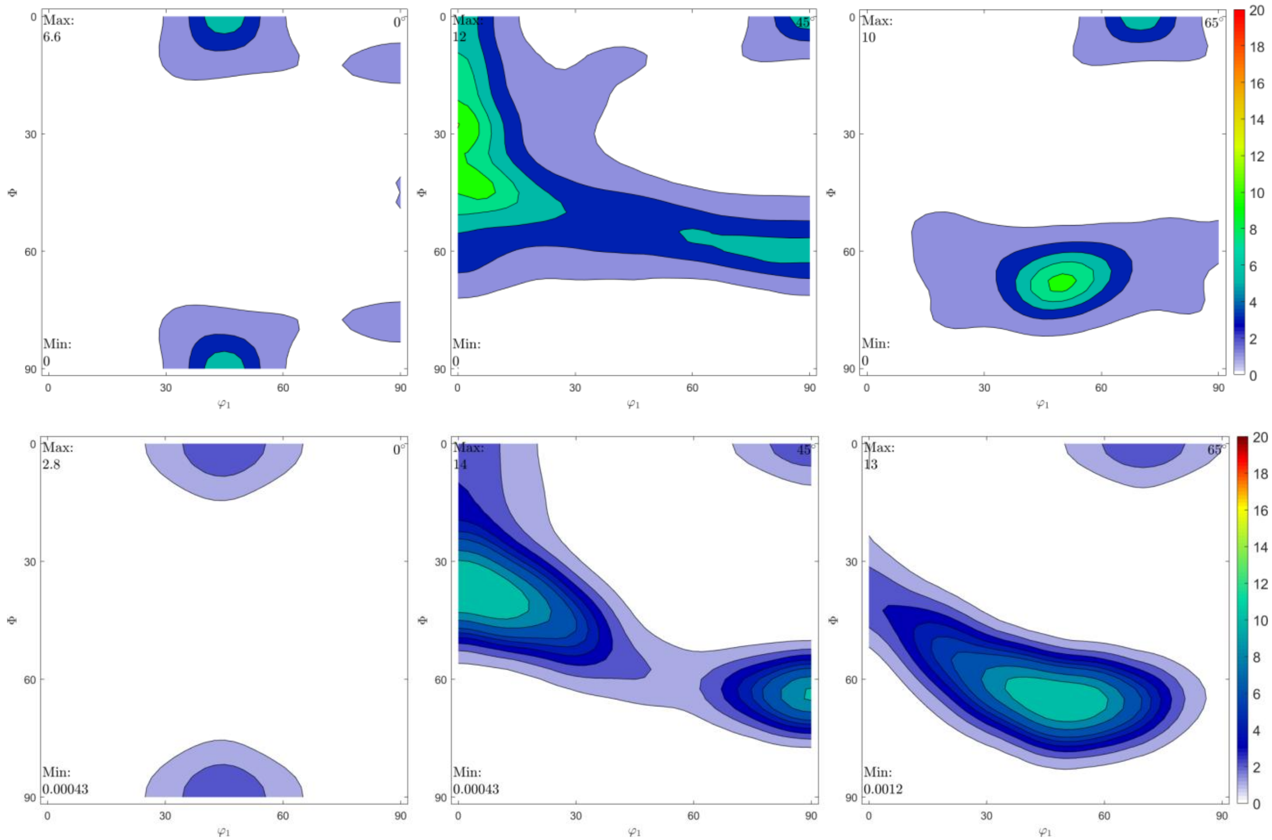
<u>Experimental texture</u>
Cold rolled IF steel,
Reduction ~70%

<u>Simulated texture</u>
With original rolling schedule and **"Engler Shake"**



Improved agreement with using "Engler Shake"

Plane strain deformation – BCC – Volume Fractions

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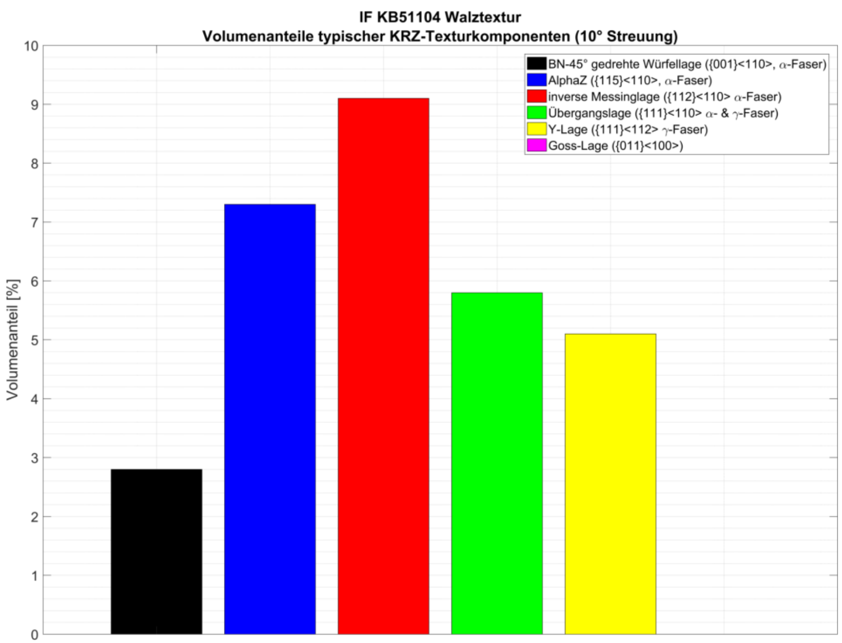
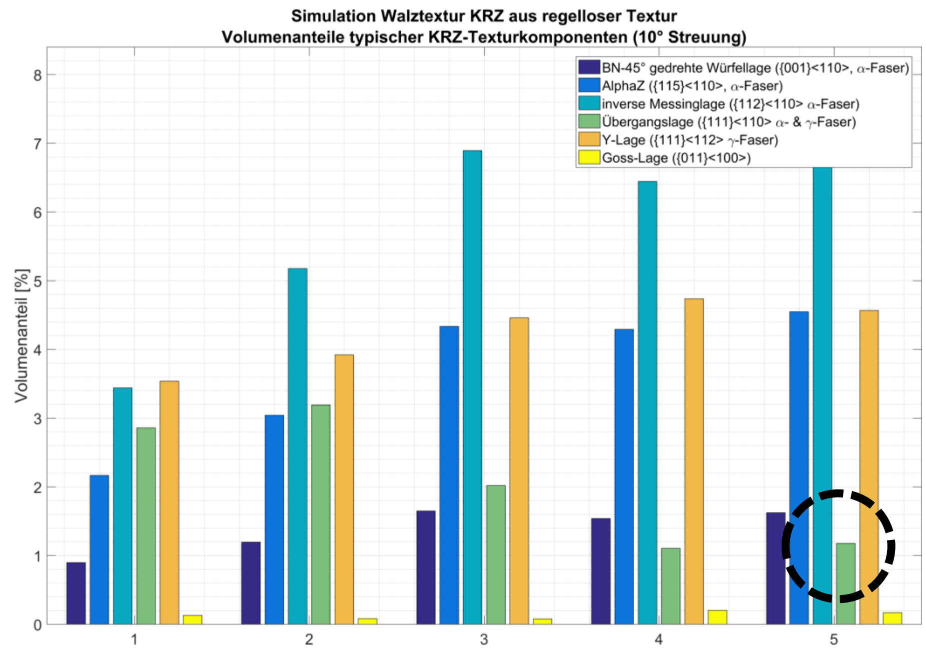
Experimental texture
Cold rolled IF steel, Reduction ~70%



Simulated texture
With original rolling schedule and **"Engler Shake"**



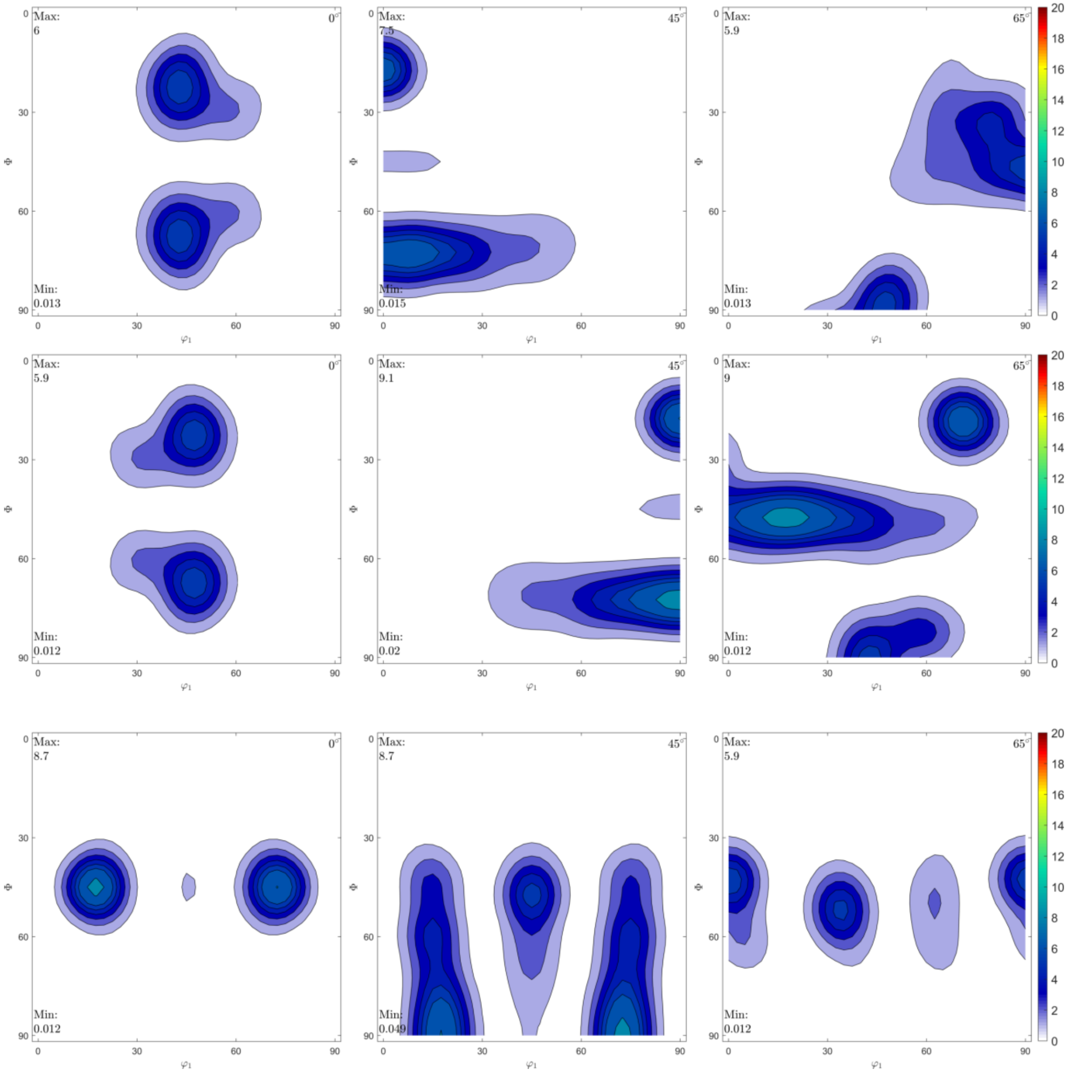
- Comparison of volume fractions shows fairly good comparison except for {111}<110> (transition between α- & γ-fiber)
- Overall texture intensity could be equalized by adjusting the ODF kernel halfwidth

Shear deformation – BCC

Shear in xy

Shear in xz

Shear in yz



- Shear textures are rotated by 90° according to the shear directions
- No typical bcc shear textures
  - Also with combined shears, e.g. xy and xz, no typical bcc shear textures could be simulated
- Typical bcc shear rolling texture resembles fcc rolling texture

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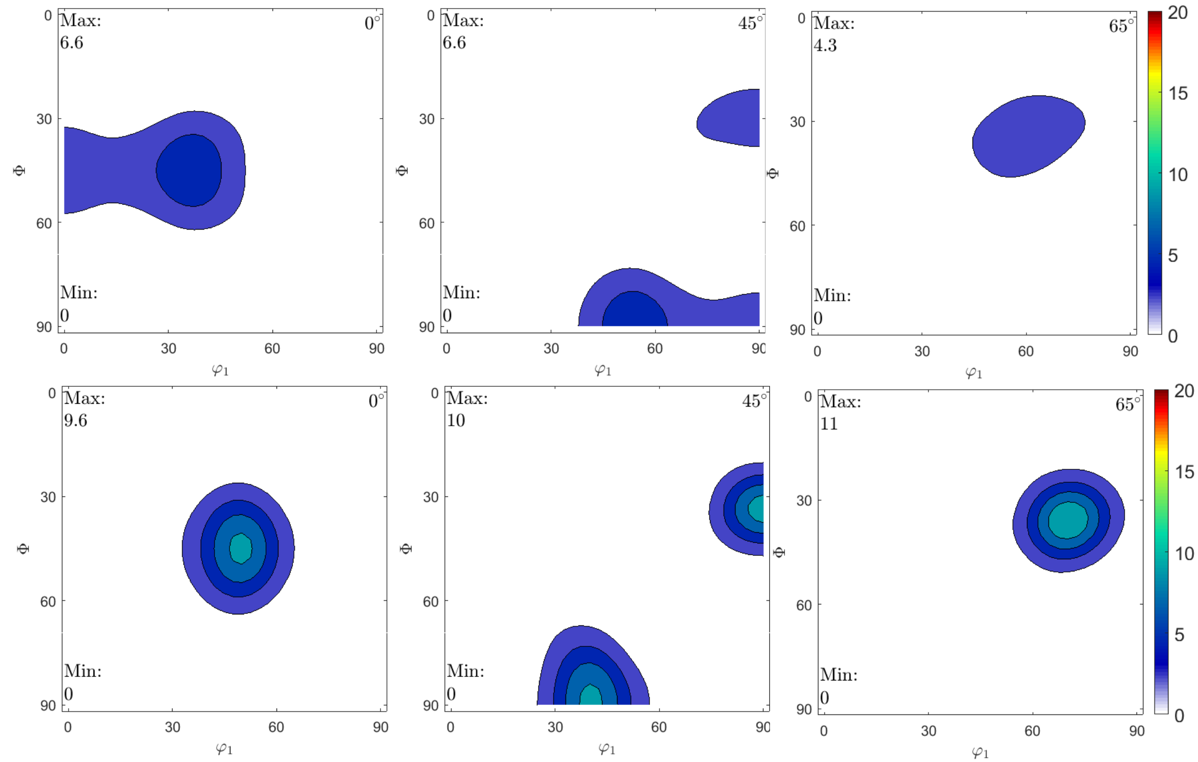
Tensile deformation - FCC – Experiment

- Tensile test of high-Mn TRIP/TWIP steel
- EBSD texture measurements

Initial texture

Texture close to fracture



- Tensile deformation leads to strengthening of fcc rolling texture.

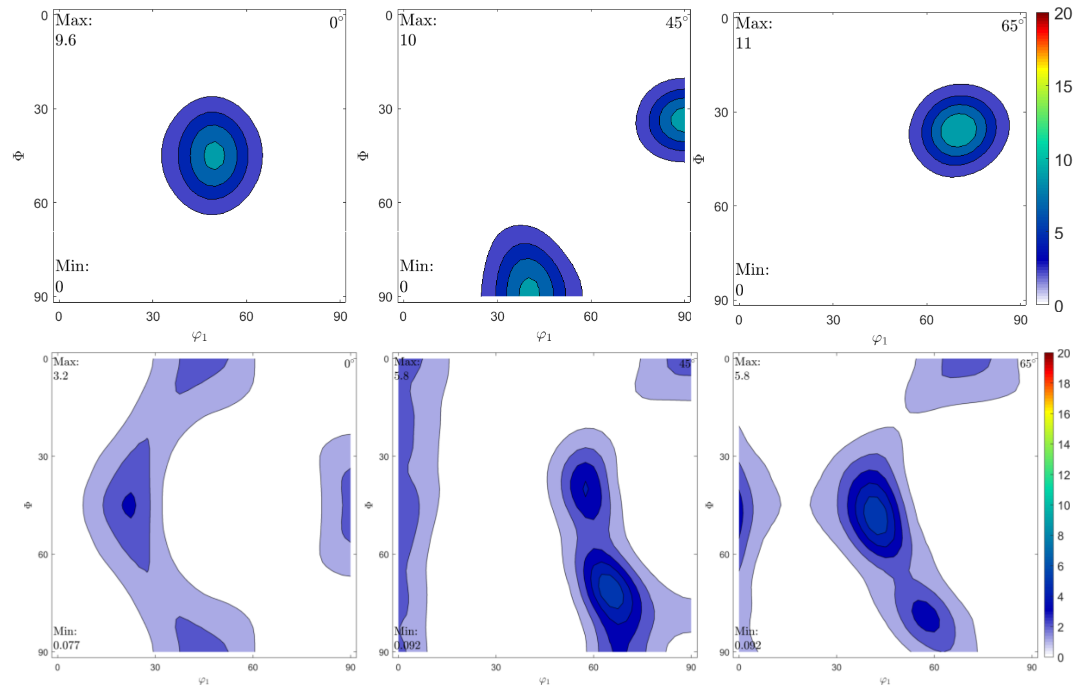
Tensile deformation – FCC – Simulation

- Start with initial experimental texture
- Tensile strain tensor:

$$\underline{\underline{\epsilon}} = \epsilon \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & -\nu & 0 \\ 0 & 0 & -\nu \end{pmatrix}$$

Texture close to fracture

Simulated texture (strain 0.4)



- Taylor simulation does not reproduce experimental texture.

Tensile deformation – BCC – Experiment

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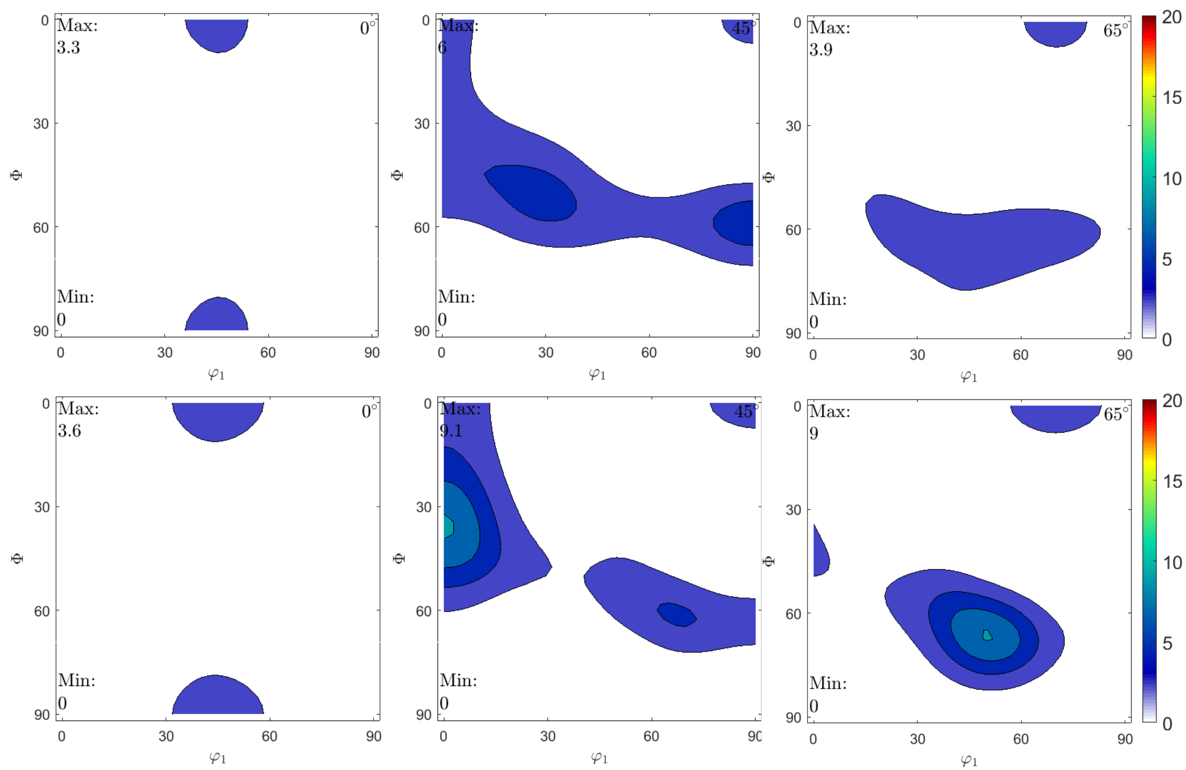
- Tensile test of high-Mn TRIP/TWIP steel
- EBSD texture measurements

Initial texture

Texture close to fracture



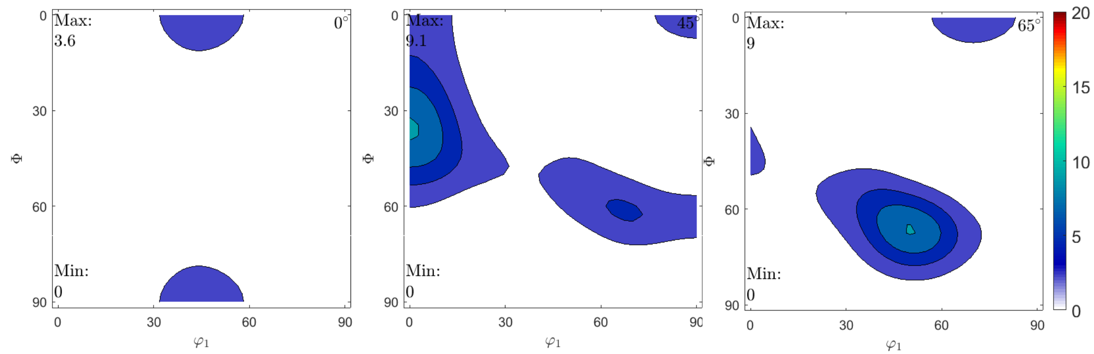
- Tensile deformation leads to strengthening of bcc α-fiber texture.

Tensile deformation – BCC – Simulation

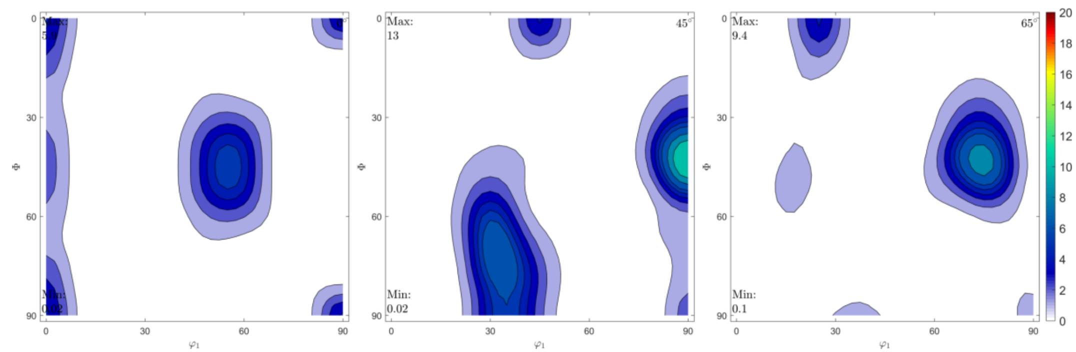
- Start with initial experimental texture
- Tensile strain tensor:

$$\underline{\underline{\epsilon}} = \epsilon \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & -\nu & 0 \\ 0 & 0 & -\nu \end{pmatrix}$$

Texture close to fracture



Simulated texture (strain 0.4)

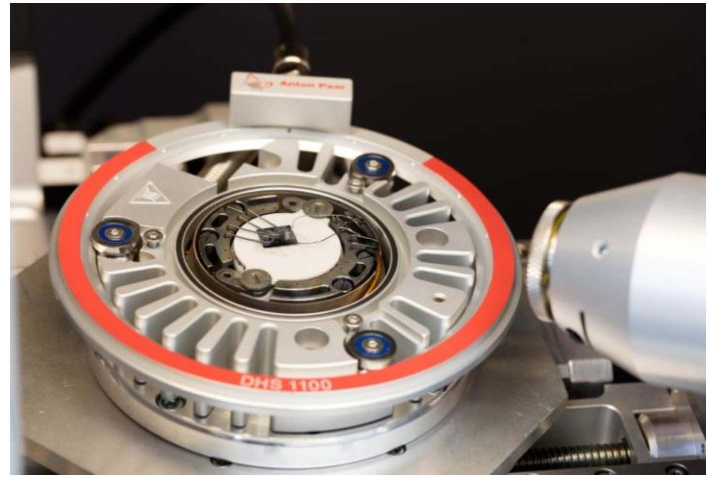


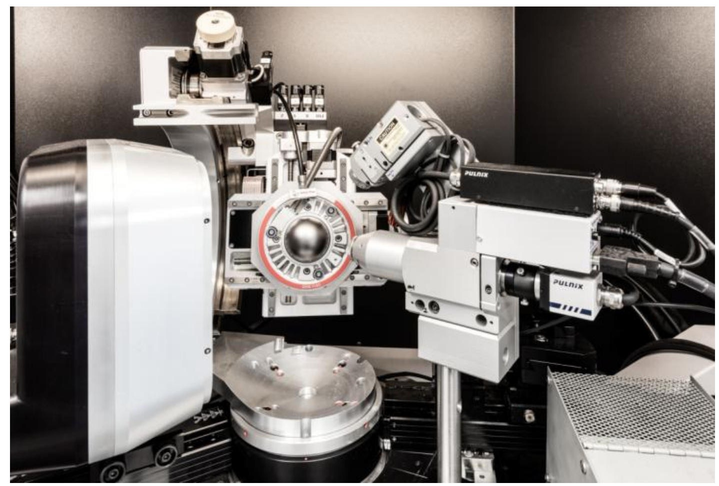
- Taylor simulation does not reproduce experimental texture.

Overview

Case study – In-situ recrystallization with XRD

- Anton Paar DHS1100 heating stage with Bruker D8 Discover x-ray diffractometer with area detector.
- Goal: Measurement of recrystallization kinetics via width reduction of x-ray reflexes (= reduction of dislocation density).
- Measurement conditions:
  - Sample: **Dual phase steel**
  - Sample preparation: cold rolled, 1.3 mm thick, grinded to 0.5 mm, electropolished
  - Heat treatment: **700°C**, heating rate 5 K/s, atmosphere He-3%H_2, soaking time 60 min
  - X-ray: $Fe_{K\alpha}$ radiation, **integration time 30s**, 2θ = 70°, ω=35°, angular coverage ~40° (→ 2 α-Fe reflexes), **no sample tilt or rotation**





Case study – In-situ recrystallization with XRD

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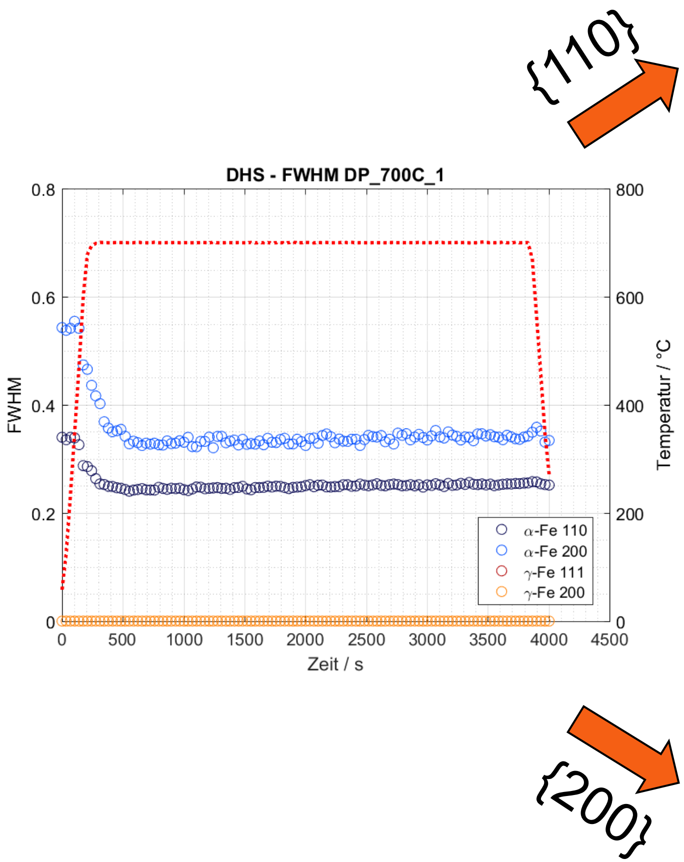
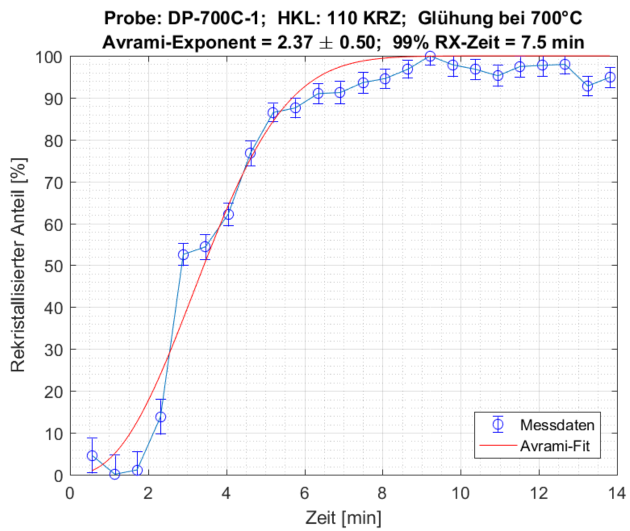
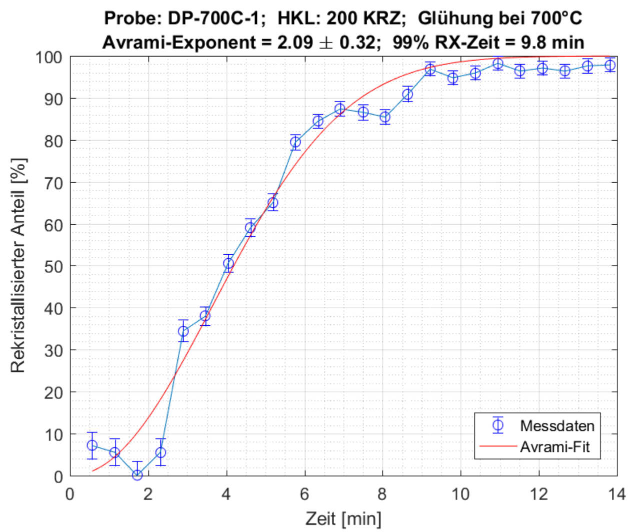




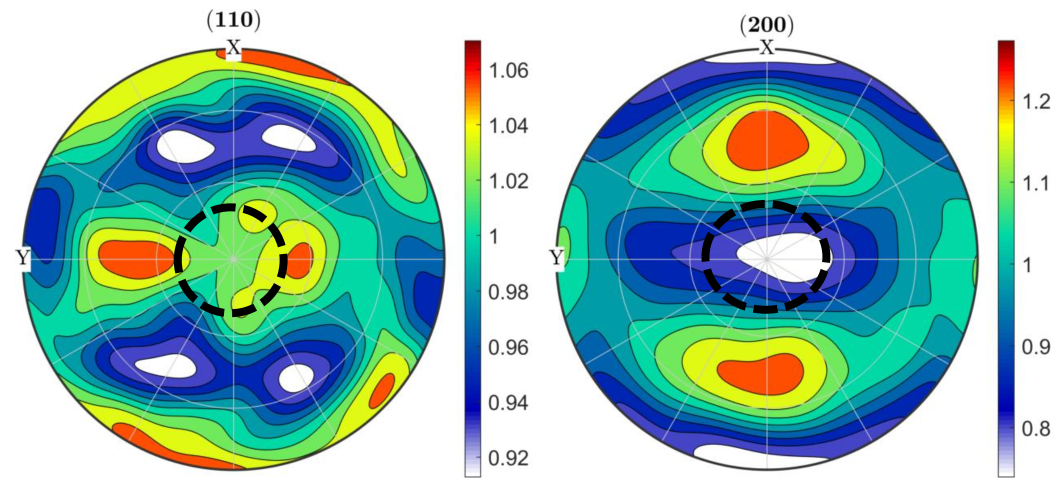


- Why does recrystallization proceed slower when determined from {200} reflex?
- Recrystallization time
  - {200}: 9.8 min
  - {111}: 7.5 min

Case study – In-situ recrystallization with XRD

- The Taylor factor of an orientation is proportional to the density of stored dislocations after deformation [5].
- Pole figures of the Taylor factor should correlate to dislocation density.

```
CS = crystalSymmetry('cubic');

% define a family of slip systems
 sS = slipSystem.bcc(CS);

% plane strain
epsilon = tensor.diag([1 0 -1],'name','strain');

% random orientations
ori = orientation.rand(10000,CS);

% compute Taylor factor for all orientations
[M,~,mori] = calcTaylor(inv(ori)*epsilon,sS.symmetrise);

% odf from random orientations with taylor factor as weights
odf = calcODF(ori,'weights',M);

% plot Taylor pole figures
figure
plotPDF(odf,Miller({1,1,0},{2,0,0},CS),'contourf','grid')
```



- The orientations used to determine the recrystallization with the {200} reflex exhibit a low dislocation density.

→ Smaller driving force for recrystallization

→ Slower recrystallization kinetic

[5] G. Mohamed, B. Bacroix, *Acta Materialia* 48 (**2000**) 3295 – 3302.

Remark: Recrystallization and stored dislocations

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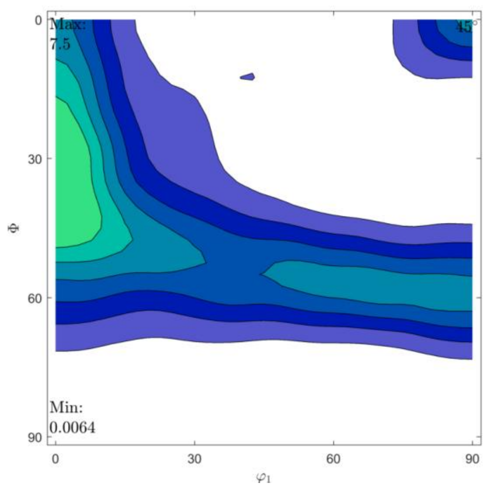
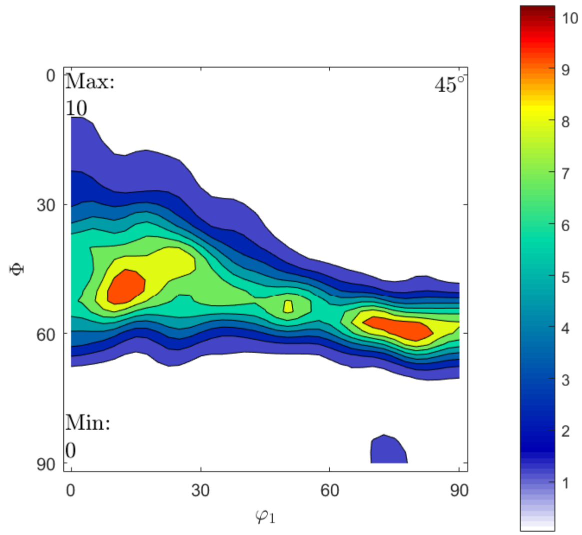
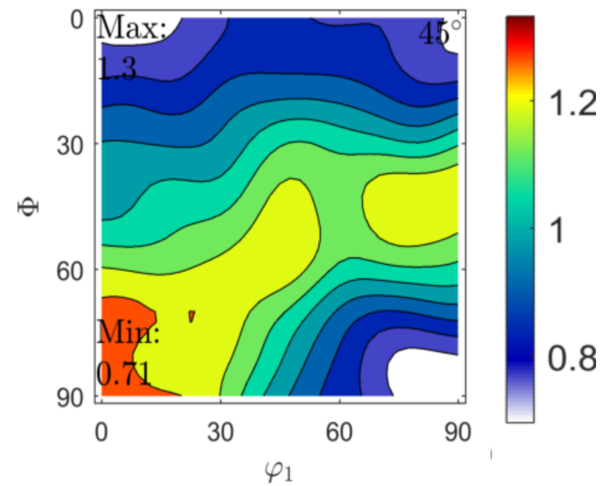
- Orientations with higher dislocation density after deformation have higher nucleation frequencies at subsequent recrystallization [6].



Cold rolled IF steel



Recrystallized IF steel



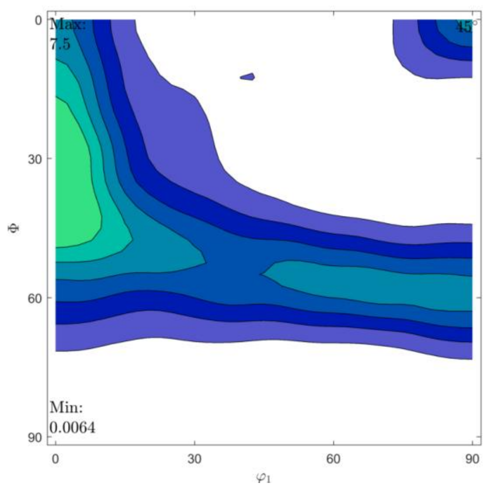
„Taylor“ ODF BCC

- γ-Fibre has higher stored dislocation density und thus strengthens by recrystallization.

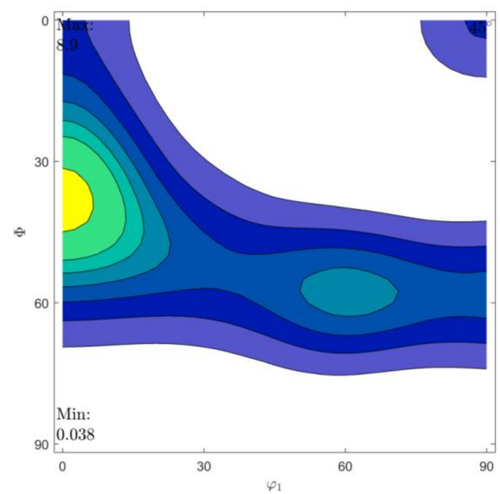
[6] G Castro Cerda et al., *Steel Res. Int.*, **2017**, *88*

Remark: Recrystallization and stored dislocations

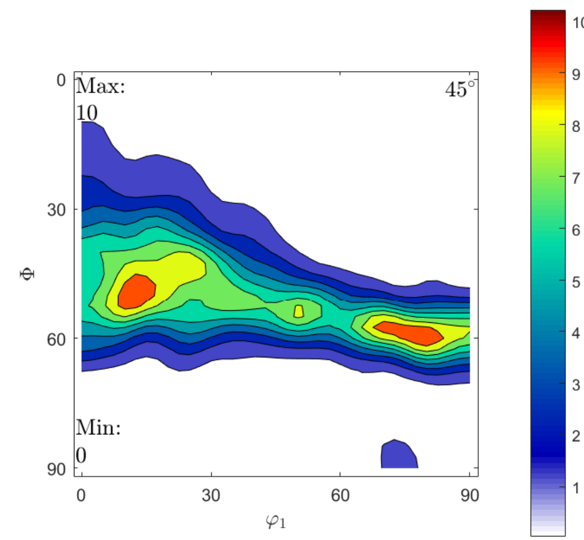
- Estimation of recrystallization texture by multiplication with Taylor factors.



Cold rolled IF steel



Estimated RX texture



Recrystallized IF steel

- Tendency is correct.
- Many factors are not considered, especially oriented growth.

Summary

- Taylor simulation with MTEX is a valuable extension to understand texture development during deformation up to medium strains.
- Relatively good comparison with experimental rolling textures
- Experimental tensile and shear textures could not be reproduced with simulations
  - Could Sachs model work better? [Stress equilibrium, only 1 active slip system]
- Calculations of Taylor factor distribution can give insight into distribution of dislocation density.

Wish list

- Speed up
- Implementation of material parameters
- Consideration of real microstructures (like VPSC, GIA or ALAMEL models)

No matter what you have planned ...

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