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Strain gradient enhanced crystal plasticity model: Application to electric steels

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M2i Cluster-1, project number: T18011

Industrial partner: Bosch Transmission Technology

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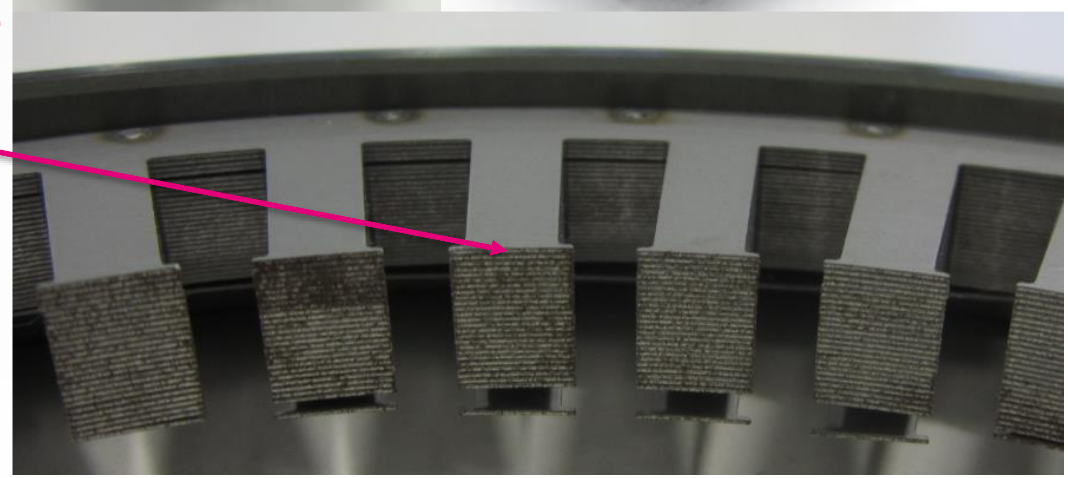
Agenda

- Industrial Aim
- Scientific Approach and Challenges
- Introduction
  - Electric Steel
  - Strain gradients and grain orientation
  - GNDs and KAM
- Strain gradient enhanced crystal plasticity
- EBSD measurements
- Tensile tests and simulation results
- Fine blanking with crystal plasticity
- Conclusions

Industrial Aim

- Supply laminate stacked cores for e-motors
- Reduce magnetic loss for competitive edge
- Fine blanking is used for cutting laminates
- Grain orientation at the cutting edge influences the magnetic loss
- Optimize the fine blanking process parameters



Overall Scientific Approach

Theories

Deformation Mechanics

Crystal Plasticity

Damage Mechanics

Simulations

Process parameters

Predict

Strain gradients / residual stresses

Grain mis-orientations / GNDs

Testing

Response

Phase-A
Current Project

Magnetic losses / Edge quality

Meta Model

Final result

Optimized fine blanking process parameter

Scientific Challenges

Simulations with Gradient Enhanced Crystal Plasticity (physically based)

- RVE cannot be defined (Grains are too large)
- Grain size and orientation variations (response will vary)
- Re-meshing
- Large computation time

Simulations with Strain Gradient continuum Plasticity

- Relatively low computation time
- Grain size and orientation not taken into account
- Model parameters for accurate predictions?

Scientific Challenges (cont'd)

Tensile tests

- Rolling direction
- Transverse direction

Gradient Enhanced Crystal plasticity Model parameters

EBSD

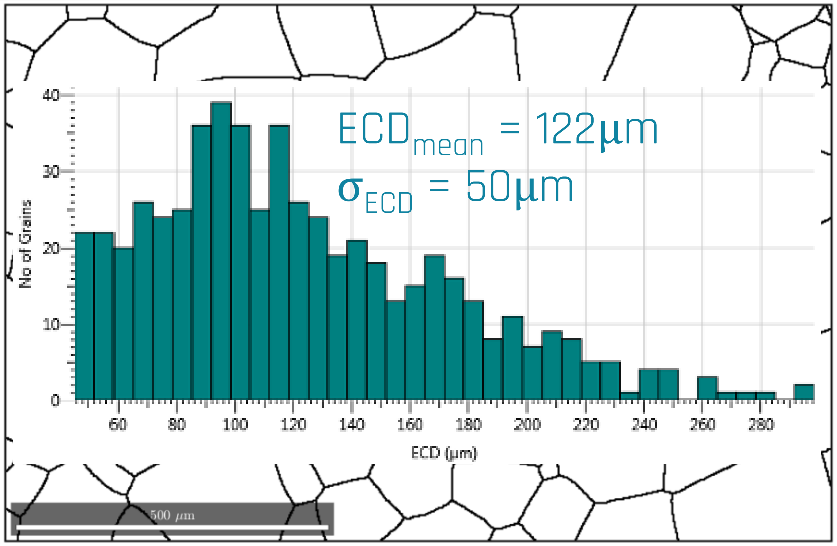
- Undeformed specimens
- Deformed specimens
- Grain size and orientations

Fit Model parameters

- Simulations
- Actual microstructure
- Actual Grain data

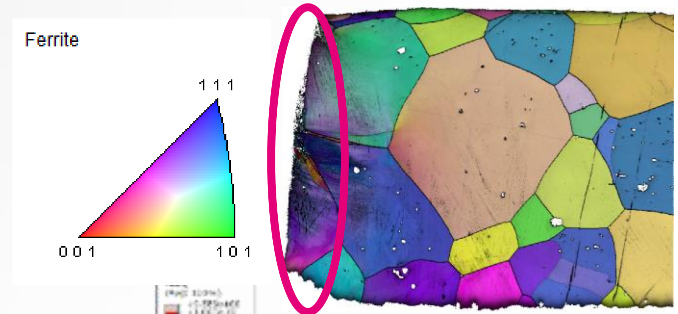
Introduction (Electric Steel)

- Excellent soft magnetic properties (magnetization behavior, permeability, coercive field and magnetic losses)
- Main Application: Electrical motors and transformers
- BCC crystals with <100> as most favorable magnetization direction
- In this project
  - Non-oriented electric steel (planar isotropic while <100> preferred normal to sheet plane)
  - 3.3% Si, 0.9% Al, t=0.2mm
  - Varnish coating C3 classification
  - Large grains



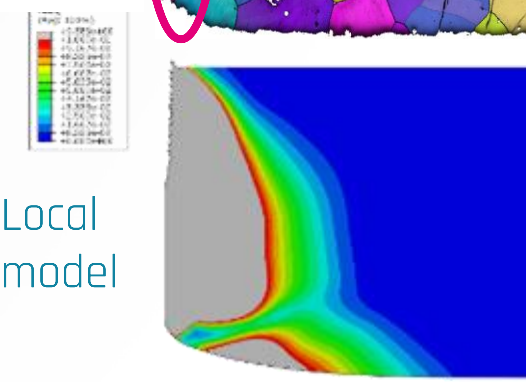
Introduction (Gradient + Grain orientations)

- Why gradient enhanced?
- Hardening is a function of strain gradient

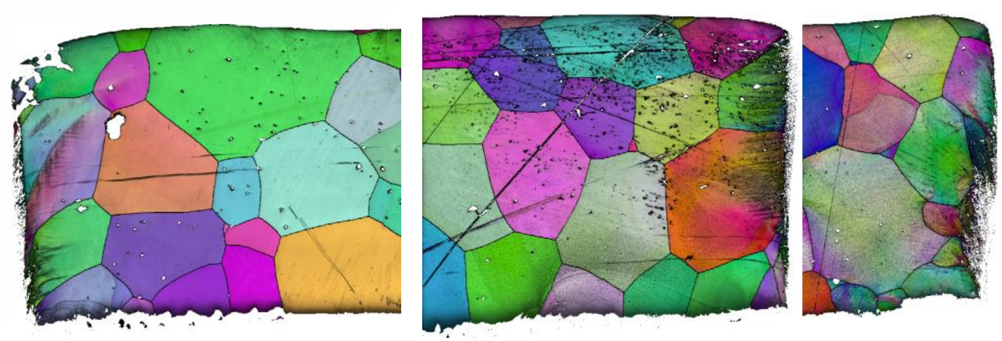


- Local models may not work

Local model



- Grain orientation at the cutting edge can have influence



Introduction (GNDs and KAM)

- GNDs are related to strain gradients (for example bending of a single crystal)
- GNDs also depend upon slip plane orientation w.r.to the bending plane of the crystal
- GNDs can be measured by the measuring the misorientation of crystals within a grain (for e.g. from EBSD)

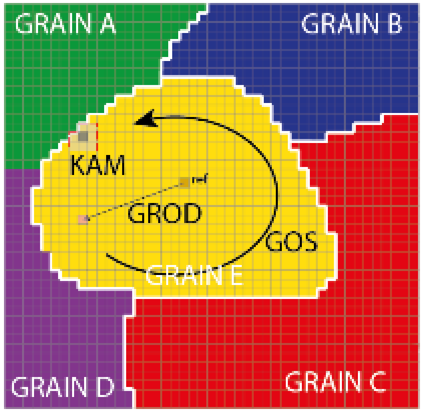
$$\Delta\theta_i^j = \cos^{-1}\left(0.5\left[\mathrm{tr}\left(\mathbf{G}_j \cdot \mathbf{G}_i^{-1}\right) - 1\right]\right) \quad , \mathbf{G}_i : \text{orientation matrix of pixel i}$$

Kernel Average Misorientation

$$\boxed{\mathrm{KAM}_i = \frac{1}{N}\sum_{j=1}^{N}\Delta\theta_i^j \quad , \text{N:neighbours}}$$

Grain Reference Orientation Deviation

$$\boxed{\mathrm{GROD}_i = \Delta\theta_i^{ref}}$$



$$\rho_{GND} = \frac{2\mathrm{KAM}}{ub}$$

u is step size in EBSD
b is burger's vector magnitude

Grain Orientation Spread

$$\boxed{\mathrm{GOS}_{\text{Grain E}} = \frac{1}{M}\sum_{i=1}^{M}\Delta\theta_i^{ref}}$$

Strain Gradient Enhanced Crystal Plasticity

- Lower order approach → enhanced hardening due to GNDs
- Rate independent crystal plasticity. Slip only on slip planes when resolved shear stress > slip resistance
- Large deformation formulation $\mathbf{F} = \hat{\mathbf{F}}_e \cdot \mathbf{F}_i$ taking $\hat{\mathbf{U}}_e \cong 1$
- Taylor's type hardening $\tau_f^{(\alpha)} = \tau_0 + \mu b \sqrt{\sum_\beta Q^{(\alpha\beta)} \rho^{(\beta)}}$

  where $Q^{(\alpha\beta)}$ defines strengthening of slip plane α due increase in dislocations density on β
- Dislocation density $\rho^{(\alpha)} = \rho_{SSD}^{(\alpha)} + \rho_{GND}^{(\alpha)}$
- Statistically stored dislocation density $\dot{\rho}_{SSD}^{(\alpha)} = \frac{\dot{\gamma}_{(\alpha)}}{\gamma^\infty} \left[\rho_{SSD}^\infty - \rho_{SSD}^{(\alpha)}\right]$

  $\dot{\gamma}$ is slip rate in slip plane α, γ^∞ and ρ_{SSD}^∞ are constants

Strain Gradient Enhanced Crystal Plasticity

- Geometrically necessary dislocation density

$$\rho_{GND}^{(\alpha)} = \frac{1}{b}\sqrt{\rho_{\vdash,GND}^{(\alpha)} + \rho_{\odot,GND}^{(\alpha)}}$$

$\rho_{\vdash,GND}^{(\alpha)}$ are edge dislocations
$\rho_{\odot,GND}^{(\alpha)}$ are screw dislocations

- Gradient enhanced formulation in lattice configuration

$$\dot{\rho}_{\vdash,GND}^{(\alpha)} = -\mathbf{s}^{(\alpha)} \cdot \nabla^{\#}\dot{\gamma}^{(\alpha)} \text{ and } \dot{\rho}_{\odot,GND}^{(\alpha)} = \mathbf{l}^{(\alpha)} \cdot \nabla^{\#}\dot{\gamma}^{(\alpha)}$$

$\mathbf{l}^{(\alpha)}$ is the unit lattice vector, $\mathbf{s}^{(\alpha)}$ is slip direction and $\nabla^{\#}\dot{\gamma}^{(\alpha)}$ is the gradient of slip rate in lattice configuration

- Gradient enhanced formulation in reference configuration

$$\dot{\rho}_{\vdash,GND}^{(\alpha)} = -\mathbf{s}^{(\alpha)} \cdot \mathbf{F}_i^{-T} \cdot \nabla_0\dot{\gamma}^{(\alpha)} = -\mathbf{s}_0^{(\alpha)} \cdot \nabla_0\dot{\gamma}^{(\alpha)} \text{and}$$
$$\dot{\rho}_{\odot,GND}^{(\alpha)} = \mathbf{l}^{(\alpha)} \cdot \mathbf{F}_i^{-T} \cdot \nabla_0\dot{\gamma}^{(\alpha)} = \mathbf{l}_0^{(\alpha)} \cdot \nabla_0\dot{\gamma}^{(\alpha)}$$

- For further details and implementation, see PhD thesis “Damage in Dual Phase Steels” E.E. Aşik

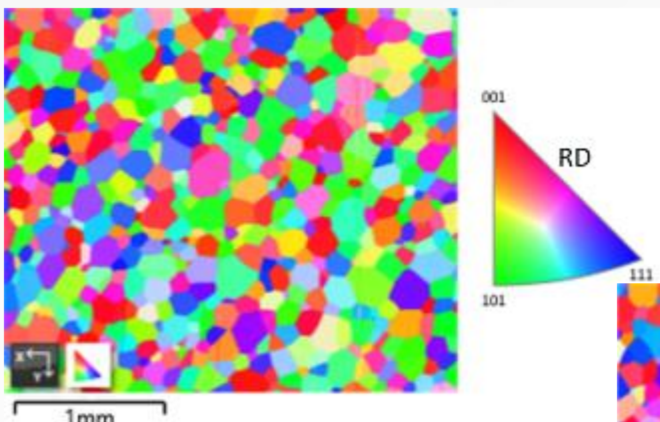
EBSD Measurements

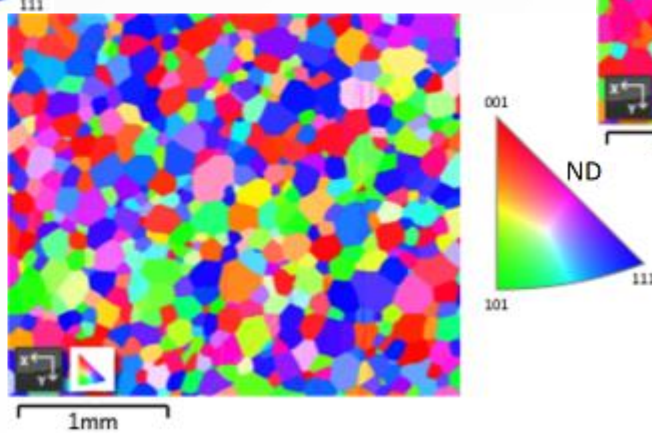
- Oxford Instruments (JSM-7200F, X-MaxN, software: AZtec)
- Undeformed and deformed material
- Sample Preparation

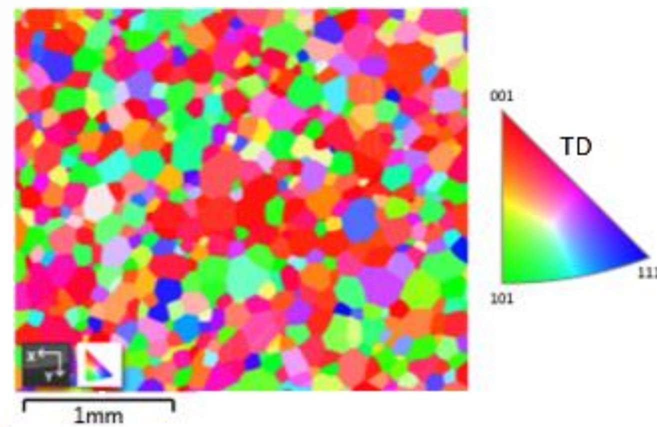
Undeformed material	Deformed material
Embedded in bakelite	Embedded in bakelite
Grinding 2000 paper (3min)	Grinding 2000 paper (10min)
Grinding 4000 paper (3min)	Grinding 4000 paper (10min)
OPS polishing (10min)→check if coating removed →if not keep polishing	OPS polishing (30min)→check if coating removed →if not keep polishing
Rinse with Ethanol and keep overnight in vaccuum	Rinse with Ethanol and keep overnight in vaccuum

EBSD Measurements (Undeformed)

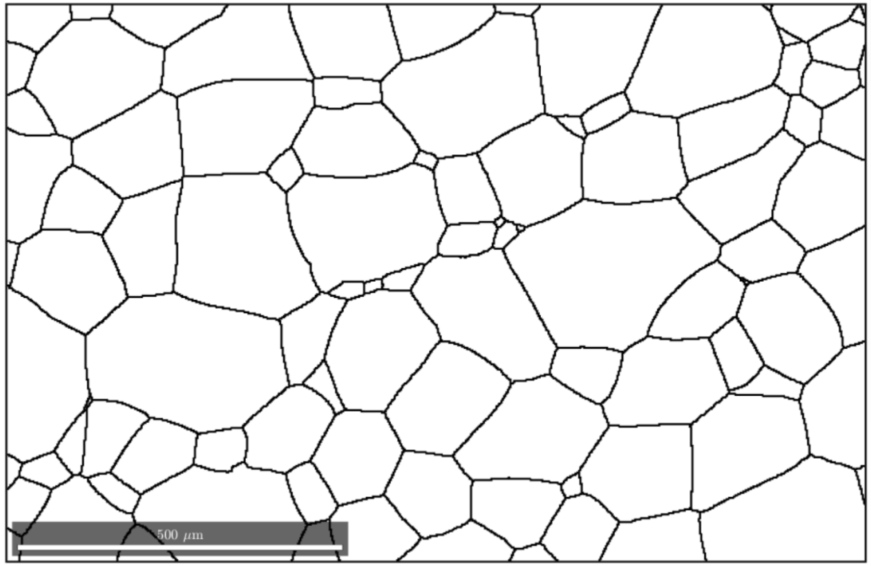
Measurement	Minimum	Maximum	Mean	Standard Deviation
Area (μm^2)	1,609.70	69,838.83	13,772.23	11,552.75
Aspect Ratio	1.11	5.39	1.55	0.46
Breadth (µm)	19.96	270.01	109.22	48.23
Length (µm)	55.46	421.89	160.51	63.66
ECD (µm)	45.27	298.20	122.35	50.70
GOS (°)	0.05	5.61	0.44	0.78
Perimeter (µm)	149.71	1,641.57	440.31	200.52







EBSD Measurements (Deformed, rolling)



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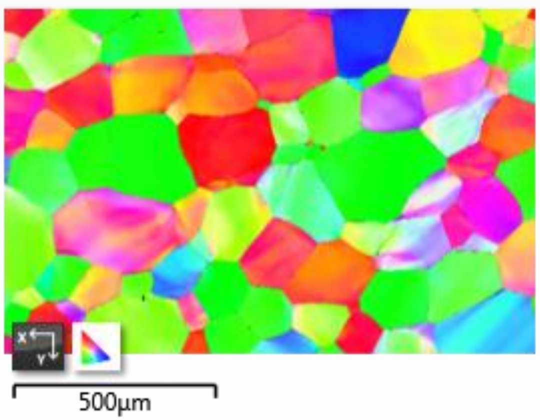

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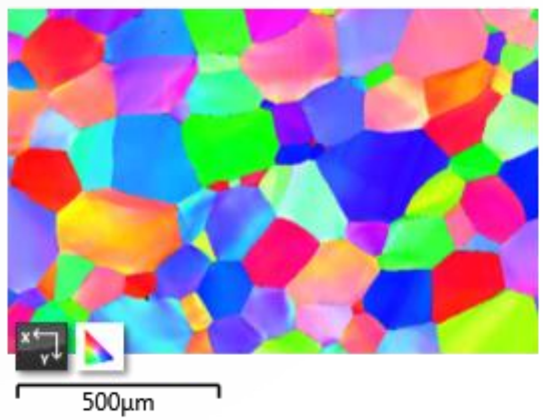

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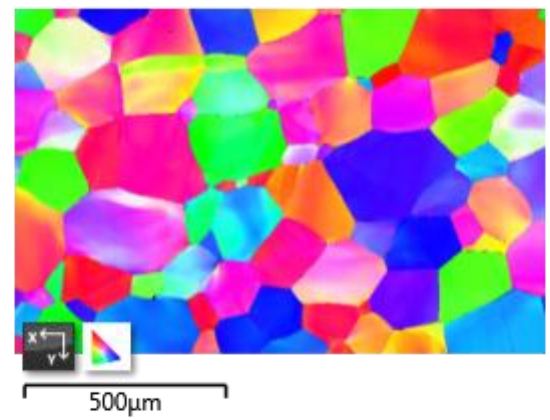
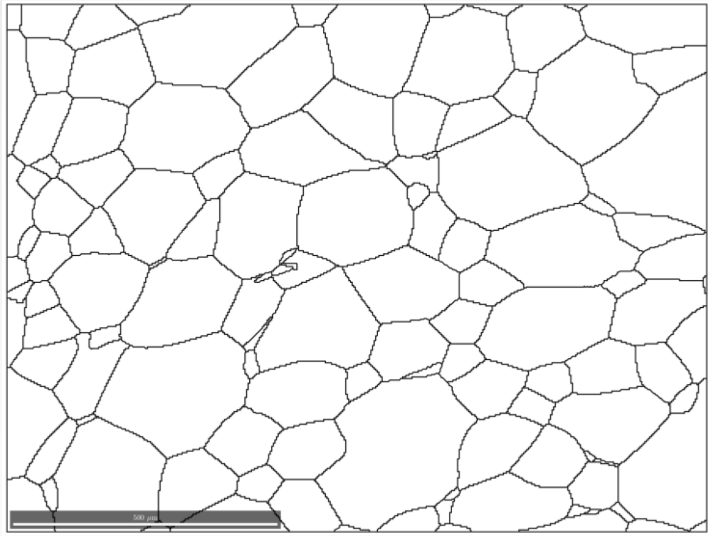


EBSD Measurements (Deformed, transverse)



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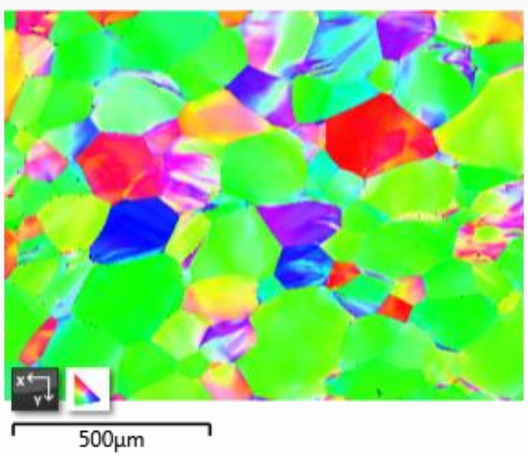

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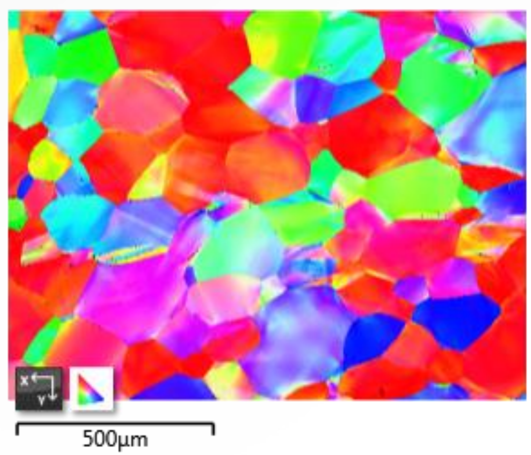

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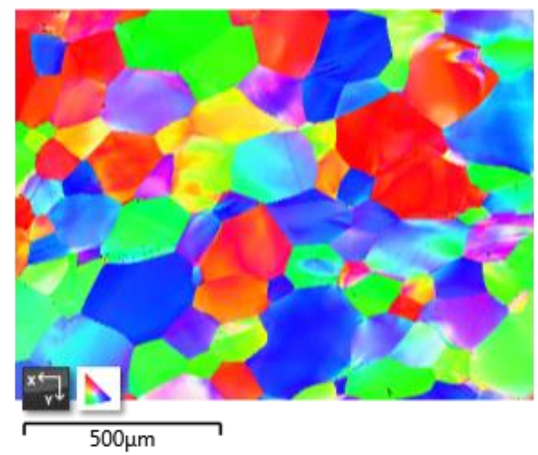
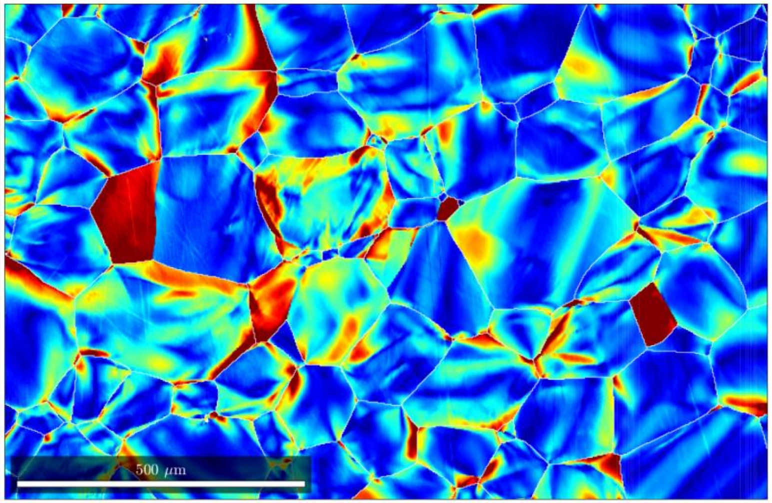
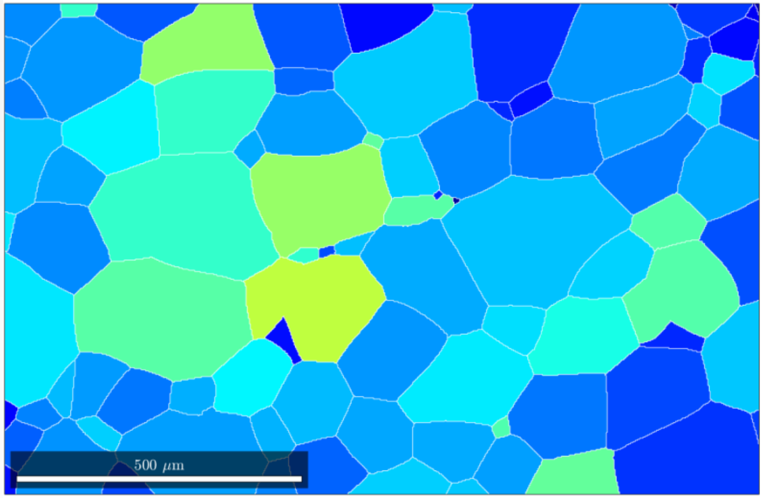


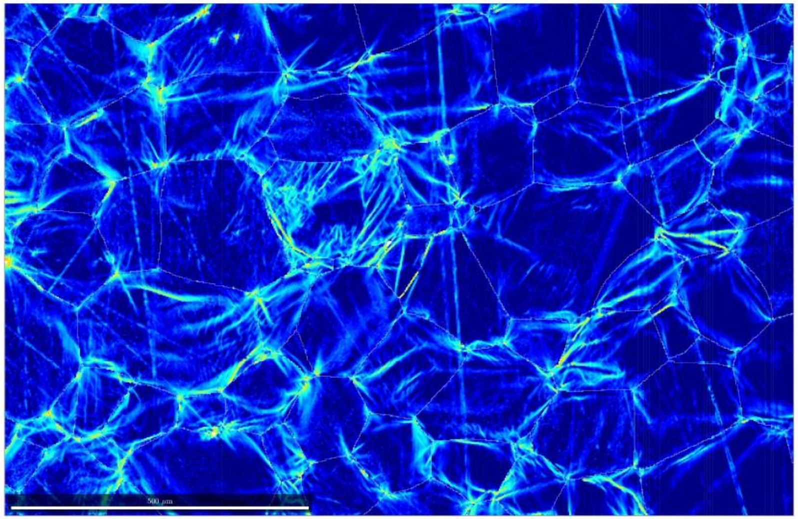
EBSD Measurements (Misorientation)



GROD

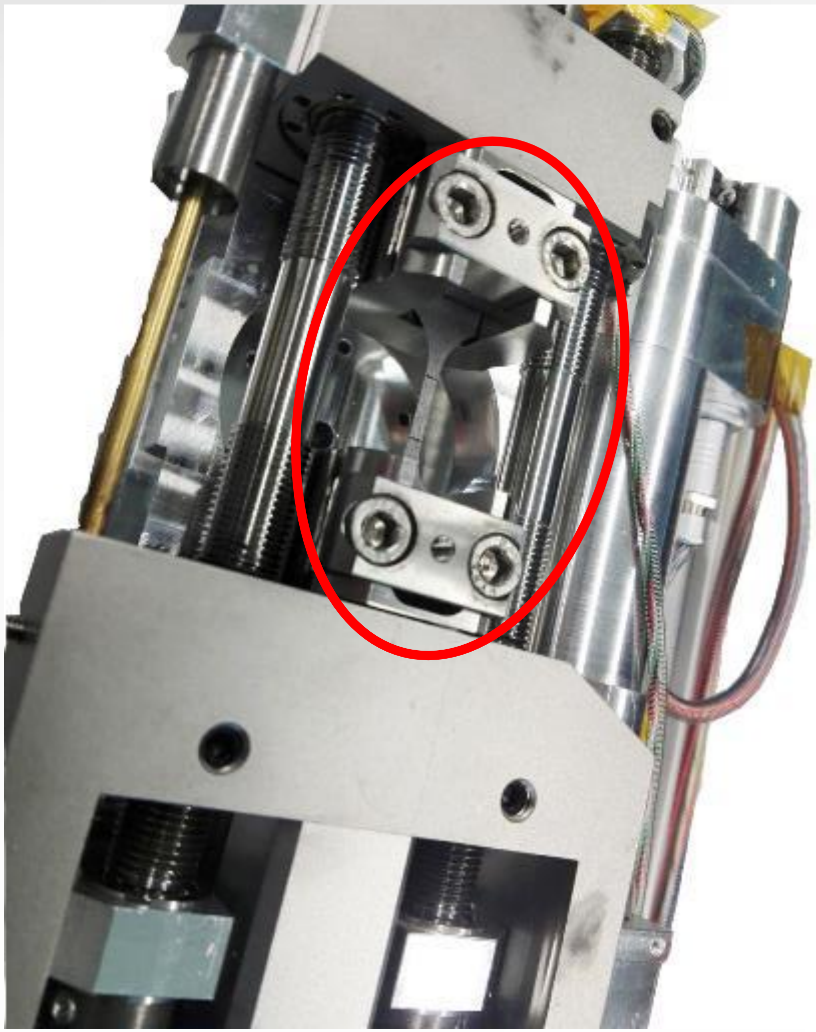


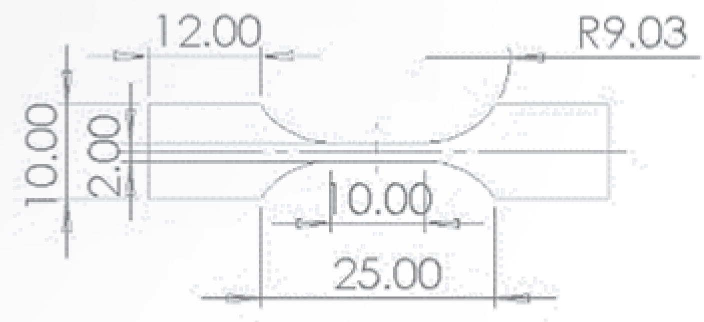
GOS



KAM → GND

Tensile Tests

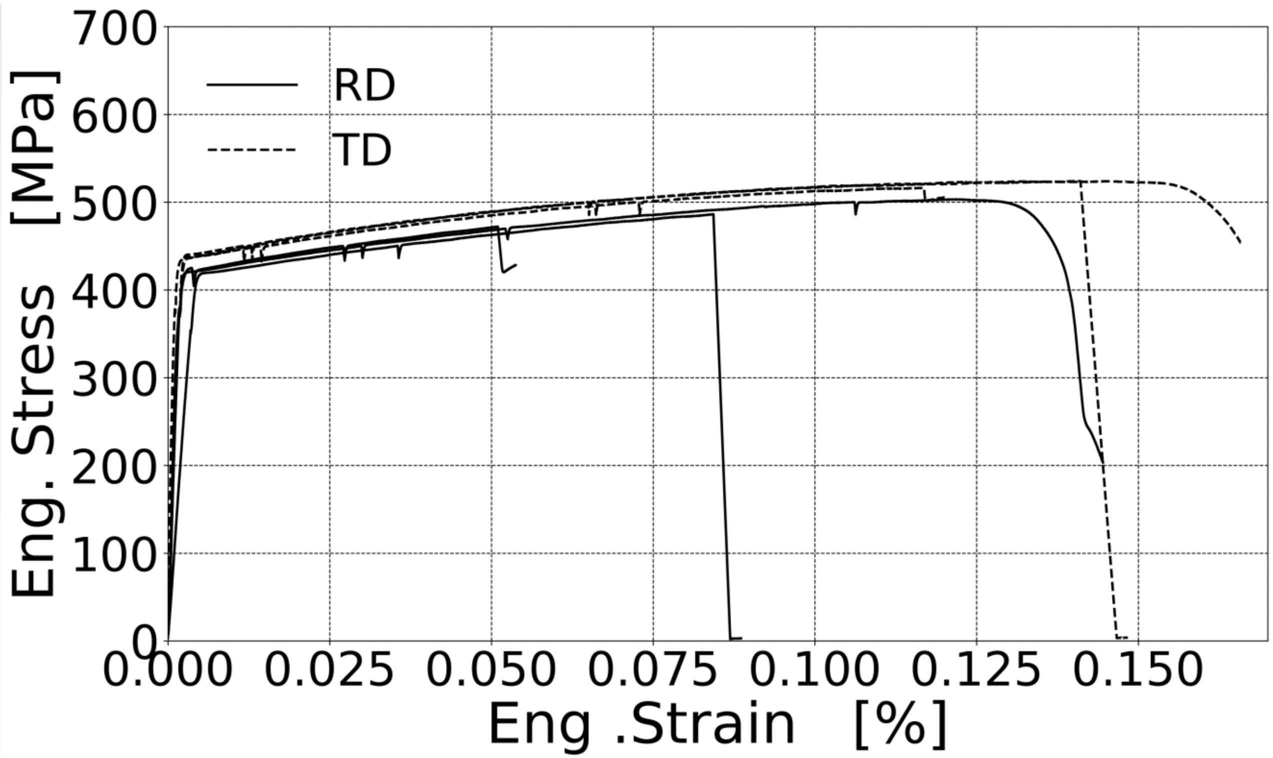




*units in mm

R1, R3,R4→ Rolling
T1.T2.T3 → Transverse

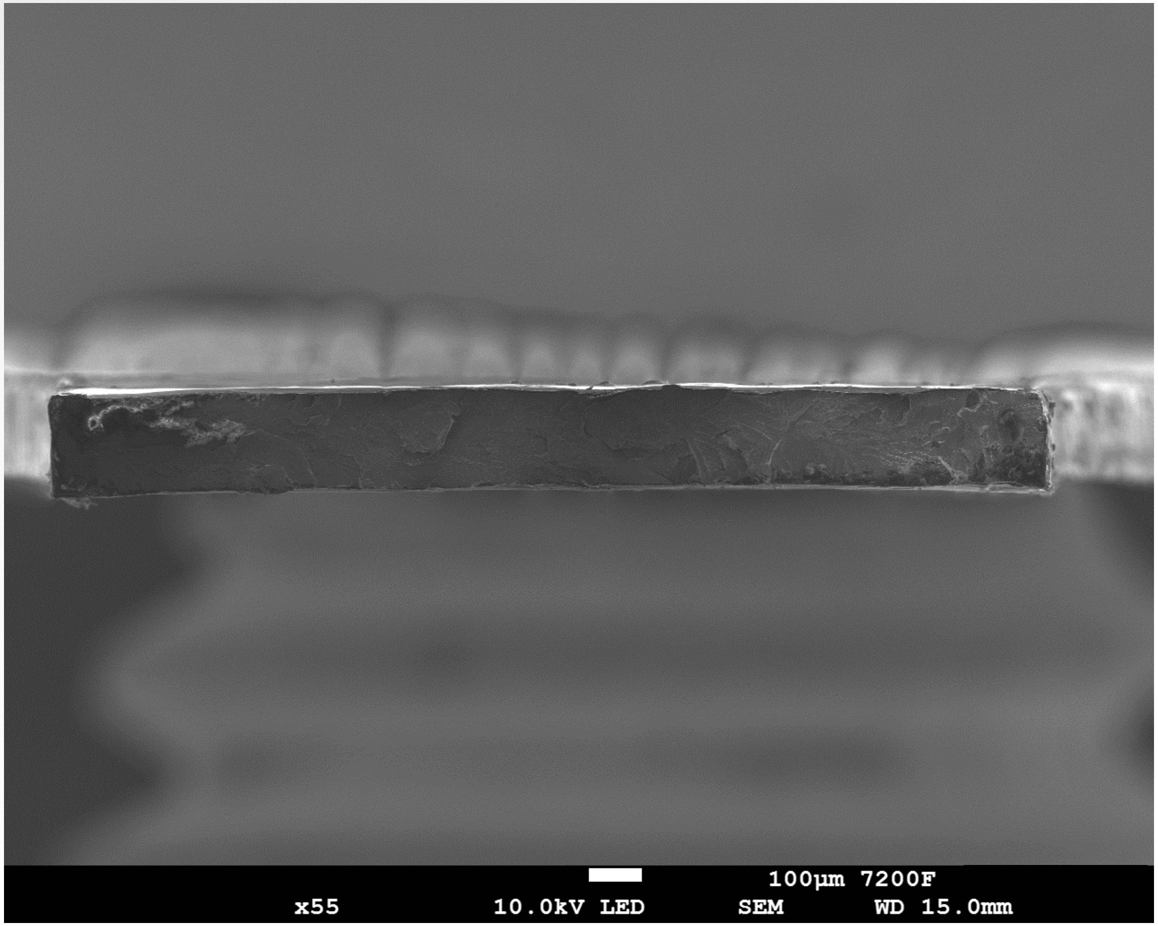
Tensile Tests



	Yield Strength [MPa]	Elastic Modulus [GPa]
Rolling Direction	420 ± 2.8	216 ± 4.0
Transvers Direction	435 ± 2.1	219 ± 1.0

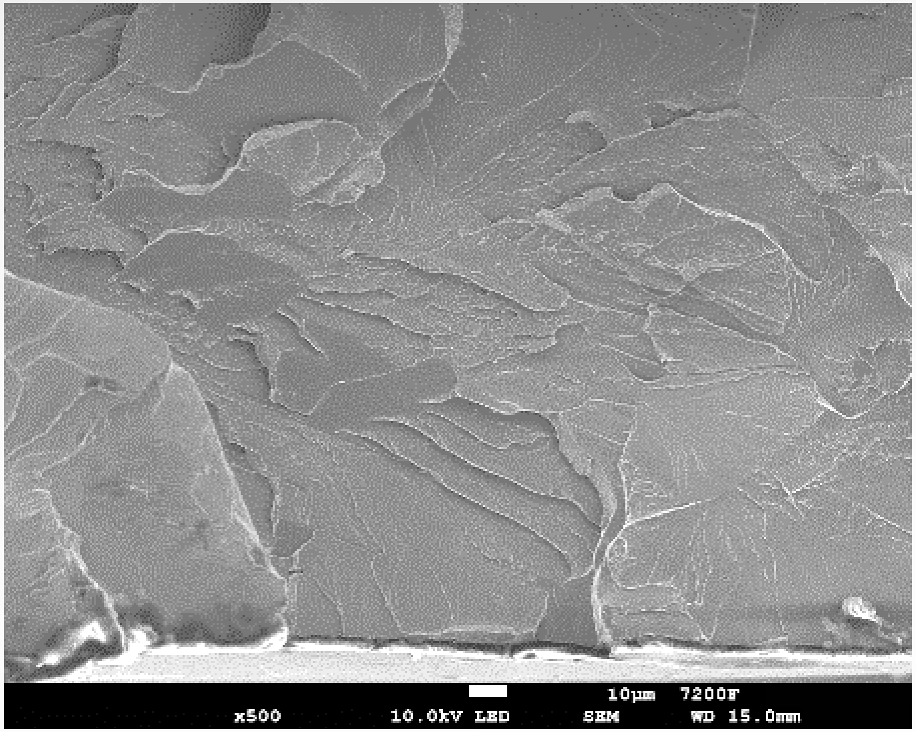
Tensile Tests

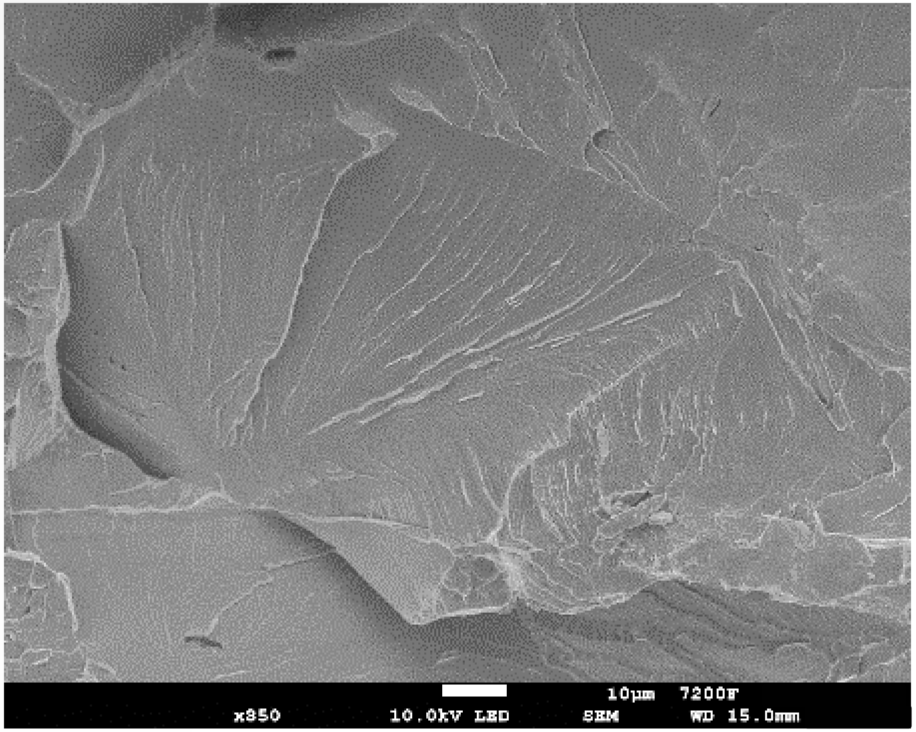
Fracture surface : Rolling direction



Tensile Tests

Fracture surface : Rolling direction

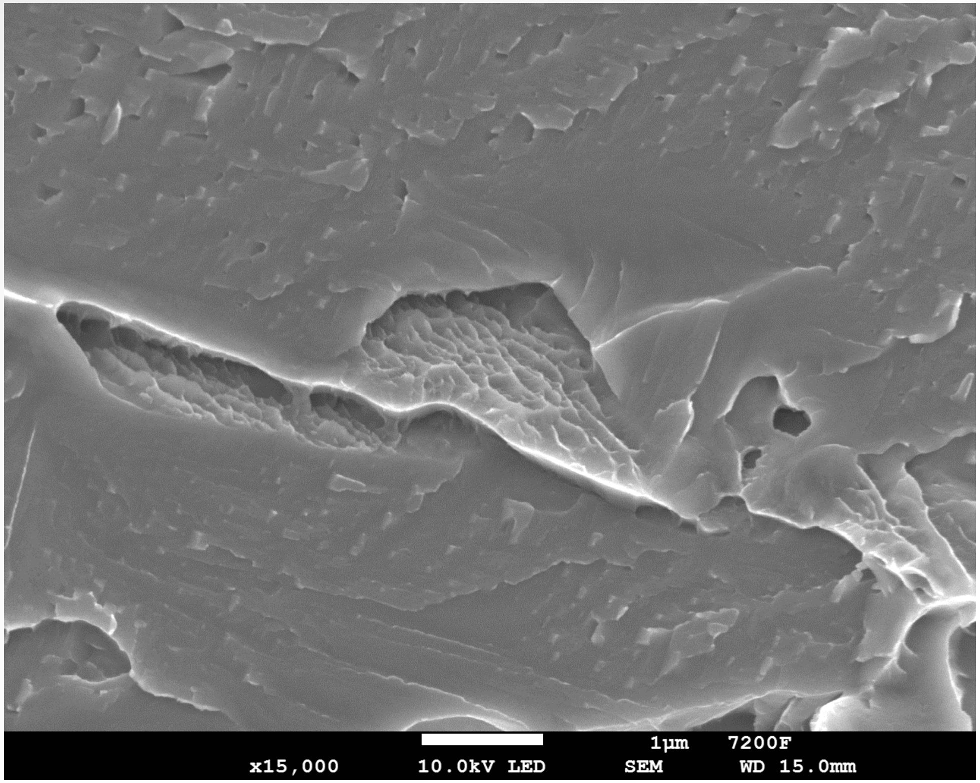




Transgranular fracture surface showing river patters as a sign of brittle fracture behavior.

Tensile Tests

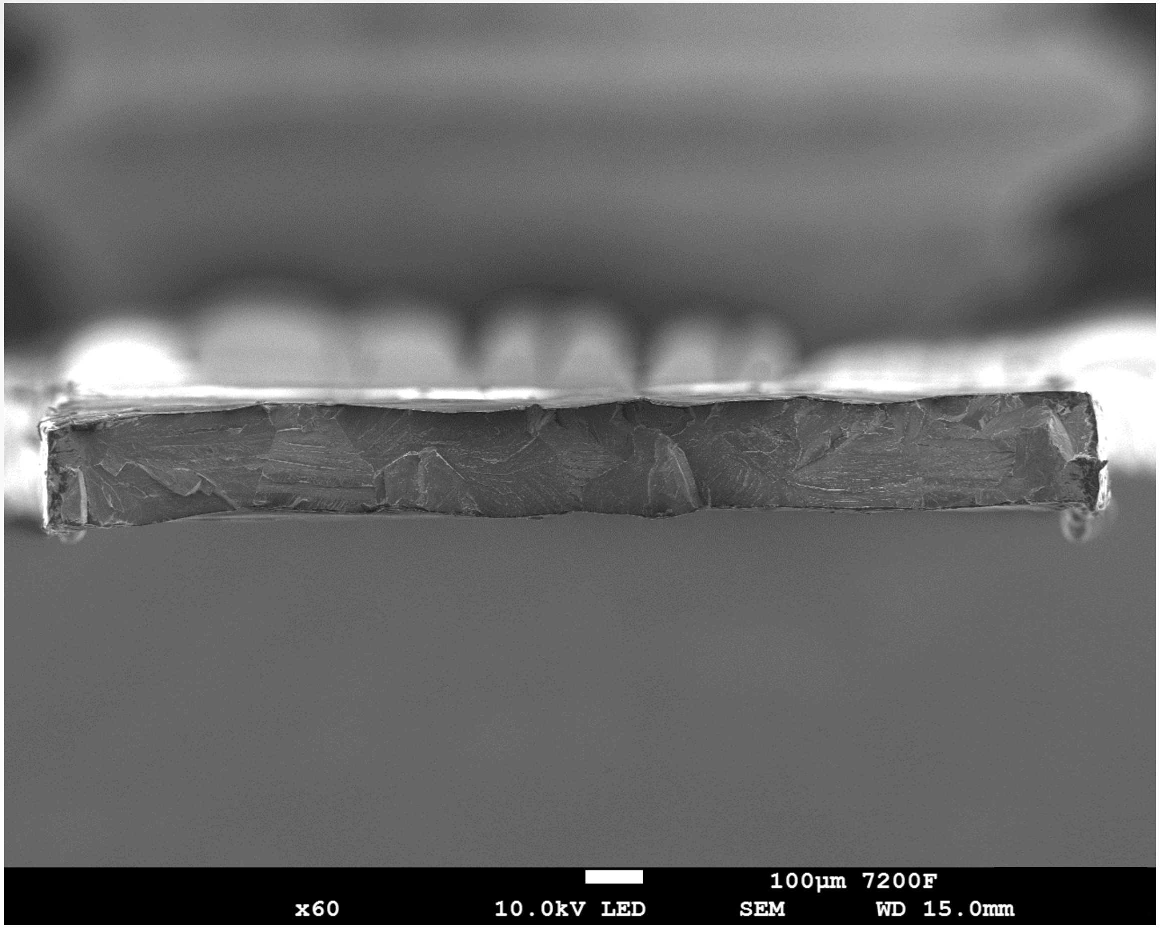
Fracture surface : Rolling direction



Some areas with dimples and micro voids as a sign of ductility.

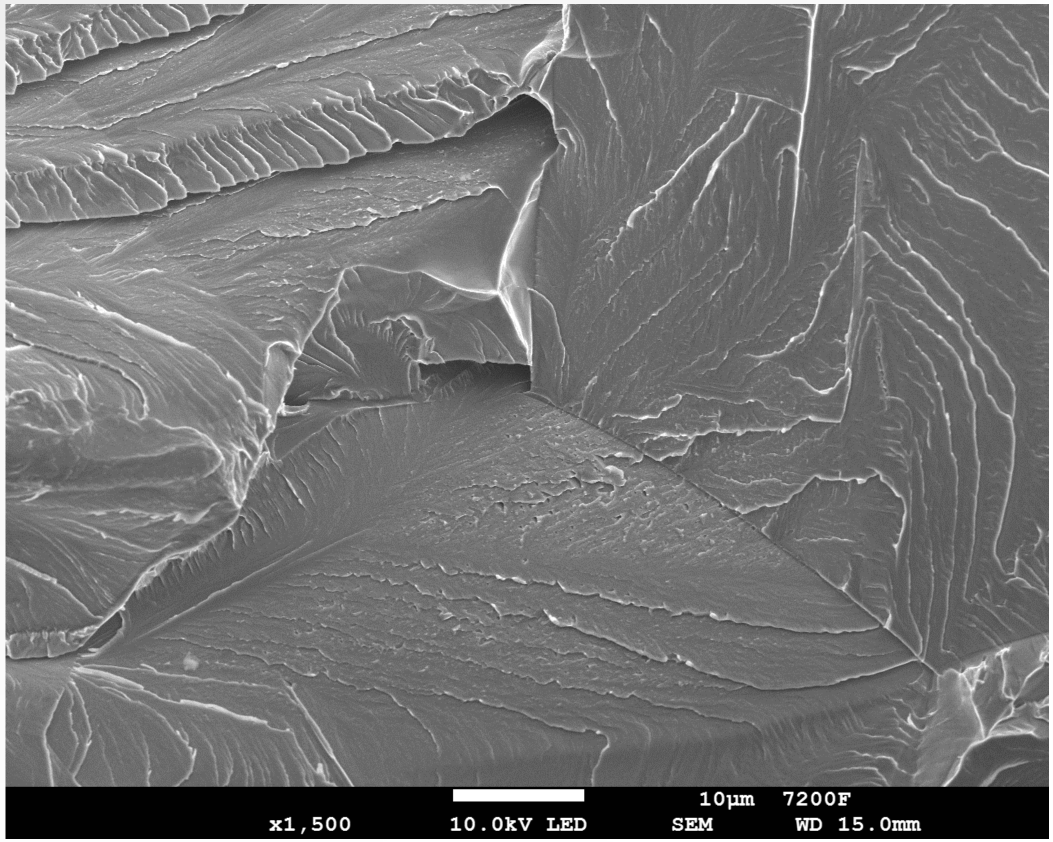
Tensile Tests

Fracture surface : Transverse direction



Tensile Tests

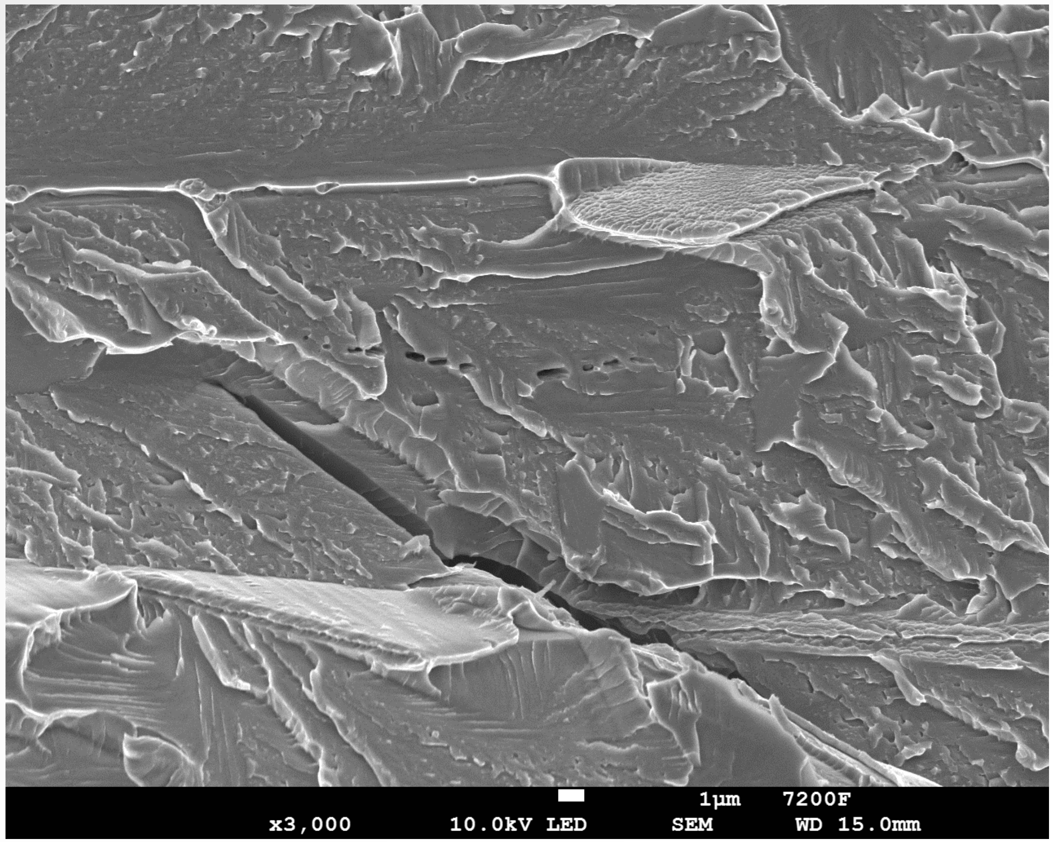
Fracture surface : Transverse direction



River patterns and grain boundary visible.

Tensile Tests

Fracture surface : Transverse direction



Micro voids and dimples

Tensile Test Simulations

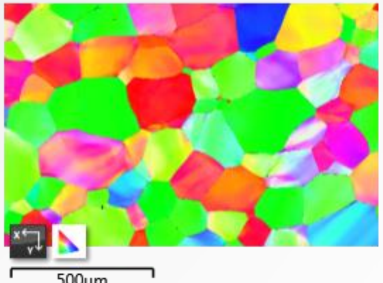
- Abaqus Implicit
- User defined subroutines (UMAT, USDFLD)
- Weakly coupled non-local scheme (gradient effect and GND hardening effect in the next increment)
- 2D Plane strain assumption
- Simulation with actual (measured) microstructure and orientations

Tensile Test Simulations

Fully automated

Grain Structure + Euler Angles → Abaqus Model

IPF X Color 6



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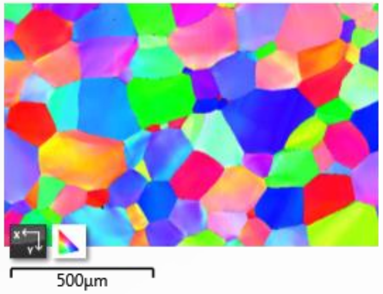

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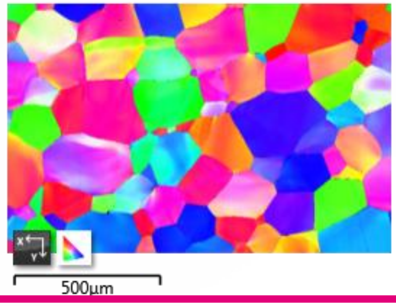
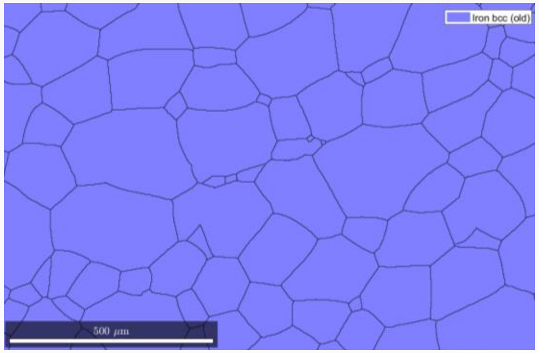
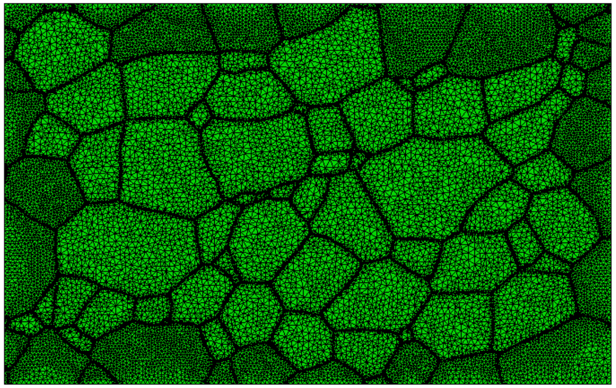


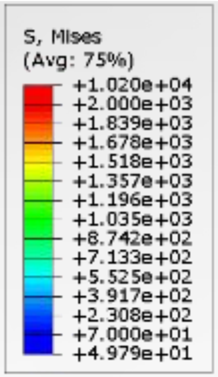


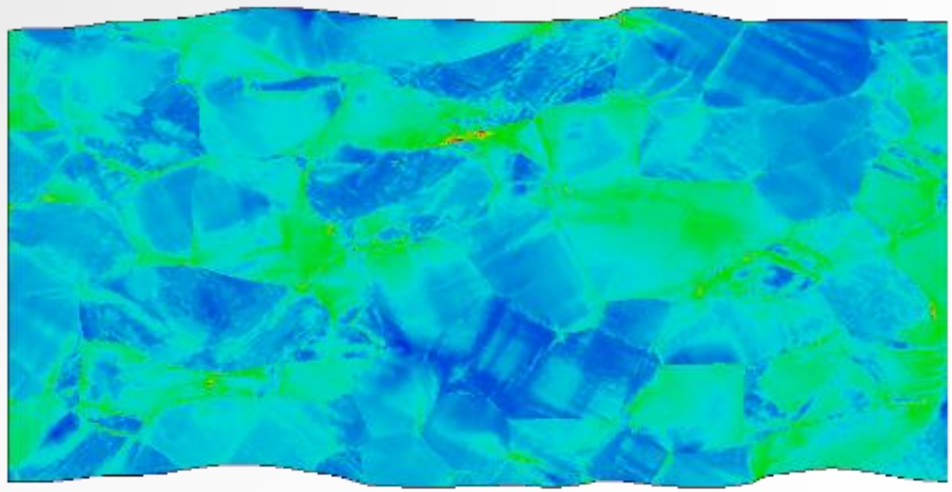
EBSD Measurements

FEA model

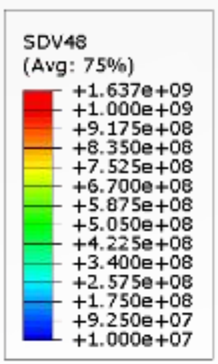


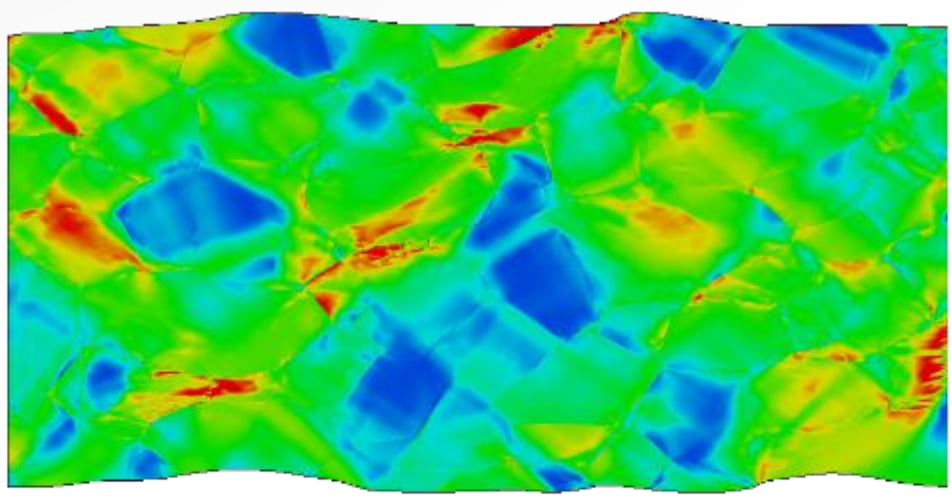
Tensile Test Simulation Results





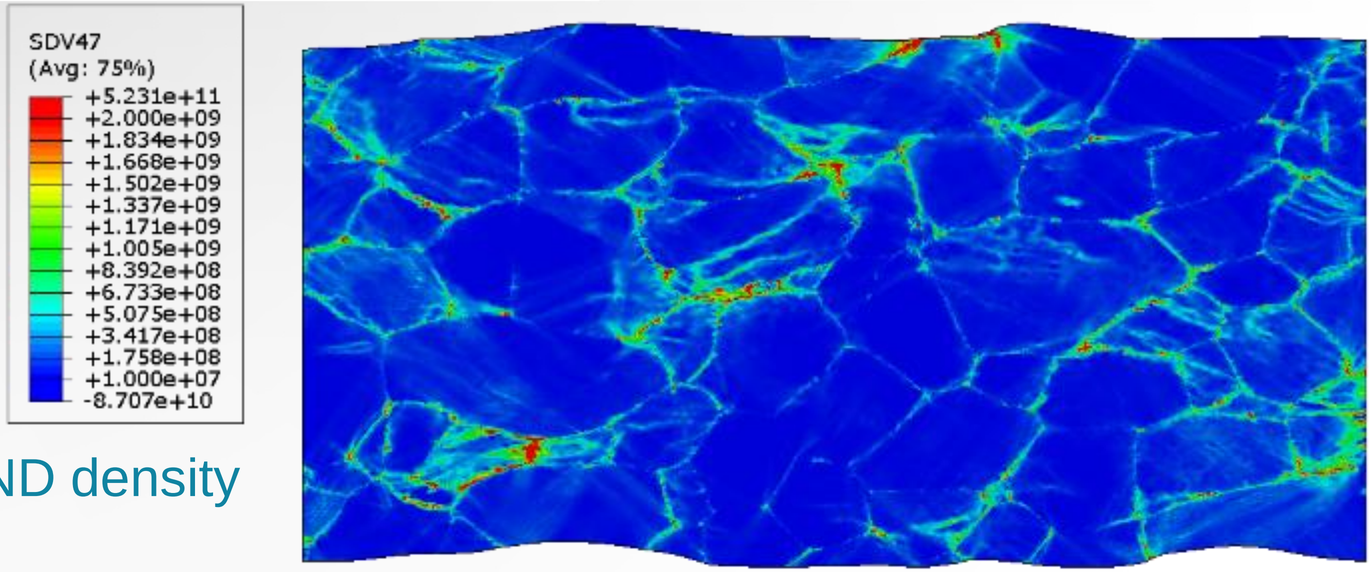
Von Mises Stress



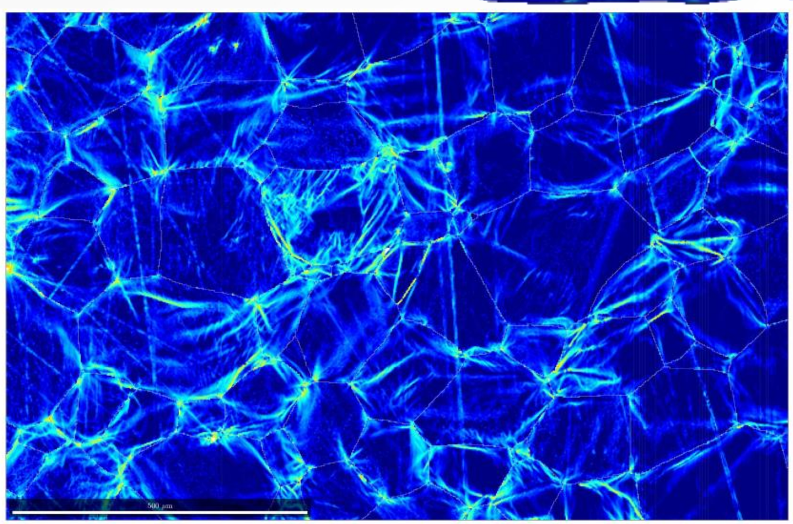


SSD

Tensile Test Simulation results



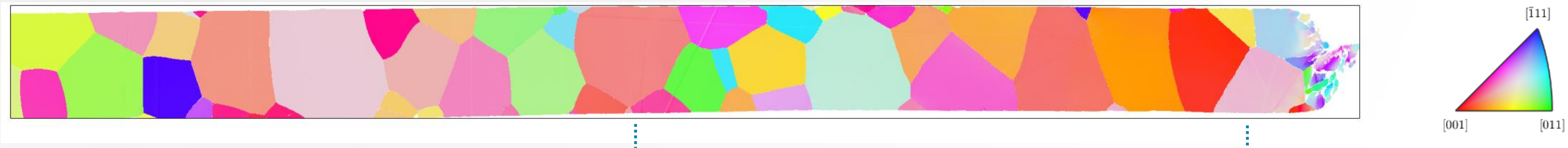
GND density



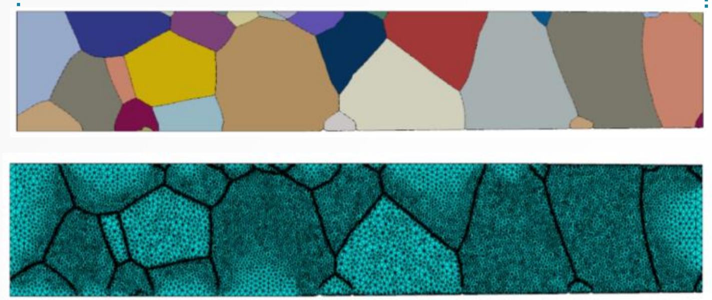
Measured

Tensile Test Simulation results

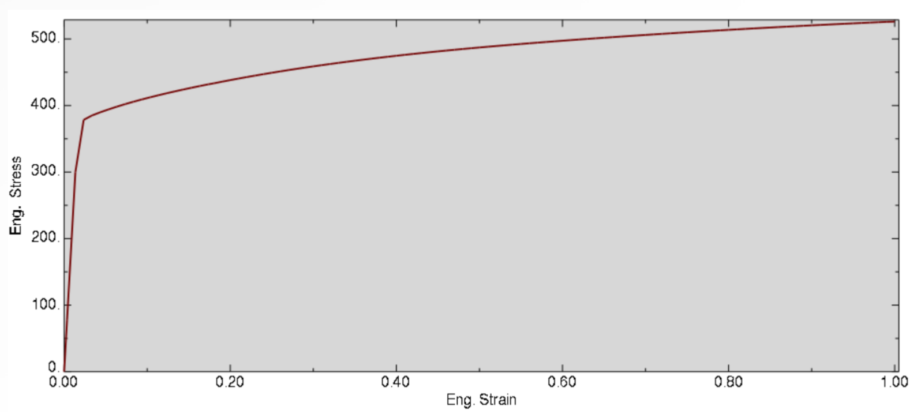
EBSD MEASUREMENT



Abaqus Model

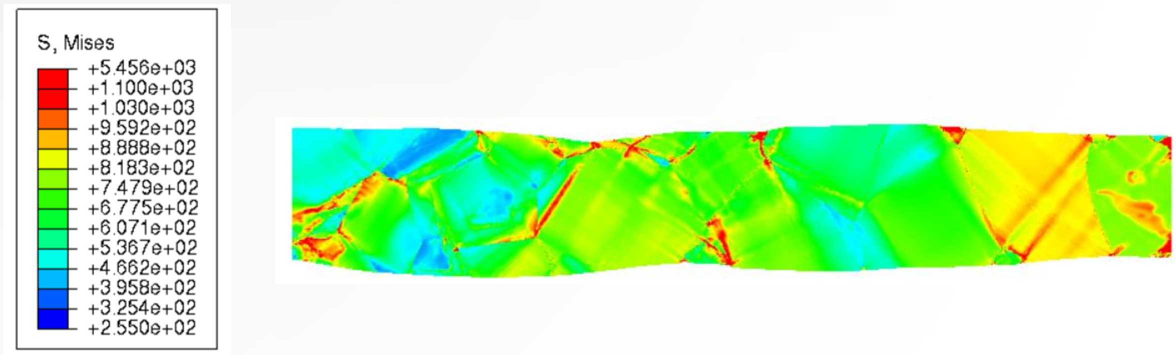


Calibration of material properties ($\gamma^{\infty}$and ρ_{SSD}^{∞})

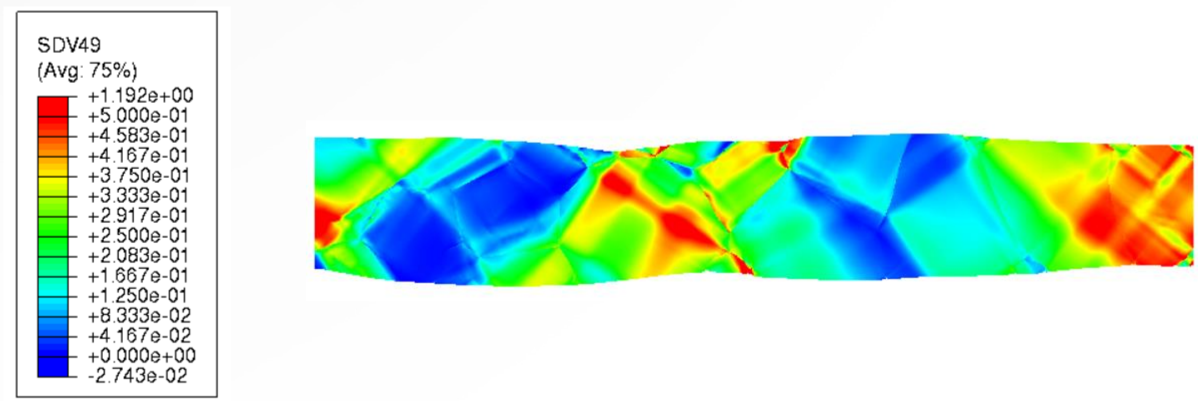


Tensile Test Simulation results

Equivalent Stress

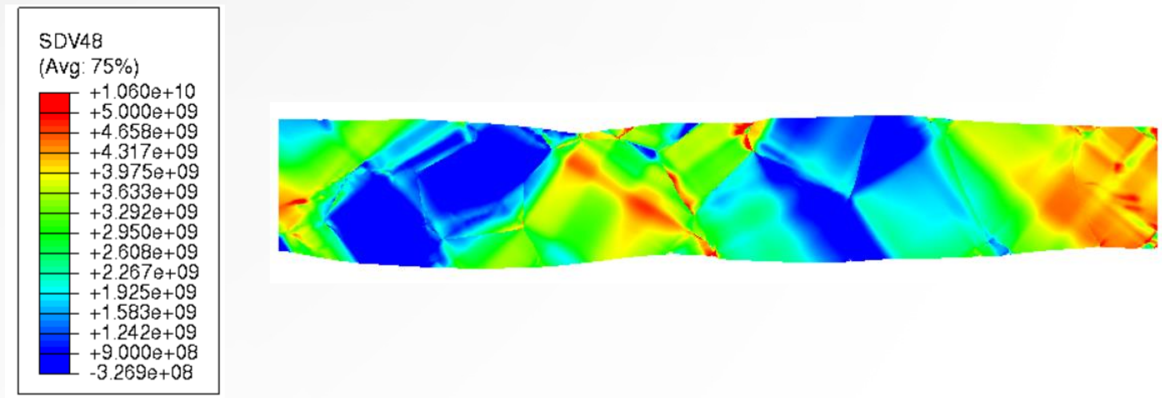


Equivalent plastic strain

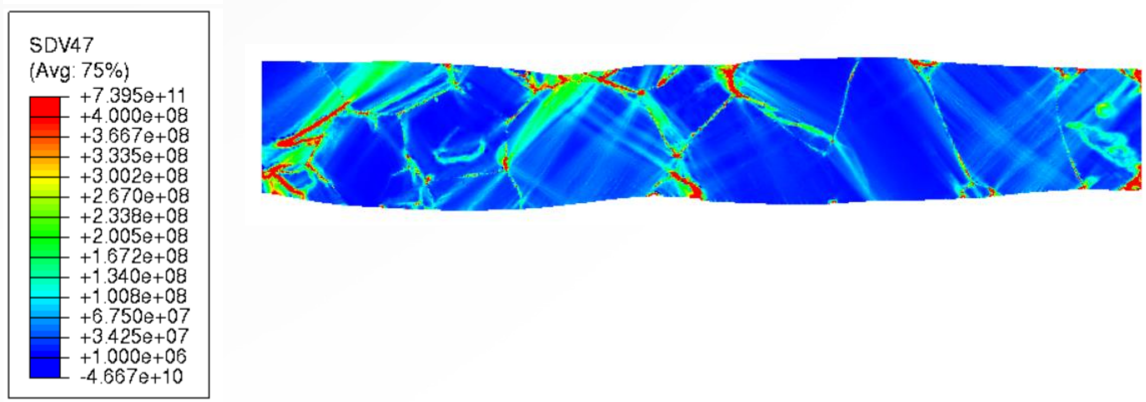


Tensile Test Simulation results

SSDs

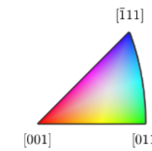


GNDs



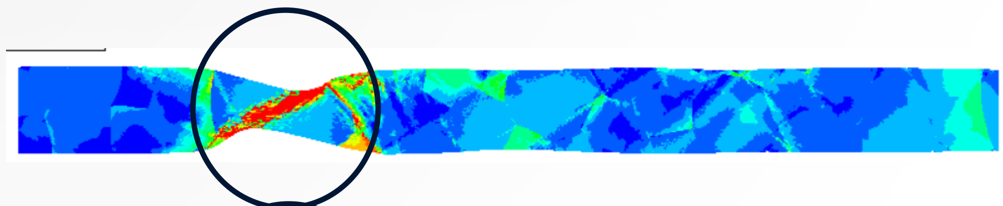
Tensile Test Simulation results

EBSD MEASUREMENT



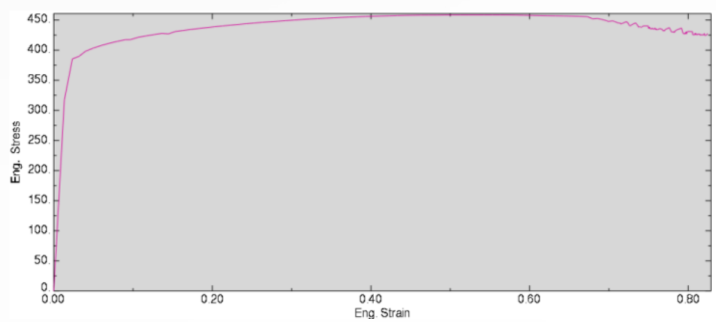
Abaqus Model

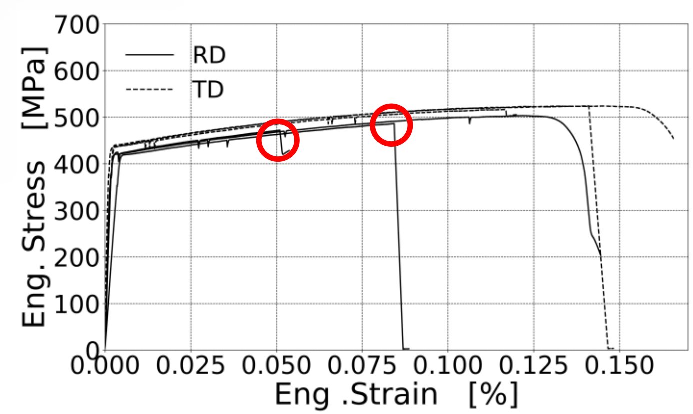
Equivalent Stress



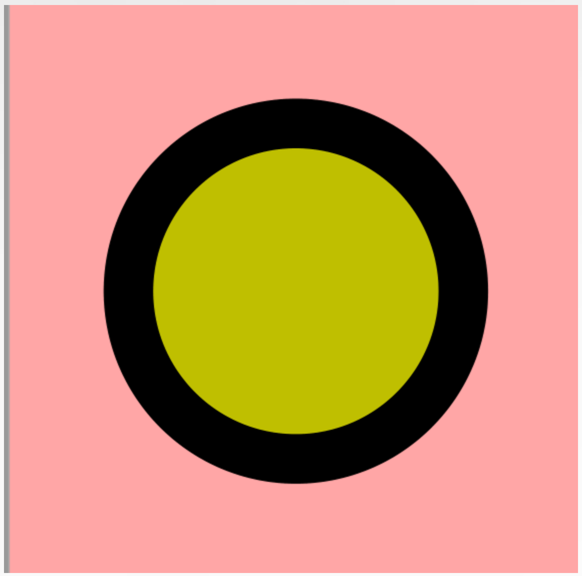
Equivalent plastic strain

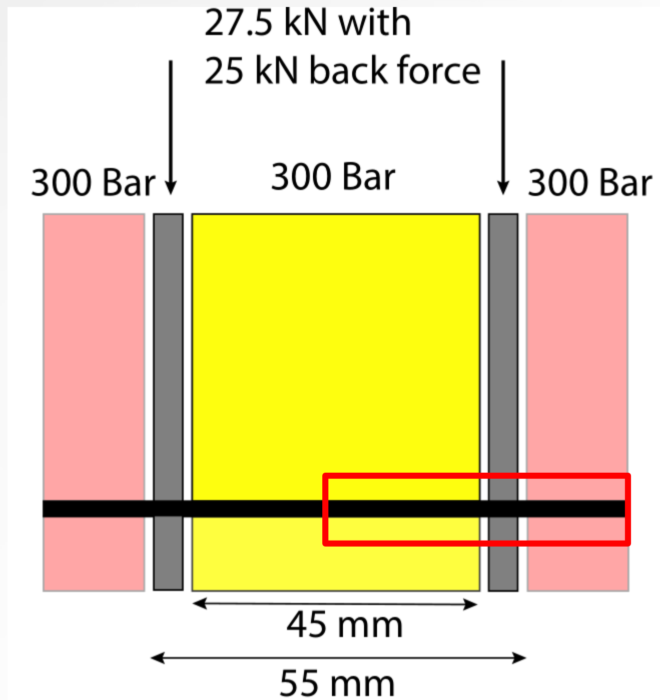
Early failure of samples



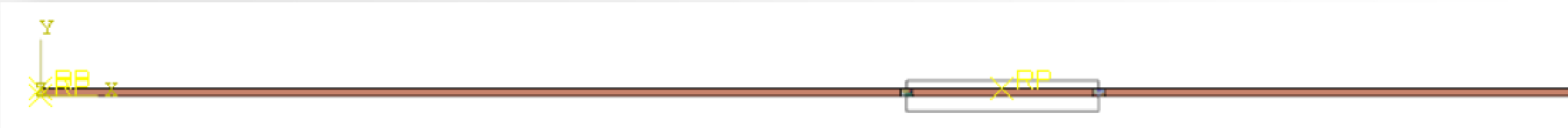


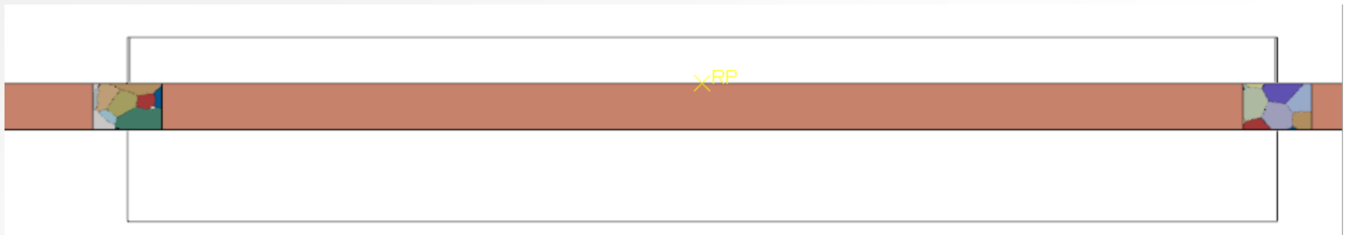
Fine Blanking with Crystal Plasticity

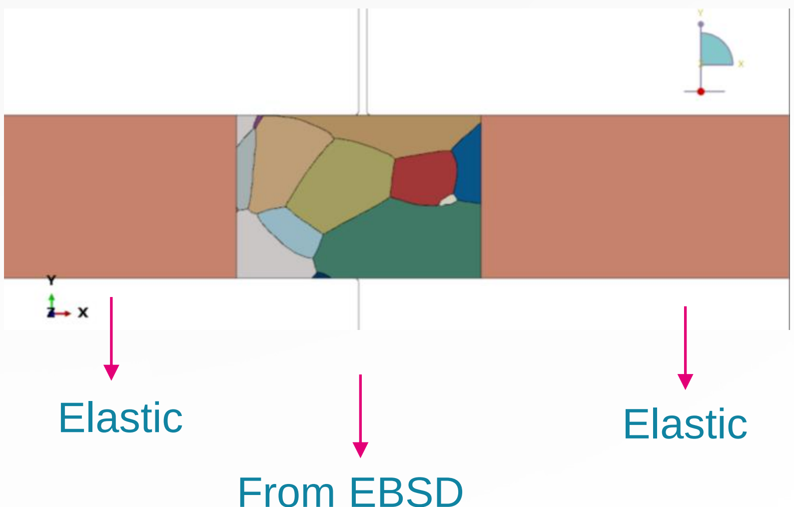


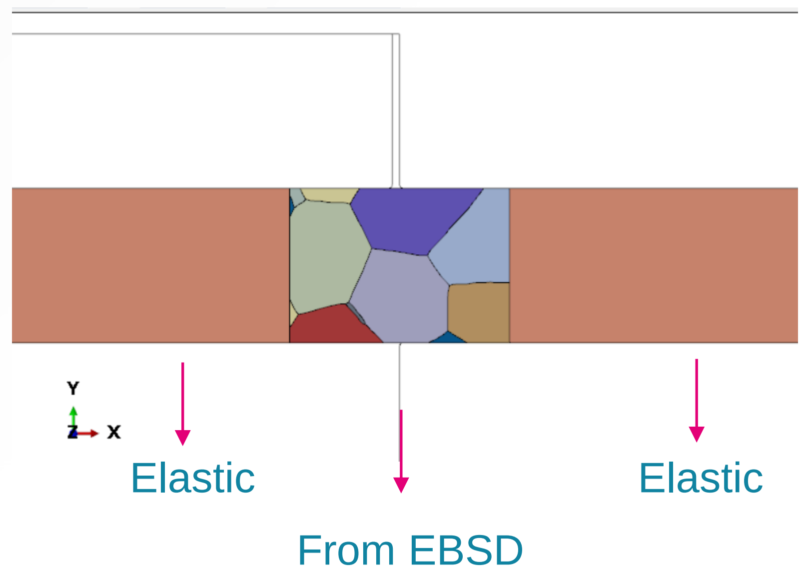


Fine Blanking with Crystal Plasticity





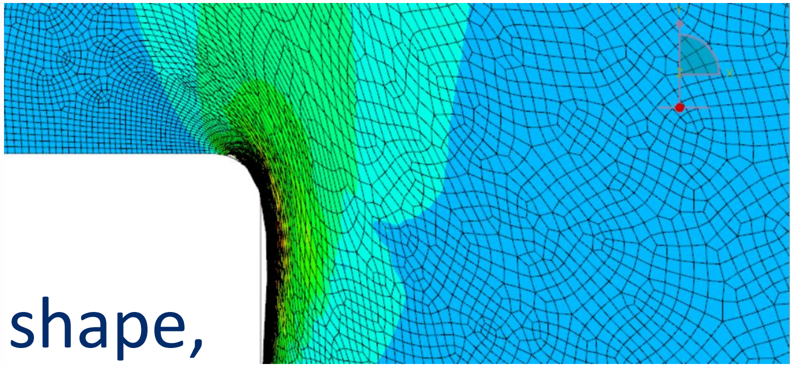




CONVERGENCE ISSUES

Remeshing Challenges

- Use of UMAT makes remeshing and remapping a challenging task due to tensorial state variables (e.g. orientation remapping)
- Abaqus does not provide an easy solution for remeshing in implicit models



Solution

- Develop remeshing algorithm
- Retain initial (parent) element shape, subdivide and map state variables to child elements
- Subdivision criterion → Improved (child) element shape

Conclusions

- **Industrial Aim**: Optimize blanking process parameters. The first phase was to simulate the fine blanking process with gradient enhanced crystal plasticity model. Not complete yet, requires a remeshing algorithm.
  - The measured grain size, shape and orientations were used in the simulations (to account for variations).
  - The material parameters were fitted to the tensile tests.
  - Tensile tests show that variation in grain size and orientation can significantly influence the outcome→ Requires robust optimization of process parameters.
  - The fracture is mainly brittle (transgranular) in nature.

Future Work

- Develop the remeshing algorithm, compatible with gradient enhanced crystal plasticity UMAT.
- Plane strain blanking simulations followed by 3D simulations.
- Simulate with varying microstructure and grain orientations (from measurements)
- Fit the strain gradient enhanced continuum model parameters to 3D simulation results obtained from crystal plasticity simulation.
- Perform robust optimization for the blanking process parameters

THANK YOU!

QUESTIONS???