Material Modeling of TWIP-Steels: Applications to Sheet Metal Forming Simulations

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Material Modeling of TWIP-Steels: Applications to Sheet Metal Forming Simulations

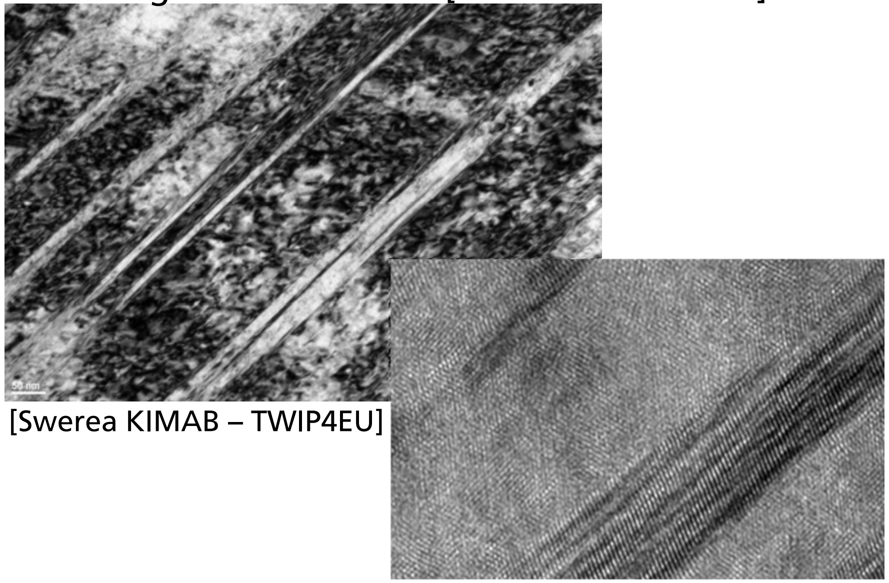
Outline

- Introduction and motivation
- Experimental results for TWIP steel
- Macroscopic constitutive model for TWIP steel
- Numerical simulations
- Conclusions and outlook

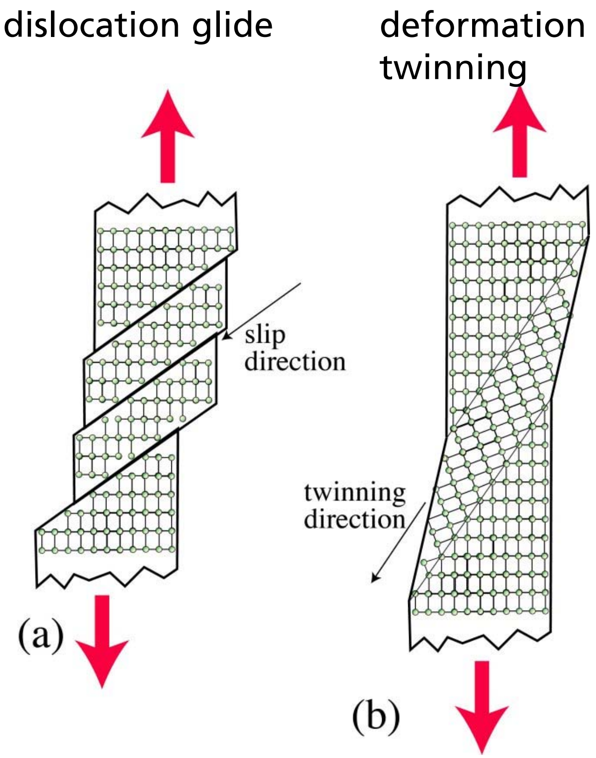
Introduction and motivation
TWIP steels

- TWIP-steel (**tw**inning **i**nduced **p**lasticity)
  - Class of high manganese austenitic steels
  - Deformation mechanism involves dislocation glide as well as twinning
  - Dynamic Hall-Petch effect leads to high hardening rates

TEM images of TWIP-Steel [KIMAB – TWIP4EU]

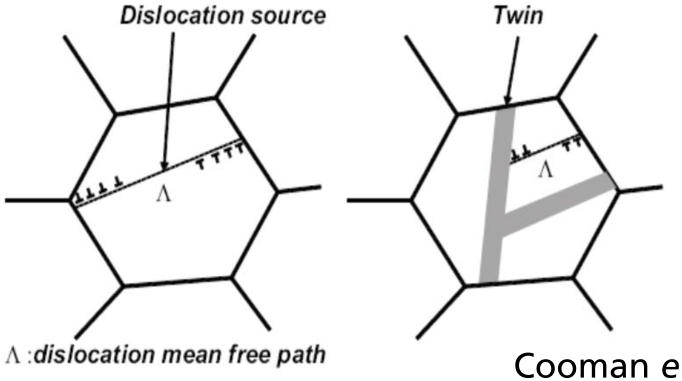


[Swerea KIMAB – TWIP4EU]



http://www.doitpoms.ac.uk

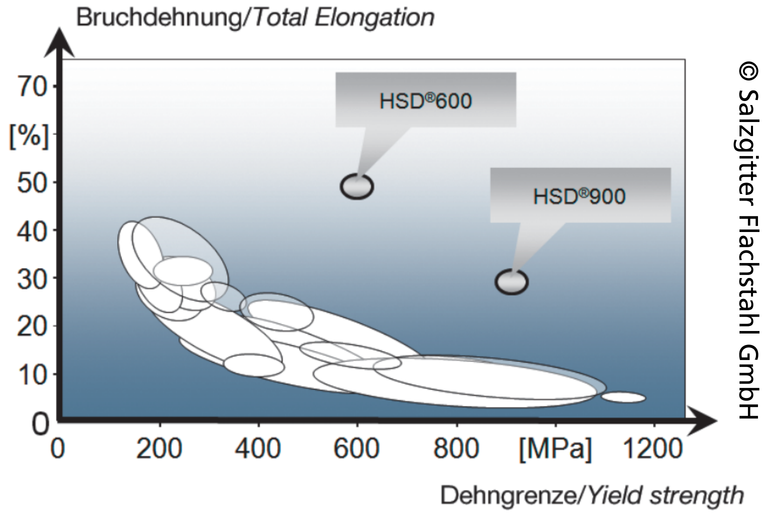
Dynamic Hall-Petch effect



Cooman *et al*., 2012

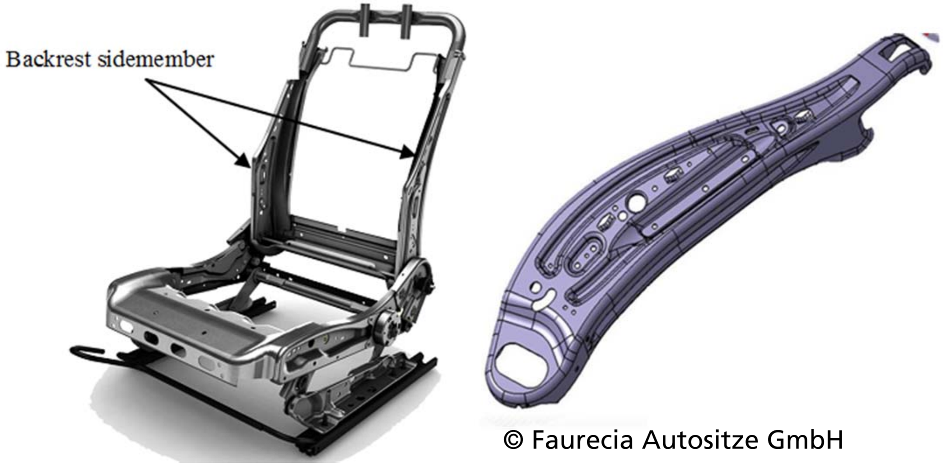
Introduction and motivation
TWIP steels

- Superior material properties of TWIP-steels
  - High strength
  - High ductility
  - Lower density/weight
- Typical applications
  - Light weight construction
  - Crash relevant components



© Salzgitter Flachstahl GmbH

HSD®-steel torsion specimen
© Salzgitter Flachstahl GmbH



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Crush testing under the same load with the same sheet thickness

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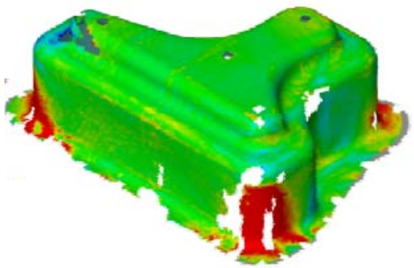
Introduction and motivation

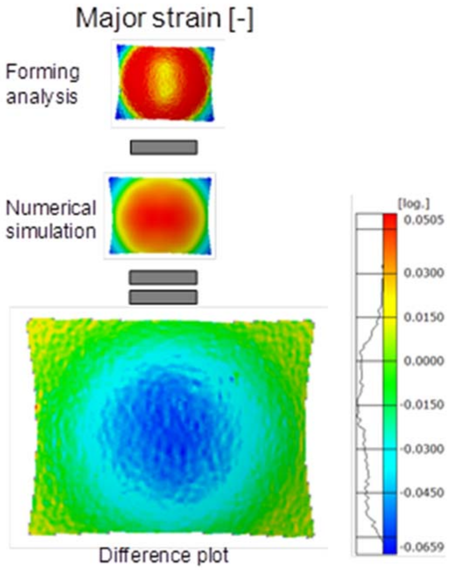
TWIP steels

- Challenges to introduce TWIP steels on the automotive market:
  - Different material behavior compared to conventional steels

    → Deviations between experiments and simulations if standard material models are used to describe the behavior of TWIP steels.



Preliminary study from SZMF: Difference between the strain field obtained from experimental data and the simulation using standard material models (red: deviation of approx. 10%)



Nakajima-test was used to evaluate standard material model: Up to 6 percentage points deviation from experiments (Salzgitter Mannesmann Forschung SZMF)

- Appropriate material models for TWIP steels should be available to introduce the material on the market.

Outline

Experimental analysis

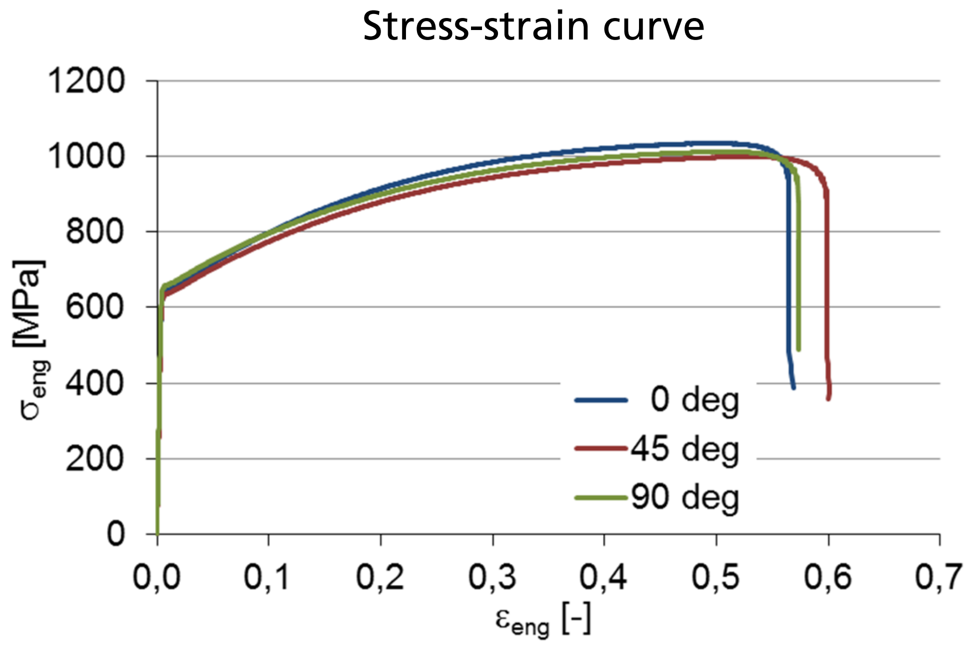
Material characterization

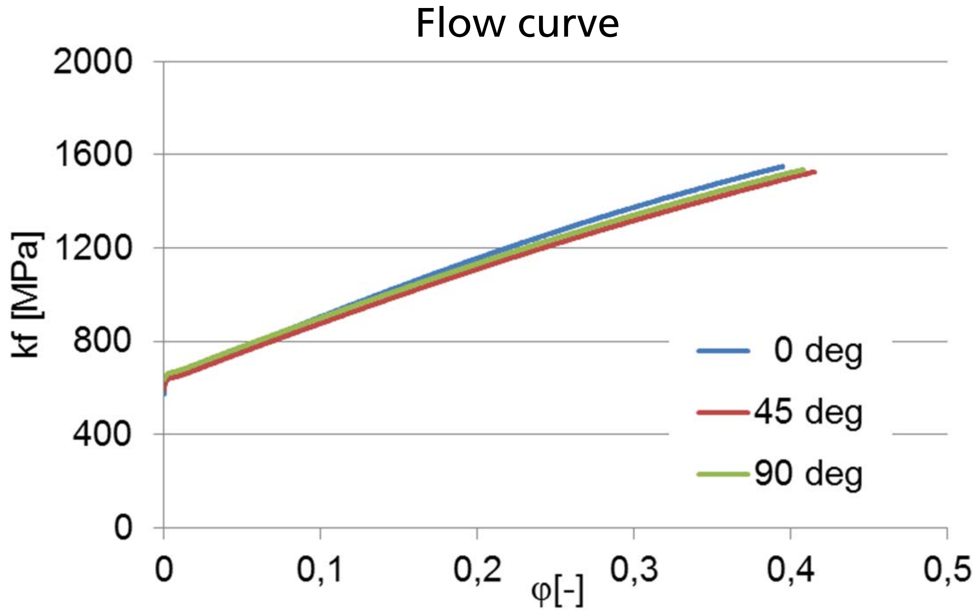
- TWIP-steel material provided by Salzgitter AG
- TWIP steel alloy Fe-15Mn-0.7C-2.5Al-2.5Si
  → Alloying concept: No delayed fracture
- Sheet thickness = 1.5 mm

Mechanical characterization was aimed at the following objectives:

- Mechanical quantities used in sheet metal forming
- Spring-back behavior
- Formability of the material

Specific values	**0 deg.**	**45 deg.**	**90 deg.**
$R_{p0.20}$ [MPa]	633	630	652
Tensile strength [MPa]	1035	999	1012
Ultimate strain A_{25} [-]	56,7	59,9	57,1
r-value (incr.) [-]	0,79	0,96	1,00
Young's modulus [MPa]	172952	168000	175000

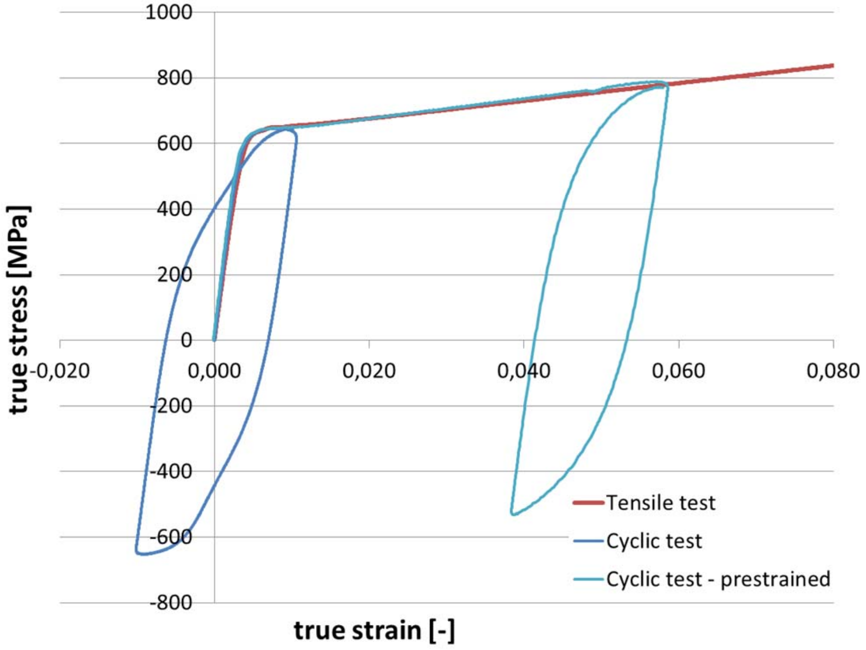




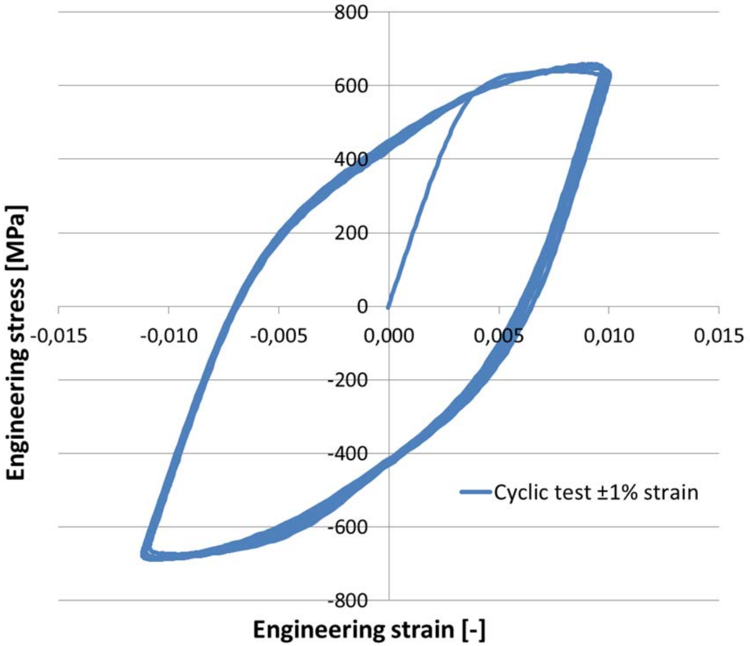
Experimental analysis
Cyclic behavior

- Significant Bauschinger effect is revealed
- No significant isotropic hardening: after several load cycles no substantial expansion of the hysteresis can be observed
- Strain amplitude limited due to buckling of the specimen

Cyclic loading and cyclic loading with pre-strain



Cyclic loading – several load cycles

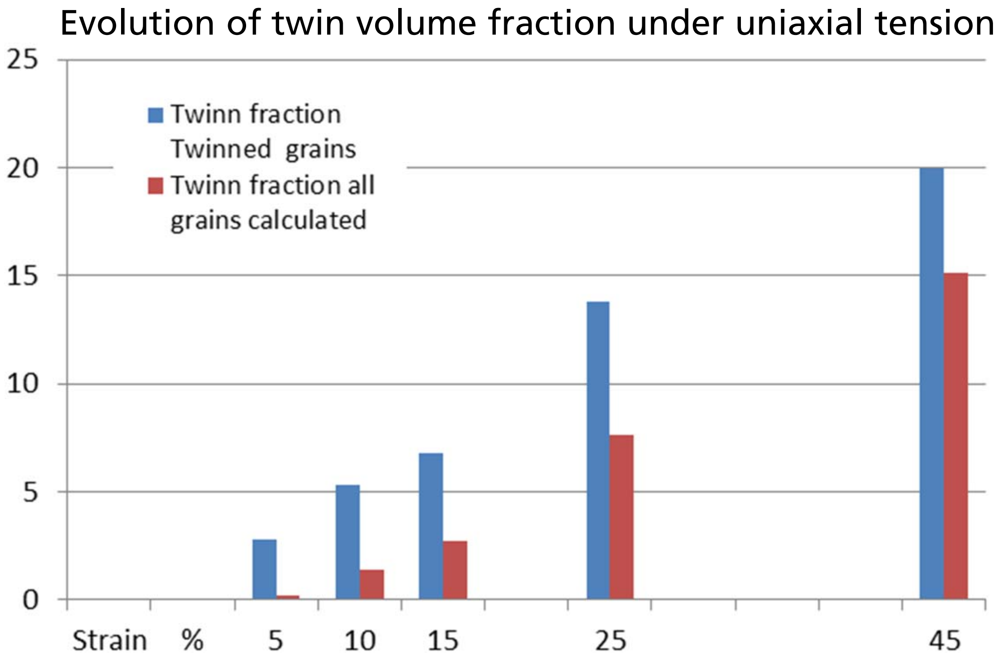


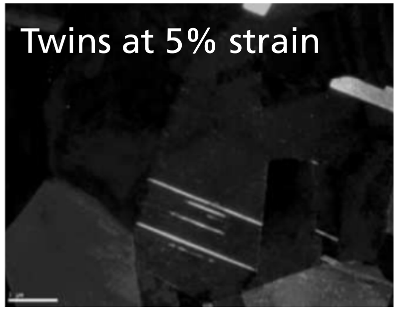
Experimental analysis

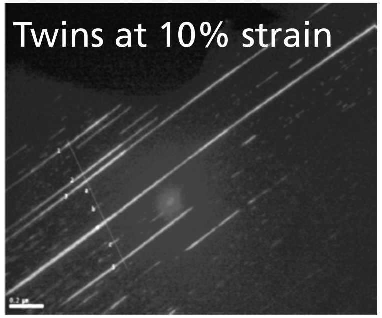
Microstructure

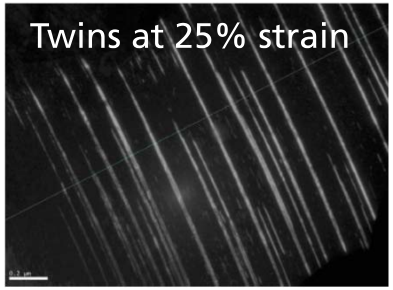
- **TEM-analysis** to evaluate twin volume fraction and dislocation density
- Twinning evolution during uniaxial tensile loading:
  - Twin volume fraction increases with increasing strain level
  - Practically no twins were observed for strains < 5%

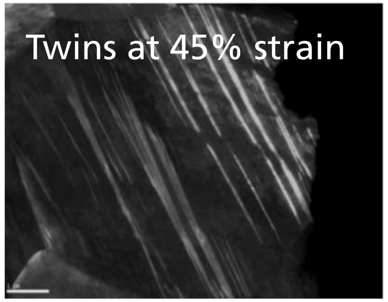
➢ Input for parameter identification of the macroscopic model


Evolution of twin volume fraction under uniaxial tension


Twins at 5% strain


Twins at 10% strain


Twins at 25% strain


Twins at 45% strain

Outline

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- Macroscopic constitutive model for TWIP steel
- Numerical simulations
- Conclusions and outlook

Macroscopic constitutive modelling of TWIP steels
3D-Elasto-plastic model for TWIP-Steels

Aim:

- Macroscopic elasto-plastic material model for TWIP-steels
- Physically motivated model based on [Bouaziz et al. 2011]
  - Twin volume fraction
  - Dislocation density

  } as internal variables

TWIP4EU - material model:

- Current extensions of the base model:
  - Extension from 1D-formulation to a 3D-formulation
  - Stress-dependent twinning evolution
  - Armstrong-Frederick type approach for the evolution of inner variables
  - Anisotropic yield function

Macroscopic constitutive modelling of TWIP steels

3D-Elasto-plastic model for TWIP-Steels

Yield function: $f = \|\boldsymbol{\sigma}^D - \boldsymbol{X}^D\| - \sqrt{\frac{2}{3}}\,(\sigma_0 + \sigma_f)$ (isotropic formulation)

- **Isotropic hardening:** $\sigma_f = \alpha M \mu b \sqrt{\rho}$
- **Kinematic hardening:** $\boldsymbol{X} = M \frac{\mu b}{L} \boldsymbol{n}$

Constants

α: constant

M: the average Taylor factor

μ: the shear modulus,
b: the Burgers vector

Internal variables:

ρ: statistical stored dislocation density

L: geometrical length scale of the microstructure

$\boldsymbol{n}$: number of dislocations stopped at the boundary

F: twin volume fraction

Macroscopic constitutive modelling of TWIP steels
3D-Elasto-plastic model for TWIP-Steels

Evolution equations for inner variables

- **Statistical stored dislocation density**

$$\frac{\mathrm{d}\rho}{\mathrm{d}s^p} = M\left(\frac{1 - J(\boldsymbol{n})/n_0}{b\ L} + \frac{k}{b}\sqrt{\rho} - f\rho\right)$$

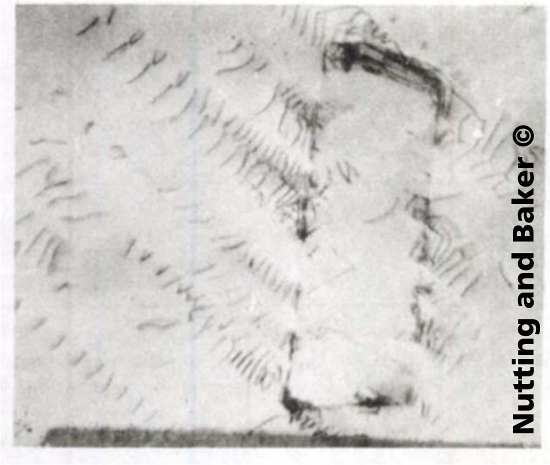
s^p: equivalent plastic strain

- **The number of dislocations which have been stopped at the boundary per slip band**

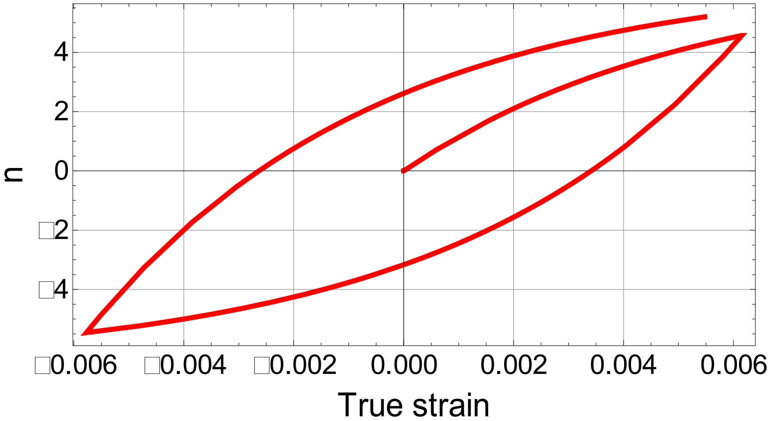
$$\frac{\mathrm{d}n}{\mathrm{d}s^p} = \frac{\lambda}{b}\left(\frac{2}{3}\boldsymbol{s}^p - \dot{s}^p\,\frac{\boldsymbol{n}}{n_0}\right)$$

λ: mean spacing between slip bands,
n_0: maximum number of dislocation loops at the boundary

Physical interpretation



➢ Assumption: Reversible nature of the dislocation flux under cyclic loading



Macroscopic constitutive modelling of TWIP steels

3D-Elasto-plastic model for TWIP-Steels

Evolution equations for inner variables

- **Statistical stored dislocation density**

$$\frac{\mathrm{d}\rho}{\mathrm{d}s^p} = M\left(\frac{1-J(\boldsymbol{n})/n_0}{b\;L} + \frac{k}{b}\sqrt{\rho} - f\rho\right)$$

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λ: mean spacing between slip bands,

n_0: maximum number of dislocation loops at the boundary

- **Twin volume fraction**

$$F = F_0\left(1 - e^{-\beta(s^p - \varepsilon_{init})}\right)^m$$

m: the stacking fault energy parameter

- **Geometrical length scale of the microstructure**

$$\frac{1}{L} = \frac{1}{d} + \frac{1}{t} \quad \text{where} \quad \frac{1}{t} = \frac{1}{2e}\frac{F}{(1-F)}$$

d: mean grain size

t: mean twin spacing

e: mean twin thickness

Extended Bouaziz-Allain model “TWIP4EU”
Stress-dependent hardening

Stress-dependent twinning evolution:

The factor k_{twin} is introduced to the definition of the twin volume increment :

$$\dot{F} = F_0 m \left[1 - e^{-\beta(s_p - \varepsilon_{\text{init}})}\right]^{m-1} \left[-e^{-ß(s_p - \varepsilon_{\text{init}})}\right] [-\beta] \dot{s}_{\text{p}} k_{\text{twin}}$$

k_{twin} is a function of the <u>current</u> stress triaxiality η:

$$k_{\text{twin}} = c\eta - \frac{c}{3} + 1, \qquad \eta = \sigma_{\text{H}}/\sigma_{\text{eq}}$$

c: slope of a linear function

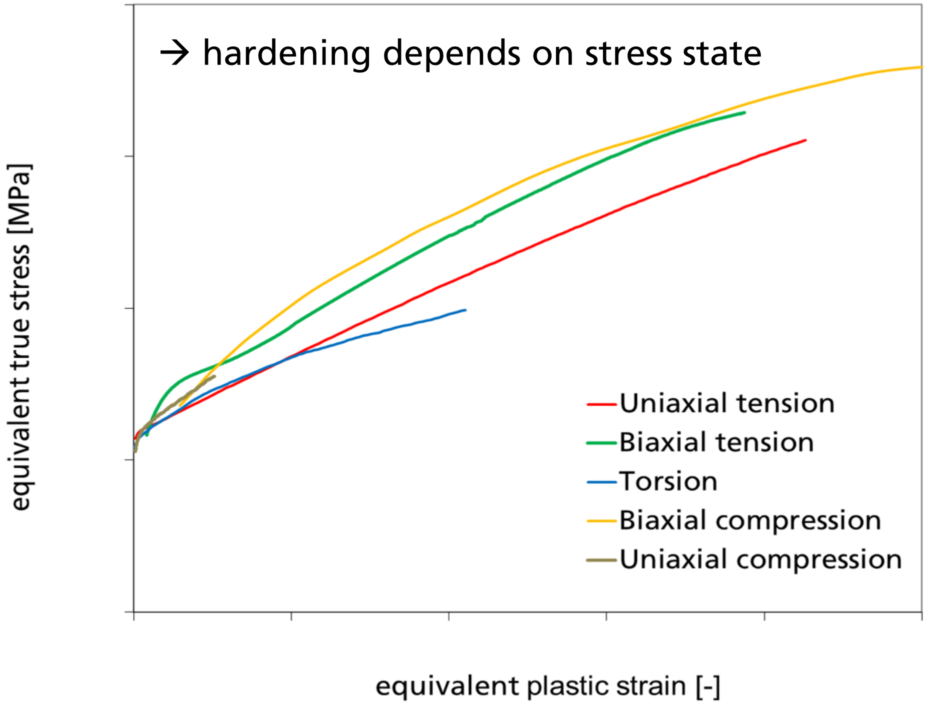
→ controls the effect of η on twinning

Twin volume evolution becomes

→ Stress dependent

→ History dependent

Preliminary analysis from SZMF:



- **Assumption:** evolution of twin volume fraction depends on the current stress state
- Stress dependent twinning was also observed by [Renard et al., 2012, Scripta Mat.]

Extended Bouaziz-Allain model “TWIP4EU”

Stress-dependent hardening

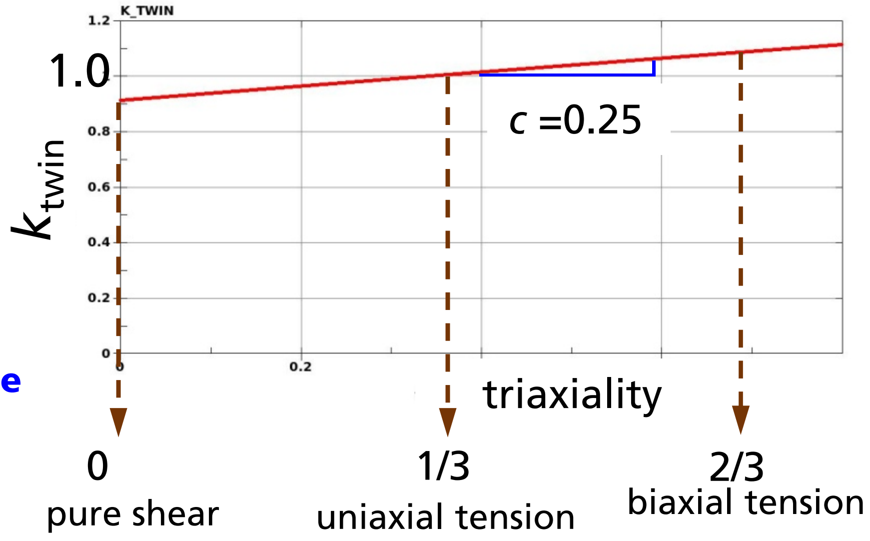
- Stress-dependent twinning evolution:

$$\dot F = F_0 m \left[1 - e^{-\beta(s_p - \varepsilon_{\text{init}})}\right]^{m-1} \left[-e^{-\text{ß}(s_p - \varepsilon_{\text{init}})}\right] [-\beta] \dot s_{\text{p}} k_{\text{twin}}$$

$$k_{\text{twin}} = c\eta - \frac{c}{3} + 1$$

$$k_{\text{twin}}\left(\eta = \frac{1}{3}\right) = 1$$

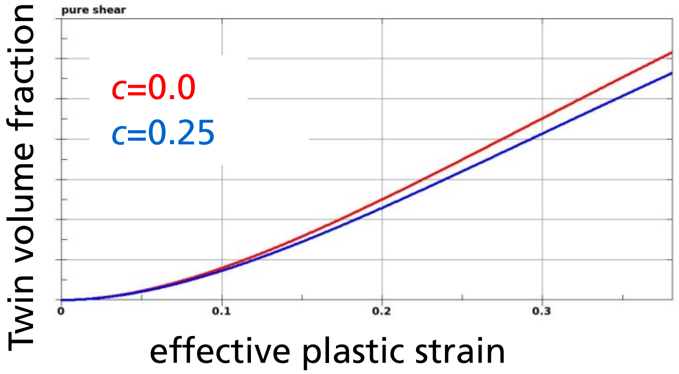
→ **No influence on uniaxial stress state**



- Twin volume fraction, *F*

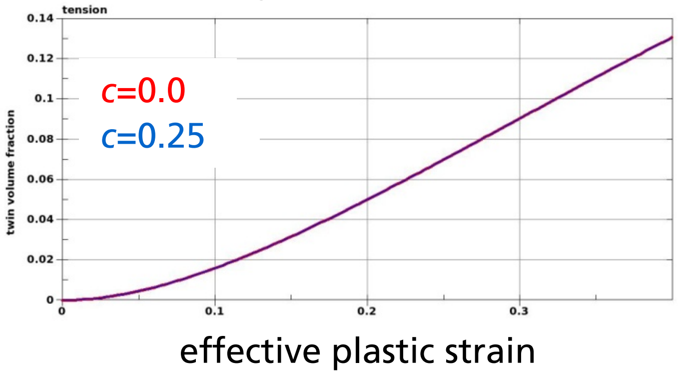
pure shear

$\eta = 0.0 \ \rightarrow k_{\text{twin}} = 1.0 - \frac{c}{3}$



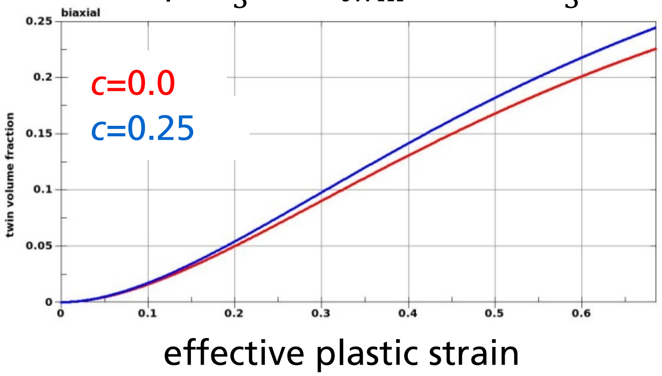
uniaxial tension

$\eta = \frac{1}{3} \rightarrow k_{\text{twin}} = 1.0$



biaxial tension

$\eta = \frac{2}{3} \rightarrow k_{\text{twin}} = 1.0 + \frac{c}{3}$



Outline

- **Introduction and motivation**
- **Analysis of the experimental results for TWIP steel**
- **Macroscopic constitutive model for TWIP steel**
- **Numerical simulations**
  - Model parameter identification
  - Preliminary simulations of metal forming tests
- **Conclusions and outlook**

Numerical simulation
Parameter identification strategy

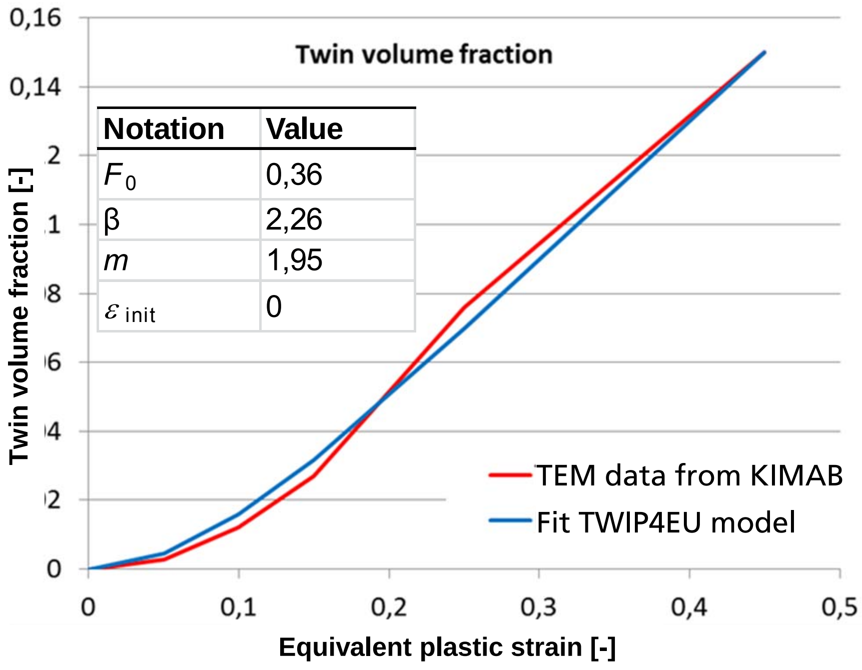
Two-step procedure for parameter identification:

Step 1: Fitting the evolution of the twin volume fraction using the data from microstructure analysis

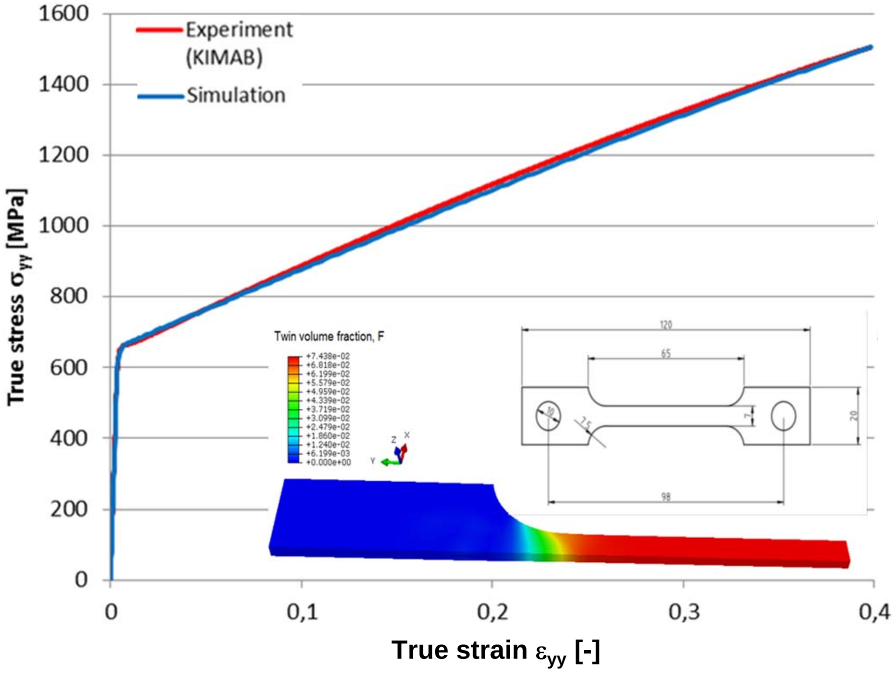
$$F = F_0\left(1 - e^{-\beta(s_p - \varepsilon_{init}}\right)^m$$

Step 2: Fit the remaining parameters to the uniaxial tensile curve using LS-OPT

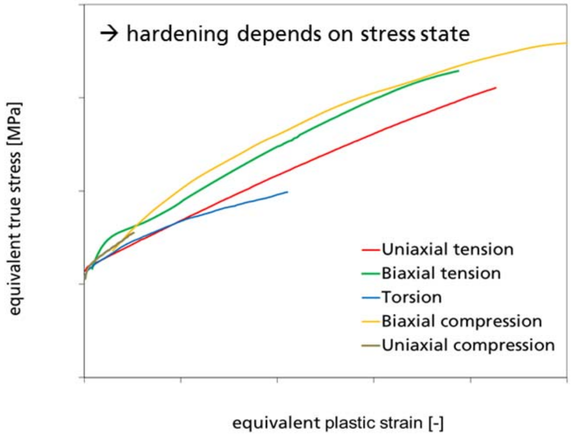
$\alpha = 0{,}388$ $\sigma_0 = 590$ MPa
$k = 0{,}019$ $n_0 = 1{,}5$
$f = 1{,}41$



Notation	Value
F_0	0,36
β	2,26
m	1,95
ε_{init}	0



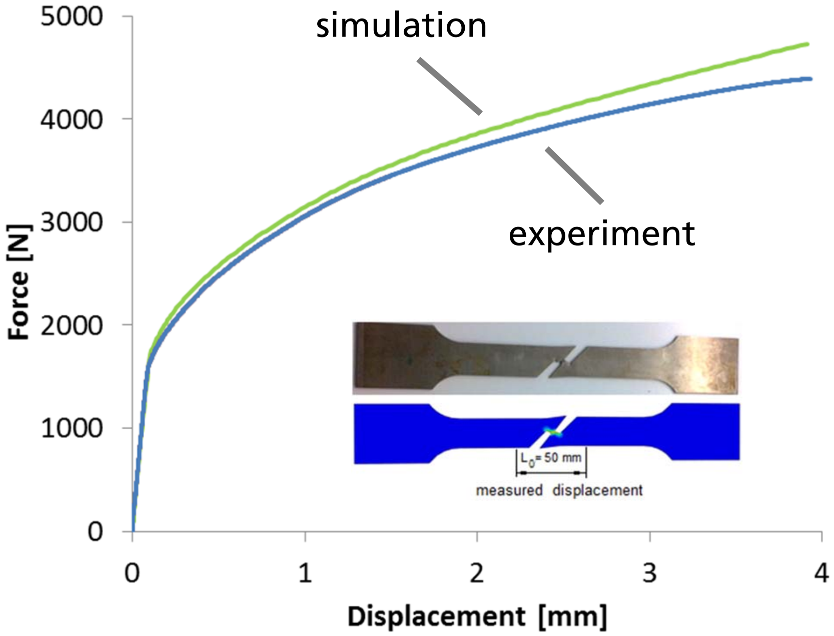
Numerical simulation
Parameter identification strategy



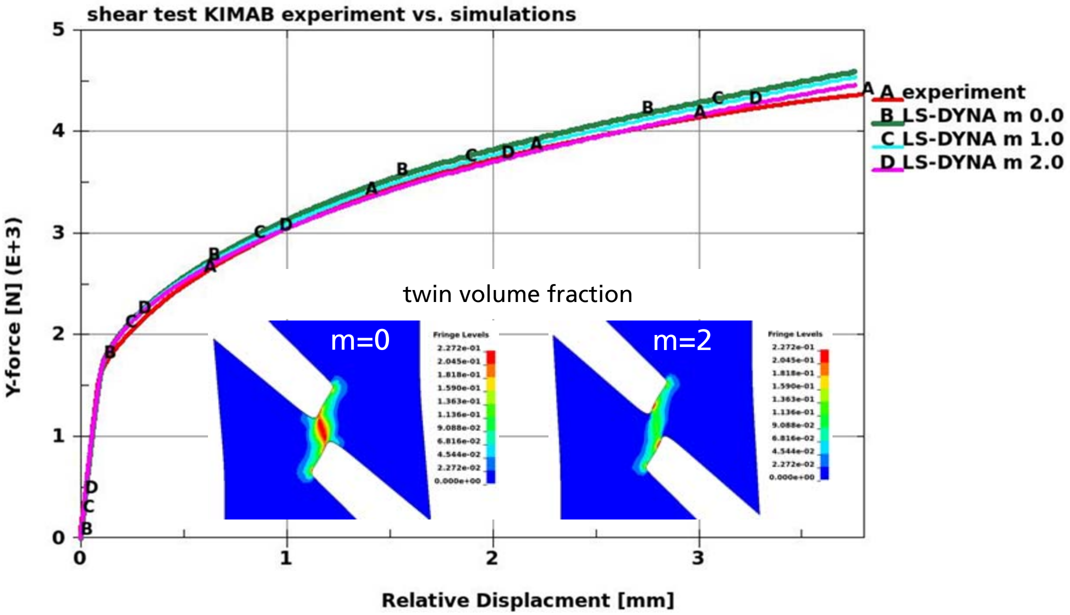
Shear test:

- Some deviations can be observed if the stress dependent hardening is neglected
- ➢ Calibration of the shear test using the stress dependent twinning evolution

Shear test without stress dependent twinning



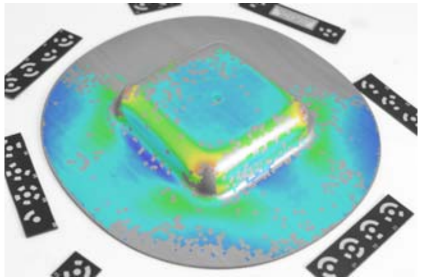
Shear test considering stress dependent twinning
→ Uniaxial tensile behavior is not influenced



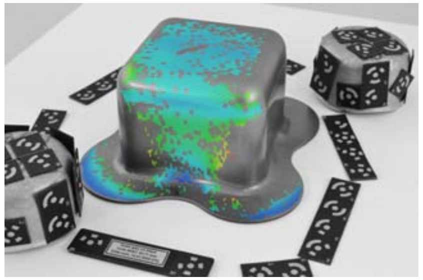
Experimental analysis
Forming experiments – deep drawing of square cups

Evaluation of strain fields using optical strain analysis tools:

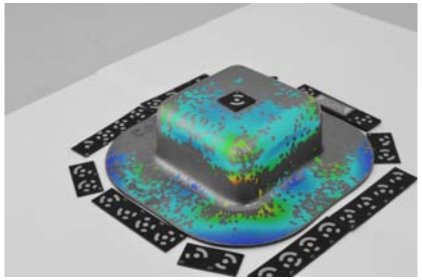
- Deep drawing of square cups
  - Very good agreement between evaluated experiments
  - High formability of TWIP-steel



draw depth: 20 mm

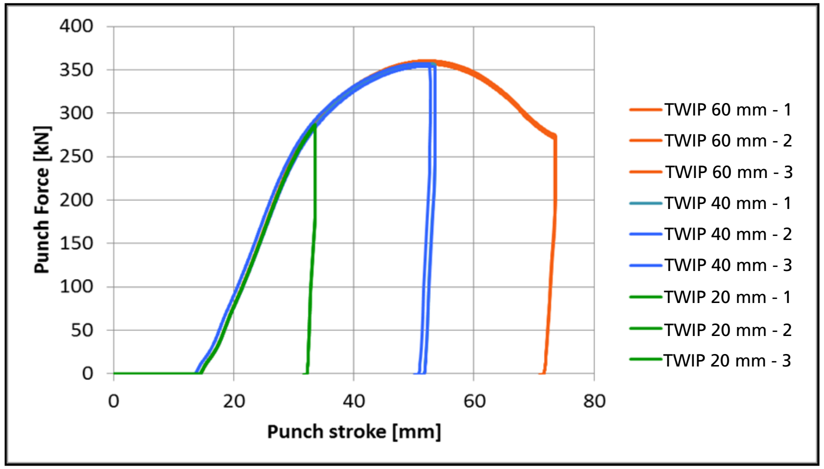


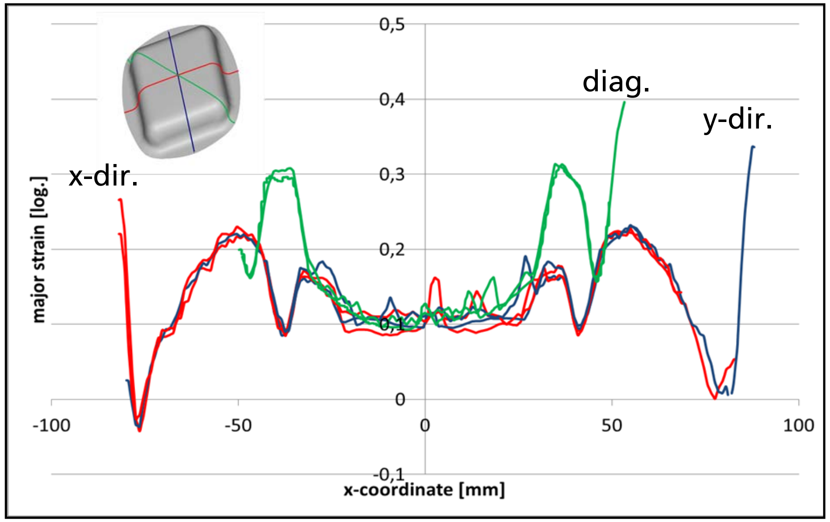
draw depth: 60 mm



draw depth: 40 mm

Strain analysis on square cups with different draw depths.
The optical strain analysis tool “Argus” was used for evaluation.





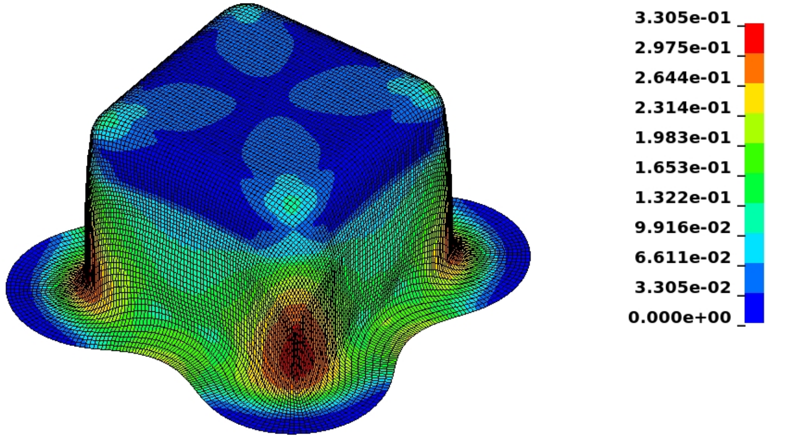
Evaluation of major strain for two square cups, draw depth = 60 mm

Numerical simulation

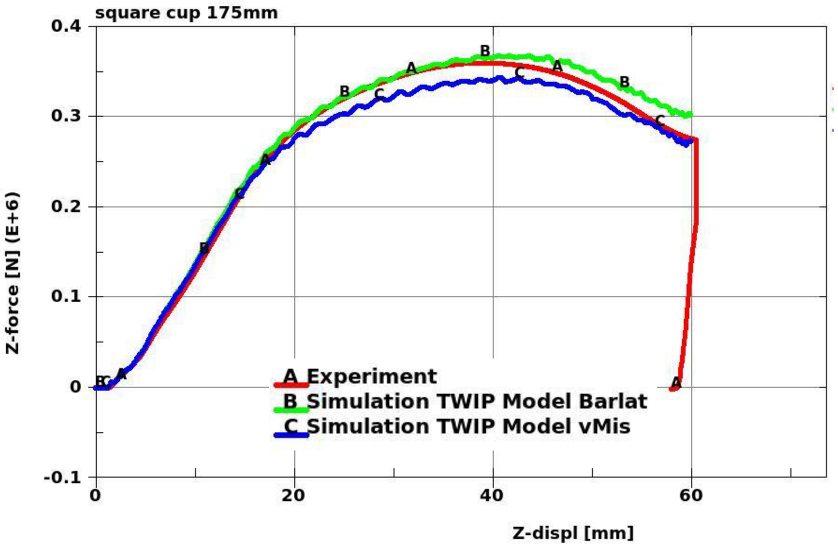
Deep drawing of a square cup

- Simulation results

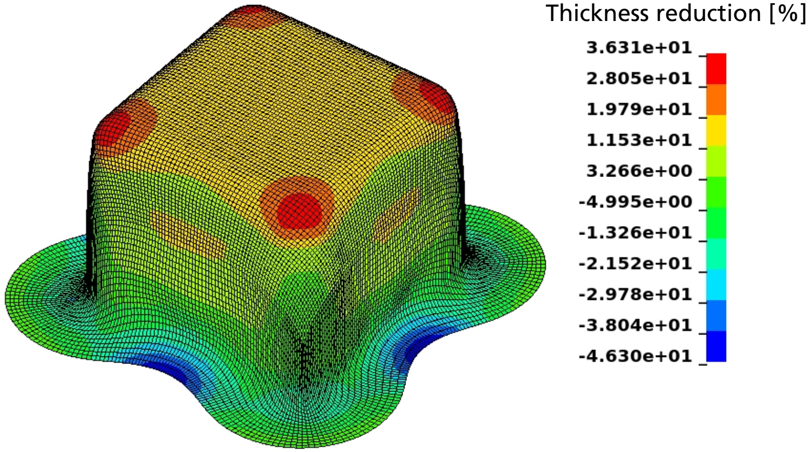
Twin volume fraction



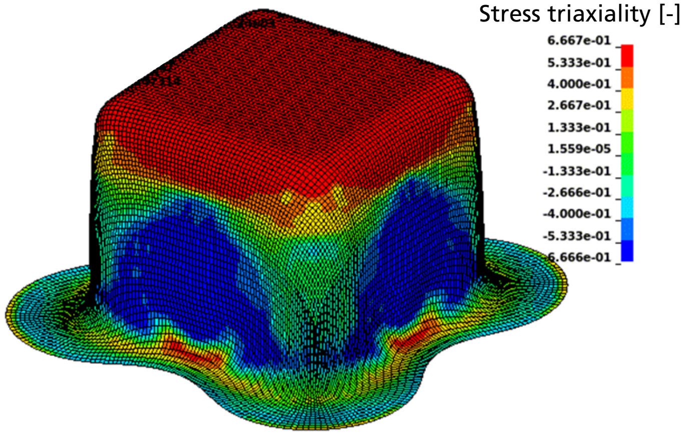
Load-Displacement



Thickness reduction



Stress triaxiality



*FE simulations performed in LS-DYNA (DYNAmore, Germany)

Prototype component

A **backrest sidemember** was chosen as prototype component

- Crash relevant for automotive industry
- Complex 3D-geometry
- Fits to maximum blank dimensions

CAD-Model of the prototype component

Seat frame

CAD-model

TWIP-steel prototype component

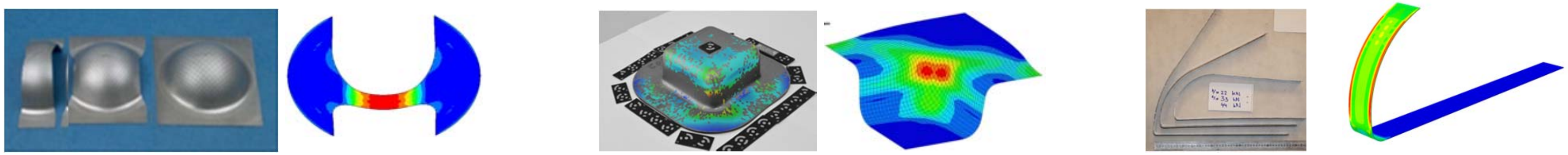
Summary and outlook

Summary

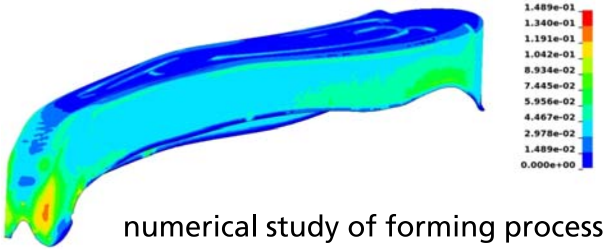
- TWIP-Steel model for sheet metal forming applications
    - Based on a micromechanically motivated approach (Bouaziz)
    - Stress depended twinning
    - Isotrop (v. Mises, 2D & 3D) and anisotropic (Barlat YLD-2000, 2D)
    - Solid and shell formulation available
- First validation of numerical results are in good agreement with experimental data

Outlook

- More accurate description of the Bauschinger-Effect
- Simulation of different forming processes and evaluation of the TWIP-Steel model:



- Simulation of prototype forming process



numerical study of forming process

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Thank you for your attention

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Research Fund for Coal & Steel

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