Virtual Process Design for Coupled Quasi-Static and Electromagnetic Forming

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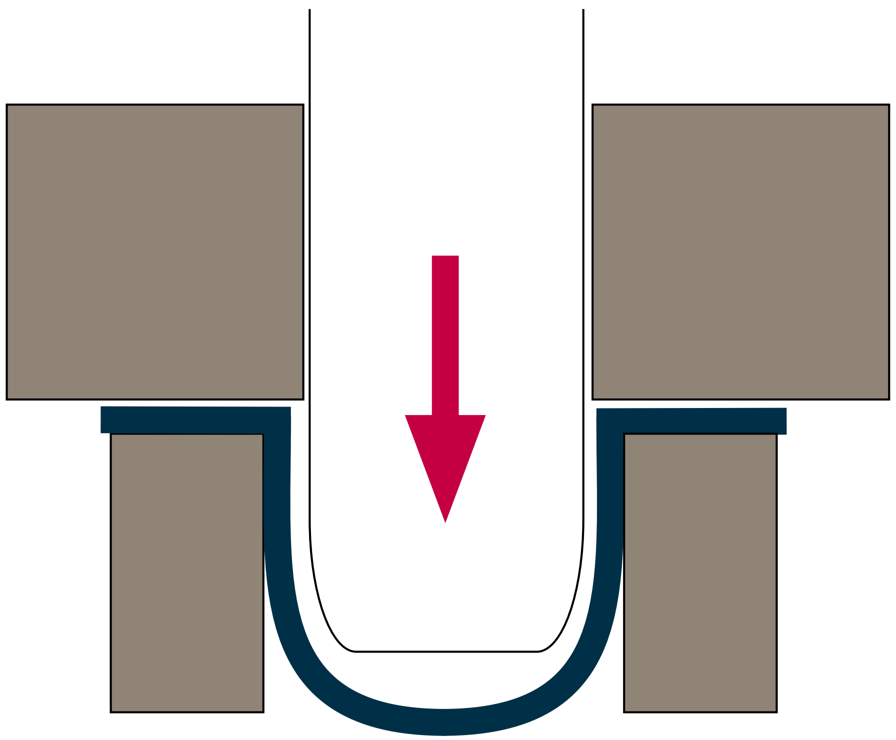
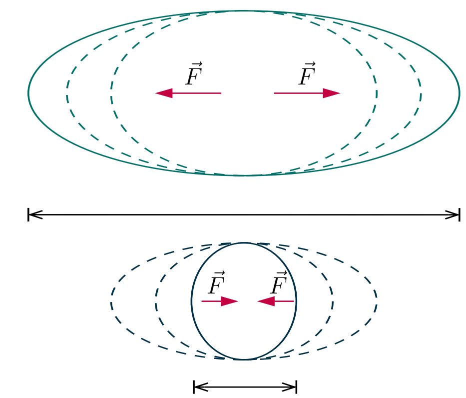
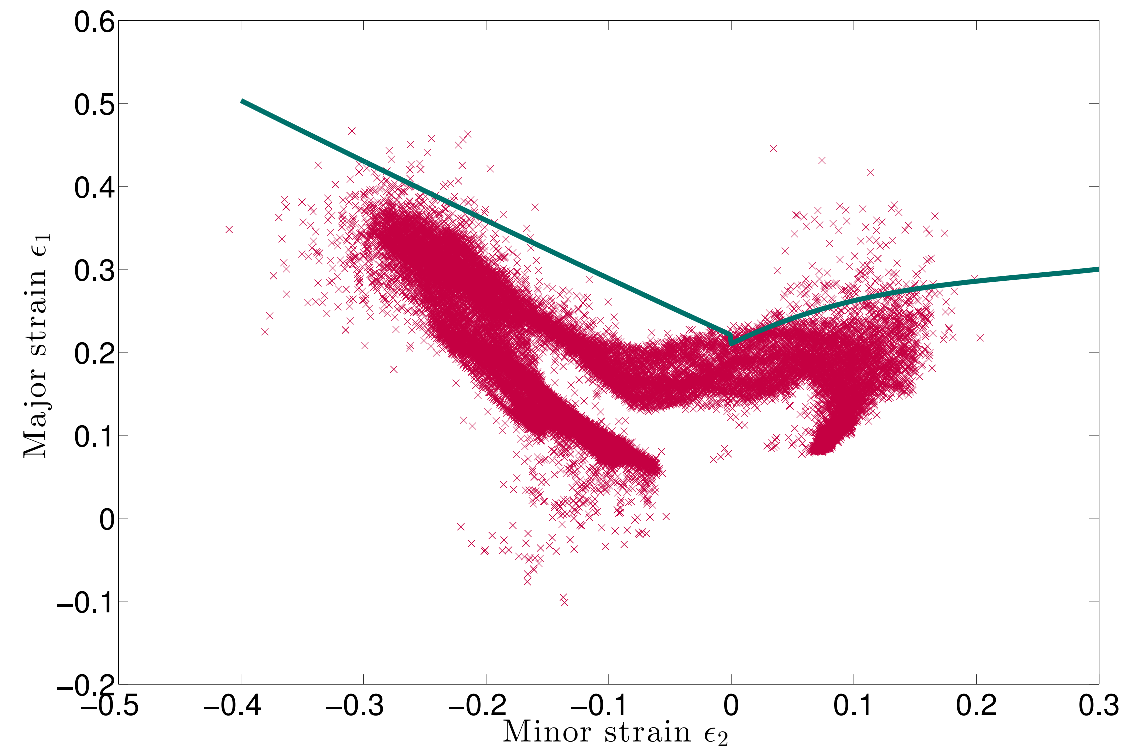
PAK 343
Methodenplanung

Theoretische Elektrotechnik

Quasi-Static Forming

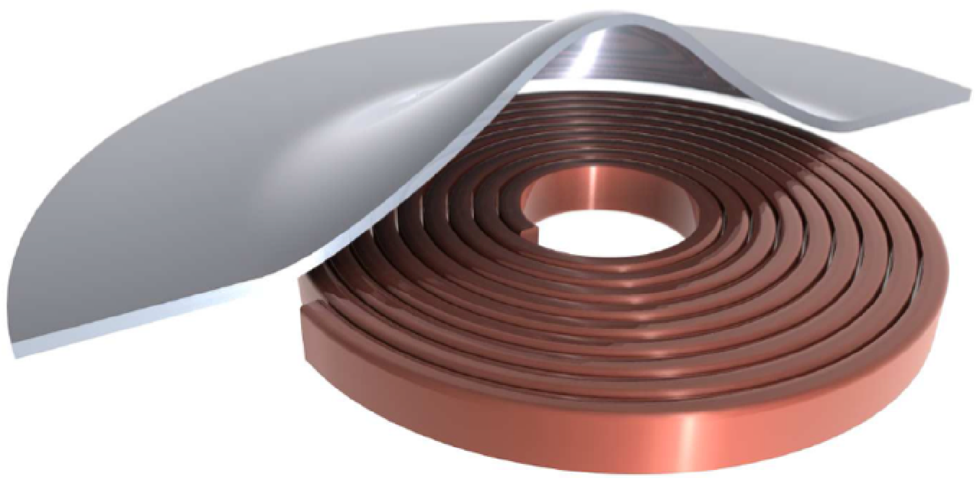


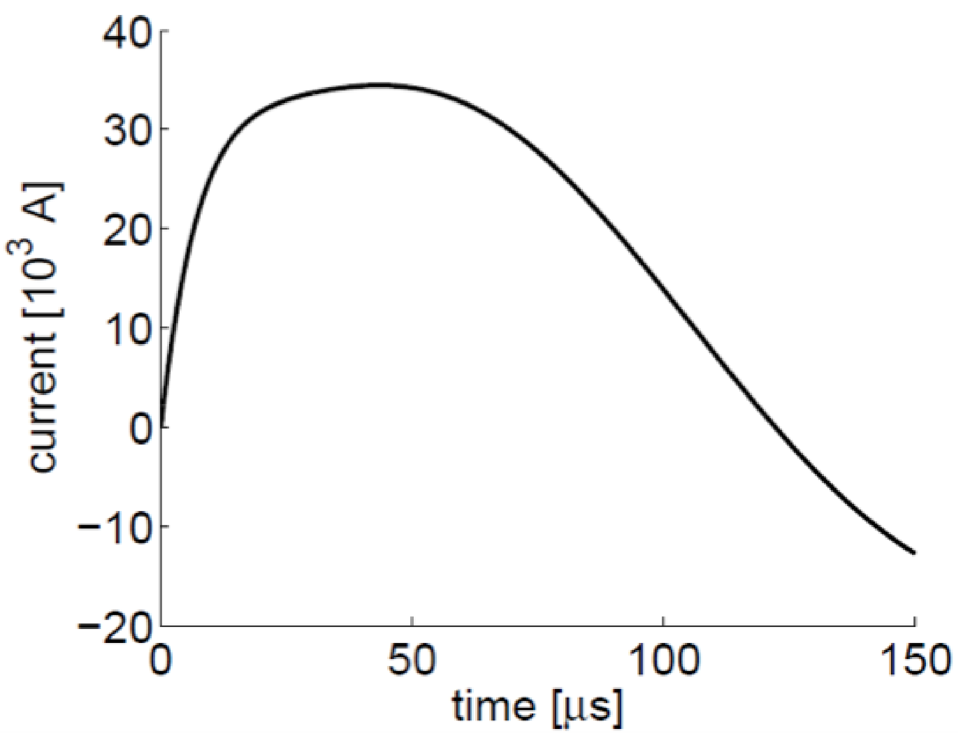




- Quasi-static forming is restricted by the forming limit
- Forming beyond limit is possible by high speed forming

Electromagnetic Impulse Forming





- Electromagnetic impulse forming with pulsed currents (e.g. 30kA within 10µs) → magnetic flux between tool coil and workpiece: 1-10 Tesla
- Induced current results in Lorentz forces → forming

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Combined Forming

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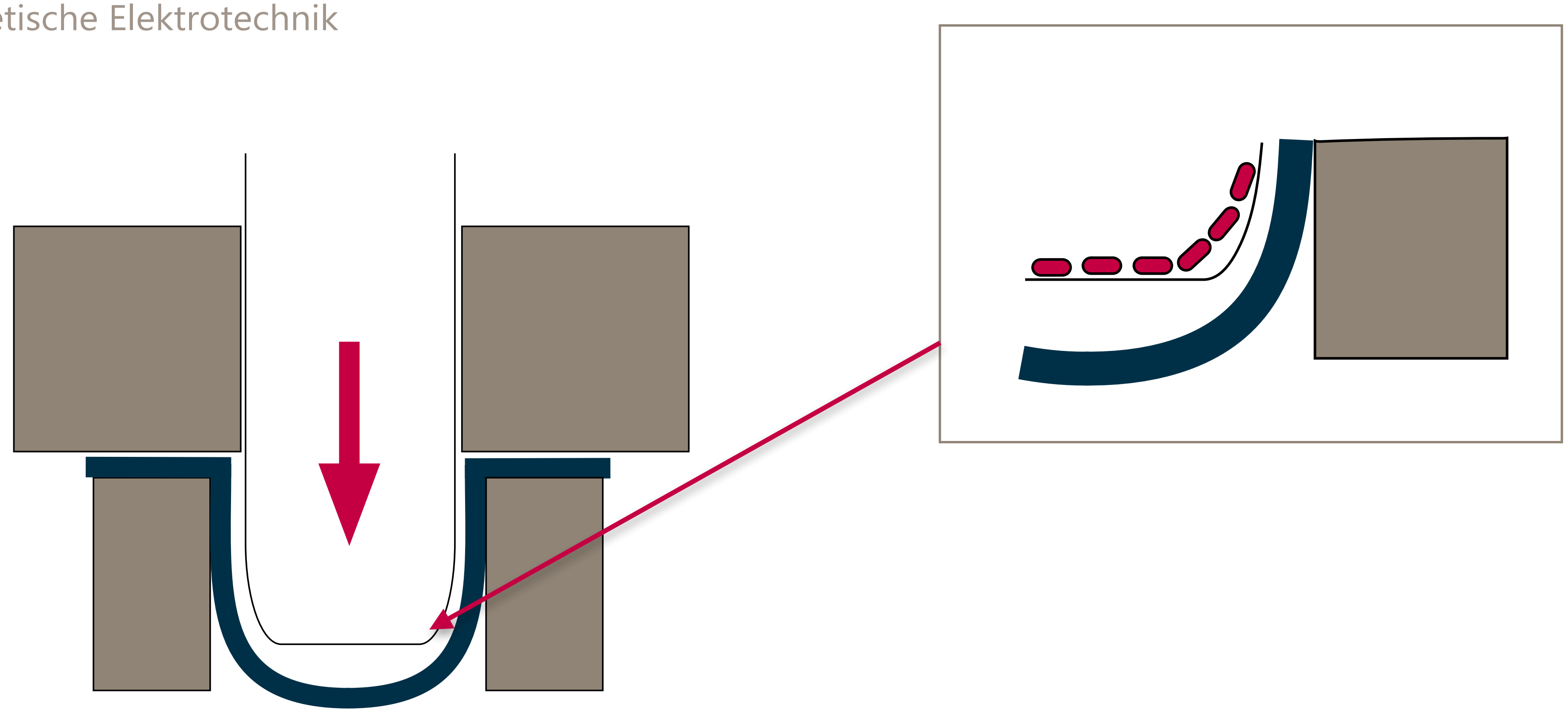

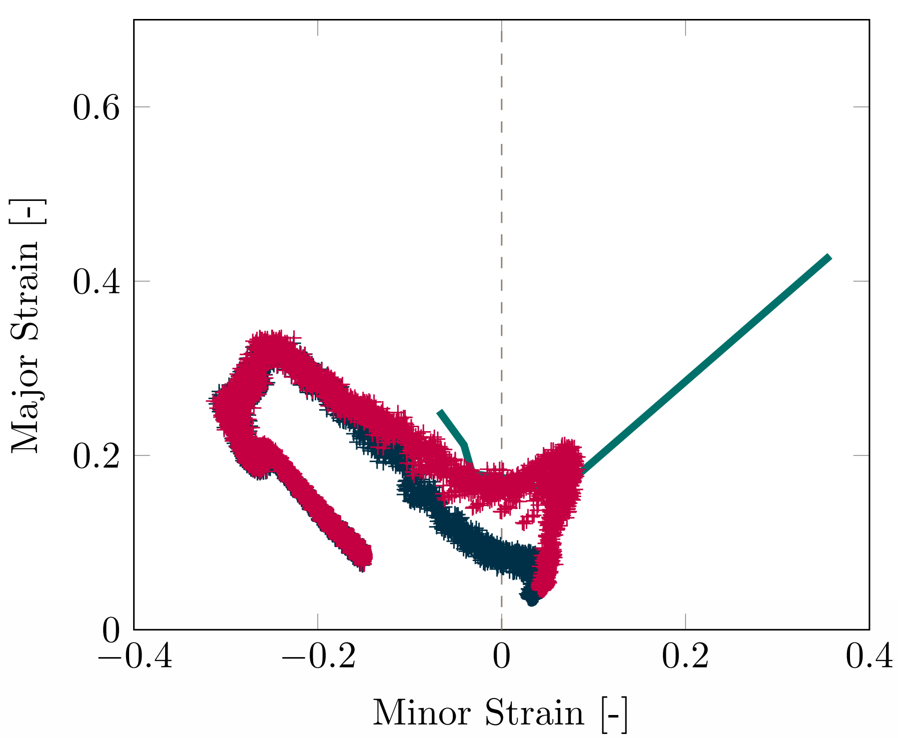

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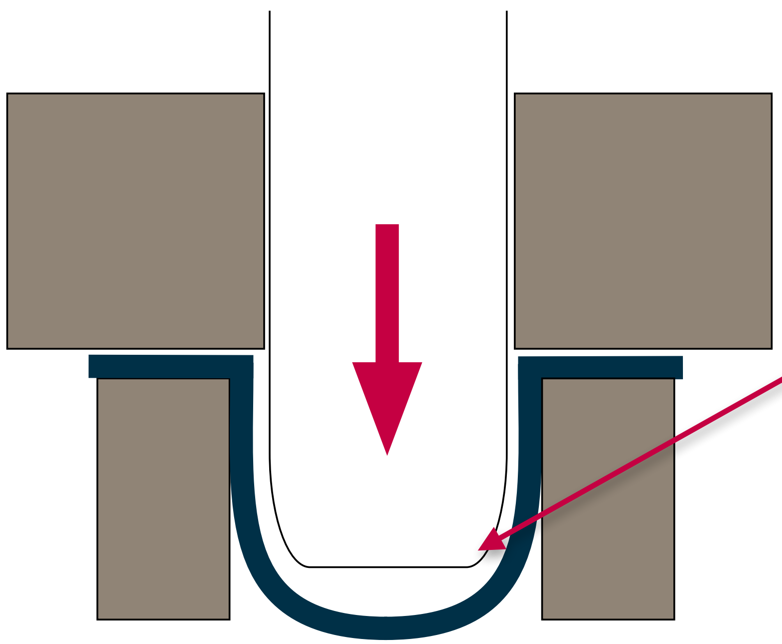
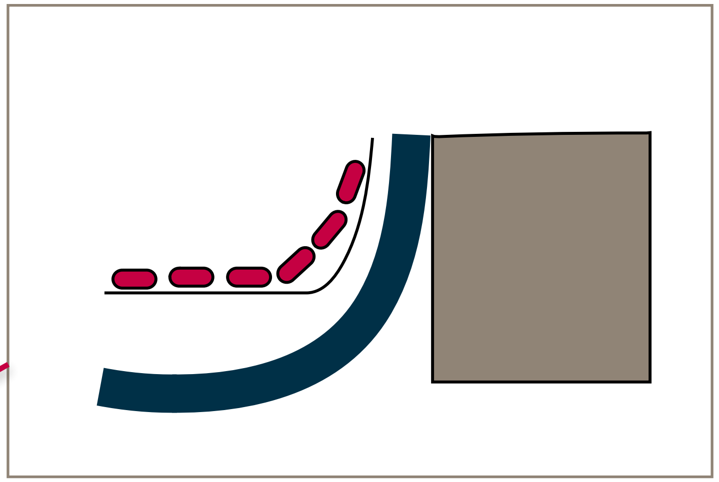
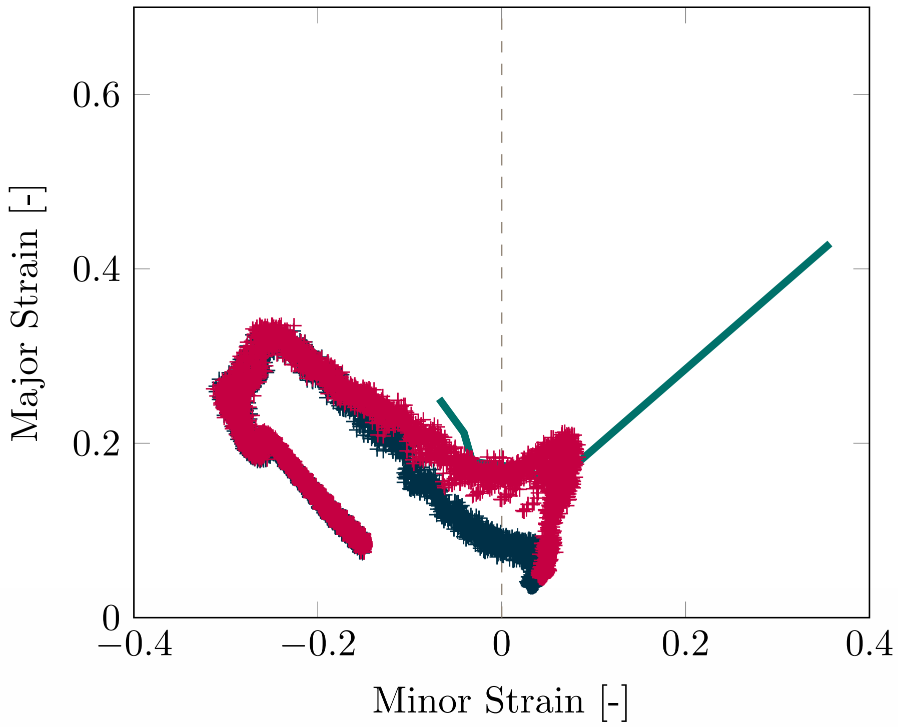
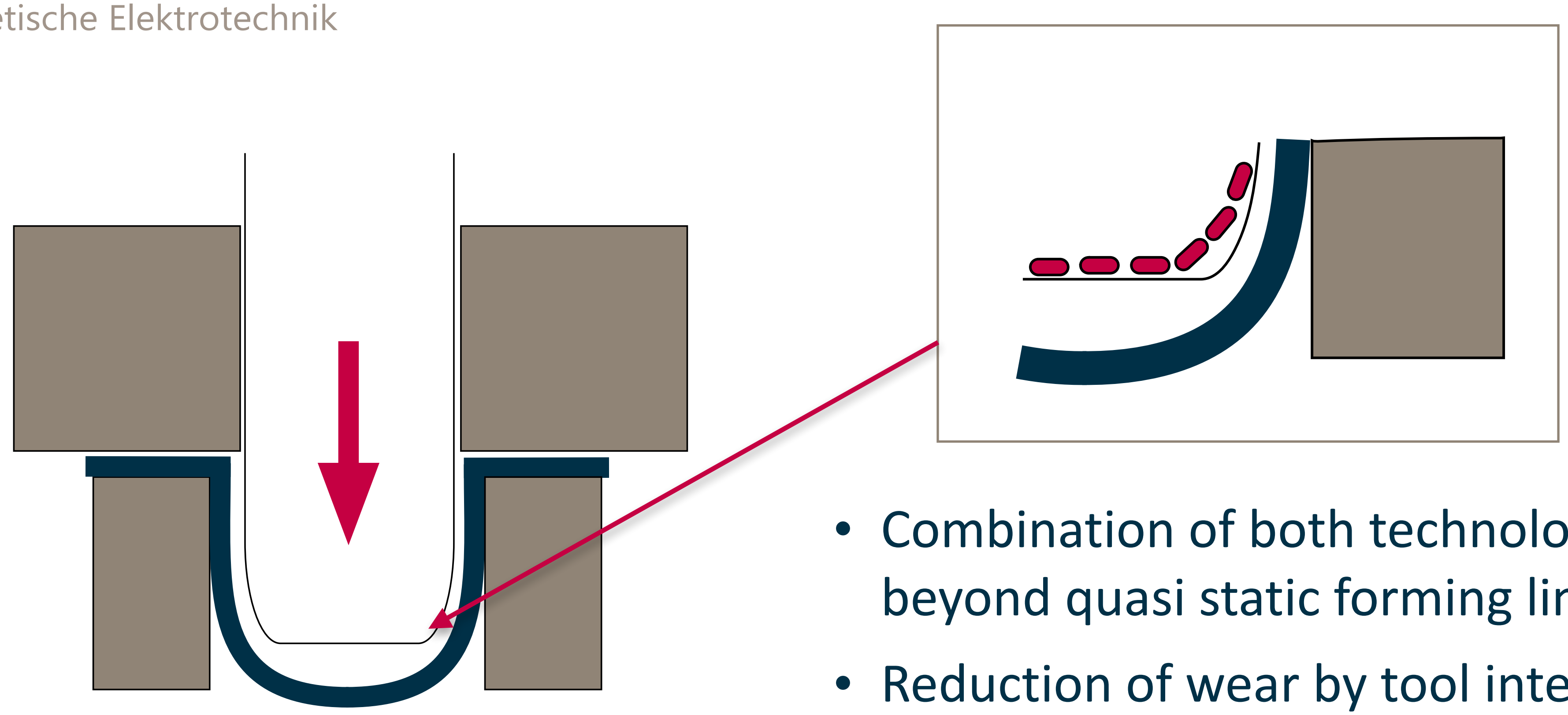


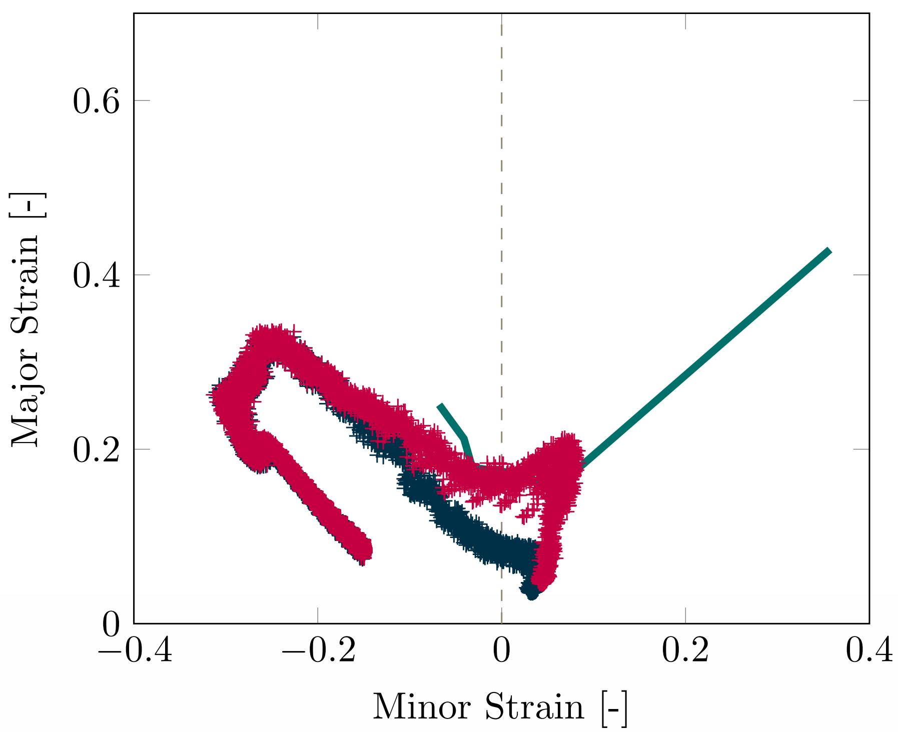




- Combination of both technologies yields forming beyond quasi static forming limits
- Reduction of wear by tool integration
- Forming of high-strength materials

Combined Forming





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- Process is subject to many parameters
- Only careful adjustments of involved parameters yield good results
- Economic process design necessary

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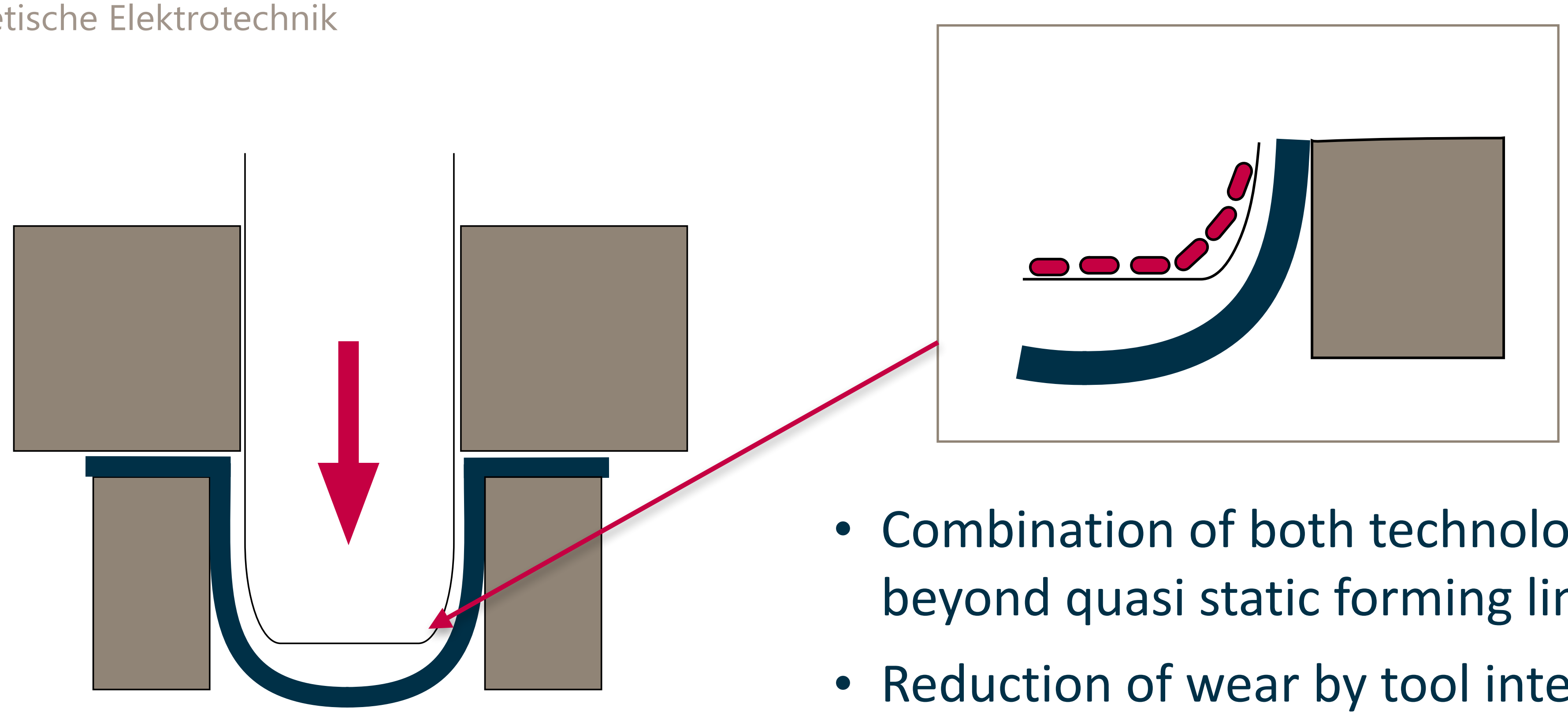

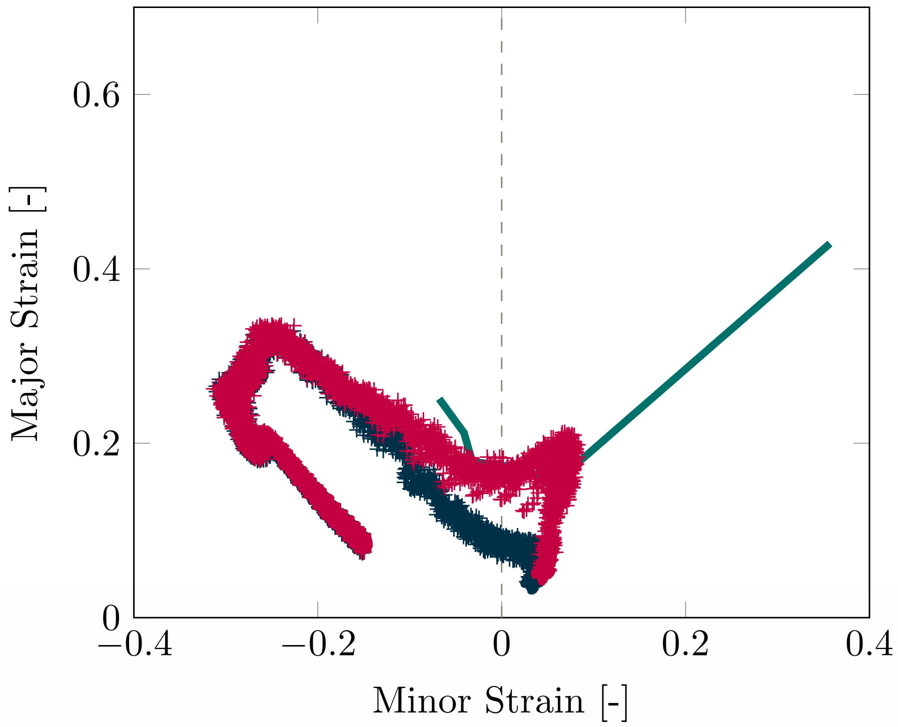

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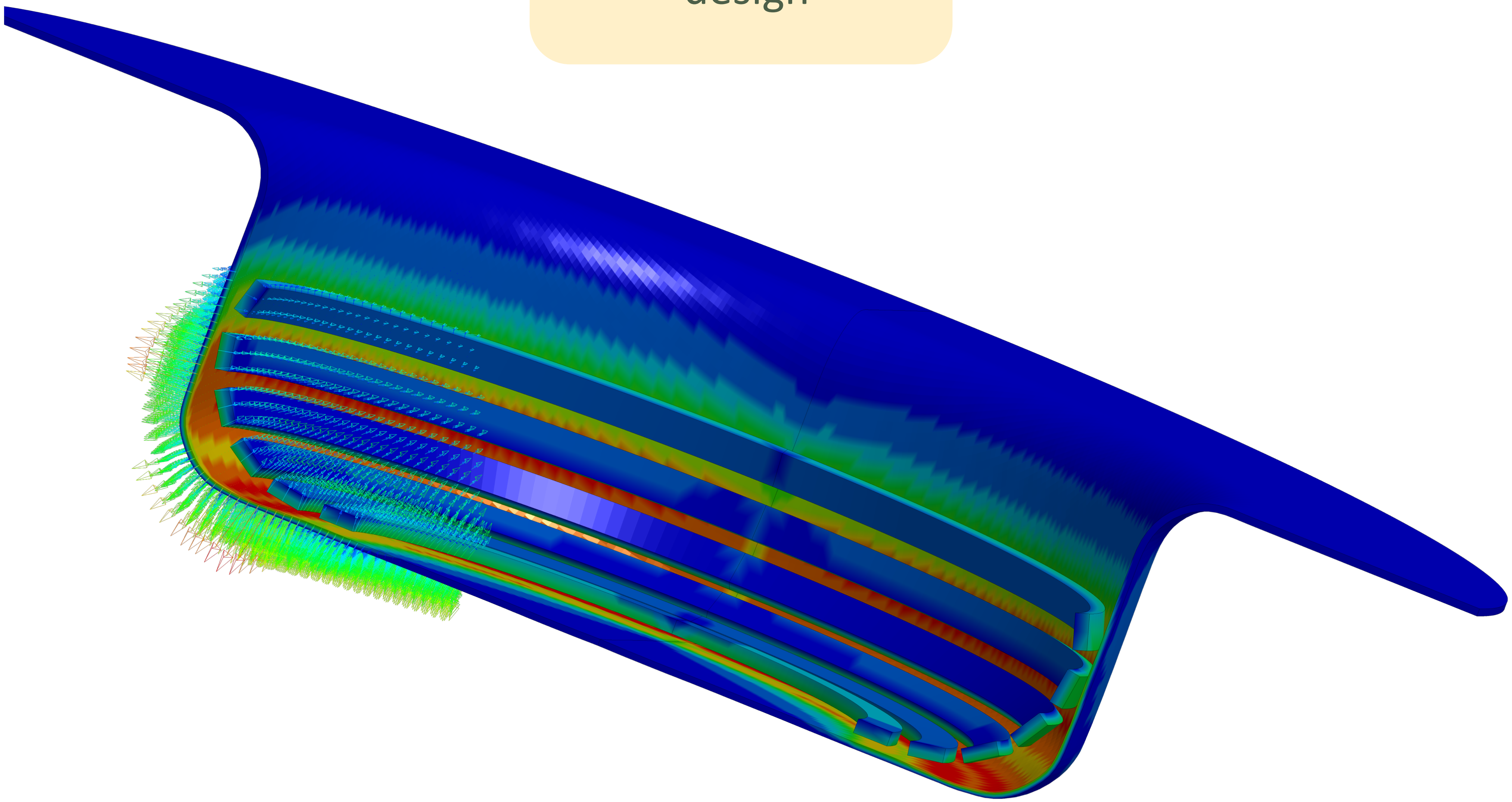
➡ Virtual process design to overcome drawbacks!

Virtual Process Design

Virtual Process Design

Enhancement by virtual process design



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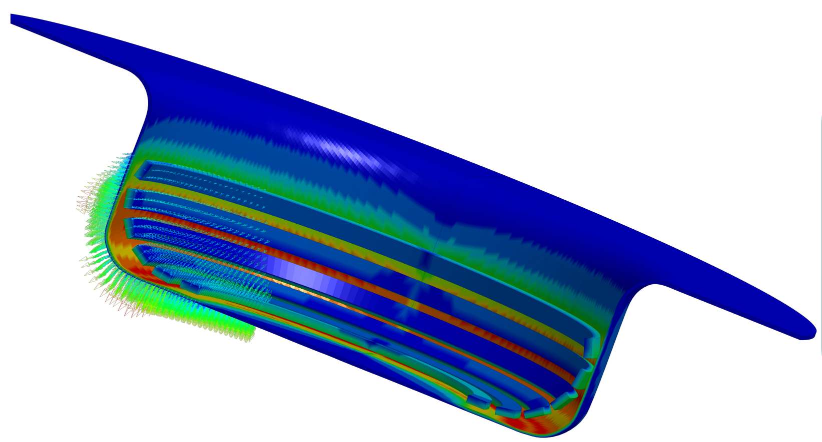
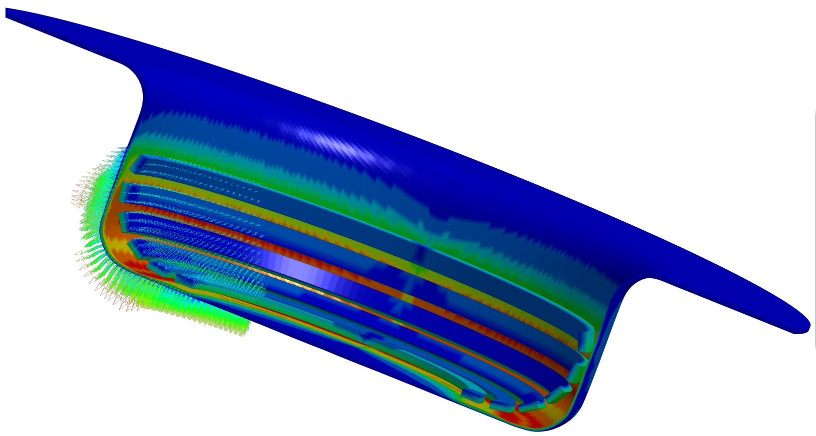


Adjustment of parameters defining the process

Virtual Process Design

Enhancement by virtual process design

Tune material model for good simulation



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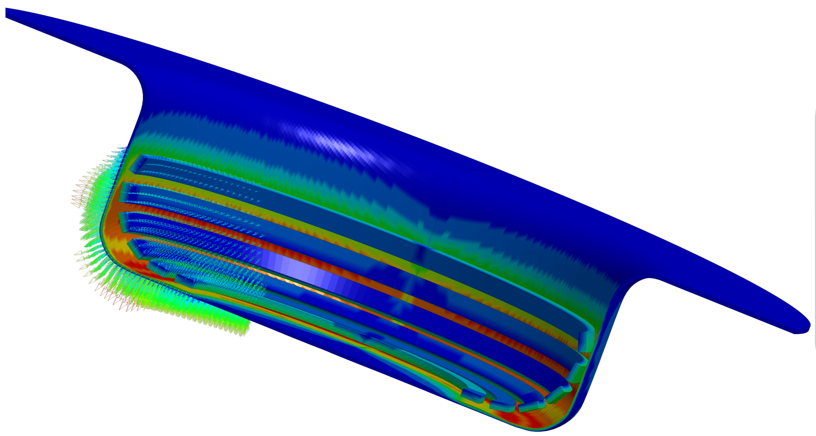

Adjustment of parameters defining the process

Mathematical optimization

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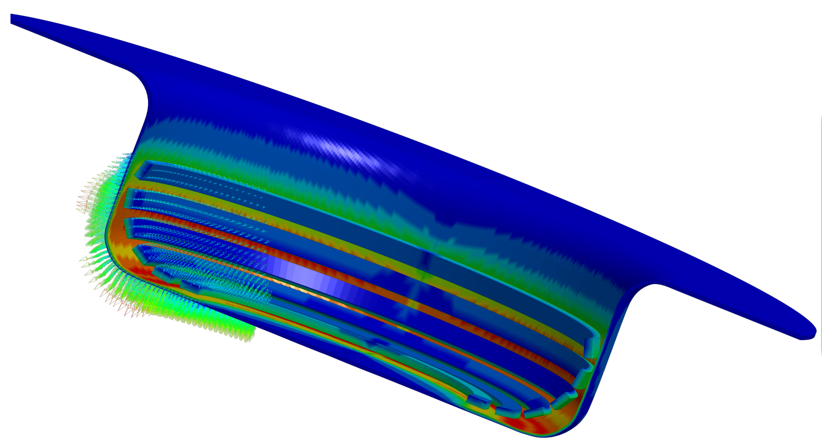

Adjustment of parameters defining the process

Mathematical optimization

Constitutive Material Model

$$S = \mu \left(C_\mathrm{p}^{-1} - C^{-1} \right) + \frac{\lambda}{2} \left(\det C \left(\det C_\mathrm{p} \right)^{-1} - 1 \right) C^{-1}, \quad X = c \left(C_{\mathrm{p}_\mathrm{i}}^{-1} - C_\mathrm{p}^{-1} \right)$$

$$Y = CS - C_\mathrm{p} X, \quad Y_\mathrm{kin} = C_\mathrm{p} X$$

Constitutive Material Model

Ingredients:

- Equations for second order Piola-Kirchhoff stress tensor S, backstress tensor X and stress-like tensors Y, Y_{kin}

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Plastic flow rule

$$\dot{C}_p = \dot{\Lambda}\frac{\operatorname{sym}\left(C_p\left(\tilde{A}\left[(Y^D)^T\right] + \left(\tilde{A}^T\left[Y^D\right]\right)^T\right)^D\right)}{\sqrt{Y^D \cdot \left(\tilde{A}\left[(Y^D)^T\right]\right)}}$$

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Isotropic hardening

$$\dot{\kappa} = \sqrt{\frac{2}{3}}\dot{\Lambda}$$

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•Evolution equations for kinematic and isotropic hardening

•Yield function of Hill-type

$$\Phi = \sqrt{Y^{\mathrm{D}} \cdot \left(\tilde{A}\left[\left(Y^{\mathrm{D}}\right)^{\mathrm{T}}\right]\right)} - \sqrt{\frac{2}{3}}\left(\sigma_{\mathrm{y}} + Q\left(1 - e^{-\beta\kappa}\right)\right)$$

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High-speed part

$$\dot{\Lambda} = \frac{\langle\Phi\rangle^{m}}{\eta}$$

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Quasi-static part

$$\dot{\Lambda} \geq 0, \quad \Phi \leq 0, \quad \dot{\Lambda}\Phi = 0$$

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- Scalar damage variable (Lamaitre type)

$$\dot{D} = \dot{\lambda}\sqrt{\frac{2}{3}}\frac{1}{1-D}\left(\frac{Y_0}{s}\right)^k H\left(\kappa - p_D\right)$$

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- Scalar damage variable (Lamaitre type)
- Effective stress contributions

$$\bar{S} = \frac{1}{1-D} S, \quad Y = C\bar{S} - C_{\mathrm{p}} X$$

Parameter of the Constitutive Material Model

- Isotropic hardening parameters in the yield function

$$\Phi = \sqrt{Y^{\mathrm{D}} \cdot \left(\tilde{\mathcal{A}}\left[\left(Y^{\mathrm{D}}\right)^{\mathrm{T}}\right]\right)} - \sqrt{\frac{2}{3}}\left(\sigma_{\mathrm{y}} + Q\left(1 - e^{-\beta\kappa}\right)\right)$$

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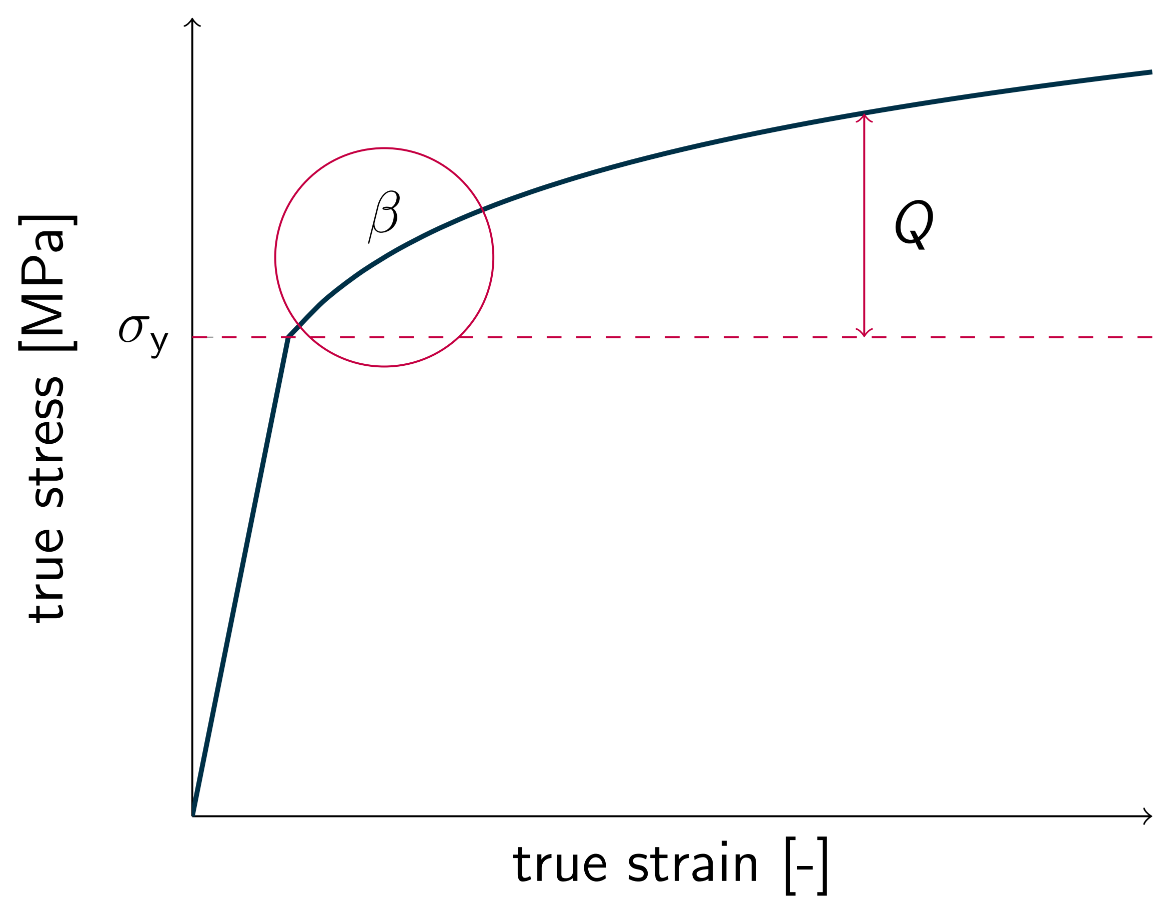

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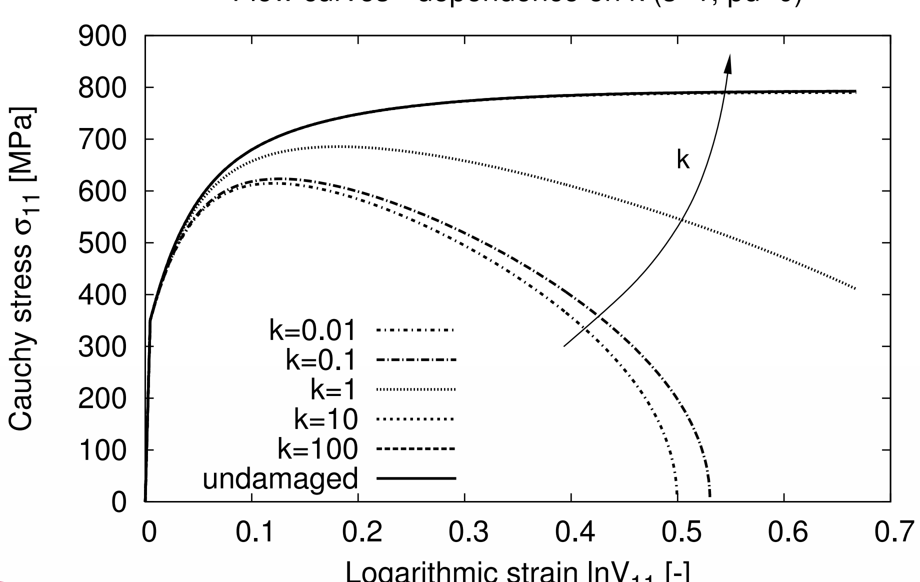
Flow curves - dependence on k (s=1, pd=0)



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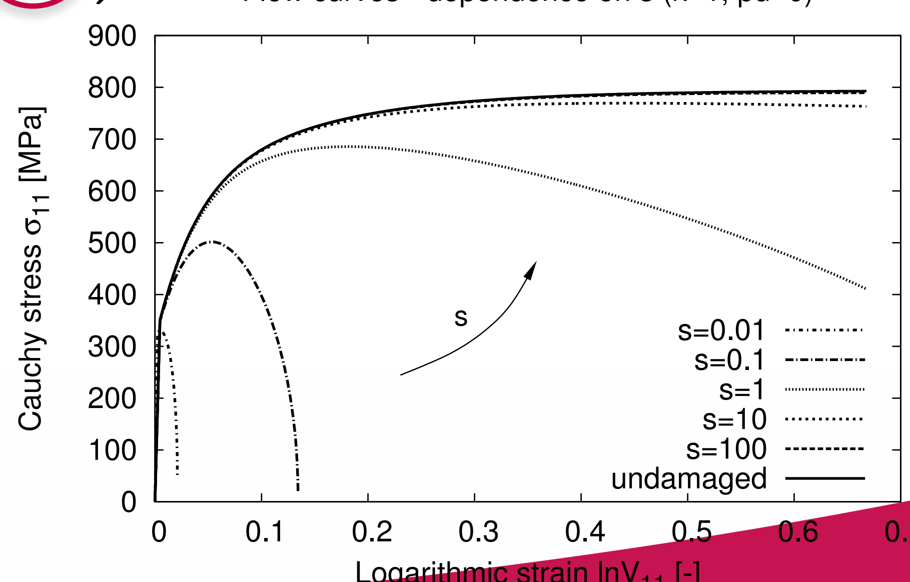

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→End up with a total of 9 parameters to be identified

Identification by Non-Linear Optimization

- Parameters are identified by fitting the model to experimental force-displacement curves

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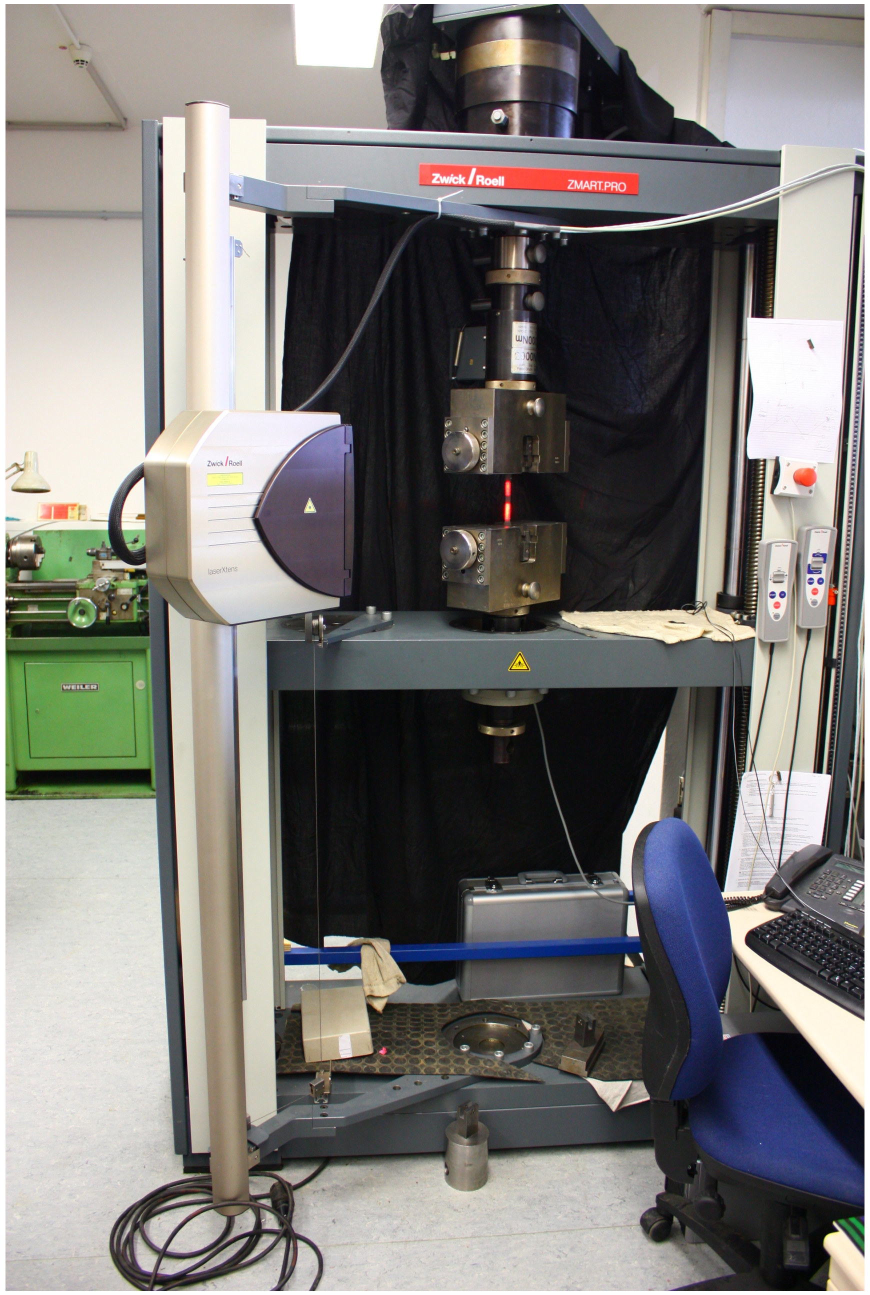

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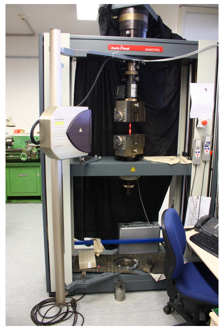

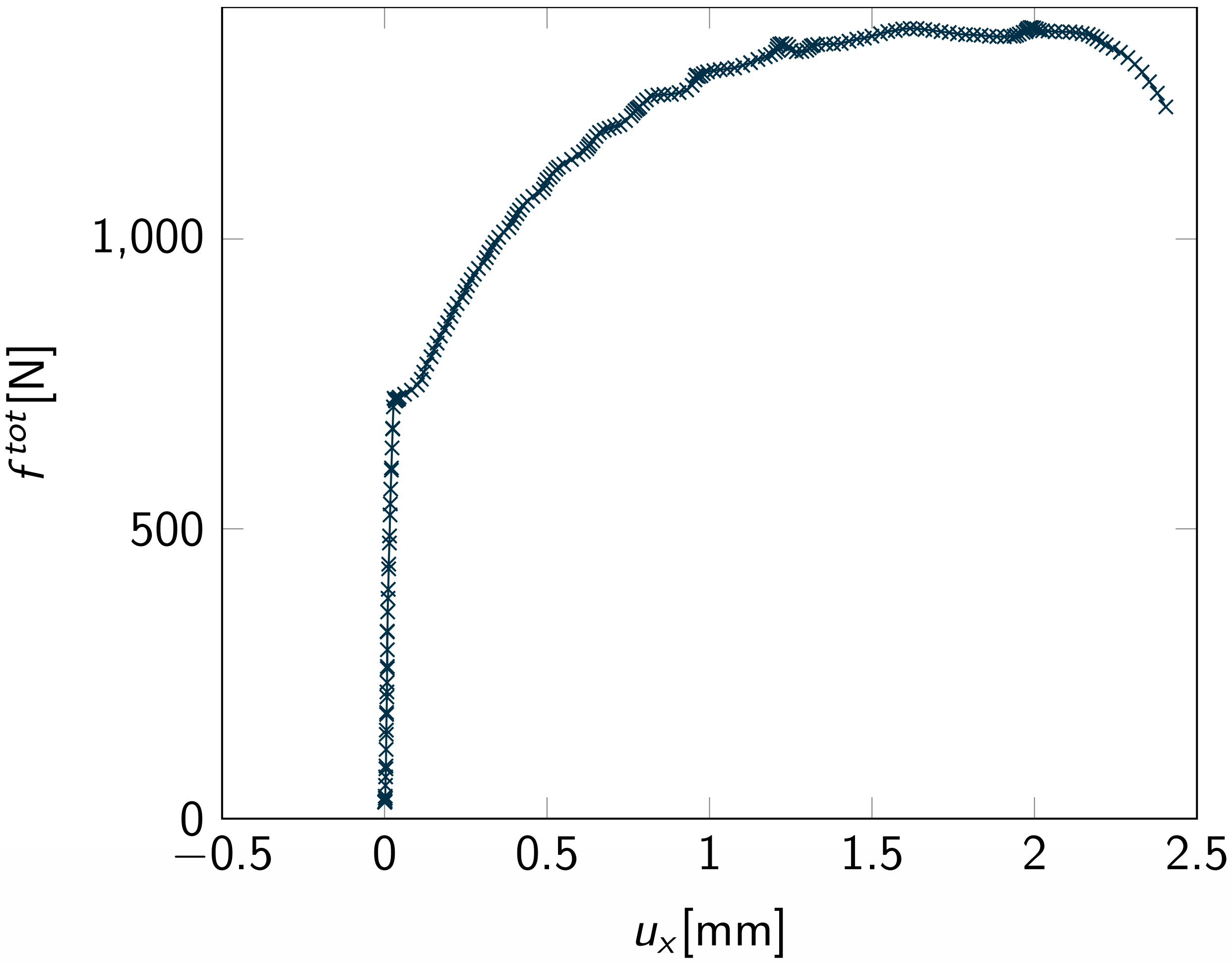

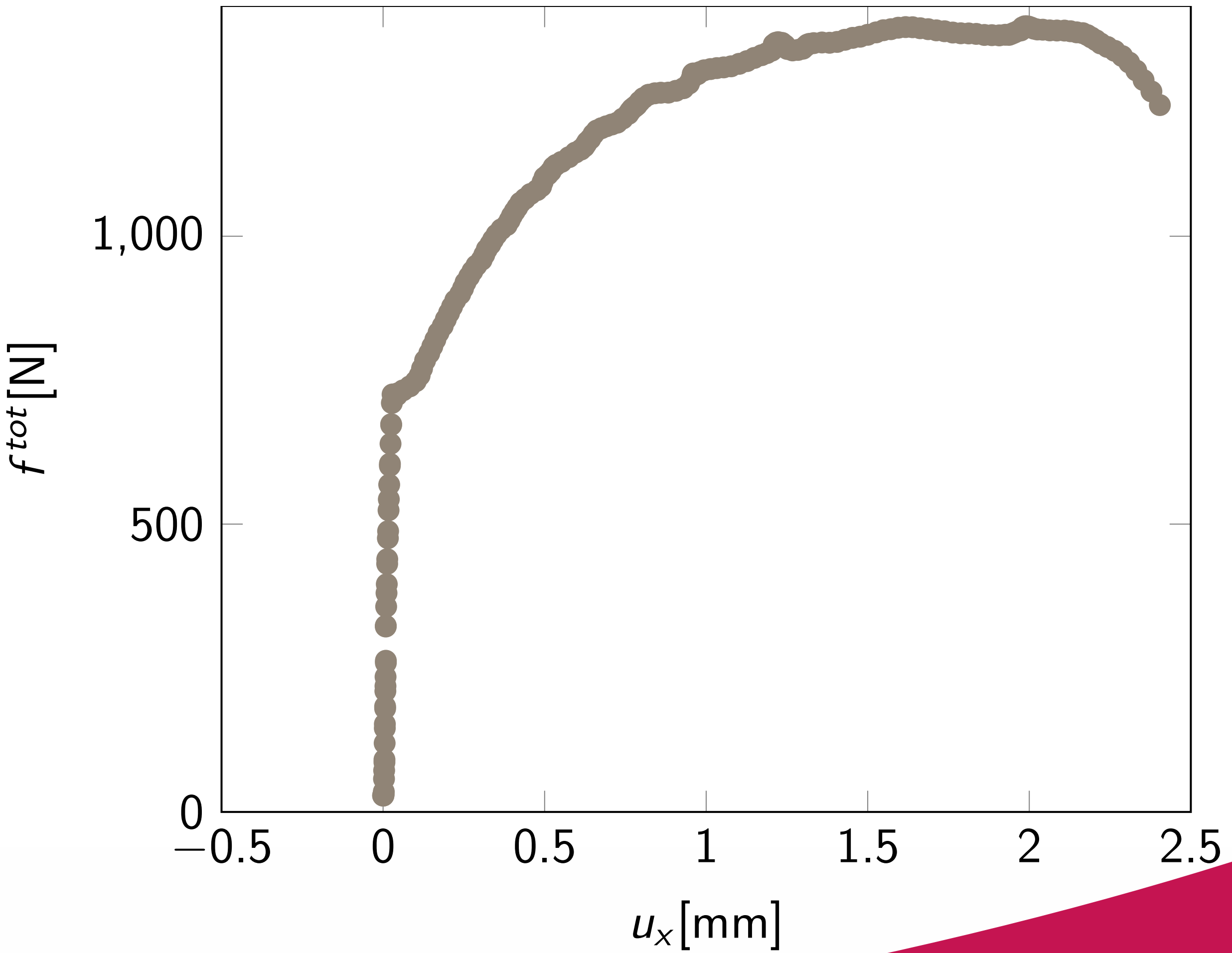

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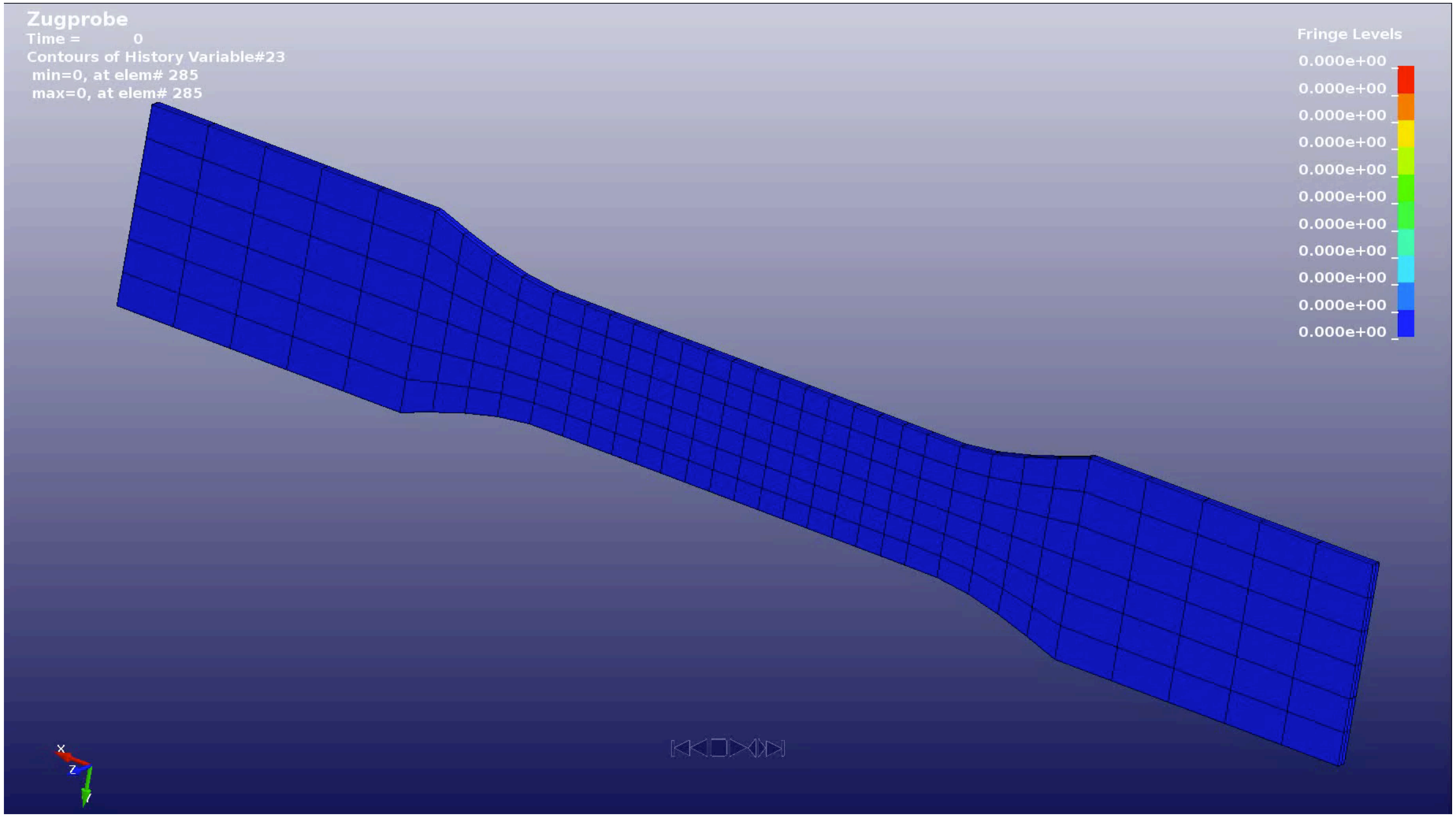
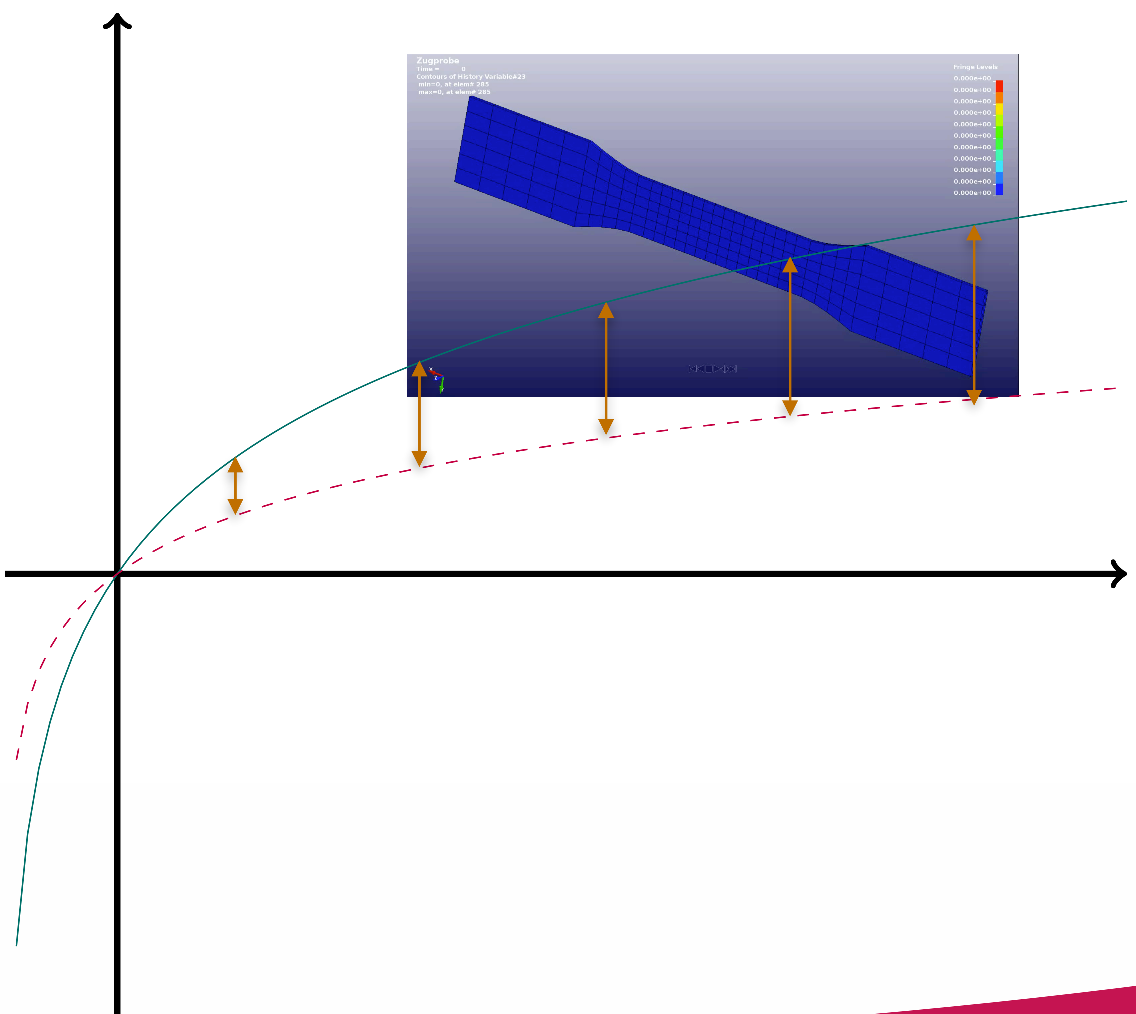


Identification by Non-Linear Optimization

- Parameters are identified by fitting the model to experimental force-displacement curves
- Non-linear objective function to identify optimal parameter vector *p*

$$F(p) = \frac{1}{2(u_N - u_1)} \sum_{i=1}^{N-1} (u_{i+1} - u_i) \left[\left(f_{i+1}^{\text{sim}}(p) - f_{i+1}^{\text{exp}}\right)^2 + \left(f_i^{\text{sim}}(p) - f_i^{\text{exp}}\right)^2 \right]$$



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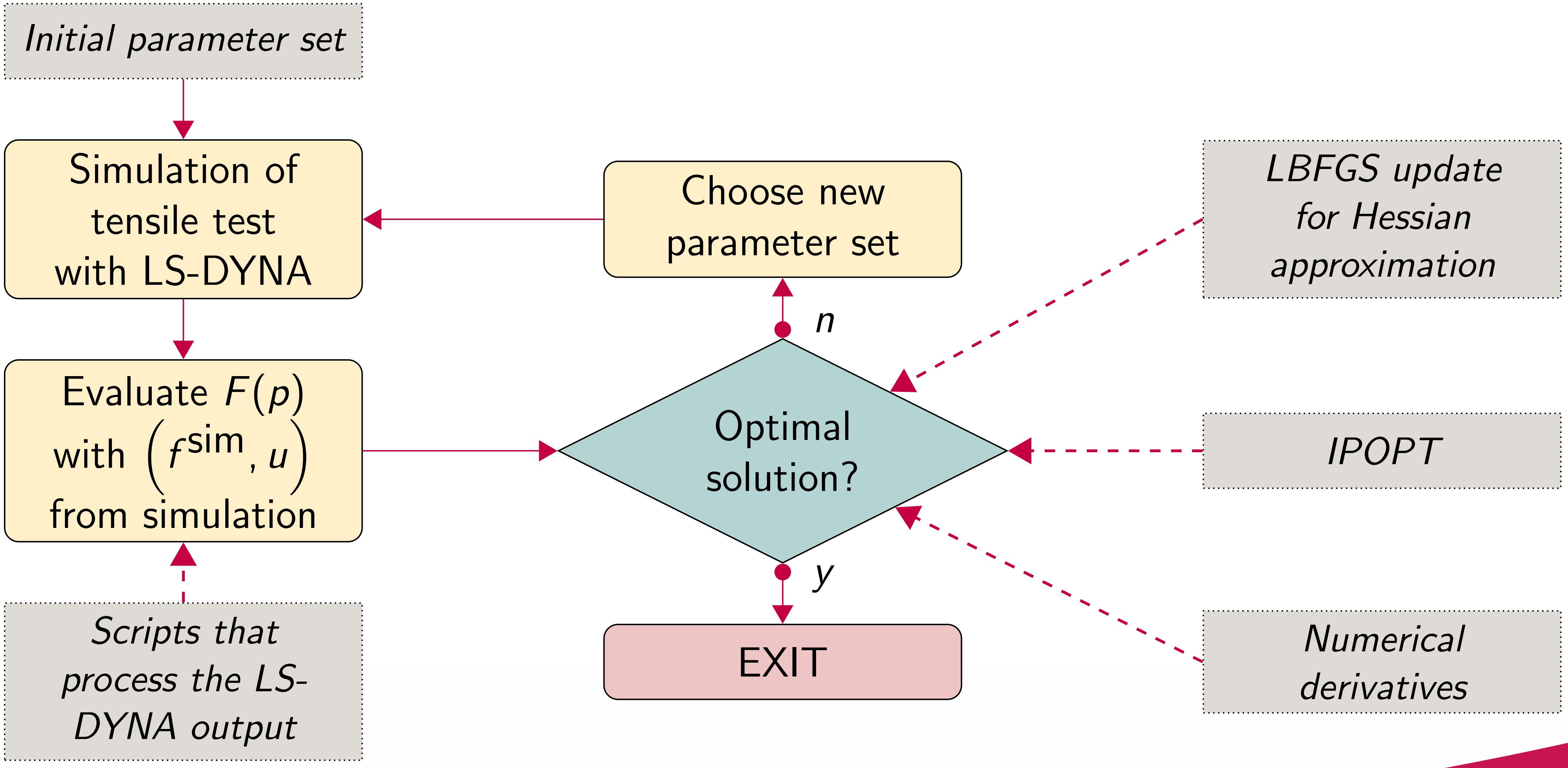

Identification by Non-Linear Optimization

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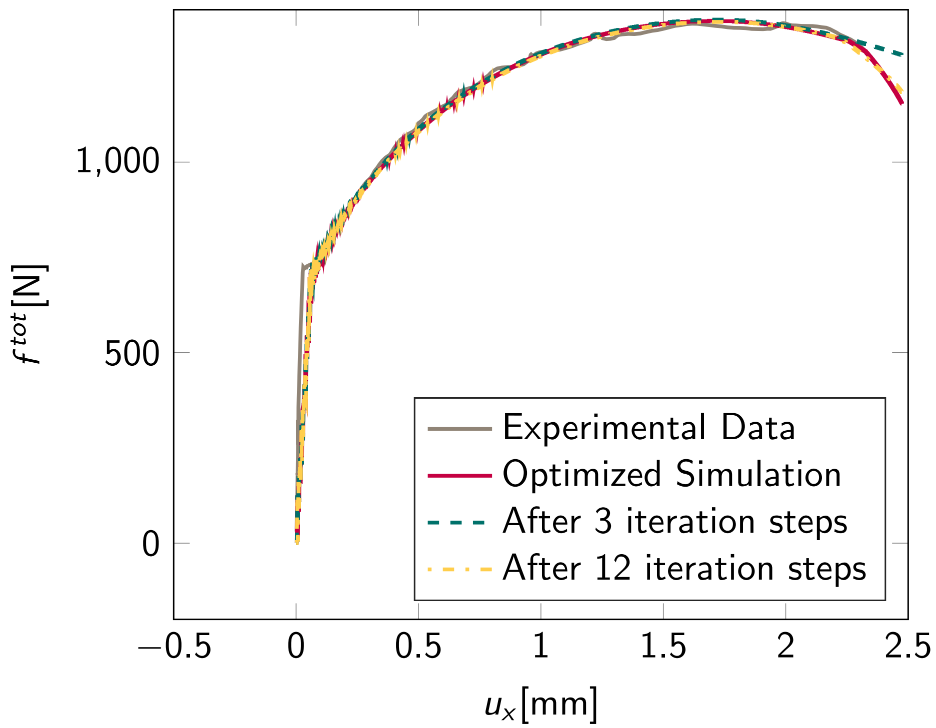
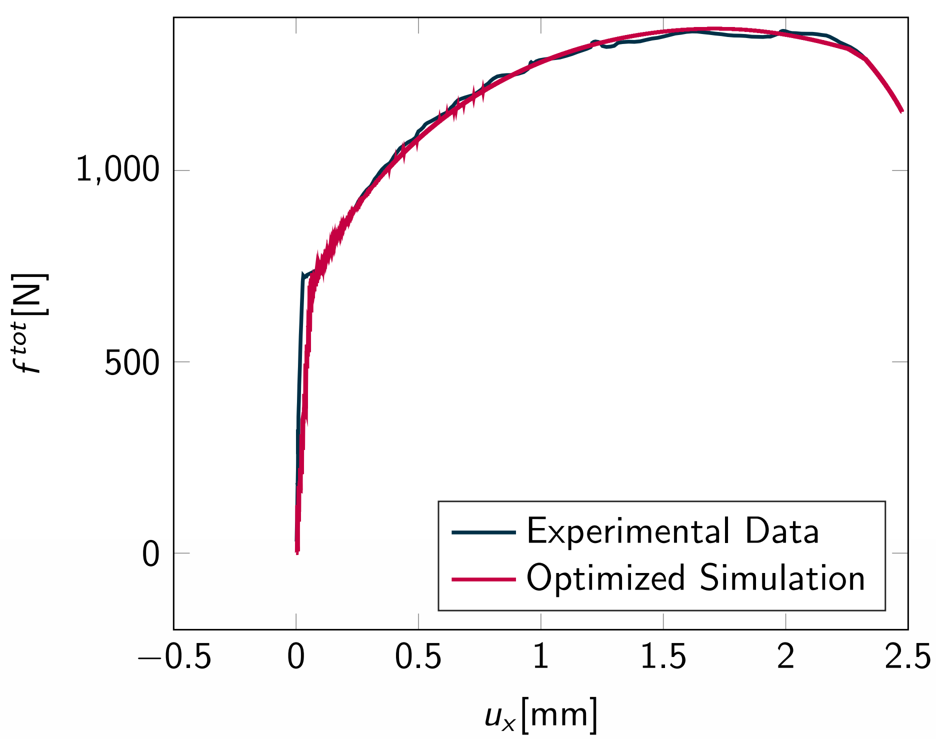
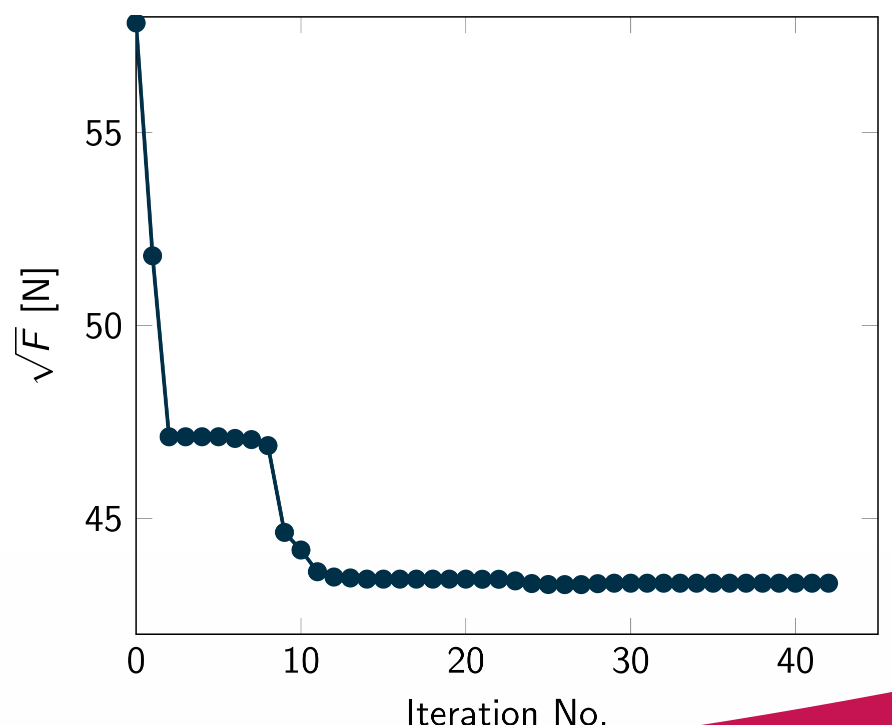


Parameter	Identified value
Q	$1.604 \cdot 10^{2}$
β	$1.265 \cdot 10^{1}$
k	$4.694 \cdot 10^{-1}$
s	$2.680 \cdot 10^{-1}$
p_D	$6.306 \cdot 10^{-1}$
E	$8.089 \cdot 10^{4}$
σ_y	$1.185 \cdot 10^{2}$
b	$5.124 \cdot 10^{-3}$
c	$4.598 \cdot 10^{-4}$





Validation and Verification

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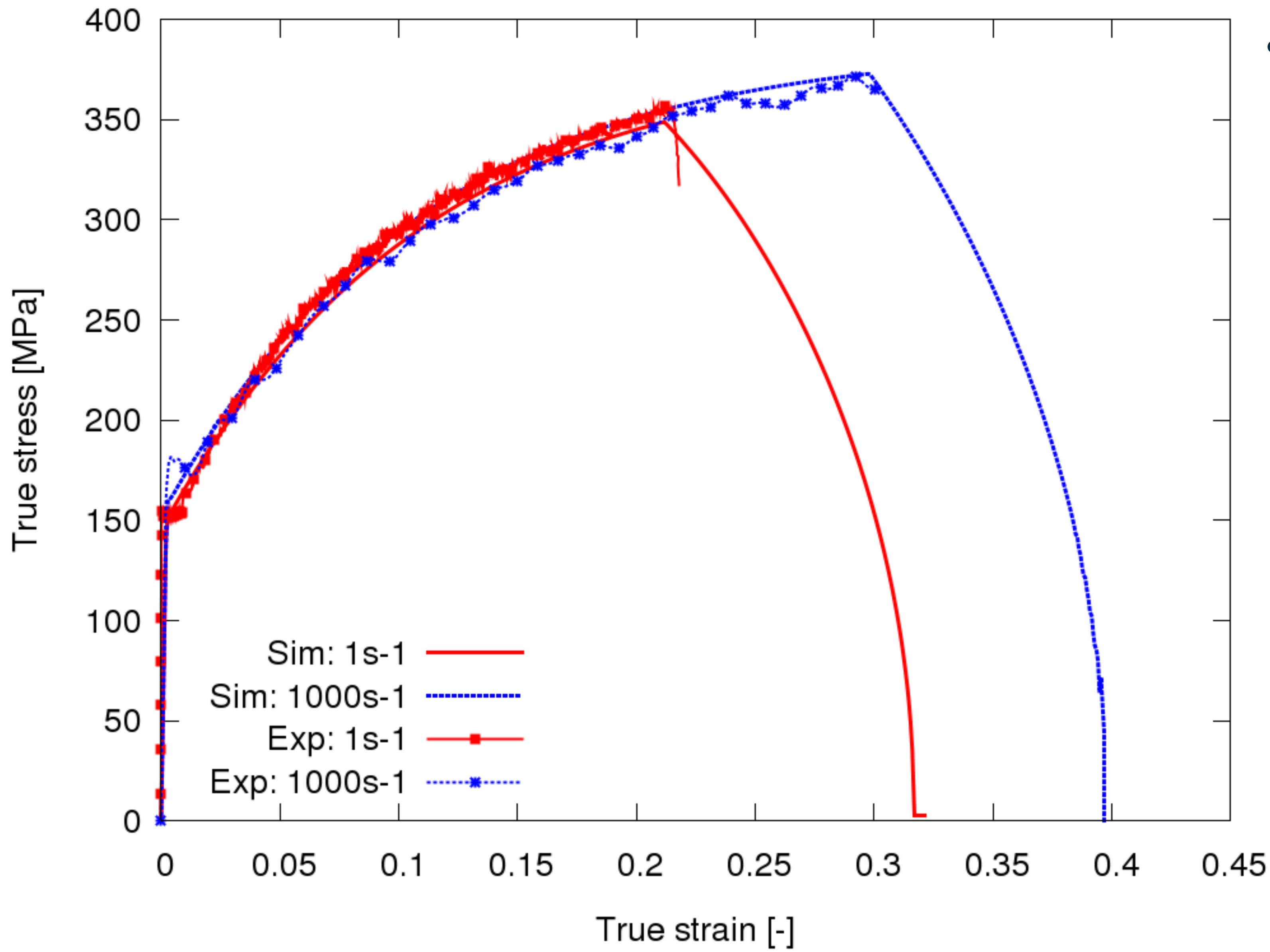
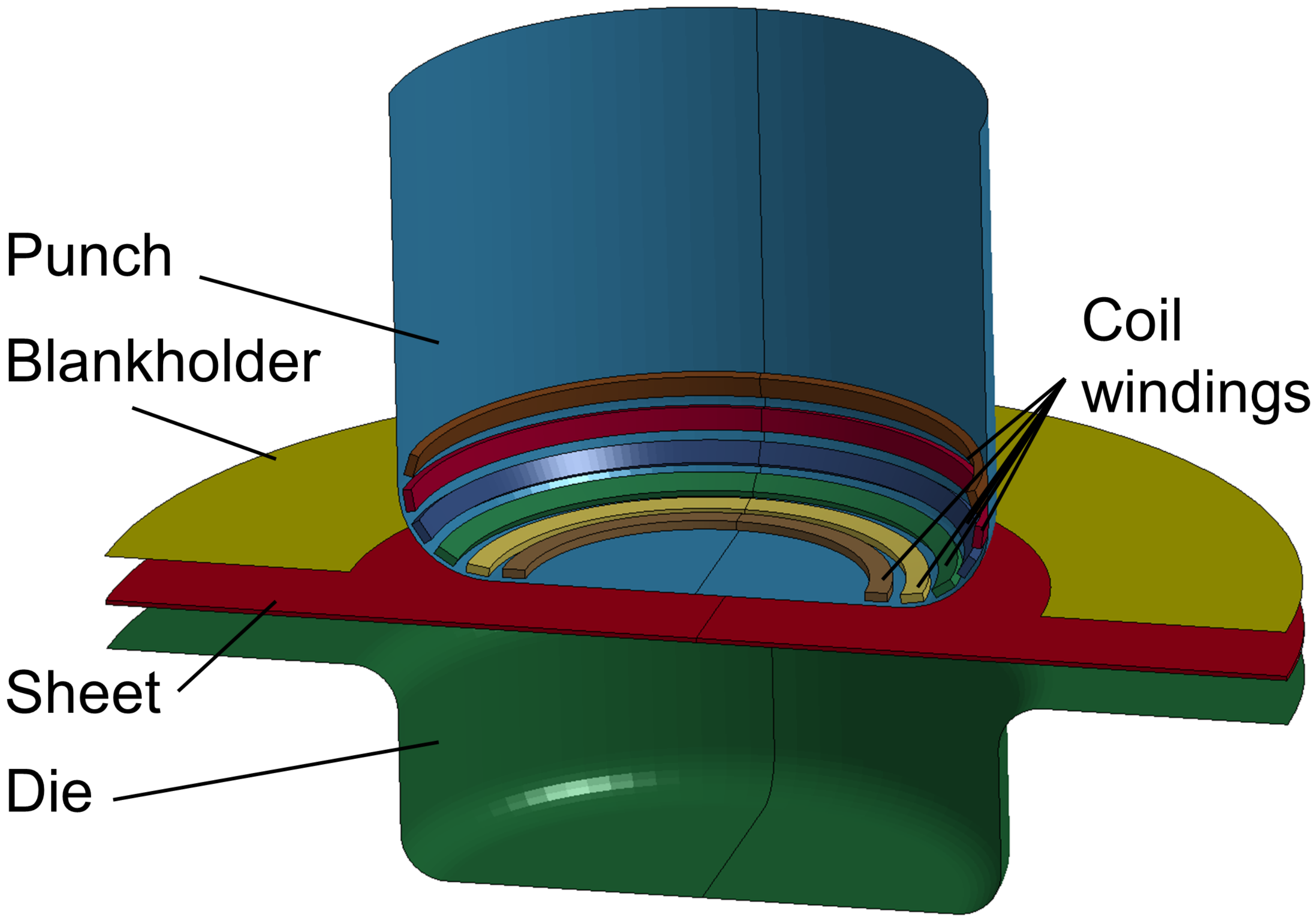
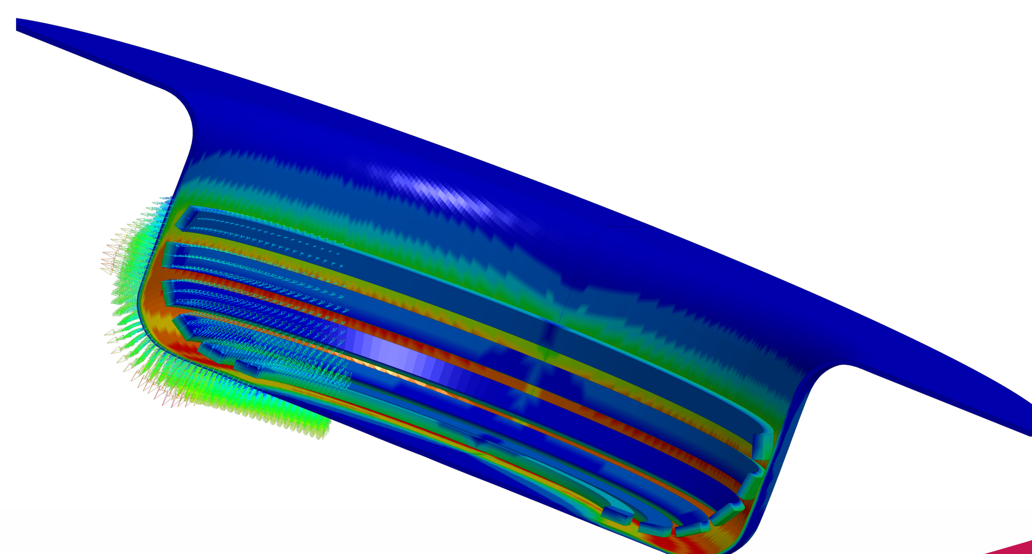


- Comparison to stress-strain curves (with evolution model for damage threshold)

Validation and Verification



- Comparison to stress-strain curves (with evolution model for damage threshold)
- Application to complex situation (cup drawing)

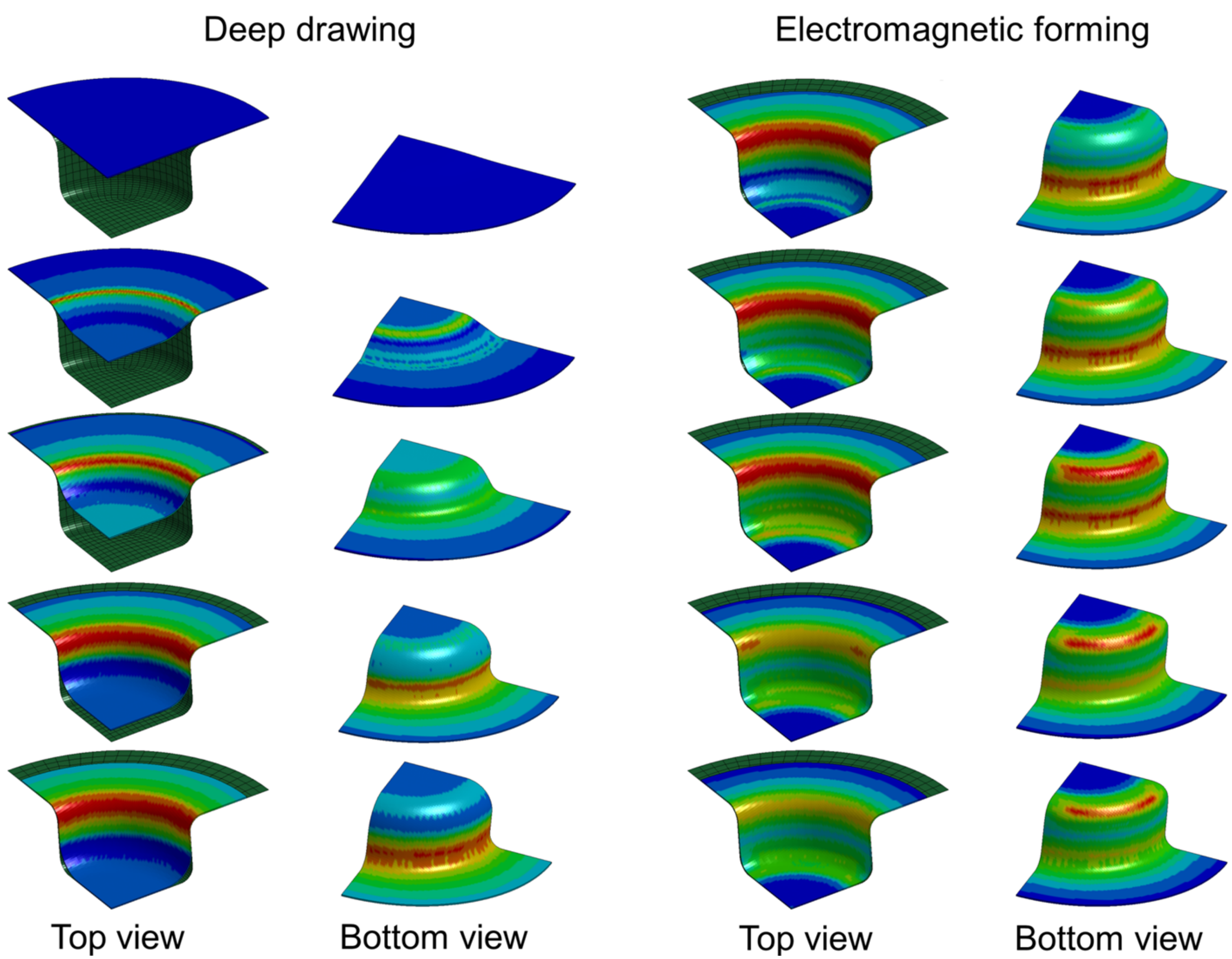


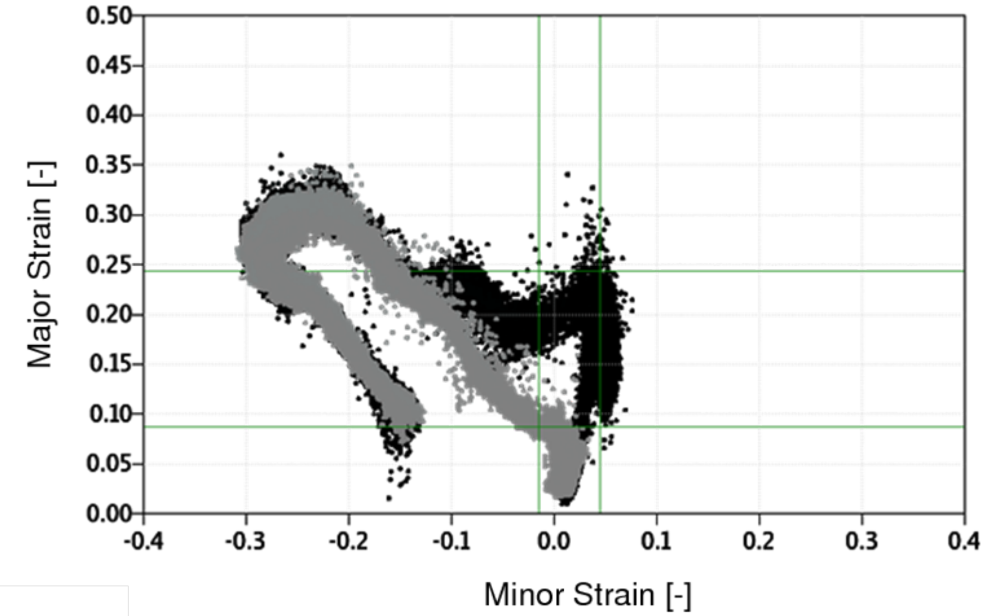
Combined Deep Drawing of a Cup

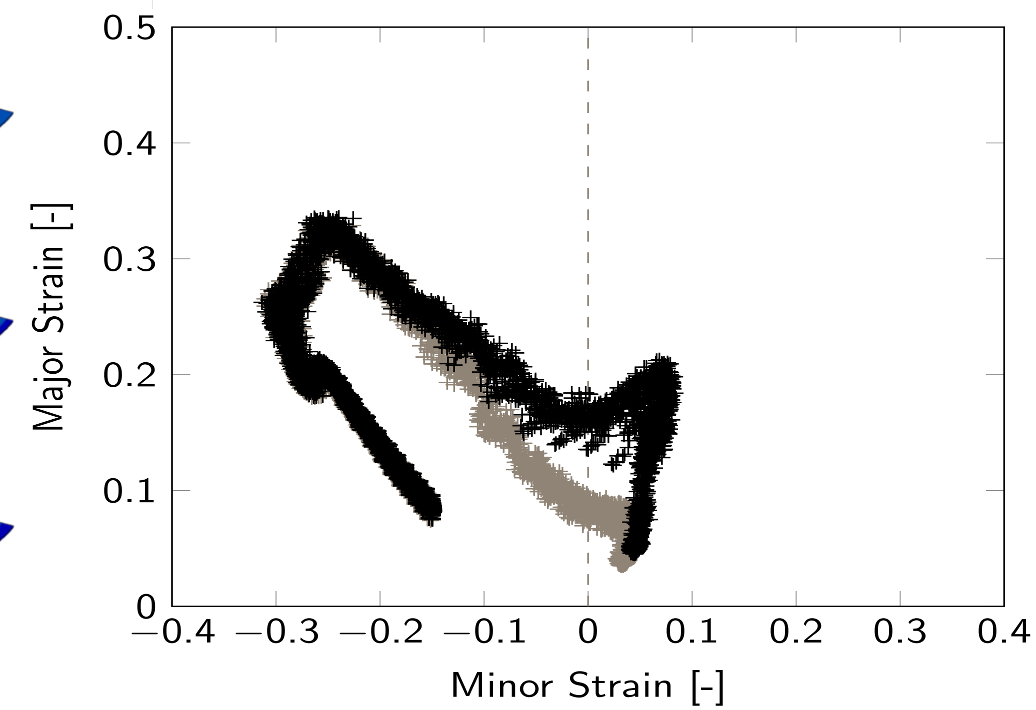
Theoretische Elektrotechnik

Combined Deep Drawing of a Cup

PAK 343 Methodenplanung







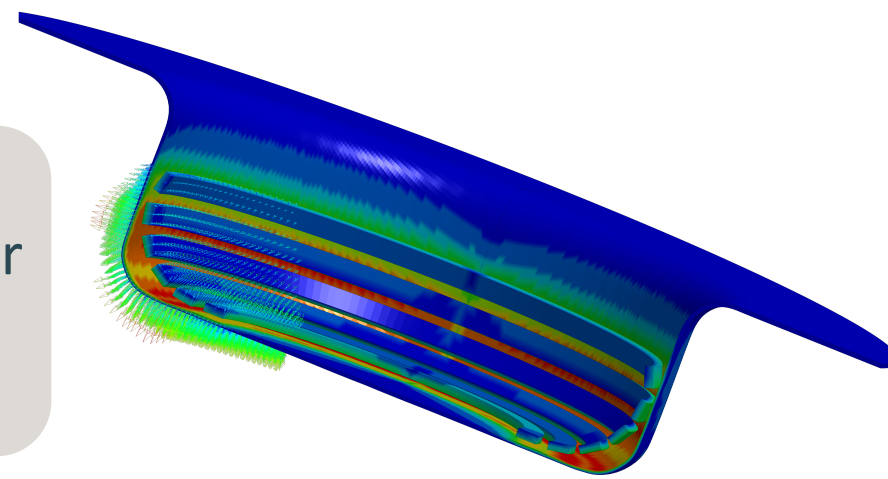
Theoretische Elektrotechnik

Virtual Process Design

PAK 343 Methodenplanung

Enhancement by virtual process design

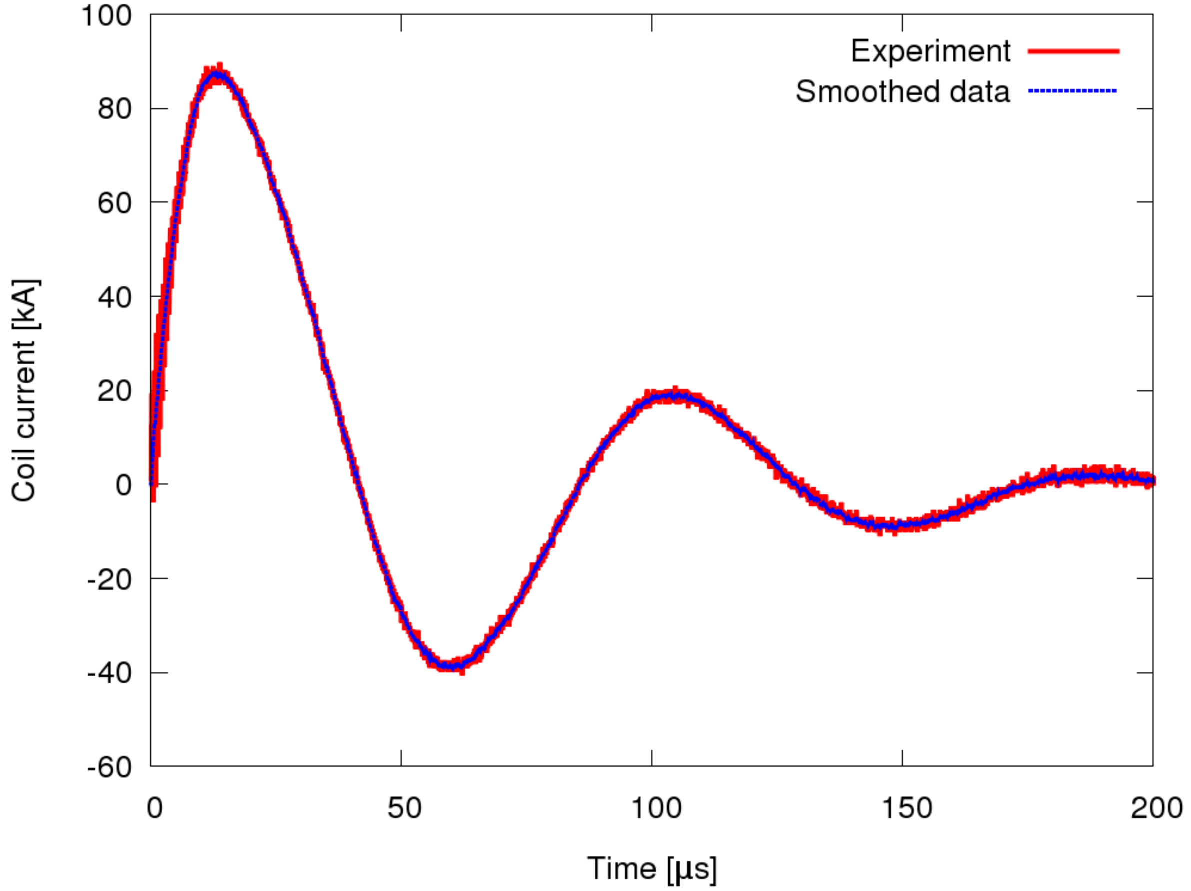
Tune material model for good simulation



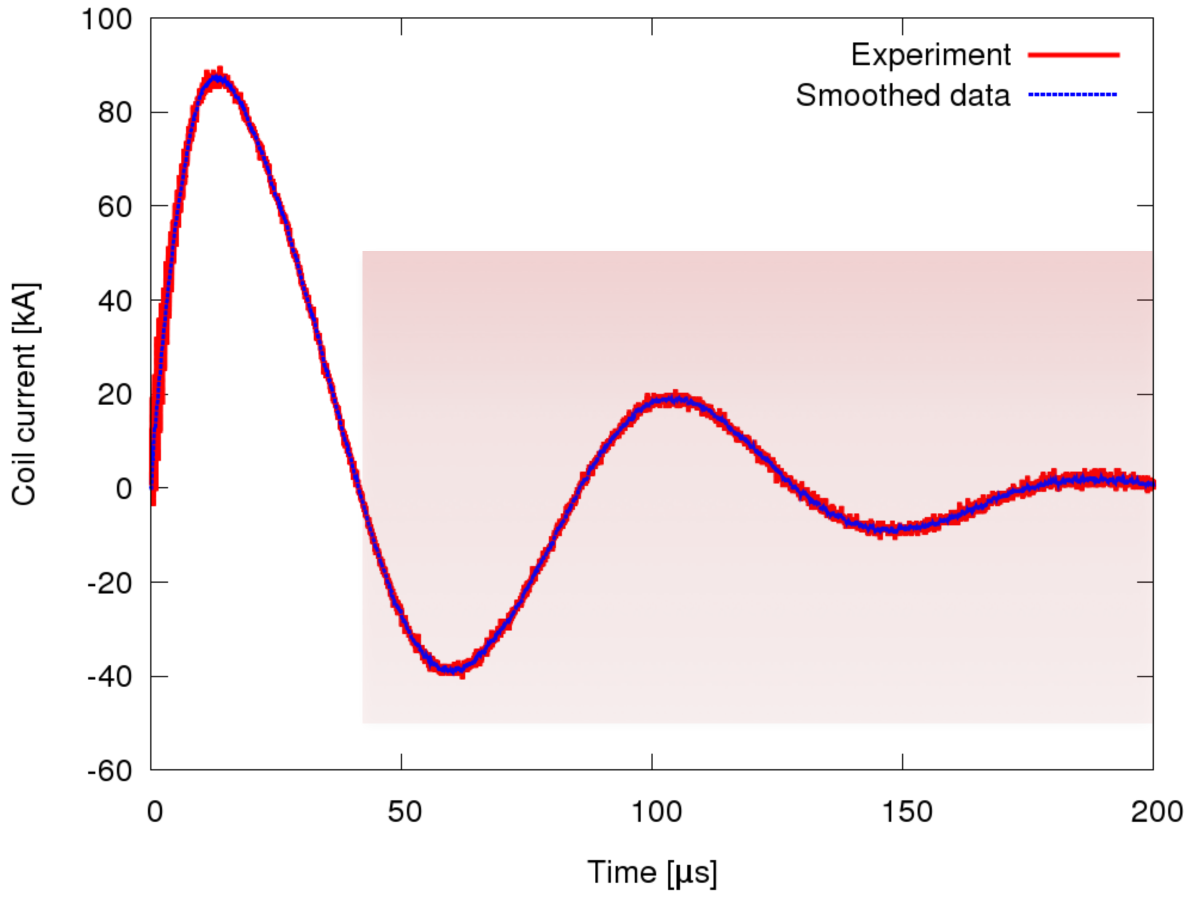
Adjustment of parameters defining the process

Mathematical optimization

Process Optimization in Cup Forming

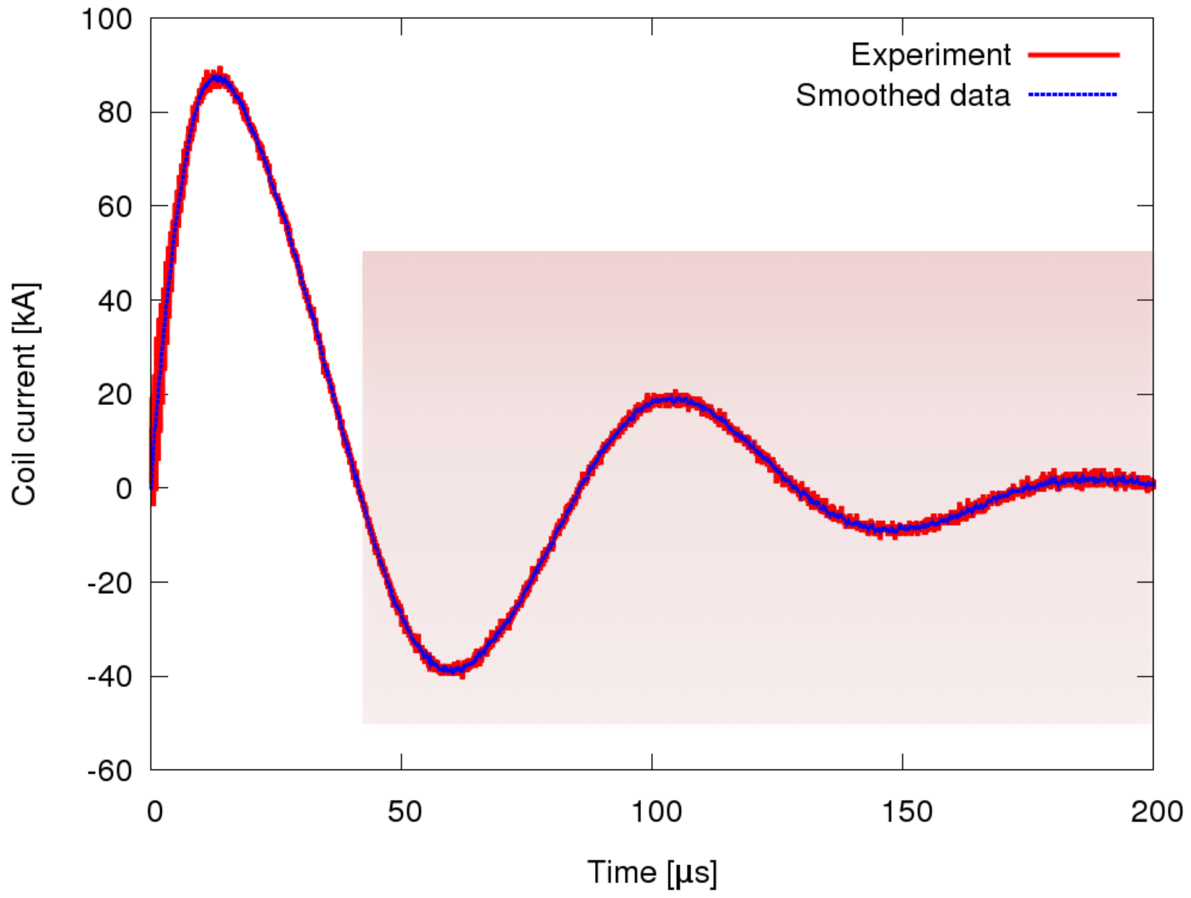


Process Optimization in Cup Forming



- Only the first half wave is relevant for forming

Process Optimization in Cup Forming

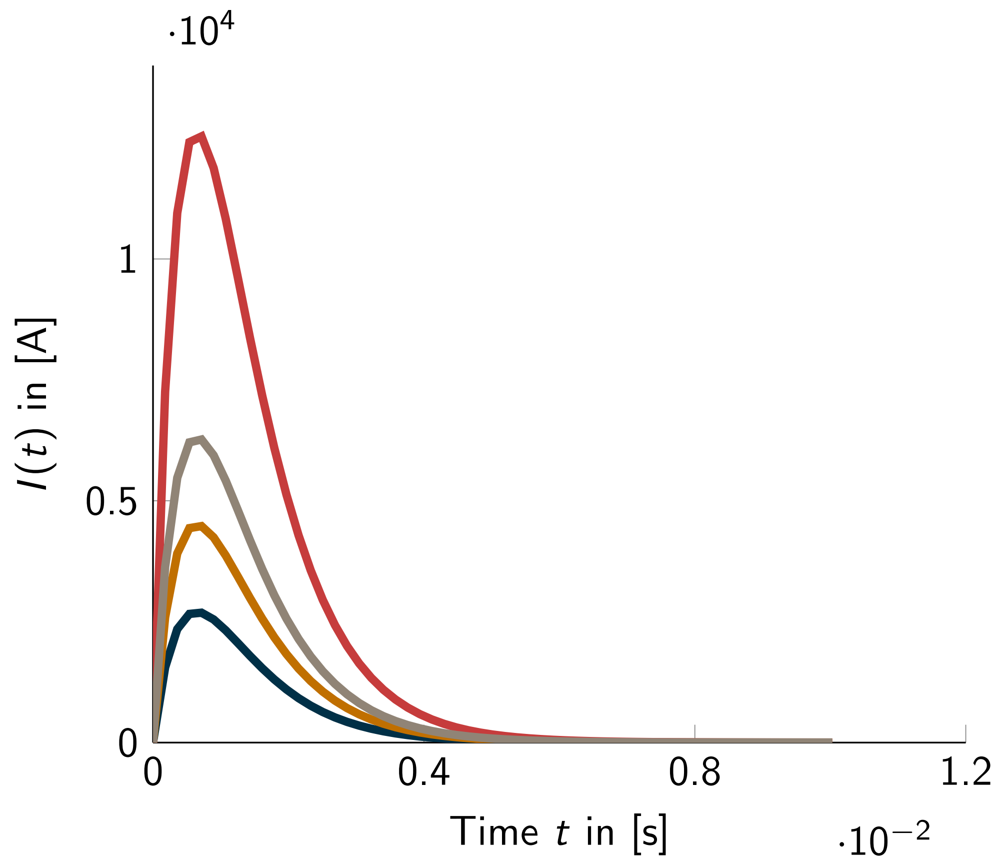


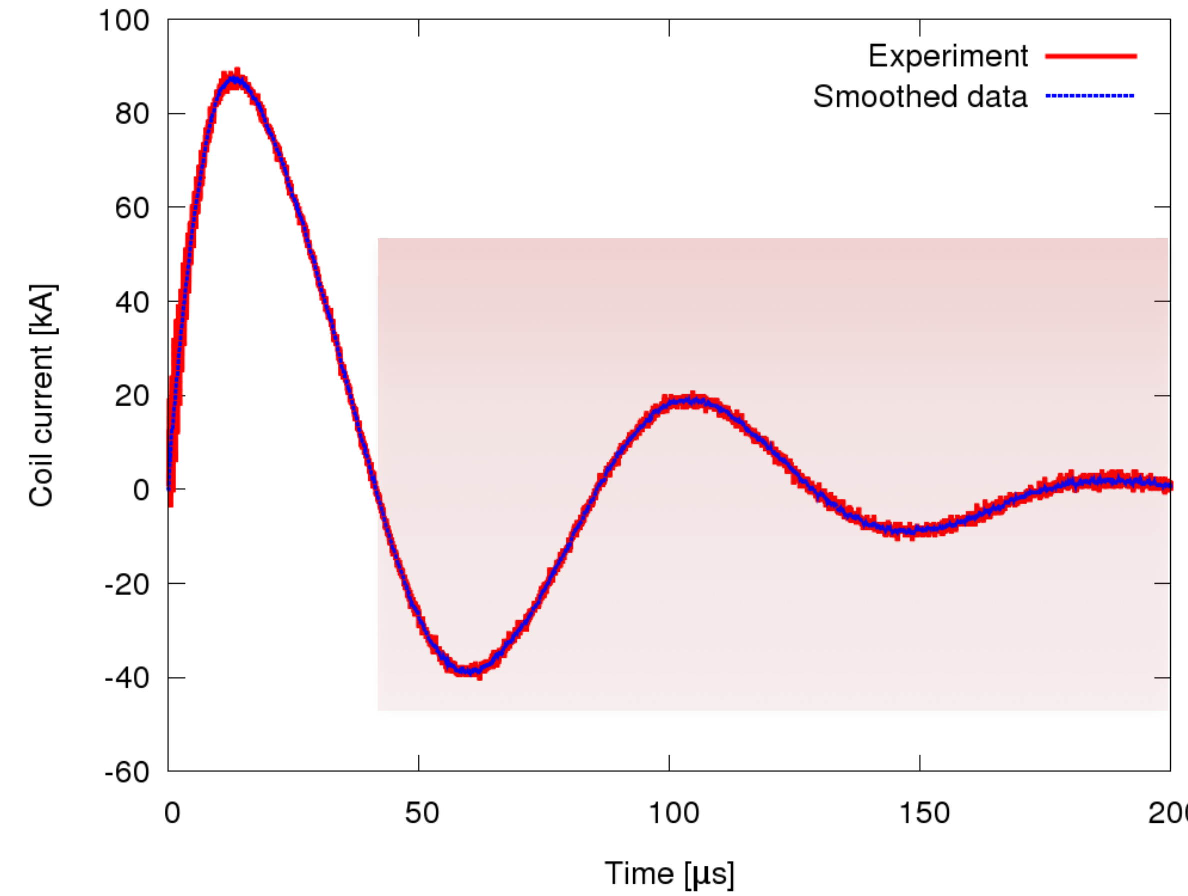
- Only the first half wave is relevant for forming

→ Remaining energy absorbed by coils

- Try novel approach to reduce wear and energy consumption

Process Optimization in Cup Forming





- Only the first half wave is relevant for forming

→ Remaining energy absorbed by coils

- Try novel approach to reduce wear and energy consumption

→ Double exponential pulse

$$I(t) = I_\alpha e^{-\alpha t} + I_\beta e^{-\beta t}$$

Process Optimization in Cup Forming

Process Optimization in Cup Forming

- Maximize the radius at bottom edge

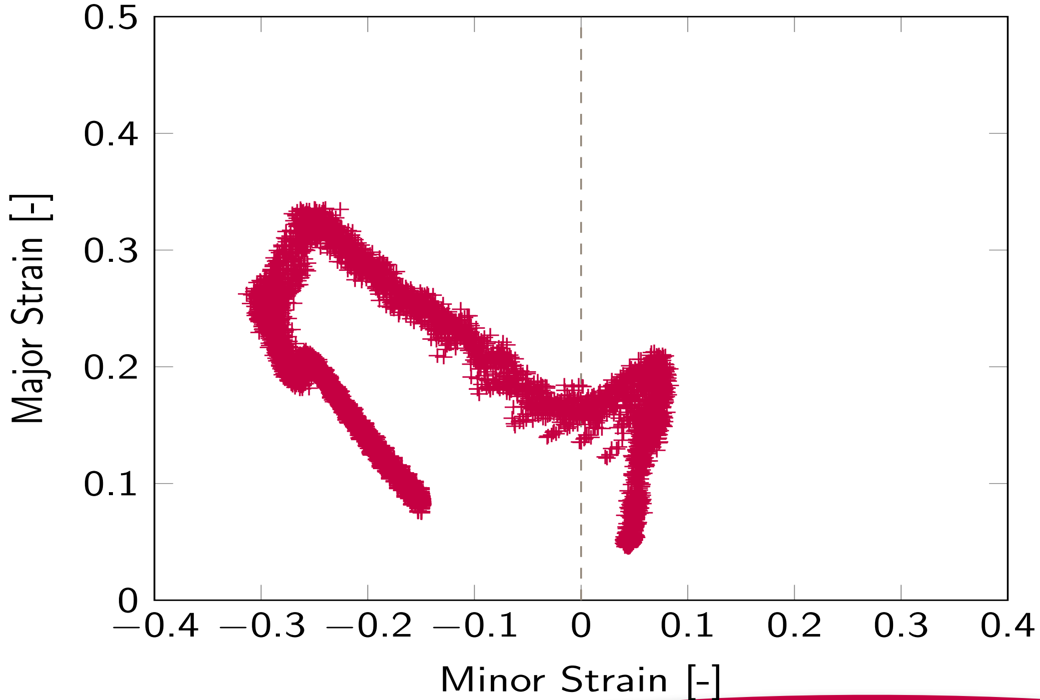
Process Optimization in Cup Forming

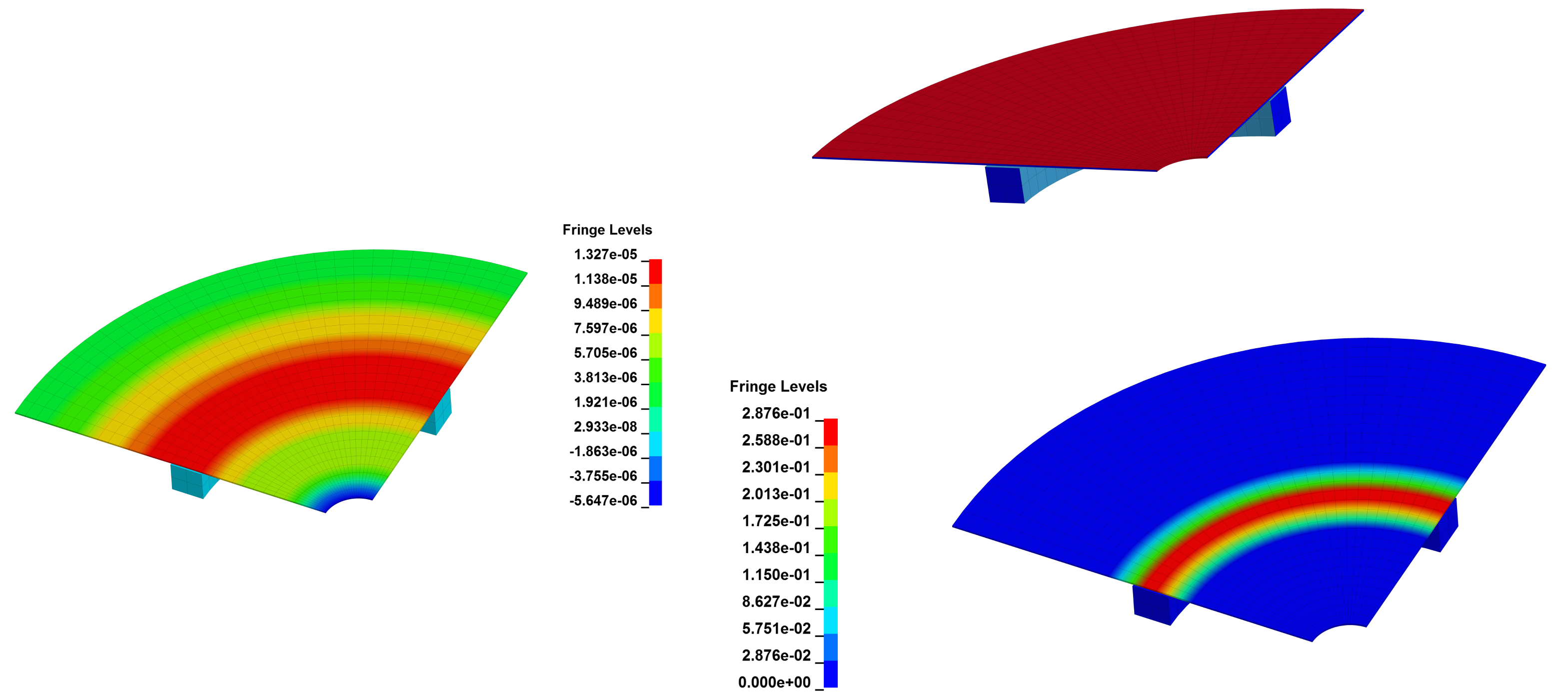
Theoretische Elektrotechnik

PAK 343 Methodenplanung

- Maximize the radius at bottom edge

  → Maximize the first principle strain





$$\min_{(I_\alpha, I_\beta, \alpha, \beta)^\top \in \mathbb{R}^4} \quad -\sum_{j=1}^{m} \varepsilon_1^j \left(I_\alpha, I_\beta, \alpha, \beta\right),$$

$$\text{subject to} \quad D_j\left(I_\alpha, I_\beta, \alpha, \beta\right) \le 1 - p, \quad \forall\, j = 1, \dots, m,$$

$$I_\alpha e^{-\alpha t_i} + I_\beta e^{-\beta t_i} \le I_{\max}, \quad \forall\, i = 1, \dots, N.$$

Process Optimization in Cup Forming

- Maximize the radius at bottom edge
  → Maximize the first principle strain
- No damage occurs
  → Constrain the damage variable in all elements

$$\begin{aligned} \min_{(I_\alpha, I_\beta, \alpha, \beta)^\top \in \mathbb{R}^4} \quad & -\sum_{j=1}^{m} \varepsilon_1^j \left(I_\alpha, I_\beta, \alpha, \beta\right), \\ \text{subject to} \quad & D_j\left(I_\alpha, I_\beta, \alpha, \beta\right) \leq 1 - p, \quad \forall\, j = 1, \dots, m, \\ & I_\alpha e^{-\alpha t_i} + I_\beta e^{-\beta t_i} \leq I_{\max}, \quad \forall\, i = 1, \dots, N. \end{aligned}$$

Process Optimization in Cup Forming

- Maximize the radius at bottom edge

  → Maximize the first principle strain
- No damage occurs

  → Constrain the damage variable in all elements
- Current must be technically reasonable

  → Constrain the current at each time step (i.e. 125 000 A)

$$\min_{(I_\alpha, I_\beta, \alpha, \beta)^\top \in \mathbb{R}^4} \quad -\sum_{j=1}^{m} \varepsilon_1^j \left(I_\alpha, I_\beta, \alpha, \beta\right),$$

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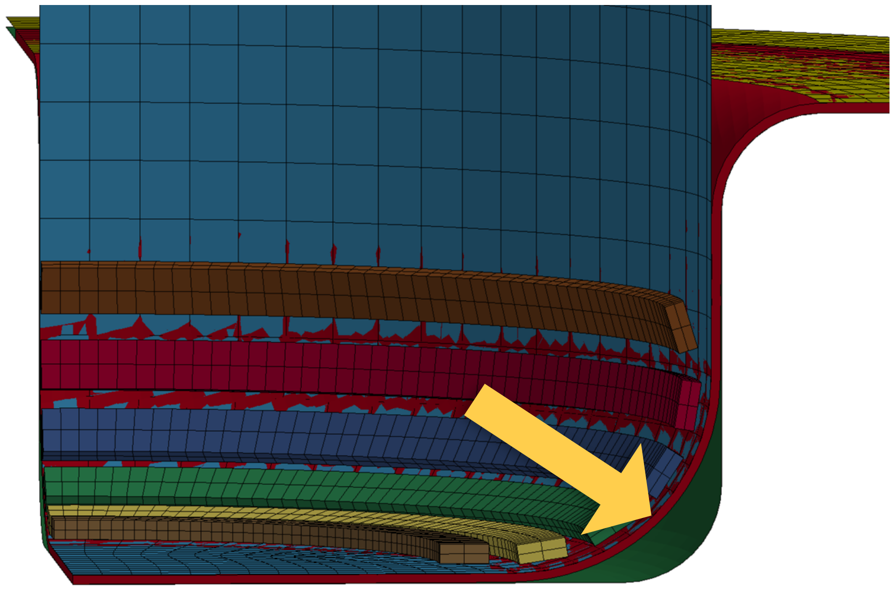
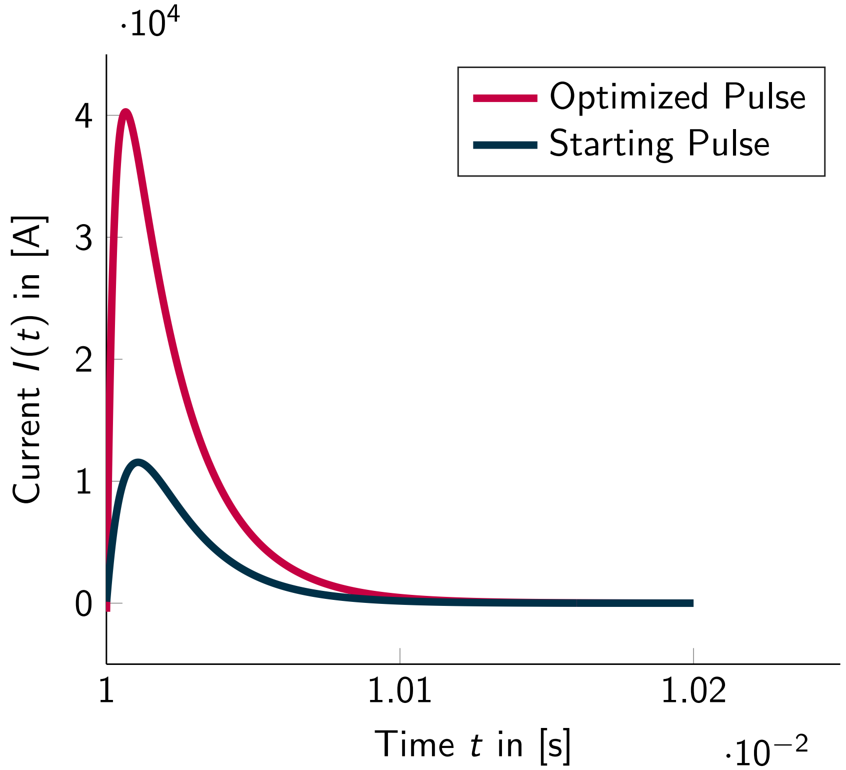
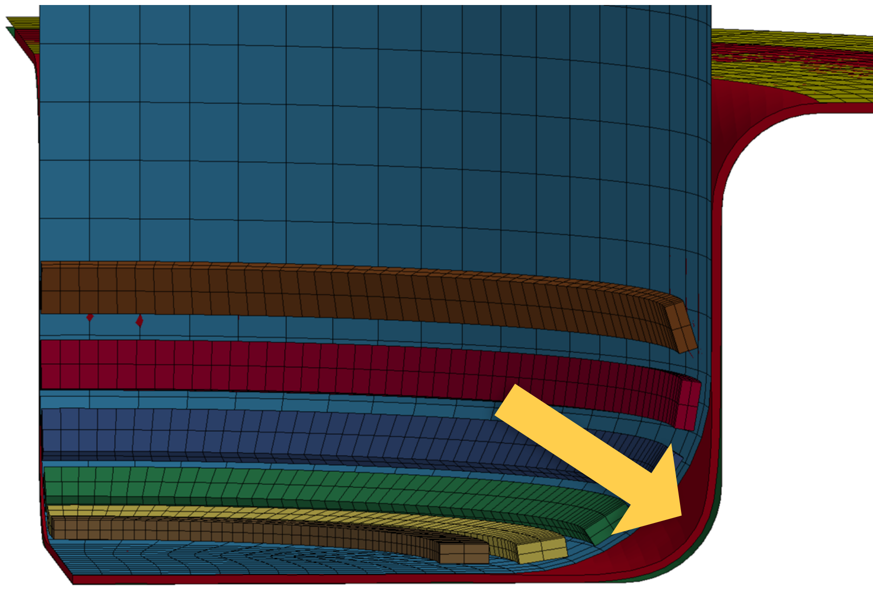
Results







$r = 20\,\text{mm}$

$d = 0.91\,\text{mm}$

$$I_\alpha = -65570.2\,\text{A}$$

$$I_\beta = 64867.8\,\text{A}$$

$$\alpha = 6878.78$$

$$\beta = 973.021$$

$r = 15.35\,\text{mm}$

$d = 0.85\,\text{mm}$

Conclusion & Outlook

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➡ Verification of computed process parameters by experiments

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✓ Linearization based scheme for process parameter identification

- First steps have been taken, but:

➡ Verification of computed process parameters by experiments

➡ Taking into account more process parameters at the same time, control of quasi-static part and electromagnetic part simultaneously

Special thanks to:

Institute for Forming Technology and
Lightweight Construction
(Dortmund University of Technology)

Institute for Materials Research
(Leibniz University Hannover)

Department of the Theory of Electrical Engineering
(Helmut Schmidt University Hamburg)

Institute for Applied Mechanics
(RWTH Aachen)