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Design of new technologies for the numerical simulation of combined quasi-static dynamic forming processes

Y. Kiliclar, I. N. Vladimirov, S. Wulfinghoff & S. Reese

A. Motivation
B. Material modelling
C. Parameter identification
D. Validation
E. Conclusion/Outlook

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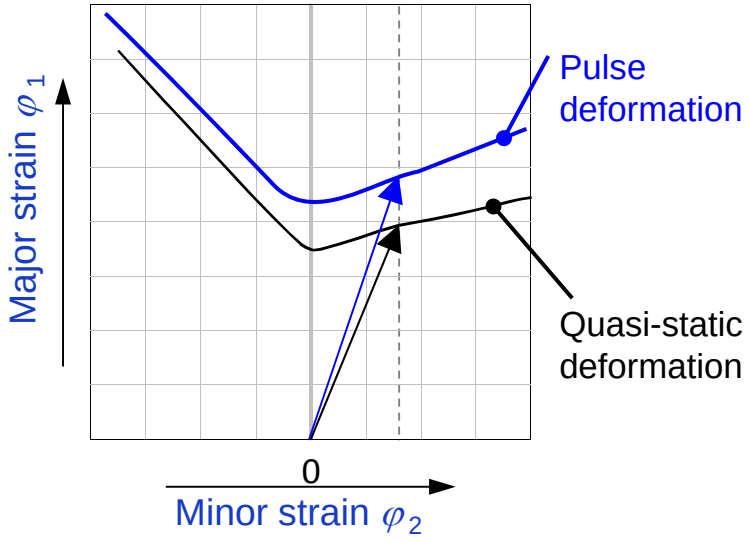
Motivation

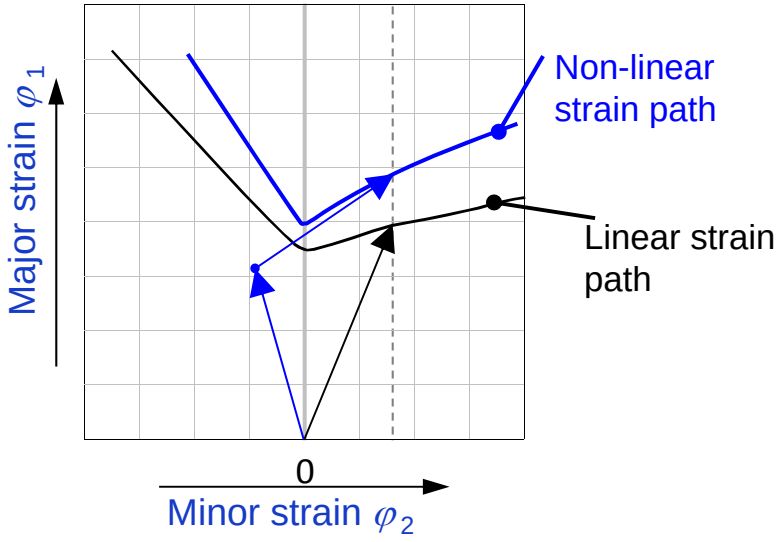
High **strain rate** (pulse forming) can shift the forming limit

Forming limit diagram (linear strain path)

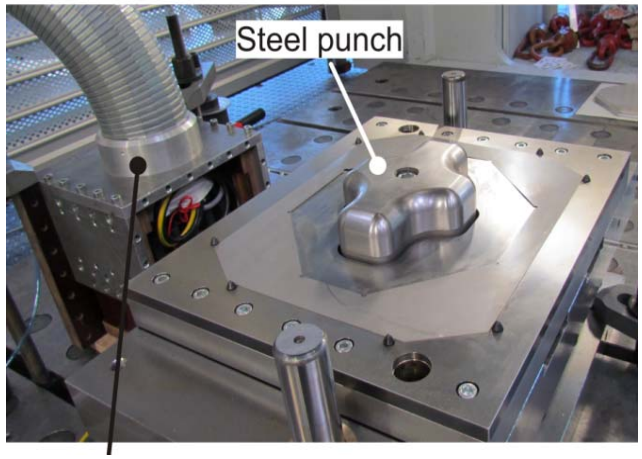


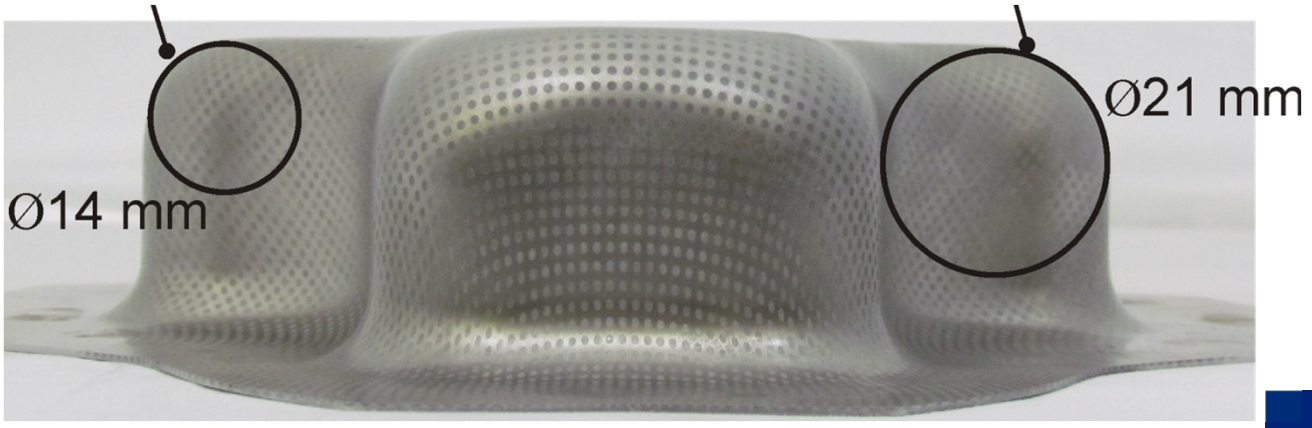
Change in the **strain path** can shift the forming limit

Forming limit diagram (quasi-static forming process)



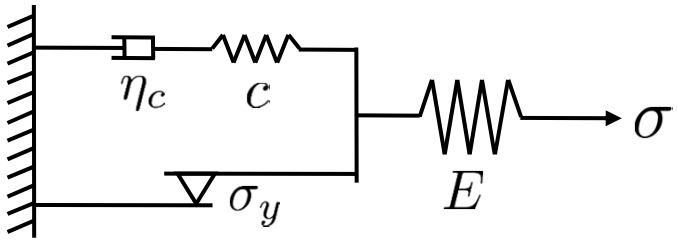
Combined QS-HS forming process





Rheological model

- Starting point:
  Elastoplasticity with nonlinear isotropic / kinematic hardening
  („pseudo viscosity“)

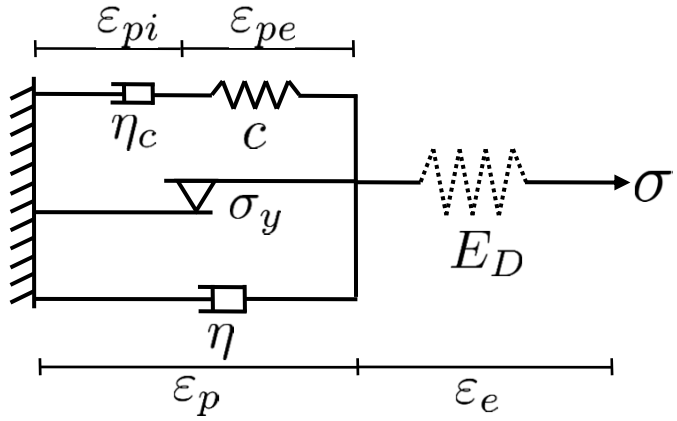


- Rate-independent:

$$\text{“}\eta_c\text{”} = \frac{c}{\dot{\lambda}\, b}$$

Vladimirov et al. 2008
Dettmer & Reese 2004

- Model extension:
  Damage coupled viscoplasticity with nonlinear isotropic / kinematic hardening



- Effective stress:

$$\widetilde{\sigma} = \frac{\sigma}{1-D} = E\,\varepsilon_e$$

$$E_D = E\,(1-D)$$

Rabotnov 1968

- Rate-dependent:

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

multiplicative split:

$$\mathbf{F} = \mathbf{F}_e\,\mathbf{F}_p,\;\; \mathbf{F}_p = \mathbf{F}_{p_e}\,\mathbf{F}_{p_i}$$

Lion 2000

Helmholtz free energy:

kinematic hardening

$$\psi = \psi_e(\mathbf{C}_e) + \psi_{kin}(\mathbf{C}_{p_e}) + \psi_{iso}(\kappa)$$

isotropic hardening

$$\mathbf{C}_e = \mathbf{F}_e^T\mathbf{F}_e = \mathbf{F}_p^{-T}\mathbf{C}\mathbf{F}_p^{-1},\;\; \mathbf{C}_{p_e} = \mathbf{F}_{p_e}^T\mathbf{F}_{p_e} = \mathbf{F}_{p_i}^{-T}\mathbf{C}_p\mathbf{F}_{p_i}^{-1}$$

Clausius-Duhem inequality (isothermal processes):

$$-\dot{\psi} + \mathbf{S}\cdot\frac{1}{2}\dot{\mathbf{C}} \geq 0$$

$$(\mathbf{S} - 2\mathbf{F}_p^{-1}\frac{\partial\psi_e}{\partial\mathbf{C}_e}\mathbf{F}_p^{-T})\cdot\frac{1}{2}\dot{\mathbf{C}} + \underbrace{(\mathbf{M} - \boldsymbol{\chi})}_{:=\boldsymbol{\Sigma}}\cdot\mathbf{d}_p + \mathbf{M}_{kin}\cdot\mathbf{d}_{p_i} + R\,\dot{\kappa} + Y\,\dot{D} \geq 0$$

Evolution equations

$$\mathbf{d}_p = \dot{\lambda}\,\frac{\partial \Phi}{\partial \boldsymbol{\Sigma}}$$

plastic flow rule

Vladimirov et al. 2011

symmetric internal variables!

$$\mathbf{d}_{p_i} = \dot{\lambda}\,\frac{b}{c}\,\mathbf{M}^D_{kin}$$

kinematic hardening

$$\dot{\kappa} = \dot{\lambda}\,\frac{\partial \Phi}{\partial R},\quad R = -Q\,(1 - e^{-\beta\,\kappa})$$

isotropic hardening

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

damage Lemaitre (1992)

$$\Phi = \sqrt{\boldsymbol{\Sigma}^D \cdot (\widetilde{A}[\boldsymbol{\Sigma}^D])} - \sqrt{\tfrac{2}{3}}\,(\sigma_y - R)$$

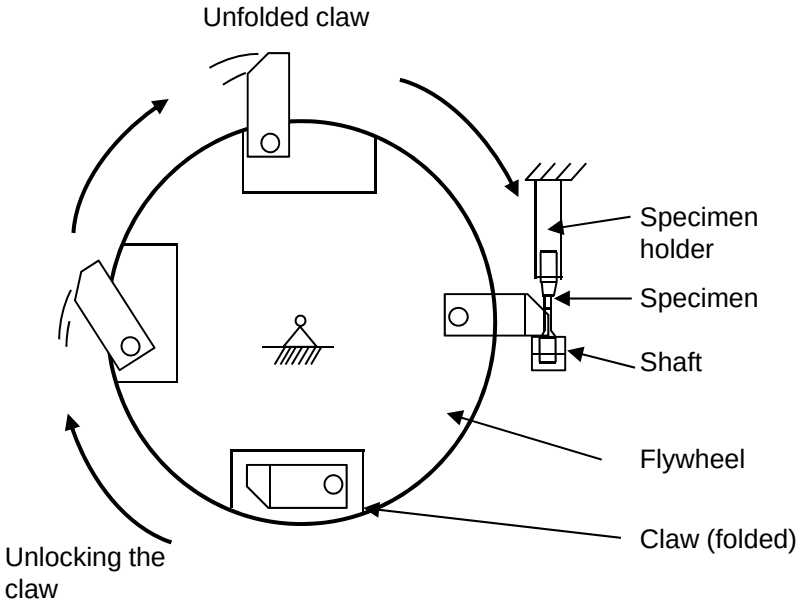
yield function (anisotropy)

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

Perzyna formulation

Pull-back to reference configuration!

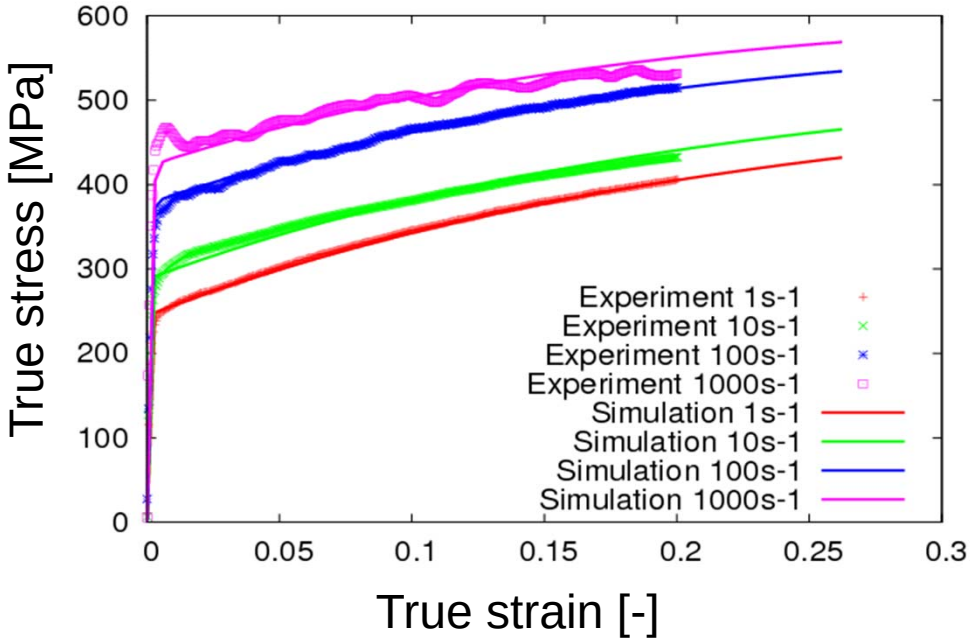
Application of material model



Experimental setup for determining the flow curves for varying strain rates

[Nordmetall]

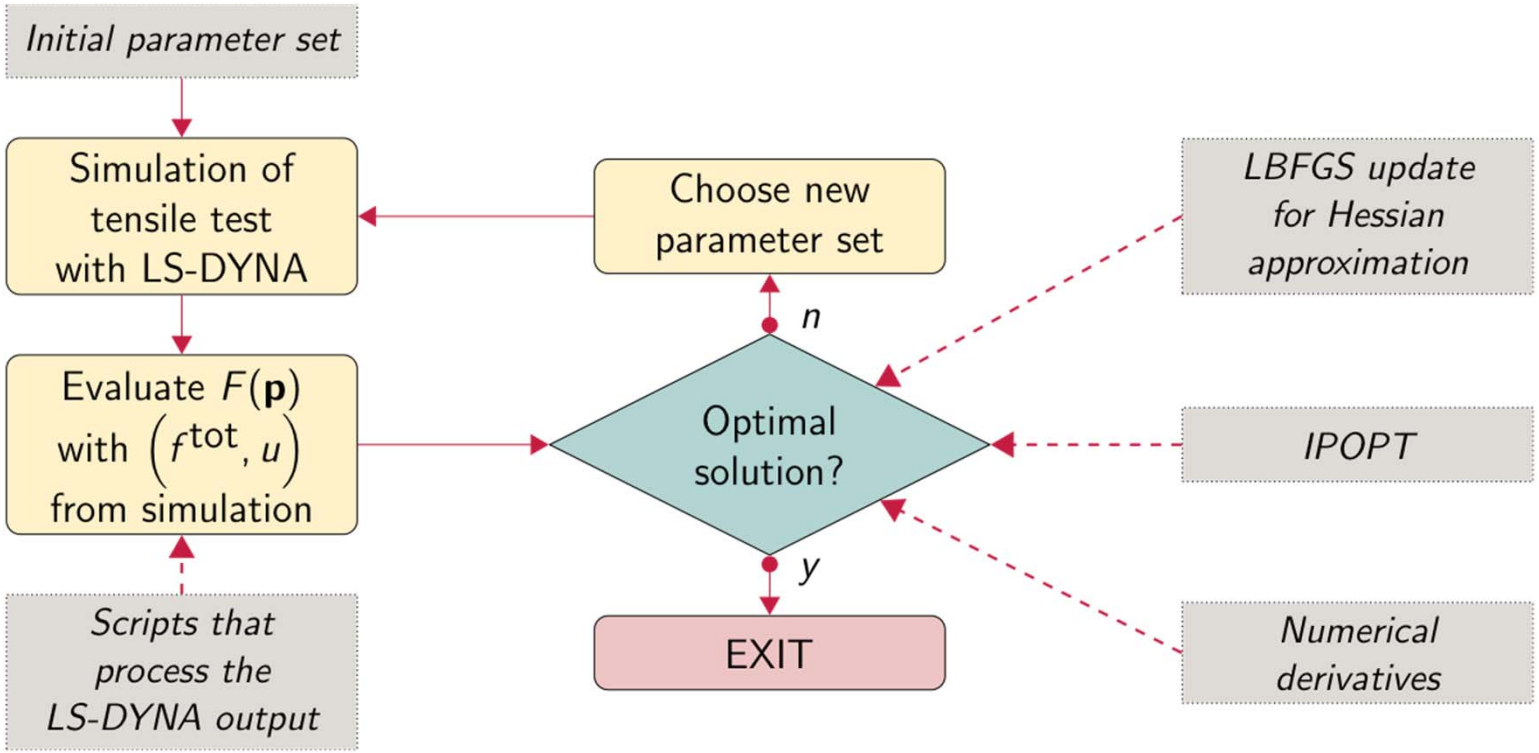
Flow curves for varying strain rates



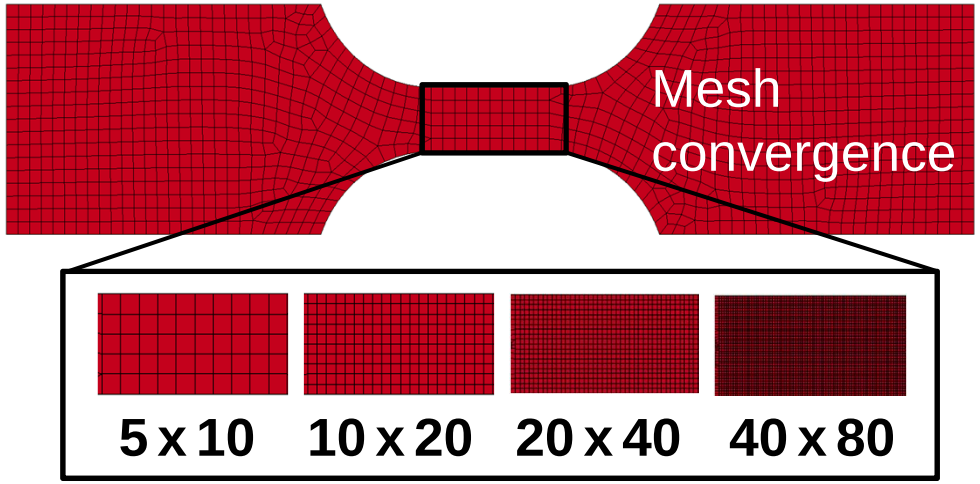
Identification by non-linear optimization

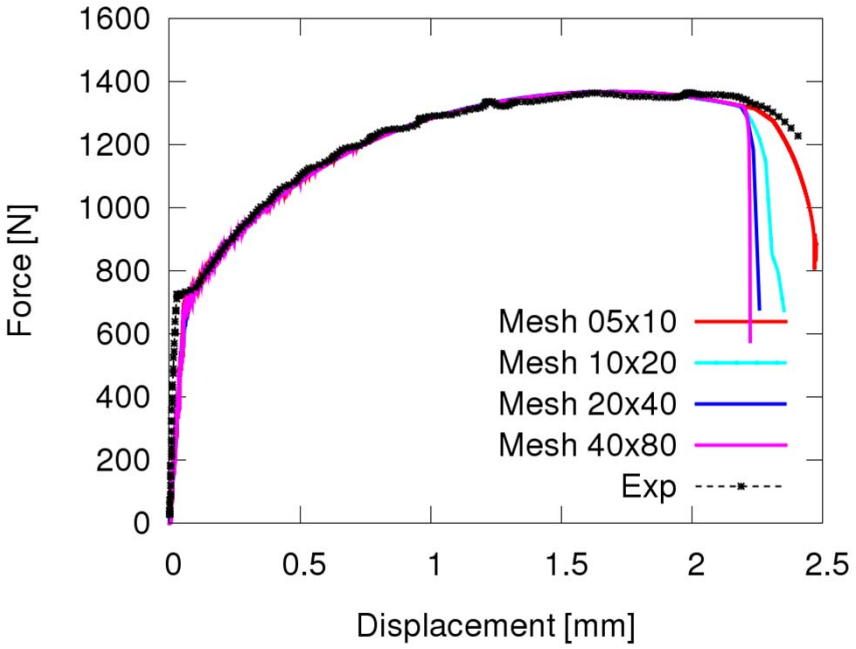
- Parameter identification based on experimental data
- Non-linear objective function to identify optimal parameter vector **p**

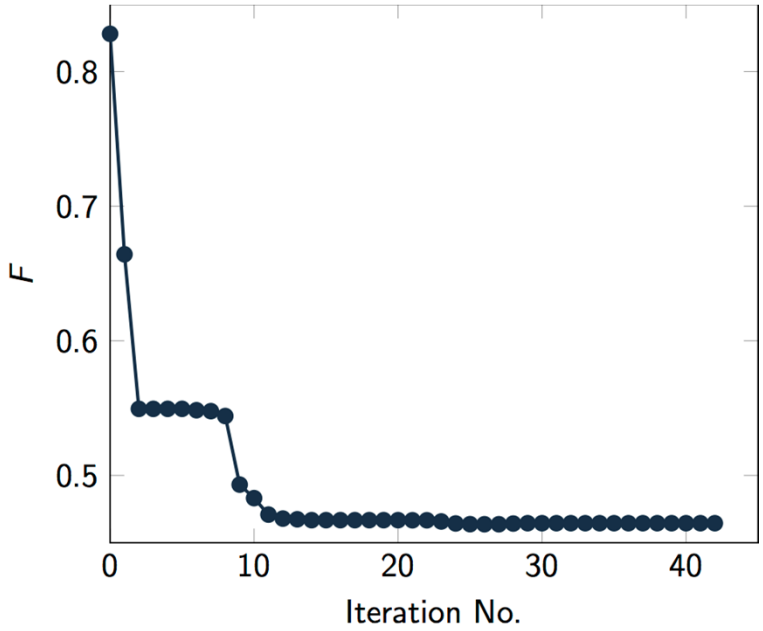
$$F(\mathbf{p}) = \frac{1}{2N} \sum_{i=1}^{N-1} (u_{i+1} - u_i)[(f_{i+1}^{tot}(\mathbf{p}) - \tilde{f}_{i+1}^{tot})^2 + (f_i^{tot}(\mathbf{p}) - \tilde{f}_i^{tot})^2]$$



Fitting on force-displacement information







- Optimization by IPOPT works fine
- Good matching of experiment and simulation
- Localization problem

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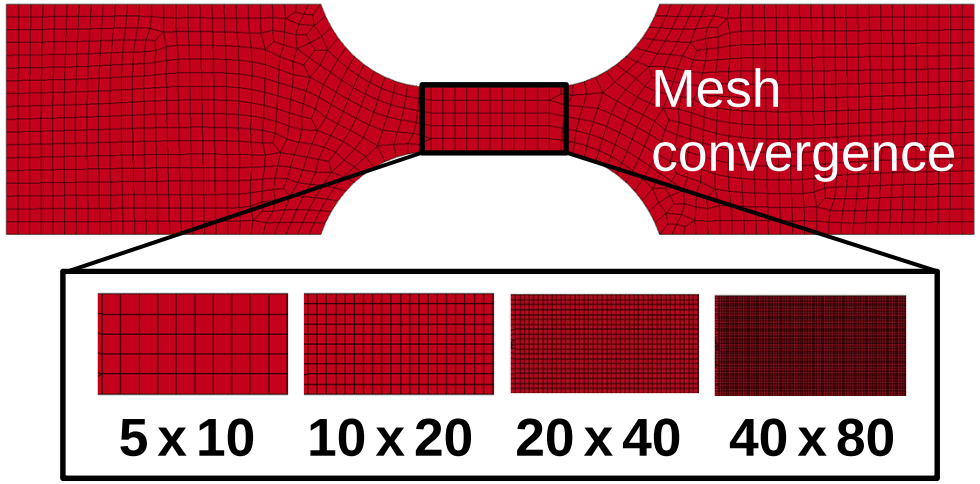
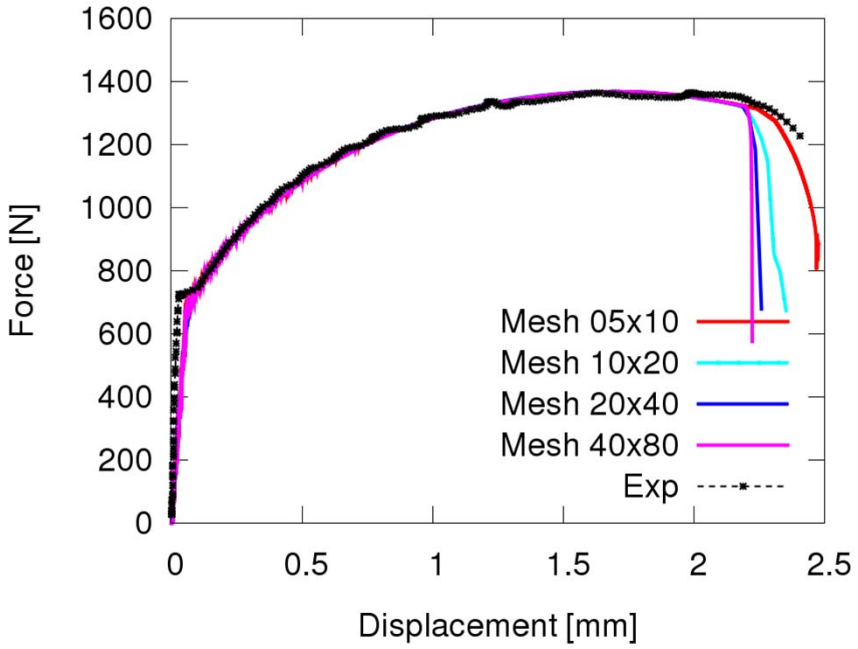
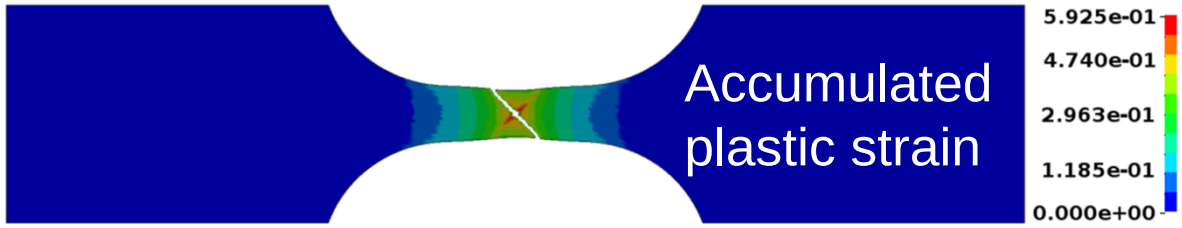
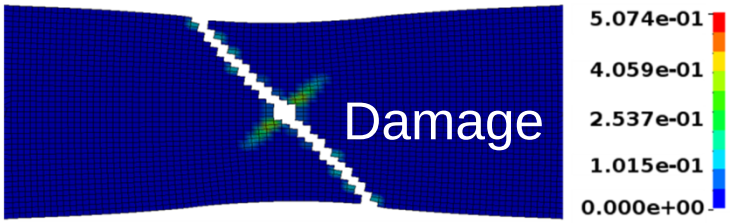
Fitting on force-displacement information









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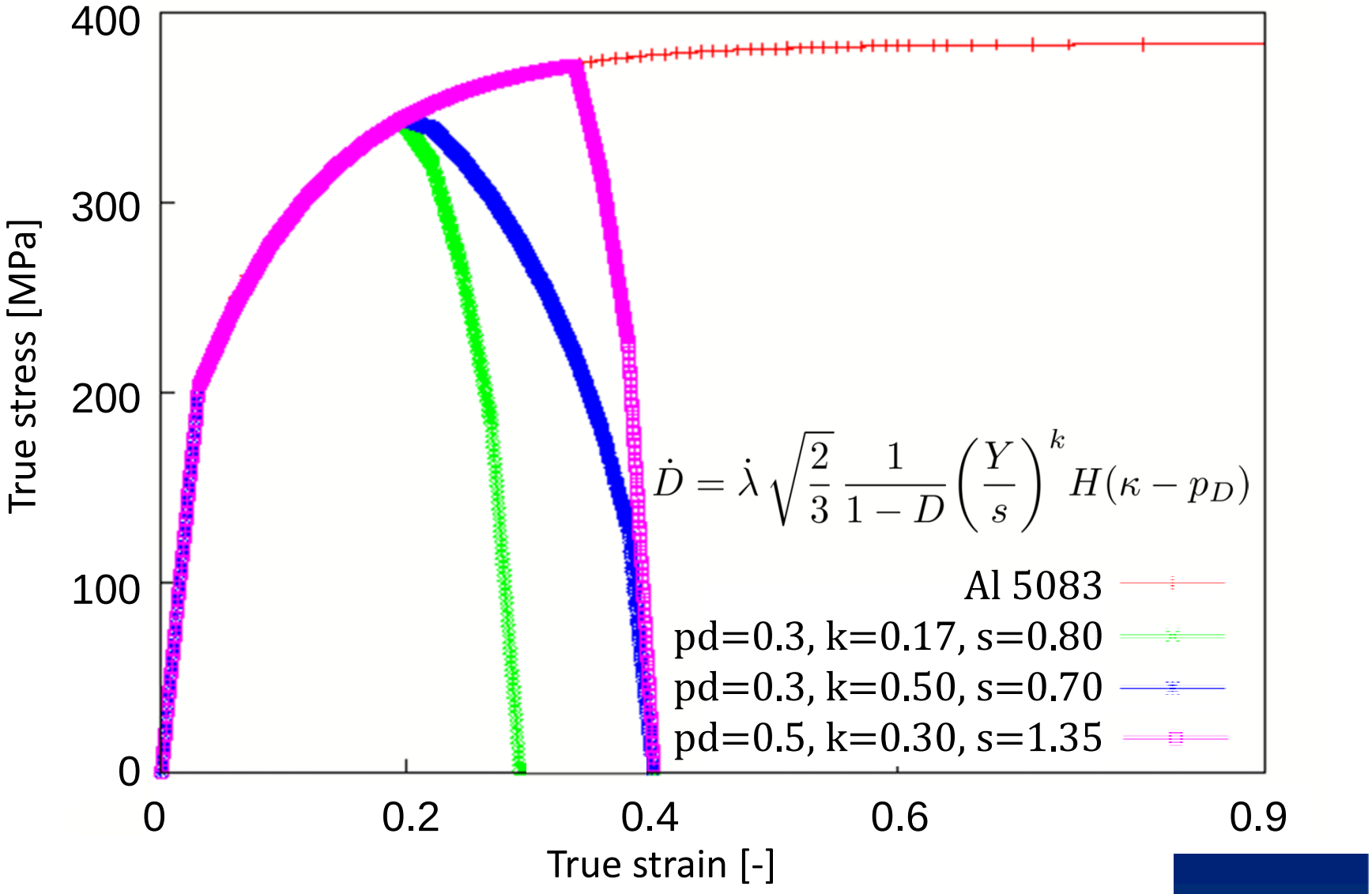
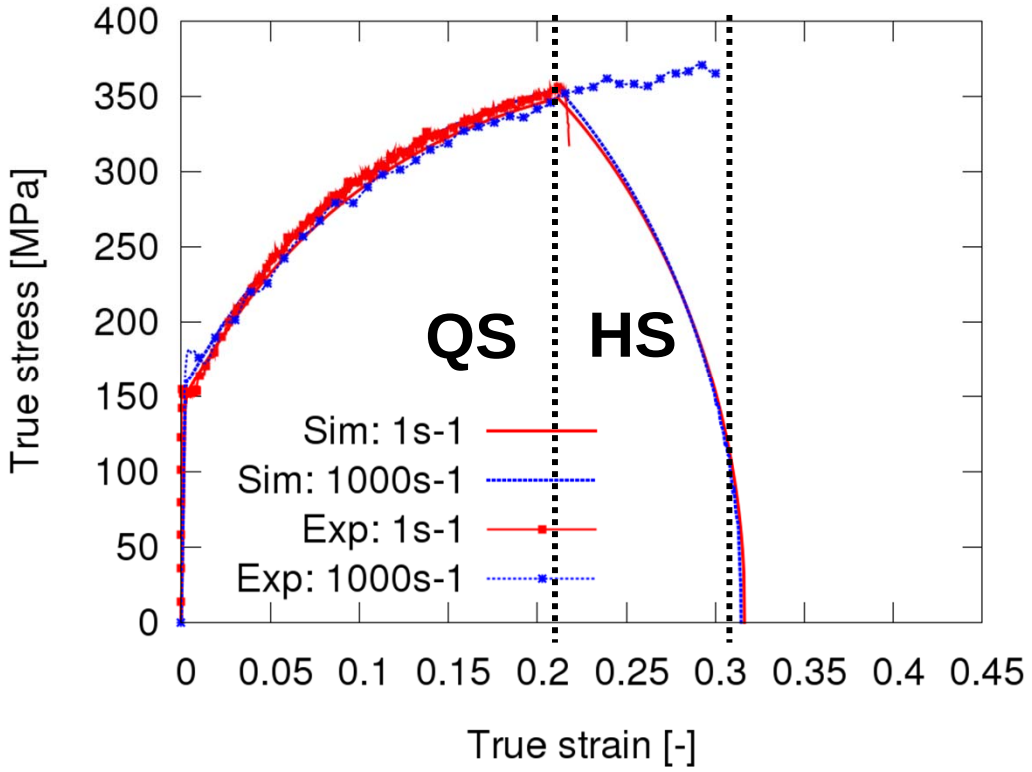
Numerical investigation on damage

Kiliclar et al. 2012

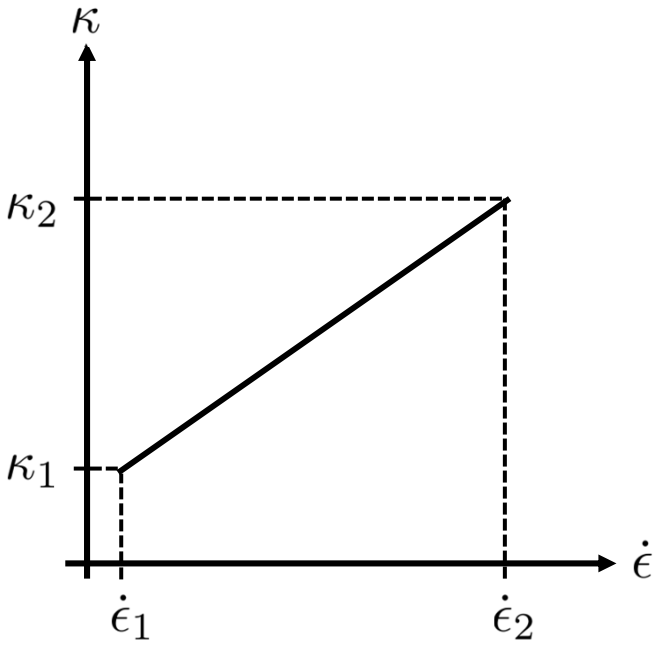


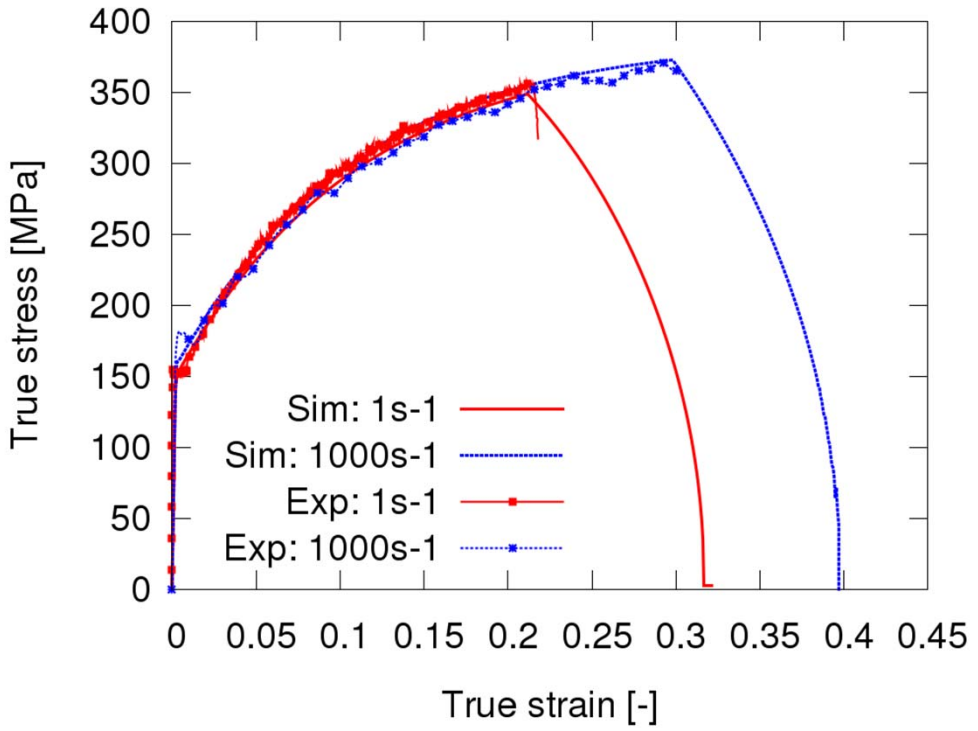
Parameter fitting on uniaxial tensile test

- Aluminum EN 5083
- Negligible strain rate sensitivity by means of higher stress level
- Higher formability with increasing strain rate



Extension of damage model

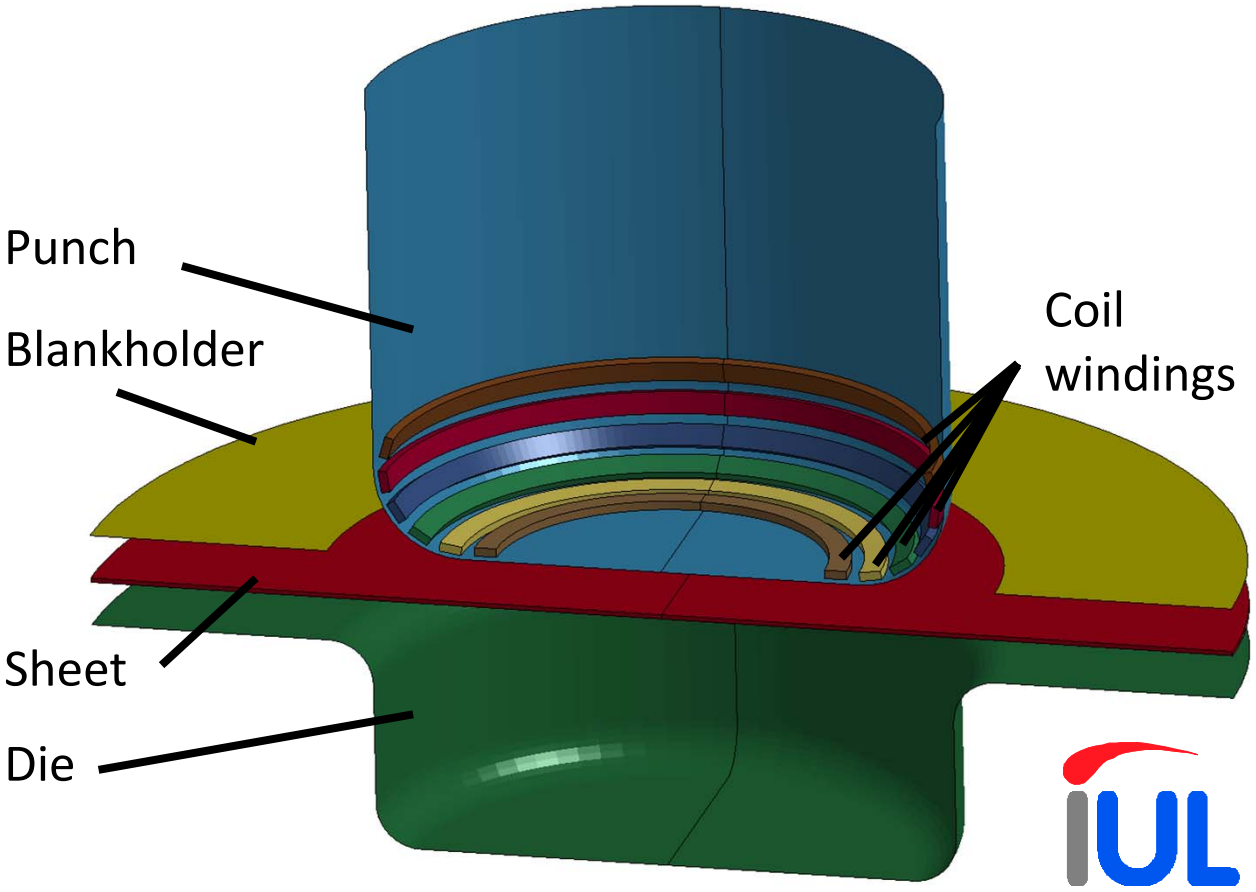




$$p_D = \kappa_1 + \frac{\kappa_2 - \kappa_1}{\dot{\epsilon}_2 - \dot{\epsilon}_1}\left(\dot{\epsilon} - \dot{\epsilon}_1\right)$$

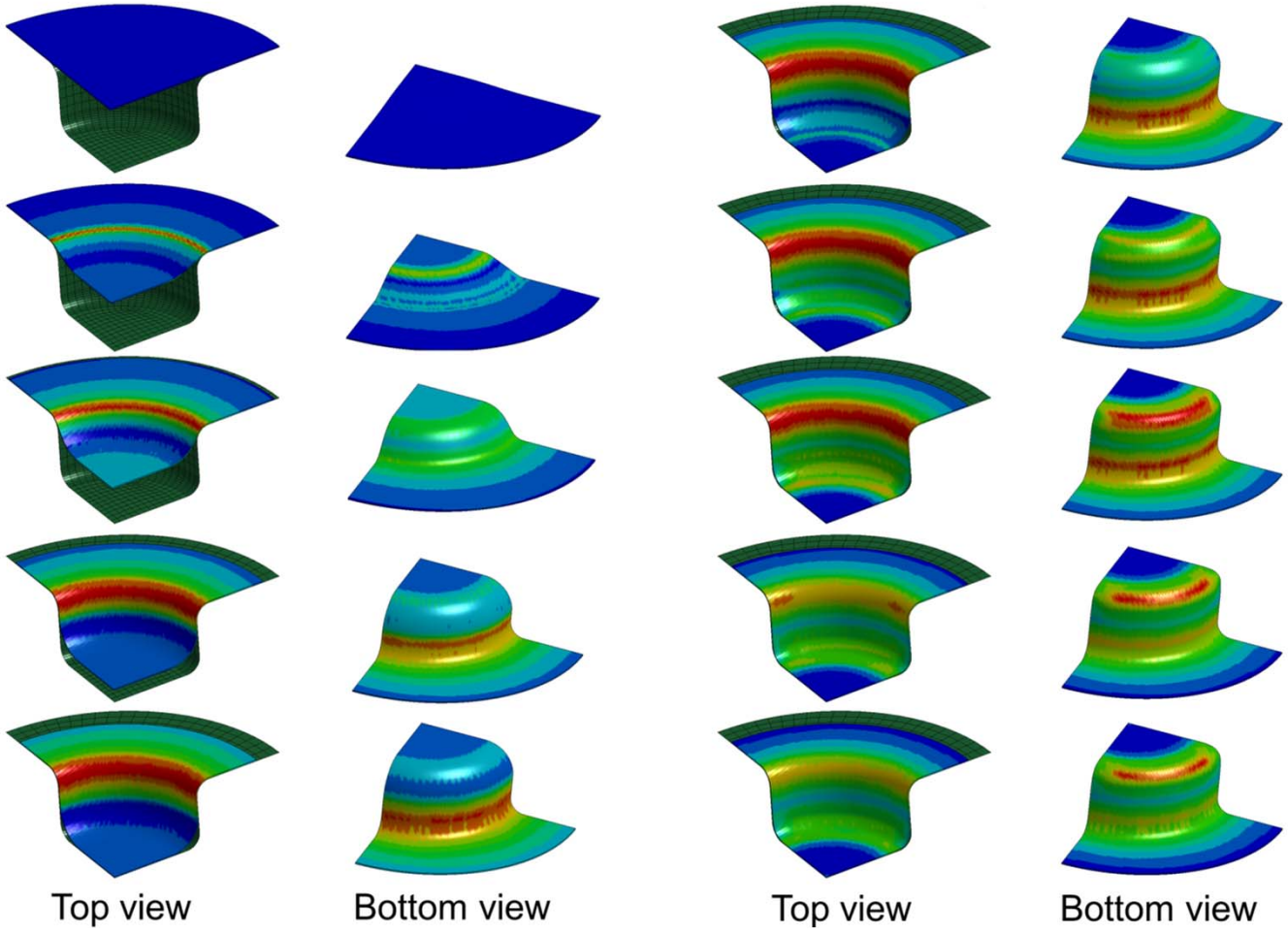
- Rate dependent (linear) damage threshold
- Damage initiation is shifted

Combined forming of a round cup



- Full coupled quasi-static and electromagnetic forming process

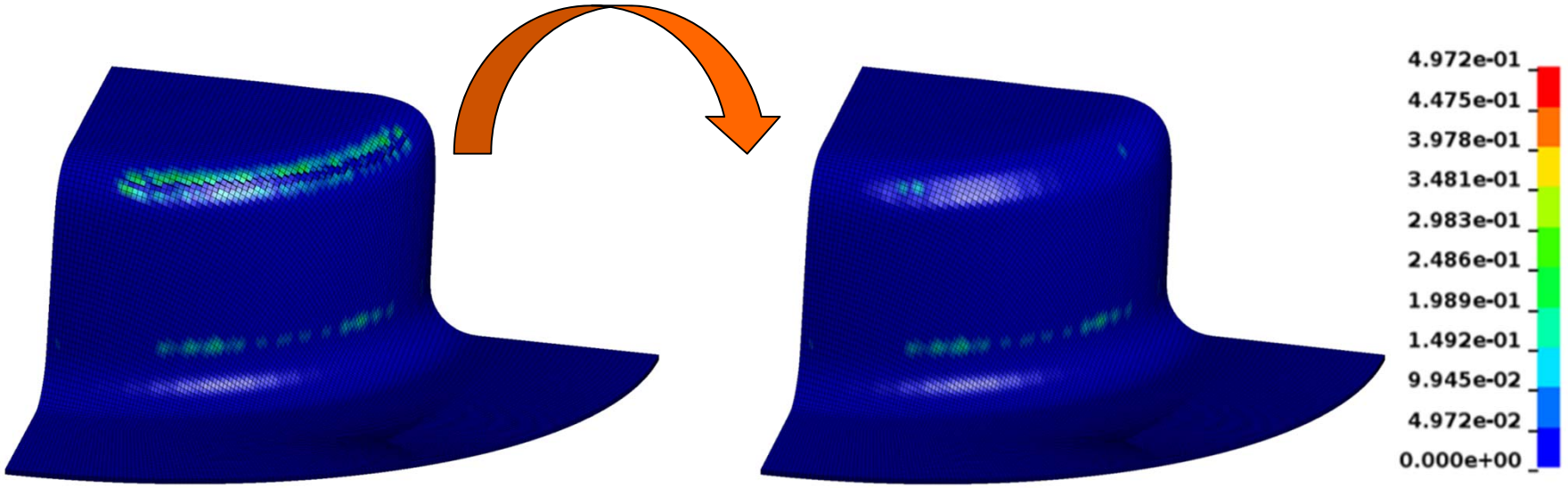
Evolution of combined forming



- Critical zone is in upper flange while deep drawing
- Critical zone moves to bottom radius while EM forming

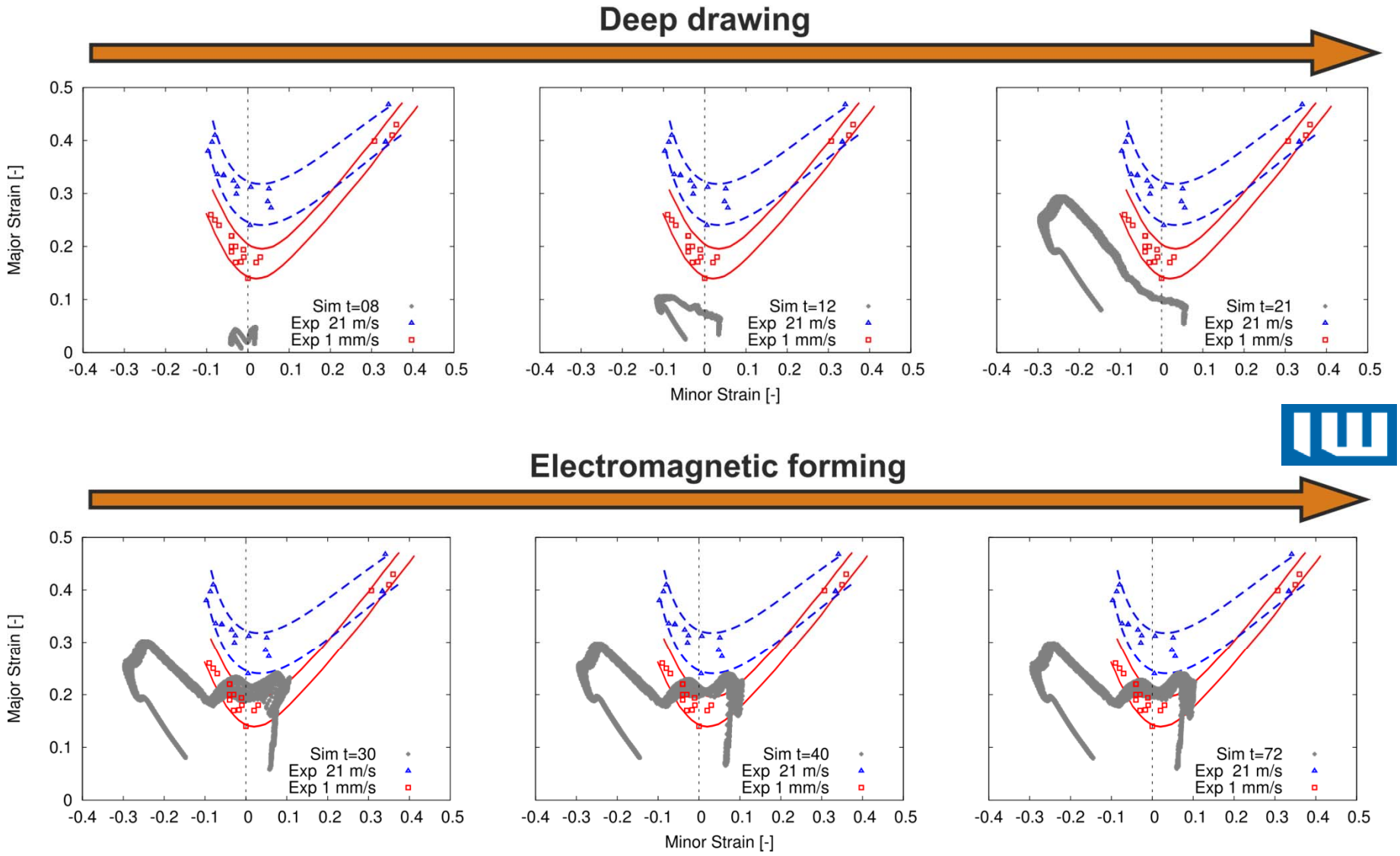
Damage distribution for round cup

Extension of damage model



- “Crack” occurs during EM forming
- No further forming process is possible
- Damage continue evolving but do not lead to failure
- Good agreement with experiments

Evolution of FLD



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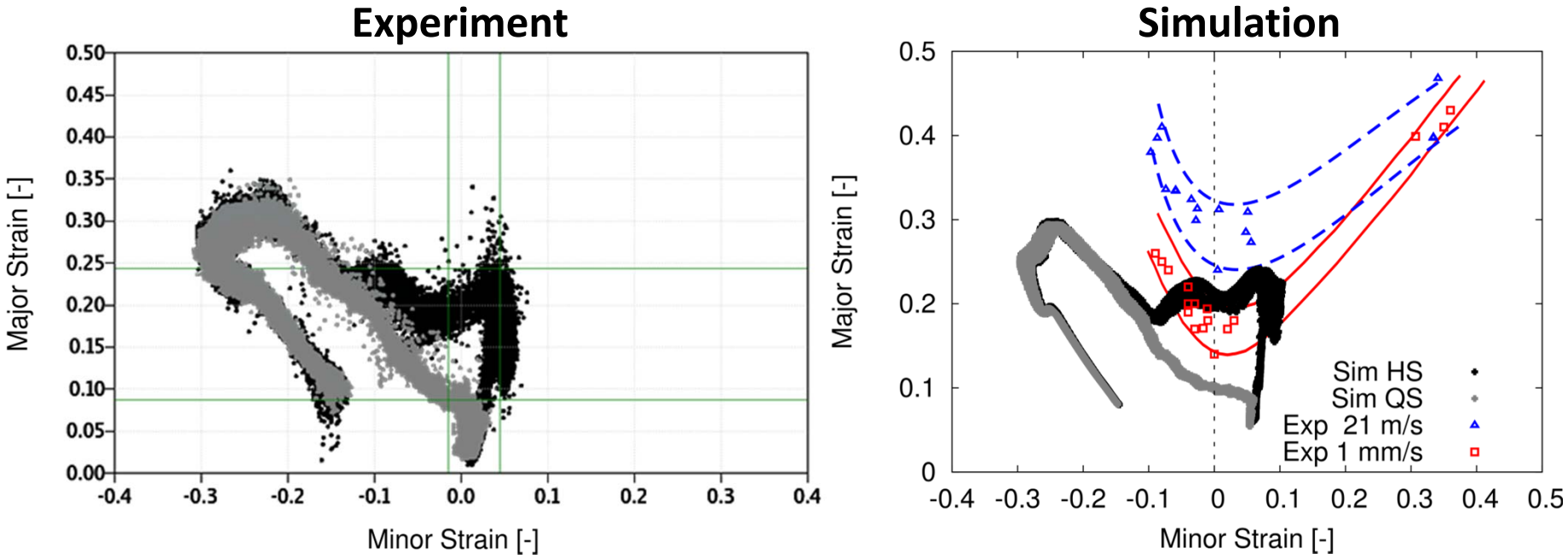
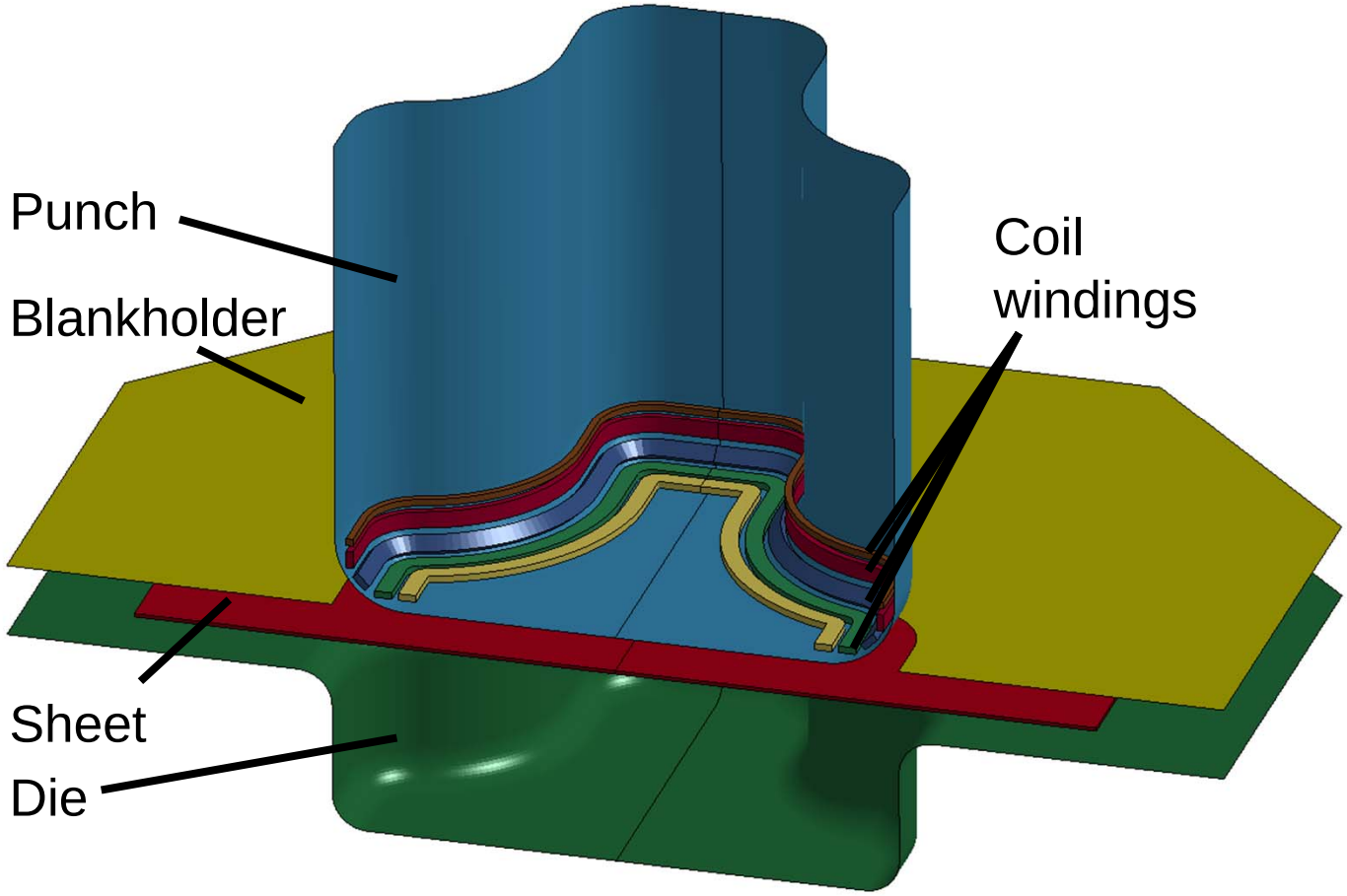
FLD: Simulation vs. experiment



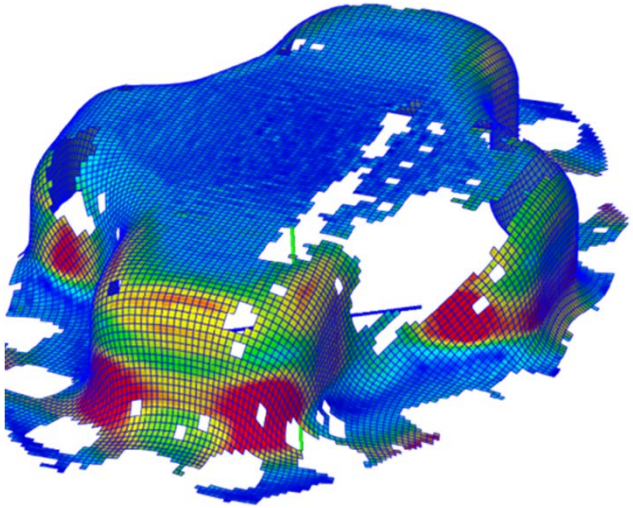
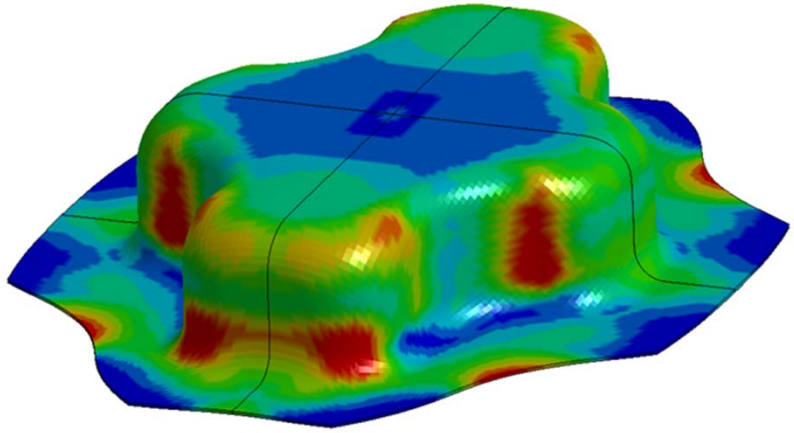
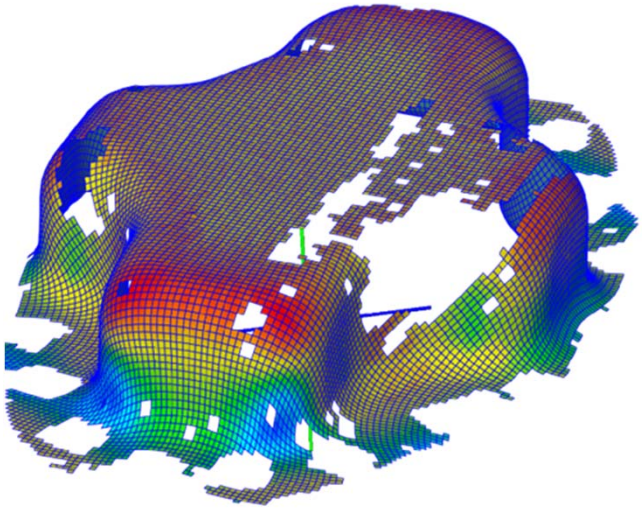
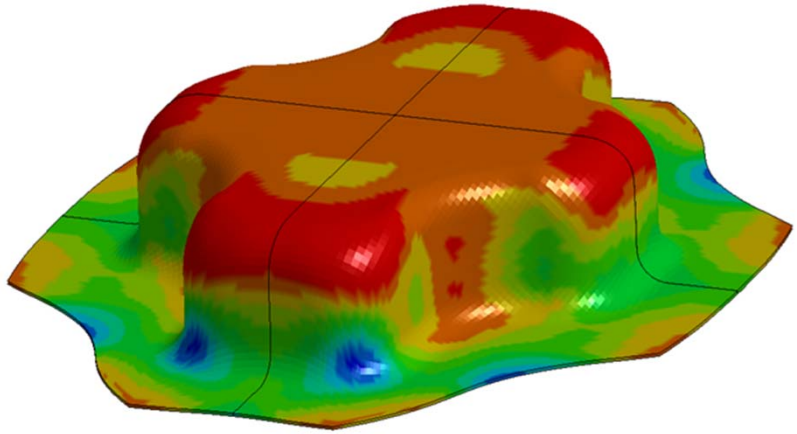
Kiliclar et al. 2015

- Strain ratio exceeds QS-FLC during high-speed forming
- Good prediction of the overall material behavior
- Quantitatively good agreement with experimental result

Combined forming of a cross die

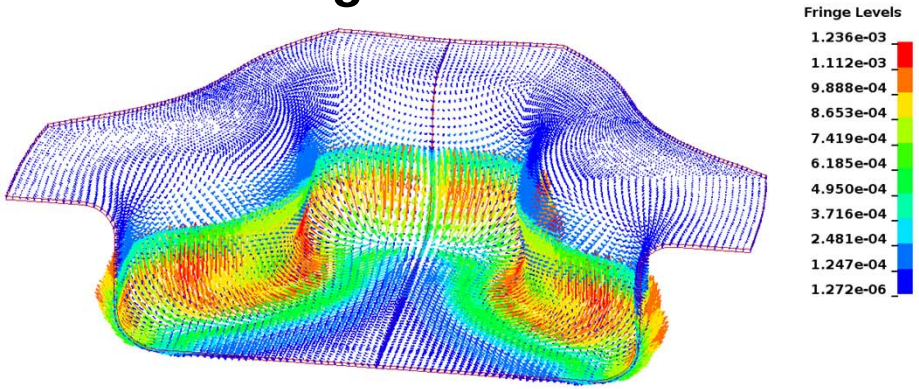


Comparison for cross die

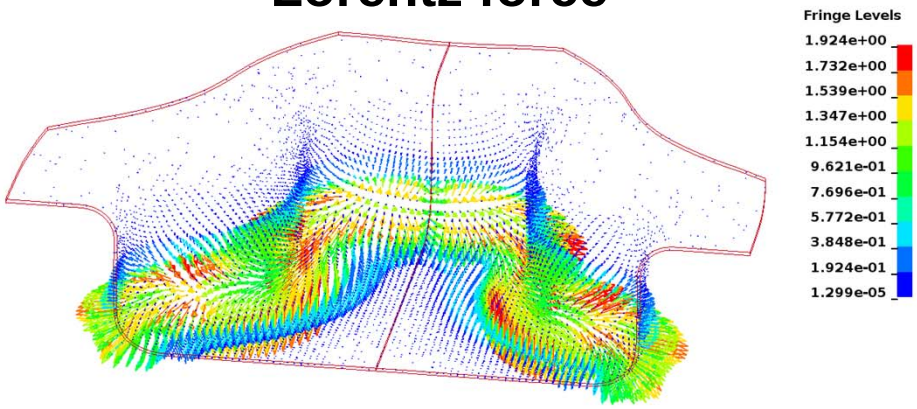
	Experiment	Simulation
Major strain		
Minor strain		

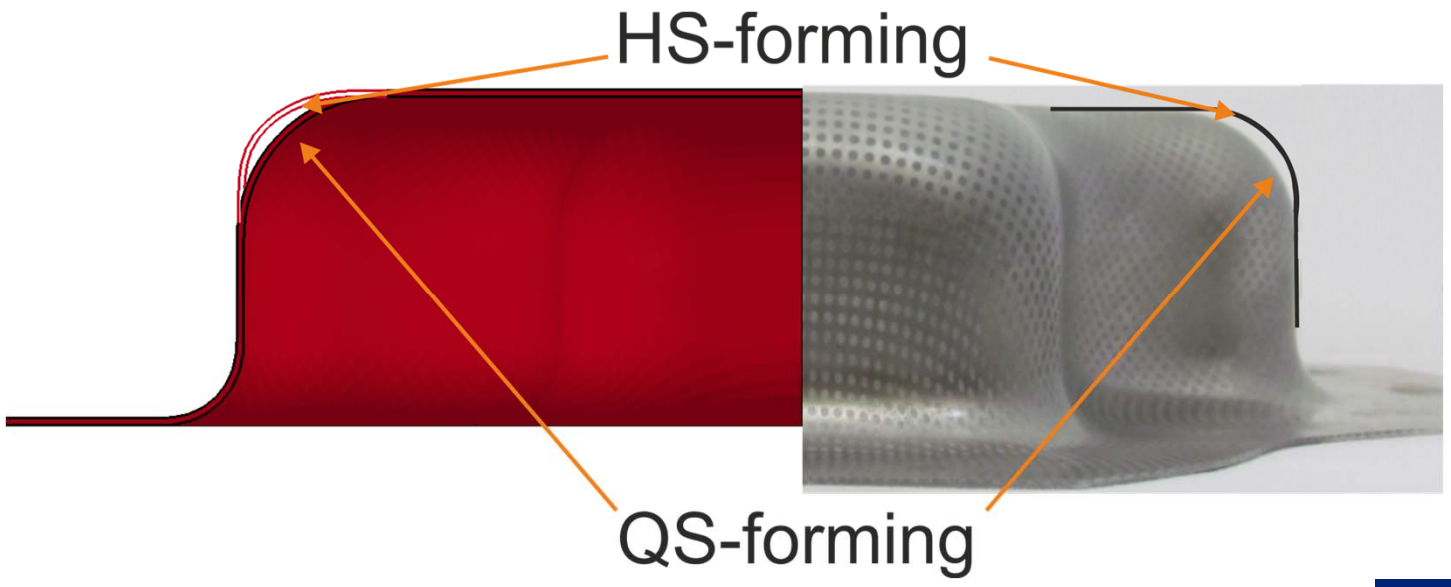
Acting mechanisms

Magnetic field

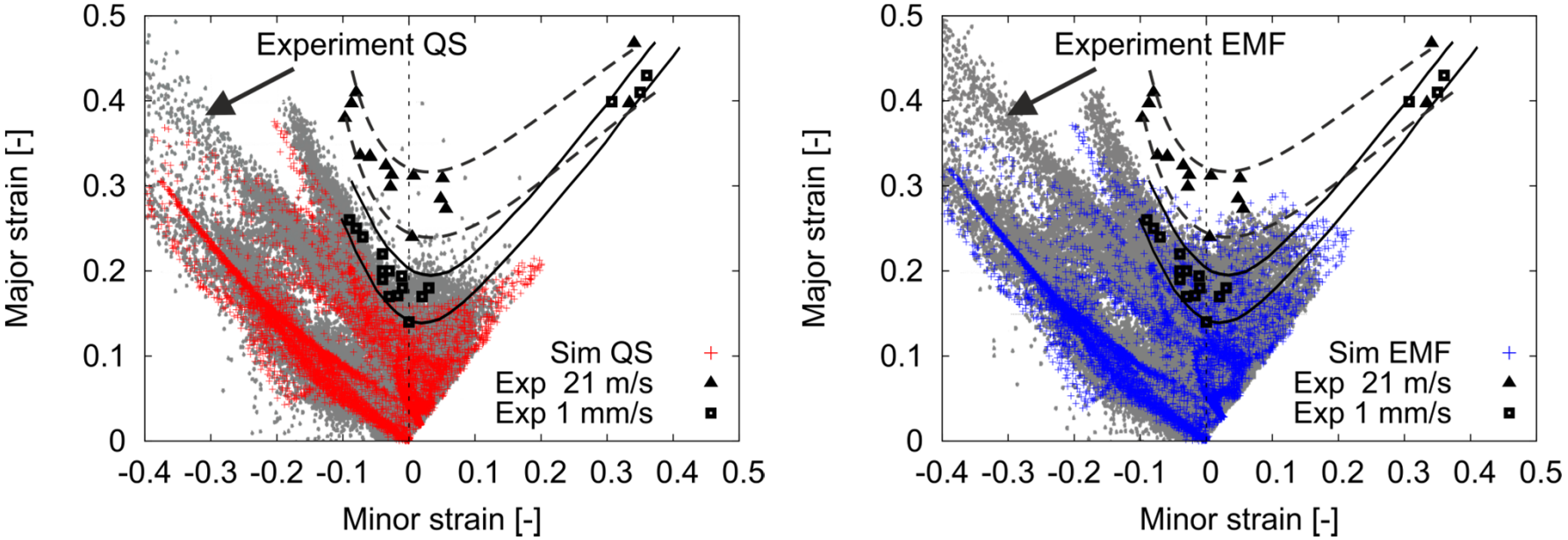


Lorentz force





FLD: Simulation vs. experiment



Kiliclar et al. 2015

- Strain ratio exceeds QS-FLD during high-speed forming
- Good prediction of the overall material behavior
- Qualitatively similarly to results of cylindrical cup

Conclusions & outlook

- Introduction of a framework for virtual process design in the context of combined quasi-static and electromagnetic impulse forming, featuring:

✓ Suitable material model

✓ Automatic parameter fitting based on experimental tensile tests

✓ Good agreement between simulation and experiment

✓ Realistic prediction regarding the combined forming processes

- First steps are taken, but:

➡ Nonlocal formulations & anisotropic damage are current research tasks

Thank you for your attention