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Ein Unternehmen der Salzgitter Gruppe

Analysis of stress states during experimental determination of cut-edge formability

Bamberg, 15th October 2018

Matthias Schneider, Matti Teschner, Sebastian Westhäuser

Agenda

Introduction

Formability of cut-edges

- Experimental determination
- Effects on hole expansion ratio

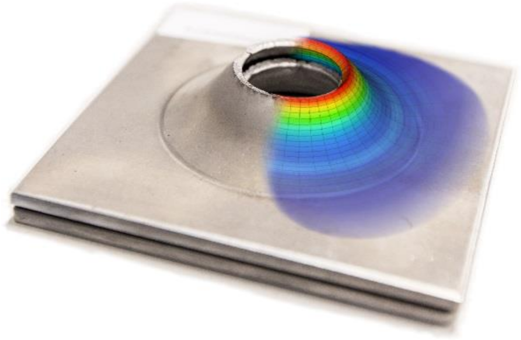
Numerical simulation

- FE-model structure
- Fitting and validation of hardening behavior

Stress analysis

- Procedure for determining
- Visualization and comparison of the occurring stress conditions

Summary, conclusion and outlook



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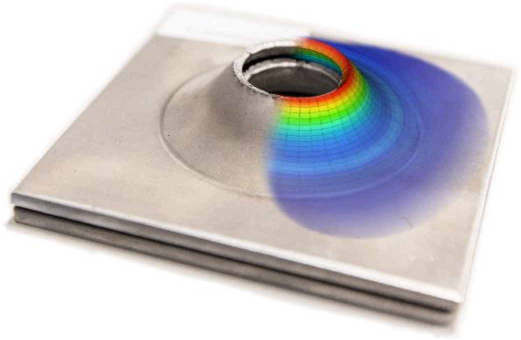
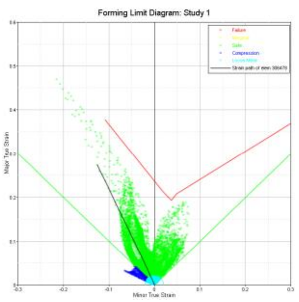


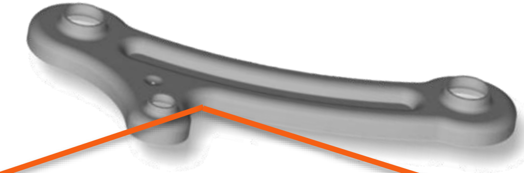
Introduction - Experimental determination of formability

State of the art: Forming Limit Curve (FLC)

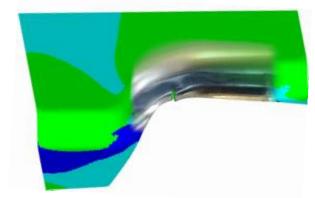
FLD of num. simulation



Positive feasibility assessment by means of FLC



Real component



But failure at cut-edges of real component

FLC not sufficient for components with shear cut-edges

- Additional tests to determine cut-edge formability
- Numerous experimental approaches published
- Results differ

[Sch15]

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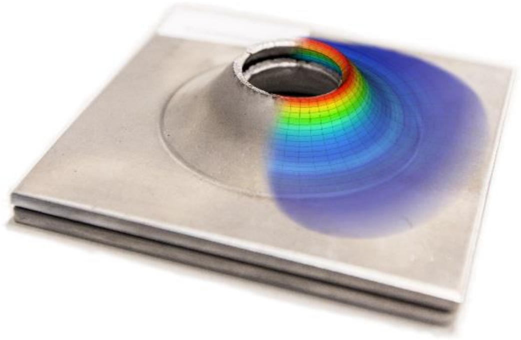

Hole expanding test (HET) with conical punch acc. to ISO 16630

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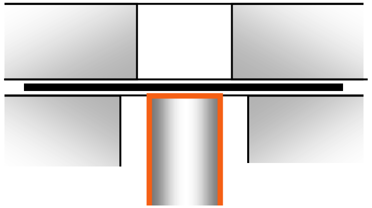
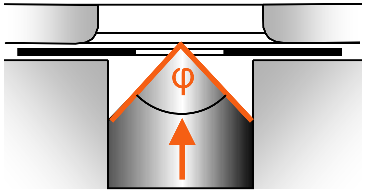
1. Cutting

- Thickness: 1.2 mm to 6.0 mm
- Sample: 90 mm x 90 mm
- Cutting punch: Ø 10 mm
- Cutting clearance: 12 %



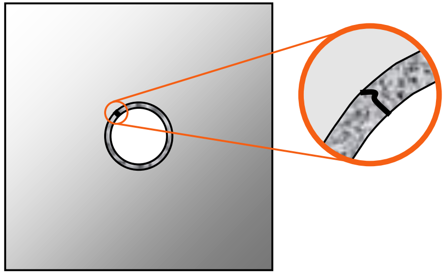
2. Forming

- Conical punch φ = 60°
- Punch velocity ≤ 1.0 mm/s



3. Stop-criterion

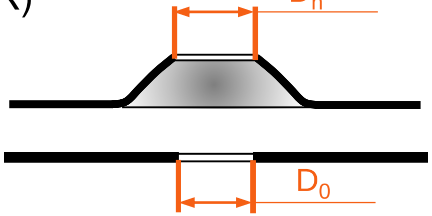
- Visual inspection: first crack through thickness



4. Evaluation

- Hole expansion ratio λ (HER)

$$\lambda = \frac{D_h - D_0}{D_0} \cdot 100$$

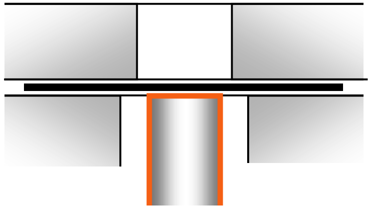


[ISO 08]

Hole expanding test (HET) with hemispherical punch acc. to Schneider

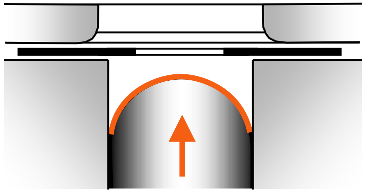
1. Cutting

- Sample: 200 mm x 200 mm
- Cutting punch: Ø 20 mm
- Cutting clearance: 12 %



2. Forming

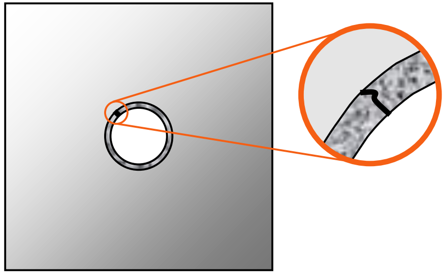
- Ø 100 mm Nakajima-Punch according to ISO 12004-2



[ISO 08]

3. Stop-criterion

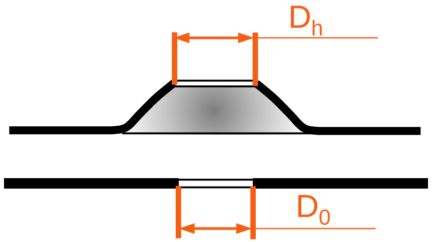
- Visible crack
- More abrupt crack compared to ISO 16630



4. Evaluation

- Hole expansion ratio λ according to ISO 16630
- Crack width correction
- Strain analysis

$$\lambda = \frac{D_h - D_0}{D_0} \cdot 100$$



[Sch16]

Hole tensile test acc. to Watanabe and Tachibana

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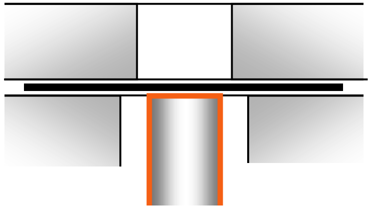
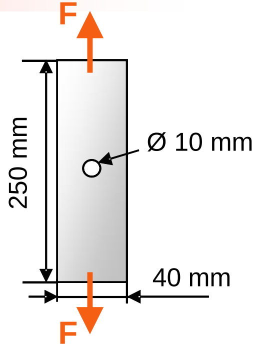
1. Cutting

- Sample: 250 mm x 40 mm
- Cutting punch: Ø 10 mm
- Cutting clearance: 12 %



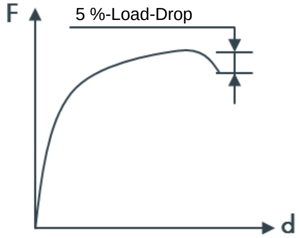
2. Forming

- Tensile test with constant velocity of 10 mm/min



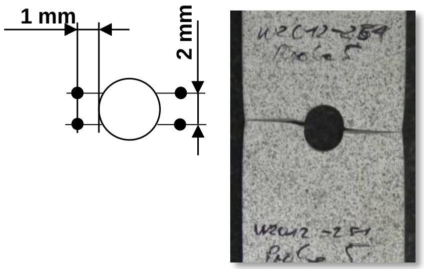
3. Stop-criterion

- Automatic stop at 5 % load-drop



4. Evaluation

- Determination of major strain based on displacement of two points



[Wat06]

Effects on cut-edge formability

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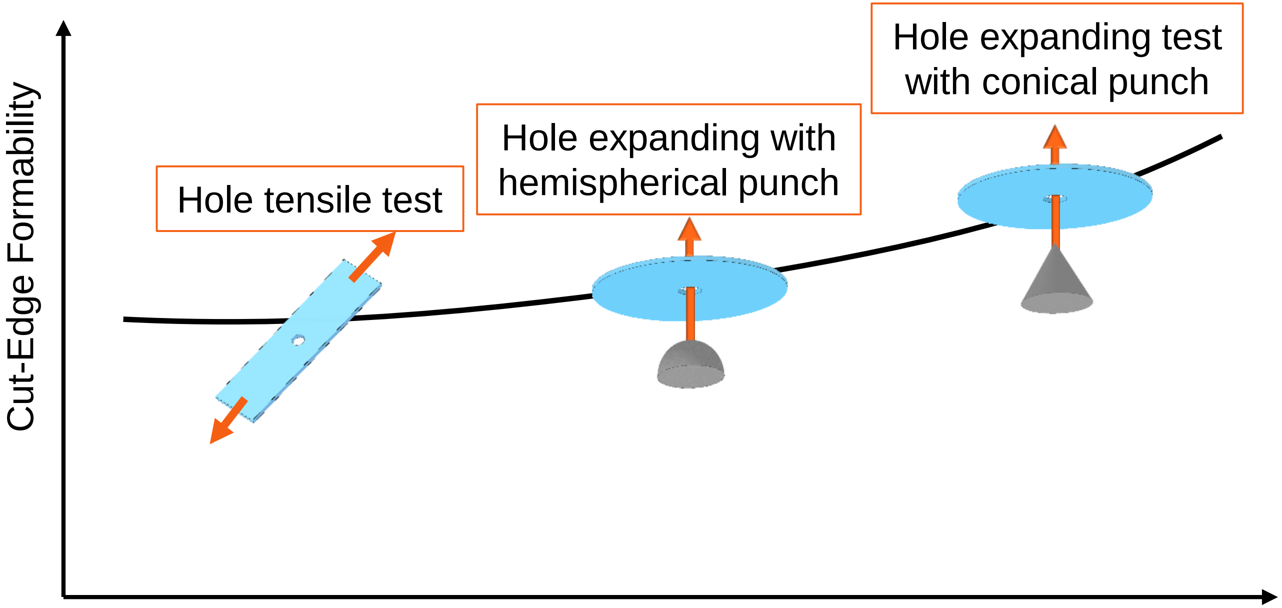
Comparability of results?



Assuming:

- same strain gauge
- same cutting process

[Kar09]
[Gul13]
[Bei16]

Possible reasons: Different radial and axial strain gradient or superimposed compression?

➡ **Target: analysis of stress states during experiment**

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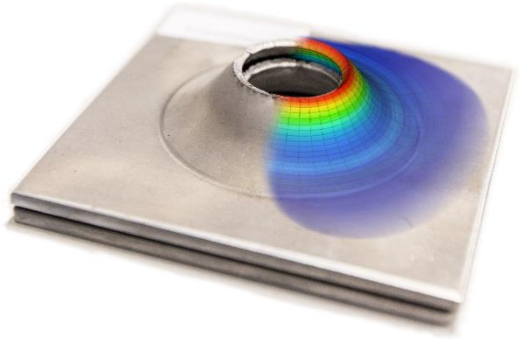
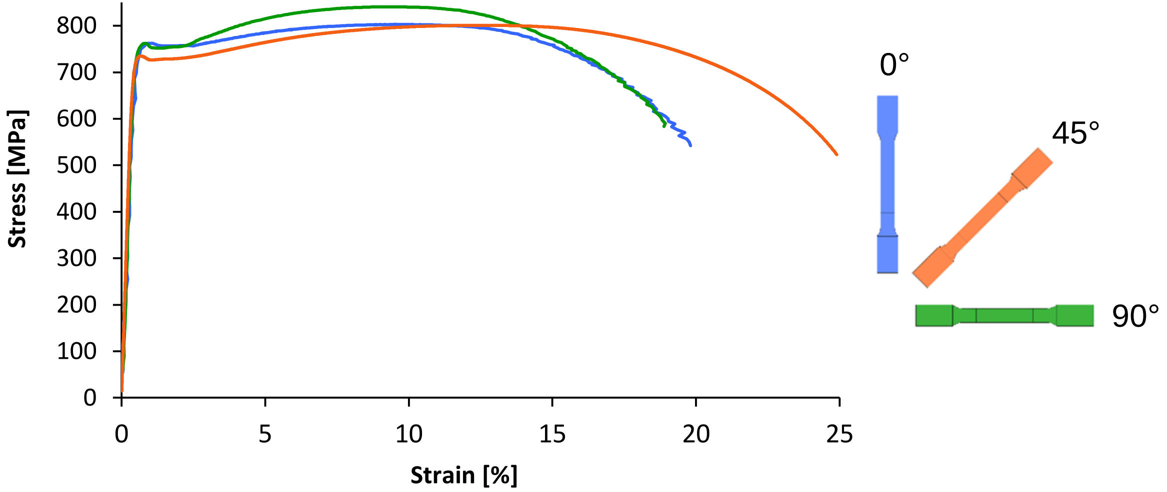
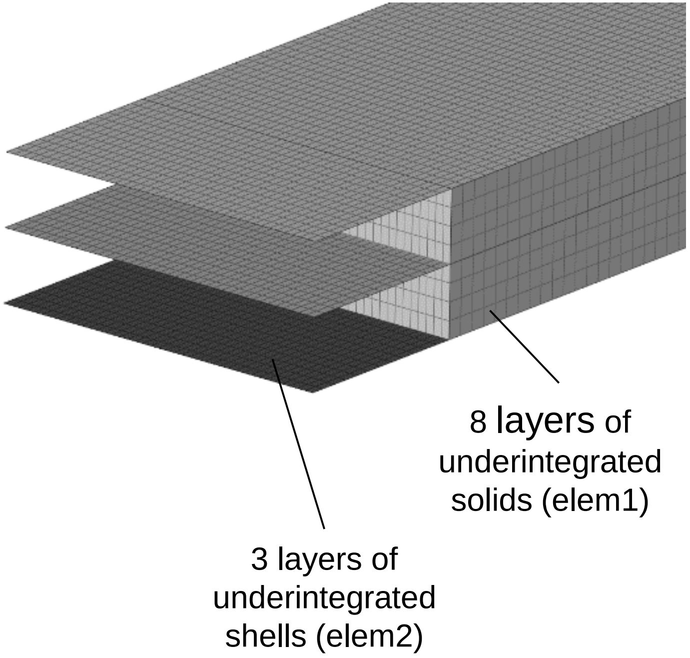


FE-model structure and material model

Material: hot rolled, bainitic steel, 4.0 mm thickness

Input data: tensile test of 0°, 45° and 90°





Requirements: Anisotropy in yield loci and hardening for shells and solids

➡ **Model:** *MAT_TABULATED_JOHNSON_COOK_ORTHO_PLASTICITY

[Hai15]
[Hai16]

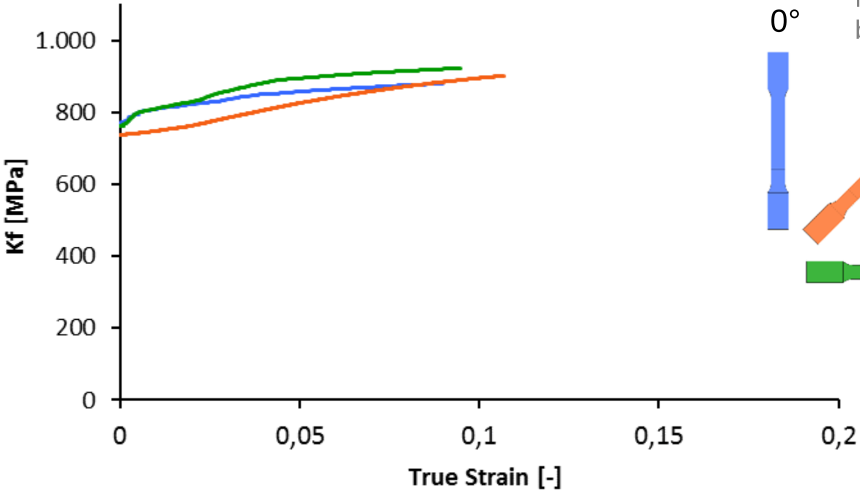
Input for optimization

Input: Flow curve from tensile test

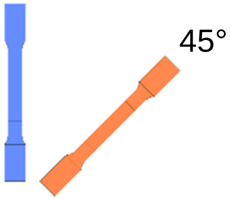
Fit: Parameter for Hockett-Sherby approximation

- ➡ Positive gradient
- ➡ Steady transition

Variable: $k_f(1)$ for 0°, 45° and 90°-curve

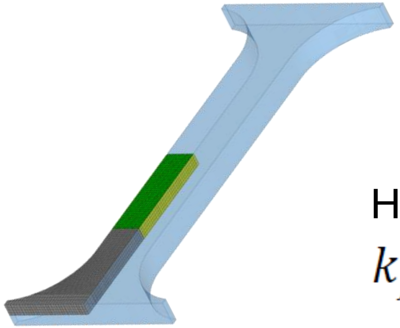


Material: hot rolled, bainitic steel, 4.0 mm



Target: Stress-strain curve with necking information

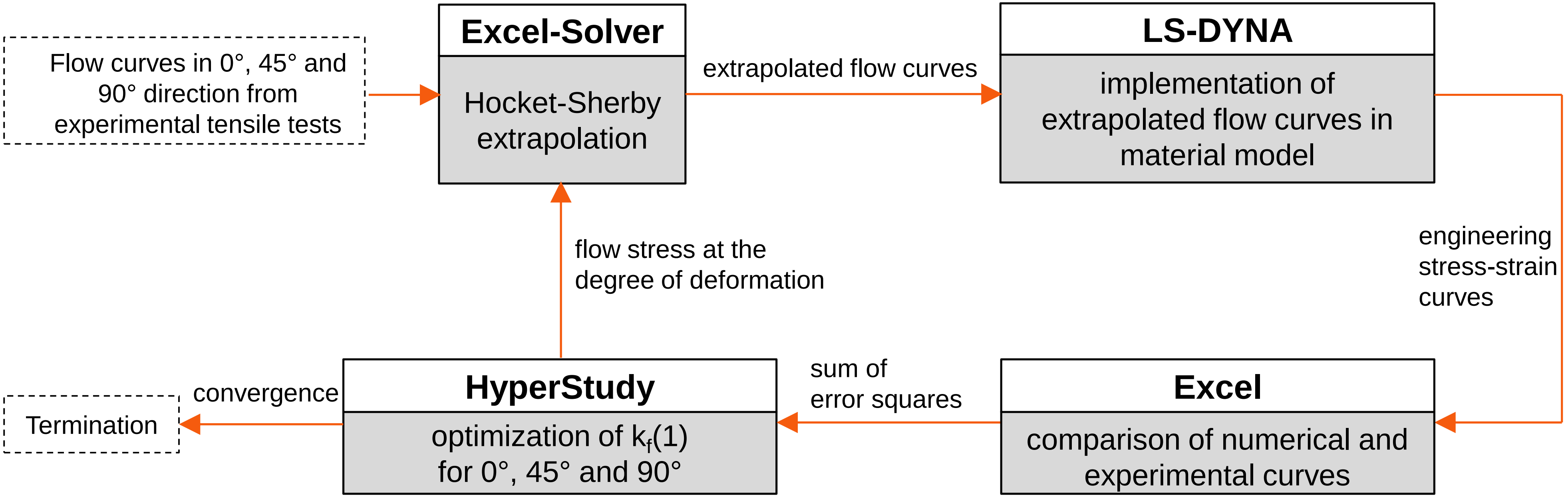
- ➡ Inverse parametrization



Hockett-Sherby

$$k_f(\varphi) = k_{f,s} - \left(k_{f,s} - k_{f,0}\right) \cdot e^{-m \cdot \varphi^p}$$

Optimization framework

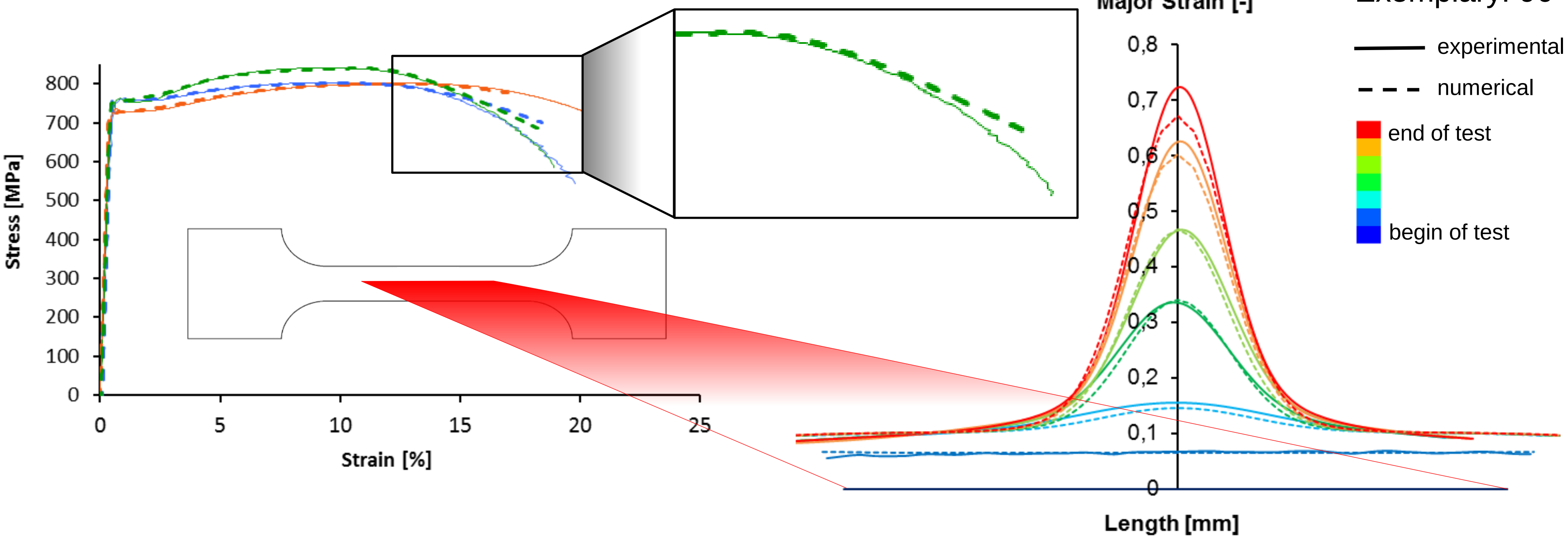


Termination criteria: convergence at minimization of sum of error squares

Validation on tensile test data

Material: hot rolled, bainitic steel, 4.0 mm

Comparison of experimental and numerical global and local strain data



➡ **Result: individual tensile tests show good correlation**

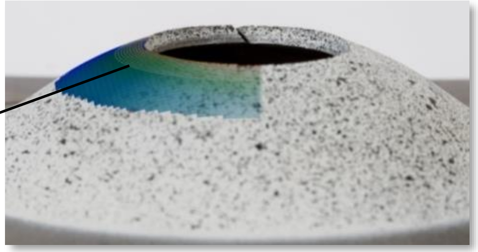
[Wes17]

Validation on hole expansion data

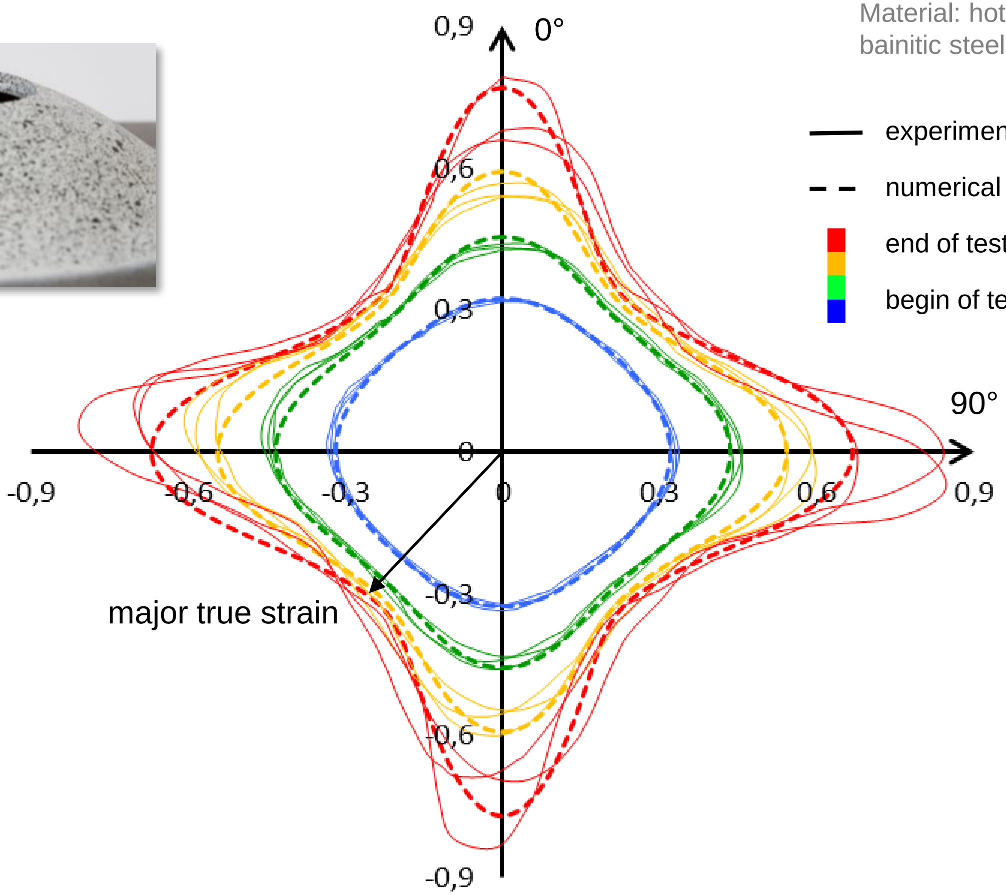
Material: hot rolled, bainitic steel, 4.0 mm

Polar diagram

- Major true strain on circle section cut close to edge



- Line color represents punch travel
- Synchronization between experimental and numerical test based on HER



➡ **Result: adequate interaction of curves**

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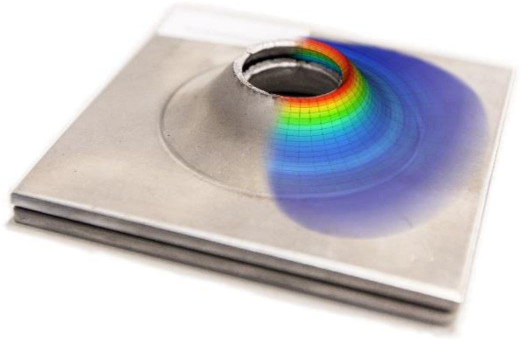

Procedure for stress analysis

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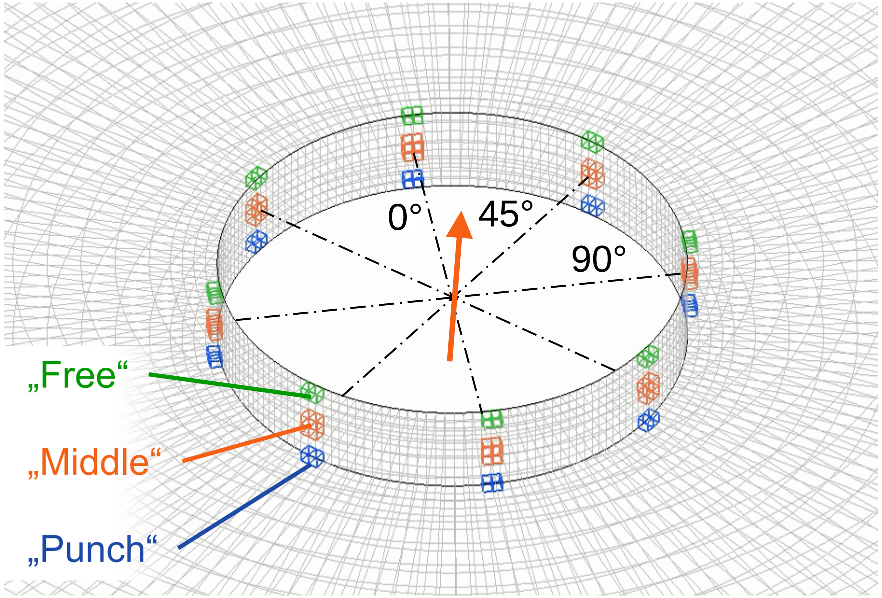
Interventions for result quality

- Low punch velocity
- Mean value of element results using model symmetry
- Low band filtering

Differentiation for stress analysis

- Position relative to the rolling direction (0°, 45° an 90°)
- Position relative to the thickness (free surface, middle and punch side)

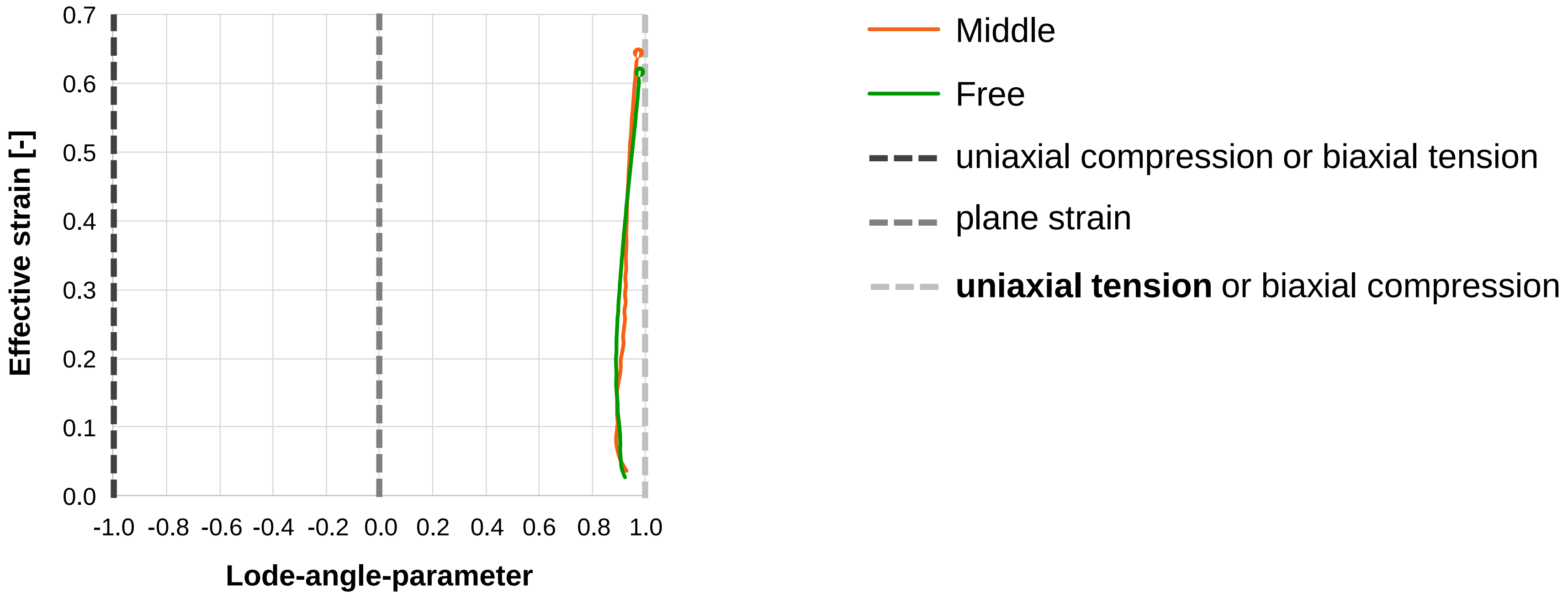
➡ Which stress states are significant **?**



Stress analysis - Hole tensile test

Material: hot rolled, bainitic steel, 4.0 mm

- Stress-triaxiality: ≈ ⅓ ≙ uniaxial tension
- Lode-angle-parameter: ≈ 1 ≙ uniaxial tension
- Could be modeled with shells



Stress analysis – HET with hemispherical punch

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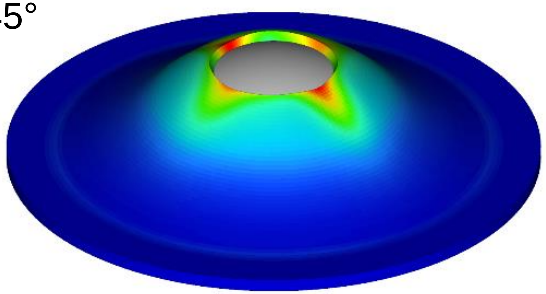
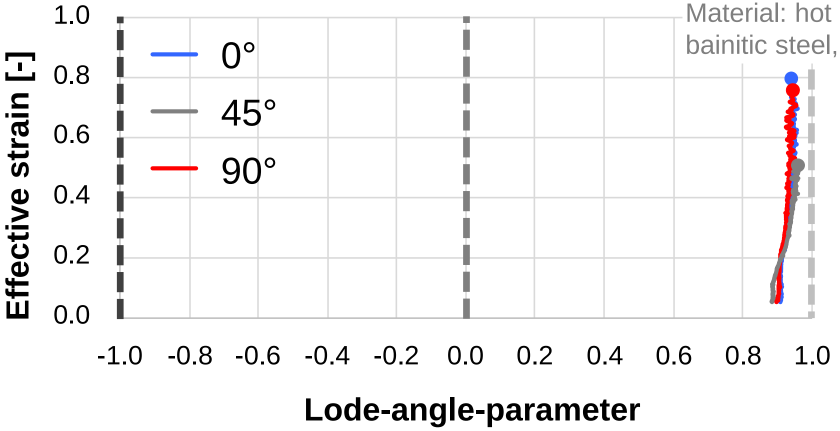
Three-dimensional necking regions

- Concavities on the upper surface
- No gap to punch on lower surface
- Contact pressure is lowered
- Stress states at 0°, 45° and 90° do not differ significantly



Material: hot rolled, bainitic steel, 4.0 mm



Lode-angle-parameter

- Starts at -1
- Moves at very low hole expansion rates to 1
- Curve characteristic fits to visual impression

Stress analysis - Hole expanding test with conical punch

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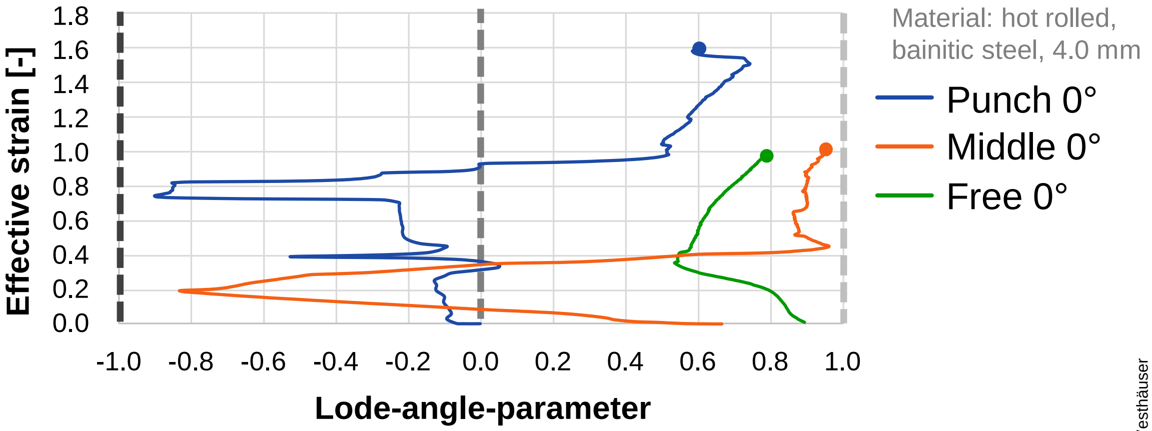
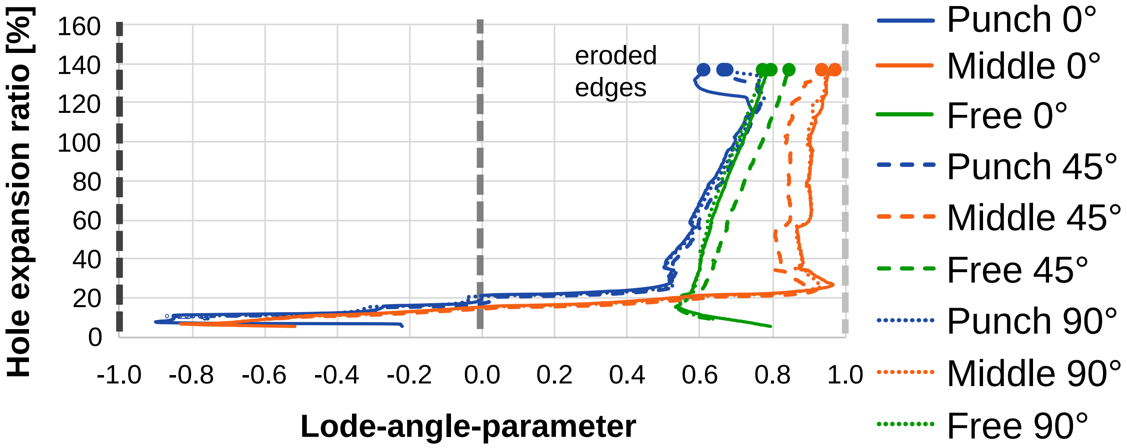
- Compression at beginning causes high plastic strains
- Higher contact pressure tends to reduce necking
- Contact angle shifts moment of separation to much higher hole expansion ratios
- Curve slope shows much variation





Very high HER due to eroded edges

➡ **Scaling to HER for shear-cut edges**

Stress states during determination of cut-edge formability

Stress analysis - Hole expanding test with conical punch

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- Compression at beginning causes high plastic strains
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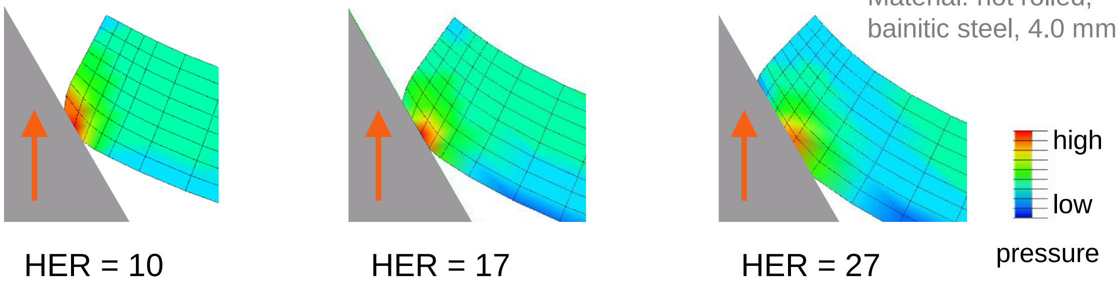
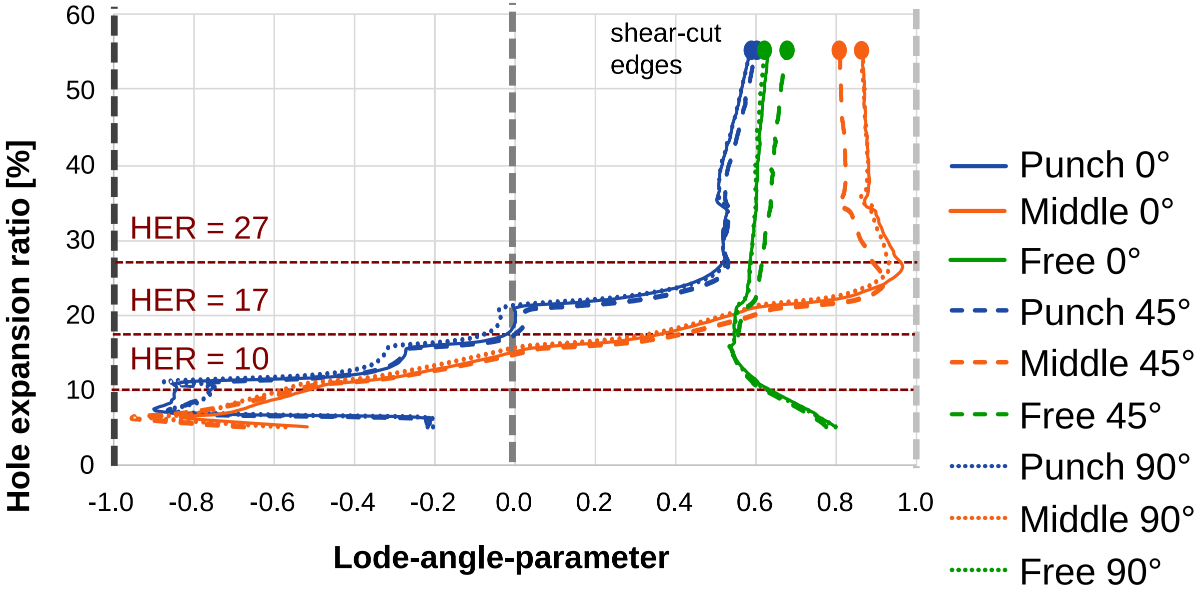
Material: hot rolled, bainitic steel, 4.0 mm





Comparison of test results complex

➡ **3D-visualization of all data**

Stress analysis - Visualization

Material: hot rolled, bainitic steel, 4.0 mm

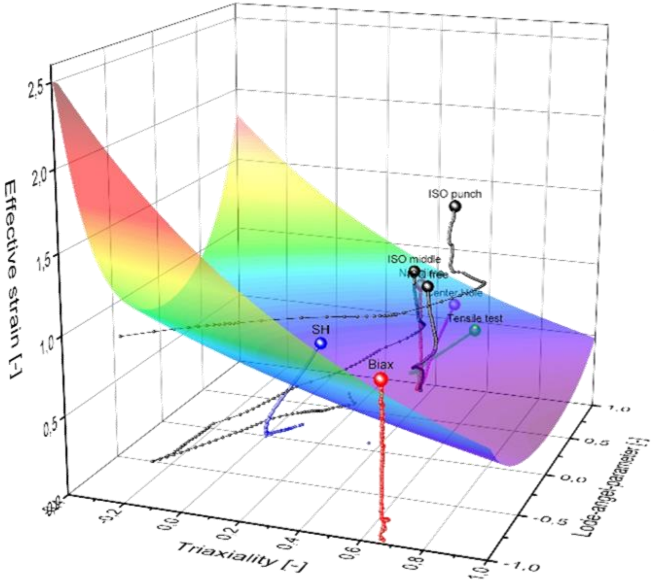
MMC fitted on data from

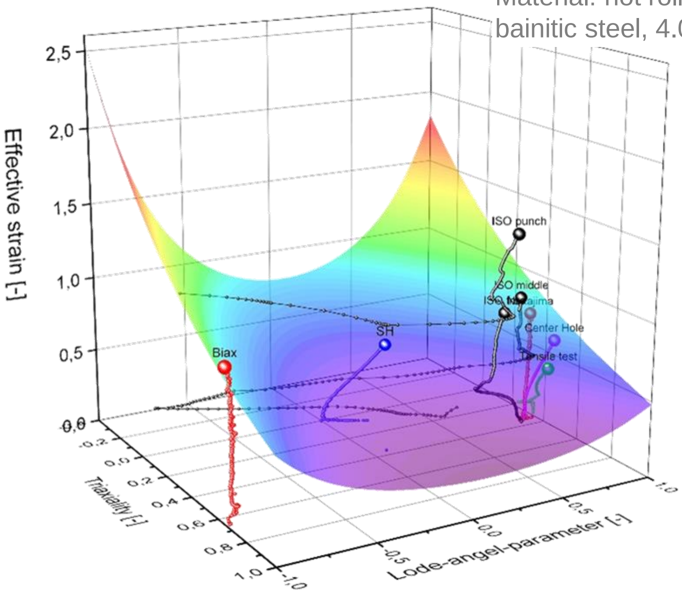
- Hole tensile test*
- HET with hemispherical punch*
- Shear test*
- Tensile test
- Biaxial test

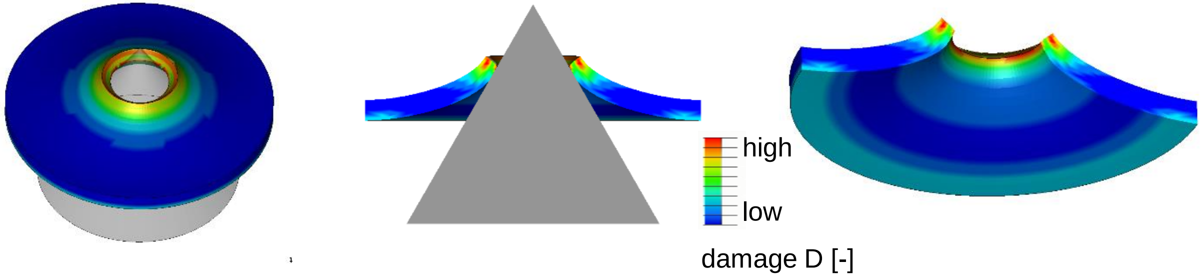
HET with conical punch*

- Nonconstant stress state
- Gradient across thickness
- Highest strains
- Adequate failure prediction

* eroded edges







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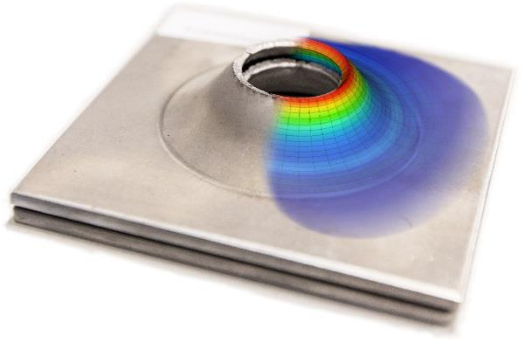


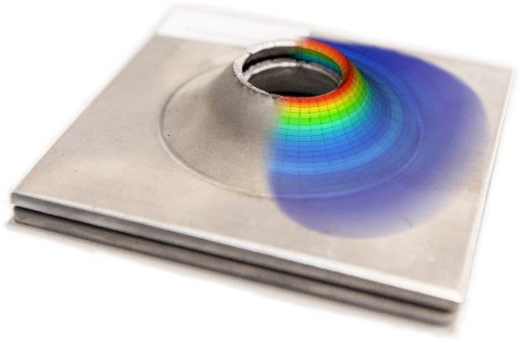
Summary

Hardening behavior

- *MAT_TABULATED_JOHNSON_COOK_ORTHO_PLASTICITY used with 3 hardening curves.
- Extrapolations fitted pragmatically by inverse parametrization.
- Good accordance of experimental and numerical strain data achieved.

Stress analysis

- Analysis of stress-triaxiality delivered the expected uniaxial tension.
- Analysis of Lode-angle-parameter enabled differentiation of investigates tests.



Outcome

- Massive effect of the punch contact pressure found for hole expansion with conical punch in accordance to the ISO 16630.
- Hole expansion with conical punch should not be used for determination of fracture strain due to unconstant stress state.

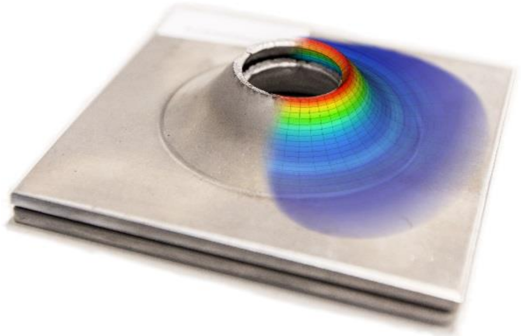
Conclusion and outlook

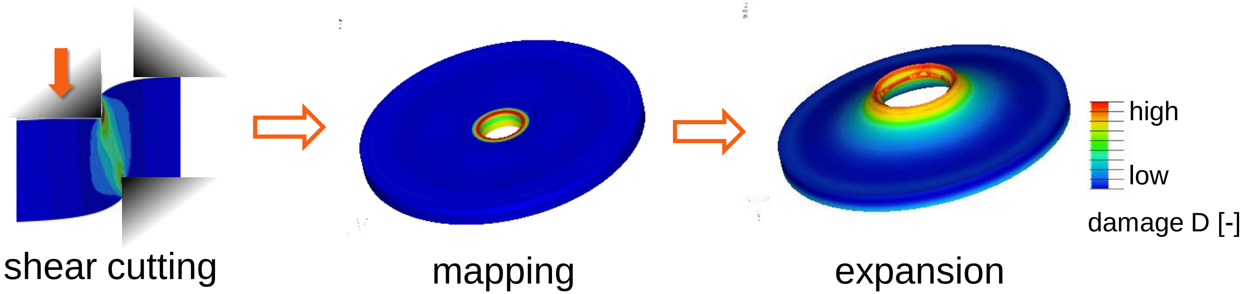
Conclusion

- Lode-angle-parameter identifies effect of contact pressure.
- Hole expansion with conical punch shows highest impact.
- This can be a reason for diverse test results when determining cut-edge formability.

Outlook

- Research on thickness and hardening influence on stress state
- Investigating damage accumulation during described tests
- Using damage caused by shear cutting as an initial edge condition





Literature

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[ISO17] International Organization for Standardization: "Hole expanding test", Metallic materials - Sheet and strip, 2017

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