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

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Stress states during determination of cut-edge formability

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
Stress states during determination of cut-edge formability

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Summary, conclusion and outlook
Introduction - Experimental determination of formability

State of the art: Forming Limit Curve (FLC)

FLC not sufficient for components with shear cut-edges

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

Positive feasibility assessment by means of FLC

But failure at cut-edges of real component

FLD of num. simulation

Real component

[Sch15]
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Hole expanding test (HET) with conical punch acc. to ISO 16630

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 $\varphi = 60^\circ$
- Punch velocity $\leq 1.0$ mm/s

3. Stop-criterion
- Visual inspection: first crack through thickness

4. Evaluation
- Hole expansion ratio $\lambda$ (HER)

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

3. Stop-criterion
   - Visible crack
   - More abrupt crack compared to ISO 16630

4. Evaluation
   - Hole expansion ratio \( \lambda \) according to ISO 16630
   - Crack width correction
   - Strain analysis
   \[ \lambda = \frac{D_h - D_0}{D_0} \cdot 100 \]
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Hole tensile test acc. to Watanabe and Tachibana

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

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Hole tensile test acc. to Watanabe and Tachibana

- Load - Drop
- 5 %
- 1 mm
- 2 mm
- 250 mm
- Ø 10 mm
- 40 mm
- F

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Wat06
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Effects on cut-edge formability

Comparability of results?

Assuming:
- same strain gauge
- same cutting process

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

Target: analysis of stress states during experiment

Hole tensile test
Hole expanding with hemispherical punch
Hole expanding test with conical punch

[Kar09] [Gul13] [Bei16]
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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]
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**Input for optimization**

**Input:** Flow curve from tensile test

**Fit:** Parameter for Hockett-Sherby approximation
- Positive gradient
- Steady transition

Variable: $k_f(1)$ for $0^\circ$, $45^\circ$, and $90^\circ$-curve

**Target:** Stress-strain curve with necking information
- Inverse parametrization

Material: hot rolled, bainitic steel, 4.0 mm

**Equation:**

$$k_f(\varphi) = k_{f,s} - (k_{f,s} - k_{f,0}) \cdot e^{-m \cdot \varphi}$$
Optimization framework

Termination criteria: convergence at minimization of sum of error squares
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Validation on tensile test data

Comparison of experimental and numerical global and local strain data

Result: individual tensile tests show good correlation

Exemplary: 90° to RD

Material: hot rolled, bainitic steel, 4.0 mm

[Wes17]
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Validation on hole expansion data

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**

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?
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**Stress analysis - Hole tensile test**

- Stress-triaxiality: \( \approx \frac{1}{3} \) \( \triangleq \) uniaxial tension
- Lode-angle-parameter: \( \approx 1 \) \( \triangleq \) uniaxial tension
- Could be modeled with shells

Material: hot rolled, bainitic steel, 4.0 mm
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**Stress analysis – HET with hemispherical punch**

**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

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

Material: hot rolled, bainitic steel, 4.0 mm
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**Stress analysis - Hole expanding test with conical punch**

- 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 analysis - Hole expanding test with conical punch

- 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

Comparison of test results complex

3D-visualization of all data
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**Stress analysis - Visualization**

**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

Material: hot rolled, bainitic steel, 4.0 mm
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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 investigated 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
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Literature


