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Characterization and Simulation of High-Speed Deformation Processes

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Subjects

- Motivation
- Characterization
  - Dynamic hardening effects
  - High-speed forming limits
- Simulation
  - Development of a new material model
  - Gauss point investigation
  - Simulation of large dynamic hardening effects
- Summary and Outlook

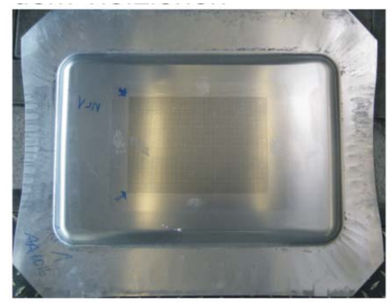
Motivation

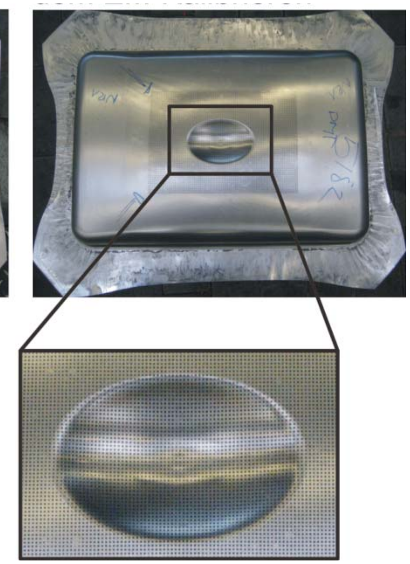
Combination of Quasi Static & High-speed Forming Processes

➔ Enhancement of process limits

Processes

- Deep Drawing Processes
- Magnetic Pulse Forming





Combined deep drawing and magnetic pulse forming

Characterization of combined forming processes

Experiments

- Dynamic material properties
- High-speed forming limits

Simulation

- Enhancement of material model
- Consideration of dynamic effects and forming limits
- Simulation of combined processes

Cooperation between

- Institute of Materials Science, Hannover
- Institute of Applied Mechanics, Aachen

Institut für Angewandte Mechanik

Dynamic Materials Properties

Problem

Thin sheets

- Only few experience and references
- Tend to buckle under compression
- No standardized measuring system available

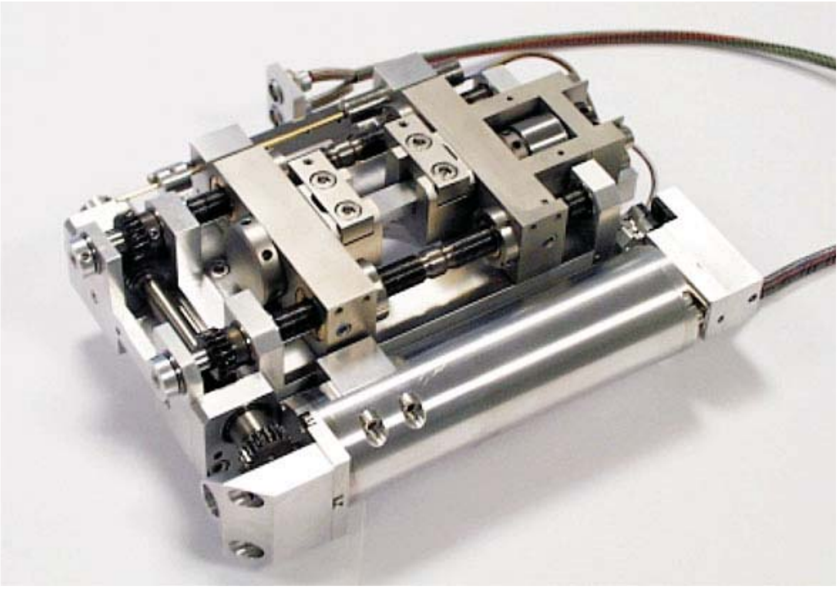
Solution

Miniaturization

- Reduced unsupported length → No buckling
- Only small forces needed

SEM

- Optical measurement of small geometries possible



Micro tensile testing device (left) and dimensions of micro specimens in mm (right)

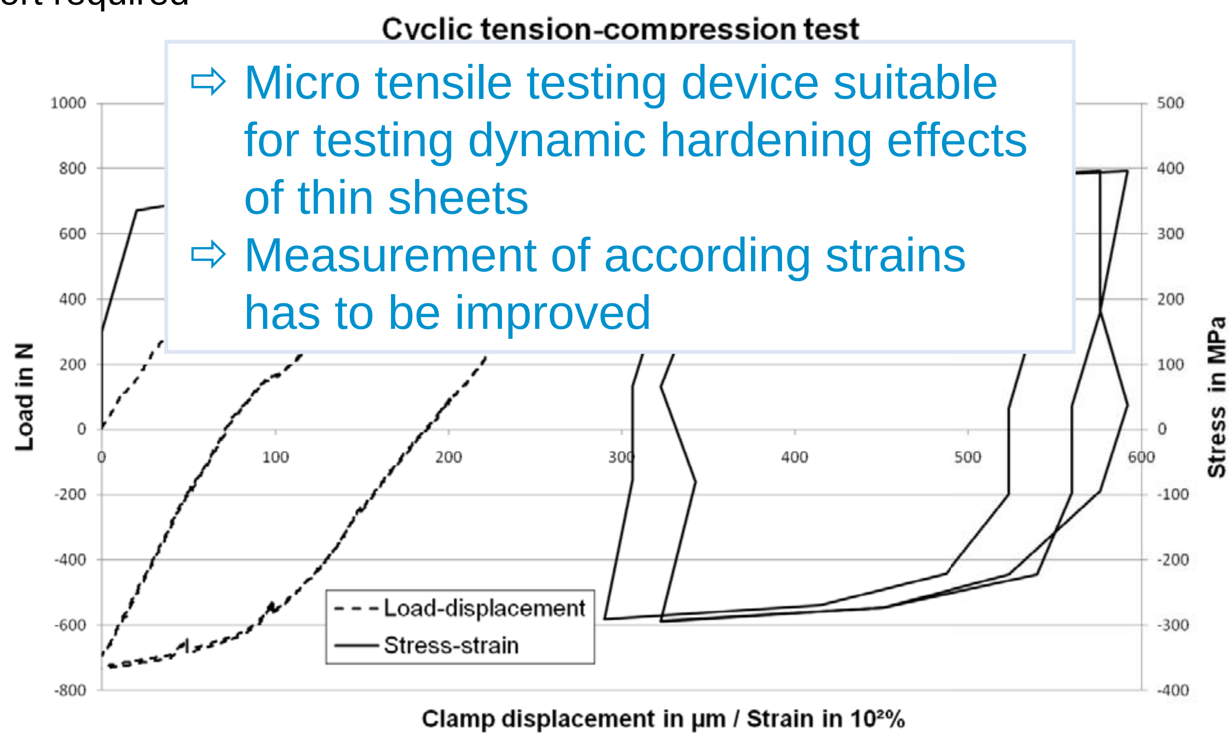
Dynamic Materials Properties

Cyclic tension- compression test

Miniaturized specimens
- No buckling
- No lateral support required

Test parameters
- Pulsating load
- 0 to +300 µm clamp displacement

Optical evaluation with SEM
- Measurement of real elongation
- Test needs to be stopped while measuring



⇨ Micro tensile testing device suitable for testing dynamic hardening effects of thin sheets

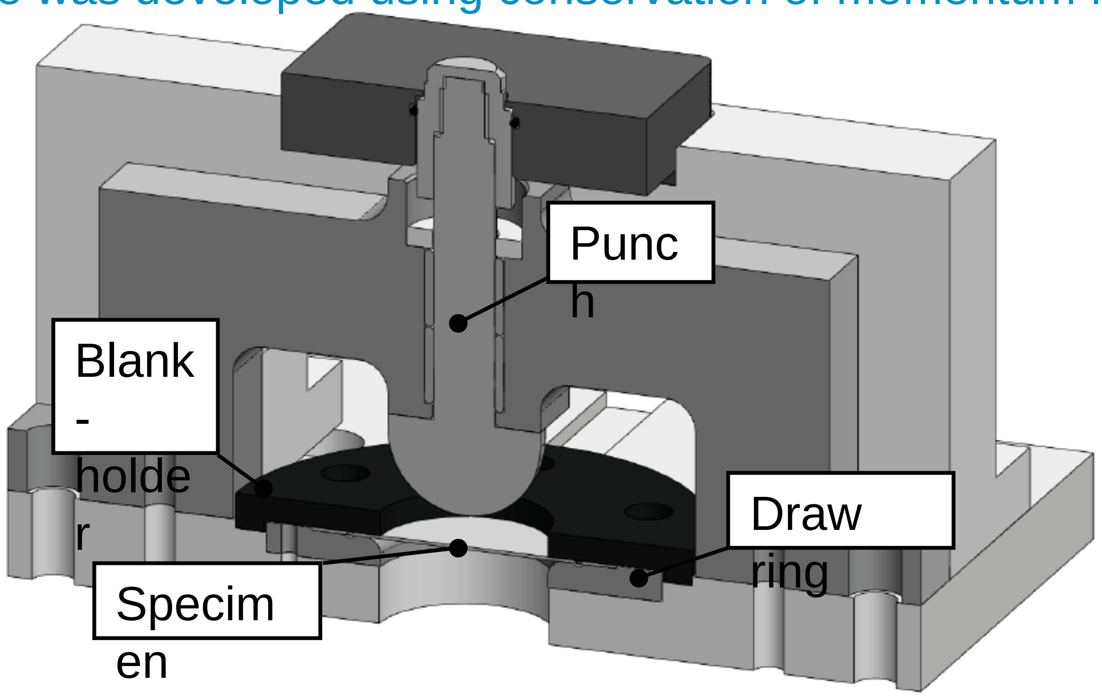
⇨ Measurement of according strains has to be improved

Load displacement (left) and stress strain curve (right)

High-speed forming limits

- **Electro-hydraulic sheet metal testing machines only suitable for quasi-static forming tests (punch speed up to 5mm/s)**
- **High-speed forming tests equivalent to magnetic pulse process require punch speeds of 100m/s and more**
- **A new measuring method and device suitable for high punch speeds needs to be developed**

⇨A testing device was developed using conservation of momentum for speed generation



CAD-model sectional view of the developed impulse device

High-speed forming limits

Drop tower for crash-tests

Up to 300 kg drop weight

Up to 6 m drop height

Up to 12,5 m/s drop speed

Feasibility testing of Impact device

- Punch weight app. 900 g
- 3 m drop height
- 90 kg drop weight

➔ 91 m/s punch speed at impact

Fig. 3: impact device (left) and drop tower (top)

High-speed forming limits

Drop tower for crash-tests

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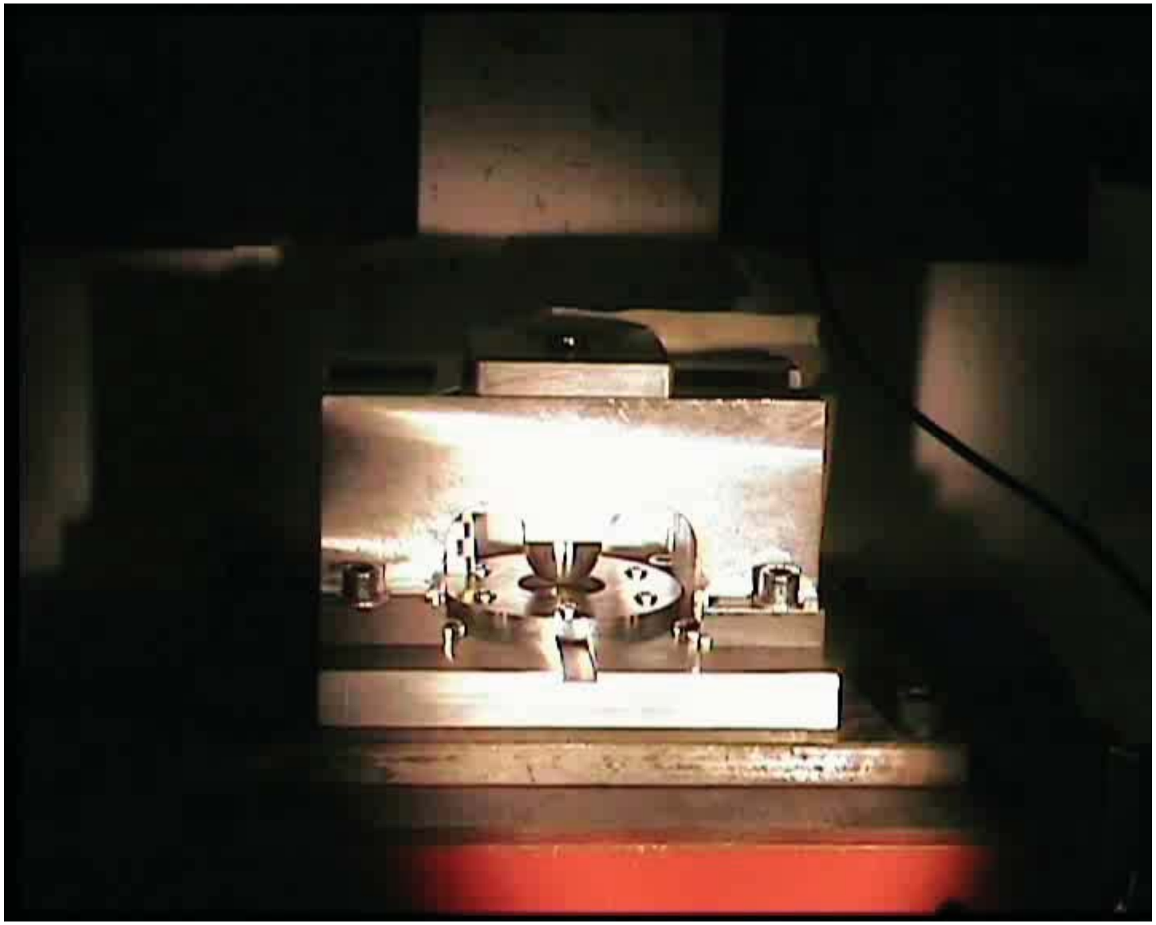

Impact device during testing inside drop tower

High-speed forming limits

Drop tower for crash-tests

Up to 300 kg drop weight

Up to 6 m drop height

Up to 12,5 m/s drop speed

Feasibility testing of Impact device

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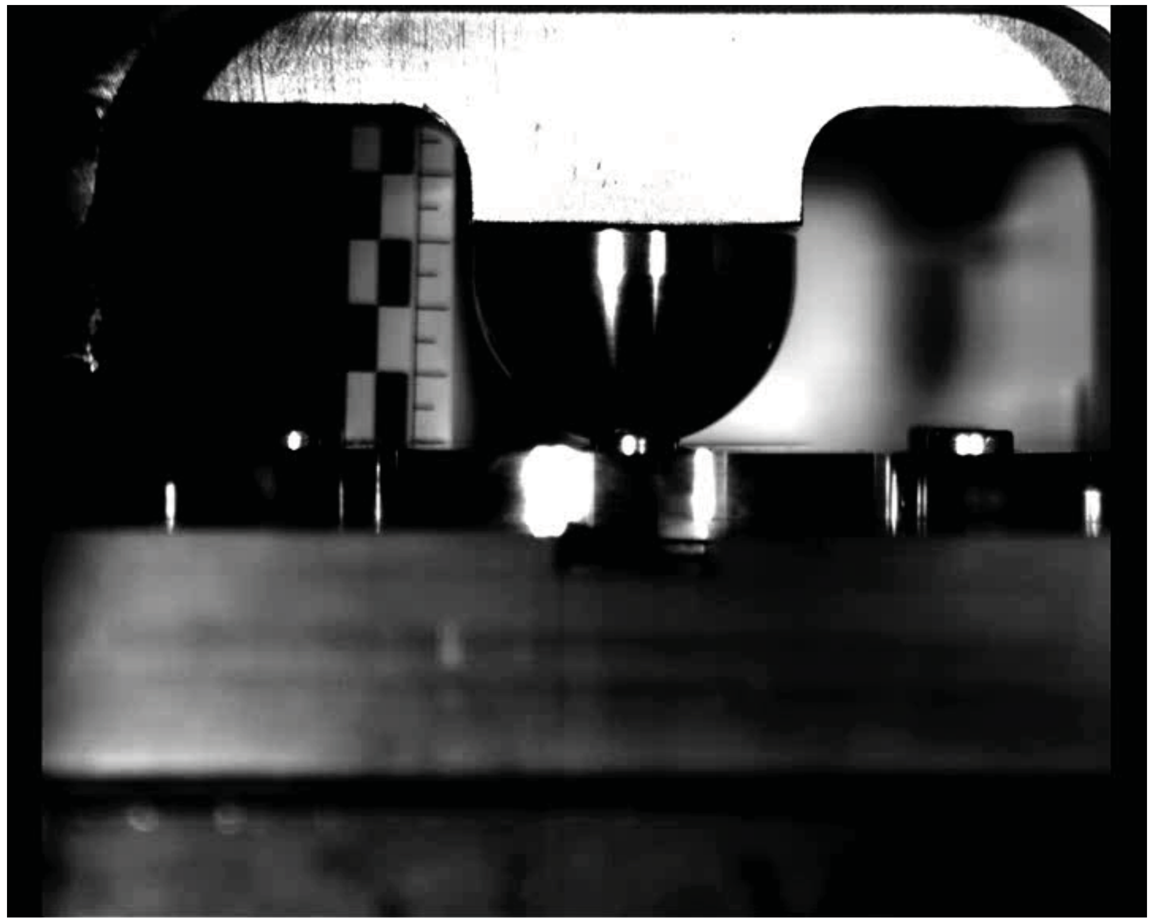


Punch displacement in slow-motion

(high-speed camera @ 12.5kHz → 0,08 x10-³ sec/step)

Nakajima-Test: Results

Experimental setup

4 geometries – equivalent to

- Deep drawing
- Uniaxial tensile testing
- Plain strain
- Stretch drawing

Materials

- EN AW 6082 T6
  (AlMgSi1, solution heat treated and artificially aged)
- 3-layer composite sheet
  (Al-Ti-Al & Al-St-Al)
- Simple teflonspray lubrication

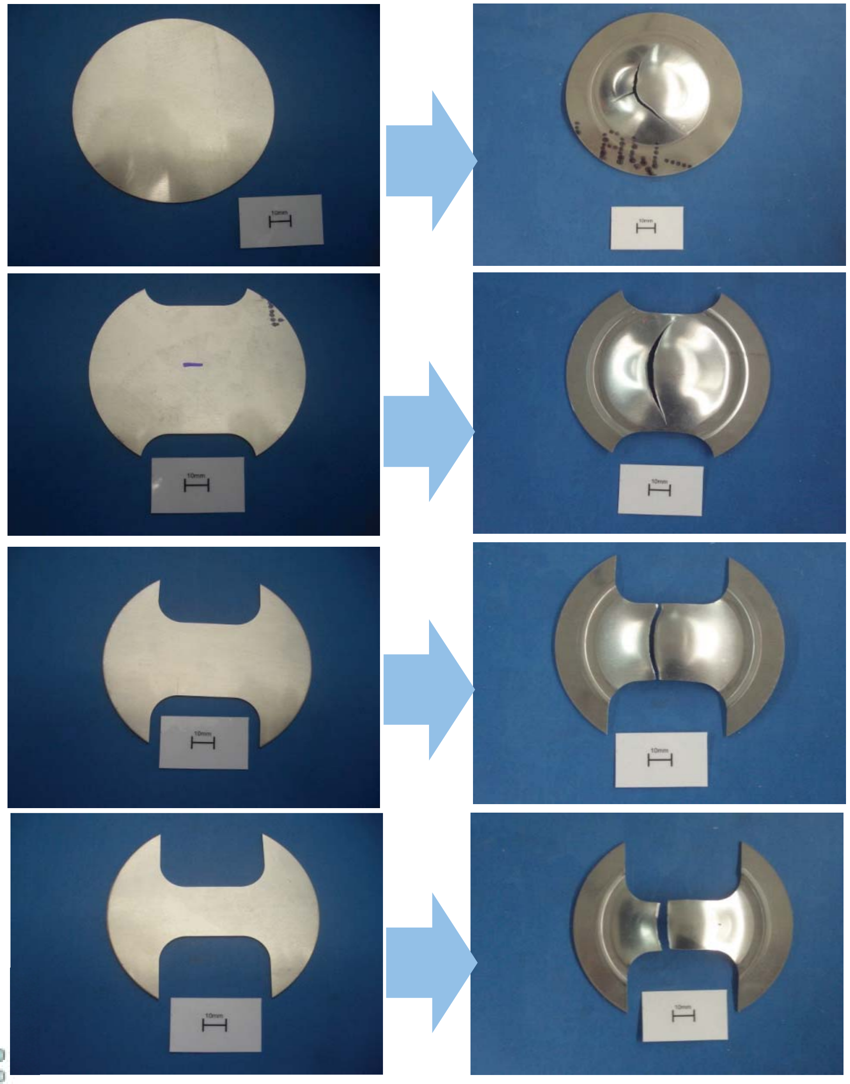
Results

⇨ Cracks occur near center

⇨ Lubrication seems to have less influence

⇨ Testing possible for all geometries

⇨ Composite sheets to complex for evaluation



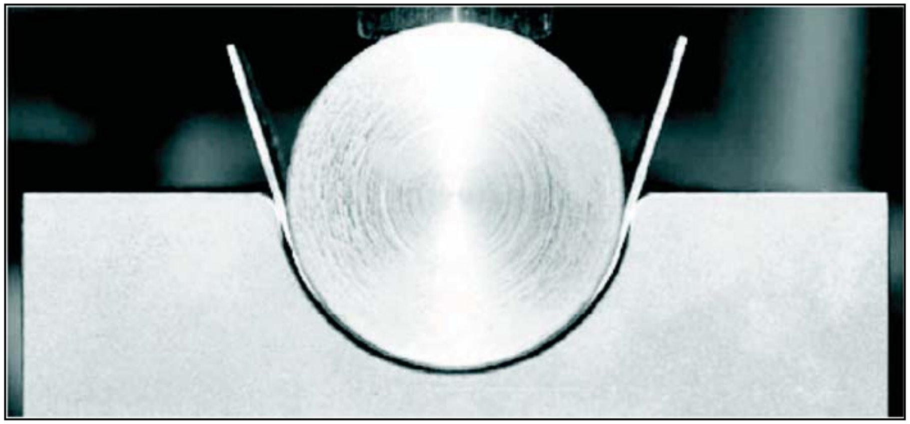
Tested specimens

Research Training Group 1378: „Manufacture, machining and qualification of hybrid material systems“

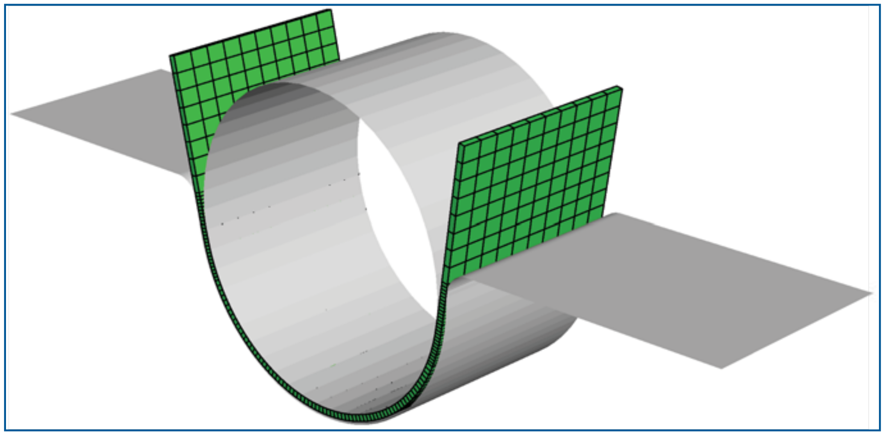
Simulation

- Development of a new module for realistic and numerically robust simulation, with focus on material and contact modeling
- Development of a new efficient finite-element-technology
- Implementation of a new material and damage model
- A new eight-node solid-shell finite element based on reduced integration with hourglass stabilization
- A finite strain constitutive model which combines nonlinear kinematic and isotropic hardening

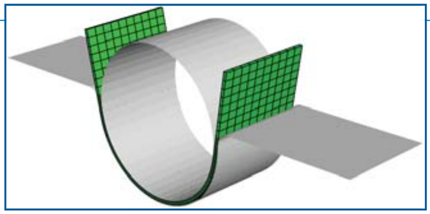
Unconstrained bending



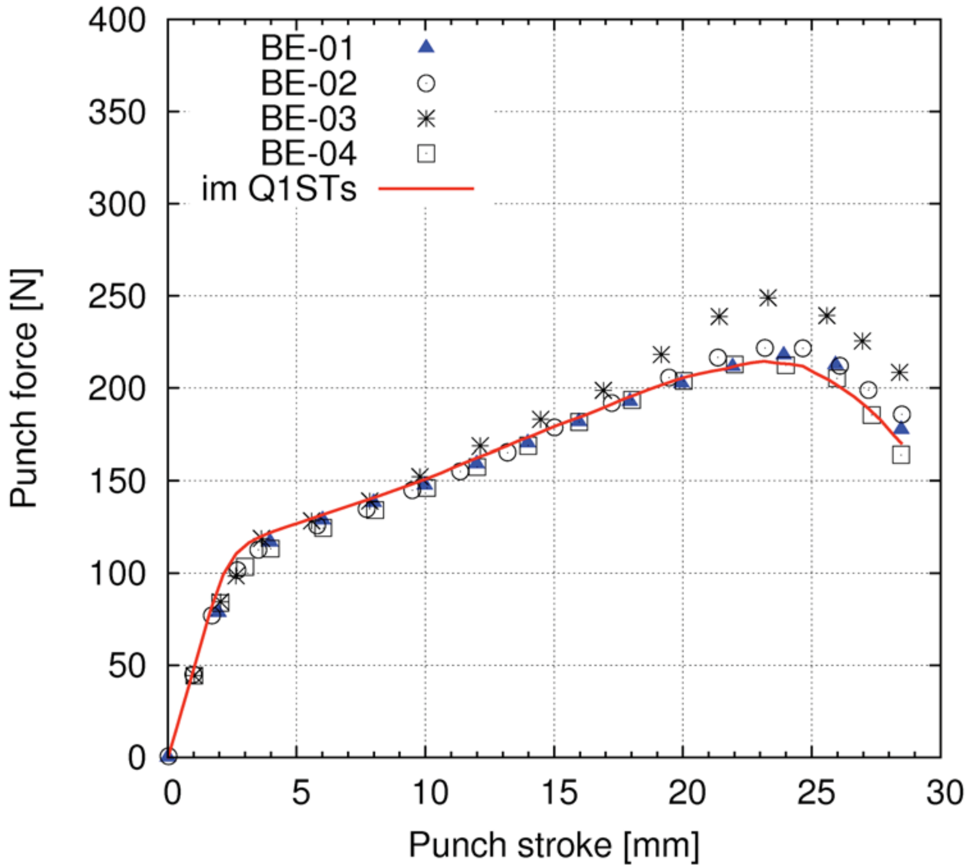
Alves de Sousa et al. (2007)



Unconstrained bending



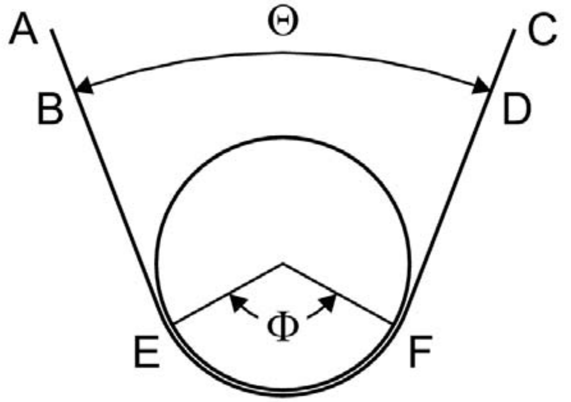
comparison with experiments:



Unconstrained bending

springback prediction:

Θ [deg]	min exp	max exp	simulation
before springback	19.1	21.3	21.0
after springback	52.8	54.2	54.2



angle between points E and F:

ϕ [deg] at stroke	min exp	max exp	simulation
7 mm	8.9	29.3	22.1
14 mm	60.0	74.7	66.3
21 mm	108.0	125.3	114.2
28.5 mm	153.3	176.0	161.2

sult

Material modeling unconstrained bending

- Multiplicative split: $F_p = F_{pe} F_{pi}$
- Deformation gradient: $F = F_e F_p$
- Helmholtz free energy: $\psi = \psi_e(C_e) + \psi_{kin}(C_{pe}) + \psi_{iso}(\kappa)$
- Elastic right Cauchy-Green tensor: $C_e = F_e^T F_e = F_p^{-T} C F_p^{-1}$
- Plastic right Cauchy-Green tensor: $C_{pe} = F_{pe}^T F_{pe} = F_{pi}^{-T} C F_{pi}^{-1}$
- Clausius-Duhem inequality: $-\dot{\psi} + S \cdot \left(\frac{1}{2}\right) \dot{C} \geq 0$

$$\Downarrow$$

Relation for second Piola-Kirchhoff stress tensor S

Constitutive equations in reference configuration

- Stress tensors:

$$S = 2F_p^{-1}\frac{\partial\psi_e}{\partial C_e}F_p^{-T},\ \ X = 2F_{pi}^{-1}\frac{\partial\psi_{kin}}{\partial C_{pe}}F_{pi}^{-T},\ Y = CS - C_pX,\ \ Y_{kin} = C_pX$$

- Evolution equations:

$$\dot{C}_p = 2\dot{\lambda}\frac{Y^D C_p}{\sqrt{Y^D\cdot(Y^D)^T}},\ \ \dot{C}_{pi} = 2\dot{\lambda}\frac{b}{c}Y_{kin}^D\,C_{pi},\ \dot{\kappa} = \sqrt{\frac{2}{3}}\dot{\lambda}$$

- Yield function:

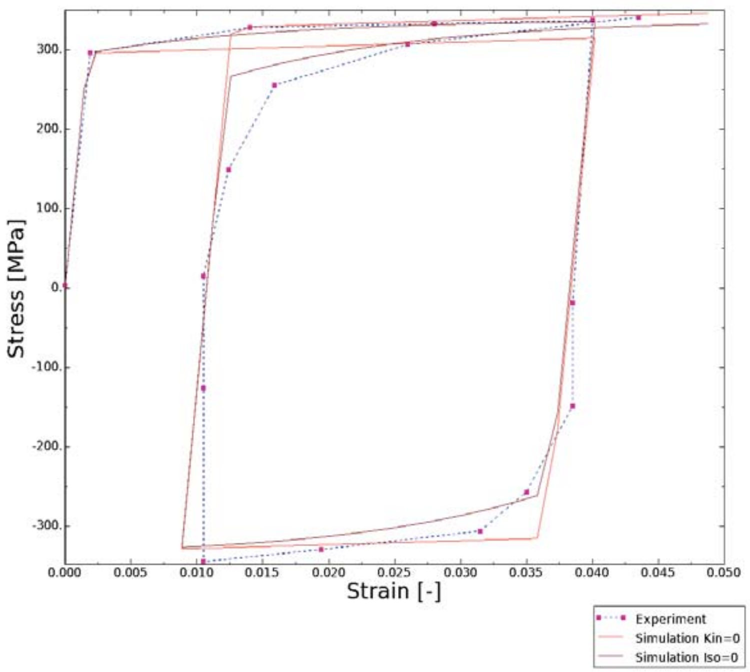
$$\Phi = \sqrt{Y^D\cdot(Y^D)^T} - \sqrt{\frac{2}{3}}(\sigma_y - R),\ \ R = -Q(1 - e^{-\beta\kappa})$$

- Kuhn-Tucker conditions:

$$\dot{\lambda}\geq 0,\ \ \Phi\leq 0,\ \ \dot{\lambda}\Phi = 0$$

Gauss point investigation

Fitting the material parameters by separating isotropic and kinematic hardening

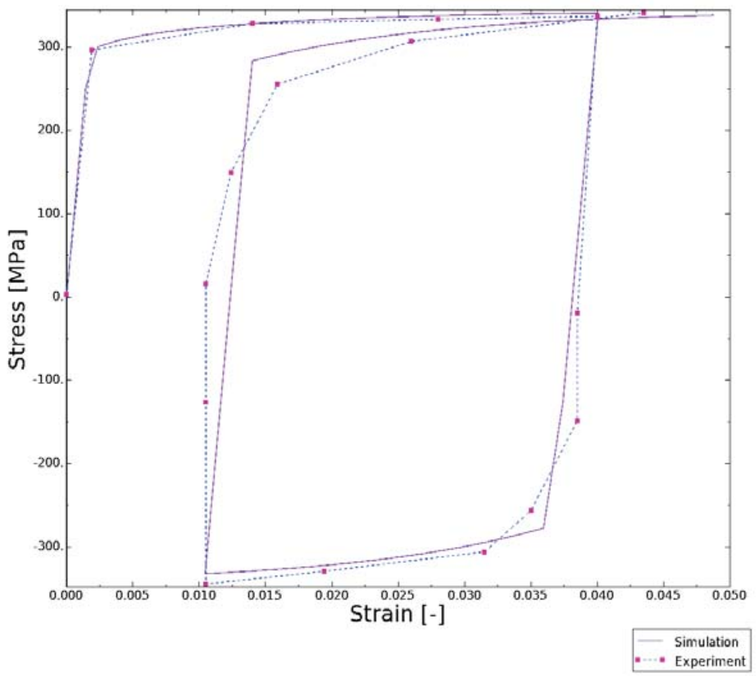


Kinematic hardening

$$\sigma_y = 296\ MPa$$

$$Q = 11\ MPa \qquad c = 0\ MPa$$

$$\beta = 200 \qquad b = 0$$



Isotropic hardening

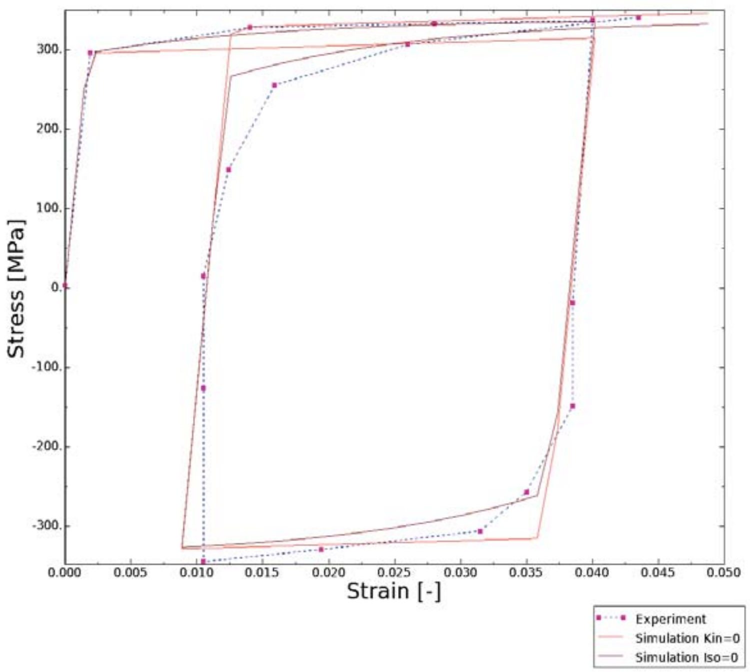
$$\sigma_y = 296\ MPa$$

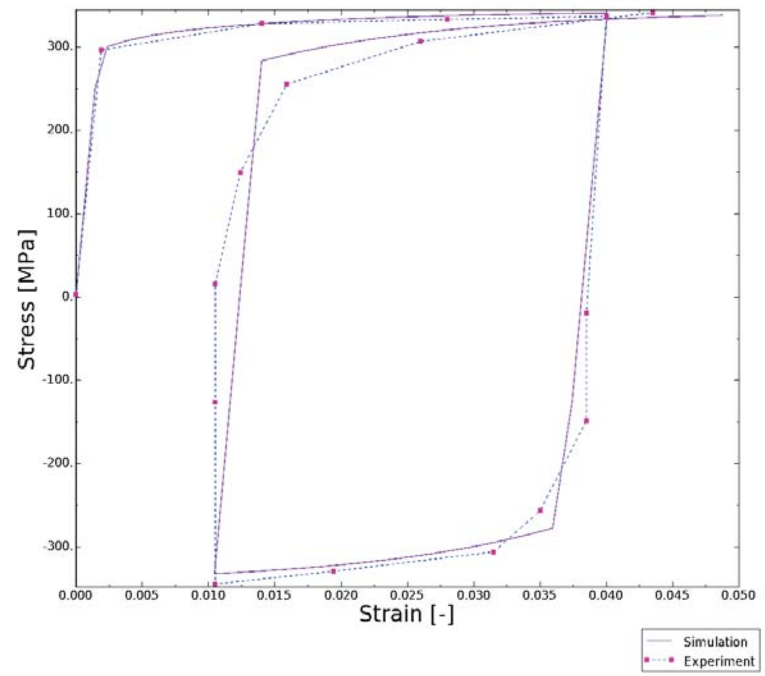
$$Q = 0\ MPa \qquad c = 2000\ MPa$$

$$\beta = 0 \qquad b = 70$$

Gauss point investigation

Combining both hardening effects





The material model is very suitable for simulating large deformation problems

Summary and Outlook

- A new method for testing dynamic material properties of thin sheets was established
- Strain measurement needs further improvement

→ New optical measurement systems for strain measurements are needed (test stage)

- A novel high-speed Nakajima testing device using conservation of momentum has been developed
- Punch speeds of 91m/s have been proved, higher punch speeds are possible
- Composite sheets cannot be tested satisfactorily due to the complex failure mechanisms

→ Further testing at different speeds and evaluation of optimal penetration depth as well as strain analysis and temperature analysis with an optical measurement system is needed

- A new material model including isotropic and kinematic hardening was developed
- The simulation shows good correspondence to experimental data

→ Need of more complex experiments with optimized measurement to fully validate the model