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Virtual Material Testing for Stamping Simulations 
Based on Polycrystal Plasticity 

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Overview

- Introduction
- Crystal Plasticity FEM
- Virtual Specimen (RVE)
- Fit Example 1: Vegter Yield Locus
- Fit Example 2: LS-Dyna MAT_103
- Conclusions
INPRO Shareholders

BASF Coatings AG
DaimlerChrysler AG
IWKA AG
Land Berlin
Volkswagen AG
ThyssenKrupp Automotive AG

IWCMM15, Kraska, Doig, Tikhomirov, Raabe, Roters
Properties of Deep Drawing Sheet Metal

Service Properties

- Strength
- Energy absorption

Forming Properties

- Springback
- Formability

<table>
<thead>
<tr>
<th>Tensile Strength [MPa]</th>
<th>Elongation A80 [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>200</td>
<td>10</td>
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<tr>
<td>400</td>
<td>20</td>
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<td>600</td>
<td>30</td>
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<tr>
<td>800</td>
<td>40</td>
</tr>
<tr>
<td>1000</td>
<td>50</td>
</tr>
<tr>
<td>1200</td>
<td>60</td>
</tr>
</tbody>
</table>

Materials:
- Eisen-Aluminium Leichtbaustähle
- IF (hochfest) FeP05 SULC
- Austenitische Rostfreistähle Hochmanganhaltige TRIP/TWIP-Stähle
- Dualphasen CP-Stähle TMS-Stähle
- AI-Mg Knetlegierungen

IWCMM15, Kraska, Doig, Tikhomirov, Raabe, Roters
Springback Simulation: Model Requirements

- Springback Compensation
  - Shaping the die such that the stamped part has the target shape after springback
  - To reduce iterative tooling, high precision planning (simulation) tools are required

- Precise Springback Simulations Depend on Appropriate Models:
  - Tool shape, sheet discretization
  - Contact and friction
  - Elasto-plastic sheet material

- Material Model Requirements
  - Reliable stress prediction
  - Multiaxial loads
  - Changing load direction (including load reversal)
  - Account for sheet orthotropy,
  - Kinematic and isotropic hardening
Other Sources of Knowledge

Macro-scale: Real Material

Meso-scale: single crystalline grains

Micro-scale: atomic lattice

Preferred Orientations
Single Crystal: Elastic and plastic Anisotropy

Elastic

Material | ⟨100⟩ | E | G | ν | c_{11} | c_{12} | c_{44} | A
---|---|---|---|---|---|---|---|---|
Fe | 134 | 118 | 0.367 | 233 | 135 | 118 | 2.41 |
Al | 63 | 28 | 0.36 | 107 | 61 | 28 | 1.22 |
Cu | 67 | 75 | 0.42 | 168 | 121 | 75 | 3.19 |

Plastic

\[ \dot{\gamma}^\alpha = \dot{\gamma}_0 \left| \frac{\tau^\alpha}{\tau_{\text{crit}}} \right|^{1/m} \text{sign}(\tau^\alpha) \]

\[ \tau_{\text{crit}}^\alpha = \sum_\beta h^{\alpha \beta} |\dot{\gamma}^\beta|, \quad h^{\alpha \beta} = q^{\alpha \beta} h^{(\beta)}, \quad h^{(\beta)} = h_0 \left\{ 1 - \frac{\tau_{\text{crit}}^\beta}{\tau_s} \right\}^a \]

\( \tau_s, \ a, \ h_0, \ q_{ki} \) material parameters
Calibration

- **Focus on bcc (ferritic) steel**
  - mild steel DC04 (St14)
  - high strength low alloy steel H320LA (ZStE 340)

- **Texture input**: 100, 110, 211 pole figures

- **Slip systems and hardening parameters**
  - 48 slip systems containing 111 direction
  - Yield curve is fitted to a single uniaxial tensile test (0°)

- **Results shown for H320LA**
  - Yield curves and r-values for simulated tensile tests 0, 45, 90°
  - Yield curves: error 1-1.6%
  - r-values: error 10-24%

- **Possible improvements**
  - Adjustment of hardening matrix (self- vs. latent hardening)

**Real test**
**Virtual test**
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Crystal plasticity FEM

- Direct use of crystal plasticity in the forming simulation
- Texture representation by random sampling of texture components (peaks and fibers) at every integration point
- Homogenization at the integration point (multiple orientations – sampled components)
- Orientation samples differ from point to point – added level of homogenization
- Demonstrated by MPIE for (fcc) Aluminum
- High CPU and memory demands
- Limited to small stamping parts with few through-thickness layers
Application to deep drawing
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**Virtual Material Testing**

- Representative Volume Element
- Virtual test program – extrapolation of calibration tests
- Parameter fit of the macro material model
- No performance loss compared to classical deep drawing simulation
- Material behaviour limited to available models in commercial FE codes
- Demonstrated by INPRO for (bcc) HSLA steel
Virtual Specimen (Representative Volume Element)

- Co-operation MPIE-INPRO
  - Based on a cooperation between MPIE and INPRO
  - Crystal plasticity provided as black box ABAQUS UMAT by MPIE
  - RVE concept, implementation and testing by INPRO

- Basic Features
  - Trade-off between accuracy and speed
  - 1000 grains
  - 1 Element per grain
  - Cubic grain shape
  - Periodic boundary conditions for load application
  - Process(test) specification by piecewise constant velocity gradient

\[
\mathbf{L}(t) \rightarrow \mathbf{F}(t) = \int \mathbf{L}(t) \, dt \rightarrow \mathbf{T}_0(t)
\]

- Velocity gradient
- Deformation gradient
- Nominal stress tensor (1PK)
**Boundary Conditions**

- All nodal displacements prescribed (Taylor model)
- Only boundary node displacements prescribed
- No direct specification except mean deformation and periodicity
Boundary Influence

- 1000 grains based on sampled texture components (measured, DC04)
- Simulated tensile test
Influence of Element Type

C3D8  
C3D8R

C3D20

C3D20R
Virtual Specimen: Process Chain

Texture data processing

exp. pole figures external format

exp. pole figures MultTex format

texture components Multex-format

texture components MPIE format

material parameters

MPIE subroutine crystal plasticity

Virtual Tests

Virtual specimen FE-model

process specification

test specification

raw virtual test data ABAQUS odb

average test results (displacement gradient, nominal stress)

plots of experimental and simulated pole figures

Uniaxial extension

tension/compression

stack compression

any other homogeneous process

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Deformation Induced Texture

Initial state (grey texture)

Simulated rolling texture (reduction by 40%)

Measured texture (DC04)
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Vegter Yield Locus

- Direct interpolation of test data
- Suitable for steel, Al and Mg
- PAMSTAMP 2G implementation available
- High number of tests required
\[ \sigma_1 = \sigma_2 \]

1 = rolling direction

1 = transverse direction

\[ \sigma_1 = -\sigma_2 \]
Deep Drawing Simulation (Vegter Model)

- Input data is directly extracted from the tests
- No fit procedure required
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Example Fit

- Material: H320LA
- Texture data: HMI
- Slip system calibration based on 0° yield curve
- Virtual tests:
  - uniaxial tension 0, 45, 90°
  - uniaxial tension-compression 0°
  - stack compression test
- Material model LS-Dyna 103
  - Hill 48 yield locus (4 params)
  - 4 params for isotropic hardening
  - 4 params for kinematic hardening (2 back stress terms)
- (10,1)-Evolution strategy
  - mutation rate and covariance matrix adaptation
Fit Quality I

- Fit for r (0°) and stress (90°) is poor.
- Hill 48 cannot in general reproduce both yield curves and r-values

Virtual test
LS-Dyna fit
Note: The slip system model has no backstress.

Even so, the RVE shows a kinematic hardening fraction of approx 25%.

This is caused by internal stresses between and inside the grains.

Virtual test

LS-Dyna fit
Summary

- Microstructure based models can potentially improve the quality of deep drawing simulations

- **Direct approach: Crystal Plasticity FEM:**
  - limited by computational resources and UMAT convergence

- **Indirect approach: Virtual Testing (RVE):**
  - in principle acceptable for application in the automotive industry (no performance loss)
  - limited by empirical models in the simulation codes
  - Texture sampling must be improved (hand work not acceptable, quality not sufficient for low numbers of grains)
  - Hardening parameters (latent vs self hardening) need further investigation (r-values differ from real testing)