Bulk Metal Forming II
Simulation Techniques in Manufacturing Technology
Lecture 2

Laboratory for Machine Tools and Production Engineering
Chair of Manufacturing Technology

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Lecture objectives

- Overview of analytic and numeric methods in process modelling
- Introduction and fundamentals in Finite Element Modelling
- Examples of process simulations in bulk forming
- Overview of damage mechanisms and damage modelling in bulk forming
- Future developments in bulk forming simulation
Outline

1. Fundamentals of FEM-Simulations

2. Simulation of bulk forming

3. Examples

4. Future Developments

5. Summary
Stress conditions with corresponding Mohr's stress circles

Uniaxial

Biaxial

Triaxial

per definition $\sigma_1 > \sigma_2 > \sigma_3$
Start of yielding

\[ F_{st} \rightarrow \frac{|\sigma_3|}{k_t} \]

\[ F_1 \rightarrow \frac{|\sigma_2|}{k_t} \]

\[ F_b \rightarrow \frac{|\sigma_1|}{k_t} \]

\[ t_0 \quad t_1 \quad t_2 \quad t_3 \quad t_4 \quad t_5 \quad t_6 \]

flow
Yield stress and yield criterion

Assumption for plastic flow (v. Mises)

\[ \sigma_V = k_f = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}} \]

Equivalent stress

Yield criterion

\[ \sigma_V = k_f \]
Comparison of the yield criterions according von Mises and Tresca

von Mises

\[ \sigma_V = k_f = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}} \]

Yield begin: deviatoric stress reaches critical value

Tresca

\[ \sigma_V = |\sigma_1 - \sigma_3| = 2\tau_{\text{max}} = k_f \]

Yield begin: shear stress \( \tau_{\text{max}} \) reaches shear yield \( k \)

Demonstration of the two yield criterions in a yield locus diagram for the state of plane stress.
Levy-Mises flow rule

**Elastic**

**Hooke’s law:**
Mathematical dependence between stress and strain.

\[ \varepsilon_1 = \frac{1}{E} \sigma_1 \]

**Plastic**

**Levy-Mises flow rule:**
Mathematical dependence between yield stress and strain rate.

The strain rate tensor and the deviatoric stress tensor are proportional to each other (\( \lambda = \text{proportionality factor} \)).

Flow rule:
\[
\begin{align*}
d\varphi_1 &= d\lambda (\sigma_1 - \sigma_m) \\
d\varphi_2 &= d\lambda (\sigma_2 - \sigma_m) \\
d\varphi_3 &= d\lambda (\sigma_3 - \sigma_m)
\end{align*}
\]

Alternative form (division by dt):
\[
\begin{align*}
\dot{\varphi}_1 &= \dot{\lambda} (\sigma_1 - \sigma_m) \\
\dot{\varphi}_2 &= \dot{\lambda} (\sigma_2 - \sigma_m) \\
\dot{\varphi}_3 &= \dot{\lambda} (\sigma_3 - \sigma_m)
\end{align*}
\]

Proportionality factor \( \lambda \) (not constant):
\[ \dot{\lambda} = f(k_f, \varphi) \]

Out of flow rule and v. Mises yield criterion follows:
\[ \dot{\lambda} = \frac{1}{k_f} \sqrt{\frac{3}{2} (\dot{\varphi}_1^2 + \dot{\varphi}_2^2 + \dot{\varphi}_3^2)} \]
Calculation methods in plasticity theory

"elementary" plasticity theory

analytical methods
- energy method
- stripe model
- disk model
- tube model
  based on simplifications

strict solution
  slip field calculation

viscoplasticity

graphical-, empirical-, analytical method

numerical methods
- upper and lower bound method
- error compensation method
- finite element method

closed solution

approximate solution
Analytical calculation methods with the stripe-, disk- and tube model

stripe model

strip

tube model

tube

disk model

disk
Equilibrium condition in drawing direction:
\[ \sigma_z + A \frac{d\sigma_z}{dA} + p(1 + \mu \cot \alpha) = 0 \]

Yield criterion according to Tresca with \( p \) (compressive stress) and \( \sigma_z \) (tensile stress) \( \geq 0 \):
\[ p + \sigma_z = k_f \]

Elimination of \( p \) results in a differential equation of 1st order:
\[ \frac{d\sigma_z}{dA} - \frac{\mu \cot \alpha}{A} \sigma_z + \frac{k_f(1 + \mu \cot \alpha)}{A} = 0 \]
\[ \sigma_z' + f(x)\sigma_z + g(x) = 0 \]

Example: drawing of rods or wire

Assumptions:
- \( v_z(r) = \text{const.} \)
- \( v_z(z) \neq \text{const.} \)
Viscoplasticity in bulk metal forming

Characterization of the velocity field by measurement of the temporary change of markers.

No information about the stress distribution.

Source: Lange, K. (1990)
Principles of metal forming: Material Laws

- Modelling of the material behavior based on mathematical material laws.

- Deduction of the modelling parameters from experimental data:
  - Elastic material behavior: Young’s Modulus, Poisson’s ratio, elastic anisotropy
  - Plastic material behavior: flow curve, strain hardening parameter, plastic anisotropy

- Usage of ideal-plastic material models are mostly sufficient for bulk forming.

- Usage of elastoplastic material models in sheet metal forming simulations.

Low accuracy / low calculation time

- Elastic
- Ideal-plastic

High accuracy / high calculation time

- Elastoplastic with strain hardening
- Plastic with strain hardening
Verification of the material law

\[ h_0 = 45 \text{ mm} \]

\[ h_0 = 45 \text{ mm} \]

Yield stress \( k_f \) / MPa

Force \( F_{St} \) / kN

Plastic strain \( \varphi \) /

Stroke \( x_{St} \) / mm

- Experimental
- Plastic, isotropic
- Elastic-plastic, isotropic
- Elastic-plastic, kinematic

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Friction laws in metal forming

- **Coulomb friction:**
  \[ |\tau_R| = \mu \cdot \sigma_N \]

- **Shear friction:**
  \[ \tau_R = m \cdot k \text{ with } k = \frac{k_f}{\sqrt{3}} \]

- Wanheim and Bay developed a more general friction law with a continuous transition of the two friction laws mentioned above:
  \[ \tau_R = f \cdot \alpha \cdot k \]

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\( \sigma_N \) – Normal stress
\( \tau_R \) – Shear stress
\( \mu, m \) – Friction coefficients
\( f \) – Friction factor
\( \alpha \) – Ratio of the contact areas
Outline

1 Fundamentals of FEM-Simulations
2 Simulation of bulk forming
3 Examples
4 Future Developments
5 Summary
Idealization of the workpiece’s geometry:

- Simplification of the original geometry by neglecting unimportant details
- Assumption of constant wall thickness
- Making use of symmetry axes and planes
- Making use of rotational symmetry: Reducing 3D-Models to 2D-Models

Advantages:
- Reduction of complexity
- Reduction of calculation time

Disadvantages:
- Less simulation accuracy
- Greater deviation from reality

Source: ABAQUS User’s Manuals
### Type of elements

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Element type (load)</th>
<th>Geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1D</strong></td>
<td>Rod (strain)</td>
<td></td>
</tr>
</tbody>
</table>
| **2D**    | Beam (strain, bending)  
Membrane (2-dim. strain)  
Shell (strain, bending) | ![2D Geometry](image) |
| **3D**    | Volume element (strain) | ![3D Geometry](image) |
Continuum discretization in Finite Element Method

- **Lagrange:**
  - Nodes and elements move with the material
  - Remeshing is necessary when elements distort
  - Suitable for simulations of instationary processes

- **Eulerian:**
  - Nodes and elements stay fixed in space
  - Material flows through a stationary mesh
  - No remeshing necessary
  - Suitable for simulation of stationary processes and fluid dynamics simulations

- **ALE (Arbitrary Lagrangian Eulerian):**
  - Combination of Lagrange and Eulerian Models
  - Reduction of mesh distortion by permitting material flow through the mesh but only within the object boundary shape
  - Suitable for stationary processes only
Mesh optimization

- Methods of mesh optimization:
  - Local and global mesh smoothing
  - Local and global remeshing

- Advantages of mesh smoothing:
  - Fast calculation time
  - Small loss of accuracy

- Advantages of remeshing:
  - No great element distortion
  - Reduction of calculation time by increasing element size in uncritical areas

An ideal mesh is decisive for the quality level of results and fast convergence of FE-simulations
Cup-extrusions process

Semi-finished product  Setup  Cup
Cup-extrusions process: effective strain, effective strain rate

Effective strain $\varphi_V$

Effective strain rate $d\varphi/V/dt$
Cup-extrusions process: mean stress, effective stress

Mean stress $\sigma_m$

Effective stress $\sigma_V$

$\sigma_m$, MPa

$\sigma_V$, MPa
Cup-extrusions process: axial and radial stress

Axial stress $\sigma_z$

Radial stress $\sigma_r$
Cup-extrusions process: damage and axial velocity

Damage $D$

Axial velocity $v_z$

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Macromechanical damage criteria

Forming process

Cylinder specimen

Collar specimen

Damage criterion

Effective strain

Norm. Cockroft & Latham

\[ D_{\text{max}} = 1,17 \]

\[ h_0 = 45 \text{ mm} \]

\[ h_{\text{crack}} = 8,2 \text{ mm} \]

\[ h_0 = 43 \text{ mm} \]

\[ h_{\text{crack}} = 22,5 \text{ mm} \]

\[ D_{\text{max}} = 1,37 \]

\[ D_{\text{max}} = 0,483 \]

\[ D_{\text{max}} = 0,334 \]

Crack

Crack

Crack

Crack

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Micromechanical damage criteria

Forming process

Cylinder specimen

Collar specimen

Damage criterion

McClintock

Crack

$D_{\text{max}} = 0.754$

Crack

$D_{\text{max}} = 0.522$

Crack

$D_{\text{max}} = 0.73$

Crack

$D_{\text{max}} = 0.424$

Mod. Rice & Tracey

$D_{\text{max}} = 0.424$
Cause of material separation

- Void nucleation starts at inclusions

- Mechanisms of void nucleation:
  - Fracture or decohesion of inclusions
  - Nucleation due to decohesion at the grain border
  - Initiation of cracks at existing voids

![Void nucleation](image1)

![Void growth](image2)

![Void coalescence](image3)

- Tensile test

- Crush test
Forming history - experiment

4 Point Bending

- Punch
- Blank holder
- Sheet
- Die
- Counter punch

<table>
<thead>
<tr>
<th>Step 1</th>
<th>Step 2</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Area</th>
<th>$\sigma_1$</th>
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<tbody>
<tr>
<td>A</td>
<td>0</td>
</tr>
<tr>
<td>B</td>
<td>0</td>
</tr>
<tr>
<td>C</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area</th>
<th>$\sigma_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>&gt;0</td>
</tr>
<tr>
<td>B</td>
<td>&lt;0</td>
</tr>
<tr>
<td>C</td>
<td>&gt;0</td>
</tr>
</tbody>
</table>

Experiment

- Thickness 10 mm
- Thickness 8 mm

Phase 1 (1. Umformung)
Phase 2 (2. Umformung)

4 Point Bending Experiment
Thickness 10 mm
Thickness 8 mm
Forming history – Area C

Forming history – Area B

Step 1

Step 2

Step 1

Step 2
Outline

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Examples FEM-3D

Geared shaft
combined backward and radial extrusion

Fender
deep drawing

Joint
radial extrusion
Examples FEM-3D DEFORM: rotary forging - mesh
Examples FEM-3D DEFORM: rotary forging - nodal velocities
Examples FEM-3D DEFORM: rotary forging - strain
Examples FEM-3D DEFORM: rotary forging - strain rate
Examples FEM-3D DEFORM: radial forging cross joint, mesh
Examples FEM-3D DEFORM: radial forging cross joint, strain rate
Examples FEM-3D ABAQUS: rolling of a slab

Source: LSTC
<table>
<thead>
<tr>
<th>Outline</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>Fundamentals of FEM-Simulations</td>
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<td>Simulation of bulk forming</td>
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<tr>
<td>4</td>
<td>Future Developments</td>
</tr>
<tr>
<td>5</td>
<td>Summary</td>
</tr>
</tbody>
</table>
Future developments: improving prediction of ductile fracture

Fundamental research

- Experiments with different geometries
- Visual identification of void nucleation
- Results: Location and time of first crack initiation
- Simulation of experiments
- Forming history

Database with different forming histories

Application in the industry

- Simulation of process
- Identification of critical locations in workpiece
- Forming history
- Using the trained neural network

Determination of formability

Training the neural network

Visual identification of void nucleation

Simulation of experiments

Forming history
Ductile fracture prediction: implementation in DEFORM

1. Saving data in memory
   - Serial transportation of DATA to USRUPD
   - Nodes, Elements
2. Calculation of forming history
   - Received all data
     - n
3. DATAMANAGER
   - Read point to be tracked from file and identify the element that contains this point
   - Read stress rate, calculate $\sigma_1$, $\sigma_3$, $\sigma_V$ and $\Theta$ and save values
   - Calculate movement of tracking point and save coordinates for next step
4. Continue simulation

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Artificial neural networks: test for formability

Analogue experiments: Compression

Other analogue experiments

Indentation test  Lateral extrusion  Tensile test  Fine blanking  Bending
Relevant mechanical parameters for the neural network

- $\sigma_1$: Consideration of void growth
- $\sigma_m$: Consideration of multi axis character
- $\sigma_V$: Consideration of stress tensor
- $\varphi_V$: Consideration of equivalent strain
- $\alpha$: Consideration of load direction
Design of artificial neural networks
Artificial neural networks: damage prediction

<table>
<thead>
<tr>
<th>Damage &lt; 100 %</th>
<th>Damage &gt; 100 %</th>
</tr>
</thead>
<tbody>
<tr>
<td>D_{ANN}</td>
<td>D_{C&amp;L}</td>
</tr>
</tbody>
</table>

D_{ANN}: Damage parameter ANN
D_{C\&L}: Damage parameter Cockroft & Latham
### Future developments: Problem orientated metal forming simulation

<table>
<thead>
<tr>
<th>Simulation input</th>
<th>Simulation output</th>
<th>Problem</th>
<th>Question to answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry</td>
<td>Forces</td>
<td>Initial rod diameter</td>
<td>Does the die break?</td>
</tr>
<tr>
<td>Material properties</td>
<td>Velocity fields</td>
<td>Final rod diameter</td>
<td>Does ductile fracture appear?</td>
</tr>
<tr>
<td>Interface conditions</td>
<td>Strains</td>
<td>Workpiece and extrusion length</td>
<td>Is annealing needed for recrystaization?</td>
</tr>
<tr>
<td>Simulation control</td>
<td>Strain rates</td>
<td>Geometry of die</td>
<td>Does the process work?</td>
</tr>
<tr>
<td>Meshing parameters</td>
<td>Stresses</td>
<td>– Standard die</td>
<td>How can I improve the process?</td>
</tr>
<tr>
<td>Material model</td>
<td>Temperatures</td>
<td>– Free geometry</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Punch velocity</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Material</td>
<td></td>
</tr>
</tbody>
</table>

- **Current status**
- **Simulation tools of the future**
## Available programs on the market

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Element type: 2D / 3D</th>
<th>Automatic remeshing: 2D / 3D</th>
<th>Main application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transvalor / F</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td>bulk forming</td>
</tr>
<tr>
<td>SFTC / USA</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td>bulk forming</td>
</tr>
<tr>
<td>MSC / USA</td>
<td>- ✓</td>
<td>✓ ✓</td>
<td>bulk forming</td>
</tr>
<tr>
<td>MSC / USA</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td>bulk forming</td>
</tr>
<tr>
<td>Quantor / RUS</td>
<td>✓ ✔</td>
<td>✓ ✓</td>
<td>bulk forming</td>
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<tr>
<td>MSC / USA</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td>bulk forming</td>
</tr>
<tr>
<td>LSTC / USA</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td>sheet and bulk</td>
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<tr>
<td>CPM / D</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td>bulk</td>
</tr>
<tr>
<td>Dynamic Software /</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td>sheet</td>
</tr>
<tr>
<td>AutoForm GmbH /</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td>sheet</td>
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<tr>
<td>inpro mbH / D</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td>sheet</td>
</tr>
</tbody>
</table>
Outline

1 Fundamentals of FEM-Simulations

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5 Summary
Summary

- Yield criteria and yield laws in metal forming
- Basic understanding of bulk forming simulation input variables, simulation and output parameters
- Damage criteria and methods for damage prediction
Questions

- Outline the Mohr`s stress circles with uni-, bi- and triaxial compressive stress conditions.
- Explain the differences between the yield criterion of von Mises and Tresca.
- Why are the two conventional friction models (shear and coulomb) not accurate enough for the description of forging processes?
- What are typical results of a bulk forming simulation?
- Explain the approach to damage and crack prediction?