Simulation of Metastable Austenitic Stainless Steels with LS-DYNA

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Agenda

- Metastable Austenitic Stainless Steels
- HänSEL – Model for metastable austenitic steels
- Simulation examples
- Summary and Outlook
Metastable Austenitic Stainless Steels I

- Deformation based phase transformation from austenite to martensite
  - strain-induced martensite
- Formation of strain-induced martensite depends on:
  - alloy composition (high martensite volume for low Ni-content)
  - martensite volume
  - temperature

Formula:
\[ \Delta T_{\text{f}} = \frac{k}{f(T)} \]

Ref.: Hänsel, ETH Zurich, (1998)

Metastable Austenitic Stainless Steels II

- Formation of martensite effects mechanical properties of material:
  - work-hardening (higher yield stress)
  - ductility/formability

Ref.: Hänsel, ETH Zurich, (1998)
Material Model in LS-DYNA:

*MAT_TRIP (*MAT_113)

- Model as suggested by Hänsel (ETH Zurich):
  - Martensite rate as a function of martensite volume and temperature
  - Extended Hocket-Sherby hardening rule

- Non-isothermal Model
  - Temperature from coupled thermo-mechanical analysis
  - Adiabatic temperature calculation

Hänsel Model:
Martensite Rate Equation

- Martensite rate as a function of martensite volume and temperature

\[
\begin{align*}
\text{if } & \varepsilon < E_{0(\text{mart})} \Rightarrow \frac{\partial V_m}{\partial \varepsilon_p} = 0, \\
\text{else if } & \varepsilon \geq E_{0(\text{mart})} \Rightarrow \frac{\partial V_m}{\partial \varepsilon_p} = \frac{B A}{P} \left( 1 - \frac{V_m}{V_m^H} \right)^\frac{1+B}{B} \left( V_m \right)^\gamma \left[ 0.5 \cdot (1 - \tanh(0.4C + 0.6T)) \right]
\end{align*}
\]

Ref.: Hänsel, ETH Zurich, (1998)
Hänsel Model: Hardening Rule

- Extended Hocket-Sherby function

\[ \sigma_y = \left[ B_{HS} - (B_{HS} - A_{HS})e^{-m(\varepsilon_p + \varepsilon_0)} \right] \left( K_1 + K_2 T \right) + \frac{\Delta H}{V_M} \]

increase of yield stress due to formation of martensite

Simulation Examples
Simulation of Tension Test

- Steel grade: 1.4301
- Coupled thermo-mechanical analysis
  - 90 % of the plastic work is converted to heat
  - heat conduction, convection, initial temperatures
  - ram speed v = 0.25 mm/s

Tension Test: Results I

- Evaluation of results at center of specimen

![Effective Stress vs. Effective Plastic Strain](image)

![Sheet Thickness](image)
Tension Test: Results II

- Evaluation of results at center of specimen

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Martensite Volume</th>
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<tbody>
<tr>
<td>- experiment</td>
<td>- simulation</td>
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Influence of thermal boundary conditions

- Estimates for heat transfer coefficient for convection to environment:
  - natural convection in air: $h \approx 5 \text{ W/m}^2\text{K}$
  - forced convection in air: $h \approx 200 \text{ W/m}^2\text{K}$

<table>
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| - experiment | - $h = 25 \text{ W/m}^2\text{K}$
  - $h = 15 \text{ W/m}^2\text{K}$
  - $h = 35 \text{ W/m}^2\text{K}$
Limit Drawing Ratio for Cup Drawing

- Metastable austenitic stainless steels:
  - temperature dependent work hardening
  - limit drawing ratio can be increased by controlling the tool temperature

Ref.: Hänsel, ETH Zurich, (1998)

Model for Cup Drawing

- $T_{\text{punch}} = 10 \, ^{\circ}\text{C}$
- $T_{\text{die}} = T_{\text{binder}} = 0, 20, 50, 80, 100$ or $120 \, ^{\circ}\text{C}$
- $T_{\text{blank}} = 20 \, ^{\circ}\text{C}$
Martensite Volume for Draw Ratio 2.2

\[ T_{\text{die}} = T_{\text{binder}} = 20 \, ^\circ\text{C} \]
\[ T_{\text{die}} = T_{\text{binder}} = 100 \, ^\circ\text{C} \]

Determination of Limit Drawing Ratio

- Simple optimization procedure with LS-OPT for each chosen temperature:
  - objective function: “maximize blank diameter”
  - strict constraint: ”preserve FLC”
Result: Limit Drawing Ratio

![Graph showing limit drawing ratio as a function of die and binder temperatures with a punch temperature of 10 °C.]

Kitchen Sink: Material 1.4301 (CrNi18 9)

Ref.: Hänsel, ETH Zurich, (1998)
Kitchen Sink

- Temperature dependency of material properties

\[ T_{\text{Tools}} = 20 \, ^\circ\text{C} \quad \text{Martensite fraction: 11.5 \%} \]

\[ T_{\text{Tools}} = 55 \, ^\circ\text{C} \quad \text{Martensite fraction: 6.8 \%} \]

Ref.: Hänsel, ETH Zurich, (1998)

Simulation Model of Sink

- Steel grade 1.4301, Sheet thickness: 0.83 mm
- Coupled thermo-mechanical analysis ...
Simulation of Kitchen Sink: Draw-in

Ref.: Hänsel, ETH Zurich, (1998)

Comparison of Martensite Volume I

- $T_{\text{Tools}} = 20 \, ^\circ\text{C}$

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Comparison of Martensite Volume II

- $T_{\text{Tools}} = 55 \, ^\circ\text{C}$

Martensite Volume

- $T_{\text{Tools}} = 20 \, ^\circ\text{C}$
- $T_{\text{Tools}} = 30 \, ^\circ\text{C}$
- $T_{\text{Tools}} = 55 \, ^\circ\text{C}$
Summary and Outlook

- Material model \texttt{*MAT_TRIP} in LS-DYNA Version 971:
  - capability to include TRIP-effect in simulation
  - in coupled thermo-mechanical analysis adequate thermal boundary conditions and thermal material parameters have to be chosen

- Current limitations:
  - isotropic Von Mises yield surface

- Further work:
  - anisotropic yield surface
  - failure prediction
  - sensitivity study regarding the thermal parameters

Thank you for your attention