Hot Stamping Process Simulation with LS-DYNA
Capabilities and Benefits

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Agenda

1. Hot Stamping and Presshardening of Boron Steel
2. Hot Stamping Feasibility Studies
3. Presshardening Cooling Simulations
4. Prediction of Microstructure in Presshardening
5. 2-stage forming of intermediate induction heat treated aluminum
6. Prediction of frictional thermal load on forming tools
Hot Stamping of Boron Steel

- **feasibility of forming**
  - tool geometry
  - process design

- **reliability of hardening**
  - coolant ducts
  - cooling system

- **optimized forming tools**
  - detailed tool design
  - stiffness optimization

**CAD**
- major design criteria
  - fracture
  - wrinkles
  - thinning

**CAE**
- simulation
  - cooling rates
  - tool temperature
  - cycle time

- CNC program
- machining

**Integrated product optimization**
- crash
- fatigue
Hot Stamping of Boron Steel

- feasibility of forming
- reliability of hardening
- optimized forming tools

- tool geometry process design
- coolant ducts cooling system
- detailed tool design stiffness optimization

- CAD
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- CAE
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- major design criteria
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- tool geometry
- process design
- fatigue
- integrated product optimization

- CNC programming
- machining
High predictive quality of a simulation requires detailed consideration of essential effects

- Which are essential effects affecting simulation accuracy?
- How are these effects considered in our models?

Simulation requires efficient model approaches to be an effective engineering tool

- Simple tool modeling without loss in accuracy?
- Numerical measures to speed up simulations?
Accuracy of forming simulations strongly depends on the consideration of temperature dependent viscoplasticity.

*DEFINE_TABLE_3D

... 20.0 101

... 500.0 104

... 800.0 108

*DEFINE_TABLE

Direct tabulated input requires a lot of material data …
Temperature dependent material properties require an accurate calculation of the inhomogeneous blank temperature during the forming operation.

- Heat transfer to the dies by:
  - contact, depending on contact pressure
  - gap conductance

- Ambient heat transfer
  - radiation
  - convection

\[ \Delta T = 141^\circ C \]
Tool surface temperature directly affects the heat flux from blank to the die

\[
\dot{q}_{\text{cont}} = h_{\text{cont}} \cdot (T_{\text{blank}} - T_{\text{tool}})
\]

Tool surface temperature before and after forming operation

thermal thick shell

thickness calibration

error +/- 10 °C

max. contact time ~5s
Tool surface temperature directly affects the heat flux from blank to the die

\[ \dot{q}_{\text{cont}} = h_{\text{cont}} \cdot (T_{\text{blank}} - T_{\text{tool}}) \]

*CONTROL_SHELL  \( TSHELL=1 \)

*CONTROL_CONTACT  \( ITHOFF=1 \)

Tool thickness for different materials:

- 1.2367  \( \lambda = 28 \text{ W/mK} \)  \( d_{\text{tool}} = 10.0 \text{ mm} \)
- HTCS-117  \( \lambda = 41 \text{ W/mK} \)  \( d_{\text{tool}} = 12.0 \text{ mm} \)
- HTCS-130  \( \lambda = 62 \text{ W/mK} \)  \( d_{\text{tool}} = 16.0 \text{ mm} \)
Accurate wrinkling analysis

- wrinkling control in areas of unsupported deformation is a difficult task
- Wrinkleless should flatten during die closing

Check if contact pressure on forming die is critical
Accurate wrinkling analysis

- wrinkling control in areas of unsupported deformation is a difficult task
- Sheet doubling during wrinkle deformation is an important failure mode in hot stamping
- Prediction of this failure is impossible without geometrical representation of wrinkles

sheet doubling process not feasible
Local deformation due to contact with guide pins

- Deformation inside trimline ⇒ o.k
- Deformation outside trimline ⇒ not o.k
A simple and fast shell only model for the cooling step

*use the thermal thick shell*

*and add an artificial heat flux to the backside*

→ the thickness is directly computed from thermal material properties
→ the heat flux is directly computed from the thickness and the conductivity
Presshardening Cooling Simulations

Modelling the watercooling system

- High mass flow through cooling channels
- Increase of water temperature from inlet to outlet < 10°C

\[ \dot{q} = h_{con} \cdot (T_{wall} - T_{water}) \]
Presshardening Cooling Simulations

**Calculating** $h_{con}$

- application of convection BCs on channel walls is simple and sufficient
- convection coefficient by established analytical solutions for pipe flow

\[
h = 0.023 \frac{k}{D} \text{Re}^{0.8} \text{Pr}^{0.3}
\]

Dittus-Boelter (conservative)

\[
h = 0.023 \frac{k}{D} \text{Re}^{0.8} \text{Pr}^{0.3} \left( \frac{\mu_{bulk}}{\mu_{wall}} \right)^{0.14}
\]

Sieder-Tate (temperature correction)

\[
h = \left( \frac{k}{D} \right) \left[ \frac{(f/8) (\text{Re} - 1000) \text{Pr}}{1 + 12.7 (f/8)^{1/2} (\text{Pr}^{2/3} - 1)} \right]
\]

Gnielinski (wall friction effect)

- average flow velocity is required
  1. given mass flow rate per channel
  2. calculation with pipe network calculator
  3. computed with CFD analysis
using an excel sheet to calculate $h_{con}(d,v,T)$

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Graph showing $h_{Dittus-Boelter}$ vs $T_{film}$
Presshardening Cooling Simulations

Cooling Simulation of a B-Pillar

- 3D mesh required for all active tool segments
- mesh contains geometry of cooling channels
- mesh generation in preprocessor is a timeconsuming task

→ 3D mesh generation in CAD System can save a lot of time
Presshardening Cooling Simulations

*Cooling Simulation of a B-Pillar*

- tool temperature after 5 s
- tool temperature after 10 s
Cycled cooling simulations - Conclusion

- If you want to verify your tool design (number of cooling bores, diameter, distance from surface) you must simulate the whole start up period.

- If you capture only the first stroke in your simulation you will always get optimistic answers, even for bad tool designs.

- An insufficient cooling design can only be compensated by longer cycle times, which will cost much money.
Prediction of final properties

Hot Stamping of an A-Pillar

- model size: 284.602 shells, 2.946.238 tet4, 634.193 nodes
- total CPU time ~20 min per stroke @ 1 node with 8 CPUs
- Fully hardened part is desired → check time-temp curves

![Initial tool temperature](initial_tool_temperature.png)

![Part removal](part_removal.png)

![Part cooling over 10 cycles](part_cooling_over_10_cycles.png)
Prediction of final properties

**MAT_UHS_STEEL (MAT_244) for advanced simulations**

**User Input:**
- alloying elements in mass percent
  B, C, Co, Mo, Cr, Ni, V, W, Cu, P, Al, As, Ti
- latent heats for phase change reaction
- activation energy for phase transformation
- initial grain size
- yield curves for each phase
- thermal expansion coefficients

**Material Output:**
- current phase fraction of ferrite, pearlite, bainite and martensite
- computed Vickers hardness
- resulting yield strength
- austenite grain size

[Diagram: Recalculated CCT diagram]
Prediction of final properties

Parameter Identification for MAT_UHS_STEEL (MAT_244)

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- martensite + bainite
- no ferrite
- small amount of ferrite
- small amount of pearlite
Parameter Identification for MAT_UHS_STEEL (MAT_244)

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Relative error in calculated Vickers hardness
Prediction of final properties

Design a Process to get parts with tailored properties

by courtesy of Daimler AG
Prediction of final properties

Solving the task to get tailored properties

**in the furnace by partial heating**

**in the tool by partial tool heating**

**in a second process step**

---

- **Ac**
- **Ms**
- **A+B**
- **A+F**
- **A+P**
- **T<sub>A</sub>**

**Note:** The diagram shows the temperature-time curves for different processes and heating methods, including conventional press hardening and partial heating in the furnace and tool.
Prediction of final properties

Tailored Tempering Process in principle

Microstructure after 14 s closing time (MAT_244)

- **Martensite**
  - Fringe Levels:
    - 9.992e-01
    - 8.993e-01
    - 7.994e-01
    - 6.995e-01
    - 6.906e-01
    - 5.905e-01
    - 4.906e-01
    - 3.907e-01
    - 2.908e-01
    - 1.988e-01
    - 9.982e-02
    - 6.000e+00

- **Bainite**
  - Fringe Levels:
    - 6.529e-01
    - 5.877e-01
    - 5.224e-01
    - 4.572e-01
    - 3.919e-01
    - 3.267e-01
    - 2.614e-01
    - 1.962e-01
    - 1.309e-01
    - 6.595e-02
    - 4.376e-04

- **Austenite**
  - Fringe Levels:
    - 9.515e-01
    - 8.564e-01
    - 7.612e-01
    - 6.661e-01
    - 5.709e-01
    - 4.758e-01
    - 3.806e-01
    - 2.855e-01
    - 1.903e-01
    - 9.529e-02
    - 4.504e-05
Calibration of die heating process

A simple tool setup for simulation calibration

testcase every 2nd heater switched off
Calibration of die heating process

**B-Pillar tool for validation of heating simulation**

→ direct use of the calibration parameters without adjustment

---

**Simulation**

**Thermographic**
Heat supported coldforming of aluminum

The main task

1 stage cold forming  2 stage coldforming with local intermediate heattreatment (IHT)

→ inductive heating at critical zones

- increased formability due to adapted material properties
- Systematic material calibration for various prestrain and heating temperature
- Integration into an existing materialmodel \( (MAT\_36 \ MAT\_133) \) possible?

Quelle: Prof. Roll Daimler AG, Automotive Grand Challenges 2011
Heat supported coldforming of aluminum

Experimental material characterization

- Reduction of yield stress due to heat treatment
- Higher slope compared to base material → higher formability
  → hardening curves should be parametrized over prestrain and IHT temperature
Heat supported coldforming of aluminum

The solution in LS-DYNA

1st forming

Springback simulation

Heat treatment simulation

Springback simulation \(\Rightarrow\) unloading, equilibrium, elastic stresses

Heat treatment simulation \(\Rightarrow\) real temperature distribution \(\Rightarrow\) IHT temperature

\[ T_{WBH} = \max\{ T(t) \} \]

evaluate correction term \(\Delta \sigma\) \(\Rightarrow\) save in dynain
prediction of frictional thermal tool load

compute and store friction energy in forming simulation

Convert energy to heat flux in a pure thermal simulation

Repeat this cycle for many times in one single simulation

by courtesy of Adam Opel AG

friction energy

1 stroke

forming transfer & binder closing

time

...
prediction of frictional thermal tool load

Result after 200 strokes @ 15 strokes per minute

\[ \mu = 1 - 0.84 \cdot e^{\left( \frac{1.38}{T-273} \right)} \]

\( \Delta T = 15 \, ^\circ C \) gives 25% higher friction

by courtesy of Adam Opel AG
prediction of frictional thermal tool load

Result after 200 strokes @ 15 strokes per minute

1 110 389 TET4 Elements
50 000 shell elements
275 736 nodes
stroke rate 15 min⁻¹
stroke time 4s, forming time 0.61s
total time for 200 strokes 800s
8 thermal timesteps per stroke
1600 timesteps for entire solution
running with mpp971_d_R6.1
Total CPU time 2½ hours @ 4 cores

⇒ solve the 200 strokes thermal is much faster than 1 stroke forming simulation
questions