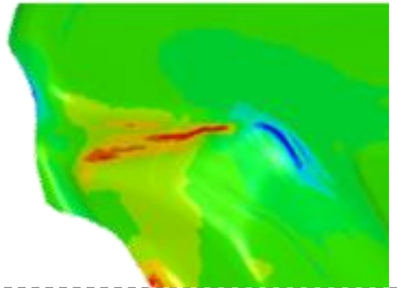
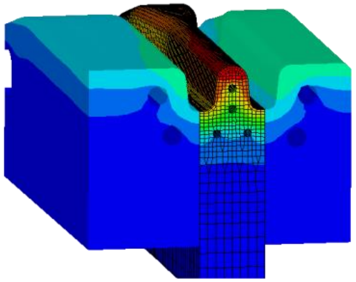
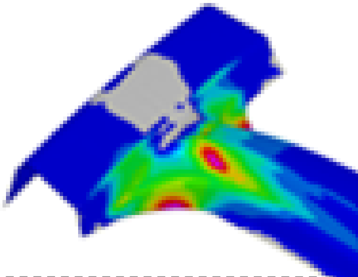
Advanced Metalforming Simulations using a thermo-mechanical coupling including phase changes

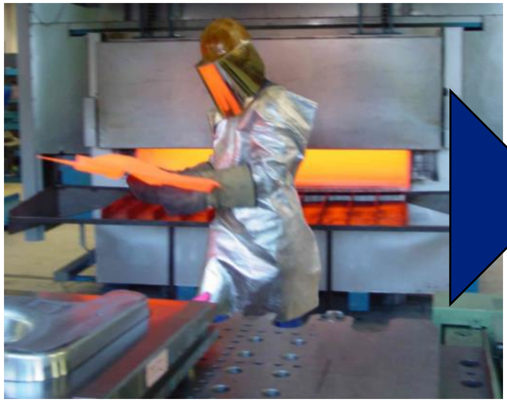
David Lorenz
DYNAmore GmbH

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. **Forming of stainless steel**

Hot Stamping of Boron Steel

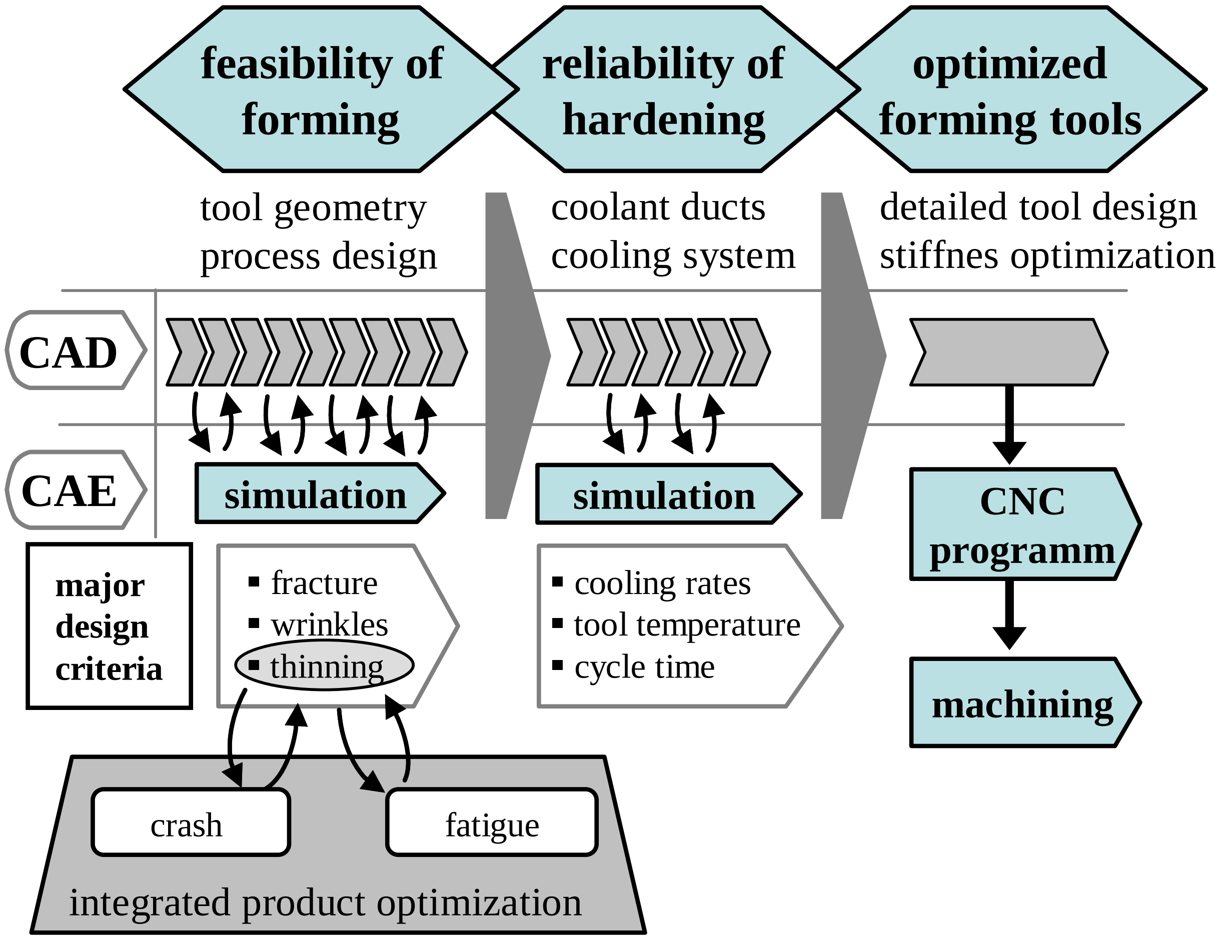


Transfer

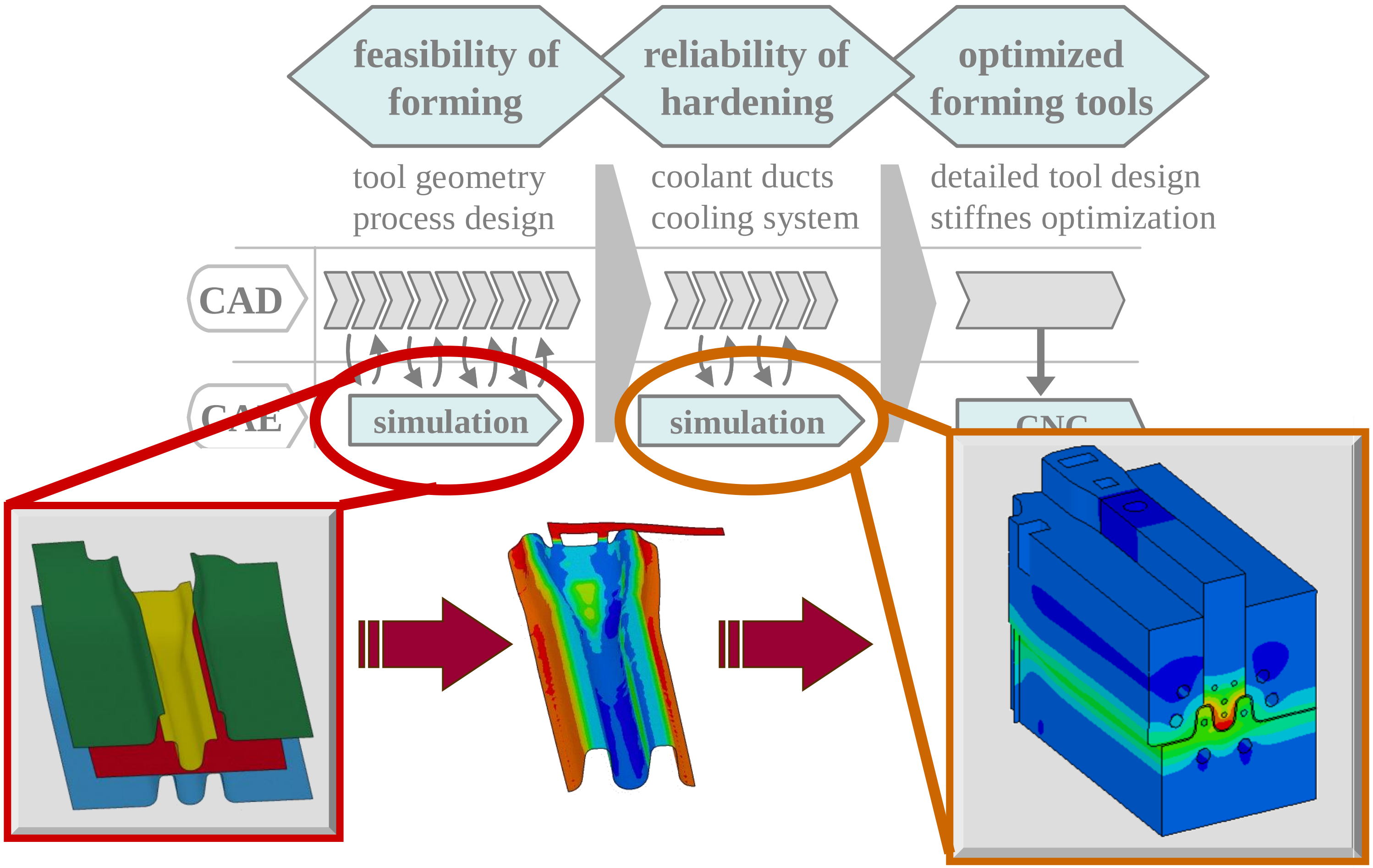
Positioning

Hot forming & Quenching

Hot Stamping of Boron Steel

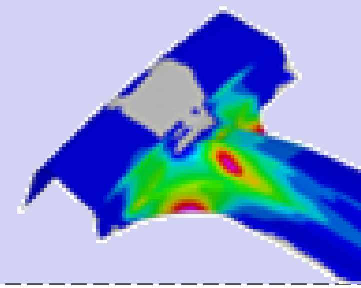


Hot Stamping of Boron Steel



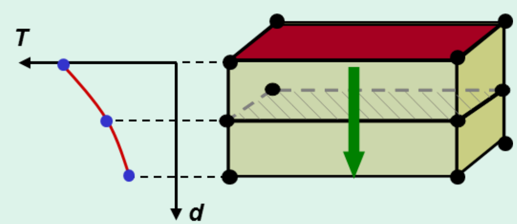
High predictive quality of a simulation requires detailed consideration of essential effects

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



Simulation requires efficient model approaches to be an effective enginering tool

- Simple tool modeling without loss in accuracy?
- Numerical measures to speed up simulations?



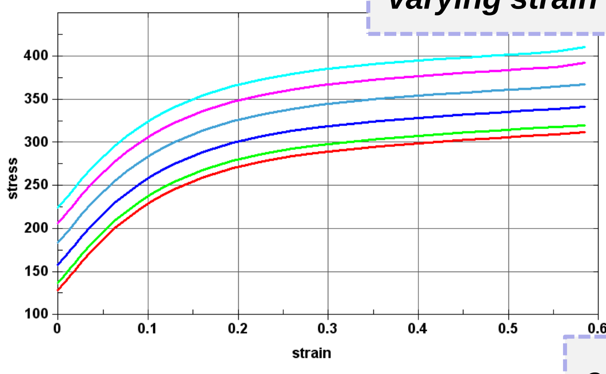
Accuracy of forming simulations strongly depends on the consideration of temperature dependent viscoplasticity

```
*DEFINE_TABLE_3D
     ...
20.0     101
     ...
500.0    104
     ...
800.0    108
     ...
```

temperature

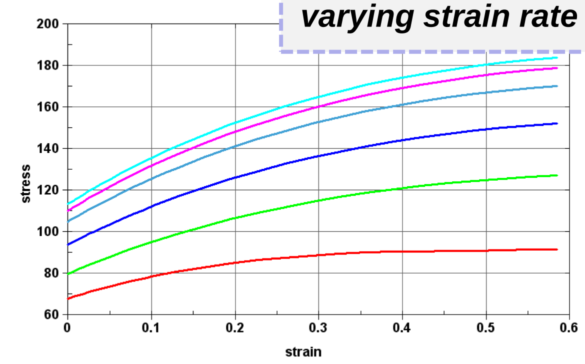
*DEFINE_TABLE

const. Temperature
varying strain rate



*DEFINE_TABLE

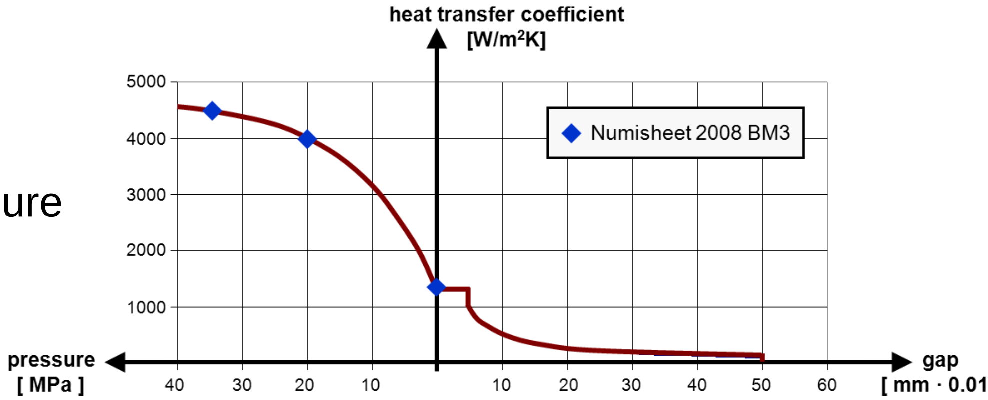
const. Temperature
varying strain rate



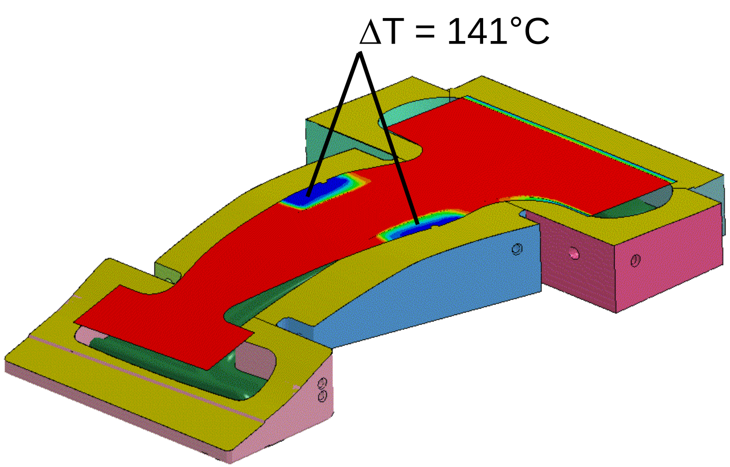
Direct tabulated input requires a lot of material data …

Temperature dependent material properties require an accurate calculation of the inhomogenuous blank temperature during the forming operation

- heat transfer to the dies by
  - → contact, depending on contact pressure
  - → gap conductance



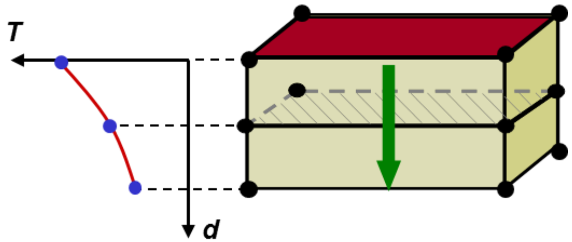
- ambient heat transfer
  - → radiation
  - → convection



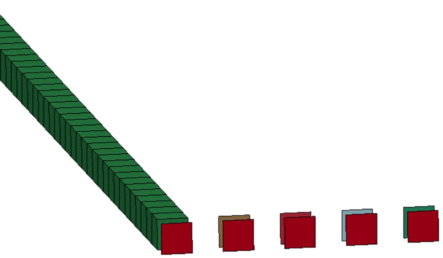
Tool surface temperature directly affects the heat flux from blank to the die

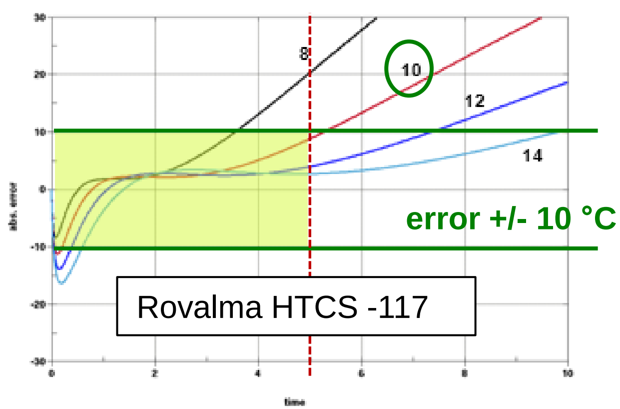
$$\dot{q}_{cont} = h_{cont} \cdot \left(T_{blank} - T_{tool}\right)$$

thermal thick shell



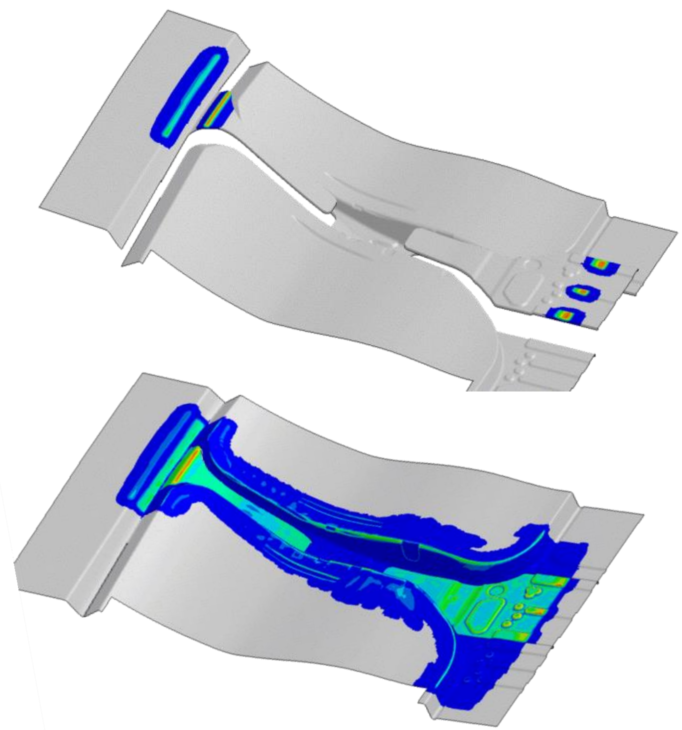
thickness calibration





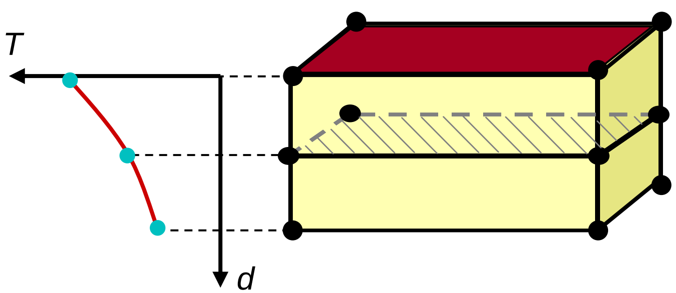
max. contact time ~5s

Tool surface temperature before and after forming operation



Tool surface temperature directly affects the heat flux from blank to the die

$$\dot{q}_{cont} = h_{cont} \cdot \left(T_{blank} - T_{tool}\right)$$

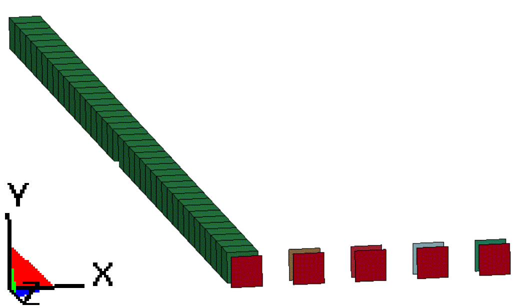


CONTROL_SHELL** ***TSHELL=1

+

CONTROL_CONTACT** ***ITHOFF=1

tool thickness for different materials

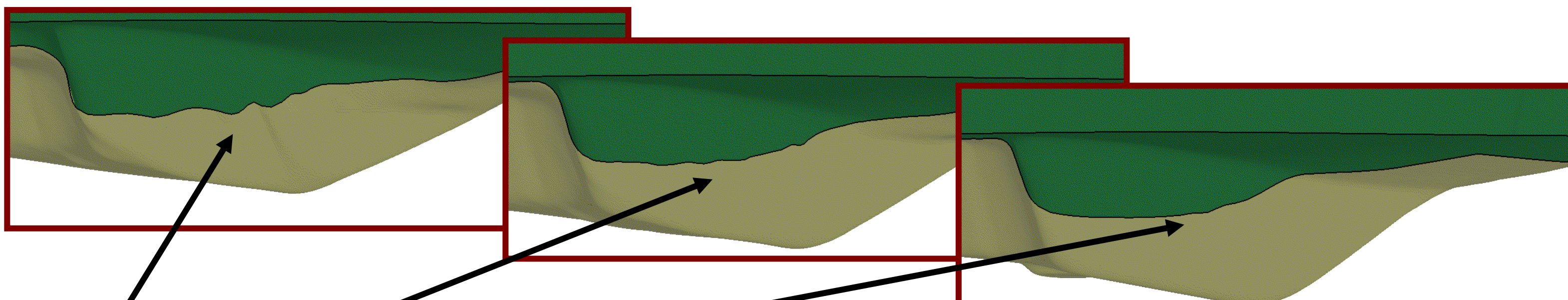


1.2367	λ = 28 W/mK	d_{tool} = 10.0 mm
HTCS-117	λ = 41 W/mK	d_{tool} = 12.0 mm
HTCS-130	λ = 62 W/mK	d_{tool} = 16.0 mm

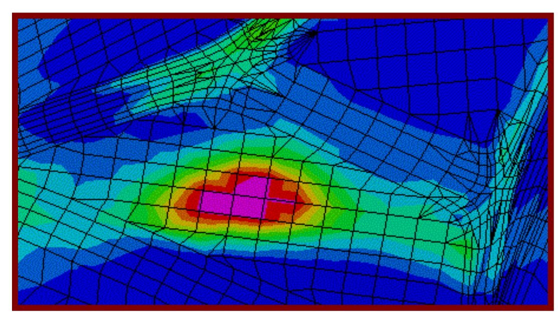
Hot Stamping Feasibility Studies

Accurate wrinkling analysis

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



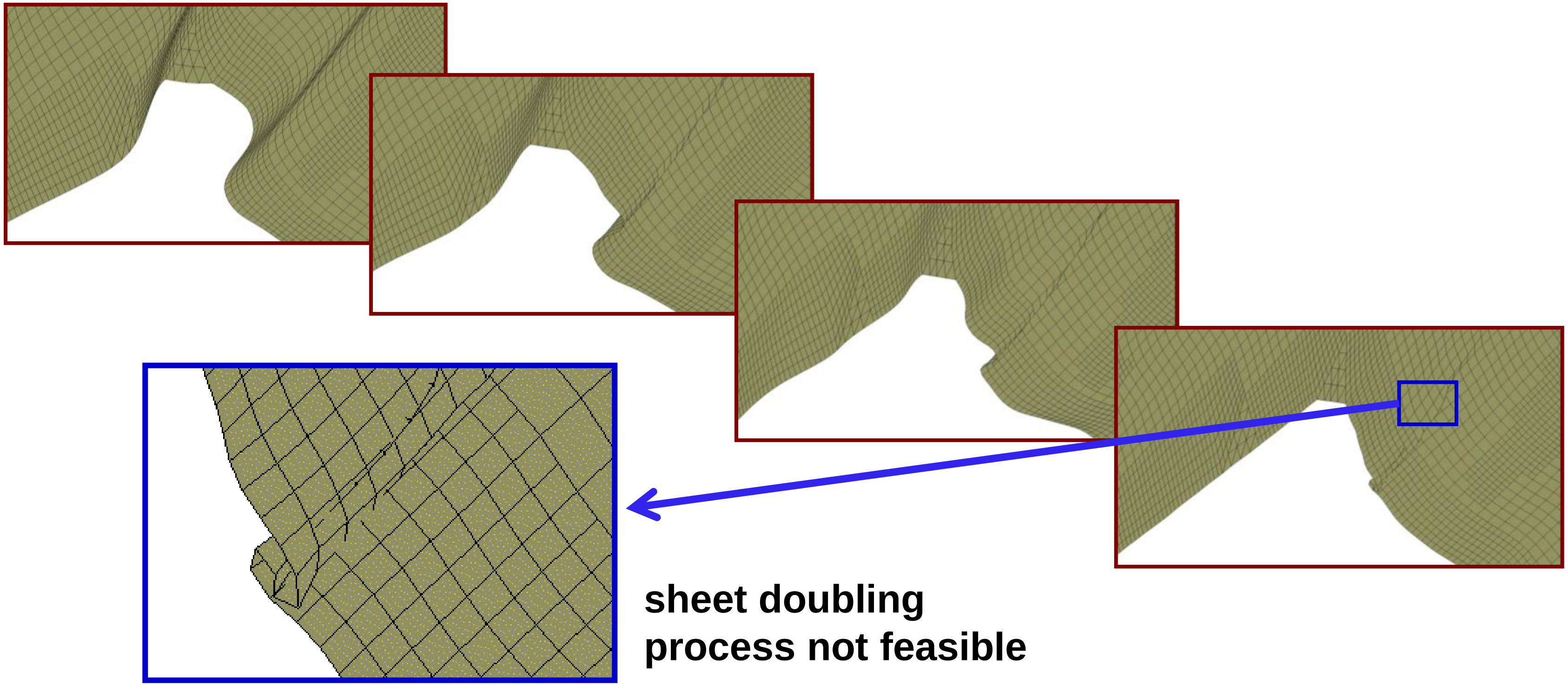
wrinkle flattening successful



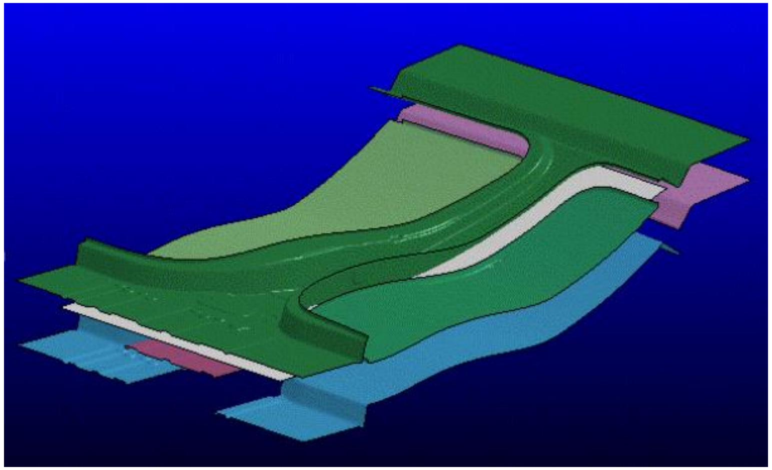
Check if contact pressure on forming die is critical

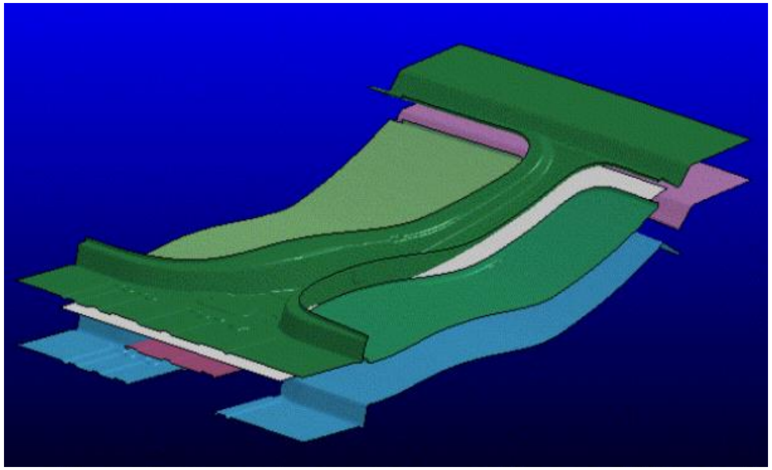
Accurate wrinkling analysis

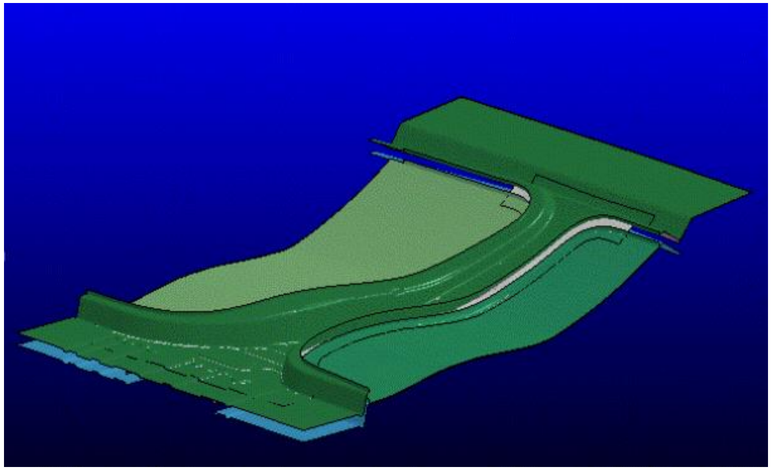
- wrinkling control in areas of unsupported deformation is a difficult task
- Sheet doubling during wrinkle deformation is an important failure mode in hot stamping
- Prediction of this failure is impossible without geometrical representation of wrinkles

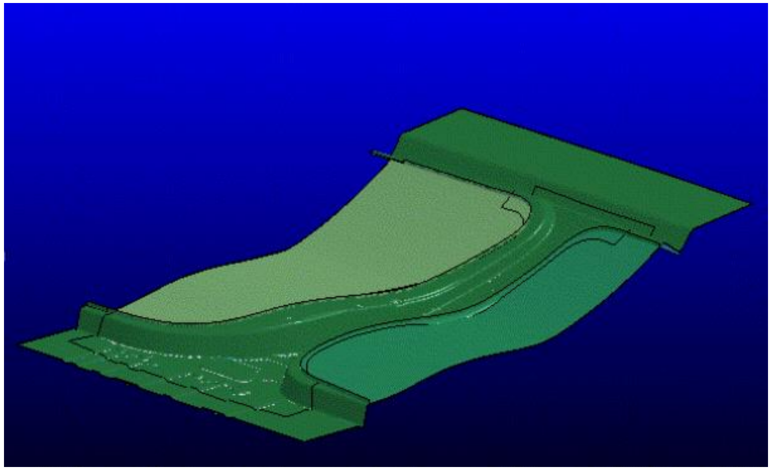


Hot Stamping of a B-Pillar

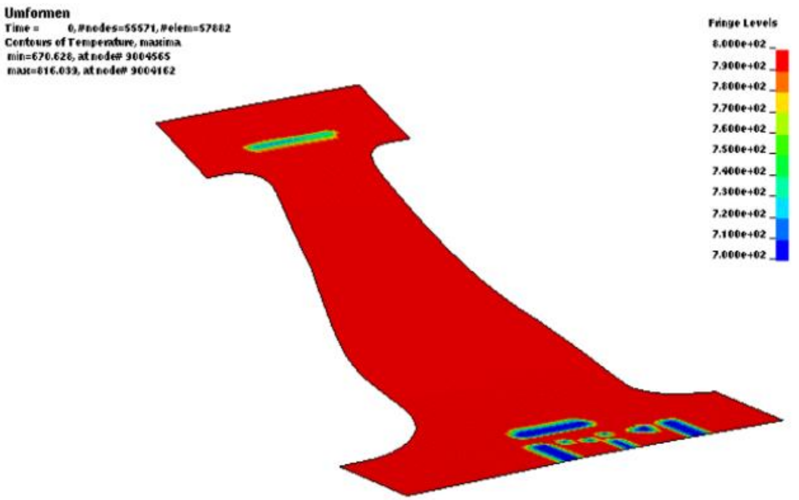


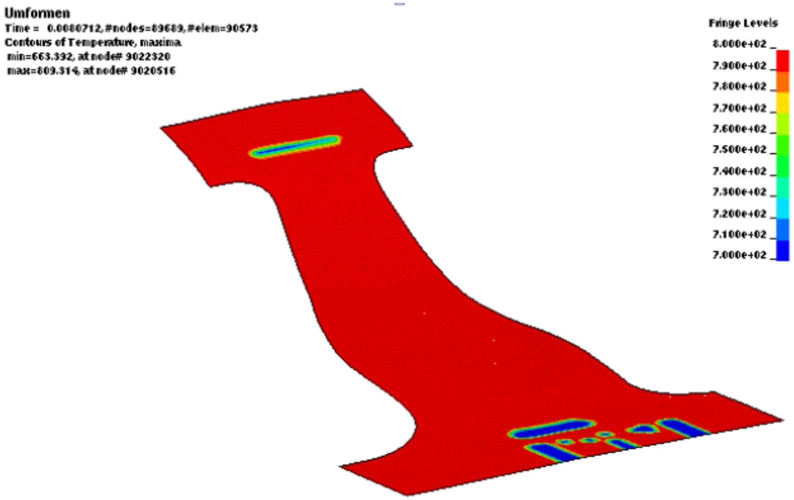


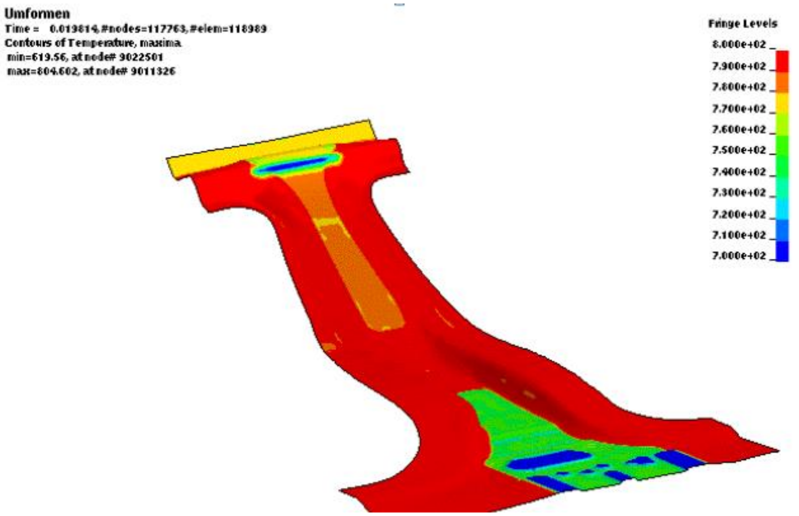


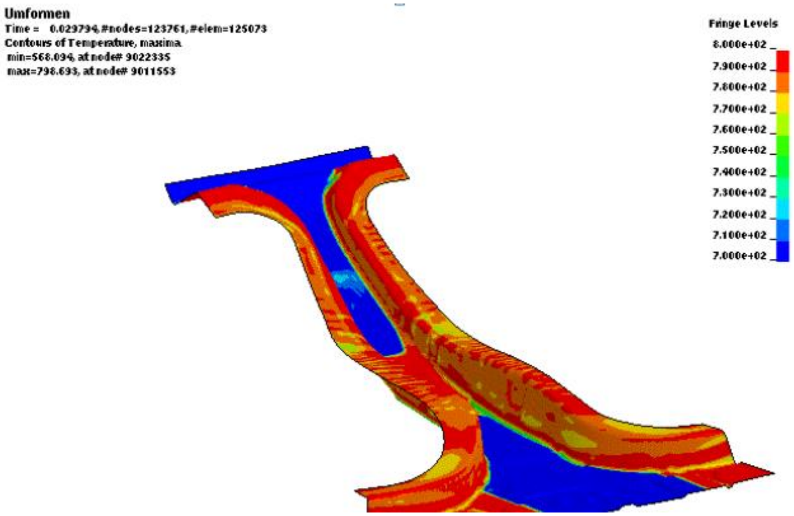


Hot Stamping of a B-Pillar: Temperature Results

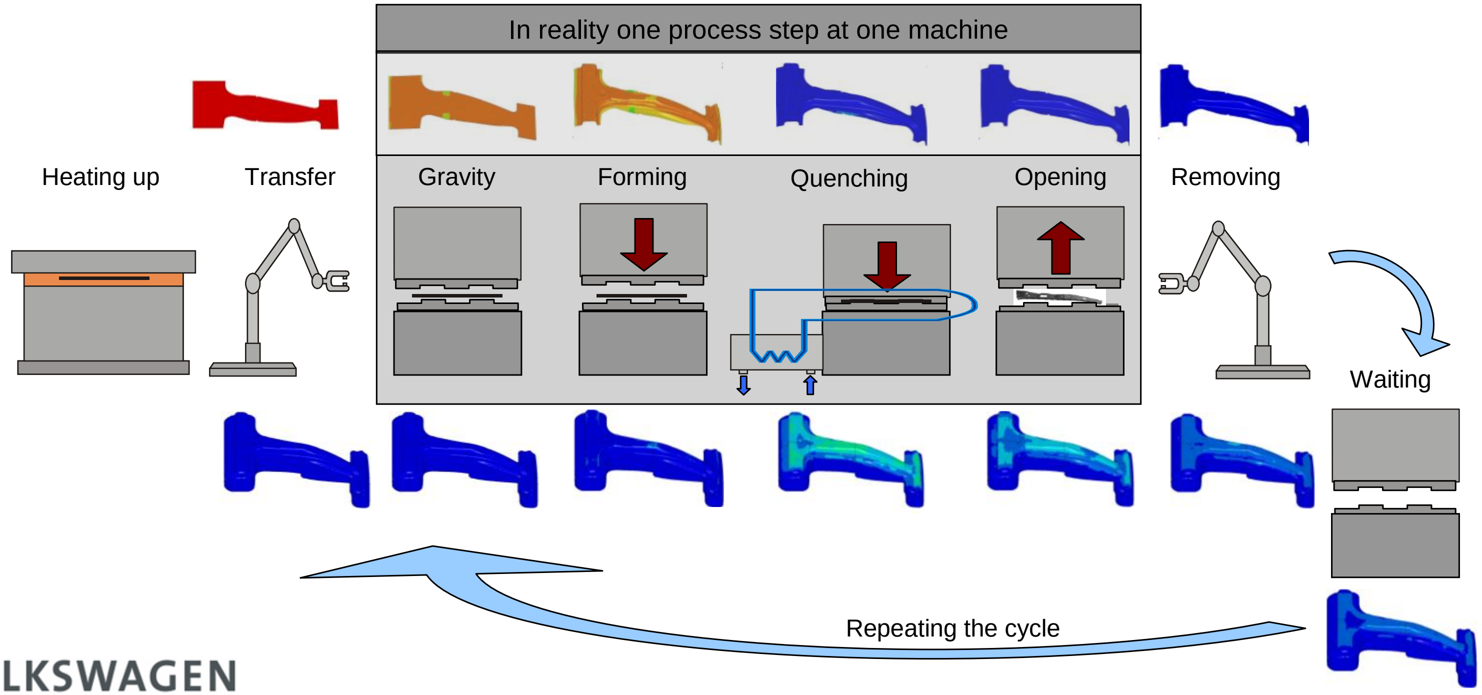








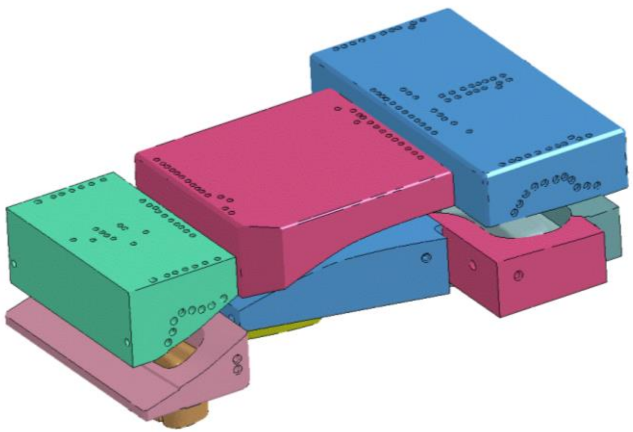
Presshardening Cooling Simulations

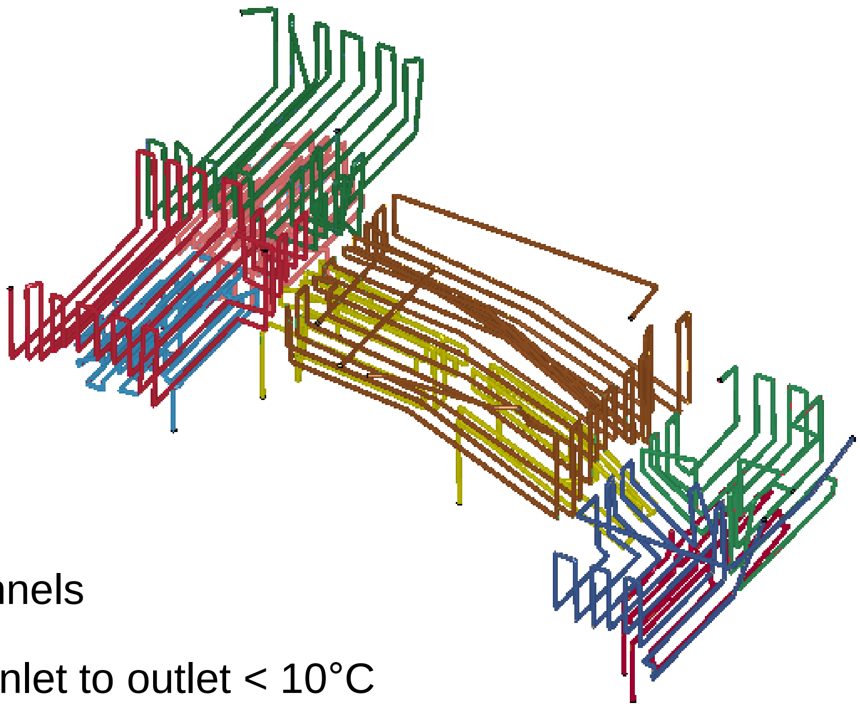


VOLKSWAGEN
AKTIENGESELLSCHAFT

courtesy of M. Medricky
Volkswagen AG

Modelling the watercooling system





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

  → convection boundary condition $\dot{q} = h_{con} \cdot \left(T_{wall} - T_{water}\right)$

?

Calculating h_{con}

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

$$\boxed{h = 0.023\frac{k}{D}\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.3}}$$ Dittus-Boelter (conservative)

$$h = 0.023\frac{k}{D}\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.3}\left(\frac{\mu_{bulk}}{\mu_{wall}}\right)^{0.14}$$ Sieder-Tate (temperature correction)

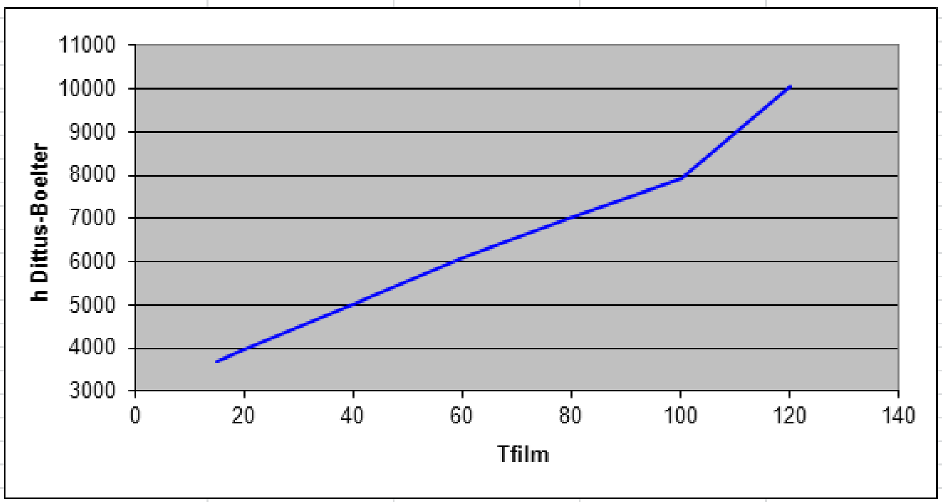
$$h = \left(\frac{k}{D}\right)\left[\frac{(f/8)(\mathrm{Re}-1000)\mathrm{Pr}}{1+12.7(f/8)^{1/2}\left(\mathrm{Pr}^{2/3}-1\right)}\right]$$ Gnielinski (wall friction effect)

- average flow velocity is required
  1. given mass flow rate per channel
  2. calculation with pipe network calculator
  3. computed with CFD analysis

Presshardening Cooling Simulations

using an excel sheet to calculate $h_{con}(d,v,T)$

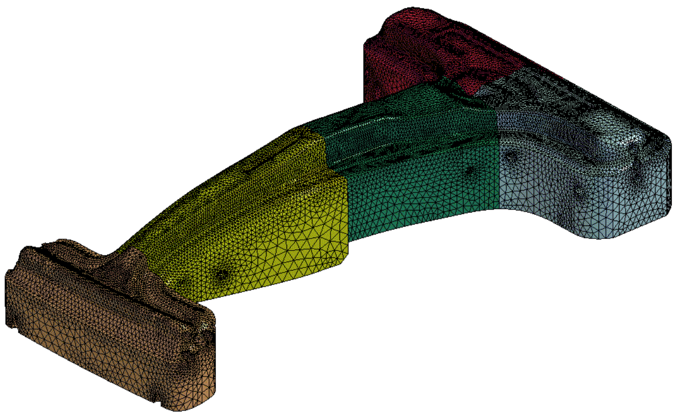
2	Diameter [mm]	6						
3	Cross Section [m^2]	2,82743E-05						
4	Flow Velocity [m/s]	5						
5	Fluid Temp [°C]	10						
6	Wall Temp [°C]	20	40	80	120	160	200	240
7	Film Temp [°C]	15	20	40	60	80	100	120
8	Density [kg/m^3]	999,162	998,028	991,886	983,171	971,885	958,028	941,599
9	Capacity [J/kgK]	4183,387	4181,743	4179,629	4184,657	4196,829	4216,143	4242,600
10	Viscosity [kg/ms]	0,001	0,001	0,001	0,000	0,000	0,000	0,000
11	Conductivity [W/m°C]	0,595	0,603	0,631	0,654	0,670	0,681	0,686
12	Re	2,67858E+07	2,99017E+07	4,55179E+07	6,44180E+07	8,26606E+07	1,03645E+08	165586390,111
13	Pr	7,863	6,941	4,328	2,932	2,209	1,717	1,055
14	h [W/m^2°C]	3710	3954	5026	6112	7027	7935	10048

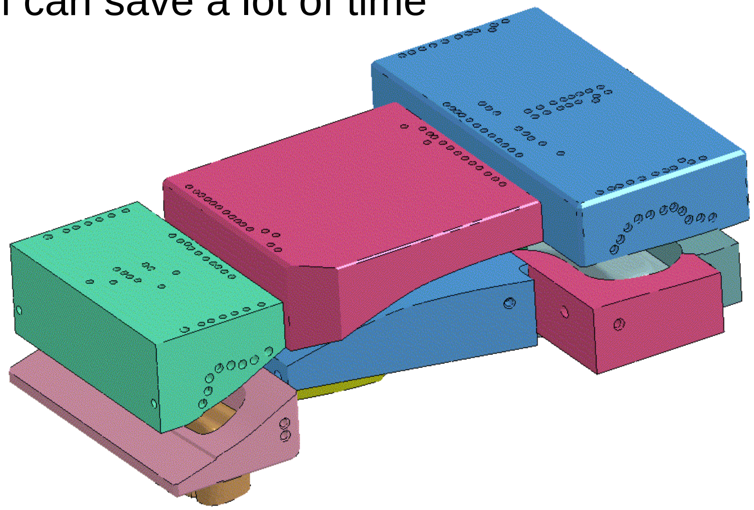


Cooling Simulation of a B-Pillar

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

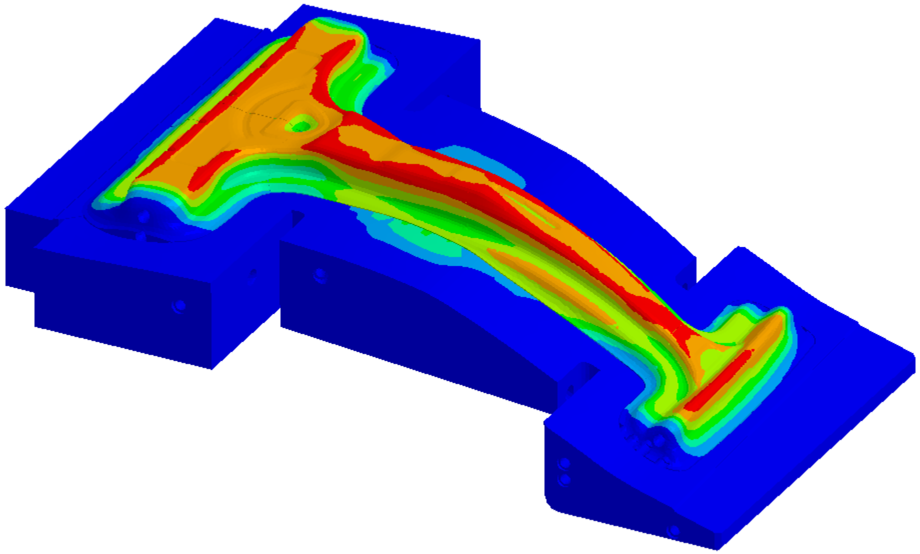
  → 3D mesh generation in CAD System can save a lot of time



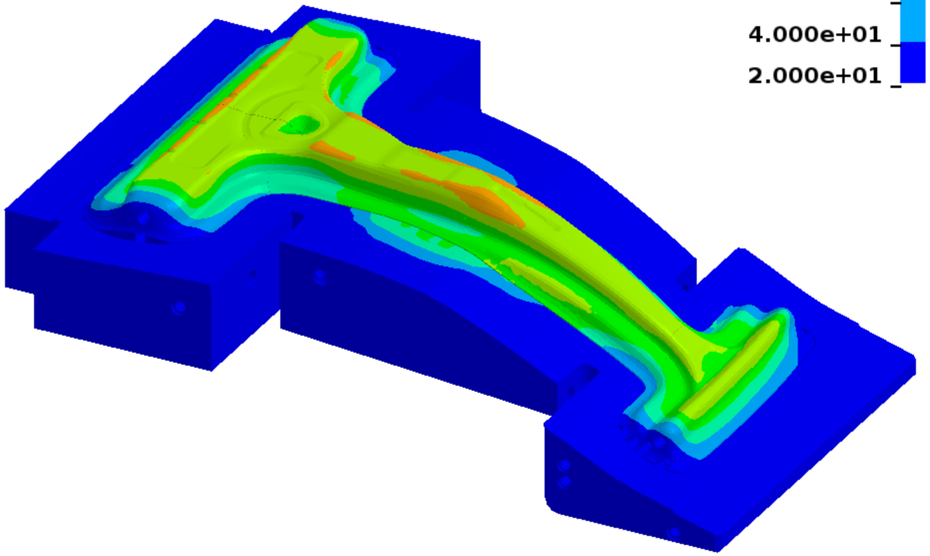


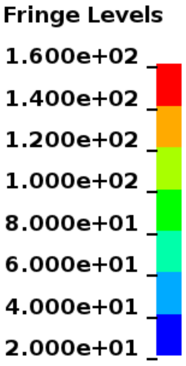
Cooling Simulation of a B-Pillar

tool temperature after 5 s

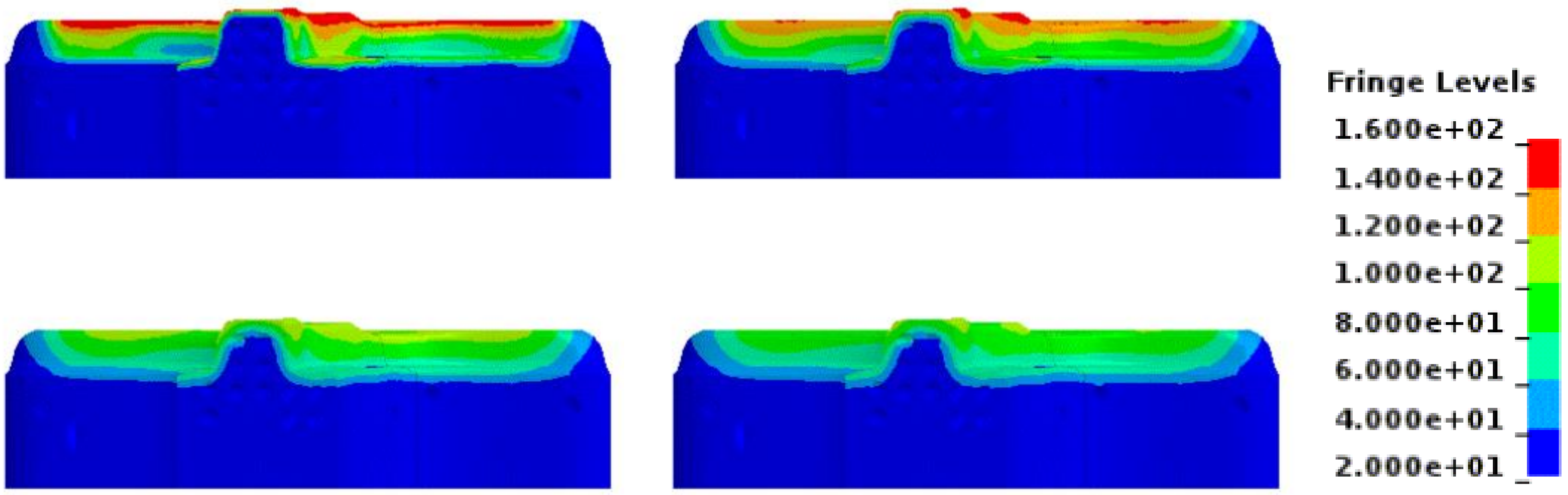


tool temperature after 10 s





Cooling Simulation of a B-Pillar

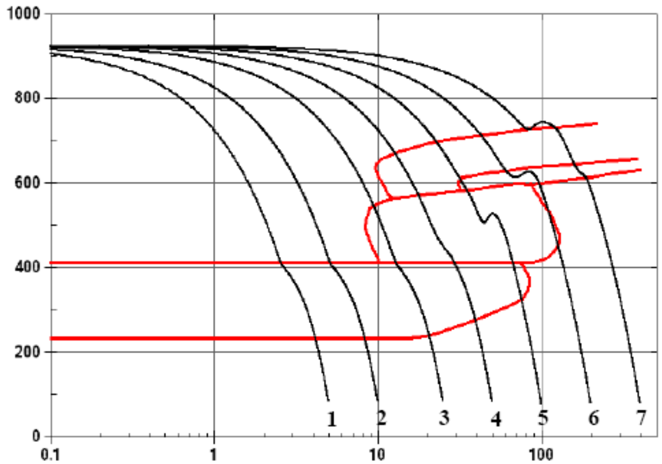


Prediction of final properties

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

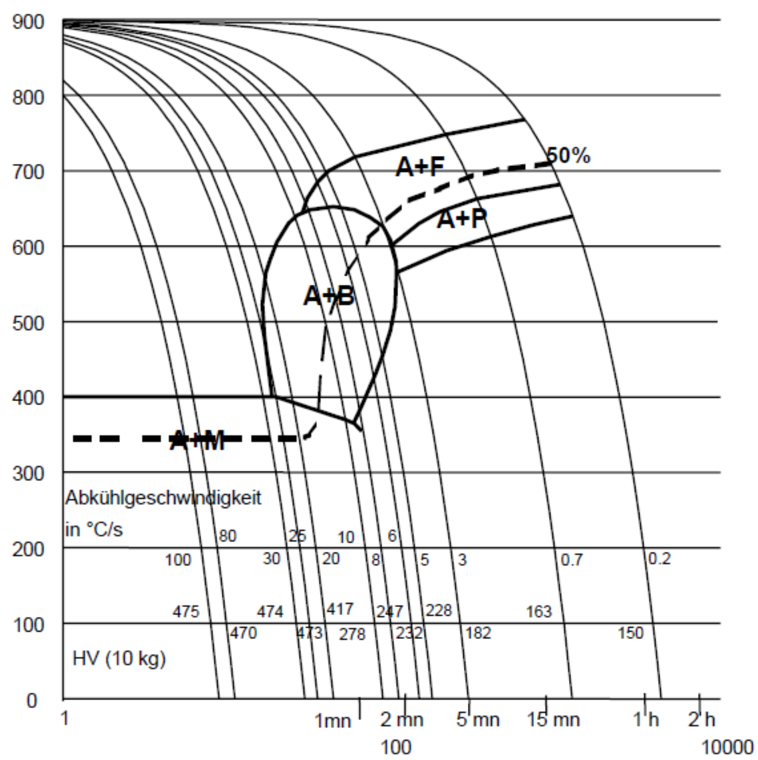


recalculated CCT diagramm

material output:

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

Parameter Identification for MAT_UHS_STEEL (MAT_244)



dT/dt	HV_{10}
100 K/s	475
80 K/s	470
30 K/s	474
25 K/s	473
20 K/s	417
10 K/s	247
8 K/s	232
3 K/s	182

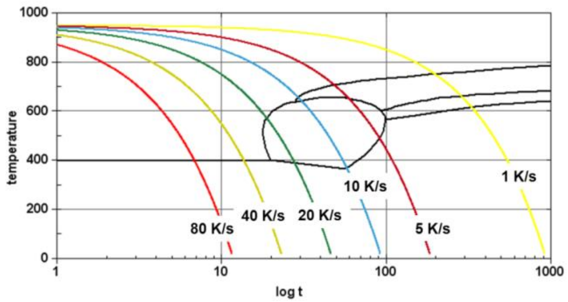
→ 20 K/s: martensite + bainite

→ 10 K/s: no ferrite

→ 8 K/s: small amount of ferrite

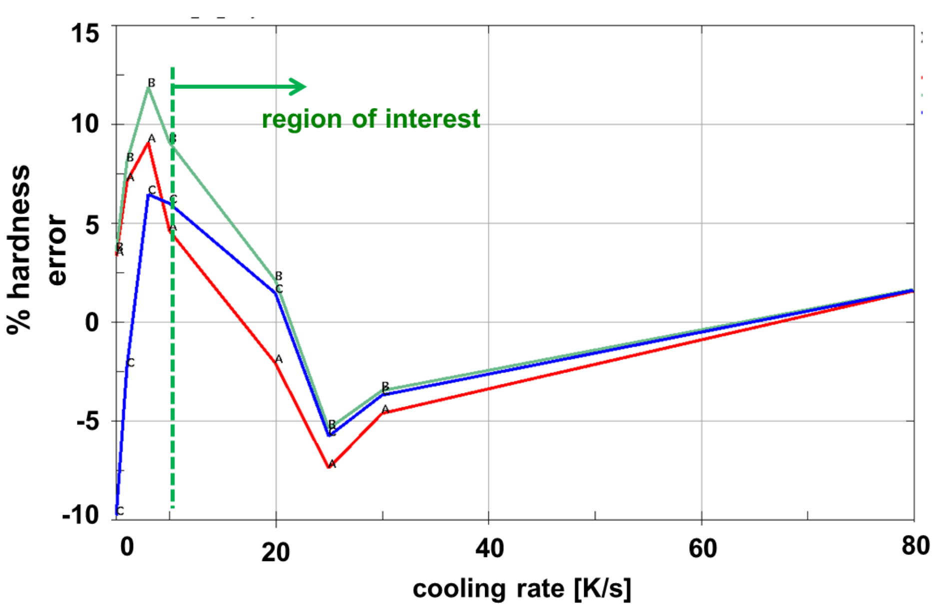
→ 3 K/s: small amount of pearlite

Parameter Identification for MAT_UHS_STEEL (MAT_244)

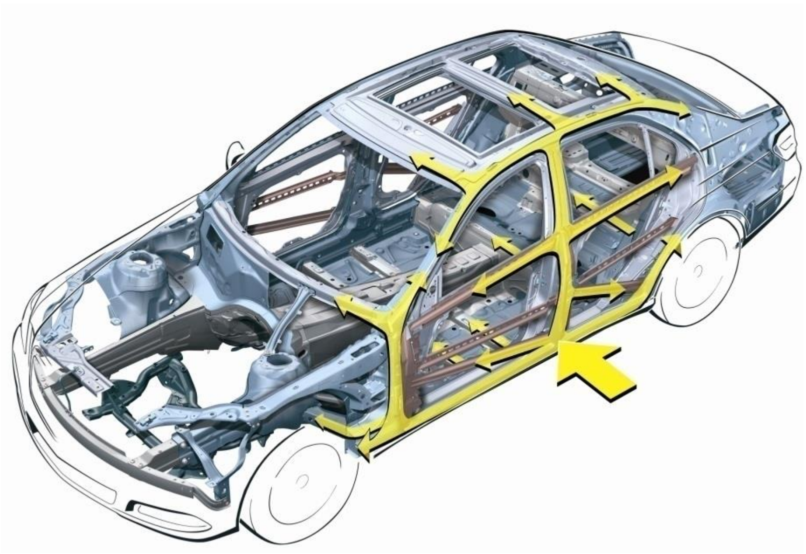


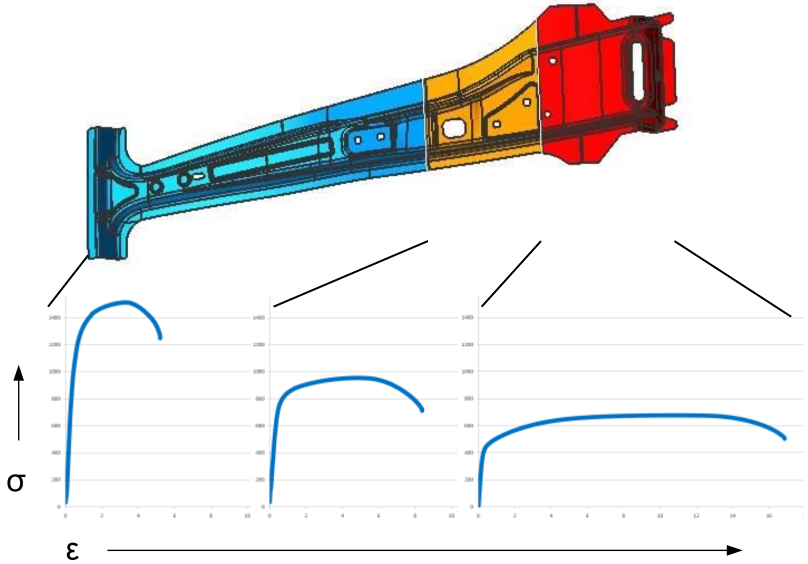
#	QR2	QR3	QR4	KFER	KPER	ALPHA
A	11600	14900	15400	3.0e+5	4340	0.033
B	11600	14900	15600	3.0e+5	4340	0.033
C	11600	14500	15600	2.0e+5	4340	0.033

Relative error in calculated Vickers hardness



Design a Process to get parts with tailored properties



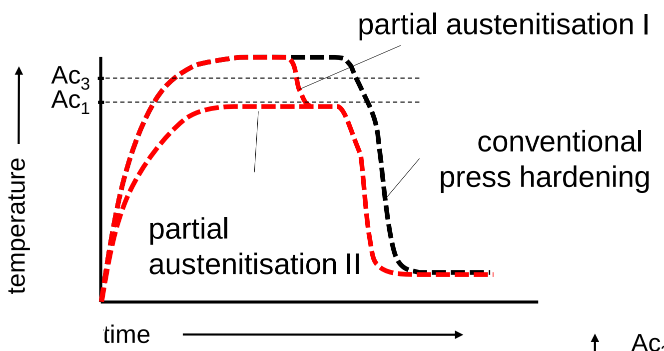


by courtesy of Daimler AG

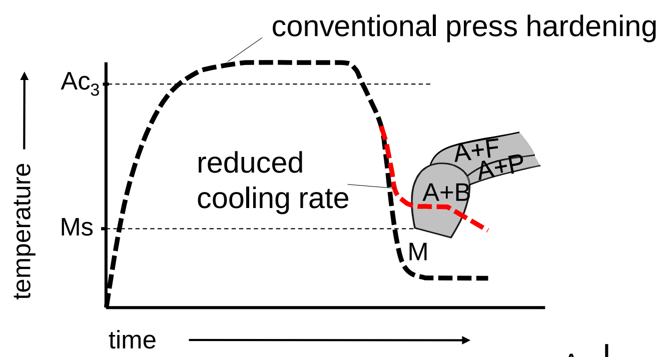
Prediction of final properties

Solving the task to get tailored properties

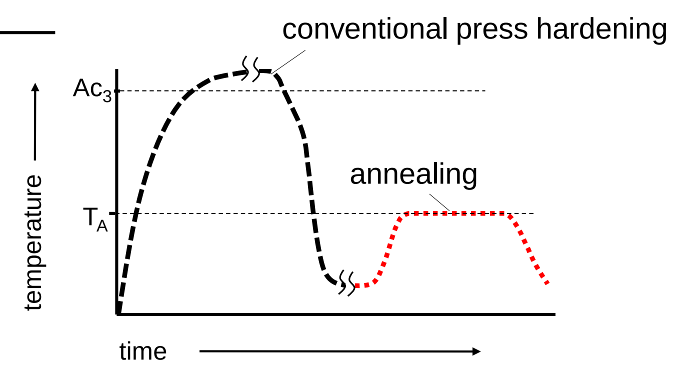
in the furnace by partial heating



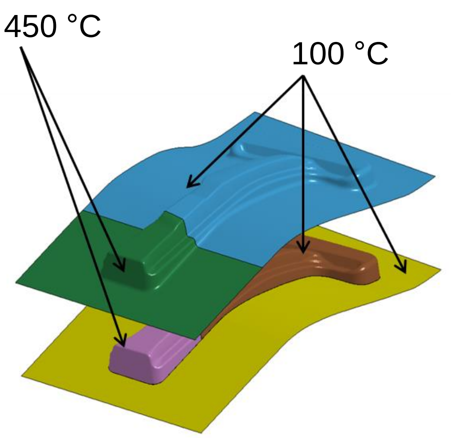
in the tool by partial tool heating

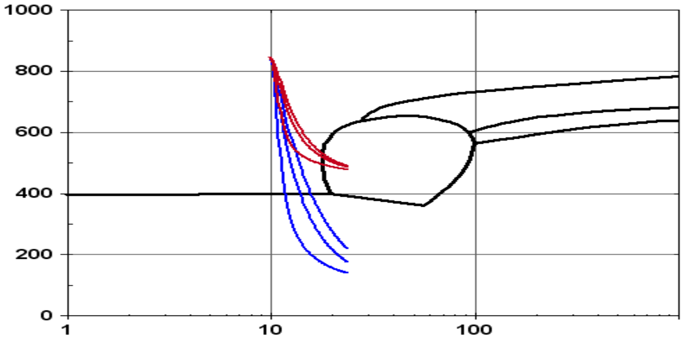


in a second process step

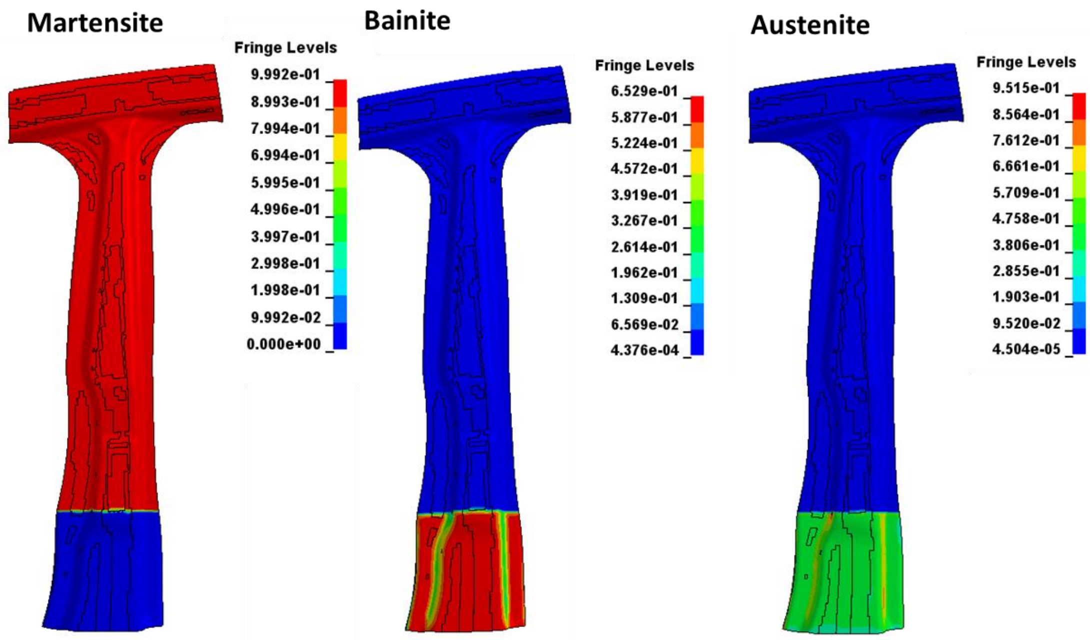


Tailored Tempering Process in principle

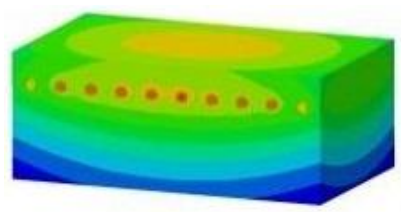


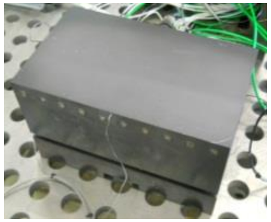


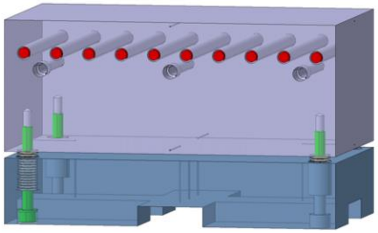
Microstructure after 14 s closing time (MAT_244)

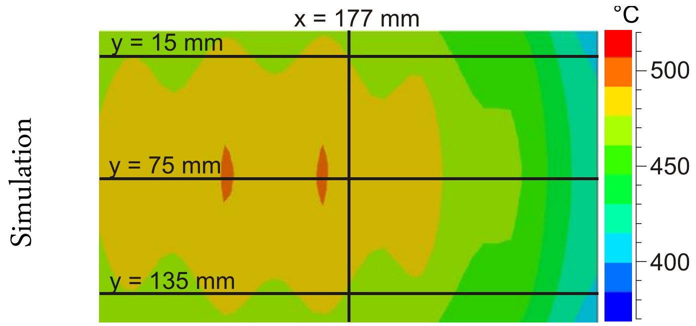


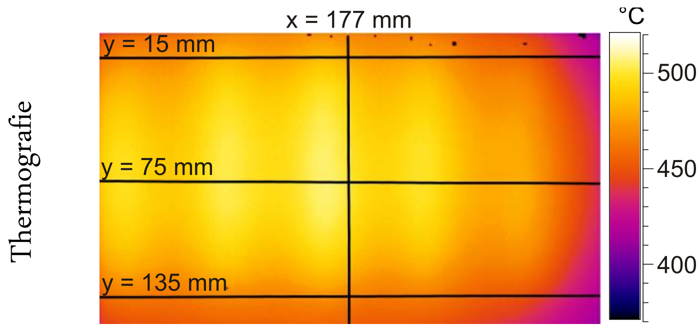
A simple tool setup for simulation calibration



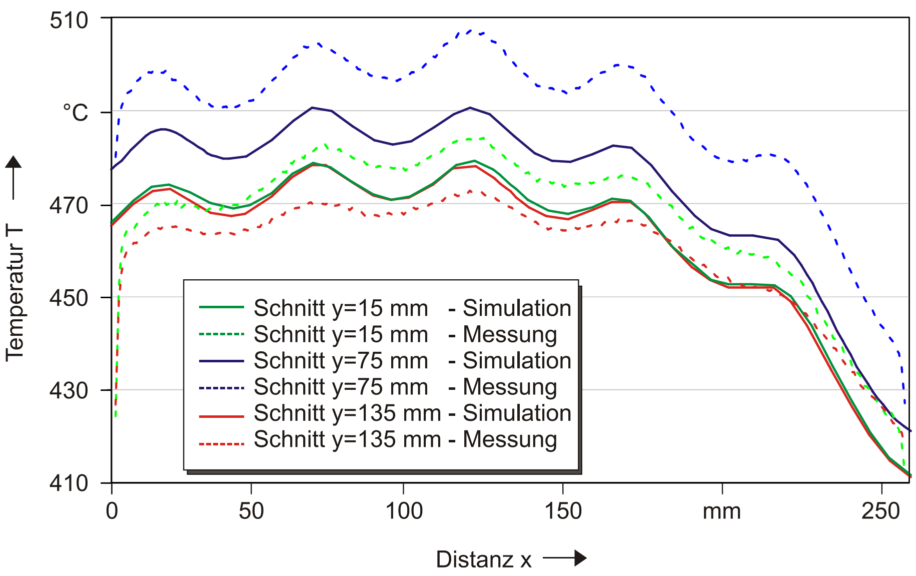








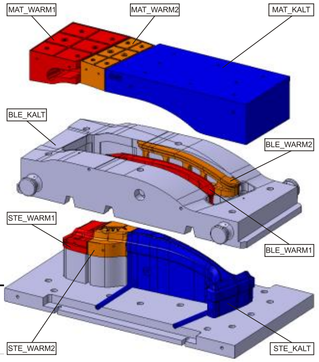
testcase every 2nd heater switched off



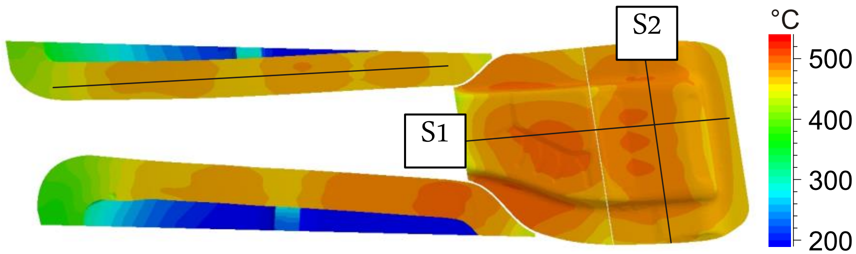
Calibration of die heating process

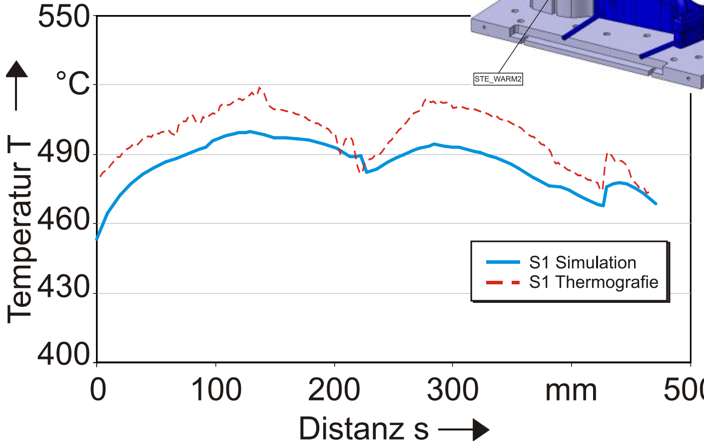
B-Pillar tool for validation of heating simulation

→ direct use of the calibration parameters without adjustment

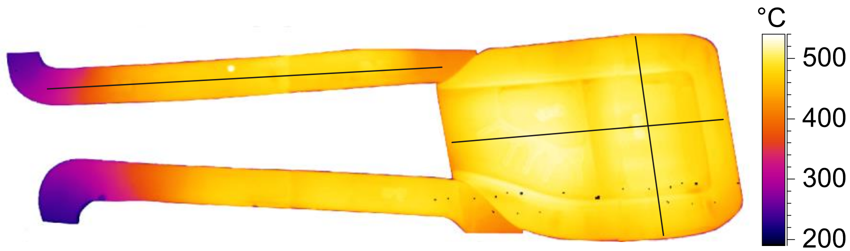


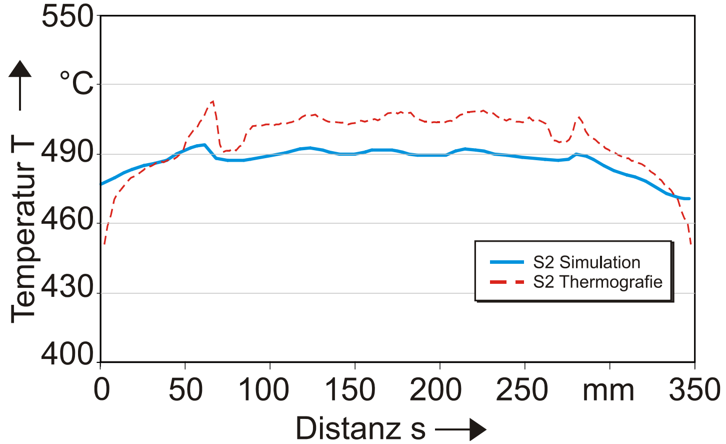
Simulation





Thermographie

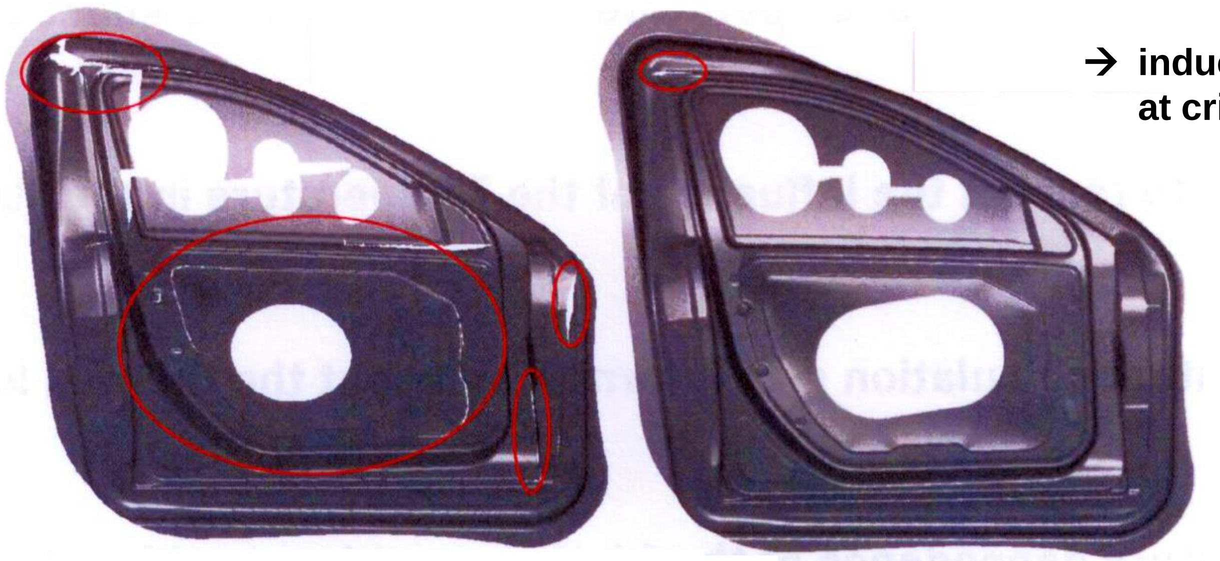




The main task

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

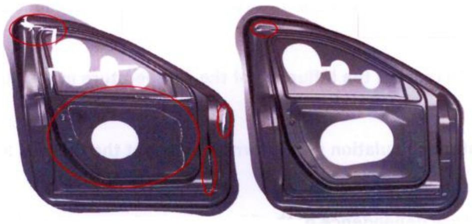
→ inductive heating at critical zones

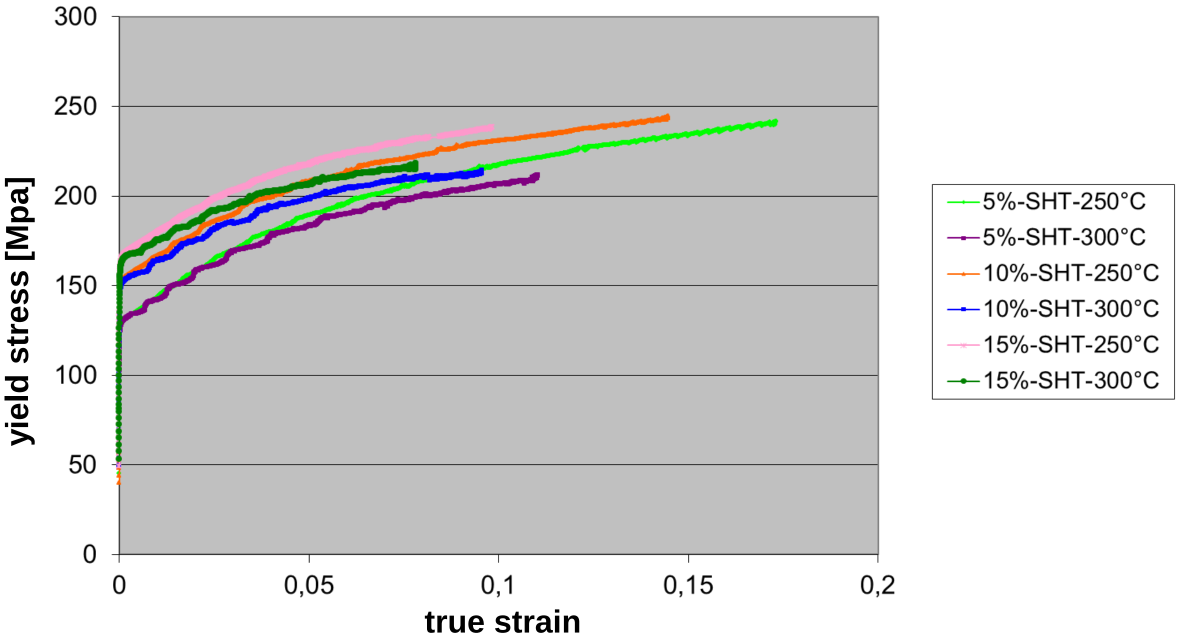


Quelle: Prof. Roll Daimler AG, Automotive Grand Challenges 2011

- 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?***

Experimental material characterization



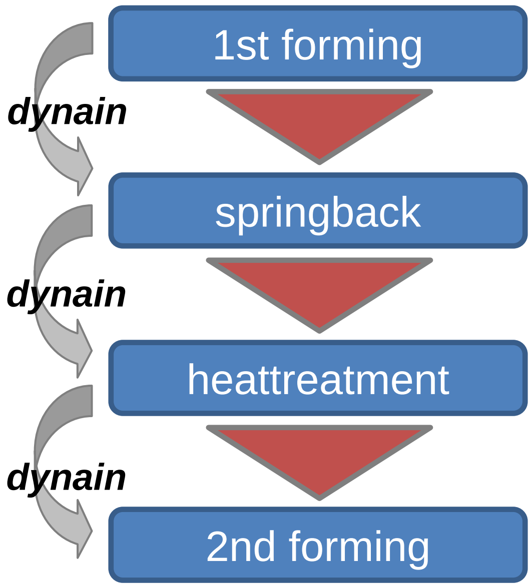


- Reduction of yield stress due to heat treatment
- Higher slope compared to base material → higher formability

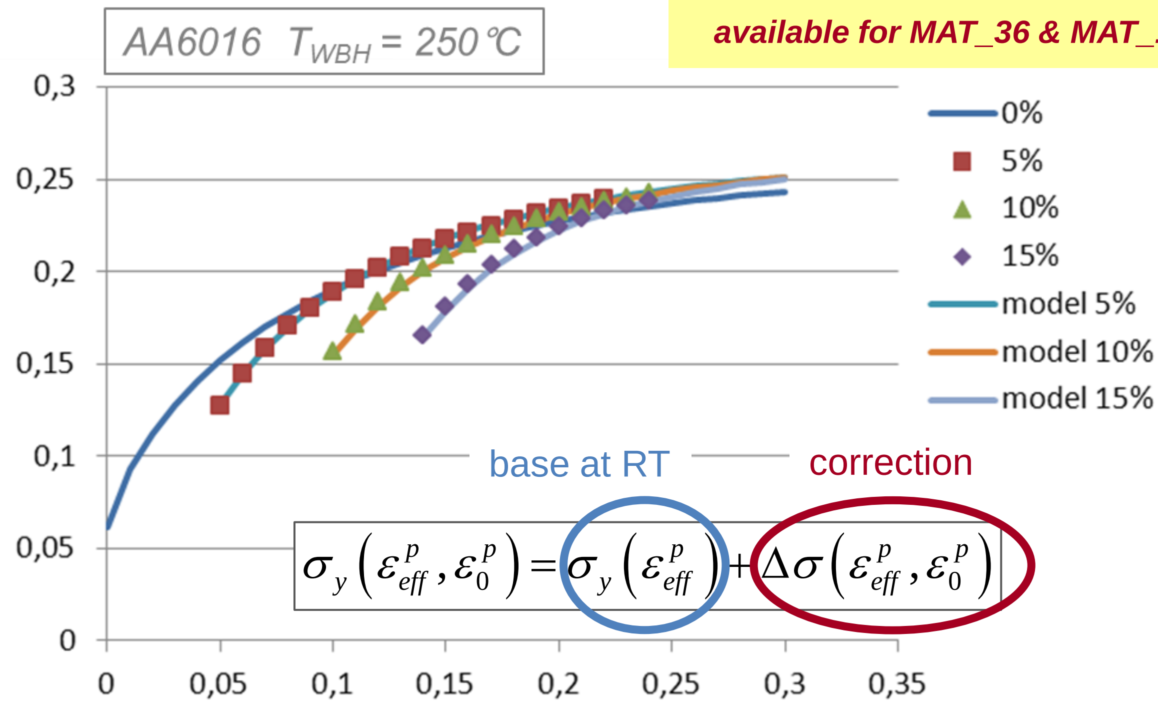
→ **hardening curves should be parametrized over prestrain and IHT temperature**

Heat supported coldforming of aluminum

The solution in LS-DYNA



available for MAT_36 & MAT_133



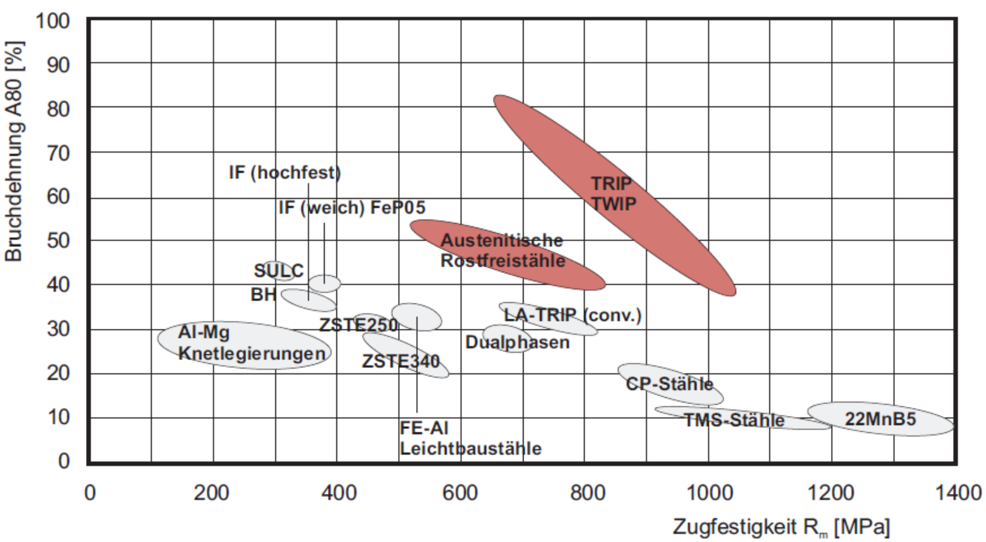
Springback simulation → unloading, equilibrium, elastic stresses

heat treatment simulation → part temperature distibution → IHT temperature

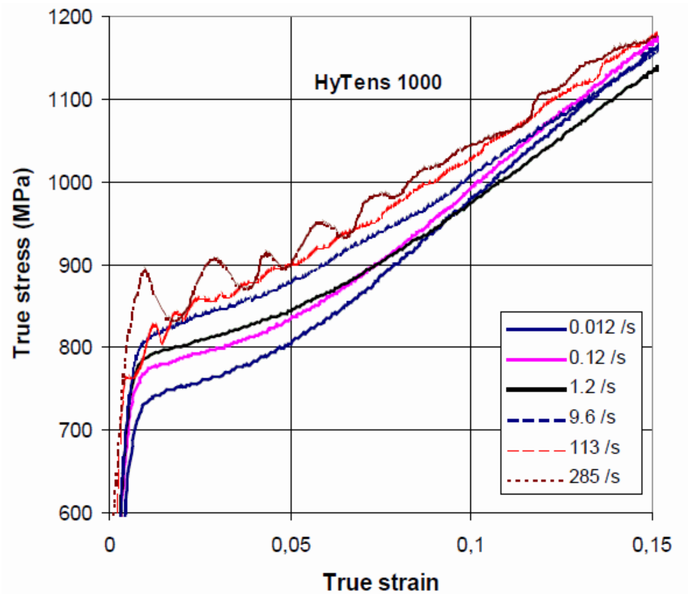
$T_{IHT} = \max\{T(t)\}$ evaluate correction term $\Delta\sigma$ → save in ***dynain***

Forming of stainless steel

- Austenitic stainless steels offer much higher deformability than comparable conventional grades (DP, CP) of same strength
- Excellent formability in drawing and stretch-forming → complex part geometries
- High energy absorption capability → crash applications
- Complex hardening behavior
- Accurate forming simulations necessitate consideration of complex hardenig behavior



formability compared to different steel grades
source: T. Schröder, Max-Planck Institut für Eisenforschung

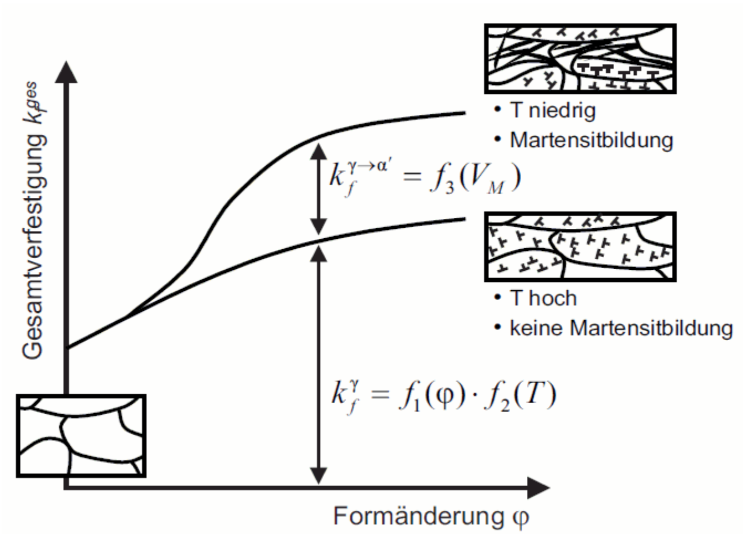


Energy AbsorptionHyTens1000
source: www.worldstainless.org

Forming of stainless steel

- Martensite formation causes characteristic hardening behavior
- Martensite formation must be considered in the material model

Hardening Behavior by Hänsel



Martensite formation in in LS-DYNA

$$\boxed{\frac{\partial V_m}{\partial \bar{\varepsilon}^p} = \frac{B}{A} e^{\frac{Q}{T}} \left(\frac{1-V_m}{V_m}\right)^{B+1/B} \cdot V_m{}^p \cdot \frac{1}{2}\left(1-\tanh\left(C+D\cdot T\right)\right)}$$

6 unbekannte Parameter: A, B, C, D, p, Q

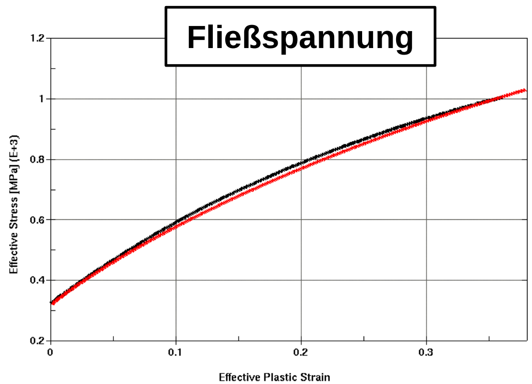
Hardening in LS-DYNA

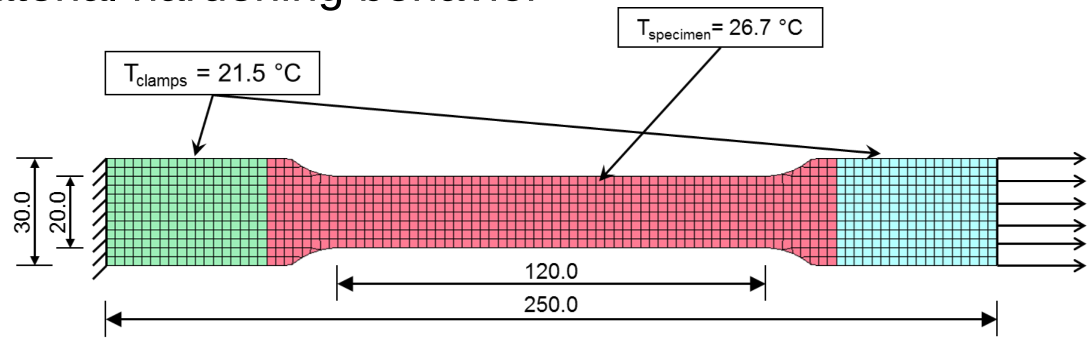
$$\boxed{\sigma_y = \sigma_{aust.}\left(\bar{\varepsilon}^p\right)\left(K_1 + K_2 T\right) + \Delta H_{\gamma\to\alpha'} \cdot V_m}$$

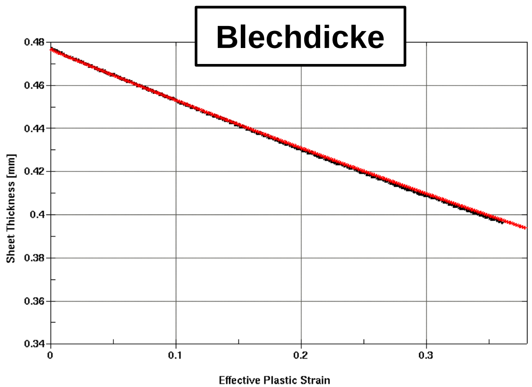
- martensite formation is temperature dependent
- requires calculation of the actual temperature during forming
- both coupled or adiabatic calculation is possible → depends on tool interaction

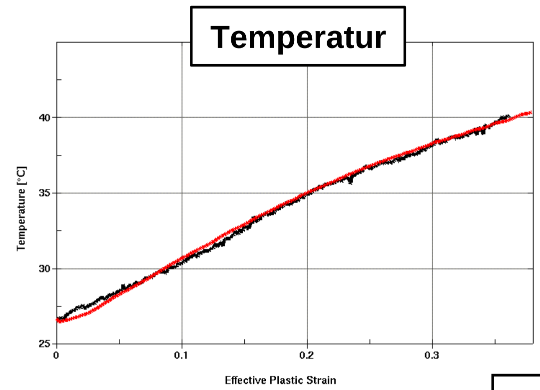
Forming of stainless steel

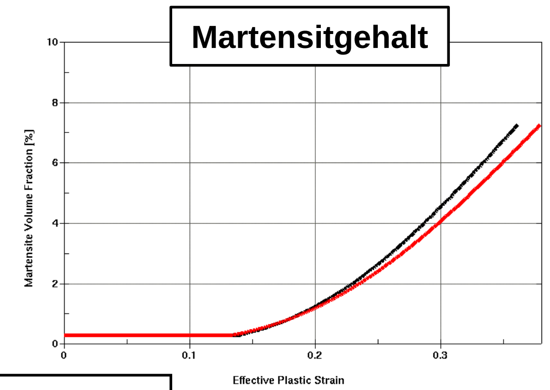
- Simulation of tensile test 1.4301 (AISI304), thickness 0.8 mm in LS-DYNA
- thermal-mechanical coupling, heat loss to ambient
- very accurate prediction of material hardening behavior









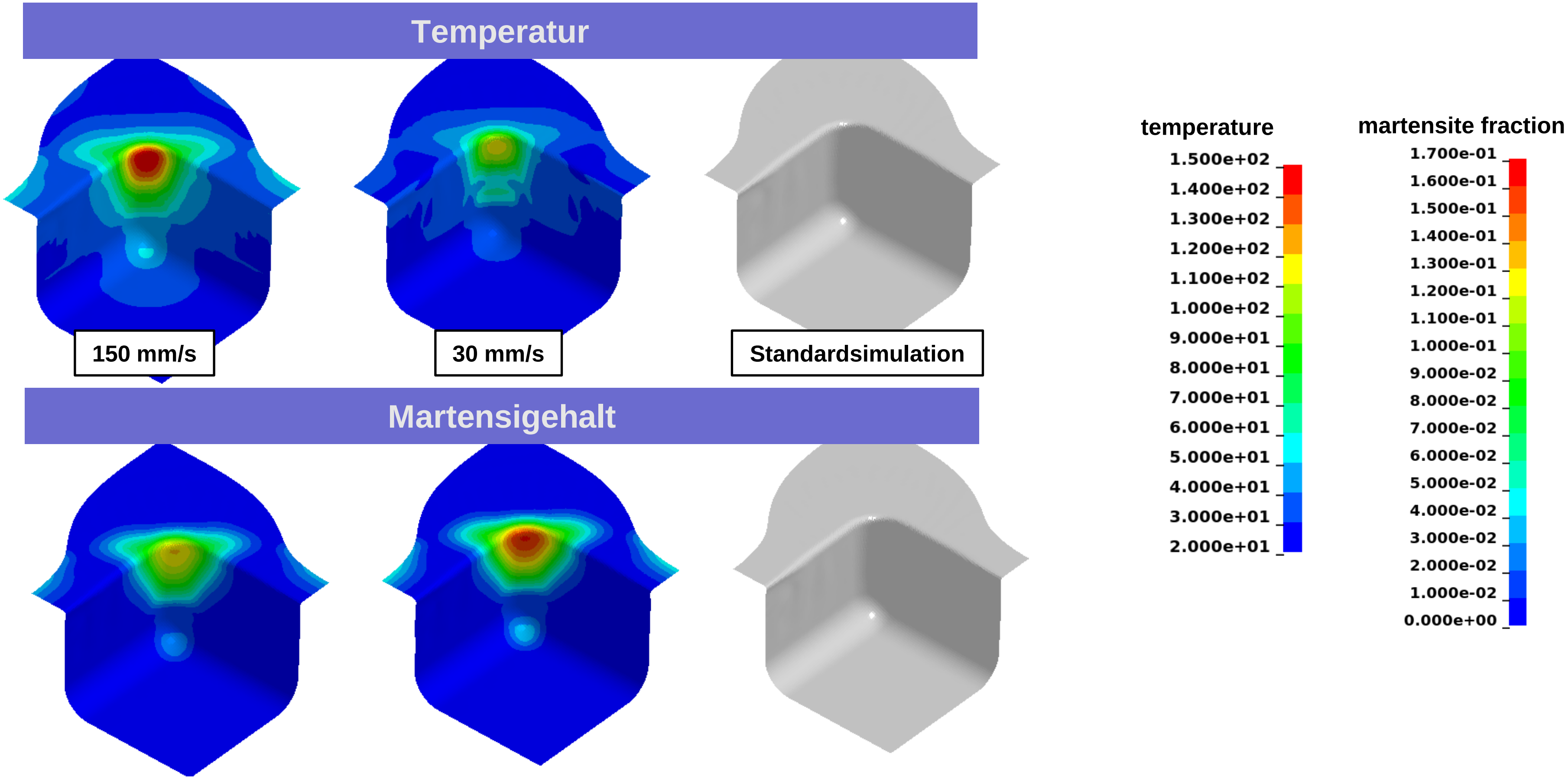


experiment
simulation

Ref.: Hochholdinger, ETH Zurich / DYNAmore Swiss, (2006)

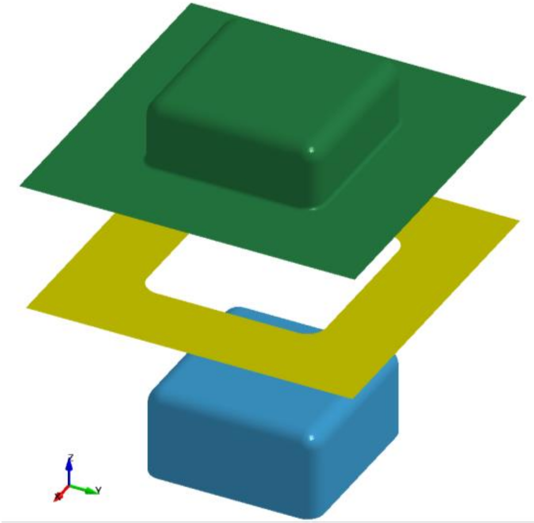
Forming of stainless steel

- demonstrating the need for a coupled simulation
- standard approach with single input stress-strain curve is insufficient
- only the advanced material model can show differences in results



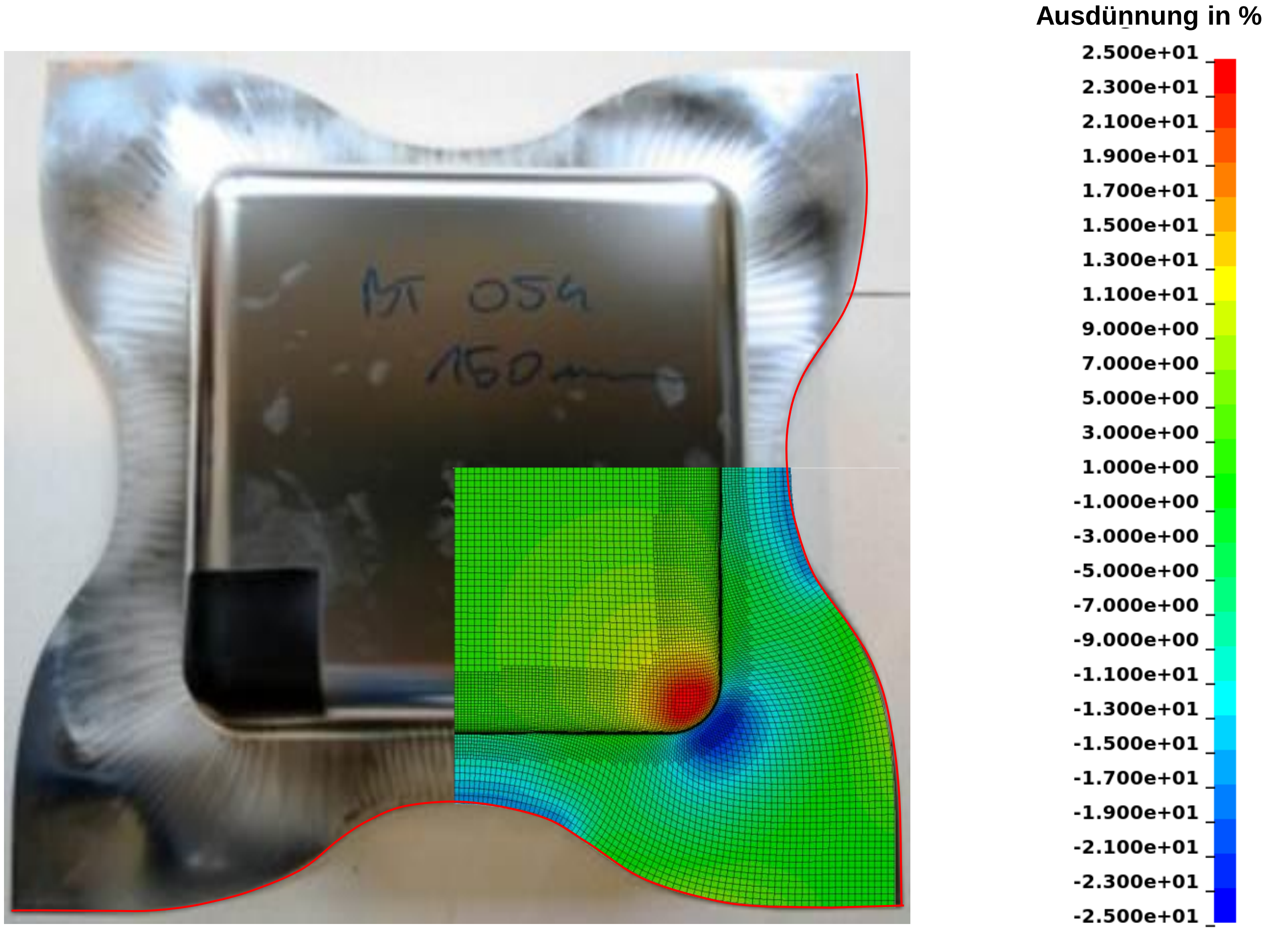
Forming of stainless steel

- validation with kitchen sink tool of TU Graz
- punch cross-section 400 mm x 400 mm
- drawing depth150 mm
- blank 750 mm x 750 mm, thickness 0.8 mm, 1.4301 (AISI304)



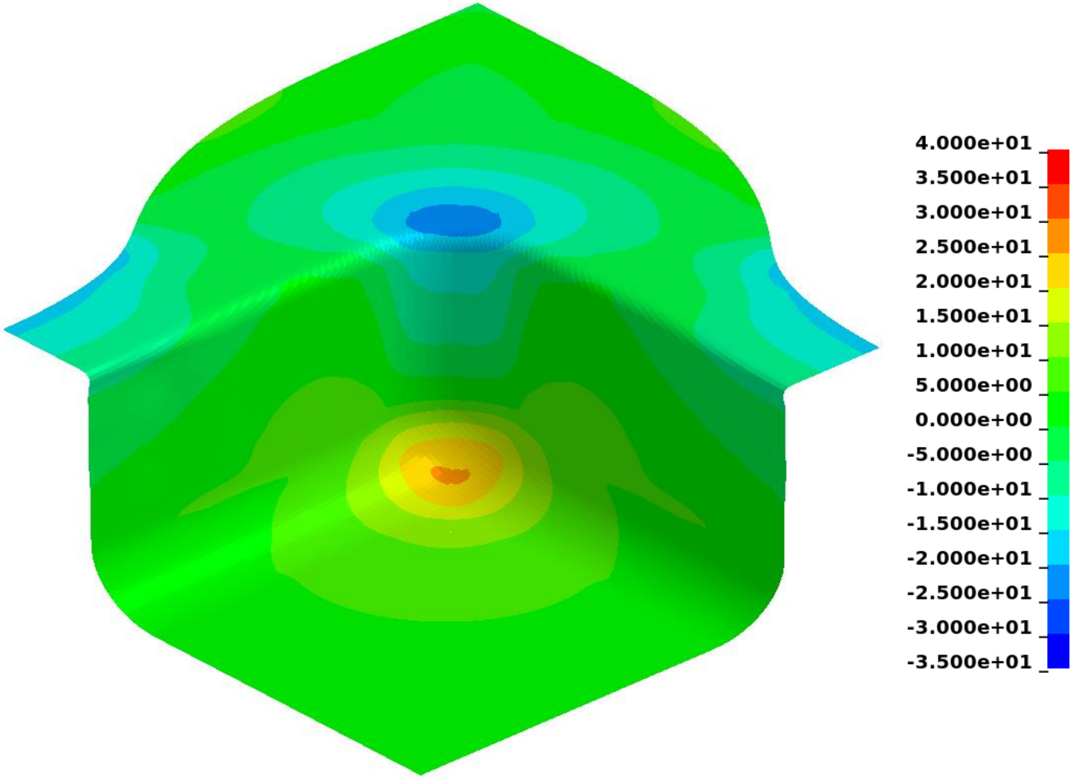
Forming of stainless steel

- good agreement of material draw in outline
- accurate prediction of plastic flow behavior of the material model

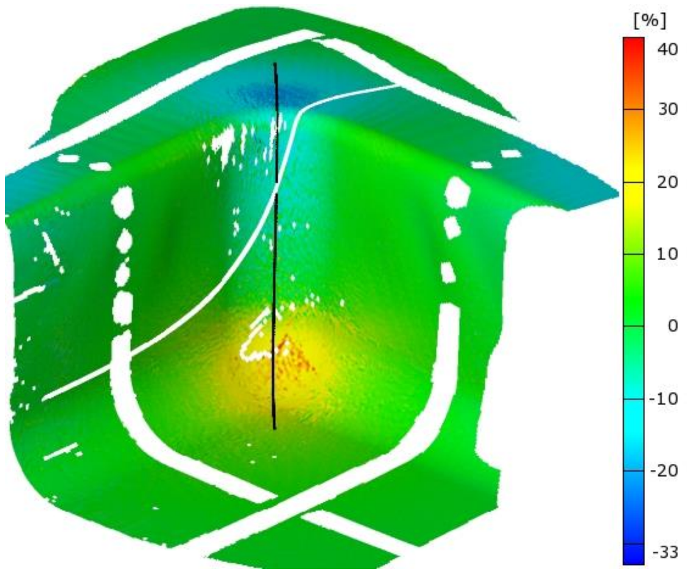


Sheet thinning percentage

Simulation



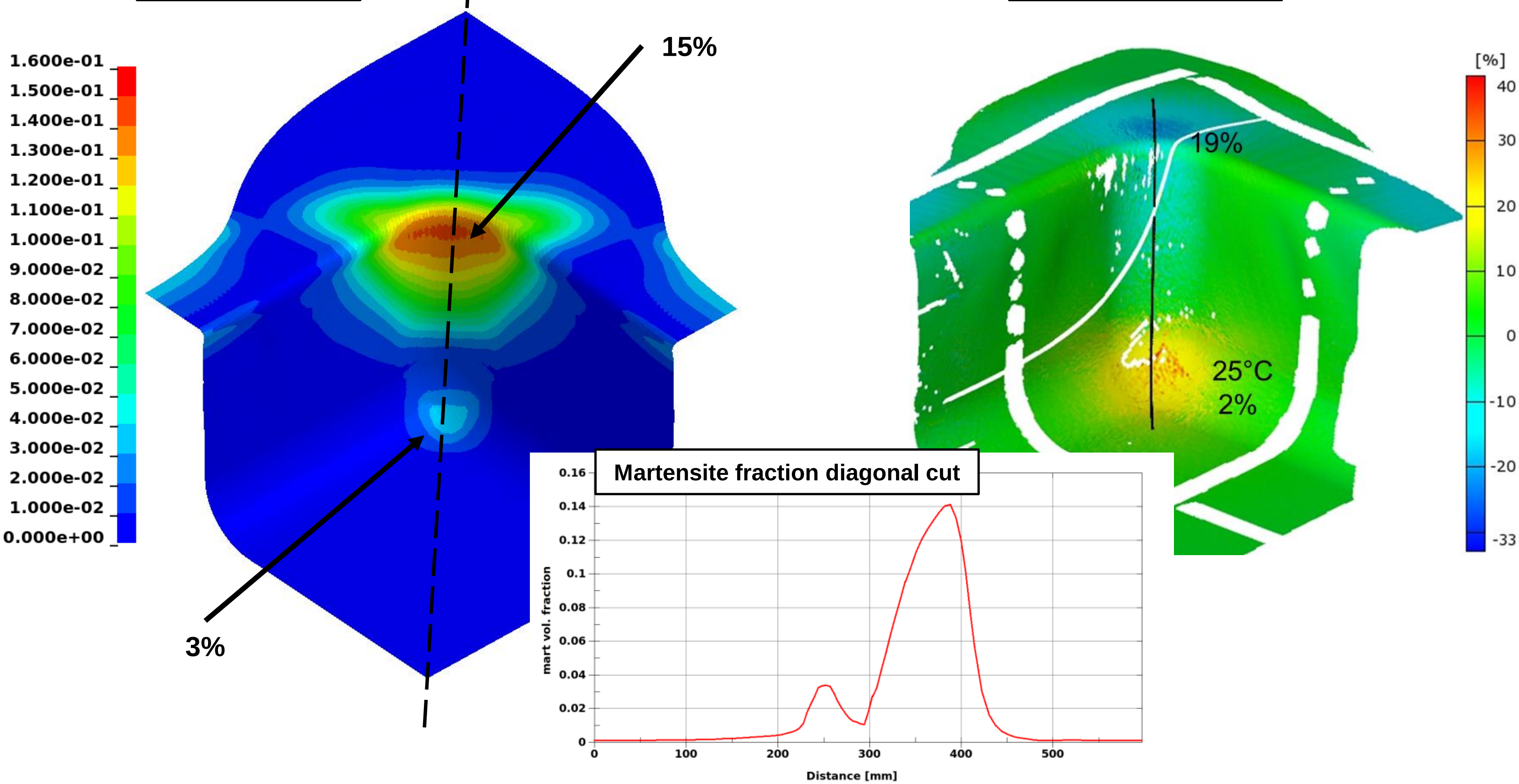
Measurement



Forming of stainless steel

martensite volume fraction compared with punctual meassures

Simulation **Measurement**



questions