Prediction of Phase Fractions and Vickers Hardness in Hot Stamping Processes with an Advanced Material Model in LS-DYNA

B. Hochholdinger, D. Lorenz, T. Erhart, M. Schill

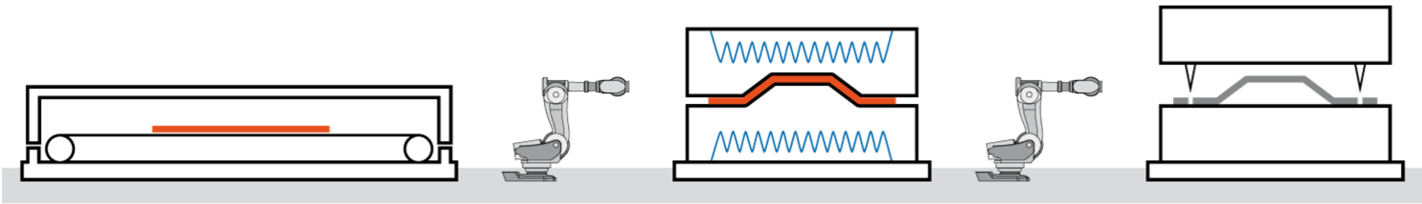
LS-DYNA Anwenderforum 2013 – Filderstadt

Agenda

- Introduction
  - Hot stamping / Press hardening
  - Standard approach for material modeling
- Advanced material model
  - Austenite decomposition model
  - Prediction of Vickers Hardness
  - Constitutive Modeling
- Recent enhancements
  - Modified reaction kinetics
  - Hardness calculation for tailored tempering
- Example

Hot Stamping / Press Hardening

Direct Press Hardening/ Hot Stamping

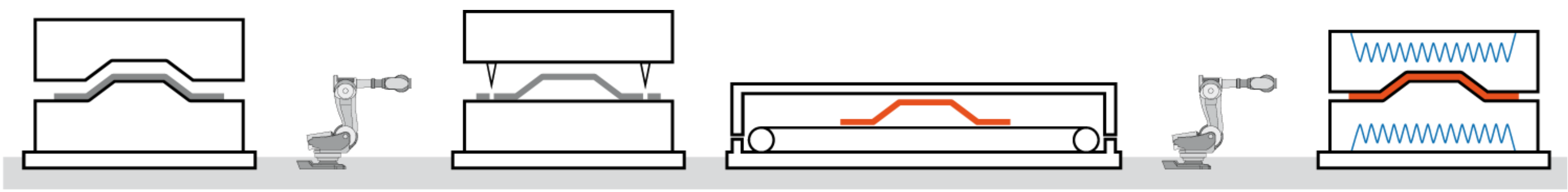


Heating and Austenitization

Forming and Quenching

Trimming

Indirect Press Hardening / PHS-Process



cold Forming to final geometry

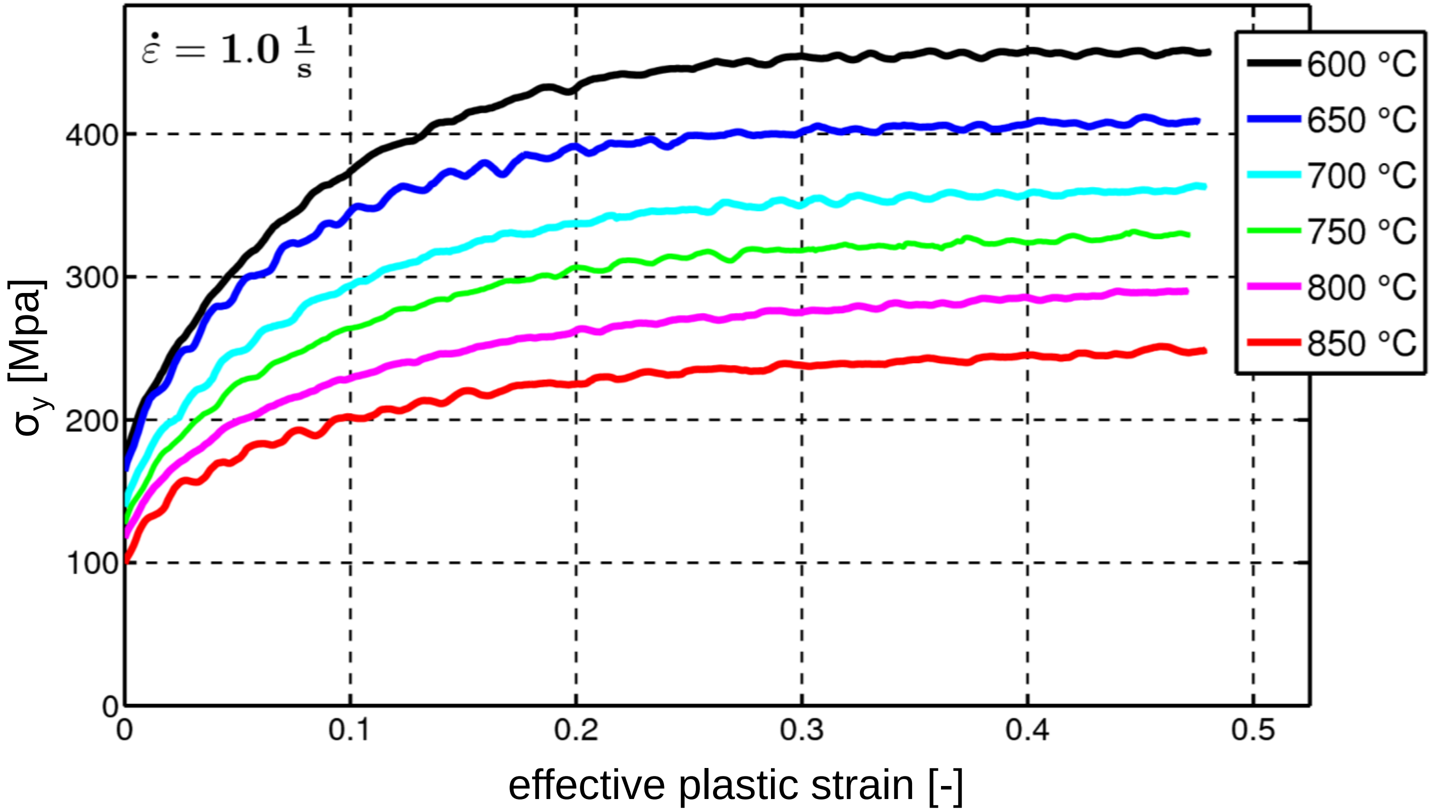
Trimming

Heating and Austenitization

Calibration and Quenching

Elasto-viscoplastic material model:

- yield stress depends on
  - effective plastic strain
  - temperature
  - strain rate



Discussion of Standard Approach

Capabilities

- correct prediction of forming in the austenitic state:
  - stresses and strains
  - thinning
  - forces
- prediction of temperature history in the blank/part

Limits

- prediction of microstructure (phase fractions) and hardness:
  - only rough estimations based on CCT diagram can be made
  - not possible for tailored tempering processes

→ only rough estimations of final part properties like strength and hardness

Advanced material model for prediction of phase fractions and Vickers hardness

Austenite Decomposition Model

- Implemented model is based on the work of P. Åkerström
- Rate equation for diffusion-controlled transformation of austenite to bainite, ferrite and pearlite as proposed by Kirkaldy et al.

$$\frac{dX_i}{dt} = F_G \cdot F_{T,i} \cdot F_{X_i} \cdot F_{C,i} \qquad i = f, p, b$$

- $\frac{dX_i}{dt}$: ghost fraction $X_i = \frac{x_i}{x_{eq,i}}$
- F_G: austenitic grain size
- $F_{T,i}$: temperature dependency
- F_{X_i}: actual phase fractions X_i
- $F_{C,i}$: chemical composition

Austenite Decomposition Model

- Transformation of austenite to ferrite

$$\frac{dX_f}{dt} = \underbrace{\left[2^{0.5(G-1)}\right]}_{F_G} \cdot \underbrace{\left[\left(T_{st,f} - T\right)^3 \cdot e^{-\frac{Q_f}{RT}}\right]}_{F_{T,f}} \cdot \underbrace{\left[X_f^{\frac{2}{3}(1-X_f)}\left(1 - X_f\right)^{\frac{2}{3}X_f}\right]}_{F_{X,f}} \cdot F_{C,f}$$

$$F_{C,f} = \left[59.6Mn + 1.45Ni + 67.7Cr + 244Mo + K_f B\right]^{-1}$$

$$T_{st,f} = 1185 - 203\sqrt{C} - 15.2Ni + 44.7Si + 104V + 31.5Mo + 13.1W$$
$$-30Mn - 11Cr - 20Cu + 700P + 400Al + 120As + 400Ti$$

Austenite Decomposition Model

- Transformation of austenite to pearlite

$$\frac{dX_p}{dt} = \underbrace{\left[2^{0.5(G-1)}\right]}_{F_G} \cdot \underbrace{\left[\left(T_{st,p} - T\right)^3 \cdot D\right]}_{F_{T,p}} \cdot \underbrace{\left[X_p^{\frac{2}{3}(1-X_p)}\left(1 - X_p\right)^{\frac{2}{3}X_p}\right]}_{F_{X,p}} \cdot F_{C,p}$$

$$F_{C,p} = \left[1.79 + 5.42\left(Cr + Mo + 4MoNi + K_p B\right)\right]^{-1}$$

$$D = \left[\frac{1}{exp\left(-Q_p/RT\right)} + \frac{0.01Cr + 0.52Mo}{exp\left(-1.34Q_p/RT\right)}\right]^{-1}$$

$$T_{st,p} = 996 - 10.7Mn - 16.9Ni + 29Si + 16.9Cr + 290As + 6.4W$$

Austenite Decomposition Model

- Transformation of austenite to bainite

$$\frac{dX_b}{dt} = \underbrace{\left[2^{0.5(G-1)}\right]}_{F_G} \cdot \underbrace{\left[\left(T_{st,b} - T\right)^2 \cdot e^{-\frac{Q_b}{RT}}\right]}_{F_{T,b}} \cdot \underbrace{\left[\frac{X_b^{\frac{2}{3}(1-X_b)}(1-X_b)^{\frac{2}{3}X_b}}{exp\left(C_r X_b^{\,2}\right)}\right]}_{F_{X,b}} \cdot F_{C,b}$$

$$C_r = 1.9C + 2.5Mn + 0.9Ni + 1.7Cr + 4Mo - 2.6$$

$$F_{C,b} = [0.0001(2.34 + 10.1C + 3.8Cr + 19Mo)]^{-1}$$

$$T_{st,b} = 929 - 58C - 35Mn - 75Si - 15Ni - 34Cr - 41Mo$$

Austenite Decomposition Model

- Diffusionless transformation of austenite to martensite is modeled with Koistinen-Marburger equation:

$$x_m = x_\gamma\left[1 - e^{-\alpha\left(T_{st,m} - T\right)}\right]$$

$$T_{st,m} = 834 - 474C - 33Mn - 17Ni - 17Cr - 21Mo$$

Prediction of Vickers Hardness

- Empirical model form Maynier et al.

$$HV = (x_f + x_p)HV_{f+p} + x_b HV_b + x_m HV_m$$

$$HV_{f+p} = 42 + 223C + 53Si + 30Mn + 12.6Ni + 7Cr + 19Mo + (10 - 19Si + 4Ni + 8Cr + 130V)\, lg\left(\frac{dT_{973}}{dt}\right)$$

$$HV_b = -323 + 185C + 330Si + 153Mn + 65Ni + 144Cr + 191Mo + (89 + 53C - 55Si - 22Mn - 10Ni - 20Cr - 33Mo)\, lg\left(\frac{dT_{973}}{dt}\right)$$

$$HV_m = 127C + 949 + 27Si + 11Mn + 8Ni + 16Cr + 21lg\left(\frac{dT_{973}}{dt}\right)$$

Constitutive Modelling

- Additive decomposition of total strain increment $\Delta\varepsilon_{ij}$:

$$\Delta\varepsilon_{ij} = \Delta\varepsilon_{el,ij} + \Delta\varepsilon_{th,ij} + \Delta\varepsilon_{pl,ij} + \Delta\varepsilon_{tp,ij}$$

- Leblond Model distinguishes two cases:

1. Global yield: von Mises yield criterion with isotropic hardening

$$f = \sqrt{\frac{3}{2}s_{ij}s_{ij}} - \sigma_y = 0$$

$$\sigma_y = \sum_i x_i \sigma_{y,i}\left(\varepsilon_{pl,i}, \dot{\varepsilon}_{pl}, T\right) \qquad i = \gamma, f, p, b, m$$

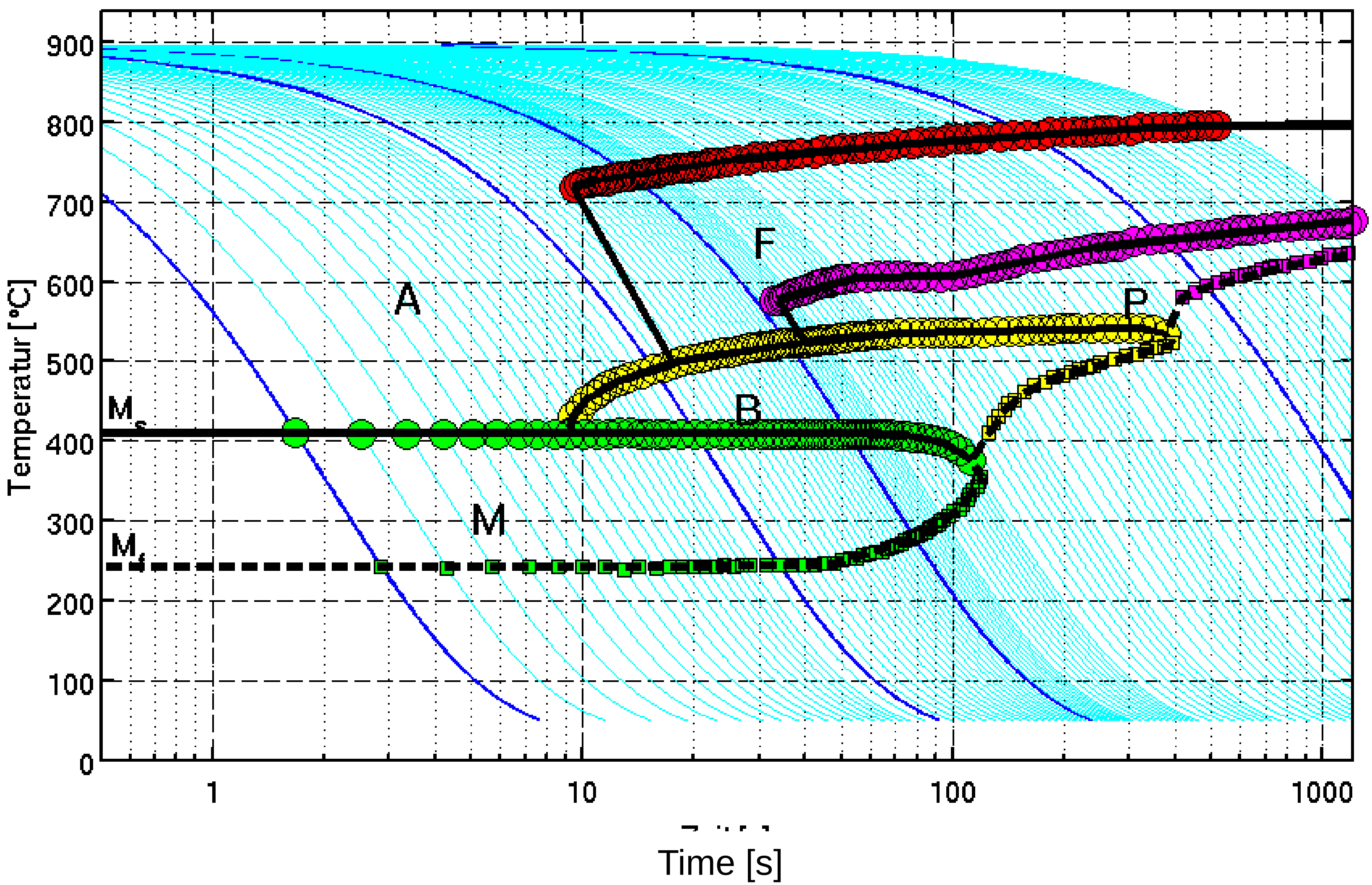
2. Local Yield: Transformation Induced Plasticity (TRIP):

$$\dot{\varepsilon}_{tp,ij} = \frac{3\Delta\varepsilon_{th,1-2}\, h\left(\frac{\bar{\sigma}}{\sigma_y}\right) \dot{z} \ln(z)}{\sigma_{y,\gamma}\left(\varepsilon_{pl,\gamma}, \dot{\varepsilon}_{pl}, T\right)}$$

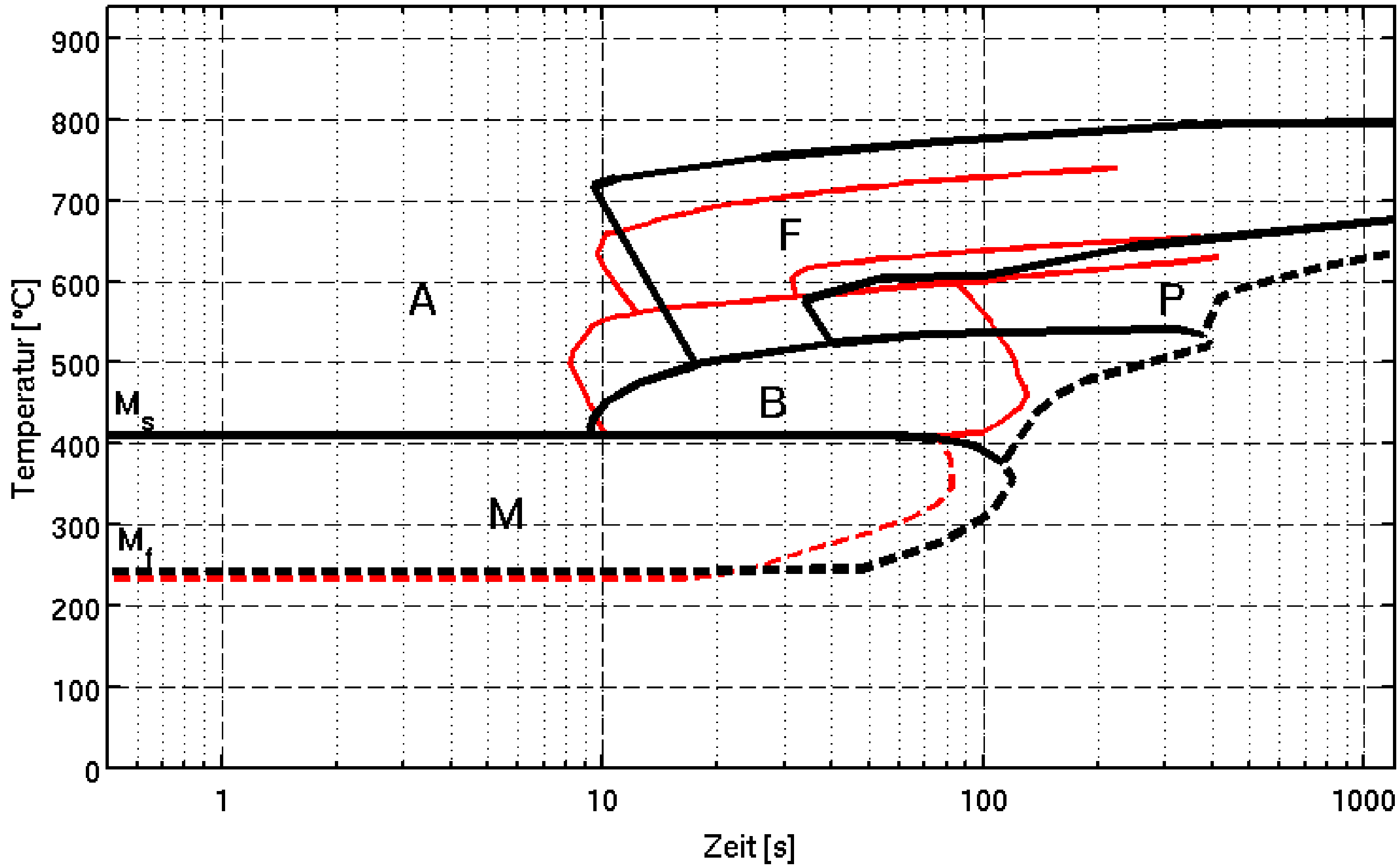
$\Delta\varepsilon_{th,1-2}$: difference in compactness between austenite and other phase
z: total amount of harder phase
$\sigma_{y,\gamma}\left(\varepsilon_{pl,\gamma}\right)$: actual yield stress of austenite

$$h\left(\frac{\bar{\sigma}}{\sigma_y}\right) = \begin{cases} 1 & if\ \frac{\bar{\sigma}}{\sigma_y} \leq \frac{1}{2} \\ 1 + 3.5\left(\frac{\bar{\sigma}}{\sigma_y} - \frac{1}{2}\right) & if\ \frac{\bar{\sigma}}{\sigma_y} > \frac{1}{2} \end{cases}$$

Simulated CCT-Diagram



Simulated vs measured CCT-Diagram



Simulated vs measured CCT-Diagram

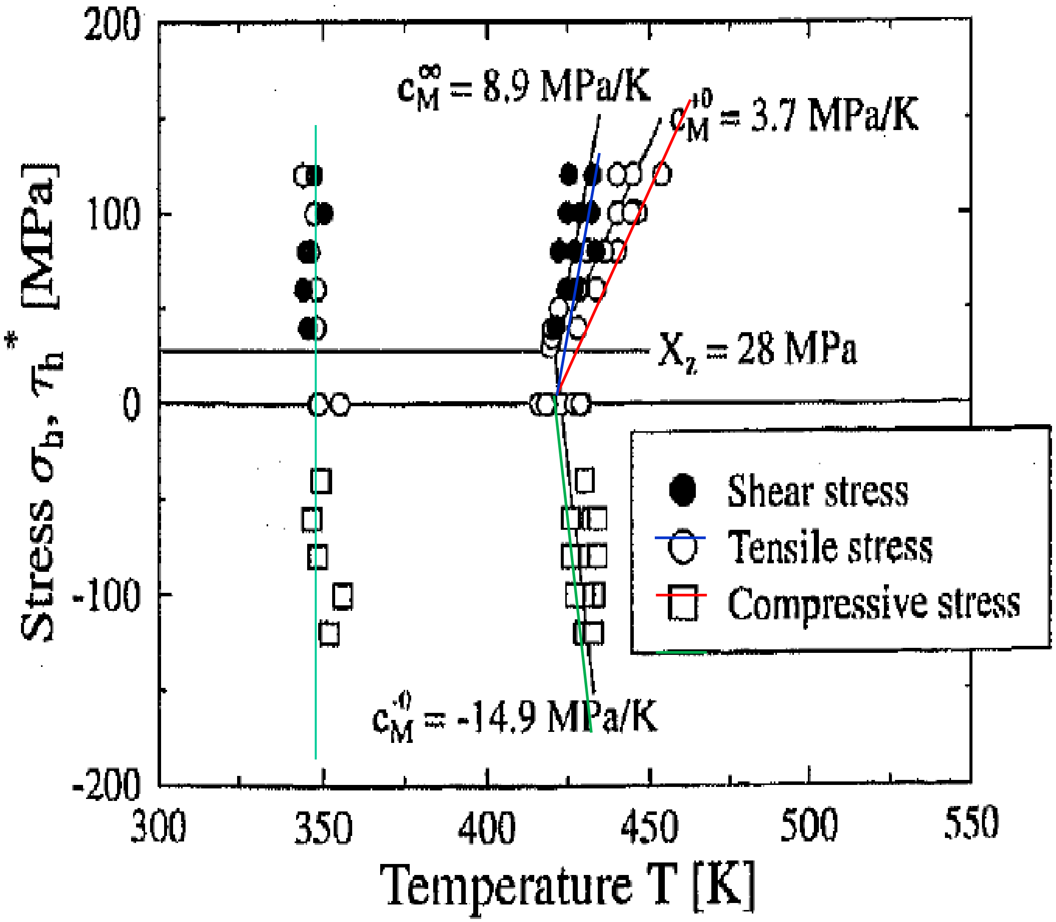
$t_{8/5}$	Simulation	Data from CCT
$t_{8/5} = 1.0\ s$	$x_m = 100\ \%$ $HV = 490$	$x_m \approx 100\ \%$ $HV \approx 471$
$t_{8/5} = 12.0\ s$	$x_m = 91.6\ \%$ $x_b = 7.9\ \%$ $x_f = 0.3\ \%$ $x_p = 0.2\ \%$ $HV = 453$	$x_m \approx 90\ \%$ $x_b \approx 10\ \%$ $x_f \approx 0\ \%$ $x_p \approx 0\ \%$ $HV \approx 428$
$t_{8/5} = 31.0\ s$	$x_m = 24.6\ \%$ $x_b = 71.4\ \%$ $x_f = 3.2\ \%$ $x_p = 0.8\ \%$ $HV = 315$	$x_m \approx 24\ \%$ $x_b \approx 72\ \%$ $x_f \approx 4\ \%$ $x_p \approx 0\ \%$ $HV \approx 250$
$t_{8/5} = 550.0\ s$	$x_f = 79.5\ \%$ $x_p = 20.5\ \%$ $HV = 168$	$x_f \approx 80\ \%$ $x_p \approx 20\ \%$ $HV \approx 156$

Recent Enhancements

Modified Start Temperatures

- User-defined start temperatures for phase transformations
- Increase of martensite start temperature due to applied stress

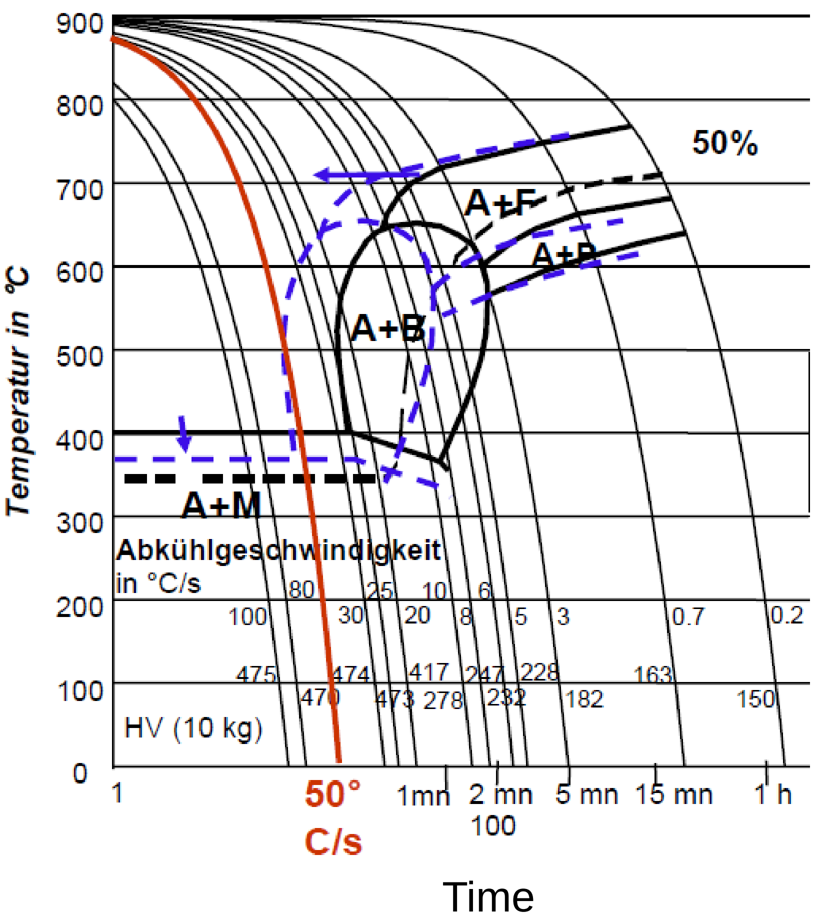
$$T_{st,m} = T_{st,m0} + M_{sig}(\eta)\sigma_{eq}$$



Source: Antretter et al.: The thermo-mechanical response to a general load path of a martensitically transforming steel

Effect of Deformation of Austenite

- Accelerated phase transformation due to plastic deformation of austenite



$$Q_{R,i}(\boldsymbol{\varepsilon_{pl,\gamma}}) = Q_{Ri} * \boldsymbol{c_i(\varepsilon_{pl,\gamma})}$$

$$F_{T,f} = (T_{st,f} - T)^3 \exp\left(-\frac{\boldsymbol{Q_{R,f}}}{T}\right)$$

$$F_{T,p} = (T_{st,p} - T)^3 \exp\left(-\frac{\boldsymbol{Q_{R,p}}}{T}\right)$$

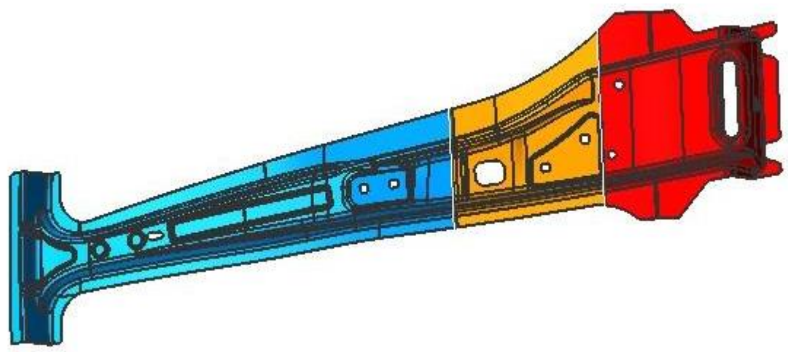
$$F_{T,b} = (T_{st,b} - T)^2 \exp\left(-\frac{\boldsymbol{Q_{R,b}}}{T}\right)$$

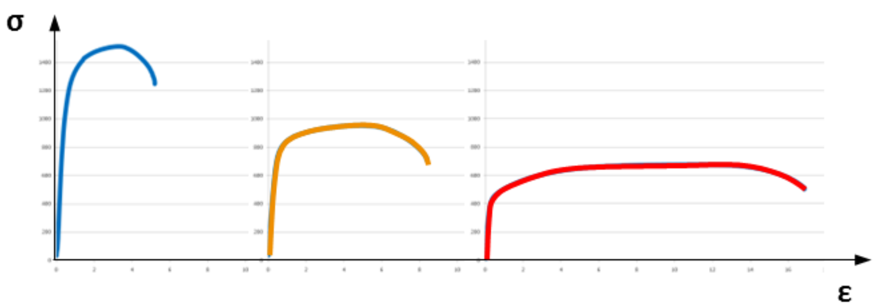
$$\begin{aligned} T_{st,msig} &= T_{st,m} \\ &\quad + M_{sig}(\eta)\sigma_{eq} \\ &\quad + \boldsymbol{\Delta T_m(\varepsilon_{pl,\gamma})} \end{aligned}$$

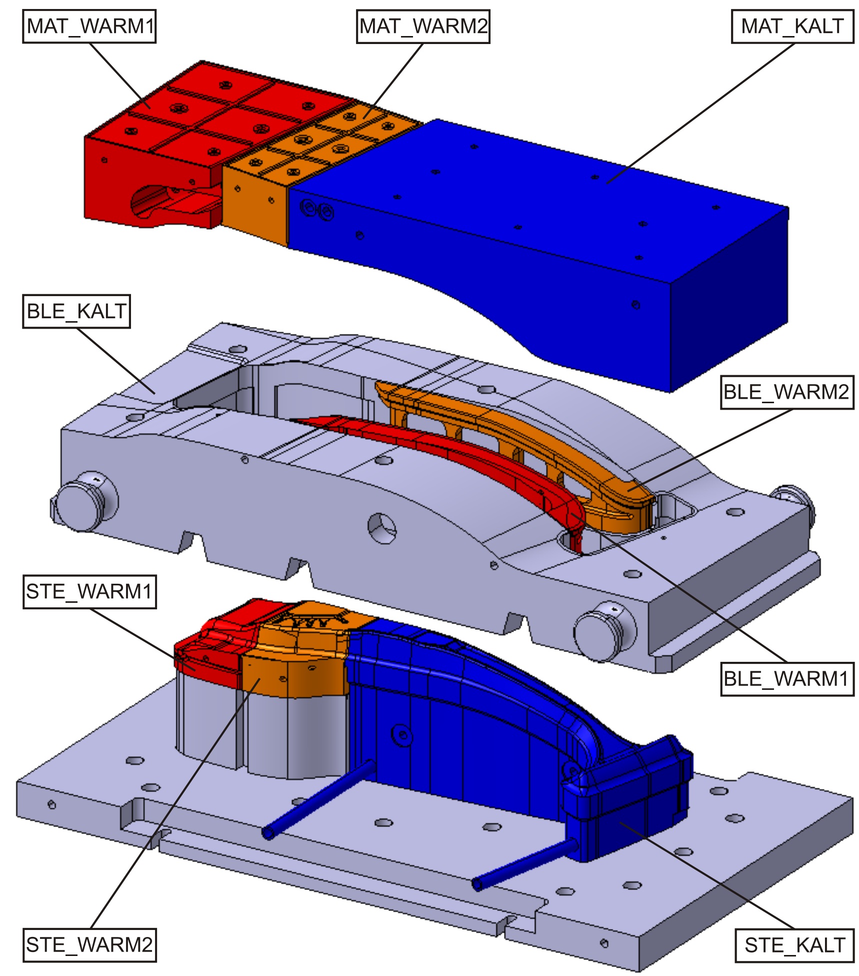
$$x_m = x_\gamma \left[1 - e^{-\alpha(\boldsymbol{T_{st,msig}} - T)}\right]$$

Tailored Tempering

- B-Pillar with different final properties (PhD Thesis P. Feuser, Daimler AG)







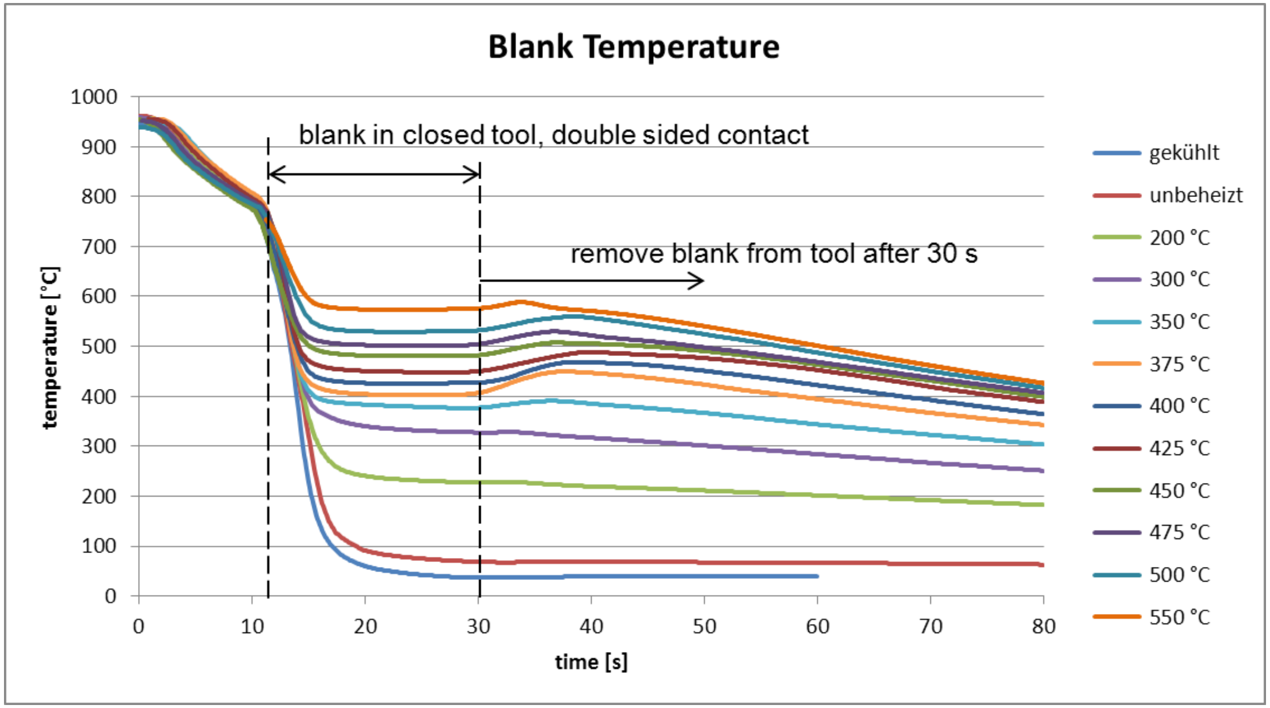
Tempering Option for Hardness Calculation

1. Automatic detection of holding phase

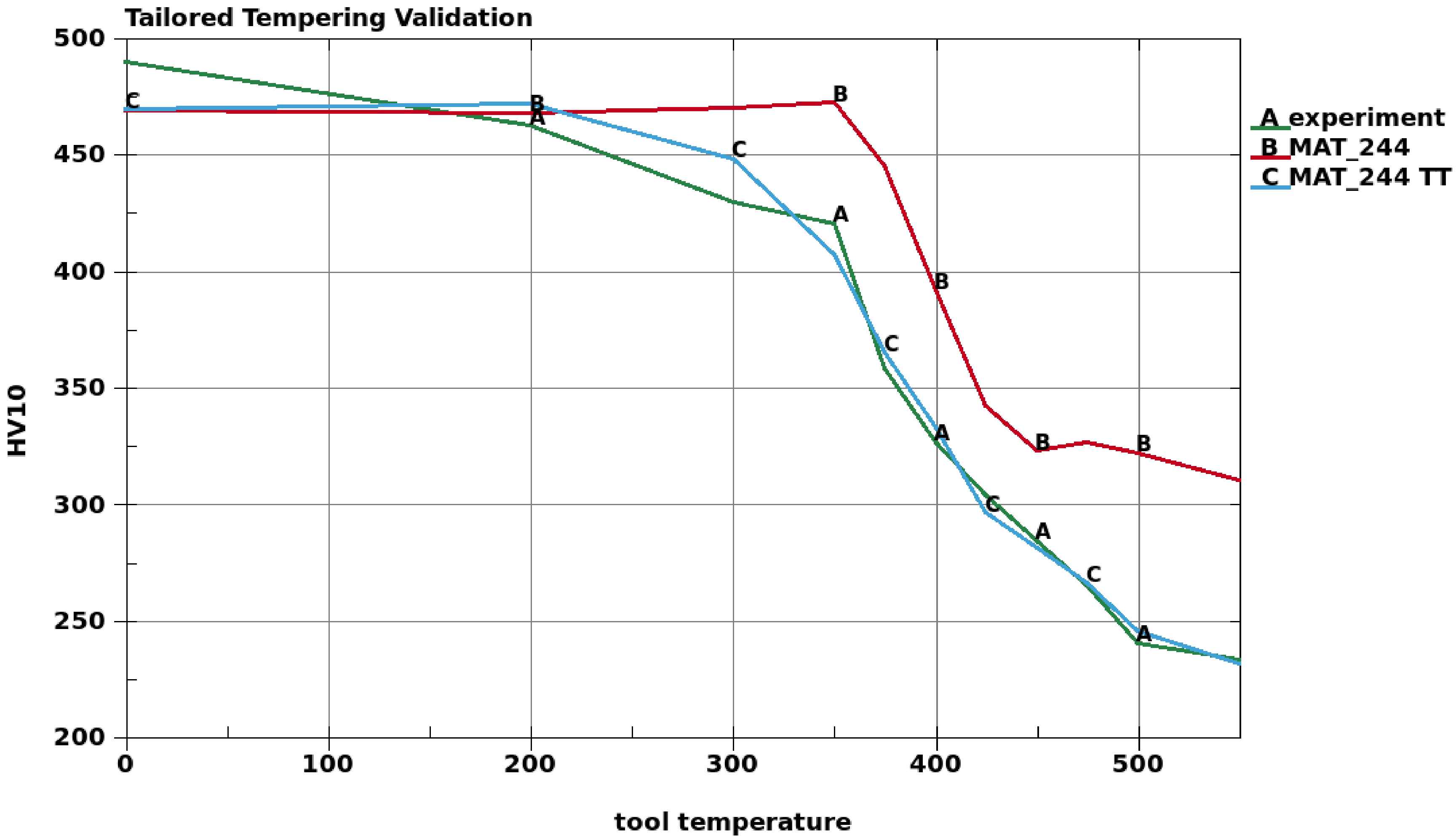
$$|\dot{T}_{avg}| \leq \dot{T}_{crit} \quad \text{and} \quad t_{thresh} > t_{sampling}$$

2. Incremental update for hardness of bainite and martensite

$$HV_i^{n+1} = \frac{x_i^n}{x_i^{n+1}} HV_i^n + \frac{x_i^{n+1} - x_i^n}{x_i^{n+1}} h_i(T) \qquad i = b, m$$



Tempering Option for Hardness Calculation



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