VDEh-Betriebsforschungsinstitut GmbH

Phase Transformation and Deformation Model for Quenching Simulations

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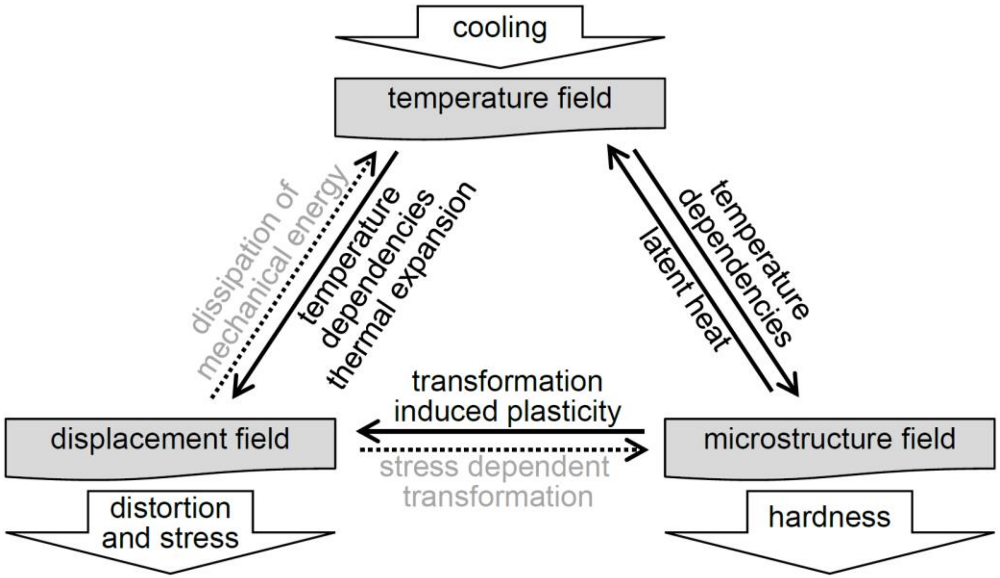
Introduction

Quenching is the rapid cooling of a workpiece to obtain certain material properties. For instance, quenching can reduce the crystal grain size of metallic materials and increasing their hardness.



Quenching of the advanced steel grades is a challenging process since the residual stress and deformation are pronounced and the quality requirements of the customers are tighter.

A comprehensive modelling of the complex phenomena to estimate the residual stress and deformation is essential for developing an optimal process control.

Computational Methods:
Temperature and Displacement Fields

Heat transfer in solids physics and solid mechanics physics are used.

All material properties depends on the temperature and microstructure. Linear mixture rules are used for $E, v, \sigma_{y0}, C_p, k$ and harmonic mixture rule is used for ρ.

$$E = f_a E_a(T) + f_b E_b(T) + f_m E_m(T)$$
$$\nu = f_a \nu_a(T) + f_b \nu_b(T) + f_m \nu_m(T)$$
$$\sigma_{y0} = f_a \sigma_{ay0}(T) + f_b \sigma_{by0}(T) + f_m \sigma_{my0}(T)$$
$$C_p = f_a C_{pa}(T) + f_b C_{pb}(T) + f_m C_{pm}(T)$$
$$k = f_a k_a(T) + f_b k_b(T) + f_m k_m(T)$$
$$\rho = \frac{1}{\frac{f_a}{\rho_a(T)} + \frac{f_b}{\rho_b(T)} + \frac{f_m}{\rho_m(T)}}$$

Latent heat of transformation as heat source $Q = L_{ab}\dot{f}_b + L_{am}\dot{f}_m$

Dilatation due to Temperature und microstructure change $dL = \sqrt[3]{\frac{\rho_a(T_{\mathrm{ref}})}{\rho}} - 1$

Inelastic strains upon Creep and TRIP $\dot{ec}_{ij} = (A_{\mathrm{tr}} + A_{\mathrm{cr}}) \cdot n_{ij}^S$ $\quad \dot{ec}_{\mathrm{eff}} = \sqrt{\frac{2}{3}\sum \dot{ec}_{ij}^2}$

$$A_{\mathrm{tr}} = \{K_b^{\mathrm{GJ}} \cdot \dot{f}_b \cdot \ln(f_b) + K_m^{\mathrm{GJ}} \cdot \dot{f}_m \cdot \ln(f_m)\} \cdot \sigma_{\mathrm{eff}}$$

$$A_{\mathrm{cr}} = \left(\frac{\sigma_{\mathrm{eff}}}{\sigma_{\mathrm{ref}}(T)}\right)^{n_{\mathrm{cr}}(T)}$$

Computational Methods:
Microstructure Field

Two types of transformations are modelled:

(1) austenite to bainite transformation, which is diffusion controlled, needs an incubation time before the transformation starts. This transformation obeys Scheil’s rule and JMAK (Johnson-Mehl-Avrami-Kolmogorow) equations:

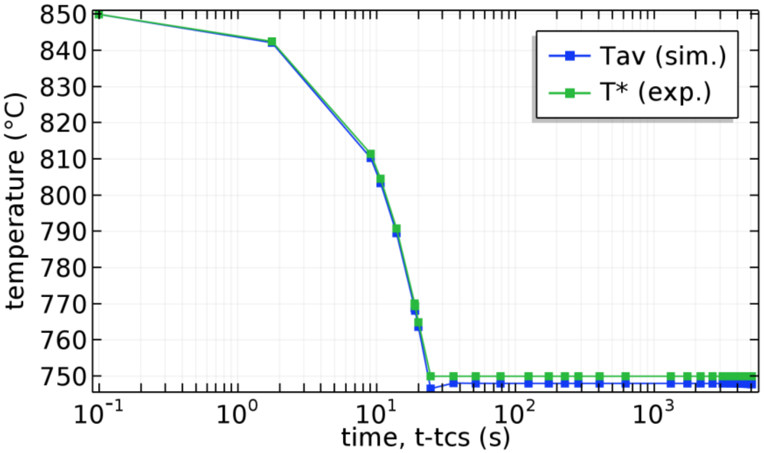
$$\dot{s}s = \frac{1}{Bs(T)} \qquad \dot{f}_b = K \cdot n \cdot t^{n-1} \cdot \exp(-K \cdot t^n)$$

(2) austenite to martensite transformation, which is diffusionless, is controlled only by temperature. This transformation is expressed by KM (Koistinen-Marburger) equation:

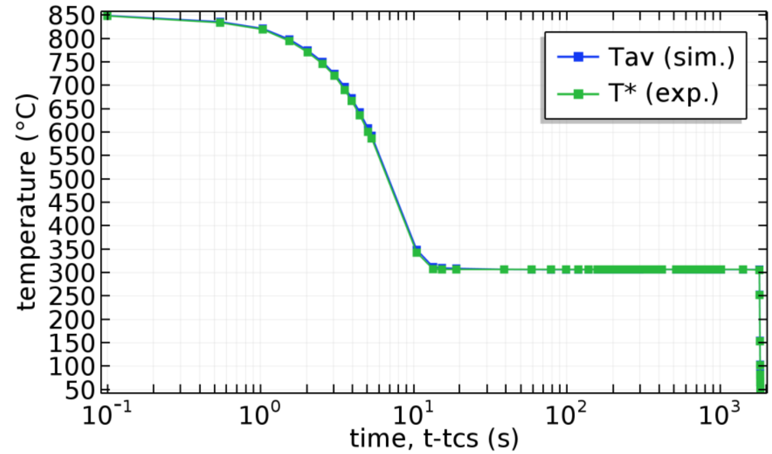
$$f_m = 1 - \exp\left(-0.011(M_s - T)\right)$$

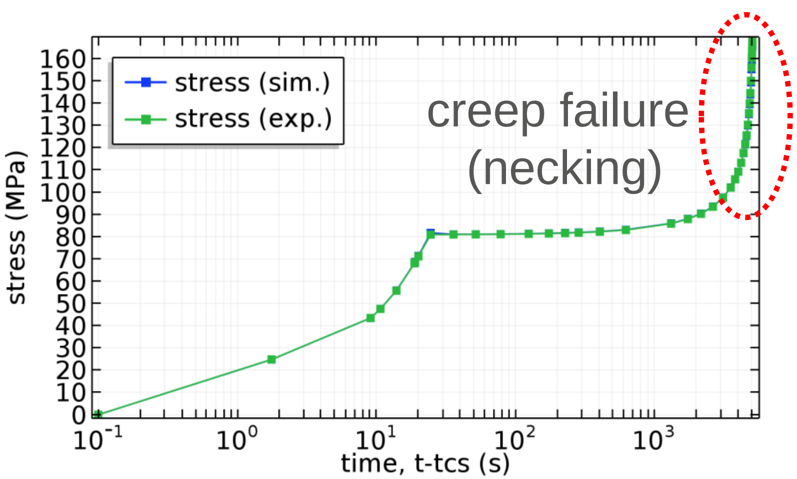
Results: Creep vs. TRIP deformation
Temperature and Mechanical Loading

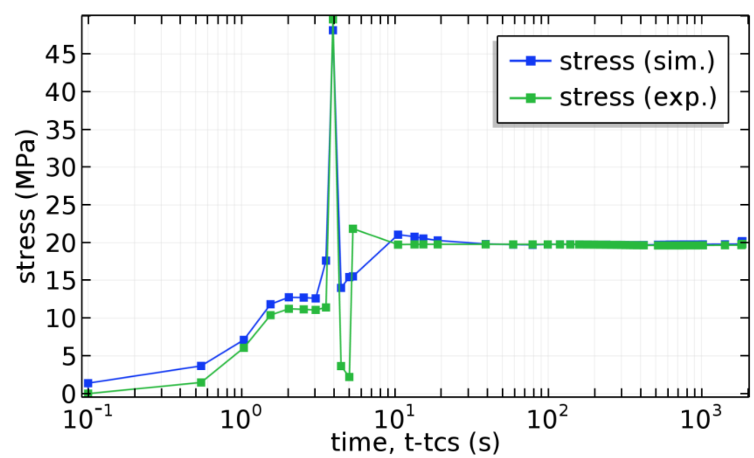
creep at T=750°C & σ=80MPa



TRIP for isothermal transformation
T=307°C & σ=20MPa

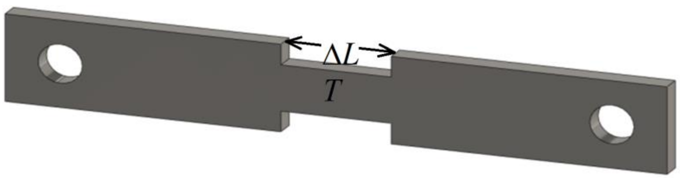




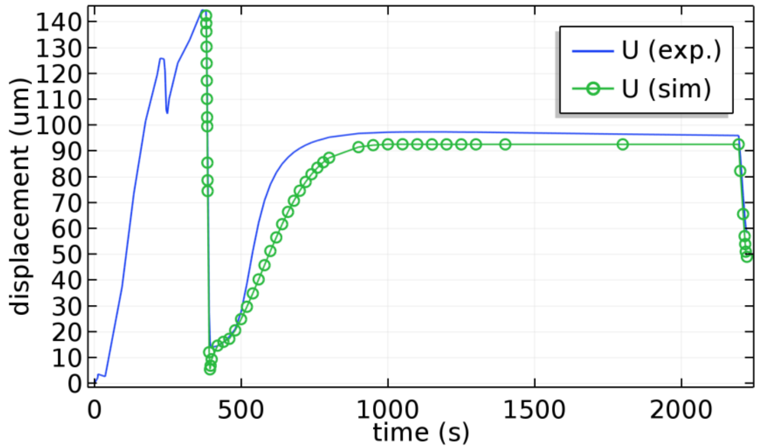


Results: Creep vs. TRIP deformation Deformation Response

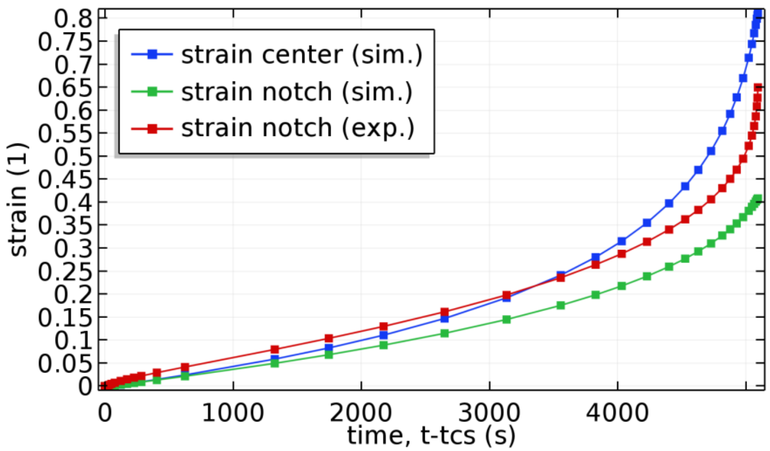
Specimen geometry



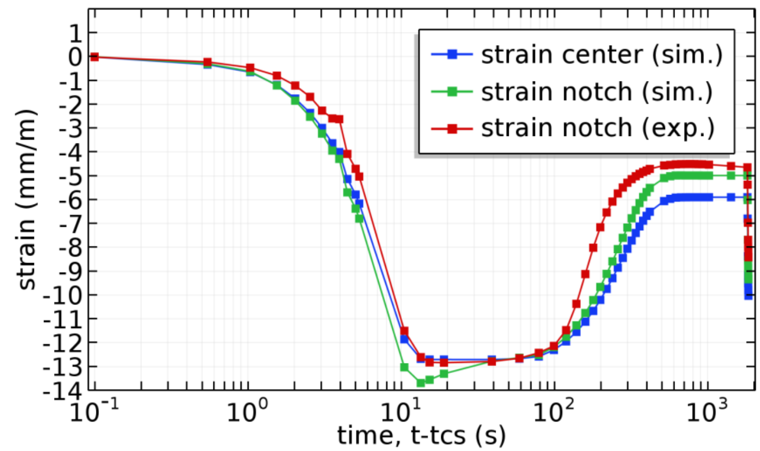
Displacement (TRIP)



Strain (Creep)



Strain (TRIP)



Results: Creep vs. TRIP deformation

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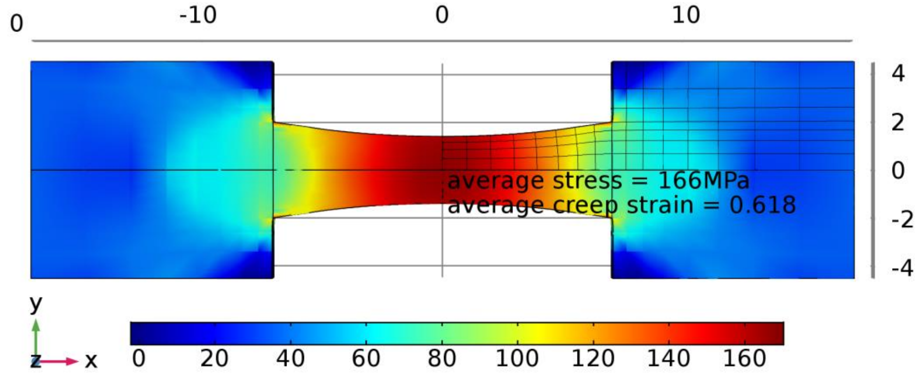
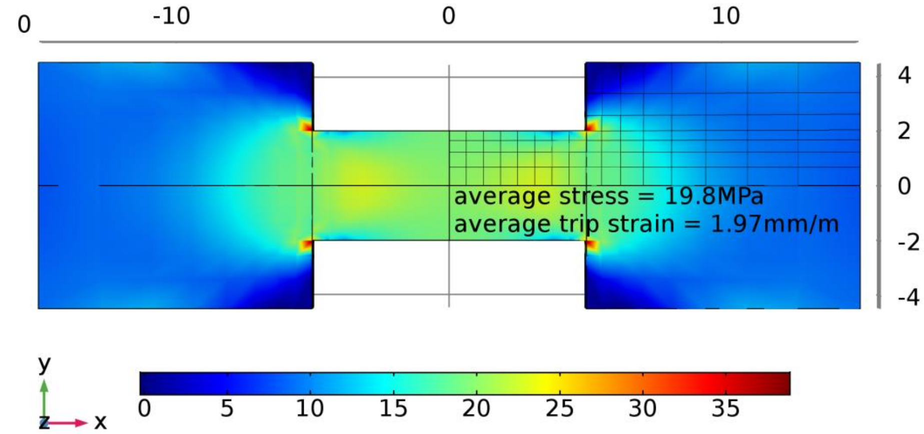
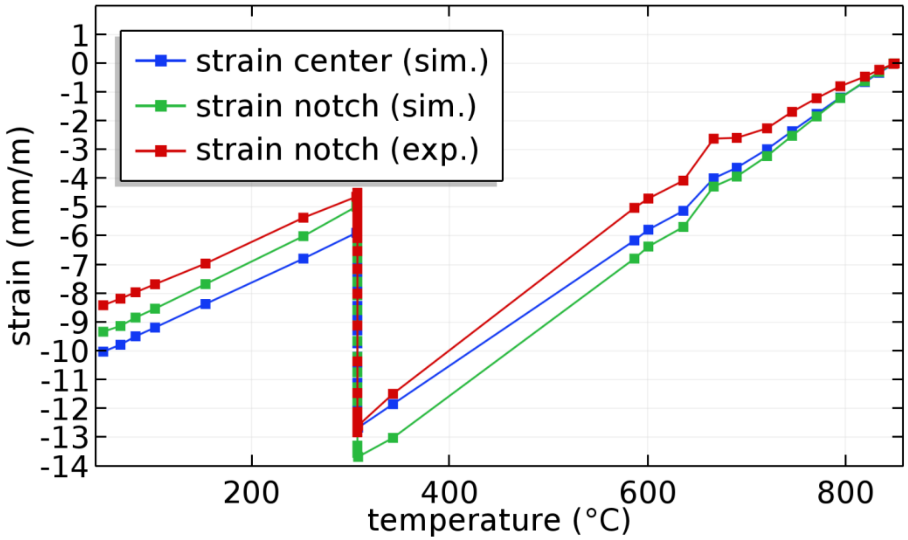
Stress distribution and necking (creep)

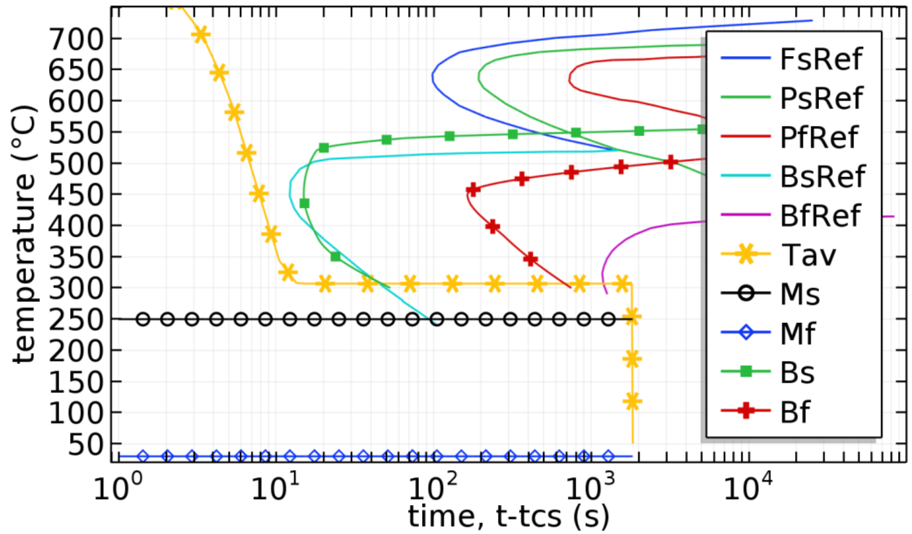


Stress distribution (TRIP)



Typical dilatometry curve for isothermal transformation and TTT diagram





Conclusions

- A complex model for the simulation of the quenching process has been introduced, which can be used in the heat treatment simulation of the advanced steel grades to compute the residual stress and deformation as well as the microstructure.
- The introduced model consists of a series of strongly coupled physics. The temperature, microstructure and displacement fields are solved by considering dilatation and nonlinear phenomena (plasticity, trip, creep, and large deformations).
- The constitutive model parameters as well as the isothermal and martensitic transformation kinetic parameters are validated and calibrated by several dilatometry tests.

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