Phase Transformation and Deformation Model for Quenching Simulations

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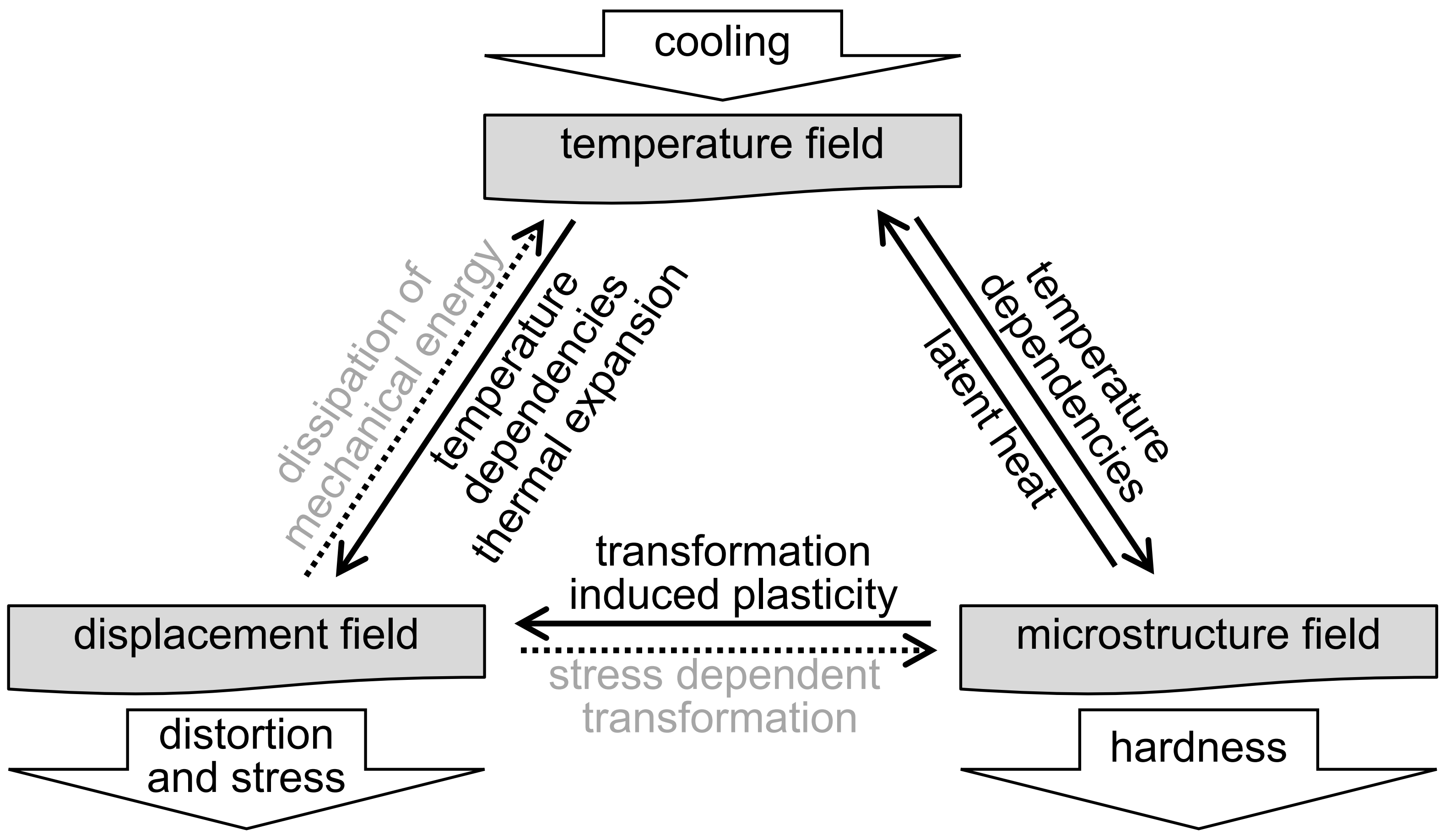
Introduction:

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 (e.g., micro-alloyed steels) is a challenging process since the residual stress/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.



cooling

temperature field

dissipation of mechanical energy

temperature dependencies thermal expansion

temperature dependencies

latent heat

transformation induced plasticity

displacement field

stress dependent transformation

microstructure field

distortion and stress

hardness

Figure 1. Coupling of fields in quenching process

Computational Methods:

The model presented here consists of strongly coupled phenomena of heat transfer, micro-structure change, deformation (due to the thermal shrinkage, microstructure change related dilatation, trip, creep, plasticity, and large deformations). The governing fields involved in the quenching process and their interactions are shown in Figure 1. In quenching, the temperature field is controlled by the cooling boundary conditions with an appropriate quenching medium. The temperature evolution drives the phase transformation kinetics, which in-turn influences the temperature field by the released latent heat. Moreover, all the material properties depend on the temperature and microstructure, which can be expressed by interpolation functions and mixture rules. The linear mixture rule is used for the Young's modulus E, Poisson's ratio ν, initial yield stress σ_{y0}, heat capacity C_p and thermal conductivity k. However, the harmonic mixture rule is used for the density ρ.

Temperature and microstructure dependency of the material properties:

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

Heat source - latent heat of the phase transformations:

$$Q = L_{ab} \dot{f}_b + L_{am} \dot{f}_m$$

Microstructure field

Incubation time for the bainite transformation is estimated using Scheil's sum:

$$\dot{s}s = \frac{1}{Bs(T)}$$

Bainite transformation rate is computed by JMAK-equation:

$$\dot{f}_b = K \cdot n \cdot t^{n-1} \cdot \exp(-K \cdot t^n)$$

Martensite volume faction is computed by KM-equation:

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

Displacement field

Volumetric strain due to temperature and microstructure change:

$$dL = \sqrt[3]{\frac{\rho_a(T_{\mathrm{ref}})}{\rho}} - 1$$

Model for trip and creep:

$$\dot{e}c_{ij} = (A_{\mathrm{tr}} + A_{\mathrm{cr}}) \cdot n_{ij}^S$$

The trip part is:

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

The creep part is

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

Results:

A series of dilatometry measurements are performed within the study. In this paper, the results of simulation model for two selected dilatometry test are presented. The region of interest is the narrow middle region of the specimen shown in Figure 2. The dilatometry device is programed to apply a given temperature and mechanical loading sequence on the specimen. The specimen temperature T is continuously monitored using a contact thermocouple as well as the relative displacement ΔL of the notches of the specimen.

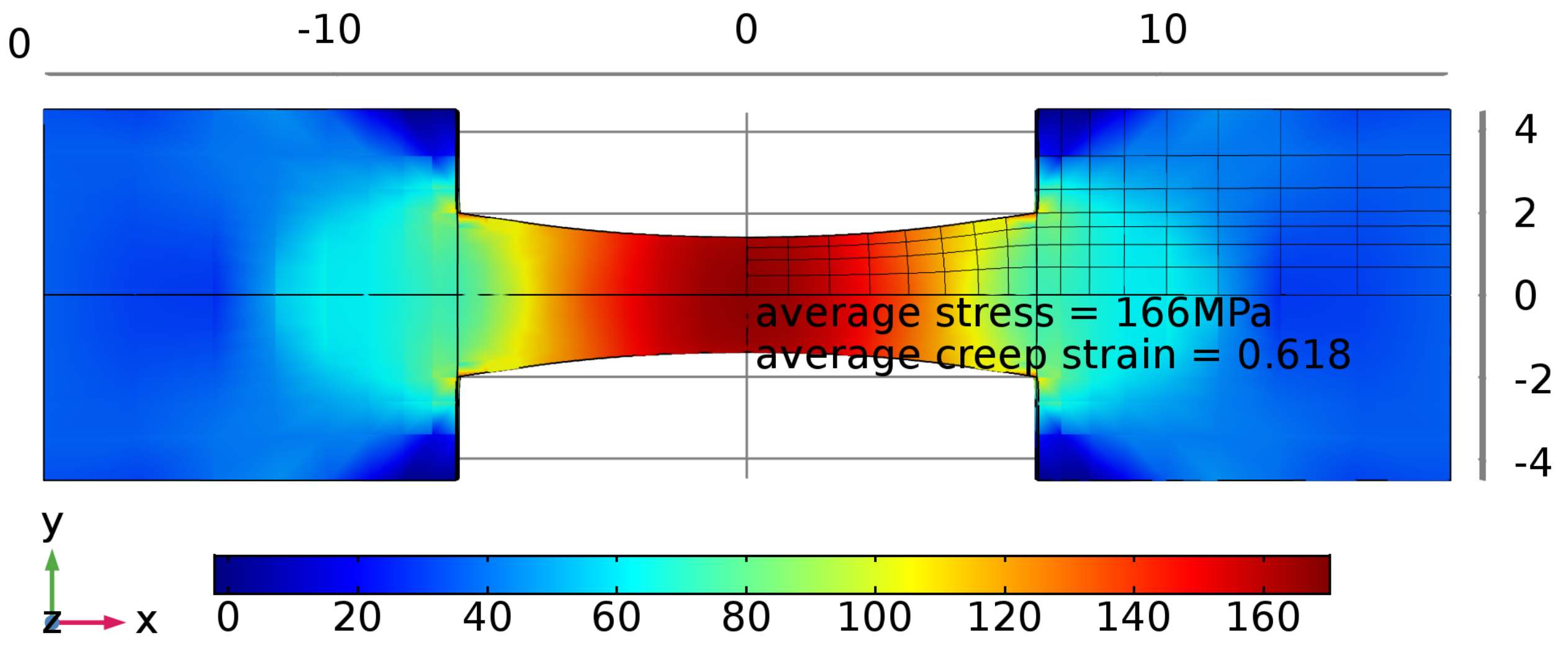


Figure 2. Stress field just before creep failure

Creep dominant behavior:

TRIP dominant behavior:

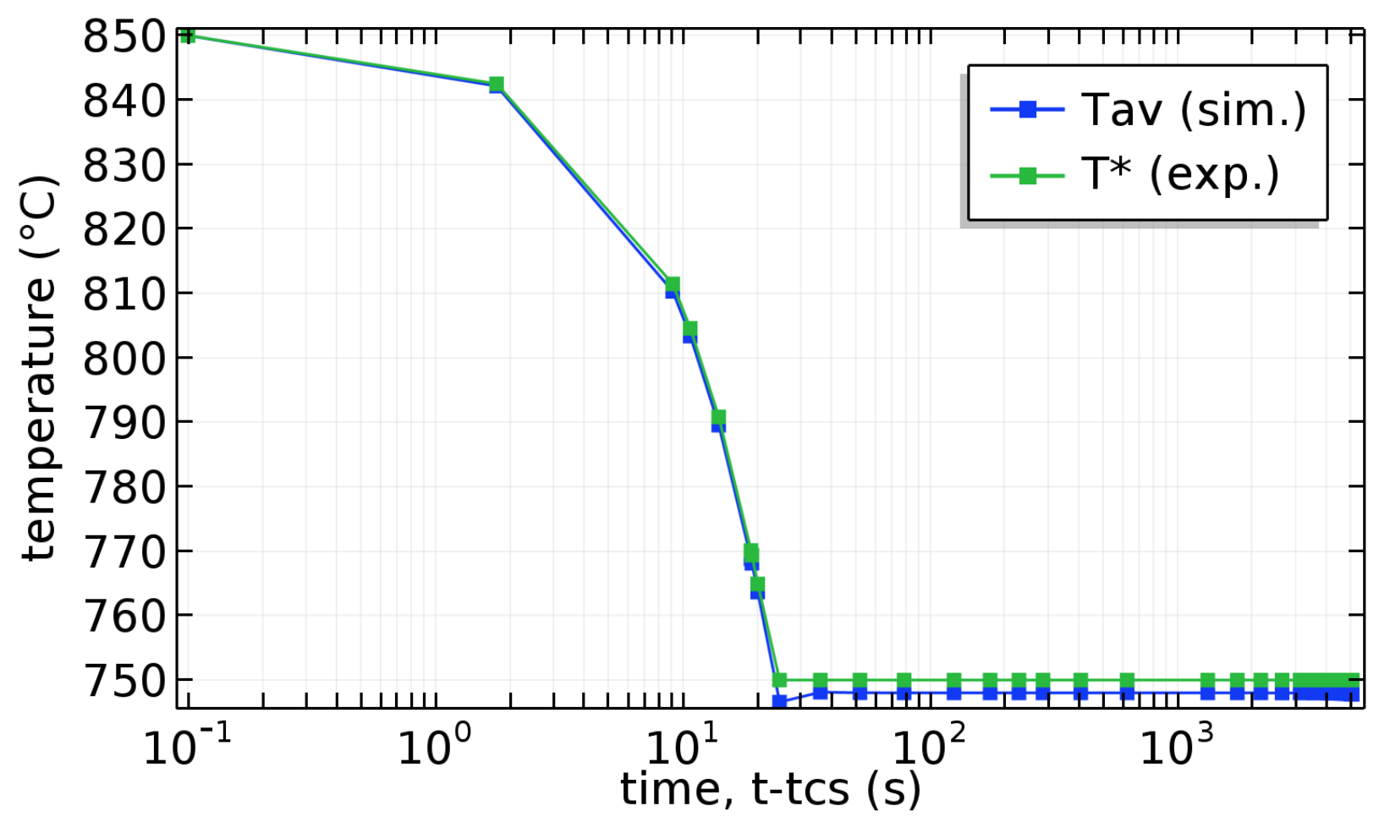


Figure 3. Specimen temperature evolution during creep experiment

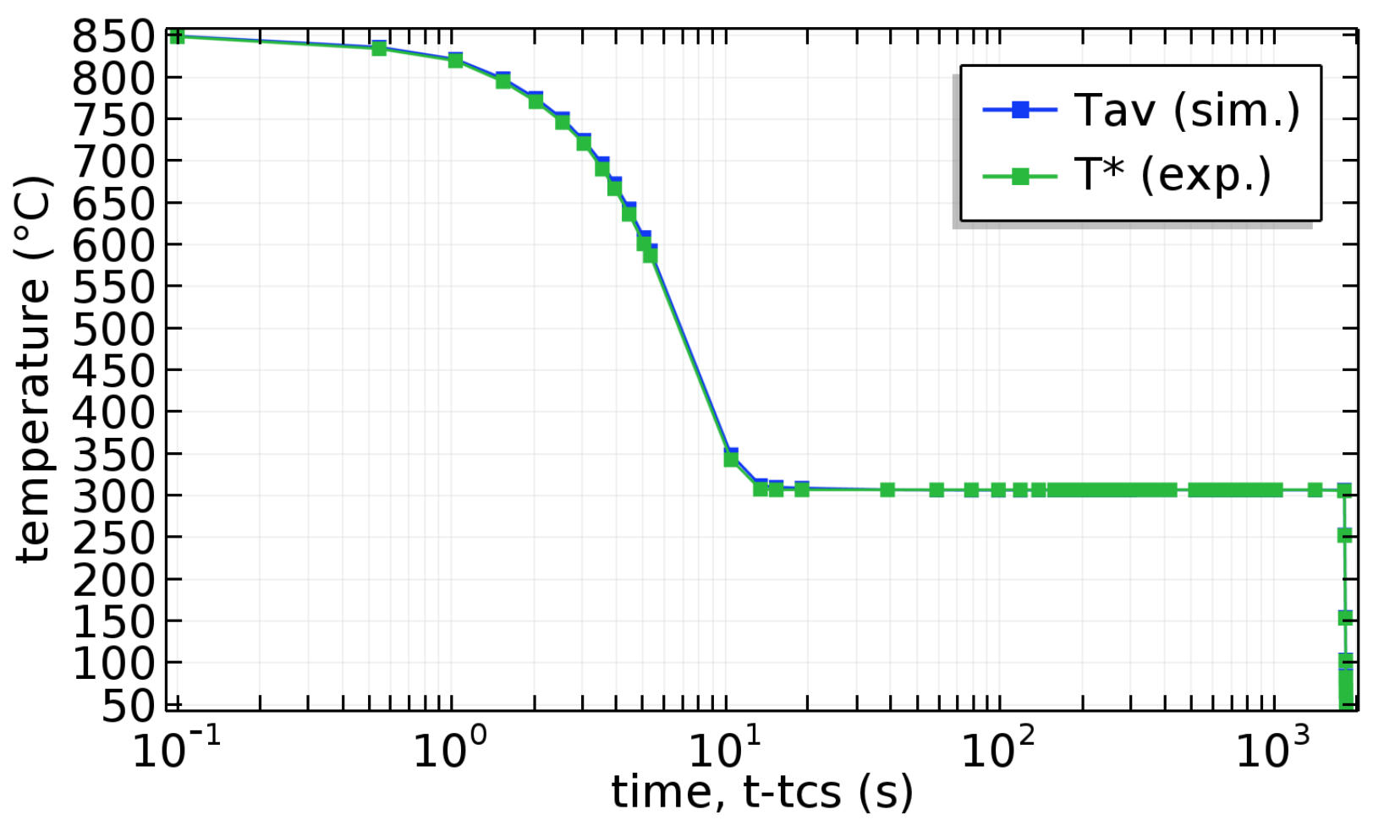


Figure 4. Specimen temperature evolution during isothermal transformation experiment

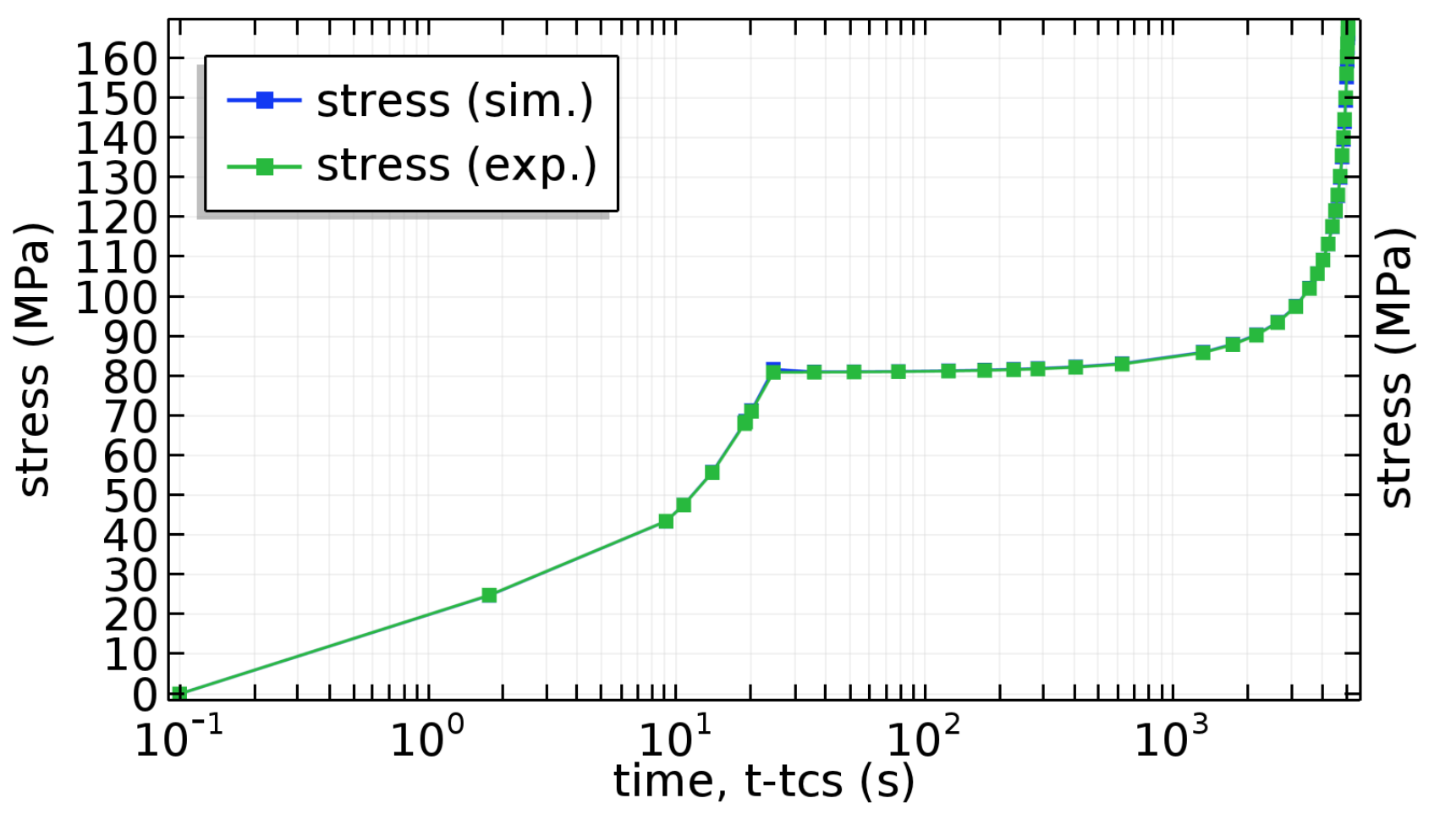


Figure 5. Specimen axial stress evolution during creep experiment

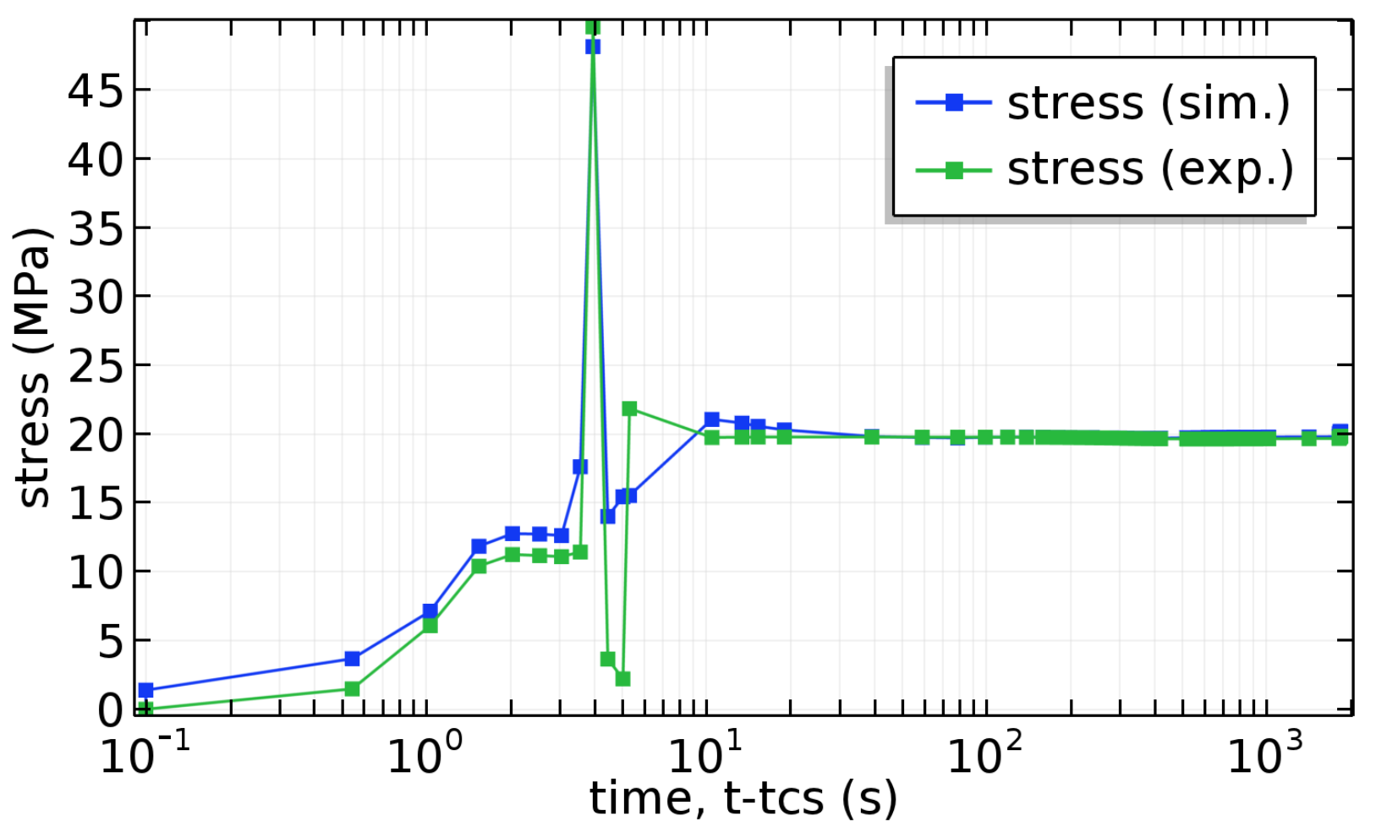


Figure 6. Specimen axial stress evolution during isothermal transformation experiment

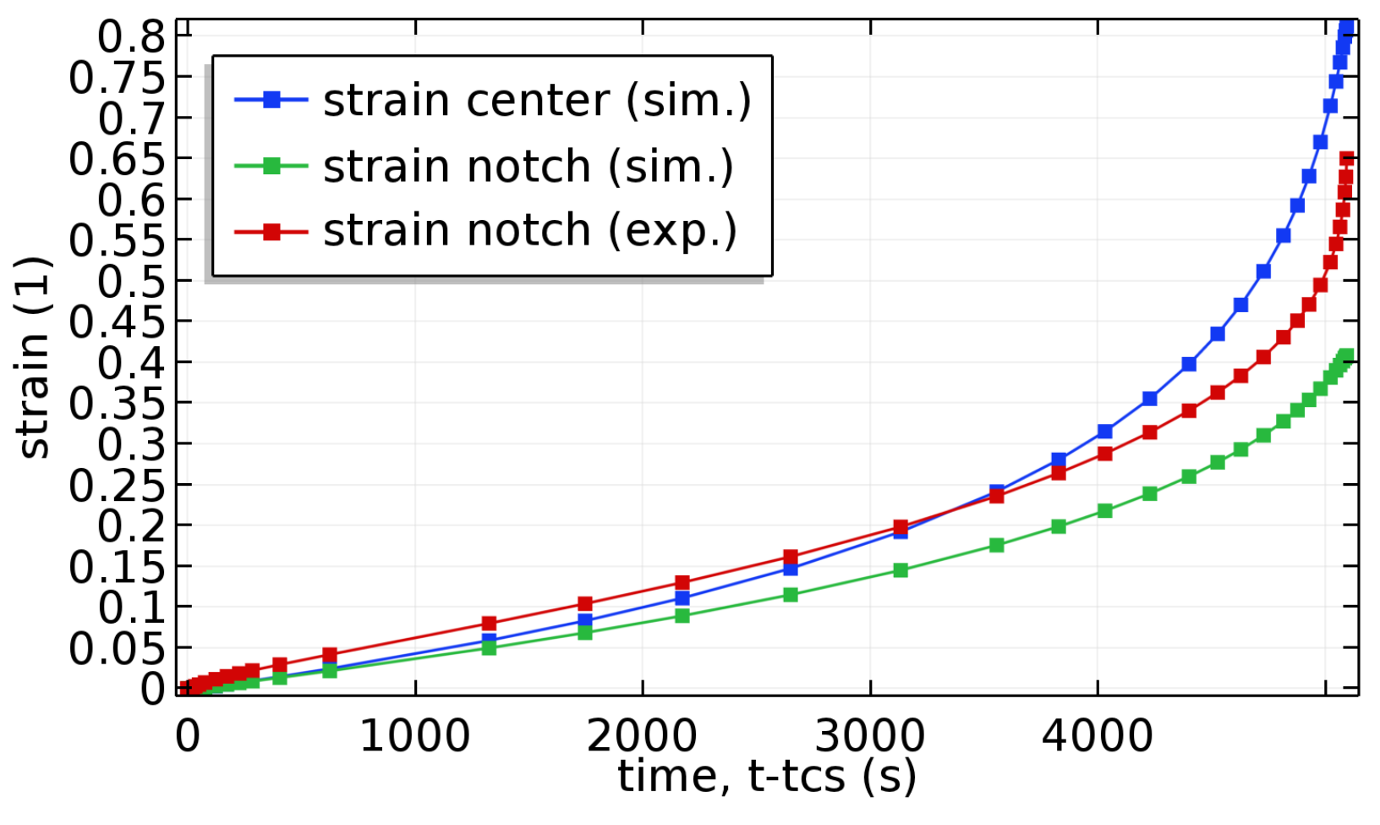


Figure 5. Specimen axial strain evolution during creep experiment

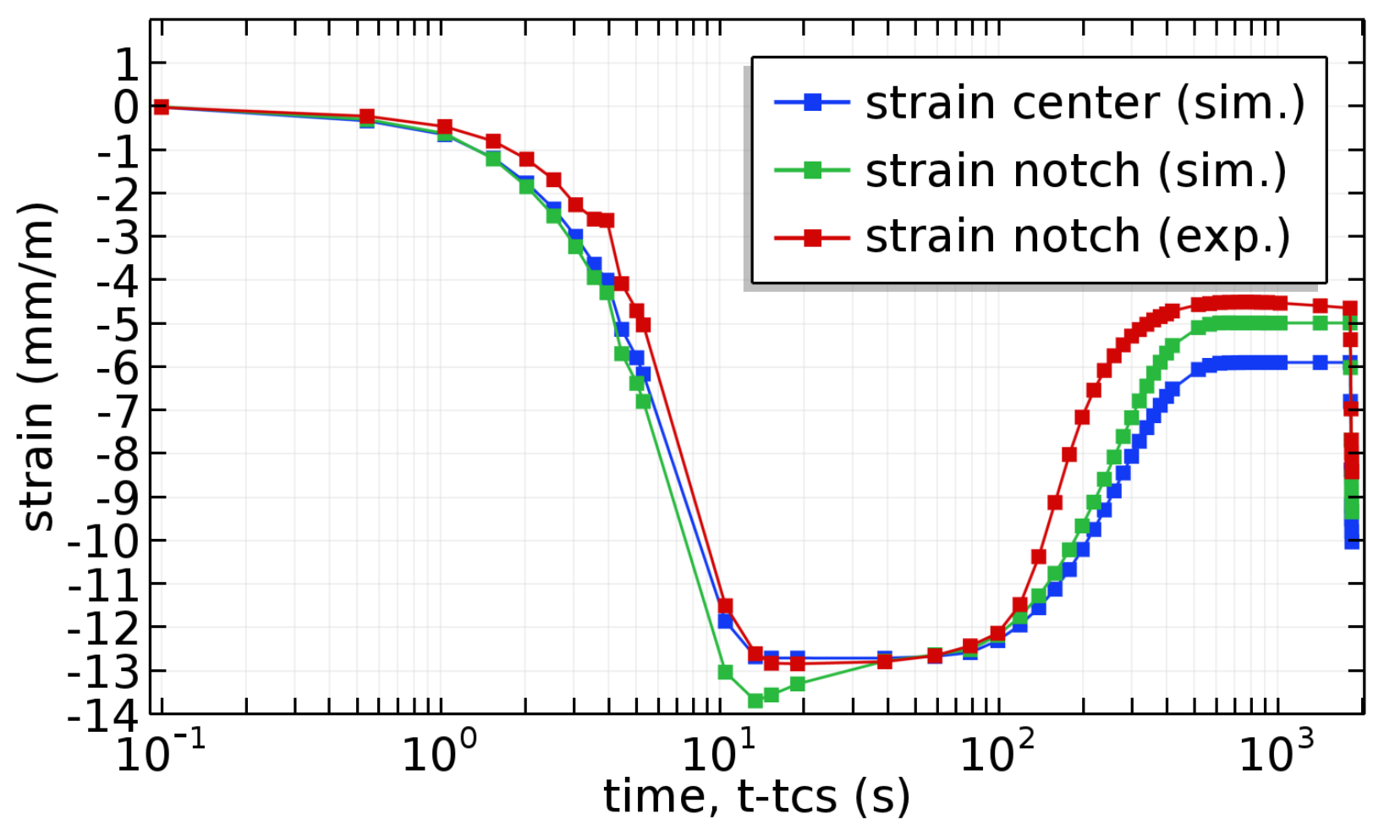


Figure 6. Specimen axial strain evolution during isothermal transformation experiment

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.

The development of the model is still in progress. As a next step, this model will be applied to the simulation of the process line, where the strips are continuously heat treated. With the help of the simulations, the heat treatment processes control will be optimized to meet the customer requirements with minimal material waste.

References:

1. Y. Kaymak, PhD Thesis: Simulation of Metal Quenching Processes for the Minimization of Distortion and Stresses, pages 17-25, Otto von Guericke University, Magdeburg (2007)