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On the numerical analysis of macro- and microscopic residual stresses in 3D

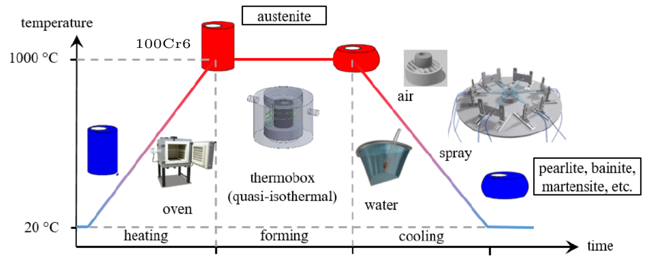
Motivation

The aim is to obtain improved targeted properties by adjusting the manufacturing process, here hot bulk forming. Therefore, a combination of experiments and numerical tools is beneficial. Moreover, two-scale Finite Element simulations reveal microscopic characteristics and residual stresses in an efficient manner.

- exploitation of thermal, mechanical, metallurgical interactions
- increased formability with various options to influence the resulting stress distribution by adjusting process parameters such as forming rate or temperature and cooling media
- integrated heat treatment as cost-, time- and energy-saving

Process

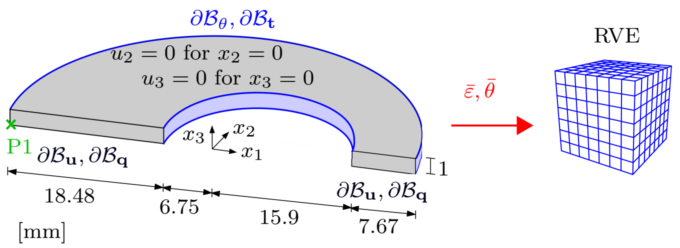
The investigated process is the hot bulk forming of a cylindrical specimen with eccentricity made from Cr-alloyed steel 100Cr6, [1].



- heating: austenization, assumption of stress-free body
- forming: reduction of height by ≈ 50%
- fast cooling: diffusionless austenite-to-martensite phase transformation characterized by volumetric expansion of unit cell

Boundary value problem

A slice of the formed cylindrical specimen exploiting symmetry conditions is taken into account as boundary value problem, [2].



- water cooling is applied on the lateral surface as Dirichlet bc's
- solving balance of momentum and balance of energy

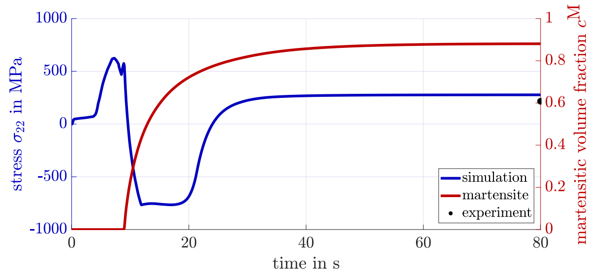
$$\operatorname{div} \boldsymbol{\sigma} = \mathbf{0} \qquad \text{and} \qquad \rho\dot{e} - \boldsymbol{\sigma} : \dot{\boldsymbol{\varepsilon}} + \operatorname{div} \boldsymbol{q} = 0$$

- additive split of total strains in elastic, plastic, thermal, transformation volumetric and TRIP (transformation induced plasticity) parts, [3]

$$\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}^{\mathrm{e}} + \boldsymbol{\varepsilon}^{\mathrm{p}} + \boldsymbol{\varepsilon}^{\theta} + \boldsymbol{\varepsilon}^{\mathrm{tv}} + \boldsymbol{\varepsilon}^{\mathrm{trip}}$$

Macroscopic stress evolution

On the macroscale, the tangential stress $\bar{\sigma}_{22} = \bar{\sigma}_{\mathrm{tang}}$ in point P1 is investigated over cooling time, since tangential stresses are most relevant w.r.t. to e.g. operating time, [1], [2].

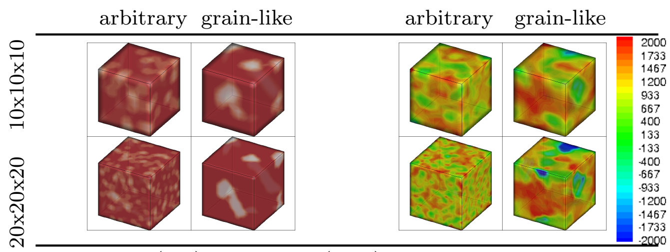


- thermal contraction: tensile stresses
- onset of phase transformation: superimposed with compressive stresses due to the volumetric expansion of the lattice
- phase transformation in bulk material: tensile stresses

FE^2-Simulation

To investigate the microstructural stress σ_{22}, a one-way coupled FE^2 simulation is carried out by applying temperature $\bar{\theta}$ and strain $\bar{\varepsilon}$ to a structured RVE. These quantities are stored during the single-scale analysis in point P1. Two ways to depict the phase transformation and two mesh densities are compared, [3].

- arbitrary: each element switches independently of its neighbors
- grain-like: 40 grains are defined, which switch one after the other element-by-element



- microstress exceeds macrostress ⇒ formation of microcracks ?
- grain-like RVE with pronounced stress peaks ⇒ failure ?

→ **importance of two-scale analysis !**

Open questions

- detailed microstructural analysis
- fully coupled two-scale simulation

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References

[1] B.-A. Behrens et al., FIIN, **85**, p. 757-771, 2021.
[2] S. Hellebrand et al., PAMM, (accepted) 2023.
[3] R. Mahnken et al., IJP, **25**, p.183-204, 2009.

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