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Simulation of quenching involved in induction hardening including mechanical effects

J. Montalvo-Urquizo *, Q. Liu, A. Schmidt

Zentrum für Technomathematik, University of Bremen, Germany

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ABSTRACT

We investigate the mathematical model for induction hardening of steel and present simulation results for the involved cooling process. The model accounts for the thermomechanical effects coupled with phase transitions that are caused by the enormous changes in temperature during the heat treatment. The mechanical part of the quenching model includes the transformation strain and transformation plasticity induced by the phase transitions (TRIP). The simulations have been performed by assuming a non-homogeneous pre-heated workpiece with an austenite profile generated via high-frequency inductive heating. The mathematical ingredients of the model are presented and the main simulation results are reported for the case of a gearing component made of steel 42CrMo4.

1. Introduction

For many applications in industry the surface of steel components is particularly stressed. Therefore, there exists a growing demand of surface hardened products. Hardening is a metallurgical and metalworking process used to increase the hardness of the boundary layers of a workpiece made of steel. The first step for hardening is the heating of the components to a temperature at which the iron phase changes from the initial phase into austenite. Then the material is quenched by applying high cooling rates on it. The reason why the hardness of steel can be changed relies on the occurring phase transitions. In the case of surface hardening, high cooling rates should be achieved so that most of the austenite phase is transformed to martensite by a diffusionless phase transition, producing the desired hardening effect.

Induction hardening is one of the most important surface hardening procedures and has been successfully applied in industry for more than 50 years. In this heat treatment method, an induction coil is connected to the power supply and the flow of alternating current through the coil generates an alternating magnetic field which in turn induces eddy currents in the workpiece. The energy dissipated due to these currents causes heat in the steel component and can be used to heat up only a specific part of it.

Although the inductive hardening is well established among practitioners, the needs for process optimization are still open. In this sense, the modeling, numerical simulation, and optimization remain areas of great interest in the applied research.

In this paper, we report on the research performed for a subproject of the network *MeFreSim—Modeling, Simulation and Optimization of Multi-Frequency Induction Hardening as Part of Modern Production* formed by the Weierstraß-Institut für Angewandte Analysis und zversität Bremen), the Institut für Mathematik (Universität Augsburg), the Stiftung Institut für Werkstoffstechnik (Bremen), and the industrial partners EFD Induction GmbH and ZF Friedrichshafen AG.

We present here our work performed within the research network, consisting of the numerical simulation of thermomechanical effects due to the phase transitions during the quenching process of gear components.

This work deals with the model and simulation for the quenching process after a high-temperature profile has been achieved with an inductor on a gearing component. The rather general model for quenching of steel is presented in Section 2, including heat conduction, phase transformations, thermoelasticity and transformation induced plasticity (TRIP) to be considered in the computations. After this, Section 3 presents the material data, simulation setting and main results for an implementation of a gearing component made of steel 42CrMo4. The final Section 4 draws some concluding remarks and present some ideas for further research.

2. The mathematical model

For the complete heat treatment cycle we usually consider four characteristic times: the beginning of the heating process t_0 (at

* Corresponding author. Tel.: +49 421218 63814.
E-mail addresses: montalvo@math.uni-bremen.de (J. Montalvo-Urquizo), liu@math.uni-bremen.de (Q. Liu), schmidt@math.uni-bremen.de (A. Schmidt).

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Nomenclature

Symbols

θ	temperature
θ_{ref}	reference temperature
θ_{ext}	external temperature
ϱ^i_{ref}	density of $z^i (i = 0,\ldots,5)$ at θ_{ref}
$\varrho(\theta,z)$	density
$c_\varepsilon(\theta,z)$	specific heat
$k(\theta,z)$	heat conductivity
q	heat flux
h	heat source
$\delta(\theta,z)$	heat transfer coefficient
u	displacement
$\varepsilon(u) = \frac{1}{2}(\nabla u + \nabla u^T)$	strain tensor
ε^{el}	elastic strain
ε^{th}	thermal strain
ε^{trip}	TRIP strain
σ	stress tensor
$\alpha^i(\theta)$	thermal expansion coefficient of phase z^i
λ, μ	Lamé coefficients
$K = \lambda + \frac{2}{3}\mu$	bulk modulus
$z = (z^0, z^1, \ldots, z^5)^T$	vector of phases
L_A	z^0-austenite latent heat
L_F	austenite–ferrite latent heat
L_P	austenite–pearlite latent heat
L_B	austenite–bainite latent heat
L_M	austenite–martensite latent heat
F_{Ps}	ferrite and pearlite start temperature
F_{Pf}	ferrite and pearlite end temperature
B_s	bainite start temperature
B_f	bainite end temperature
M_s	martensite start temperature
M_f	martensite end temperature
K^{gj}_l	Greenwood–Johnson parameter

room temperature), the end of the heating process t_1, the end of a maintained high temperature $\tilde{t}_1$, and the end of the quenching process t_2. In the case of induction hardening the stabilization period $[t_1, \tilde{t}_1]$ is very small and can be neglected such that the process is only characterized by the heating interval $[t_0, t_1)$ and the quenching interval $[t_1, t_2]$.

At time t_0 steel is assumed to consist of a mixture of ferrite, pearlite, bainite, and some martensite (the last one typically representing the smallest amount). Unfortunately the exact phase distribution of such mixture of phases is unknown in practice and represents an uncertainty factor in the model. For this reason we introduce the symbol Z^0 which will be reserved in the following for the initial phase mixture prior to the heat treatment. During the heating process Z^0 is (partially) transformed to austenite. Later, during the (rapid) cooling stage, the austenitic phase is transformed mainly into marteniste, but it may also be transformed into ferrite, pearlite, and bainte in a much smaller portion; the remaining volume fraction of Z^0 remains unchanged.

A good model for describing the heat treatment of steel is based on the thermal and mechanical equations for the description of temperature and mechanical deformations in the material pieces. Similar models with coupled equations for thermomechanical problems have been previously simulated for processes like heat treatment, welding and shape rolling, among others (cf. e.g. [1,5,11,13]).

The rapid cooling rates are obtained by prescribing appropriate boundary conditions in a heat equation and the temperature gives rise to the time evolution of the single phases. The coupling between the thermal and the mechanical models is determined by the density changes in material resulting from temperature and phase changes, as well as by the mechanical dissipation. At the same time, the phases' evolution is a direct consequence of the temperature changes, as described below.

2.1. The phase transitions

Mathematical models for phase transitions in steel have been considered e.g. in [4–6,8,13,16–18]. In many works, the description of the diffusive phase transitions in the isothermal case is done via the Johnson–Mehl equation. In order to establish a general model for isothermal multi-phase case during the cooling process we introduce the following notations:

- $z^0(t)$: the volume fraction of Z^0, i.e., the mixture of phases present before the heating process.
- z^1_0: the volume fraction of austenite at time t_1 which stands for the end-time of the heating process (i.e. the start of quenching).
- $z^1(t)$: the volume fraction of remaining austenite during the cooling process.
- $z^2(t), \ldots, z^5(t)$: volume fraction of ferrite, pearlite, bainite, martensite, which have been transformed from austenite during cooling.

As mentioned, the workpiece has the phase configuration Z^0 at time t_0, thus we have $z^0(t_0) = 1$. Since the outer layers of the workpiece have been transformed to austenite from Z^0 during the heating process, it is observed that the phases at the end of heating correspond to a portion of Z^0 and a portion of austenite, it is $z^0(t_1) + z^1(t_1) = 1$.

During quenching, austenite is transformed into ferrite, pearlite, bainite and marteniste, then we can conclude

$$z^1(t_1) \equiv z^1_0 = z^1(t) + z^2(t) + z^3(t) + z^4(t) + z^5(t) \text{for} t \in (t_1, t_2].$$

and the remaining fraction of Z^0 remains unchanged during cooling and equals to $z^0(t_1)$.

We describe the evolution of volume fractions during the cooling process which occurs for $t \in [t_1, t_2]$ by the following equations:

$$\begin{cases} z^2(t) + z^3(t) = z^1_0\left(1 - e^{-b(\theta)(t-t_1)^{a(\theta)}}\right) & \text{for } F_{P_f} \leqslant \theta \leqslant F_{P_s}, \\ z^4(t) = (z^1_0 - (z^2(t) + z^3(t)))\left(1 - e^{-\tilde{b}(\theta)(t-t_1)^{\tilde{a}(\theta)}}\right) & \text{for } B_f \leqslant \theta \leqslant B_s, \\ z^5(t) = (z^1_0 - z^2(t) - z^3(t) - z^4(t))\left(1 - \left(\frac{\theta - M_f}{M_s - M_f}\right)^n\right) & \text{for } M_f \leqslant \theta \leqslant M_s, \end{cases} \tag{1}$$

where the evolutions of ferrite, pearlite and bainite (the first and the second equations) arise from the Johnson–Mehl–Avrami equation and the austenite–marteniste phase change (the third equation) is from Schröder's approach, see e.g. [12]. The parameters $b(\theta), a(\theta), \tilde{b}(\theta), \tilde{a}(\theta)$ and n have to be identified using experimental data as in [10]. $F_{P_s}(F_{P_f})$, $B_s(B_f)$, and $M_s(M_f)$ denote the start (end) temperatures of formations of ferrite/pearlite, bainite and martensite, respectively.

Eqs. (1) may be then be reduced to a system of ODEs. For simplicity, let $\tilde{z}$ denote $z^2 + z^3$, then it is easy to verify from the first equation in Eq. (1) that