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State estimation and advanced control of the 2D temperature field in an experimental oscillating annealing device

L. Jadachowski [a,b,*], A. Steinboeck [b], A. Kugi [a,b]

[a] Christian Doppler Laboratory for Model-Based Control in the Steel Industry, Vienna University of Technology, Gußhausstraße 27-29, 1040 Vienna, Austria
[b] Automation and Control Institute, Vienna University of Technology, Gußhausstraße 27-29, 1040 Vienna, Austria

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ABSTRACT

Annealing plays a crucial role in industrial steel strip production lines. Laboratory annealing devices are experimental furnaces that allow the simulation of the annealing process in large-scale production lines and are employed, e.g., to design new or improve existing heat treatment cycles. The furnace considered in this paper is equipped with individually controlled infrared heaters. It is used to reheat flat specimens of steel strips accurately and homogeneously in space according to predefined temperature trajectories. In view of the complex furnace geometry with highly specular surfaces and thermal radiation as the main heat transfer mode, the operation of this furnace constitutes a 2-dimensional nonlinear distributed-parameter thermal control problem. The basic control inputs are the electric powers of infrared heating lamps, which are controlled by six phase-fired thyristors. For temperature tracking, a two-degree-of-freedom control concept is applied, which comprises an optimal feedforward controller and a state feedback controller. The feedforward controller is based on the solution of a dynamic optimization problem. The feedback part contains a Linear–Quadratic–Gaussian controller, which requires knowledge of the actual temperature field of the specimen. Since in the considered annealing device, this temperature field cannot be completely measured, an extended Kalman filter is used for the estimation of spatial temperature profiles. This estimation is based on just three local measurements of the surface temperature of the specimen. The proposed control approach was implemented and experimentally validated in several annealing runs. The effect of an oscillating motion of the specimen on the temperature homogeneity is investigated by comparisons of measurement results with a fixed specimen position. It is shown that the temperature inhomogeneity can be significantly reduced if the specimen oscillation is systematically taken into account in the mathematical model, the state estimation, and the control design.

1. Introduction

In the steel industry, annealing is a heat treatment process to reduce internal stresses, to ensure specific metallurgical properties, or to prepare optimum surface conditions for subsequent production operations, e.g., hot-dip galvanization (Bordignon et al., 2002; Totten, 2006). Annealing is a typical processing step in strip production lines, where the temperature evolution of the strip should follow a desired reference trajectory.

So called continuous-type annealing furnaces are used in the steel industry for heat treatment of strips in production lines (Mullinger & Jenkins, 2014). The coiled strip is uncoiled and conveyed with a velocity in the range of 1.5–3 m/s through the furnace and the temperature evolution along the length of the axially moving strip, i.e., along one spatial variable, has to be controlled according to the metallurgical requirements, see, e.g., (Niederer, Strommer, Steinboeck, and Kugi, 2016) and (Strommer, Niederer, Steinboeck, and Kugi, 2018).

Batch-operated annealing devices are typically employed for laboratory reasons. In the steel industry, they serve as experimental ovens to develop and investigate new annealing curves, to emulate continuous production lines, and to optimize their process parameters. Seyrkammer et al. (2010) developed a tracking controller for the mean temperature of a sheet metal specimen in a laboratory annealing test rig with Ohmic heating. Depending on the furnace design and the heating elements, other laboratory-scale furnaces allow also to control the spatial temperature distribution in the specimens. This is especially true for the experimental furnace considered in this paper. The furnace is operated by voestalpine Stahl GmbH to simulate and improve continuous annealing processes in the production lines. In the considered experimental

* Corresponding author at: Automation and Control Institute, Vienna University of Technology, Gußhausstraße 27-29, 1040 Vienna, Austria.
E-mail address: jadachowski@acin.tuwien.ac.at (L. Jadachowski).

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furnace, flat specimens are heated by electrically powered infrared (IR) lamps. They are connected and controlled in groups to minimize temperature inhomogeneities of the specimen. Such inhomogeneities can be caused by an inadequate temperature controller that does not take into account the distributed nature of the system. Moreover, they may result from electric power limitations combined with a fixed and unsuitable geometric arrangement of the IR-lamps and the specimen. Hence, accurate control of 2-dimensional (2D) temperature fields plays an important role when operating such annealing devices.

A thorough review of the relevant literature reveals only few papers that consider practical implementation and experimental validation of 2D temperature control. A combination of the flatness-based feedforward controller and proportional–integral–derivative output error feedback controller is proposed by Böhm and Meurer (2017) to control the temperature evolution of a deep drawing tool at 12 sensor positions. Girault and Videcoq (2013) considered an experimental device with a thin aluminum plate heated by a mobile radiative heat source. They employ a Linear–Quadratic Regulator to control the temperature of the plate at 3 locations around the steady-state temperature distribution. They use a Kalman filter with up to 8 thermocouple measurements for temperature estimation. Control of the temperature homogeneity is also a traditional research topic in semiconductor manufacturing. In (Ebert et al., 2004) and (Logerais, Riou, Delaleux, Durastanti, and Bouteville, 2015), the authors mainly focus on the temperature profiles along the radial coordinate of the rotating circular wafers while assuming homogeneity along the tangential direction. Temperature control along a single spatial variable is also addressed by Abeykoon et al. (2011) and Lipár, Noga, and Hulkó (2013) in polymer extrusion processes and by Shen, He, Yang, Gui, and Xu (2016) in aluminum quenching furnaces.

The main contribution of this paper is the development and implementation of an advanced control concept for the 2D temperature field of the specimen in an oscillating annealing furnace. The proposed control approach consists of an optimal feedforward controller, a state observer for the 2D temperature profile, and a state feedback control law with an integral term. The main goal is to determine trajectories of the electric power supplied to the IR-lamps to ensure that the real temperature field of the specimen follows a desired reference temperature. In particular, the primary control objective is that the mean specimen temperature tracks the desired trajectory $T_{\mathrm{ref}}(t)$, which defines a transition of the mean temperature between two steady-state values within a finite time t_E. A simultaneous minimization of the temperature inhomogeneity constitutes the secondary control objective. Under nominal furnace conditions, both control objectives are satisfied by the model-based feedforward controller developed by Jadachowski, Steinboeck, and Kugi (2018). The underlying mathematical model was presented by Jadachowski, Steinboeck, and Kugi (2017b) for a fixed specimen position and extended in (Jadachowski et al. 2018) to capture also the oscillating motion of the specimen. To allow for the compensation of tracking errors, a Linear–Quadratic–Gaussian (LQG) feedback controller is designed. It requires the estimation of time evolutions of 2D temperature fields of the specimen. For this, an extended Kalman filter (EKF) is developed on the basis of the specimen temperature model and three local measurements of the specimen surface temperature. The overall estimation and control performance is evaluated by measurements. Different annealing cycles were performed to investigate the accuracy of the temperature estimation and the tracking controller and to examine the effect of the oscillating motion on the temperature homogeneity of the specimen.

The paper is structured as follows: In Section 2, the development of three mathematical models of the temperature evolution in the oscillating specimen is summarized. This includes a full-state finite-difference model, a reduced-order finite-element model, and a reduced-order time-averaged model. In Section 3, the temperature estimation problem is formulated and the EKF is designed. Section 4 is dedicated to the tracking control strategy consisting of the optimal feedforward controller and the LQG feedback law with the integral control action. Measurement and estimation results are presented and analyzed in Section 5. Final remarks are given in Section 6.

Notation. Arguments of functions are omitted whenever they are clear from the context. Moreover, $\nabla T(\mathbf{x},t)$ denotes the temperature gradient with respect to the spatial coordinates $\mathbf{x} = (x, y)$, and $\partial_* T(\mathbf{x},t)$ denotes the partial derivative w.r.t. $*$. Temperatures of the entity $\star$ are assembled in the vector $\mathbf{T}_\star = \left[T_{\star,i}\right]$. The vector of their fourth powers is written in the form $\mathbf{T}_\star^4 = \left[T_{\star,i}^4\right]$. Finally, $\mathbf{1}_n$ refers to the vector of dimension n with all entries equal to 1 and $\mathbf{I}$ is the identity matrix.

2. Mathematical modeling

The geometry of the considered furnace is presented in Fig. 1. It shows cross-sections of the heating chamber.

This chamber consists of a water-cooled housing with a flat steel specimen (length L_s, width W_s, thickness B_s) clamped between two specimen holders, which can be moved vertically. On both sides of the specimen, two arrays of IR-lamps (N_h horizontal and N_v vertical IR-lamps) are mounted on gold-coated water-cooled reflectors. The distance between two horizontal and two vertical lamps is L_h and L_v, respectively. Inert gas streams into the heating zone through a gap between the upper specimen holder and the housing and leaves the IR-zone via the bottom gap. When supplying electric power to the IR-lamps, the specimen is heated by means of thermal radiation. In particular, the spatial temperature field in the specimen fillet $\Omega_f := \{(x, y) \in \mathbb{R}^2 \mid 0.25L_s < x < 0.75L_s,\ 0.2W_s < y < 0.8W_s\}$, with the area $A_f = L_f W_f$ and the dimensions $L_f = 0.5L_s$ and $W_f = 0.6W_s$, is of main interest. A small Biot-number $Bi \approx 8.87 \times 10^{-4} \ll 1$ (cf. Incropera, Dewitt, Bergman, & Lavine, 2007) justifies the assumption of a homogeneous strip temperature along the thickness direction z. The IR-lamps are controlled in groups by means of six phase-fired thyristors. Four thyristors T_i^h, $i = 1,\dots,4$ are used for the horizontal lamps and two T_i^v, $i = 1{,}2$ for the vertical lamps. The mobile specimen holders allow the specimen to oscillate vertically with a maximum amplitude of $\bar{\eta} = 0.25L_f$.

In the following, three mathematical models of the temperature evolution in the oscillating specimen are briefly summarized for reference. The presentation of a full-order finite-difference (FD) model is followed by a reduced-order finite-element (FE) model. The third model is obtained by time averaging of the FE model.

2.1. Full-order FD-model of an oscillating specimen

A distributed-parameter first principles model of the 2D spatio-temporal temperature evolution for a non-moving steel specimen was derived and validated by Jadachowski et al. (2017b). In (Jadachowski et al., 2018), this temperature model was extended to take into account the oscillating motion of the specimen. The specimen position $\eta(t)$ varies periodically in time along the vertical direction whereas the IR-lamps have fixed positions. In view of this motion, the Lagrangian coordinates xyz are used, i.e., the frame $(0xyz)$ is fixed to the specimen. The model describes the 2D temperature field $T(\mathbf{x},t)$ of the specimen in K by the time-varying quasilinear non-local parabolic PDE

$$\rho c_p(T)\partial_t T(\mathbf{x},t) = \nabla \cdot \left(\lambda(T)\nabla T(\mathbf{x},t)\right) + \dot{q}(\mathbf{x},T,\mathbf{u},\eta), \tag{1}$$

which depends on the time t and the spatial coordinates $\mathbf{x} = (x, y) \in \Omega := \{\mathbf{x} \in \mathbb{R}^2 \mid 0 < x < L_s,\ 0 < y < W_s\}$. Moreover, ρ in kg/m^3 denotes the mass density, $c_p(T)$ in J/(kg K) the specific heat capacity, and $\lambda(T)$ in W/(m K) the thermal conductivity. In (1), the source term

$$\dot{q}(\mathbf{x},T,\mathbf{u},\eta) = -\frac{\dot{q}_r(\mathbf{x},T,\mathbf{u},\eta) + \dot{q}_c(\mathbf{x},T) + \dot{q}_h(\mathbf{x},T)}{B_s} \tag{2}$$

contains the net heat flux (W/m^2) due to thermal radiation $\dot{q}_r(\mathbf{x},T,\mathbf{u},\eta)$, forced convection $\dot{q}_c(\mathbf{x},T)$, and heat losses into the specimen holders