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Adaptive electrodeposition process control through Zakai filtering

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ABSTRACT

The stochastic evolutionary process inspired by the electrodeposition of metal ions on an electrode surface is considered in one dimension. The process is fixed on one boundary and is observed-controlled on the other boundary where the process is additionally influenced by unmodelled side reactions – their effect on the boundary is considered as a random process applied to the controls and measurements. The electrodeposition process is given by a diffusion process model, whose main parameters are unknown – the diffusivity of species and the thickness of the diffusion layer are unknown and no knowledge is available about the current losses in the plating bath or the throwing power of the electrolyte. Furthermore the side reactions have an unknown systematic component. Even so this paper verifies that the electrodeposition process can be boundary controlled using feed-forward and feedback controls adapted with the parameters estimated by Zakai filtering. The consistency of the estimates as well as the stabilising property of the adaptive controls is validated by simulations.

1. Introduction

The stochastic control and the nonlinear filtering (e.g., [1,2]), are well established theories. For a profound survey of the past and recent results, see Pham [3], Borkar [4] and the references therein. These theories allow the conversion of a partially observed control problem into a completely observed one. Unfortunately, for nonlinear systems, it converts a finite dimensional process into an infinite dimensional process that can be expressed in several forms of a filter. The Kushner filter [5] and Zakai filter [6] are often used as a system for control; this method of control is known as the separated control [7]. The optimality conditions for such a system are expressed as the Mortensen equation analysed in Beneš [8], Gozzi and Swiech [9] and more deeply in Beneš et al. [10] for the predicted miss problem, which remains the only explicit problem solved up to now. Alternatively, the optimality conditions can also be represented as a Bellman equation by discrete approximations of the spatial variables. However, practically a numerical solution of such a representation is unreachable due to a large dimension system needing to be solved, if the infinite dimensional system is approximated with the finite dimensional one. Moreover, the separated control system is degenerate and one must deal with a singular part of the Bellman equation as well, i.e., to deal with the Bellman equation in the lattice of measures [11,12]. The probabilistic method [13] that approximates the original system with a Markov chain allows solving the Bellman equation numerically through its finite-difference approximation in time and state-space, if the system is non-degenerate and low in dimension (say, 1 or 2). However, in a nonlinear process case the separated control system is neither non-degenerate nor low dimensional.

The existence of optimal controls is another difficult issue. The existence has been shown for so called wide sense controls [7] when the admissible controls allow a weak solution [14] of the controlled system. The existence of optimal controls has not been shown for controls in the usual strict sense and that they allow a strong solution of the system. Therefore, the practical problem, if solved, should be proven to be relevant to any Wiener process, which has been done in this paper through repeated simulations.

Regardless of the established theories, few applications are known: the linear regulator problem and some other problems in financial markets, e.g., risk-sensitive control, portfolio selection and mean-variance hedging (see the topical references in [3]) are some problems solved in the spirit of stochastic control theory. The aim of this paper is to enlarge the list of applications solving an electroplating process stabilisation problem. This process is nonlinear and includes several types of uncertainties [15,16,17]; it can be maintained at the desired reference with a certain type of adaptive boundary controls investigated in this paper. The particular problem solved in this work stems from an industrial plating process, where the production maximisation is an operational target. This is closely related to the plating rate maximisation and this in turn means maximisation of the current density. However,

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a large increase of the current density ends up with depletion of the oxidising species. Therefore, the species' concentration control is a more relaxed control problem that helps to avoid the depletion while maximising the current density through a sensible reference concentration. The concentration control is a transient control problem. It aims to bring the current concentration in the near vicinity of the cathode surface from a bulk concentration level to a low level in an entirely controlled manner. Providentially, from the practical viewpoint, the transient process control is not as important as the stabilisation of the process at a desired reference. In case of known parameters the stabilising control has been developed in the spirit of proportional and past boundary controls in [18]. In this paper these controls are applied in the conditions of unknown parameters.

The standpoint for the current work follows from the fact that the stabilisation problem has been solved and applied in the early papers ([15,16,17,18]; etc.) in deterministic and stochastic statements and with the assumption that the electrodeposition process model is complete. In the present paper the model is incomplete due to several uncertain parameters: the diffusivity of species, the thickness of the diffusion layer and the efficiency of electric power use are all unknown. Beside the main reaction there are side reactions; they affect the diffusion process on the boundary and in the entire diffusion layer. The systematic effect of side reactions is an unknown parameter, as well.

Since the problem is complex by uncertainties a relatively simple diffusion process in one dimension is analysed. The diffusion process is fixed on one boundary (Dirichlet data) and observed/controlled on the other boundary through the mass flux (Neumann data). Due to the presence of the side reactions, the control is disturbed by random noise on the controlled boundary.

Generally there is not enough data provided by the electric current (proportional to the mass flux) measurements on the boundary in order to perform state and parameter estimation. The concern is of physical nature, because the measured mass flux on the boundary reveals little about the concentration level of species at the boundary. Furthermore, no knowledge exists of how good the diffusion is and how extensive the stagnation layer is where the diffusion process involves. Furthermore, there are unmodelled side reactions with an unknown effect on the electrodeposition process and also the measured electric current includes the parasitic current losses in the bath that steal current that should be directed towards the surface being plated.

However in this paper the idea of estimation and control works, because of the specific controls applied. These controls are built up as certain representations of the proportional control $u(t)$ that depends on the concentration $c(t,0)$ on the boundary

$$u(t) = -K_P(c(t,0) - c_d), \tag{1}$$

where $u(t)$ is the mass flux measured in process as the electric current; K_P is the control gain and c_d is the desired reference. Assuming that (1) is a realisable control (in fact its certain representations are realisable) an observation model can be constructed as a similar model to the case where one measures the concentration of species on the boundary $\xi(t)$ with certain observation error dW.

$$d\xi = -K_P(c(t,0) - c_d)dt + dW \tag{2}$$

This model makes the estimation of parameters effective. Indeed, if the concentration on the boundary is observed, the distribution of the concentration in the entire diffusion layer can be estimated. For example, a Kalman filter can be applied if the diffusion equation is approximated with a linear system of ordinary differential equations (ODE) in the diffusion layer and with a linear stochastic differential equation (SDE) on the boundary. Moreover, if the diffusivity coefficient is unknown the first thought is to apply an extended Kalman filter, which is inadequate though, because the system is bilinear by extended state variables (unknown diffusivity and concentration of species) and in this case a closed form calculation of the statistics is impossible. The statistics (moments) can still be found based on the evolution of probability density solved from the Zakai equation or Kushner equation both developed for nonlinear filtering. Also other unknown parameters (efficiency of the electric power use, thickness of the diffusion layer and systematic mass flux of the side reactions) can be found by using this method in the assumption that the measured process is given, otherwise some additional data must be assumed to solve the problem.

The last important step that makes this method practical is the use of some applicable representations of controls instead of the proportional control itself that uses unavailable concentration measurements at the cathode surface. Three types of control representations are applied in this paper.

A specific observation model that allows parameter estimation and process control in the presence of unknown side reactions and unknown nonlinear parameters in a closed-loop system is the main contribution of the paper.

2. Electrodeposition process model and control

An electrodeposition process boundary control problem is formulated and an observation model is developed based on the structure of side reactions and representations of the boundary controls in suitable forms for filtering and adaptive control.

2.1. The stochastic system

Consider a stochastic evolutionary process that represents an electrodeposition of metal ions on the cathode surface [19]. These species in the diffusion layer between the bulk solution and cathode surface evolve as a partly unknown diffusion process covered by the model (3)–(6).

$$c(0,x) = c_b, \quad 0 < x < \delta \tag{3}$$

$$c(t,\delta) = c_b, \quad t > 0 \tag{4}$$

$$\frac{\partial c(t,x)}{\partial t} = D\frac{\partial^2 c(t,x)}{\partial x^2}, \quad 0 < x < \delta \quad t > 0 \tag{5}$$

$$D\frac{\partial c(t,x)}{\partial x} = u(t,\omega), \quad x = 0, \quad t > 0 \tag{6}$$

Here $c(t,x)$ is the ion concentration of species, initially given by the bulk solution concentration c_b of electrolyte (3); at the outer boundary (4) this concentration is similar. The ion concentration $c(t,x)$ evolves as a diffusion process (5) controlled with the stochastic mass flux $u(t,\omega)$ on the Neumann boundary (6); a random element denoted by ω includes the uncertainties of the side reactions and unknown parameters (explained below). The process $c(t,x)$ is also stochastic $c(t,x,\omega)$ since, the control applied is uncertain because of the unknown side reactions and the parameters of the process are unknown. The diffusivity D of species and thickness δ of the diffusion layer are unknown and also the throwing power of electrolyte is unknown (explained later).

2.2. The side reaction

In electrodeposition, a number of side reactions take place simultaneously with the main reaction [19]; their physical description is mostly unknown. The diffusion model without accounting for the side reactions is a strong simplification of the real process and the control applied in the presence of side reactions is an uncertain control. The situation improves if the uncertainty of side reactions is considered formally as a white noise $\dot{W}(t)$ that deviates from an average level $\mu \leq 0$ with certain noise intensity B. The