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A discussion of the control of nonferrous metallurgical processes ⋆

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Abstract: Nonferrous metallurgical processes are featured by their complex nature. Control of nonferrous metallurgical processes is non-trivial and related to multiple disciplines. An example is presented to illustrate the basic procedure of nonferrous metallurgical process control. A feasible way to construct a unified control approach and the potential developments of nonferrous metallurgical process control are discussed.

Keywords: nonferrous metallurgical processes, process control, process analysis, control strategy, concept design.

1. INTRODUCTION

Nonferrous metals hold crucial positions in economy and industry(Gui et al. (2013)). Start from the raw ores, products of nonferrous metals are derived by means of various nonferrous metallurgical processes. Production, energy and material consumption, product quality and pollution are the main concerns in the operation of nonferrous metallurgical processes, especially at current age with resources shortage, accelerating energy consumption and consequent climate change(Gui et al. (2013),Lee (2014)). The environmental-friendly and economic-effective operation of nonferrous metallurgical processes, which lies in the successful implementation of process control, is the persistent pursuit of industrial community.

Control of nonferrous metallurgical processes, which covers a range of topics from metallurgical engineering to control theory, is by no means trivial. A nonferrous metallurgical process is physically composed of multiple different-functioned subprocedures (Fig. 1). Without loss of generality, a nonferrous metallurgical process can be divided into multiple levels as shown in Fig. 2. Simi-

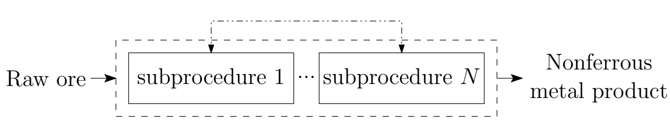

Fig. 1. A nonferrous metallurgical process composed of N subprocedures, $N > 1$, $N \in N^+$

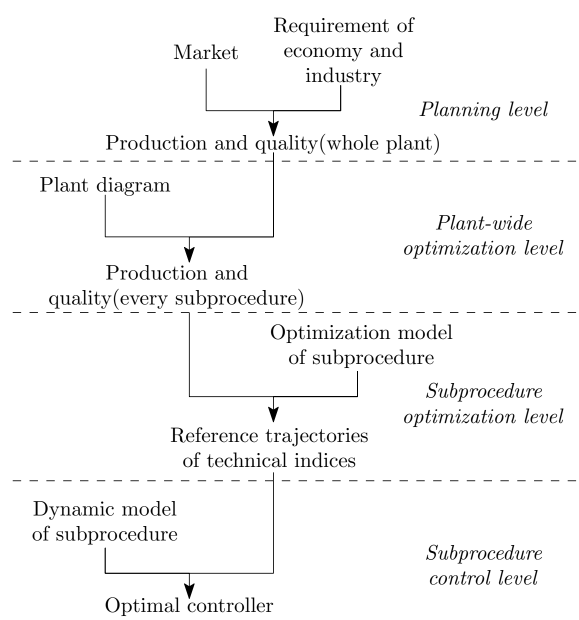

Fig. 2. Different levels of a nonferrous metallurgical process

lar plant decision hierarchies are proposed by Skogestad (2000) and Darby et al. (2011). As indicated by Fig. 2, control of a nonferrous metallurgical process includes higher level optimization, i.e., planning and plant-wide optimization, and control of each subprocedure. Difficulties in the control of nonferrous metallurgical processes appear on different levels. For planning and plant-wide optimization level, the difficulties are the selection of appropriate performance indicators, multiple objectives, treatment of environmental issues and market uncertainty(Nikolopoulou and Ierapetritou (2012)). While for the optimization and control of each subprocedure, the difficul-

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ties include complex system dynamics(Kravaris and Kantor (1990), Vieira et al. (2003), Gui et al. (2013)), process uncertainties(Christofides and El-Farra (2005)), absence of the online determination of important technical indices(Yang et al. (2009)), time-delay(Wang et al. (2012)), etc. During the development of process control, numerous approaches have been proposed and applied, such as Proportional Integral Derivative(PID) control(Åström and Hägglund (2001)), fuzzy control(King and Mamdani (1977)), expert control(Åström et al. (1986)), Model Predictive Control(MPC)(Qin and Badgwell (2003)), Statistical Process Control(SPC)(MacGregor and Kourti (1995)), Cased Based Reasoning(CBR)(Dutta et al. (1997)), intelligent integrated control(Wang (2001)), simultaneous dynamic optimization(Kameswaran and Biegler (2006)), Real-Time Optimization(RTO)(Darby et al. (2011)), etc. Among these approaches, MPC is the standard approach for solving constrained, multivariable process control problems, especially in chemical and petrochemical industries. However, due to the diversity and hard-to-model characteristic, at current stage, there is no unified optimal control approach that can be widely applied to nonferrous metallurgical processes(Chai et al. (2014),Sun et al. (2014b)).

The existence of the aforementioned difficulties is rooted in the inherent complex nature of nonferrous metallurgical processes. Inside each subprocedure, complex physical and chemical reactions and frequent phase transitions are taken place. In these reactions, there are not only the controlled reaction which is our main concern, but also other parallel reactions whose dynamics and interaction mechanism with the controlled reaction are not thoroughly known. In addition, for each subprocedure, it interacts with other subprocedures through mass or energy transfers, recycles or reentrances(Fig. 1). Moreover, the raw ores may contain intricately mixed minerals with randomly varying properties, especially in the metallurgy plants whose raw ores are purchased from different mines(Sun et al. (2014b)). A single controller is usually insufficient to control such complex systems. Thus, the control of each subprocedure should not only involves design of optimal feedback controllers that the closed loop system is stable and the controlled variables follow the setpoints as closely as possible(Chai et al. (2014)), but also design of supporting modules, such as process monitoring(Kourti and MacGregor (1995)), soft sensoring(Kadlec et al. (2009)), control performance evaluation(Huang (2008)), modeling(Foss et al. (1998)), etc, to provide information of current process status and key technical indices(Fig. 3). In practice, a feasible approach to control a nonferrous metallurgical process is to design the control strategy based on an indepth process analysis and then design the controller. In other words, the control of nonferrous metallurgical processes is an integration of process analysis, control strategy design and controller design.

The aim of this paper is not to provide a review of nonferrous metallurgical process control, but rather to deliver a personal understanding of nonferrous metallurgical process control gained through a long period of participation in both academic research and industry practice. Some interesting problems and potential developments in the control of nonferrous metallurgical processes are also

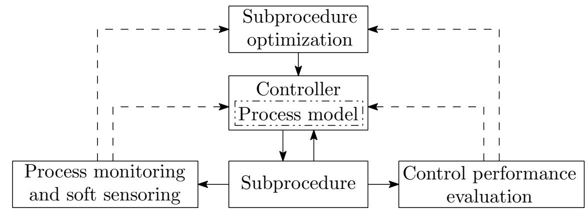

Fig. 3. A complete control framework of a subprocedure

discussed. The rest of the paper is organized as follows. In Section 2, a practical example is used to illustrate the difficulties in modeling, optimization and control of a nonferrous metallurgical process. In Section 3, the classic design procedure of the control system for a nonferrous metallurgical process is presented. Some open problems and future trends in the control of nonferrous metallurgical processes are listed and discussed. The concluding remarks are given in Section 4.

2. CONTROL OF COBALT REMOVAL PROCESS: A PRACTICAL EXAMPLE

This section provides an example to illustrate the procedure of nonferrous metallurgical process control. For another typical example, please refer to Yang et al. (2002).

2.1 Process description and analysis

Cobalt removal process is an important step in zinc hydrometallurgy(Fugleberg and A. Jarvinen (1993), Sun et al. (2013), Sun et al. (2014b)). More than 80% of the worlds zinc metal output is produced using zinc hydrometallurgy, which is composed of roasting-leaching-electrowinning or direct leaching-electrowinning. The impurity cobalt must be removed prior to electrowinning or it will cause large drops of current efficiency in electrowinning.

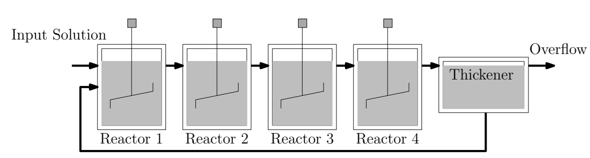

Fig. 4. Cobalt removal process

Cobalt removal process is a continuous process composed of consecutive continuous stirred tank reactors and a thickener(Fig. 4). Cobalt removal takes place at a high temperature and an acid environment. Zinc dust and arsenic trioxide are added into the reactors and remove cobalt ions in zinc sulphate solution by forming alloys between cobalt, arsenic, copper and zinc.

$$As^{3+} + 3Cu^{2+} + 4.5Zn = Cu_3As + 4.5Zn^{2+} \quad (1)$$

$$Cu_3As + Co^{2+} + Zn = 3Cu + CoAs + Zn^{2+} \quad (2)$$

Zinc dust assumption and cobalt ion concentration after purification are the economical and technical index of cobalt removal process. The control objective is to use the least amount of zinc dust and guarantee that the outlet cobalt ion concentration of the last reactor is below a predefined threshold: