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Hybrid modeling of an industrial grinding-classification process

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ABSTRACT

An industrial grinding-classification process of diasporic bauxite is modeled based on the integration of phenomenological and statistical learning methods. The breakage characteristics of the ore and running status of the whole process are first investigated by laboratory testing and process sampling, respectively. Based on the population balance model (PBM) framework, the breakage distribution function is estimated from laboratory test data. The breakage rates are back-calculated directly from the industrial data, where a nonlinear breakage rate function is proposed for coarse particles. They are then correlated to the operating variables (including the water flow rate and feed flow rate), ball characteristics and material properties using the least squares support vector machine (LSSVM) method so that the model is suitable to various grinding conditions. Material transportation through the mill was treated as two equal smaller fully mixed reactors followed by a large one. The particle size distribution (PSD) of the mill product is then predicted by sequentially solving the reactors in series, considering the nonlinear breakage kinetics. A spiral classifier model is obtained with the Rosin–Rammer curve, where the bypass, real classification effect and operating conditions are included. The simulation results of the whole process by using the sequential module approach (SMA) demonstrate reasonable agreement between the predicted and measured industrial process data. The models are finally applied to the process for the prediction of particle size indices and to provide valuable information for the operation and further optimization of the process.

1. Introduction

Grinding is a common size reduction process in mineral processing, the pharmaceutical and cement industries, and other fields. In mineral processing, it is usually followed by a classification process to produce a slurry with a desired particle size and solid concentration for flotation. The performance of the grinding-classification process plays a determinative role on the financial and technical indices of the whole mineral processing plant.

Diasporic bauxite is the main raw ore for alumina production in China, where a large percentage of the world's alumina is produced. Due to the low grade of the ores, mineral processing, which is a potential method of using high silica bauxite [1], is applied before the Bayer process in China to greatly reduce the cost of alumina production and environmental pollution. In this process, diasporic ores excavated from several deposits are crushed and homogenized in a heap using a complex procedure to prepare the feed for grinding. The deposits are not the same for different heaps, and the grades of the ores steadily decrease, which has a strong effects on the grindability and floatability when a changeover between the heaps occurs. In addition, the process indices are manually measured and time-delayed and are then controlled by operators, depending on their experience. As a result, many problems, including a large fluctuation of product quality and throughput, waste of flotation agents, and low recovery of useful minerals, increase the cost. Therefore, modeling and process simulation are carried out to improve the process indices, including the particle size and solid concentration of the slurry flows.

The population balance model (PBM) introduced by Refs. [2,3] is a popular way to model the grinding process. It predicts the product size distribution from the feed size distribution by dividing the process into two parts, material transport through the mill (described using the residence time distribution (RTD)) and breakage within the mill, including the selection of the particles for breakage (described using a breakage rate function) and the actual breakage resulting in a particular distribution of fragment sizes after the particle is selected (described using a breakage distribution function). Based on this mass balance framework, different PBMs have been proposed and used for design, simulation, control and optimization [e.g., 4–12] to improve the grinding effectiveness. The main difference between these models lies in the form of the breakage rate function and the material transport description.

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PBM can also be combined with other methods to integrate the advantages of different methods. A combination of PBM with the discrete element method (DEM) is popular, where DEM is used to simulate different types of breakage, such as impact breakage and abrasion/chipping breakage [13,14]. Akkisetty et al. [15] proposed a model combining PBM with a neural network, where the neural network is used for the prediction of the breakage rate and breakage distribution. The model is only validated by laboratory data.

Models using solely data-based methods, such as neural networks, support vector regression, or fuzzy inference, have also been developed for soft sensing the particle size indices in the grinding-classification process [e.g., 16–18].

One key problem in predicting the particle size distribution is the lack of knowledge of the breakage rate of the material being ground. The properties of different materials are different, and each grinding-classification process also has its own features. For an industrial continuous grinding process, it is especially difficult to obtain accurate prediction values due to the complicated running conditions. Therefore, much work has been conducted to develop a ball mill model and a spiral classifier model for the processing of bauxite.

In this work, we present a hybrid ball mill model and a spiral classifier model for the grinding-classification process of bauxite, where the material characteristics and operation conditions are all considered. The models are useful for particle size distribution (PSD) prediction, process simulation and further optimization.

The work is organized as follows: In the next section, the process knowledge and sampling campaign are introduced. The laboratory test method and findings are provided in Section 3, and the breakage distribution is estimated. In Section 4, the continuous ball milling process is modeled, including the residence time distribution and the breakage rate function. Section 5 discusses the modeling of the two spiral classifiers. The simulation and application results using the sequential module approach (SMA) are shown and analyzed in Section 6. Finally, the work is concluded.

2. Process description and sampling campaign

2.1. Process description

The industrial grinding-classification process consists of one ball mill and two spiral classifiers, as the schematic diagram shows in Fig. 1.

The ball mill has an inner diameter of 3.6 m and a length of 5.0 m. The initial media charge of the ball mill is 80 tons of cast steel balls with a make-up diameter of 70:50 mm and a ratio of 2:1. A certain amount of 90-mm diameter fresh balls are replenished to the mill once a week.

Diasporic ores excavated from several deposits are crushed and homogenized into heaps through a complex procedure and then used as the feed of the ball mill. The designed maximum size in the feed is 12 mm, but it usually contains more than 30% of +12 mm particles because of the low efficiency of the crushing process, so that the performance of the milling process is reduced.

The maximum diameter of the two spiral classifiers is 3 m. Spiral classifier 1 is of the high-weir type so that it is suited for classifying coarse particles, while classifier 2 is of the sinking type, which is suited for fine particles. The underflow of classifier 2 is directly taken as the concentrate due to the obvious selective breakage of the bauxite ore, which is different from the usual grinding process of many other ores.

2.2. Sampling campaigns

Several sampling campaigns were carried out on the whole grinding-classification process to assess the mill-classifier operation and to collect data for modeling. It is difficult to keep the samples representative because of the high flow rates of some streams and the rapid coarse particle sinking. Therefore, each flow was sampled four times in 2 h to obtain one blended sample. The PSD and concentration of each sample were carefully analyzed. Meanwhile, the operating conditions, including the flow rate of the fresh ore, water flow rate, and currents of mill and classifiers, were recorded from the on-line monitoring system.

The sampling campaign was carried out twice a day, and 30 groups of data were finally obtained. The chemical compositions of all of the flows and each size interval of these flows were analyzed.

When the sampling campaign was started, the balls were used for a long period of time so that their make-up was not clear. Therefore, the ball distribution and the ball load were sampled and estimated when the ball mill was stopped after the sampling campaign.

Data reconciliation was then conducted using the commercial package Bilmat® to minimize the sampling and analysis errors and estimate the immeasurable slurry flow rates. The adjusted data were then used to investigate the process performance and perform the modeling work.

2.3. Process data analysis

The process data show a large fluctuation of the grinding-classification circuit. The maximum and minimum circulating loads are 142.2% and 495.1%, respectively, in all of the samples. The process indices of the greatest significance (including the −0.075-mm particle size fraction and the solid concentration in the two overflows) are also unstable, as illustrated in Table 1. The grindability of the ore is a non-negligible disturbance. This may also be related to the great variation of the amount of coarse particles in the fresh feed, as shown in Fig. 2, where the mean value of the 30 samples and the max and the min values of each size interval are given. It can be seen that, in addition to the coarse particles, the fraction of the fine particles in the feed is large as well.

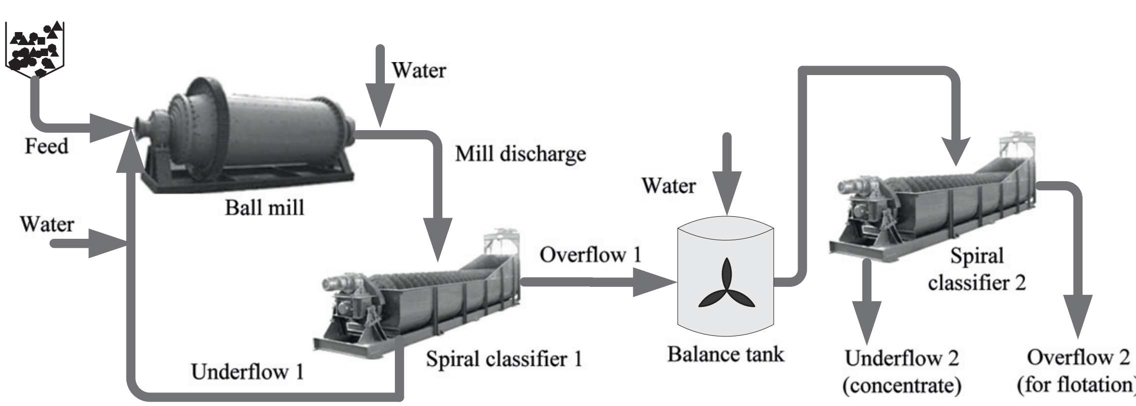

Fig. 1. Schematic diagram of the grinding-classification process.