Minerals Engineering 86 (2016) 66–74

Contents lists available at ScienceDirect

Minerals Engineering

journal homepage: www.elsevier.com/locate/mineng

A specific energy-based ball mill model: From batch grinding to continuous operation

Fengnian Shi *, Weiguo Xie

The University of Queensland, Sustainable Minerals Institute, Julius Kruttschnitt Mineral Research Centre, Qld 4068, Australia

ARTICLE INFO

Article history:
Received 6 October 2015
Revised 17 November 2015
Accepted 1 December 2015
Available online 14 December 2015

Keywords:
Comminution
Grinding
Ball mill model
Ore breakage characterisation

ABSTRACT

A specific energy-based size reduction model for batch grinding ball mills was reported in a previous paper (Shi and Xie, 2015). A discharge function modified from the Whiten classification efficiency equation has been incorporated in the size reduction model to extend its applications from batch grinding to continuous operation. Five sets of the industrial ball milling survey data were used to validate the ball mill model. The data were acquired from four full scale ball mills covering primary and secondary grinding duties in a gold concentrator and a PGM concentrator. In all cases, the model fits the ball mill operational data well.

Features of the specific energy-based ball mill model include the use of an ore-specific and size-dependent breakage function, whose parameters are independently measured with a fine particle breakage characterisation device, the JKFBC. This allows simulations of the effect on ground product size distribution of changing ore breakage characteristics. The model utilises separate selection function and discharge function, which permits the investigation of the influences of mill operational conditions on grinding performance.

1. Introduction

A specific energy-based size reduction model for batch grinding ball mills has been developed (Shi and Xie, 2015). The objective of this work was to overcome the limitations in the existing JKMRC (Julius Kruttschnitt Mineral Research Centre) perfect mixing ball mill model, including the use of a set of default breakage appearance functions for all ores, and the lumped model parameter r/d^* for breakage rate and mass discharge rate.

As a first step approach to upgrading the ball mill model, a specific energy-based size reduction model was developed. In this batch grinding size reduction model, no mass transport or discharge mechanism occurs, and the product size distribution solely represents the size reduction results in relation to specific energy input and material breakage characteristics.

A Fine-particle Breakage Characteriser (JKFBC, Shi and Zuo, 2014; Shi, 2014a,b) was employed to measure ball mill feed breakage characteristic parameters. The JKFBC is modified from the traditional Hardgrove ball-race mill popularly used by the coal industry to determine coal grindability (HGI). A precision torquemeter was installed on the HGI mill shaft to record torque readings during the experiments. The computer logged torque readings are converted to power by mill geometry and operational condition, and integral with grinding time to give the consumed energy. The JKFBC is suitable to test -4.75 mm ore particles. The particle size (between 0.106 mm and 4.75 mm) tested in the JKFBC represents approximately 70–80% of particles by mass feeding to a typical secondary grinding ball mill. For each ore sample, three to five narrowly sized fractions are tested, each with three different grinding revolutions. A constant volume (60 ml, approximately 40–50 g depending on solids density) of particles is used for each test. A size-dependent breakage model (Shi and Kojovic, 2007; Shi et al., 2015) was used for the JKFBC testing data reduction to generate breakage characteristic parameters, M, p and q, for the ore of interest. Thus the default breakage appearance function in the existing perfect mixing ball mill model is replaced by the ore-specific breakage characteristic parameters.

A model to describe size reduction in a batch grinding ball mill was developed. This model is based on the mass-size balance, or mass conservation, which is expressed by Eq. (1).

$$p_i = \sum_{j=1}^{i-1} f_i \cdot m_{ij} \tag{1}$$

The variable m_{ij} is a lower-triangular breakage matrix, indicating the mass fraction of appearance of size i material produced by

---

* Corresponding author.
E-mail address: f.shi@uq.edu.au (F. Shi).

http://dx.doi.org/10.1016/j.mineng.2015.12.004
0892-6875/

Nomenclature

$A \times b$	ore competence indicator, the large value indicating the less resistance to breakage
C	the maximum probability of particles reporting to the fine component (–)
D_i	the discharge rate for size i (h^{-1})
d_i	geometric mean particle size in fraction i (mm)
D_{max}	the maximum discharge rate for the ground product exiting the ball mill like water (h^{-1})
d_{50c}	the particle size at which classification efficiency is 0.5 (mm)
E_i	mass specific energy ($J\ kg^{-1}$)
EF	classification efficiency for material reporting to the fine component (–)
f_i	mass fractions of size i in the mill feed
f_{mat}	parameter in the size-dependent breakage model ($kg\ J^{-1}\ m^{-1}$)
H_i	the mass holdup of the mill ground product in size i (t)
M, p, q	size dependent breakage model parameters, M in %
m_{ij}	lower-triangular breakage matrix (–)
P_i	mass flow rate of the ground product in size i exiting the mill, ($t\ h^{-1}$)
p_i	mass fractions of size i in the mill product
t_{10i}	product cumulative passing $1/10^{th}$ of the mean particle size in feed size i (%)
t_n	product cumulative passing $1/n^{th}$ of the initial particle size (%)
x_i	particle size in the size-dependent breakage model (m)

Greek letters

α	classification efficiency parameter (–)

fracture of size j material. For each size i, the summation sign sums up the total material from sizes larger than i to size $i-1$. The breakage matrix m_{ij} is ore-specific, size-dependent and specific energy-based.

The breakage matrix m_{ij} is calculated from the particle breakage index, t_{10}, and the product size distribution using the t_{10}–t_n relationships. The breakage index t_{10} for each feed size i is calculated using Eqs. (2) and (3) based on the size-specific energy and the given ore characteristic parameters:

$$t_{10i} = M \cdot \{1 - exp[-f_{mat} \cdot x_i \cdot E_i]\} \tag{2}$$

$$f_{mat} = p \cdot d_i^{-q} \tag{3}$$

where M, p and q are ore breakage characteristic parameters determined from the JKFBC tests, and E_i is size-specific energy that is calculated by mill power draw and a breakage selective function.

It is worth noting that the ore testing data are not simply used in the ball mill model as a single number (e.g. t_{10}), or a single column of appearance vector, which may be questioned on the rationale due to the differences between the two breakage devices. In modelling the ball mill size reduction, Eqs. (2) and (3) are employed to calculate the ground product t_{10} by the given ore characteristic parameters of M, p, q from the feed size x_i (in narrow size fractions) and the energy applied to each particle size fraction E_i. Thus for each feed size and its associated specific energy level the breakage results can be calculated, and a lower-triangular appearance matrix (m_{ij}) determined. It is emphasised that for a ball mill to treat the same ore with different mill feed size distributions and in different mill operational conditions (reflected in the different size-specific energy levels), the appearance matrix (m_{ij}) is different. This approach was developed from the successful exercise in hammer mill model (Shi, 2002; Shi et al., 2003) and the vertical spindle models (Shi et al., 2015; Kojovic et al., 2015).

The size-specific energy term E_i in Eq. (2) explicitly takes into account the mill operational conditions, such as mill geometry, ball charge volume, and mill throughput, if the mill power draw is calculated by Morrell's power model (Morrell, 1992) or DEM; or implicitly if the mill power is directly measured. In the specific energy-based ball mill model the mill is no longer treated as a 'black box'; instead both the machine factor and material factor have been mechanistically incorporated in the size reduction model. Note that the ball mill model does not incorporate breakage rate as in the population balance model. However, the model does incorporate a selection function in determine the size-specific energy. The assumption behind is that the size-specific energy selection function is related to the ball size distribution, charge volume, mill diameter, mill speed, liner condition, feed size, etc, and can be called "scale-up parameters". Currently, the selection function at three or four size knots is fitted to the experimental data of mill product size distribution. Ultimately, the selection function may be calculated from the mill geometry and operational conditions.

A number of batch grinding test datasets using a standard Bond ball mill were used to validate the size reduction model. The model fits the batch grinding data well. The calibrated model from one ore sample was used to predict the breakage results for another ore with the measured ore characteristic parameters. The same approach was applied to the JKSimMet ball mill model. Comparison of the predictions by the two models shows better results from the specific energy-based ball mill model.

As a second step in the ball mill model development, the specific energy-based size reduction model was extended from batch grinding to full scale ball milling in continuous operation mode, which is reported in this paper.

2. Modelling discharge function

In essence the size reduction model can be applied as a basic structure for both batch grinding and continuous grinding ball mills. For a continuous grinding mill, however, a classification mechanism and a discharge function must be added into the size reduction model to allow discharge of the ground product based on the particle size.

2.1. The classification function

The literature on tumbling mill classification mechanisms was reviewed. A set of classification data collected by Man (2001) from the internal sampling of an operational ball mill reveals that the classification in a ball mill (Fig. 1a) is similar to that in an AG/SAG mill. The classification function is characterised by two regions. The first extends up to a critical particle size, where the discharge rate is largely constant and equal to that of water. For particles above the critical size the discharge rate progressively reduces. Inspection of the ball mill classification data found that the shape of the classification function is similar to the Whiten expression for corrected efficiency to overflow (Fig. 1b, refer to