Powder Technology 268 (2014) 373–376

Contents lists available at ScienceDirect

Powder Technology

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

Ceramic ball wear prediction in tumbling mills as a grinding media selection tool

Ismael E. Rivera Madrid [a], Beatriz Álvarez Rodríguez [b], Oswaldo Bustamante [a], Oscar Jaime Restrepo Baena [a], Juan M. Menéndez-Aguado [b,*]

[a] CIMEX, Facultad de Minas, Universidad Nacional de Colombia, Medellín, Spain
[b] Escuela Politécnica de Mieres, Universidad de Oviedo, Spain

ARTICLE INFO

Article history:
Received 11 September 2013
Received in revised form 19 July 2014
Accepted 21 August 2014
Available online 28 August 2014

Keywords:
Ceramic grinding
Population balance model
Ball mill wear

ABSTRACT

This article presents the results of applying a media selection methodology based on a population balance model to a ceramic ball mill; the experimental data were obtained through the marked ball test in a white-cement grinding pilot plant. Three types of balls from different suppliers (I, II and III) were used in order to study the wear occurring in each type of ball. Tests were carried out for 576 h and the law of wear for all three types of balls was found to be zero order. These results were introduced into the model to obtain the ball charge of the mill at steady state and the alumina consumption by wear.

1. Introduction

The kinetics of grinding media wear is estimated based on theories put forward shortly before the second half of the Twentieth Century, as is evidenced in the work of Sepúlveda [1], which uses the theory of linear wear to calculate specific rate constant wear. Other research approaches were found such as that of Albertin and Sinatora [2], in which ball wear showing linear behaviour in a laboratory mill was compared with an industrial mill to calculate the rate of ball wear caused by various minerals. Albertin and Lucia de Moraes [3] also conducted further research on coal grinding for four different ball types and all four presented a linear behaviour in their wear. However, all tests were limited to steel balls.

Plant results have shown that ball diameter is an operating variable in the grinding process that directly affects mill efficiency. In fact, according to Austin et al. [4] and Gupta et al. [5], it is known that there is a ball size that maximizes the breaking rate of a given feed particle size; in this respect, the ball size ratio and particle size were initially modelled by Bond [6], who, using a criterion based on the characterization of the mill feed size distribution, developed equations to select the ball sizes at the start-up operation, but provide us with little information about ball recharge into the mill.

From this perspective it is important to study ball recharge and grinding media wear. From the point of view of kinetic equations governing steel ball wear and their applications in population balance models, the contributions of Menacho and Concha [7,8] constitute a good advance; this is proven by the goodness of fit between theoretical and experimental results. An introduction to population balance models and their applications, with a wide variety of references can be found in Jakobsen [9]; in this paper some of the equations proposed by Menacho and Concha are applied to ceramic ball wear behaviour prediction.

2. Experimental equipment and materials

Experiments were conducted using a laboratory mill (0.19 m in diameter) filled with alumina balls with a filling factor $J = 45\%$, and operated at 75% critical speed. Single-sized feed of quartz was used with 100% fractional filling ($U = 1$), with a bulk density of 2.601 g/cm^3 and a sample net weight of 2.2 kg.

The diameter, weight and density of the three ball types, as well as the volume calculated from these variables, can be seen in Table 1.

3. Mathematical model of ball wear in grinding mills

3.1. Kinetic ball wear

The mathematical model corresponds to a population balance equation. Particularly if $g(d) = \alpha$, we get

$$\frac{\partial N(d,t)}{\partial t} + \alpha \frac{\partial N(d,t)}{\partial d} = \varphi_I \sum_{R=1}^{K} m_0^I(d) \delta(d - d_R). \tag{1}$$

* Corresponding author at: Escuela Politécnica de Mieres, c/Gonzalo Gutierrez Quiros, s/n 33600 - Mieres - Spain. Tel.: +34 985458033; fax: +34 985458182.
E-mail address: maguado@uniovi.es (J.M. Menéndez-Aguado).

http://dx.doi.org/10.1016/j.powtec.2014.08.056
0032-5910/

Table 1
Ceramic ball diameter calculation.

Ball type	Weight (g)	Density (g/cm^3)	Volume (cm^3)	Diameter (cm)
I	130.70	3.73	35.04	4.06
II	116.40	3.72	31.30	3.91
III	113.70	3.54	32.02	3.94

Whose solution by the method of characteristics (Salsa [10]) is

$$N(d,t) = N_0(d-\alpha t) + \frac{\varphi_I}{\alpha}\sum_{R=1}^{K} m_0^I(d_R)\{U(d-d_R)-U(d-\alpha t-d_R)\}. \quad (2)$$

At steady state

$$N^{SS}(d) = \frac{\varphi_I}{\alpha}\sum_{R=1}^{K_1} d^{-\beta} m_0^I(d_R)[U(d-d_R)-1] \quad (3)$$

where

- $N\ (d, t)$ is the number of balls with diameter d and time t in the ball charge
- ϕ_1 is the total number of balls at the mill inlet
- $m_0^I(d_R)$ is the relative number frequency for the balls of size d at the inlet flow
- δ is the Dirac delta function
- d_1 is the size of the largest ball entering the mill
- d_0 is the size of the balls leaving the mill
- K_1 is the number of ball size classes in the charge.

In this work, we used a 'zero-order' wear rate as the kinetic equation for $g\ (d)$ [$g\ (d) =$ constant], as will be shown in Fig. 1.

3.2. Ball addition

In industrial practice, ball-filling level is set at steady state. Then, considering the law of wear, input and output ball size, daily ball addition can be calculated using the following formula:

$$\varphi = \left.\frac{6\alpha(4-\beta)w_B}{\pi\rho\sum_{R=1}^{k} m_0^I(d_R)\left\{d_0^{4-\beta}-d_R^{4-\beta}\right\}}\right) \quad (4)$$

Table 2
Kinetic equations.

	Equation	R^2
Type I	y = −0.0064x + 41.027	0.84867
Type II	y = −0.0051x + 39.428	0.61691
Type III	y = −0.0079x + 39.118	0.89461

where:

- φ daily ball addition (number of balls/day)
- α specific wear rate (cm/day)
- β wear rate order
- w_B mass hold-up of balls in mill (kg)
- ρ ball density (kg/cm^3)
- d_R mill input ball diameter (cm)
- d_0 mill output ball diameter (cm).

In this case, the following considerations are assumed:

$$\beta = 0 (\text{wear kinetics is zero order})$$

$$\sum_{R=1}^{k} m_0^I(d_R) = 1 (\text{recharge is made with only one ball size}).$$

Then, Eq. (4) can be expressed as follows:

$$\varphi = \frac{24\alpha w_B}{\pi\rho\{d_0^4-d_R^4\}}. \quad (5)$$

3.3. Consumption by wear

This is defined by:

$$C_D = 4w_B\alpha\frac{\sum_{R=1}^{k} m_0^I(d_R)\left\{d_R^3-d_0^3\right\}}{\sum_{R=1}^{k} m_0^I(d_R)\left\{d_o^4-d_R^4\right\}} \quad (6)$$

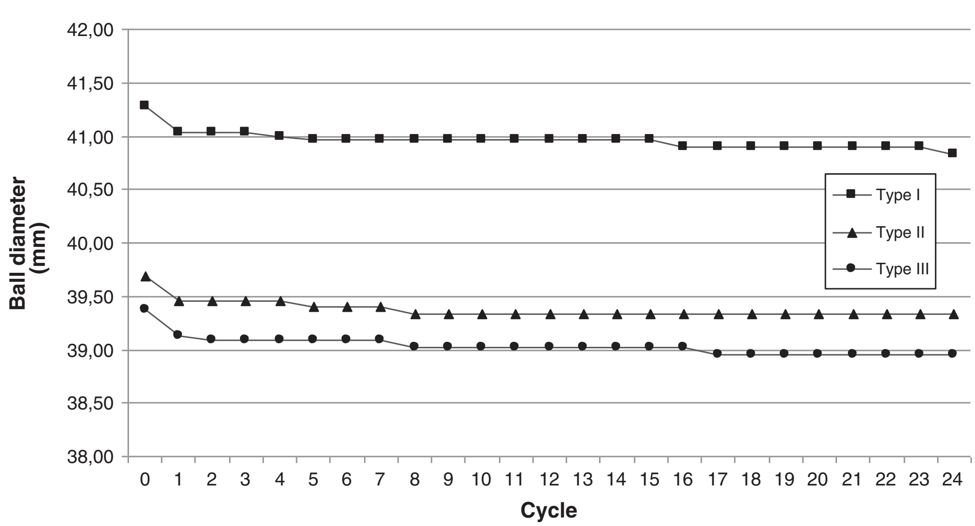

Fig. 1. Kinetic ball wear.