WEARING PERFORMANCE OF STEEL BALLS IN WET GRINDING ①

Xie Hengxing and Li Songren
Department of Mineral Engineering, Central South University of Technology, Changsha 410083, P. R. China
Li Dinghuo
Department of Chemical Engineering, Wuhan Institute of Chemical Technology, Wuhan 430073, P. R. China

ABSTRACT The forms of the dynamic and statistic models of the wear of steel balls in wet grinding have been deduced from theories. The effects of five main factors(ball charge ratio, mass of feed, pulp density, pH value and contents of H_2O_2 in pulp) on the parameter of the dynamic model were studied in tests. The regression equation between the wearing rate of the steel balls and the grinding conditions was established. The result showed that the wearing rate of steel balls decreases with growth of the ball charge ratio, increases with growth of the contents of H_2O_2 in pulp, and reaches a minimum when the volume of feed is about 5% of the internal volume of the mill. There is insignificant effect of the pulp density and the pH of pulp on the wearing rate of steel balls under the circumstances of these tests.

Key words wearing performance steel ball ball mill wet grinding

1 INTRODUCTION

Steel balls and steel rods are two main kinds of grinding medium, but in practice the steel balls are more widely used than steel rods[1]. To study the wearing performance of steel balls, therefore, is of momentous significance for reasonable supply of steel balls, improvement of grinding efficiency, decrease of consumption of energy and steel material, and study of grinding kinetics.

Researchers put particular emphasis on the mechanical wearing performance of steel balls in past studies[2-7]. In fact, however, the wear of the steel balls in wet grinding is not only caused by impact and abrasion but also by corrosion[8-12]. The purpose of this study is of revealing the impact, abrasion and corrosion wearing laws and the effects of grinding conditions on the wearing rate of steel balls in the wet ball mill from both theories and tests.

2 DYNAMIC MODEL

The motion of steel balls in the ball mill is very complex. That of a single ball is a random process, and is subject to the laws of probability. There are interactions between the ball each other, the ball and liner, and the ball and ore in the grinding process. The impact wear due to the forces acting normally takes place on the ball body[4], and the abrasion wear and corrosion wear, due to the forces acting tangentially and oxidation action, only take place on the surface of the ball in the medium of pulp. According to the principle of repeated addition, the total consumption of the ball is the sum of the impact wear, L_1, the abrasion wear, L_2, and the corrosion wear, L_3.

Let M be the mass of one steel ball with the diameter D, and t be the time during which the mill operates continuously. Then,

$$dM/dt = -(L_1 + L_2 + L_3) \quad (1)$$

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We know from theories that the impact wear, L_1, is directly proportional to the mass of the ball, M; and the abrasion wear, L_2, proportional to the product of the surface area of the ball, S, and the tangential velocity at the point of contact, v; and the corrosion wear, L_3, is also proportional to the product of the corrodible surface area of the ball, S', and the relative velocity on the interface between the ball and the pulp, v'. Thus $L_1 = k_1 M$, $L_2 = k_2 S v$ and $L_3 = k_3 S' v'$, where k_1, k_2 and k_3 are proportional coefficients relating to grinding conditions, properties of ores and characteristics of steel balls. Since the ball is coated with pulp, and the corrosion may take place on almost all of the surface, S' is approximately equal to S. The relative motion between the ball and the pulp is similar to the circle path[12]. Therefore, $v' \approx v = n\pi D/60$, and because $M = \pi D^3 \rho g/6$, $S = \pi D^2$, $dM = \pi \rho g D^2 dD/2$, then

$$\frac{dD}{dt} = -\left[\frac{k_1}{3} + \frac{n\pi}{30\rho g}(k_2 + k_3)\right]D = -KD \tag{2}$$

Solving differential equation (2) with the initial condition $D|_{t=0} = D_0$, we get the dynamic model of the wear of a single steel ball as follows:

$$D = D_0 e^{-Kt} \tag{3}$$

where $K = \frac{k_1}{3} + \frac{n\pi}{30\rho g}(k_2 + k_3)$, n is the relative rotation speed of the ball, ρ is the density of steel ball, and g is the gravity acceleration.

3 STATISTIC MODEL

Assume G being the sum of mass of all steel balls in the mill. If the worn part of the balls in time interval dt equal to dG/dt, then it can be exactly compensated by j balls added to the mill at the same time interval, then

$$dG/dt = -jM \tag{4}$$

Substitute equation (2) into equation (4), so

$$dG = \frac{j\pi\rho g}{6K}D^2 dD \tag{5}$$

Hence, the cumulative mass of the balls over size D in the mill at any moment is deduced as follows:

$$G_{D-D_0} = \int_D^{D_0} \frac{j\pi\rho g}{6K}D^2 dD = \frac{j\pi\rho g}{18K}(D_0^3 - D^3) \tag{6}$$

The all-up mass of all balls in the mill is given by

$$G_{0-D_0} = \int_0^{D_0} \frac{j\pi\rho g}{6K}D^2 dD = \frac{j\pi\rho g}{18K}D_0^3$$

Therefore, the ratio of the cumulative mass of the balls over size D to the all-up mass of all balls in the mill, R, is expressed by

$$R = \frac{G_{D-D_0}}{G_{0-D_0}} = 1 - \left(\frac{D}{D_0}\right)^3 \tag{7}$$

The statistic model (7) can be used to calculate the cumulative mass fraction of any size of steel balls and the size distribution of the ball charge in the mill. Obviously, it can also be used as a theoretical formula of adding steel balls to the mill in the practice.

4 TEST RESULTS AND DATA PROCESSING

The conical ball mill with the speed of 96 r/min, XMQ-67, was used in test. Steel balls used in test, with diameters 30 mm, 25 mm and 20 mm, were produced by Wuhan Prospecting Machinery Plant of China. The size distribution of the balls filled into the mill was determined by equation (7). The sample ores from Wangji Phosphorite Ore Mine, Hubei province, China, mainly contain phosphate, carbonate and silicate minerals.

There are many factors influencing the wearing rate of steel balls, but in this paper, only the effects of some main factors on the wearing rate were studied. They are ball charge ratio, X_1 in %; mass of feed, X_2 in kg; pulp density, X_3 in %; pH of pulp, X_4; and contents of H_2O_2 in pulp, X_5 in volume fraction (vs H_2O). Conditions and results of tests are shown in Table 1.

In given grinding conditions, with respect to the same size steel balls, such as the balls with the original diameter of 30 mm, the diameters D_i can be directly measured after different grinding time interval t_i. Meanwhile, the values of D_i' can be calculated from formula (3) correspond-

Table 1 Conditions and results of tests

No.	Conditions					Results
	X_1	X_2	X_3	X_4	X_5	$K/10^5$
1	30	0.7	40	10.1	0.002	3.6723
2	30	0.6	50	10.8	0	2.9058
3	30	0.5	60	5.1	0.02	1.6872
4	30	0.4	70	7.3	0.01	2.1933
5	25	0.7	50	5.1	0.01	5.4605
6	25	0.6	40	7.3	0.02	3.6295
7	25	0.5	70	10.1	0	1.9304
8	25	0.4	60	10.8	0.002	4.607
9	20	0.7	60	7.3	0	5.8016
10	20	0.6	70	5.1	0.002	5.2332
11	20	0.5	40	10.8	0.01	4.2854
12	20	0.4	50	20.1	0.02	4.3549
13	15	0.7	70	10.8	0.02	6.252
14	15	0.6	60	10.1	0.01	4.974
15	15	0.5	50	7.3	0.002	4.7877
16	15	0.4	40	5.1	0	3.9163

ingly. On the basis of the least squares parameter estimation, the total sum of squares of variances between measured results and calculated values of the diameter should be minimum, i.e.

$$Q_1 = \min\sum_{i=1}^{p}[(D_i)_{30} - (D'_i)_{30}]^2 \qquad (8)$$

Equation (8) can be rewritten as

$$Q_1 = \min\sum_{i=1}^{p}[\ln(\frac{D_i}{D_0})_{30} - \ln(\frac{D'_i}{D_0})_{30}]^2 \qquad (9)$$

or

$$Q_1 = \min\sum_{i=1}^{p}[\ln(\frac{D_i}{D_0})_{30} + K_{30}t_i]^2 \qquad (10)$$

Let $\frac{\partial Q_1}{\partial K_{30}} = 0$, then

$$K_{30} = -\sum_{i=1}^{p}\ln(\frac{D_i}{D_0})_{30} / \sum_{i=1}^{p} t_i \qquad (11)$$

Similarly, for the balls with the original diameter of 25 mm, 20 mm,

$$K_{25} = -\sum_{i=1}^{p}\ln(\frac{D_i}{D_0})_{25} / \sum_{i=1}^{p} t_i \qquad (12)$$

$$K_{20} = -\sum_{i=1}^{p}\ln(\frac{D_i}{D_0})_{20} / \sum_{i=1}^{p} t_i \qquad (13)$$

where p is the number of repeating test, and $p = 4$ in the study. The data of the repeating tests were omitted in this paper.

As mentioned above, the parameter K varies with grinding conditions but irrelevant to the initial diameter of the ball. Therefore, under the same grinding conditions, the values of K of three kinds of steel balls should be the same, because the properties of ores and steel balls are constant in tests. From formula (10) the objective function is established as follows:

$$Q_2 = \min\{\sum_{i=1}^{p}[\ln(\frac{D_i}{D_0})_{30} + Kt_i]^2 + \sum_{i=1}^{p}[\ln(\frac{D_i}{D_0})_{25} + Kt_i]^2 + \sum_{i=1}^{p}[\ln(\frac{D_i}{D_0})_{20} + Kt_i]^2\} \qquad (14)$$

Let $\partial Q_2 / \partial K = 0$, then

$$K = -[\sum_{i=1}^{p}\ln(\frac{D_i}{D_0})_{30} + \sum_{i=1}^{p}\ln(\frac{D_i}{D_0})_{25} + \sum_{i=1}^{p}\ln(\frac{D_i}{D_0})_{20}] / 3\sum_{i=1}^{p} t_i \qquad (15)$$

or

$$K = (K_{30} + K_{25} + K_{20})/3 \qquad (16)$$

The optimization estimators of the parameter K in the dynamic model (3) under different grinding conditions can be determined by formula (15) (Shown in Table 1).

5 REGRESSION EQUATION OF PARAMETER *K*

The data in Table 1 shows that K varies with grinding conditions. In order to reveal the relationships between the parameter K in the dynamic model (3) and the grinding conditions X_1, X_2, X_3, X_4 and X_5, a stepwise regression analysis and a computer program were used to deal with the data in Table 1. The regression equation of parameter K was established as follows:

$$K = (1.54 - 3.69X_1^2 - 4.13X_2 + 4.27X_2^2 + 0.15X_5) \times 10^{-4} \qquad (17)$$

Equation (17) shows that the wearing rate of steel balls decreases with growth of the ball charge ratio, X_1, increases with growth of the contents of H_2O_2 in pulp, X_5, and reaches a minimum when the volume of feed is about 5% of the internal volume of the mill. There is insignificant effect of the pulp density and the pH of pulp on the wearing rate of steel balls under the circumstances of these tests.

Hence, combining equation (3) with equation (17) yields

$$D = D_0\exp[-(1.54 - 3.69X_1^2 - 4.13X_2 + 4.27X_2^2 + 0.15X_5) \times 10^{-4}t] \quad (18)$$

Equation (18) can be used to analyse, simulate and predict the wearing performance of steel balls in the wet ball mill. It can also be used to determine the scheme for adding steel balls to the mill and provide the effective ways for prolonging the working period of steel balls.

6 CONCLUSIONS

(1) The wear of steel balls in the wet ball mill is not only in impact and abrasion but also in corrosion.

(2) The dynamic model of the wear of steel balls is given by

$$D = D_0\exp[-(1.54 - 3.69X_1^2 - 4.13X_2 + 4.27X_2^2 + 0.15X_5) \times 10^{-4}t]$$

and the statistic model of that by

$$R = 1 - \left(\frac{D}{D_0}\right)^3$$

(3) The wearing rate of steel balls decreases with growth of the ball charge ratio, icreases with growth of the contents of H_2O_2 in pulp, and reaches a minimum when the volume of feed is about 5% of the internal volume of the mill. There is insignificant effect of the pulp density and the pH of pulp on the wearing rate of steel ball under the circumstances of these tests.

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