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Effects of slurry filling and mill speed on the net power draw of a tumbling ball mill

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ABSTRACT

The pool of slurry is known to lower the power drawn to the mill. An attempt to ascertain this observation by relating load orientation to mill power for a range of speeds and slurry fillings was undertaken.

To this end, a Platinum ore (−850 μm) was used to prepare a slurry at 65% solids concentration by mass. The Wits pilot mill (552 × 400 mm), initially loaded with 10 mm balls at 20% volumetric filling, was run at 5 different speeds between 65% and 85% of critical. The net power draw and media charge position were measured. After this, the slurried ore was gradually added to the media charge for slurry filling U between 0 and 3. A proximity probe and a conductivity sensor mounted on the mill shell provided a means of measuring both the position of the media charge and that of slurry. The data collected for the load behaviour and net power draw was later analysed.

It was found that Morrell's model could not fully explain the effect of slurry volume on net power draw especially for an under-filled media charge (i.e., for $U < 1$). The size of lifters and grinding balls used could be the reason for this. That is why a piece-wise function was curve-fitted to the power data to help make sense of the inconsistencies observed.

1. Introduction

It has been widely observed that the power draw of overflow mills is lower compared to that of grate mills under similar mill geometry and milling conditions (King, 2001; Napier-Munn et al., 1996). This is ascribed to the presence of a pool of slurry in the toe region of the mill load.

In 1993, Morrell proposed a theoretical mill power model capable of accounting for the effects of slurry pool. The model set the benchmark in power modelling with its accuracy and applicability to autogenous, semi-autogenous and ball mills.

In the present work, the ability of Morrell's model to detect changes in slurry volume relative to grinding ball filling was assessed. To this end, a pilot mill was loaded with a constant volume of balls. The net power draw was measured for successive slurry fillings including under slurry pooling conditions. The corresponding positions of both the media charge and the free surface of the slurry pool were recorded using a set of two sensors: the proximity probe and the conductivity sensor (Moys, 1985; Kiangi and Moys, 2006). The data was then analysed and compared to Morrell's predictions to determine how sensitive the power model is to the presence of a slurry pool of variable volume. This is important for the improvement of automatic control schemes and inferential measurement strategies, especially when they are organised around Morrell's model (Apelt et al., 2001).

2. Morrell's power model

The theoretical power draw model of a mill or Morrell's power model is an elegant solution to mill power modelling. It has the merit of treating autogenous, semi-autogenous, and ball mills as one single class of devices for which the power draw could be predicted with the same equations. The model, initially intended for full-scale wet milling, has proved to work also well for dry milling (Erdem et al., 2004; Kiangi, 2011). In addition, the effect of slurry pool is accounted for as the model is based on the crescent shape of the load shown in Fig. 1. The shoulder and toe of the media charge as well as the free surface of the slurry pool are labelled θ_S, θ_T and θ_{TO} respectively.

However, the use of Morrell's model should be limited to speeds not exceeding 90% of critical and mills with a high diameter-to-length ratio as commonly encountered in the Australian industry. In this regard, Moys and Smit (1998) argued that Morrell's model needed testing on tube mills (i.e. low D/L) and mills operating around the critical speed as is typical in the South African gold industry (Powell et al., 2001).

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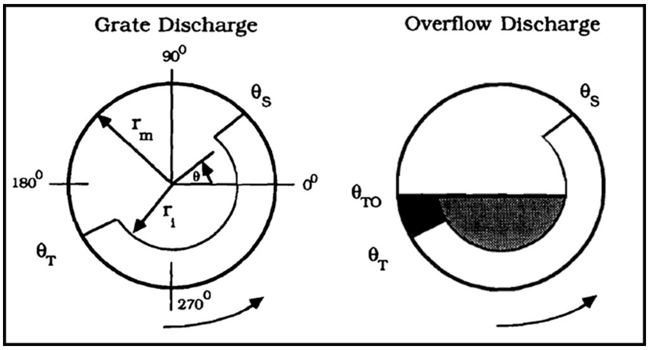

Fig. 1. Simplified shape of the mill charge (Morrell et al., 1992).

With the theoretical shape of the mill load shown in Fig. 1, Morrell (1993) showed that the net power draw of a ball mill can be calculated as follows:

$$P_{net} = \frac{\pi g L N_m r_m}{3(r_m - z r_i)}\left[2r_m^3 - 3zr_m^2 r_i + r_i^3(3z-2)\right] \times \left[\rho_c(\sin\theta_S - \sin\theta_T) + \rho_p(\sin\theta_T - \sin\theta_{TO})\right] + L\rho_c\left[\frac{N_m r_m \pi}{(r_m - z r_i)}\right]^3\left[(r_m - zr_i)^4 - r_i^4(z-1)^4\right] \quad (1)$$

where r_m is the internal radius of the mill given by $r_m = D/2$; z is an empirical parameter equated to $z = (1 - J_B)^{0.4532}$ with J_B being the fractional ball filling of the mill; N_m is the rotational speed of the mill; L is the mill length; g is the gravity constant.

The inner surface radius of the charge is given by $r_i = r_m \cdot \left(1 - \frac{2\pi\cdot\beta\cdot J_B}{2\pi + \theta_S - \theta_T}\right)^{1/2}$ where β is the fraction of the charge making up the active charge and defined between the toe, the shoulder, the charge inner surface and the mill internal shell. It is given by $\beta = \frac{t_c}{t_f + t_c}$.

In the definition of β, t_c represents the time for a particle to move from toe to shoulder within the active charge while t_f is the time taken to travel between the shoulder and the toe in free-fall during cascading or cataracting. Morrell (1993) was able to demonstrate that $t_c \approx \frac{2\pi - \theta_T + \theta_S}{2\pi \cdot \bar{N}}$ and $t_f \approx \left[\frac{2\cdot\bar{r}\cdot(\sin\theta_S - \sin\theta_T)}{g}\right]^{1/2}$ with $\bar{N} \approx \frac{N_m}{2}$ and $\bar{r} \approx \frac{r_m}{2}\cdot\left[1 + \left(1 - \frac{2\pi J_B}{2\pi + \theta_S - \theta_T}\right)^{1/2}\right]$.

This brings us to discuss the definition of the average density of the grinding charge ρ_c. Depending on the presence/absence of the slurry pool, the average charge density ρ_c is calculated differently. For $U > 1$, that is, when the slurry pool is present, $\rho_c = \frac{(1-\varepsilon)\cdot\rho_B + \varepsilon\cdot U\cdot S\cdot\rho_0 + (1-S)\cdot\varepsilon\cdot U}{1 + \varepsilon\cdot(U-1)}$ while for $U \leqslant 1$, that is, in the absence of the slurry pool, $\rho_c = (1-\varepsilon)\cdot\rho_B + \varepsilon\cdot U\cdot S\cdot\rho_0 + (1-S)\cdot\varepsilon\cdot U$.

As for the average density of the slurry ρ_p which is the same as the density of the pool, it can be calculated as (Napier-Munn et al., 1996): $\rho_p = \frac{\rho_0}{C_w + \rho_0\cdot(1 - C_w)}$ where ρ_0 is the specific density of the ore and C_w the solids concentration by mass in slurry. This formula applies only with water as the fluid carrier.

As far as the media charge is concerned, the angular positions (in radians) of the toe θ_T and shoulder θ_S are given respectively by

$$\theta_T = 2.5307 \times (1.2796 - J_B) \times \left[1 - e^{-19.42.(\phi_c - \phi)}\right] + \frac{\pi}{2} \quad (2)$$

$$\theta_S = \frac{\pi}{2} - \left(\theta_T - \frac{\pi}{2}\right) \times \left[(0.3386 + 0.1041\phi) + (1.54 - 2.5673\phi)\cdot J_B\right] \quad (3)$$

Parameter ϕ in Eqs. (2) and (3) is the fraction of theoretical critical speed N_c at which the mill is run. Note that the theoretical critical speed [in revolutions per minute] for grinding balls of maximum diameter d [in metres] loaded in a mill of diameter D [in metres] is given by $N_c = \frac{42.3}{\sqrt{D-d}}$.

Parameter ϕ_c in Eq. (2), on the other hand, is the experimentally determined fraction of the theoretical critical speed at which centrifuging is fully established. It is given by the following mathematical expressions:

$$\begin{cases} \phi_c = \phi, & \text{for } \phi > 0.35 \times (3.364 - J_B) \\ \phi_c = 0.35 \times (3.364 - J_B), & \text{for } \phi \leqslant 0.35 \times (3.364 - J_B) \end{cases}$$

The angular position of the free surface of the slurry pool θ_{TO} (referred to in this work as the pool angle) is in general the same as the media toe angle θ_T for grate discharge mills. And for overflow discharge mills, the pool angle is related to the diameter of the discharge trunnion and to the slurry filling. By the same token, Katubilwa and Moys (2011) studied slurry pooling using a Perspex mill (552×180 mm) run in batch mode. Image analysis of the videoed transparent mill enabled them to propose a model for the pool angle θ_P as a function of slurry filling U. The empirical model of the pool angle is given below:

$$\theta_P = C \cdot U^k \quad (4)$$

where C and k are fitting parameters.

Eq. (4) has been tested using glycerol solutions for the range of slurry fillings $1.2 \leqslant U \leqslant 3.0$ and for viscosities between 0 and 60 mPa s.

If one considers a ball mill of internal volume V_{mill}, it is understood that the mill can theoretically carry a volume of grinding media equal to its own volume. In practice, however, only a fraction of the volume V_{balls} is occupied by grinding balls. The ratio between the volume occupied by grinding balls at rest and that of the mill is defined as ball filling J_B.

In addition to the bed of grinding balls, and for wet milling specifically, slurry (which is a mixture of ore particles and water in some proportion) is loaded into the mill. Depending on the volume loaded, slurry occupies first the interstices between grinding balls before immersing the bed of balls at rest.

The ratio between the volume of slurry V_{sl} loaded to the volume of ball interstices available within the bed at rest is defined as the slurry filling U. It can be calculated using the following expression: $U = \frac{V_{sl}}{\varepsilon\cdot J\cdot V_{mill}}$ where $J\cdot V_{mill}$ represents the volume occupied by grinding media whereas ε represents the static porosity of the bed of grinding balls assumed to be 0.4 on average.

3. Experimental

3.1. Wits pilot mill

Katubilwa and Moys (2011) reported the use of a Perspex mill for the study of slurry pooling. Although useful for preliminary work, this mill had limitations. The motor driving the roller on which the drum sat was not powerful enough to handle ball fillings as high as 25%. Slippages became inevitable; that is why, after trial and error, it was decided to settle for 20% ball filling. The other problem was the low speed of the mill (60% of critical). And the most critical one was that power measurement could not be taken.

To address this, the Wits pilot mill was brought in. This mill was fitted with two non-invasive sensors for the study of load behaviour: the conductivity probe and the inductive proximity probe. The first was used to accurately measure the position of pulp whereas the second took care of the media charge. The sophistication of the pilot mill also provided a facility for speed adjustment over a wide range (i.e. 0–120% N_c).