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An overfilling indicator for wet overflow ball mills

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ABSTRACT

The lack of constraints in ball mill capacity in the published ball mill models may result in unrealistic predictions of mill throughput. This paper presents an overfilling indicator for wet overflow discharge ball mills. The overfilling indicator is based on the slurry residence time in a given mill and given operational conditions. Mathematical descriptions of the method to estimate the volume-based residence time of slurry are presented. A database consisting of 121 sets of industrial overflow ball mill surveys worldwide was used to establish the pattern of the slurry residence time in the full scale operational overflow ball mills. According to the pattern, the residence time thresholds beyond which overfilling a ball mill is likely to occur were defined. For a ball mill with an internal diameter smaller than 5.9 m, the volume-based residence time threshold is set at 2 min; and for a ball mill larger than 5.9 m in diameter, the threshold is set at 1 min. In addition to being incorporated in ball mill models to warn of any unrealistic simulations, the overfilling indicator can also be utilised at ball mill operation sites to guide the mill throughput control and optimisation.

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1. Introduction

It is commonly considered that there are two basic events occurring inside a grinding mill: particle breakage and mass transport. Since particle breakage action is dependent on the time that the material spends in a mill, the residence time is a more fundamental descriptor of the mill (Austin et al., 1984). The mean residence time is defined by Eq. (1):

$$\tau_m = \frac{60H}{F} \tag{1}$$

The term H is the mass of ground material in the mill, which is commonly called the holdup in the mill and F is mass feed rate. Since both H and F in Eq. (1) are based on mass, the term τ_m is named mass-based residence time. Research on mass transport in grinding mills has been undertaken with two different approaches, viz. through directly measuring the residence time and through modelling the mill holdup. The literature contains numerous reports on the residence time distribution (RTD) measurement and modelling (eg. Mardulier and Wightman, 1971; Rogers and Gardner, 1979; Weller, 1980; Marchand et al., 1980; Austin et al., 1984; Nomura, 2012; Gupta and Patel, 2015), and the development of holdup models (eg. Vahl and Kingma, 1952; Kramer and Crookewit, 1952; Hogg et al., 1975; Hogg and Rogovin, 1982; Moys, 1986; Morrell and Stephenson, 1996; Latchireddi and Morrell, 2003a, 2003b). However, in the study of mass transport, the information on how to predict the onset point of overfilling for a grinding mill, particularly for wet grinding ball milling, is very rare, if not absent.

Knowing when a mill is overfilled is important for operators to control grinding mills, and for engineers to run simulations or circuit design with more confidence by using a grinding mill model. In an AG/SAG mill, increasing mill feed rate will generally result in increasing the mill charge load. The increased mill charge load will lead to an increase in mill power draw. The onset point of overfilling an AG/SAG mill can be indicated when the mill power draw exceeds the safe operation power threshold. In a ball mill, however, the mill power draw is dominated by ball media charge volume for a given mill rotational speed. Variation in mill throughput only has a minor influence on ball mill power draw. This can be evidenced from the SAG – ball mill grinding circuit control system, which often showed large variations in AG/SAG mill power draw over a period of grinding time due to the variations in ore feed rate, particle size distribution and ore competence, while the ball mill power draw trend was relatively stable at the same grinding period treating the same ore.

The effect on overflow ball mill power draw of the minor changes attributable to the increased feed rate may be different to that on an AG/SAG mill. For an overflow ball mill, the increased slurry pool volume resulting from the increased mill feed rate will not lead to an increase in ball mill power draw; rather more often the opposite. This is attributed to the fact that the slurry pool on

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Nomenclature

b	height of the stationary ball charge in Fig. 4 (m)
Δb	distance between the stationary ball charge level and the lower trunnion opening edge in Fig. 4 (m)
D_t	trunnion opening diameter (m)
F	mass feed rate of ore (t h^{-1})
F_{80}	80% passing size in mill combined feed (mm)
g	gravitational acceleration constant (m s^{-2})
H	mass hold up of ore in ball mill (t)
h	slurry height inside the mill (m)
Δh	height of slurry level above the discharge trunnion opening edge in Fig. 2 (m)
J_t	fractional mill filling (–)
L_m	mill length inside liners (m)
M_f	combined mill feed rate (dry t h^{-1})
M_w	water addition rate (t h^{-1})
$\mathrm{N_m}$	rotational rate at mill shell (rev s^{-1})
$\overline{N}$	mean value of rotational rate (rev s^{-1})
P_{80}	80% passing size in mill discharge product (mm)
Q	volumetric flow rate of slurry (m^3 h^{-1})
$\bar{r}$	mean radial position of the active charge (m)
R_m	mill radius inside liners (m)
R_t	trunnion opening radius (m)
R_i	radial position of the charge inner surface (m)
S_{pool}	area of slurry pool at the discharge end (m^2)
$S_{0\ ball}$	area of the stationary ball media (including ball interstices) at the discharge end (m^2)
$S_{net\ ball}$	area occupied by balls (excluding ball interstices) below the pool at the discharge end (m^2)
$S_{ball\ above\ pool}$	area of the active charge above pool at the discharge end (m^2)
t_c	time taken for a particle to move between the toe and shoulder within the charge (s)
t_f	time taken for a particle to move between the shoulder and toe in free flight (s)
V_1	volume available for slurry hold up below pool level (m^3)
V_2	volume of slurry held-up in the dynamic interstices of balls above pool (m^3)
V_{total}	total volume in the mill available to hold up slurry (m^3)

Greek letters

α, β	angles indicated in Fig. 2 (rads.)
ϵ_d	dynamic porosity (–)
ϕ	fraction of theoretical critical speed at which the mill is run (–)
ϕ_c	fraction of theoretical critical speed at which centrifuging was fully developed (–)
ξ	fraction of the active charge of the total charge (–)
θ_b	angle ∠TOP at the centre in Fig. 2 (rads.)
θ_{0b}	angle ∠AOB at the centre in Fig. 4 (rads.)
θ_p	angle ∠AOP at the centre in Fig. 2 (rads.)
θ_t	angular displacement of toe position at the mill shell (rads.)
θ_s	angular displacement of shoulder position at the mill shell (rads.)
ρ	slurry density (t m^{-3})
τ_m	mass-based residence time (min)
τ_v	volume-based residence time (min)

the opposite side of the rising ball media would counter the torque required to rotate the mill shell and lift the ball media, leading to a decreased mill power draw. Therefore, unlike the AG/SAG mill, the power draw data cannot be used as an indicator of overfilling for an overflow ball mill.

Due to the lack of overfilling indicator, many of the published ball mill models, such as the one incorporated in JKSimMet comminution software, do not implement any constraint in the simulated mill feed rate. This can result in unrealistic simulations of mill capacity. Although experienced users of JKSimMet may stop increasing mill feed rate further, judged by the change in hydrocyclone performance that is in closed circuit with the secondary wet grinding ball mill, the uncertainty associated with the simulated ball mill capacity renders difficulties in plant optimisation, particularly when the ball mill capacity is a major bottleneck for increasing productivity in a concentrator.

To upgrade the JKSimMet ball mill model, a specific energy-based ball mill model for batch grinding and continuous grinding has been developed (Shi and Xie, 2015, 2016). As a third component of the upgraded ball mill model, this paper reports the work on developing an overfilling indicator to limit unrealistic mill capacity predictions for the specific energy-based ball mill model.

2. Mechanism to identify the onset point of overfilling

The slurry residence time is used in this work to identify the onset point of overfilling in ball mills. The investigation was limited to wet grinding overflow discharge ball mills, as the majority of operational ball mills are of this type.

In a grinding mill, particles require sufficient time to be ground in order to achieve the desired size reduction. If the mill is operated with an excessively high feed rate, particles would be 'washed out' from the mill with little size reduction. In a normal operation, the mill should be controlled to provide sufficient residence time for ore particles being retained in the mill for breakage and size reduction.

There are different definitions of the residence time. The one presented in Eq. (1) is based on mass holdup and mass feed rate, which can be called mass-based residence time. Since the mass holdup cannot be directly measured in an operational ball mill, it has to be predicted by models. There are various empirical holdup models reported in the literature. These models incorporate a number of model parameters that need to be calibrated to a specific grinding system. The calibrated holdup model may only be valid for that system, which limits the model applicability.

In this study, the residence time calculation is based on the total volume available to hold up slurry (V_{total}) in given mill operational conditions and the mill discharge volumetric flow rate (Q) by Eq. (2):

$$\tau_v = \frac{60 V_{total}}{Q} \tag{2}$$

According to the ball mill survey database presented in Section 4, the volume-based residence time of slurry in an overflow ball mill should be greater than 2 min for a less than 5.9 m diameter ball mill, and 1 min for a larger than 5.9 m ball mill.

The total volume available for slurry holdup in an overflow ball mill can be determined using a method similar to that presented by Shi (1995). This includes the effective volume below the slurry

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