The effect of overloading and premature centrifuging on the power of an autogenous mill

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Synopsis

Load behaviour in an industrial mill has been measured directly by inserting probes through liner bolts. The data from conductivity probes have indicated the presence of premature centrifuging during manipulation of the load mass. Overloading conditions were also encountered. Overloading and premature centrifuging both reduce the power drawn by the mill. These effects have been successfully modelled.

Introduction

Mill load behaviour has a dramatic impact on the efficiency of grinding mill circuits. Work is ongoing at the University of the Witwatersrand into understanding load behaviour. This includes direct measurement of load behaviour[1,2,3] leading to modelling of load behaviour as a function of process variables. The increased knowledge and understanding of load behaviour in grinding mills will allow us to obtain improvements in mill control and efficiency.

As part of this study, two sets of experiments were conducted on an industrial scale mill. During these programmes overloading and premature centrifuging of the load were detected. These phenomena are described in this paper. Their effect on mill power is described and modelled.

The mill and probes

A fully autogenous run-of-mine mill at the Kinross Gold Mine, South Africa, was used for the experimental work. The mill (4.027 m inside liners diameter, 6.096 m length) draws approximately 1MW and processes 45 t/h of ROM ore. During the first experimental programme classical grid liners were in use. At the time of the second experimental programme the liners had been changed to grid liners with low (±75 mm) lifters. The product is discharged through a grate and removed through the discharge trunnion with the help of pan lifters. The circuit is closed by a hydrocyclone.

Load behaviour was monitored directly by means of probes mounted on or through mill liner bolts. Three types of probes were used for the experimental programmes, namely, conductivity, movement and temperature probes. However, only some of the data obtained by the conductivity probes will be discussed here.

The conductivity probe was made by machining a mill liner bolt, as shown in Figure 1. A brass rod was inserted through this hole and set in an insulator made of epoxy resin. Conductivity of the slurry is then measured between the tip of the rod and the surrounding bolt head, across the expanded surface of the insulator.

Three conductivity probes were placed along the length of the mill at the feed, middle and discharge ends of the mill (Figure 1). Data from the conductivity probes was taken off the mill either by slip-rings (first experimental programme) or by telemetry (second experimental programme).

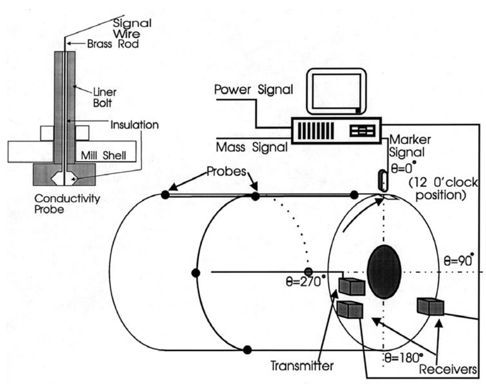

Figure 1—Experimental set-up on the industrial mill. Probes were placed along the length of the mill (feed, middle and discharge) as well as around the mill circumference at the middle of the mill length. The insert shows the design of the modified liner bolt conductivity probe

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In addition, power readings and load cell readings (providing an estimate of mill mass) were obtained from the mill monitoring system at the mine. The load cell readings were calibrated during each experimental programme by manual measurements of the fractional load volume when the mill was stationary. During the second experimental programme, measurements of load volume were taken in a very narrow band making extrapolation to other values uncertain. The mine personnel calibrated the power signal. A marker signal (see Figure 1) indicated the position of the probes in a mill revolution at any time.

Experimental programme

Part of both the experimental programmes was to vary the load mass over a wide range of values. During this variation the mill power, load cell signal and conductivity probe data were collected. The top graphs in Figure 2 presents the load mass (as a per cent of load beam reading) and power data for the second experimental programme. Increasing the feed to the mill from 45 t/h to approximately 100 t/h from 3.4 to 4.3 hours increased load mass. Then the load was ground out while the feed rate was set to zero (4.3 to 6.7 hours).

During the variation of load mass, the feed and middle conductivity probes as shown on the bottom graphs of Figure 2 detected premature centrifuging. The discharge end probe as the probes rotate with the mill shell demonstrates the normal variation of the conductivity probe data. The conductivity signal increases sharply as the probe goes under the load at the toe of the load; the signal decreases sharply as the probe comes out from under the load at the shoulder of the load. The discharge end conductivity probe did not detect premature centrifuging. The feed and middle probe conductivity profiles become flat as premature centrifuging occurs in the mill at the position of the probe.

No premature centrifuging was detected during the first experimental programme.

Analysis of conductivity data

The conductivity data show that premature centrifuging started at the feed end of the mill followed shortly by centrifuging at the middle of the mill as indicated in Figure 2. The centrifuging stopped at the feed end, then at the middle of the mill. It is surprising that the centrifuging occurs first at the feed end of the mill; it was expected that premature centrifuging would occur at the discharge end of the mill where the slurry is expected to be more viscous. At this point no good reason can be given for this apparent contradiction.

To give an indication of the degree of centrifuging, the standard deviation of the conductivity probe data for seven revolutions of data at a time was determined. This was done for all three conductivity probes. The results are shown in Figure 3.

The standard deviation of the conductivity data reduce rapidly with the onset of premature centrifuging. A parabola was fitted to the feed and middle probe data analysis results. This will be used later in the power modelling to give an objective value for the extent of centrifuging.

Power data

According to the conventional understanding of overloading, it is characterized by mill power decreasing as load mass increases, and vice versa. In the time range from 3.6 to 5.1 hours, the mill is clearly in an overloaded condition as indicated in Figure 2.

The effect of centrifuging on the power can be seen in Figure 2. The power drops rapidly at the time when

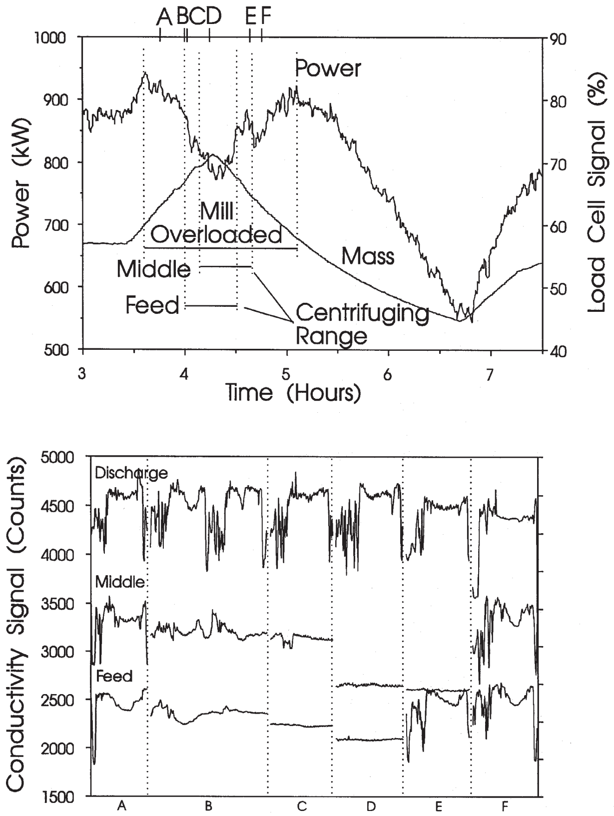

Figure 2—The top graph shows the response of the mill power to a wide variation in load mass. The bottom graph shows conductivity probe profiles indicating the presence of premature centrifuging at the axial position of the probe

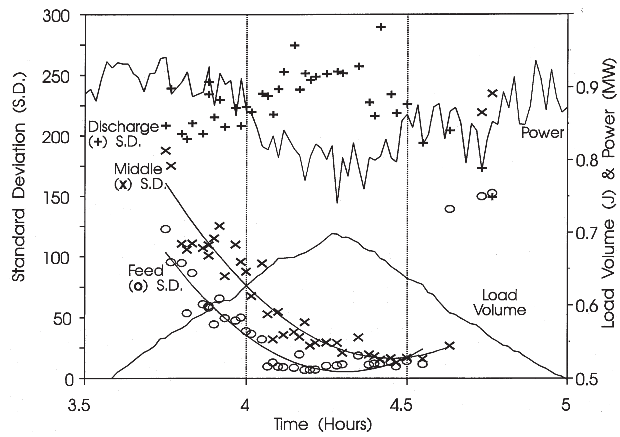

Figure 3—Conductivity data standard deviations, showing the degree of premature centifuging as a function of time at the feed (o), and middle (x) probes. Parabolas were fitted through these data. The mill load volume and power is also shown

centrifuging starts at 4 hours. When the centrifuging stops at the feed probe at approximately 4.5 hours, the power rises rapidly as might be expected. However, the power then drops rapidly at the time when the centrifuging stops at the middle probe. It is difficult to explain this phenomenon; the reader must bear in mind that centrifuging was only detected in the neighbourhood of the probes, and may have been occurring to an unknown extent at other points on the mill shell.

In spite of this apparent anomaly the challenge is to model this power as a function of operating variables.

Power model

The power model used to model the data collected during the experimental program is Moys' power model[4]. Moys adapted the Bond power model so that power is expressed as a function of mill design and operating variables.

Load behaviour is complex, including portions of the load that are cascading, cataracting and centrifuging. To simplify this, the model assumes that the load is divided into two parts: 'centrifuged completely (thus drawing no power) and the active, non-centrifuged portion of the load, drawing power according to Bond's power model applied to a mill with a reduced effective diameter. Because of this simplified approach the model cannot be expected to predict the mill speed at which centrifuging actually starts, nor will it predict the actual thickness of the centrifuged layer'[4]:

$$P = K_2 D_{eff}^{x} \sin \alpha \rho_L J_{eff} \left(1 \pm \beta J_{eff}\right) N_{eff} L \qquad [1]$$

P : mill power [W]

K_2 : constant (affected by liner design and slurry properties)

x : The value of x in Bond's and Moys' models is 2.3. However the theoretical value is 2.5 and is used in this paper for modelling power.

D_{eff} : Effective diameter due to centrifuged layer, given by:

$$D_{eff} = \left(1 \pm 2\delta_c\right) D \qquad [2]$$

δ_c : Thickness of centrifuged layer (according to the model) as a fraction of the mill diameter (D). δ_c is modelled empirically as function of operating variables as follows:

$$\delta_c = J^{\Delta_J} \exp\left[\pm \frac{N^* \pm N}{\Delta_N}\right] \qquad [3]$$

J : Total load volume as a fraction of total mill volume

N : Mill Speed as a percentage of the Critical Speed

Δ_J : governs the strength of the dependence of δ_c on J and is a strong function of liner profile. Moys[4] showed that lifters dramatically reduced the effect of J on δ_c.

Δ_N : Parameter that is a strong function of liner profile and slurry viscosity.

N^* : was found to be approximately constant at a value of 136 by Moys[4].

α : angle of repose of the load (an average value of 37° was found from the conductivity probe data from the first experimental programme during the variation of load mass. There was no indication that α is a function of load volume)

ρ_L : load density [kg/m^3] (an approximate value of 2000 kg/m^3 was used for this paper)

β : Bond model parameter determining at which load volume maximum power occurs (it is assumed that $\beta = 1$ in this paper as this is the only value that gives $P = 0$ for $J = 1$ as required)

L : Mill length (m)

J_{eff} : The volume of load not 'centrifuged' as a fraction of the remaining available mill volume given by:

$$J_{eff} = \frac{J \pm 4\delta_c\left(1 \pm \delta_c\right)}{\left(1 \pm 2\delta_c\right)^2} \qquad [4]$$

($J_{eff} = 0$ for $\delta_c \geq 0.5[1-(1-J)^{0.5}]$)

N_{eff} : Effective speed (% of critical) calculated from:

$$N_{eff} = \sqrt{\frac{D_{eff}}{D}} N. \qquad [5]$$

Modelling of power data

The model of power as developed by Moys was found to have different values of the model parameters depending on the liner type used. For a mesh liner in a laboratory mill (approximating industrial mill grid liners) the values for the parameters are shown in column 2 of Table I. However, these parameters are not applicable to the industrial mill as slurry viscosity and scale-up factors come into play. It was decided to fit the power model to the experimental power data to find the parameters appropriate to this mill.

Table I

Parameters in Moys' power model

Parameter	Laboratory (mesh liner)	Kinross 1st program	Kinross 2nd program
K_2	0.122	0.8109	0.2066
β	0.91	1	1
Δ_J	0.77	1.2023	0
N^*	136	136	136
Δ_N	16.9	35.50	13.38

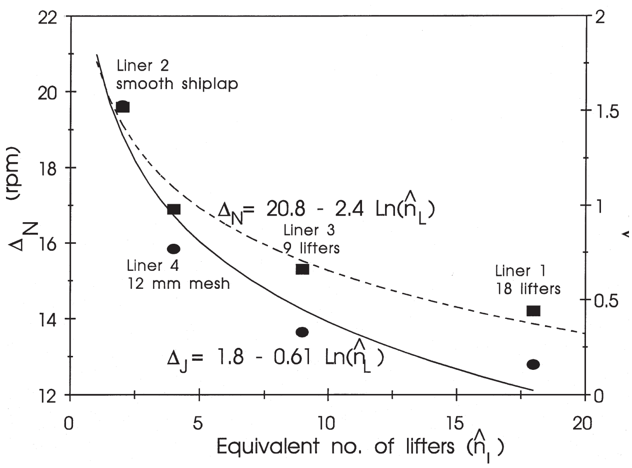

Figure 4—The parameters Δ_J and Δ_N as a function of equivalent number of lifters produced as a result of Moys' work[4] on a laboratory mill

Due to changes between the two experimental programs the model was fitted to the power data of both experimental sets independently. A broken girth gear on the mill was repaired shortly after the first experimental program. The liner design was also changed. Thus the actual power readings for the first experimental program were much higher, possibly due to the higher friction generated by the broken girth gear. Changes in feed ore properties such as size distribution can also cause dramatic changes in the power drawn by the mill.

To exclude the effect of premature centrifuging on these parameters, the data during which premature centrifuging occurred were not included when the model was fitted (t=3.5 to t=5.5 hours) to the second experimental program's power data. The parameters found are shown in Table I.

The parameters Δ_J and Δ_N are functions of lifter profile. Figure 4 shows the relationship of these parameters as a function of the number of lifters (n_L) taken from Moys' experimental data[4]. The high values of the parameters for the first experimental program indicate that the grid liners behave closely to smooth liners (the correlation in Figure 4 suggests an equivalent number of lifters ≈ 2.7 from the Δ_J correlation and ≈ 0 from the Δ_N correlation). The decrease in the value of both Δ_J and Δ_N for the second experimental program is consistent with the addition of low lifters to the liner profile (equivalent number of lifters ≈ 19.1 from Δ_J and ≈ 22 from Δ_N).

The model (see Figure 5) shows the power loss due to overloading in the second data set, where the mill was taken to higher load volumes than for the first experimental data set. The model fits the experimental power data well, except during the time when the mill was shown to be centrifuged by the conductivity probes during the second experimental program (as stated above, these data were excluded when the model was fitted).

The model now needs to take into account the effect of the measured premature centrifuging on mill power. The model was adjusted to take into account the axial variation of load conditions in the presence of premature centrifuging. The mill is divided into '3 mills in series', each containing a third of the load. The thickness of the centrifuged layer in each sub-mill, i, as defined by Moys' model is now calculated as :

$$\delta'_{c,i} = \delta_c + \lambda_i d_{c,i} \qquad [6]$$

where

δ_c : Original centrifuging layer thickness from Moys' model

$\delta'_{c,i}$: Adjusted centrifuged layer thickness

λ_i : function of time indicating degree of centrifuging 0–1 at probe i. The standard deviation (Std. Dev.) of the conductivity data were used here:

$$\lambda_i(t) = 1 - \frac{Std.Dev._i(t)}{Std.Dev._{\max}} \qquad [7]$$

$d_{c,i}$: Maximum thickness of centrifuged layer at probe i

i : probe at feed end (f), middle (m) or discharge end (d) of the mill.

The power of each third of the mill is now calculated separately, with the adjusted thickness of the centrifuged layer obtained from the relevant conductivity probe data as a basis.

The model power is calculated using the parameters found in the previous section, and the values of $d_{c,i}$ are found by fitting the model to the data. The values of the fitted parameters are found in Table II. The results are shown in Figure 6, showing the effect of premature centrifuging on the power. The power of the mill is reduced significantly as a result of premature centrifuging.

Conclusions

The load volume of an industrial grinding mill was varied over a wide range. During this manipulation the mill was taken to high load volumes that included overloading. The

Table II

Parameters in modified Moys' power model

Parameter	Laboratory experiments	Kinross 1st program	Kinross 2nd program
$d_{c,f}$	NA	0	0.004
$d_{c,m}$	NA	0	0.036
$d_{c,d}$	NA	0	0

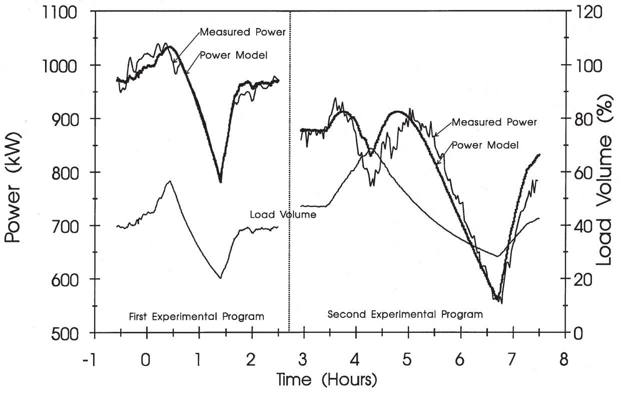

Figure 5—Load volume and power data for both experimental programs. The power model is shown without taking into account the premature centrifuging. The power model shows the effect of overloading on the power

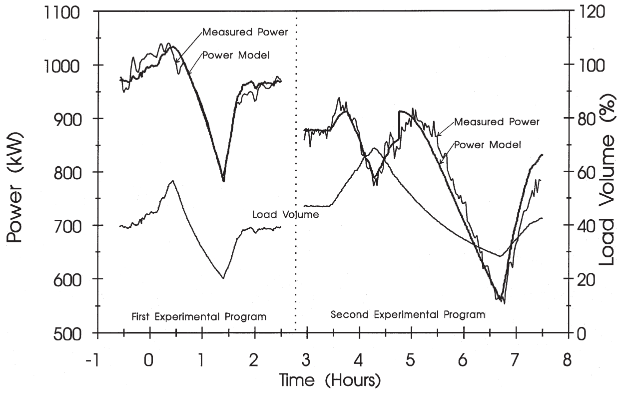

Figure 6—Load volume and power data for both experimental programs. The modified power model shows the effect of premature centrifuging on mill power

presence of premature centrifuging has been detected in the mill during the experimental programme.

The mill power has been successfully modelled as a function of operating conditions. The changes in liner profile between the two experimental programs resulted in changes in mill power which are consistent with the published model that was used to analyse the data. The effect of overloading and premature centrifuging on mill power has been shown to decrease the power drawn by the mill, as expected. The power model was modified to take the premature centrifuging into account and described the observed behaviour with fair success.

This work confirms, in an industrial environment, a previously published model for power as affected by liner profile and load volume; and extends this model to incorporate axial variations in load behaviour, including the premature centrifuging phenomenon.

Acknowledgements

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