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Effects of load filling, slurry concentration and feed flowrate on the attainable region path of an open milling circuit

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ABSTRACT

In this paper, the concept of conversion used in reaction engineering is applied to ball milling. The motivation is to assess the ability of a mill to produce optimally and efficiently a narrowly-sized product.

To this end, a sampling campaign was initiated on a full-scale mill in open circuit. Data pertaining to the residence time distribution was collected for a range of ball filling, slurry concentration and feed flow-rate. Feed and product size distributions were also measured.

After data processing, a model of the milling circuit was developed to allow for material transport and size reduction. Then, simulations were undertaken in order to determine the mill conversion of a feed material less than 850 μm into particles in the range −75 + 10 μm, termed in this work middlings.

Based on the exploratory work, it was found that the middlings could be produced selectively at high ball filling and low slurry concentration. And perhaps the most important point to make is that the attainable region technique can find applications in cases where milling needs to be done under size constraints dictated by the downstream operation.

1. Introduction

Milling is generally used to reduce the size of a particulate material down to a predefined size. Once the material has reached the required fineness, it is sent to the next processing stage. The downstream process therefore determines what the optimum mill product fineness should be.

In the minerals industry, fineness is commonly defined in terms of passing size. For instance, if 80% of a given material passes through a sieve of size 150 μm, and only 20% of the initial material is retained on the sieve, the material is said to be of size $d_{80} = 150$ μm. The work by Vermeulen et al. (1991) is one example where a ball mill in open circuit was optimised to produce a material of size less than 75 μm. It can be argued in this case that the targeted fineness was $d_{100} = 75$ μm, that is, 100% of the product passing 75 μm.

It has been widely observed that unit operations used in mineral processing perform effectively within a certain particle size range and not below a cut-off size defined by d_{80} for instance. Fig. 1 illustrates that the effective size range for froth flotation is anywhere between 5 and 500 μm. High Intensity wet magnets, on the other hand, are effective in the size range 20–600 μm.

It is therefore clear that instead of optimising the milling process based on a single-point size specification, the focus should be to meet the size requirements for effective separation in the downstream process.

Glasser and Hildebrandt (1997) pioneered the Attainable Region (AR) as a tool for the analysis of chemical engineering reactor systems. The tool has reached good grounding in comminution with promising prospects. One classical use of the AR technique applied to ball milling is in optimising the production of a size range (Metzger et al., 2009, 2011; Mulenga and Chimwani, 2013; Chimwani et al., 2014, 2015). It is in line with this that the present work attempts to ascertain the ability of an open ball milling circuit to selectively generate a product within a predefined size range.

To this end, a simulation model of an open ball milling circuit was built. This simulation model is an improved version constructed from previous models listed here in increasing order of prediction ability: Mulenga and Chimwani (2013), Chimwani et al. (2014, 2015a,b), Mulenga and Bwalya (2015).

With the help of the simulator, data was generated for different combinations of load filling, slurry concentration and feed flowrate. Afterwards, the effects of the three aforementioned operating conditions on the production of −75 + 10 μm material were

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Nomenclature

a_T	selection function parameter representing the milling rate of particles of size 1 mm. It is mainly dependent on milling conditions and is calculated from batch grinding data (min^{-1})
$b_{i,j}$	primary breakage distribution function of a particle of size j breaking into size i (–)
$B_{i,j}$	cumulative breakage distribution function for particles of size j reporting to size i after breakage (–)
c	scale-up parameter the value of which is 1.32 when scale-up is done for wet full-scale milling (–)
$c_{i,j}$	transformation matrix used for the generation of the transfer function matrix $d_{i,j}$ which describes the breakage process within the population balance framework (–)
C_1	scale-up correction factor allowing for the difference in mill diameter between batch and full-scale milling (–)
C_2	scale-up correction factor allowing for the difference in ball diameter between batch and full-scale milling (–)
C_3	scale-up correction factor allowing for the design of the full-scale mill, that is, tube or pancake mill (–)
C_4	scale-up correction factor allowing for the difference in ball and slurry fillings between batch and full-scale milling (–)
C_5	scale-up correction factor allowing for the difference in mill speed between batch and full-scale milling (–)
C_w	concentration of solids in slurry by mass (%)
$d_{80}^{(f)}$	particle size of the mill feed corresponding to 80% passing material (μm)
$d_{80}^{(p)}$	particle size of the mill product corresponding to 80% passing material (μm)
d_i	diameter of grinding balls used in full-scale milling and falling in size class i (mm)
$d_{i,j}$	fraction of feed size j transferred to size i in the product via the repeated breakage steps over time τ (–)
$d_{\min}$	diameter of smallest grinding balls still existent inside the full-scale mill (mm)
$d_{\max}$	diameter of grinding balls added to the full-scale mill (mm)
d_T	diameter of grinding balls used in laboratory batch milling (mm)
D	diameter of the full-scale mill inside liners (m)
D_T	diameter of the laboratory mill (m)
e_i	residence time distribution factor as defined in Eq. (4) (–)
f_i	mass fraction of the initial feed in size class i (–)
F_i or $F(x_i)$	mass fraction of the feed passing size x_i or cumulative distribution function of the distribution density function f_i (–)
J	ball filling under full-scale milling conditions (%)
J_T	ball filling under batch milling conditions (%)
L	centre-line length of the full-scale mill (m)
L_T	length of the laboratory batch mill (m)
m_i	equilibrium ball size distribution or mass fraction of balls of diameter d_i inside the full-scale mill (–)
n	number of size classes (–)
N_0	scale-up parameter accounting for the change in ball diameter used between batch and full-scale milling; its default value is 1 (–)
N_1	scale-up parameter accounting for the design of the full-scale mill, i.e. tube or pancake mill; its default value is 0.5 (–)
N_2	parameter accounting for the change in mill diameter when scaling up from batch to full-scale milling; its default value is 0.2 (–)
p_i	mass fraction of the final mill product present in size class i (–)
Q	feed flow rate measured at the mill inlet (m^3/h)
S_i	average selection function of a mixture of balls of different sizes inside the mill. It is calculated as the weighted contribution of individual balls to the breakage of particles of size x_i (min^{-1})
$S_{i,j}$	selection function of particles of size x_i due to grinding balls of diameter d_j (min^{-1})
t	residence time or time spent by particles inside a mill (min)
U	powder filling under full-scale milling conditions (–)
U_T	powder filling under batch milling conditions (–)
$w_i(0)$	mass fraction of the initial feed in size class i (–)
$w_i(t)$	mass fraction of the mill product in size class i produced after grinding time or residence time t (–)
$x_{63.2}$	particle size corresponding to 63.2% of the initial particulate material passing through (mm)
x_i	upper size of the particle size interval i under consideration (mm)

Greek symbols

α	selection function parameter allowing for the increase in selection function with particle size. It is dependent on the ore (–)
β	the breakage function parameter which is material-dependent (–)
γ	breakage function parameter which is material-dependent (–)
δ	parameter accounting for mills of diameter larger than 3.81 m; it has a value of 0.2
$\varDelta$	parameter for the wear rate kinetics of grinding balls. It has a value between 0 and 2 (–)
$\varepsilon_r^{(Q)}$	relative standard deviation corresponding to the average feed slurry flow-rate (%)
λ	slope of a particle size distribution when plotted on a Rosin–Rammler coordinate system as defined in Eq. (20) (–)
$\varPsi(t)$	represents the cumulative fraction of feed material that exits the mill in the removed product up to time t after admission (–)
$\varLambda$	selection function parameter dependent on the ore (–)
μ_T	selection function parameter dependent on milling conditions and calculated from batch grinding data (mm)
$\varPhi$	breakage function parameter which is material-dependent (–)
ϕ_c	rotational speed of the full-scale mill expressed as a percent of its theoretical critical speed (% of critical speed)
ϕ_{cT}	rotational speed of the laboratory mill expressed as a percent of its theoretical critical speed (% of critical speed)
$\varphi(t)$	rate of discharge of the feed or fraction per unit time of the feed that leaves the mill after a residence time t (min^{-1})
$\Psi(t)$	residence time distribution function; it represents the cumulative fraction of traced feed which has been discharged at time t after admission into the mill (–)
ρ_0	specific density of the ore to be milled (kg/m^3)
ρ_B	specific density of the grinding balls (kg/m^3)
τ	average residence time of the full-scale mill and defined by Eq. (15) (min)
τ_0	average residence time of the dead zone before the full-scale mill in the RTD model as defined in Eq. (16) (min)