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Plant-wide control of grinding mill circuits: Top-down analysis

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Abstract: A generic top-down control structure is proposed for the optimal steady-state operation of a grinding mill circuit. The economic cost function of the grinding mill circuit is defined with reference to the final product of the larger mineral processing plant. A mineral processing plant in this study consists of a comminution and a separation circuit. The comminution circuit's operational performance primarily depends on the mill's performance. Since grindcurves define the operational performance range of a mill, the grindcurves are used to define the setpoints for the economic controlled variables for optimal steady-state operation. For a given metal price, processing cost, and transportation cost, the proposed structure can be used to define the optimal operating region of a grinding mill circuit for the best economic return of the mineral processing plant.

Keywords: comminution, grinding mill, plant-wide control

1. INTRODUCTION

As depicted in Fig. 1, a mineral processing plant in this study consists of a comminution and separation process and excludes the metal refinery. The mineral processing plant sells the concentrate to a refinery where the metal is extracted to produce the final marketable metal product. The objective of the mineral processing plant is to maximise the economic value of the separator concentrate sold to the refinery by reducing the bulk of ore and increasing the contained value of the ore (Hodouin et al., 2001).

The comminution objective is to produce a product with a consistent fineness while maximizing throughput, whereas the separation objective is to maintain a constant concentrate grade while maximising metal recovery. The value of the concentrate sold to the smelter depends on the relationship between the recovery and grade of the concentrate. The concentrate grade is the fraction marketable product content in the concentrate. The recovery is the fraction of total valuable metals in the concentrate recovered from the separator feed. Optimisation of the comminution and separation objectives individually may lead to a sub-optimal solution. Because the concentrate produced by the separation process is the main revenue generator of the plant, economic optimisation of the comminution circuit only makes sense if done with reference to the separation circuit. Examples of optimally interfacing comminution and separation plants are shown in McIvor and Finch (1991), Munoz and Cipriano (1999), Sosa-Blanco et al. (2000), and Wei and Craig (2009). In all cases a relationship between the comminution product particle size and the concentrate recovery and grade is used to define the revenue generated from selling the concentrate to a metal refinery.

The aim of this work is to formulate a general top-down control strategy for a comminution process in terms of the economic objectives of the larger mineral processing plant. The control strategy is developed according to the plant-wide control structure design procedure outlined by Skogestad (2004). The top-down procedure for steady-state operation consists of the following steps:

1. Define the operational economic objective.
2. Determine the optimal steady-state operation.
3. Select the primary controlled variables influencing the economic cost function.
4. Select the throughput manipulator.

2. COMMINUTION PROCESS

The semi-autogenous (SAG) mill in Fig. 2 receives four streams: mined ore (MFO), water (MIW), steel balls (MFB), and underflow from the hydrocyclone. The mill charge constitutes a mixture of grinding media and slurry. Grinding media refers to the steel balls and large rocks used for breaking ore, and slurry refers to the water and all ore material that exhibit the same flow characteristics

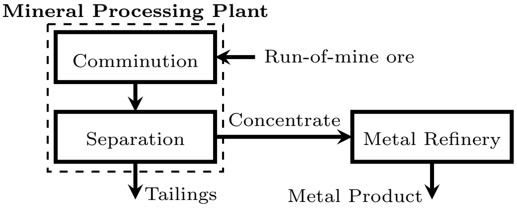

Fig. 1. Chain of processes in a mineral processing plant.

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as water. The mill's fractional volumetric filling by the total charge is represented by J_T, and the fractional volumetric filling of balls by J_B. The mill is rotated along its longitudinal axis by a motor. The charge in the mill is lifted by the inner liners on the mill walls to a certain height from where it cascades down, only to be lifted again by the rotating action of the mill. The rotational speed (ϕ_c) is expressed as a fraction of the critical mill speed. If the mill turns sufficiently fast the material in the charge becomes airborne. The uppermost point where material leaves the mill shell is the charge shoulder. The airborne particles follow a parabolic path making contact again with the charge at the bottom of the mill at the impact toe. The mill motor power draw (P_{mill}) provides an indication of the kinetic and potential energy imparted to the charge.

The ground ore in the mill mixes with the water to create a slurry. The slurry in the mill is discharged through an end-discharge-screen where the end-discharge-screen aperture size limits the particle size of the discharged slurry. The mill grind (ψ) is the fraction of material in the mill discharge below the specification size and indicates the mill's efficiency to break ore. The discharge solids flow-rate and density is given by Q_S and ρ_Q respectively. Ore larger than the discharge-screen aperture are referred to as 'rocks', and ore smaller than the aperture size as 'solids'. The discharged slurry is collected in a sump. The volume of slurry in the sump ($SVOL$) is diluted with water (SFW) before it is pumped to the cyclone via a variable-speed pump. The flow-rate and density of slurry pumped from the sump to cyclone is given by CFF and CFD respectively. The cyclone is responsible for the classification of material. The lighter and smaller particles in the slurry pass to the cyclone's overflow, while the heavier and larger particles pass to the underflow. The underflow is passed to the mill for further grinding. The overflow is passed to the separation process. The fraction of particles in the product flow smaller than the specification size (PSE) defines the product's quality. The ore smaller than the specification size is referred to as 'fines', and ore larger than the specification size but smaller than the discharge-screen aperture size as 'coarse' ore. Solids are the combination of coarse and fine ore. The mass flow-rate of solids in the overflow is the circuit's throughput (TP) and is equal to MFO at steady-state operation. The cyclone product density and flow-rate is given by CPD and CPF respectively. The circuit variables are listed in Table 1.

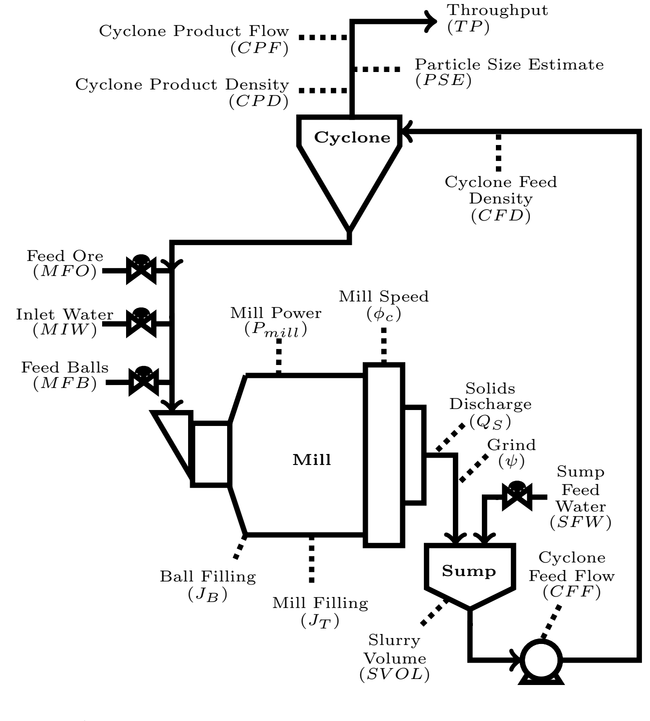

Fig. 2. A single-stage closed grinding mill circuit.

3. RELATIONSHIP BETWEEN COMMINUTION AND SEPARATION

The comminution circuit has limited influence on the variables that determine the performance of a separation circuit. Throughout the rest of this study it is assumed separation is achieved through flotation. (See Craig et al. (1992) for a study of how a comminution circuit influences the separation efficiency of a leaching separation process.) Variations in the content of valuable metals or minerals in the ore, CPF, CPD, and PSE are considered the main disturbances to the flotation circuit. The ore's mineral content cannot be influenced by the comminution circuit. Only the latter three disturbances can be influenced. Should the comminution circuit operate efficiently, there should be minimal variations in CPF, CPD, and PSE (Shean and Cilliers, 2011).

The concentrate grade (γ_C) and recovery (Υ) are accepted metallurgical performance measures of a mineral processing plant, but are not measures of the economic performance by themselves. Rather, the separation process' optimal economic operation is determined by establishing the most profitable region on the grade-recovery curve. As shown in Fig. 3, if a very high γ_C is desired from

Table 1. Description of circuit variables.

Variable	Unit	Description
		Manipulated Variables
MFB	[t/h]	feed-rate of steel balls to the mill
MFO	[t/h]	feed-rate of ore to the mill
MIW	[m^3/h]	flow-rate of water to the mill
SFW	[m^3/h]	flow-rate of water to the sump
CFF	[m^3/h]	flow-rate of slurry to the classifier
ϕ_c	[-]	fraction of critical mill speed
		Controlled Variables
J_T	[-]	fraction of mill volume filled by total charge
PSE	[-]	particle size estimate, i.e. fraction of particles < 75 μm in cyclone overflow
$SVOL$	[m^3]	volume of slurry in sump
		Additional Variables
α_f	[-]	fraction fines in the feed ore
α_r	[-]	fraction rock in the feed ore
CFD	[t/m^3]	cyclone feed density
CPD	[t/m^3]	cyclone product density
CPF	[m^3/h]	cyclone product flow-rate
J_B	[-]	fraction of mill volume filled with balls
P_{mill}	[kW]	mill power draw
Q_S	[m^3/h]	mill discharge solids flow-rate
ρ_Q	[t/m^3]	mill slurry density
TP	[t/h]	solids throughput at cyclone overflow
ψ	[-]	mill grind, i.e. fraction of particles in mill discharge < 75 μm