Powder Technology 274 (2015) 14–19

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

# A laboratory scale application of the attainable region technique on a platinum ore

G. Danha *, D. Hildebrandt [1], D. Glasser [1], C. Bhondayi [1]

*Department of Civil and Chemical Engineering, University of South Africa, Private Bag X6, Johannesburg, South Africa*

ARTICLE INFO

*Article history:*
Received 11 September 2014
Received in revised form 21 November 2014
Accepted 28 December 2014
Available online 6 January 2015

*Keywords:*
Attainable region
Wet milling
Selective grinding

ABSTRACT

We investigated the effects of slurry density, grinding time and grinding energy on the grindability of a typical platinum ore in a tumbling ball mill on a laboratory scale. We then used the Attainable Region (AR) method to find ways of reducing the grinding period and grinding energy required to achieve a specific result; and also of maximizing the amount of material in the desired size range. No work on utilizing the AR technique to optimize the size reduction of a PGM ore in slurry has been published as yet, although researchers have used the method for comminution carried out under dry conditions only. The investigation reported in this paper is not intended to set out ideal operating parameters for industrial mills, but aims to show how the AR technique can be used to develop some ways of improving mill performance. The experimental results we obtained proved that this method could be successfully applied to identifying opportunities for higher efficiency in milling a typical industrial ore. In our particular case, a solids concentration of 33% by mass, milled for between 15 and 30 minutes, gave us the maximum amount of material in the intermediate size class.

## 1. Introduction

In the work described in this paper, we apply the Attainable Region (AR) method (which we summarize in Section 1.3 below) to a PGM ore, in order to find ways of:

- reducing the grinding energy and durations required for a given result; and
- maximizing the mineral phase in the desired product size range, when comminution is carried out on a typical industrial ore and under wet conditions.

The power of the AR tool lies in its capacity to represent only the variables of interest in a process. No work on utilizing the AR to optimize the size reduction of a PGM ore in slurry has been reported previously. However, former and current researchers at the Material and Process Synthesis (MaPS) research group have used the AR method for comminution carried out under dry conditions only [7,10,11,12]. The behavior of Platinum Group Minerals (PGMs) during milling of the UG2 ore is still poorly understood [13], which is the reason why this study was undertaken.

As a general recommendation, a good PGM recovery requires that the ore should be ground to an 80% passing 75 μm product size [3], which is sufficient to ensure the liberation of the valuable species. Ideally, operating parameters such as grinding times, grinding energy and slurry solid concentrations should be set in such a way that the feed particles are reduced to as close to the desired product particle size range as possible. Some size reduction operations use fine screens to achieve the desired particle size range, with recycling of oversized material to the mill, but various difficulties are associated with screening, especially when it is carried out on fine material and under wet conditions. If the grinding could be done in such a way as to get the required size distribution in the mill without having to screen, then this would obviously be preferable. The AR technique may be a useful tool to look at size reduction of PGMs. The AR technique allows us to look at the effect of either control variables or independent parameters on the performance of mills. In this work we use the AR to look at the effect of slurry density and grind time on the laboratory batch mill performance. This work is not intended to directly give operating parameters for industrial mills, but rather to show how the technique can be used and to highlight some opportunities for improvement in mill performance.

### 1.1. The Attainable Region (AR) analysis method

The AR is a theoretical approach that has been successfully applied in many different fields of chemical engineering for optimization purposes. In chemical reactor engineering, it has been used to identify and select ideal reactor configurations [2]. The approach was first proposed as a solution to the problem of reactor synthesis by Horn [4], who sought to find the best reactor structure for a given set of competing reactions and the associated kinetics. He noted that, given specific

---

* Corresponding author. Tel.: +27 116709288.
*E-mail address:* gdanha@gmail.com (G. Danha).
[1] Tel.: +27 116709288.

http://dx.doi.org/10.1016/j.powtec.2014.12.048
0032-5910/© 2015 Elsevier B.V. All rights reserved.

kinetics and feeds, it might be possible to find the set of all possible output concentrations from all possible reactor systems. He called the set of all possible products the Attainable Region.

Since milling can also be considered a rate process in which the various size classes break from larger to smaller sizes in a manner analogous to reactor systems, the AR approach has been extended and successfully applied to comminution [5–7]. The power of the AR approach is that it describes the behavior of different size classes throughout the milling process, and it can represent particle size distributions (PSDs) as single points in space [6]. This allows the connectivity of the points to be used for process description and optimization purposes.

In this study, we assemble AR plots by focusing on the essential features of the process, what is desired, and what is currently available. These can include, but are not limited to, grinding energy, grinding time and mass fraction of different size classes. Any number of size classes can be considered, but typically three of them are used for easy visualization. These are grouped as follows:

(i) the feed size class, which is taken as the top size class or size class 1;
(ii) the middle size class, which is the result of moderate breakage, and is designated as size class 2; and
(iii) the fines size class, which is a result of a relatively intensive extent of breakage, referred to as size class 3.

An example of an AR plot is presented in Fig. 1. It is constructed by following the procedure outlined by Metzger et al. [11] and Khumalo et al. [6] to plot the mass fraction of material in size classes 1 and 2 in a phase space, where these two size classes are compared. Each point corresponds to a different duration of mill operation, starting from a single feed point. This simple plot provides some very important information on the process, including the following two indicators:

1. The boundary curve not only describes the processes that are taking place, but can be interpreted in terms of the pieces of equipment used for the purpose. This in turn suggests the form of equipment arrangement that will be best suited to achieving the desired results.
2. The turning point of the curve marks the point at which the mass in the intermediate size class is greatest. This solves the optimization problem, and provides the run time required to achieve that end. This in turn provides a process control policy.

The values considered for the grinding times in an AR plot, are not preselected, but are influenced by the profile of the AR plot being developed. Fig. 1 illustrates that one cannot stop after 5, 10 or even 30 minutes of milling because the turning point would not have been attained or is still not yet well pronounced. So basically one does not get to choose how long he will mill, because this will be determined by whether or not you have a turning point. The further implications of using an AR plot will be explained in the sections that follow.

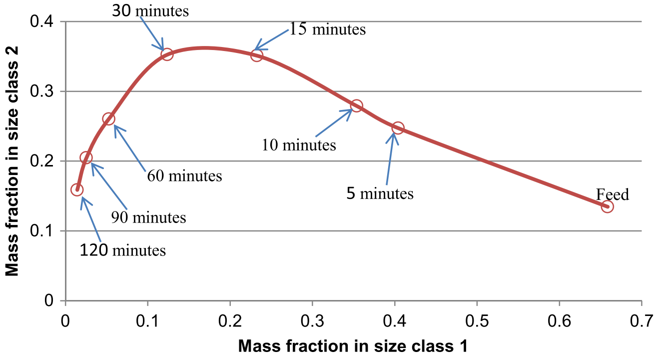

**Fig. 1.** A typical Attainable Region plot of mass fraction of material in the intermediate size class versus mass fraction of material in the feed size class (this graph is obtained from Section 1.3 Fig. 7).

### 1.2. Size reduction of ores

Apart from the main objective, which is bringing about size reduction, the liberation and extraction of PGMs is critically dependent upon milling [14], and this is because liberation occurs as a result of size reduction in the mills. In addition to the problem of the effectiveness of the comminution process in the liberation and extraction of minerals from ores, milling is a highly energy-consuming process [1], which has a significant bearing on the operating cost of mineral processing plants. Comminution consumes 3%–4% of the total world production of electrical energy [9], which is why energy efficiency has become an area of increasing concern to the mineral processing industry. Escalating power costs have added to the urgency with which South African platinum producers, for example, are investing significant effort and resources in investigating energy-efficient milling technologies, with the aim of making the extraction of PGMs less energy-intensive [14]. The research done so far indicates that to bring this about, comminution circuits should operate under those conditions and design configurations that result in optimal recovery of PGMs while operating at the lowest possible cost.

Experience has shown that the best grinding conditions for ores in ball mills are created by a slurry density of between 70% and 80% solids by mass [15,16]. This implies that the milling rates are highest within this range. However, if the objective of a particular milling operation is to maximize the amount of material in a specific size class, a different optimum density can be specified. In current practice, most mineral processing operators would always choose a density (75%) that maximizes the rate over achieving the yield of the target size range.

### 1.3. Experimental procedure

After sample preparation, we started the batch wet milling experiments on the ore samples. For each batch test, we charged a feed sample weighing 500 g of platinum ore into the 30.2 × 29.5 cm ball mill. The grinding medium consisted of 7.8 kg of single-sized 10 mm stainless steel balls. The effect of ball size was not considered in this work, and so the ball size was kept constant in all the experiments. We then added varying measured amounts of distilled water to the samples in the mill in order to obtain different slurry densities. Distilled water was used in place of tap water because we wanted to eliminate the possibility of size reduction occurring as a result of any known or unknown chemical effects.

From the mill control room, we activated the wave-view software that records the voltage supply to the mill, and on the mill rig we set the speed of rotation of the mill at 68 revolutions per minute (RPM), so that we could use the voltage supplied and the speed of rotation of the mill to calculate the power drawn during milling. The effect of mill speed was not considered in this work, so the mill speed was kept the same in all experiments. The mill was then run for grinding times ranging between 5 and 120 minutes for the different slurry densities. After each specific test grind period, we emptied the mill contents and separated the product slurry from the grinding media on a wire mesh. We retained the product slurry in a pan, and washed the balls so that they would be clean for the next batch test.

The cumulative plots that we constructed, based on the experimental data obtained from the Mastersizer, enabled us to classify the product PSD into three size classes, in accordance with the AR technique. Size class 1 was chosen to be the mass fraction of material for particle sizes above 45 μm in diameter, size class 2 as the mass fraction of material for particle sizes between 15 and 45 μm and size class 3 as the mass fraction for particle sizes below 15 μm. We would like to point out that any set of size classes can be used, but this work is based on those chosen above. As previously noted, these size classes were chosen to set size