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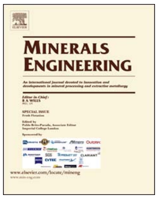

Comparison of sample properties and leaching characteristics of gold ore from jaw crusher and HPGR

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ABSTRACT

Despite high pressure grinding rolls (HPGR) have been widely used in mining industry during the past decades, there are limited systematic quantifications on the properties of the particles after comminution. Furthermore, the influence of micro-cracks on gold ore leaching has not been further investigated.

Gold ore samples were subjected to two different open-circuit comminutions: conventional jaw crusher and HPGR. Particle size distribution was measured and the fractal dimension based on fractal theory was obtained. Combined with scanning electron microscopy (SEM) and stereomicroscopy, particle spherical indices and micro-crack properties were further explored. The results show that HPGR produced higher proportion of fines and less uniformity in comparison with the jaw crusher, reflected by the larger fractal dimension. There was a marked increase in spherical indices from HPGR in 9.5–4.0 mm size fraction. Through the quasi-hydrostatic pressure, more micro-cracks were generated in the HPGR products, resulting in enhanced infiltration of leaching reagent and gold recovery in full-slime and heap cyanide leaching. This paper highlights the importance of the effective micro-crack formation and proposes a leaching kinetic model for further prediction of leaching cycle.

1. Introduction

Declining head grade and finer dissemination in gold ores have increasingly caused difficulties in mineral processing, attaching more and more importance to fine grinding or ultra-fine grinding. Increased findings of refractory gold ores have significantly increased the comminution costs. The “More crushing and less grinding” concept had been proposed to improve the processing capability of comminution circuits and further reduce plant energy consumption. It is considered to be the most effective way in terms of reducing costs and increasing capacity for the current mining industry. HPGR has been recognized as an alternative to the conventional tertiary and quaternary crusher and has wide industrial applications (Clarke and Wills, 1989; Fuerstenau and Kapur, 1995; Apling and Bwalya, 1997; Wang and Forssberg, 2007; Batterham, 2011).

HPGR was first introduced into the cement industry in the 1980s. It is based on the principle of inter-particle comminution through the high pressure which results in micro-fracturing of the ore. This equipment offers several potential advantages including energy saving (Schonert, 1988; Dunne et al., 1996; Celik and Oner, 2006), non-selective crushing of coarse particles (Tavares, 2005) and improved mineral liberation due to micro-crack formation in comparison to other crushers (i.e. jaw crusher, cone crusher) (Battersby et al., 1992; Kodali et al., 2011). Studies also emerged on the ability of HPGR in terms of greater size reduction ratio and processing capability, lower grinding media consumption, smaller footprint, less noise and adaptability (Maxton et al., 2003; Tavares, 2005; Zhao et al., 2011; Altun et al., 2011; Fan et al., 2012). Other research also showed improvements in beneficiation indicators, operational recovery and significant reduction in the subsequent grinding energy consumption due to greater proportion of fine products in comparison with the jaw crusher (Gutsche and Fuerstenau, 2004; Michaelis, 2005; Daniel, 2007).

Saramak et al. (2014) reported a phenomenal improvement in flotation recoveries for HPGR products. Gray (2005) found the gravity gold recovery was increased by 30% when HPGR was used. The HPGR produced higher specific surface areas and pore volumes in the fines than the jaw crusher measured by Brunauer, Emmett and Teller (BET) technique (Han et al., 2012). Petersen and Dixon (2007) studied the main parameters i.e. the oxygen gas–liquid mass transfer, delivery of acid and temperature distribution that determine the overall rate of leaching. In terms of gold ores, it was thought that the improvement of heap leaching rate was due to the generation of micro-cracks on coarse particle surface (Kelly and Spottiswood, 1990; Patzelt et al., 1995). However, studies of HPGR on gold ores are very rare and most of them

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have been mainly focused on the energy saving of HPGR. Different physical, chemical and surface properties associated with the products including particle size, shape, roughness, surface area, porosity and micro-cracks arising from the two comminution techniques should also be explored in detail.

The objective of this paper is to explore the differences in product physical properties (particle size, shape and micro-cracks) between jaw crusher and HPGR, with particular focus on the leaching behaviors of different sizes of particles and its application in both full-slime cyanide and heap leaching process.

2. Materials and methods

2.1. Samples

Low grade and non-refractory gold oxide ore samples were taken from a mine in Fujian province in the southeast of China. Gold exists in the form of native metal. The ore sample has a notably high content of limonite ($FeO(OH){\cdot}H_2O$) and pyrite (FeS_2) together with small amount of covellite (CuS) and digenite ($Cu_{1.8}S$). Gold grains range from 0.10 mm to 0.02 mm. Quartz forms the major gangue mineral with trace amounts of dickite ($Al_4[Si_4O_{10}](OH)_8$) and alunite ($KAl_3(SO_4)_2(OH)_6$). Detailed chemical composition of the sample was analyzed by the X-ray fluorescence (Axios PW-4400) and presented in Table 1.

Table 1
Chemical composition of the samples by X-ray fluorescence (mass fraction %).

Au*	Ag*	Cu	Total Fe	S	SiO_2	CaO	MgO	Al_2O_3	As
0.36	6.30	0.08	2.16	0.25	91.04	0.11	0.03	3.66	0.03

* Unit of Au and Ag is g/t.

2.2. Samples analysis after comminution

2.2.1. Particle size distribution

The gold ore sample of 200 kg was first fed to the primary crusher (PEX-150 × 250 mm) and secondary crusher (XPC-60 × 100 mm) to ensure all the sample could pass through a sieve of 20 mm. The comminuted ore was then thoroughly mixed and divided, fed to the single-toggle jaw crusher (PEF-60 × 100 mm) and HPGR (CLM-100 × 250 mm, with applied pressure of 5.5 N/mm^2) respectively. The distance between the two rollers of the HPGR was 6.0 mm, so that it matched the width of jaw crusher discharge port. The particle size distribution (PSD), average grain size and uniformity were then analyzed. The average grain size of the particles was obtained from Eq. (1).

$$M=\frac{\sum r_i d_i}{\sum r_i}=\frac{\sum r_i d_i}{100} \tag{1}$$

where r_i is grain yield (%) and d_i is the average grain size (mm) in different size fractions.

Fractal dimension was derived from Eqs. (2) and (3) to further characterize the uniformity and distribution of particles from different comminution methods (Turcotte, 1986; Tyler and Wheatcraft, 1992). As reported by Zhang et al. (2007), positive correlation existed between fractal dimension and the uniformity of particle size distribution within the same particle size range.

$$W(d)=k\cdot\left(\frac{d}{d_{\max}}\right)^{3-D} \tag{2}$$

By taking the logarithm on both sides of the Eq. (2), it can be expressed as below:

$$\ln W(d)=(3-D)(\ln d-\ln d_{\max})+\ln k \tag{3}$$

where d is sieve mesh (mm), $W(d)$ is the cumulative yield less than d (%), $d_{\max}$ is the maximum particle size in that size fraction (mm), k is a constant which depends on the particle size, and D is the fractal dimension of PSD.

2.2.2. Particle shape

Given the important influence of particle shape on heap leaching behavior, changes in particle shape after comminution using the two different techniques were examined. Products were sieved by mechanical vibrating sieving machine with standard sieves and each size fraction was evenly mixed and divided to prepare sample for analysis. A total of seven particle size fractions (+13.20, 13.20–9.50, 9.50–6.70, 6.70–4.00, 4.00–2.00, 2.00–1.00, 1.00–0.15 mm) were prepared. More than 200 particles from each size fraction were examined with SEM and stereomicroscope for particle shape analysis.

The average spherical index was used to describe the particle shape quantitatively and the calculation formula is shown in Eq. (4) (Pye, 1994).

$$F=\frac{c}{\sqrt{ab}} \tag{4}$$

where F is the particle spherical index and $F \leq 1$; a is the length of the particle (mm), b is the width (mm) and c is the depth (mm), with all variables perpendicular to each other. Statistical analysis of particle shape was carried out and the value of particle spherical index was obtained from the average of the duplicate runs.

2.2.3. Micro-cracks

Different minerals have different resistances to external mechanical forces. When the same pressure exerts on the minerals, stress deformation and crack formation usually occurs at grain boundaries due to its lower strength than the crystal interiors (Kobayashi, 2004). These micro-cracks (width less than 0.2 mm) are beneficial for flotation and leaching processes.

The 10 kg representative sample was evenly mixed and sieved into nine different size fractions (+13.20, 13.20–9.50, 9.50–6.70, 6.70–4.00, 4.00–1.00, 1.00–0.15, 0.15–0.074, 0.074–0.038 and −0.038 mm). The average occurrence of micro-cracks in the total of nine size fractions was randomly counted by SEM and stereomicroscopy. 10 visual fields and at least 200 particles were selected randomly. The observation of each field was done in duplicate and the test results were the average of the two results to reduce the accidental errors. Micro-cracks from these size fractions were analyzed under SEM (for particles less than 1.0 mm) and stereomicroscopy (for the coarser particles).

2.3. Leaching tests

In order to assess the sample properties after comminution by two different methods, cyanide leaching was carried out to determine the rate of gold recovery. Three leaching tests were conducted namely full-slime, mini-column and laboratory-column leaching. Sodium cyanide was used as the leaching solution. The recovery of gold leaching ε can be expressed as Eq. (5) where m is the mass of gold grain at $t = 0$ (g), m_t is the remaining mass of gold grain at time t (g). Detailed leaching experimental procedures are shown in Table 2.

$$\varepsilon=\frac{m-m_t}{m}\times 100\% \tag{5}$$

2.3.1. Full-slime leaching

200 g of −0.15 mm gold ore samples from HPGR and jaw crusher, together with 300 ml water were fed to a 3 L reactor. 1.5 g/l of sodium cyanide was introduced to the reactor under pH 11.5 and the test lasted for 24 h.