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Comparison of different comminution flowsheets in terms of minerals liberation and separation properties

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A B S T R A C T

Comparative mineral liberation and separation tests of hematite ores were conducted for three comminution flowsheet options to produce relatively fine products at the 70% and 90% passing 74 µm: Option A uses a high pressure grinding roll (HPGR) with screening and subsequent ball milling, Option B uses an HPGR with an air classification, and Option C uses a jaw crusher with screening and subsequent ball milling.

Cracks growing inwards are relatively flat along the direction of applied force during conventional crushing. However, cracks surround the weak interface during HPGR crushing, generating a large number of "mosaic-type" locked-particles. Mineral liberation was only affected after the final grinding mode, not by the crushing method before grinding. "Mosaic-type" locked-particles produced via the particle-bed breakage have no better way to liberate in downstream ball-mill grinding.

Fine mineral grains are then detached from the ore under the high compressive stress, which leads to a significant and clean liberation of the mineral phases in HPGR coarse grinding. Overall, HPGR grinding is more beneficial to the quartz liberation, while ball mill grinding is more beneficial to oxidised iron minerals at a coarse grinding fineness; these advantages disappeared after the further fine grinding.

The coarse-sized liberated quartz, although well-liberated, raised rejection of coarse gangue in magnetic separation during HPGR grinding. Finally, recovery of the HPGR grinding process increased by 4.4–5.2 percentage points higher than that of the ball milling process.

1. Introduction

Recovery of minerals using ore dressing and concentration operations is based on methods that separate particles via their physical or chemical properties. Individual minerals can be separated completely only if each particle contains a single mineral. Separating minerals at the particulate level is referred to as liberation since the individual minerals are liberated from each other in a physical way. Liberation of the valuable minerals from the gangue is accomplished by comminution, which involves crushing, and, if necessary, grinding. The grinding is performed until the particle reaches such a size that the product is a mixture of relatively clean particles of mineral and gangue (King, 2001).

Comminution in an HPGR is the result of high inter-particle stresses generated when a bed of solids is compressed, while moving down the gap between two pressurized rolls. The specific pressure (SP) (i.e., total force divided by projected roller area) is typical in the range of 3–9 N/mm^2 depending on the application, while pressures up to 1000 N/mm^2 have been recorded within the operating gap (Maxton et al., 2003). Several possible applications of the HPGR in comminution circuits include the following: (1) one step comminution in the fine crushing-to-coarse grinding size range, (2) pretreatment of the feed of a conventional tumbling mill in open or closed circuits, (3) production of the final product in a closed circuit. In these configurations, the benefits of the HPGR can be a 10–50% reduction in energy consumption, 20–30% increase in throughput, and significant reduction in operating costs. These benefits are determined via a comparison of HPGR to conventional circuits AG/SAG mills involved with primary grinding applications (Daniel, 2007; Rosario and Hall, 2008; Hilden and Suthers, 2010). A closed-circuit operation with classification can be used to provide a defined stage product, a fixed-top size and high fines content. The application of classification could be wet screening or hydrocyclone, dry screening, or dry air classification. Dry screening can be applied for aperture sizes as small as approximately 5 mm, while wet screening is applied for finer cut sizes (van der Meer and Gruendken, 2010). In dry grinding applications, closed circuit HPGR utilises screens or air classification for dry classification and recirculation. While dry screens are only applicable to coarse product sizes, due to the issue of

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agglomeration, air classification standards may be applied for P_{80} sizes between 25 and 1500 µm. Van der Meer et al. (2012) reported the feasibility of testing dry grinding via the HPGR of a North American magnetite ore; this was done as an alternative to tertiary crushing and ball milling for a size reduction from approximately 50 mm to 90 µm.

Particle-bed breakage, via the use of an HPGR, has often been suggested as a way to enhance mineral liberation properties relative to conventional breakage methods. Tavares (2005) argued that due to inter-particle bed breakage, which occurs when the compressive forces from rotating rolls, such as the HPGR, transmit energy through layers of particles, a preferential weakening of the coarser particles occurs. This may result in preferential liberation. There is some evidence in the literature that particle bed breakage occurring during the high-pressure roll press has the potential to enhance liberation of minerals via the preferential breakage of composite mineral particles along grain boundaries. Ozcan and Benzer (2013) reported that the liberation enhancement of the coarser size fractions of two copper ores can be ascribed to the phenomenon of micro-cracking of individual progeny particles due to the very high stress present in the piston-die press compression zone. For finer size fractions, there is no significant difference between the liberation degree of valuable minerals. Micro-cracking occurs predominantly at grain boundaries, thus increasing the liberation and lixiviant penetration of coarser-size fractions. Similar conclusions have been reached in previous studies, on clinker (Celik and Oner, 2006), chromite (Hosten and Ozbay, 1998), galena and sphalerite (Apling and Bwalya, 1997; Apling and Raissi, 2000). However, these results have been disputed in several studies. Vizcarra et al. (2010) reported size-by-size liberation properties of two sulfide ores in northern-west Queensland, claiming that they were independent of both the method used to comminute (a hammer mill and a piston-die compression unit) the samples and the particle size distribution of the final products. Chapman et al. (2011) and Solomon et al. (2011) reported no improvement in the platinum group minerals (PGM) liberation after using HPGR, although the base metal sulfide (BMS) minerals showed improved liberation. Hence, the body of evidence surrounding these observations is still unclear and conflicting, and this is probably connected with the mineralogical textures of different ores. Palm et al. (2010) get a similar conclusion from a study on BMS ore.

When the fracture pattern developed in the ore during comminution is not independent of the mineralogical texture, the fracture process is considered to be non-random (King, 2001). Previous work (Han et al., 2012) showed that intragranular and intergranular micro-cracks were generated in hematite ores by HPGR via two main non-random breakage forms, namely, *preferential* breakage and *phase-boundary* breakage. This phenomenon indicates that a potential advantage of the liberation of HPGR is the liberation of progeny particles in Anshan Style hematite ores.

In this study, we report a detailed investigation into the mineral liberation properties of a hematite ore as a function of the breakage method employed, using the modern Mineral Liberation Analyser (MLA) based technologies that are currently employed for accurate and reliable liberation analysis. Three flowsheet options were tested in the present study to comminute the samples of two different product sizes (70% and 90% passing 74 µm). Then, the mineralogical properties of the progeny particles were measured on a size-by-size basis using MLA. Flowsheet A is comprised of an HPGR closed with a 2-mm screen, producing feed for a downstream ball mill that generates the final product (HPGR + BM grinding), while flowsheet B is comprised of the same HPGR closed with an air classifier that generates the final product (HPGR grinding). Flowsheet C is comprised of a jaw crusher closed with a 2-mm screen, producing feed for a downstream ball mill that generates the final product (JC + BM grinding) (see Fig. 1).

2. Experimental details

2.1. Feed materials

Hematite samples were taken from Qidashan Mine in China. The sample has a d_{50} of 11.2 mm, d_{80} of 18.5 mm, and a moisture content of less than 0.5%. The raw ores were submitted for mineralogical characterization via MLA. Parameters such as mineral grain size, mineral locking, mineral associations, and mineral constituents, among others, were then measured by the system. Mineral phases of the hematite samples, determined via MLA, are provided in Tables 1. Iron oxide minerals (including hematite, magnetite, and limonite) are the valuable minerals, present at ca. 41.49%. The gangue phases are primarily composed of quartz, present at 56.71%. An image of a feed particle is shown in Fig. 2.

2.2. Flowsheet A and C test

In flowsheet A, a laboratory-scale CLM-2510 HPGR manufactured by CHENGDU LEEJUN INDUSTRIAL CO., Ltd, in China, was constructed with two counter-rotating rolls, each 250 mm in diameter and 100 mm in width, with a work gap between 4 mm and 9 mm. This fully instrumented mill was powered via two 5.5 kW D.C. motors. The working pressure, roll speed, and power consumption were logged by a computer with Lab-view software. The controlling parameter were the specific pressing force of 5.2 N/mm2 and the roll speed of 0.18 m/s (Fig. 3). In flowsheet C, a laboratory XP-60 × 100 jaw crusher was used.

For each crushing cycle, 20 kg of sample was passed through the HPGR and jaw crusher followed by dry screening in a 2-mm screen. Feed for the next cycle was produced by adding fresh feed equivalent to the amount removed by the screen undersize to the screen oversize. Circulating loads remained stable (approximately 180% for HPGR and 300% for jaw crusher) after four locked cycles. Another four locked cycles were performed again. All −2 mm products were combined, homogenised and split to produce a 500-g sample for grind testing and size analysis.

Grinding experiments were performed in a 140 mm × 160 mm (D × L) steel mill with a smooth inner surface. The mill was loaded with a 3.75-kg ball charge and a 25-mm (13 balls), 20-mm (23balls) and 15-mm (5balls) size distribution, also had a running speed of 310 rpm. For every test, hematite ores of the HPGR and CC products were individually ground to a mass of 500 g, with a solids percentage of 65% (wt) in the pulp. Two different-sized final grinding products were obtained at approximately 70% and 90% passing 74 µm. A full-size distribution of the collected product was obtained using nested screens in decreasing size order from the top screen down to the 15-µm screen. Liberation of progeny particles was then measured, on a size-by-size basis, using an MLA.

2.3. Flowsheet B test

A rotating wheel air classifier was utilised to control the final product sizes of the test work, comprising a motor, product storage and dust cyclone. The air classifier was joined together via a bucket elevator (Fig. 4). For each cycle, a 20-kg sample passed through the HPGR followed by air classification. Fresh feed, equivalent to the quantity of removed fine product, was added to the coarse product of the air classifier, homogenised and utilised as feed for the next cycle. Two different sized products were obtained at the 70% and 90% passing 74 µm. For each product size, eight locked cycles were completed at the determined press force, with product samples taken for liberation on a size-by-size basis via MLA.