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Improved characterisation of ball milling energy requirements for HPGR products

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ABSTRACT

This paper describes a method for assessing the downstream milling energy requirements for high pressure grinding rolls (HPGR) products based on a Bond mill test procedure. Multiple trade-off studies have reported the performance of HPGR versus SAG milling with energy savings of between 11 and 32 per cent. One factor that is often inconsistently defined in these studies is the change in the Bond Ball Work Index (BBWi). The Bond test can overestimate the reduction in ball milling energy requirements for HPGR products, not due to a change in the breakage characteristics of the particles, but because the Bond test feed for a sample crushed in a HPGR has a greater fines content than a conventionally-crushed sample. This paper rigorously assesses the actual change in BBWi achieved through the use of HPGR technology.

The reduction in BBWi was found to not be dependent on the ore hardness and thus the expression of the change as a per cent is incorrect. When the size distribution of the HPGR product was matched to the crushed product, more than 95% of the samples tested resulted in a reduction in Work Index, with an average reduction of 1.9 kWh/t. A proportional reduction was seen when the Size Specific Energy (SSE) was calculated for the reconstituted samples. Six samples were tested where the original size distributions were retained and these saw greater reduction in BBWi than SSE.

A gold mine was surveyed to investigate the ball milling requirements of an industrial HPGR circuit. Two surveys of the ball mill operating at different conditions found that milling efficiency could be improved by 20%. These results highlight the importance of the mills operating conditions on energy efficiency as they can overwhelm the potential benefits of HPGR pre-conditioning.

1. Introduction

The introduction of high pressure grinding rolls (HPGRs) to the minerals industry has not led to it overtaking the well-established semi-autogenous grinding (SAG) technology despite the widely reported efficiency benefits. Multiple trade-off studies comparing different comminution circuit options have estimated that HPGR circuits can offer energy savings of between 11 and 32 per cent compared with SAG milling circuits (Davaanyam et al., 2015). The confined-bed breakage mechanism employed by the HPGR requires less energy to achieve the same degree of size reduction as SAG milling. The cost of the grinding media consumed in SAG mills provides an additional benefit that is greater for more competent ores. However, the focus of this paper is the reduced energy requirements of ball milling circuits following HPGRs. This is typically quantified based on Bond ball work index (BBWi) tests of HPGR products, which generally report a significantly lower BBWi value than for the HPGR feed (Wang et al., 2013). The implications for the equipment sizing of the downstream ball mills can be significant (Patzelt et al., 2006). Schönert (1988) estimated that replacing existing circuits with HPGR-ball mill circuits could increase circuit capacity by 12–25%, and reduce energy by 10–20%. However, for this to be achieved the HPGR must produce at least 10% of the final circuit product and, furthermore, damage those particles remaining unbroken.

The reduction in BBWi has been shown (Baum et al., 1997; Daniel, 2007; Esna-Ashari and Kellerwessel, 1988; Otte, 1988), at least in part, to be due to the appearance of "microcracking" fracturing of particles in the HPGR. Daniel (2007) observed microcracks in HPGR product using mineral liberation analysis while Lin et al. (2012) measured the specific

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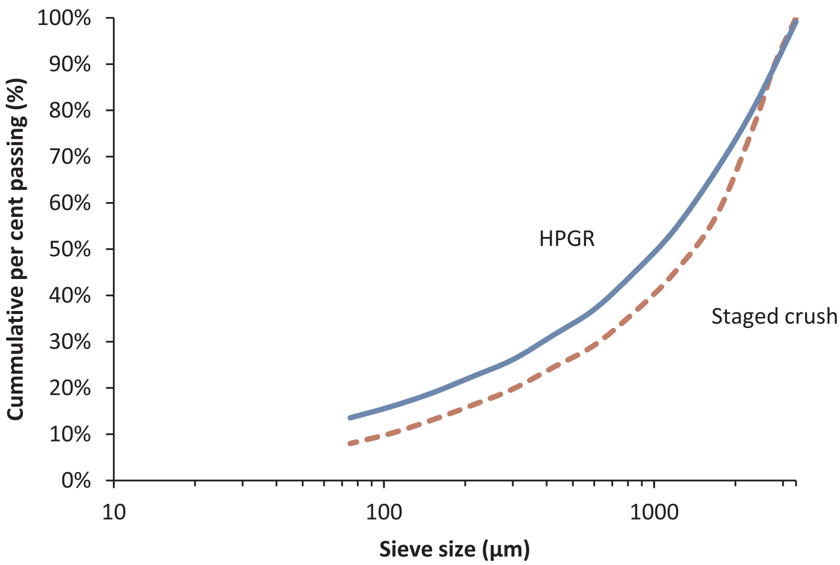

Fig. 1. Size distributions of the product from HPGR locked cycle test with 3.35 mm screen and staged crushing to 100% −3.35 mm using the same ore.

internal surface area contained within them using tomography, but their contribution to reductions in BBWi has not been directly quantified.

Tavares (2005) found that HPGR product particles coarser than 1.5 mm required on average 35% less energy to fracture in comparison to crushing and produced finer progeny when subjected to single particle impact crushing. This weakening was found to increase with compaction pressure and was independent of particle position within the confined bed, but was not observed for particles finer than 1.5 mm. Tavares (2005) used this methodology to decouple the effects of increased fines production and particle weakening on the ball mill through simulation of multiple sequential breakage steps. Shi et al. (2006) also found that the increased grindability of HPGR products was greater when coarser closing screen sizes were used in the Bond Ball Mill test. van der Meer and Schnabel (1997) used pilot plant tests, torque mills of different sizes, a Hardgrove mill as well as standard Bond Ball mill tests to show that the grindability of HPGR products were reduced in comparison to crushed products, and that this reduction increased with applied pressure. Watson and Brooks (1994) supported the finding that the Work Index reduced linearly with increasing pressing force. Stephenson (1997) also found that the reduction in competence was ore-dependent, and either related to the rock structure (presence of vesicles reduced the degree of microcracks) or the fracture toughness (reduction in work index was only observed for ores with high fracture toughness). Morrell (2009) suggested that a reduction in work index of 5% could be assumed in the absence of full scale data.

There is some evidence that microcracks could lead to increased liberation if the mineral association promotes cracks following the inter-species grain boundaries (Battersby et al., 1992). The evidence for this is inconclusive and Daniel (2007) noted that accurate quantification of the effect of breakage mechanism on liberation as measured using SEM-based liberation analysis is not straightforward. Clarke and Wills (1989) compared tin ore crushed using a rod mill and HPGR and found that liberation was enhanced by compression breakage. Studies by Patzelt and Knecht (1996) and Baum and Ausburn (2011) for example have compared leachability of ores from HPGR and crushers finding that high-pressure rolls have a higher leaching rate, in particular in the coarsest size fractions. Additionally, Shi et al. (2006) found that HPGR treated material showed increased flotation responses. In contrast however, neither Palm et al. (2010) nor Solomon et al. (2011) found evidence that HPGR offered any preferential breakage or increased flotation recovery for South African PGM ores. Kodali et al. (2011) found no increase in leaching kinetics for a sulphide copper ore but some improvement for an oxide copper ore. Vizcarra et al. (2010) did not find any increase in liberation between compression and impact breakage and Garcia et al. (2009) and Xu et al. (2013) observed increased liberation only at impractical compression rates of 0.5 cm/day or slower. Therefore, although HPGR use compression breakage and increased liberation can be achieved via this breakage mechanism, the rate required for high throughput may be too fast for this to be realised in practice.

The Bond Ball Mill Work index (BBWi) is the industry standard procedure for assessing the grindability of ores. The test involves conducting a locked-cycle grinding test using Bond's standard mill design. The locked-cycle test enables a batch process to emulate the grinding behaviour of a continuous mill with a 250% recirculating load. The mill product from each cycle is screened and the oversize is combined with fresh feed (of the same mass as the screen undersize which is removed) to maintain a constant filling. This process is repeated for as many cycles as is required to obtain a constant production rate of screen undersize. The standard feed for the test is prepared through staged crushing a sample to 100% passing a 3.35 mm sieve. Bond (1961) defines his work index according to:

$$\text{BBWi} = 4.91/[P_1^{0.23}\text{Gpr}^{0.82}(P_{80}^{-0.5}-F_{80}^{-0.5})]; \tag{1}$$

where P_1 is the closing screen opening, in microns; P_{80} and F_{80} are the test product and feed 80% passing sizes, respectively, in microns; Gpr is the net grams per revolution averaged from the last three cycles. The numerator in Eq. (1) of 4.45 published in the original equation corresponds to the work index for a short tonne, whereas 4.91 should be used when using the metric tonnes.

An implicit requirement of the Bond test is that its feed and product size distributions should be, at least approximately, parallel (Musa and Morrison, 2009). The product from a HPGR (and SAG mills) tend to contain a higher proportion of fine material than a crushed feed specified for the standard Bond test (van der Meer and Gruendken, 2010). However, even with significant differences in the feed size distributions, the product size distributions from the Bond tests have been found to be identical and solely controlled by the closing screen aperture (Shi et al., 2006). Hence the Bond ball mill test should be modified when applied to the grindability of HPGR product. Fig. 1 shows the product of progressive crushing to 100% −3.35 mm (standard Bond procedure) and the product of a HPGR locked-cycle test with a closing screen of 3.35 mm. Although the 80% passing sizes are similar, in this example, there was 14% material finer than 75 µm in the HPGR product compared with 8% in the crusher product, but the difference can be greater in some circumstances. The Bond test procedure can account for differences in the quantity of fines in the feed by calculating the net grams