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An experimental study of the effect of microwave treatment on long term bioleaching of coarse, massive zinc sulphide ore particles

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ABSTRACT

For some years it has been suggested that microwave treatment (MT) of ores might result in preferential grain boundary fracture that would have potential benefits during downstream recovery processes. These benefits include energy savings during subsequent comminution due to particle weakening and improved exposure or liberation of value grains. This suggests that heap leaching could benefit from microwave-induced grain boundary fracture, as the extent and kinetics of heap leaching processes depend on the accessibility of grains to lixiviants. The aim of this study was to determine if microwave treatment (microwave exposure time of 1 s and specific energy inputs of between 2 and 3 kWh/t) of small (5 + 4.75 mm), medium (16 + 9.5 mm), and large (25 + 19 mm) crushed sphalerite ore particles prior to heap leaching would result in improved metal extraction. Column bioleaching experiments showed improved metal recoveries (over 23% to 26%) for microwave treated particles of all sizes. Analysis of the particles by X-ray computed tomography and image analysis techniques showed increased internal cracking due to microwave treatment. This was correlated with the increased recovery during heap bioleaching.

1. Introduction

Heap leaching is a cheap, energy efficient, hydrometallurgical processing option for extracting metals from complex low-grade ores such as copper, zinc, nickel and gold (Pradhan et al., 2008). Heap leaching involves the dissolution of metals by reaction with a lixiviant that percolates through a heap of crushed ore or agglomerated material. In heap leaching, the ore is typically crushed to a size fraction suitable for controlled irrigation and percolation of lixiviant and deposited in heaps. The heaps are irrigated with the lixiviant that reacts with the minerals present in the ore particles. The resultant pregnant leach solution is collected for further processing to extract the valuable metals. The kinetics of heap leaching reactions are a complex function of particle size distribution, ore mineralogy, surface properties, crack size distribution and ore permeability (Ghorbani et al., 2011b; Petersen and Dixon, 2007). One major drawback of heap leaching is the low recovery as compared to recovery by milling and flotation. This is because heap leaching is generally characterised by the extraction of valuable metals from poorly liberated, relatively coarse particles. Although mineral exposure increases with decreasing particle size, heap leaching of too finely crushed ore may result in solution percolation and air flow problems in the heap (Hsih et al., 1995; King, 1979; Miller et al., 2003). Thus heap leaching typically involves the recovery of metals from relatively coarse particles, often > 1 mm (Ghorbani et al., 2011a; Pradhan et al., 2008). Valuable mineral grain exposure and accessibility to lixiviant in these coarse particles are important factors that limit the extent of metal recovery in heap leaching. Where microorganisms are used to catalyse the oxidation of sulphide minerals, the process is referred to as heap bioleaching. Heap leaching could benefit from microwave-induced grain boundary fracture, as the extent and kinetics of heap leaching processes depend on the accessibility of grains to lixiviants.

Numerous investigations have shown the potential process benefits resulting from the thermal fracture induced by microwave heating of ores (Al-Harahsheh and Kingman, 2004; Bradshaw et al., 2007; Haque, 1999; Kingman, 2006). Most of the work reported in literature has focused on microwave assisted comminution, where the ability of microwaves to selectively heat a multi-phase ore is exploited, to weaken ores before further grinding (Batchelor et al., 2015; Jones et al., 2005; Kingman et al., 2004a; Kingman and Rowson, 1998; Kingman et al., 2000; Kobusheshe, 2010; Scott et al., 2008). Some of the earlier work reported in literature was carried out at economically unfavourable energy input levels (> 5 kW h/t) (Clark and Sutton, 1996; Haque, 1999; Kingman and Rowson, 1998). The extent of microwave induced damage was measured indirectly using point load and drop weight tests (Kingman et al., 2004b; Kobusheshe, 2010). Significant reductions in

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strength and increases in liberation of milled microwave treated ore feed have been reported for some ores (Kingman, 2006; Kingman et al., 2004b; Kobusheshe, 2010). Results of these material strength tests, showed a high degree of variability due to the destructive nature of the test which made it impossible to conduct strength test on the same fragment of ore before and after microwave treatment (Kobusheshe, 2010). This suggests a need to apply direct measurement techniques such as X-ray Computed tomography (XCT), to quantify microwave induced crack damage and to assess its potential process benefits. There is a gap in literature pertaining to information on the application of such direct measurement techniques to quantify and characterise microwave induced crack damage in ores.

It has been suggested that the best way to gain improved liberation in microwave treated ore is by subsequent crushing using slow compression breakage and producing a coarse product (Ali and Bradshaw, 2011). Modifications to the existing conventional flowsheets are required to aid the recovery of the coarser liberated fractions in microwave treated feeds, such as coarse grinding followed by coarse particle flotation (Charikinya, 2011). This suggests a need to explore alternative ore processing methods that directly exploit microwave induced damage in ores such as heap leaching.

A number of experimental studies have been carried out to determine the downstream processing benefits of microwave assisted comminution of different ores (Batchelor et al., 2016; Charikinya, 2011; Kobusheshe, 2010; Marion et al., 2016; Scott et al., 2008). Sahyoun et al. (2005) showed improvements in copper recovery of between 6 and 15% from comparative batch flotation test of microwave treated and untreated ore. Scott et al. (2008) demonstrated improved liberation of low-grade copper carbonatite ore after microwave treatment at economically feasible energy inputs (0.1–5 kW h/t). Marion et al. (2016) reported a reduction in Bond Work Index of 22% in microwave treated copper ore in a 3.0 kW multimodal microwave oven (2.45 GHz) for 60 s. Batchelor et al. (2016) reported a ~1% increase in copper recovery and a ~50–60 μm increase in grind size or an approximate 2.5% increase in liberation at an equivalent grind size. In spite of these promising results, the uptake of Microwave technology in the mineral processing industry has been slow. The authors consider the slow adoption of the technology to be due to the difficulties of providing an engineered solution to demonstrate the results at a more significant scale.

There has been limited studies in literature on the application of microwave treatment as an ore preparation method for heap bioleaching (Al-Harahsheh and Kingman, 2004; Olubambi, 2009; Schmuhl et al., 2011). Various studies have demonstrated the role of microcracks, produced during size reduction operations, in aiding recovery of metals in heap bioleach operations (Ghorbani et al., 2012; Kodali et al., 2011; Olubambi et al., 2007; Schmuhl et al., 2011). The role of cracks induced during comminution in aiding recovery during heap leaching has been shown to be a function of the following crack characteristics: micro crack density, mode of fracture and crack width. There is a limited understanding on the characteristics and potential role of microwave induced cracks in aiding coarse particle bioleaching. Demonstrating experimentally the potential process benefits of bioleaching of microwave treated ore is an important step towards commercial adaption of microwave technology to heap leaching. A comprehensive experimental investigation to determine the effects of microwave induced cracks on overall recovery, will give a clear understanding on the role of microwave induced cracks during heap bioleaching.

A recent study applying a combination of high resolution 3D X-ray Computed Tomography (XCT) and conventional QEMSCAN techniques have shown that MT of small (−5 + 4.75 mm), medium (−16 + 9.5 mm), and large (−25 + 19 mm) sphalerite particles results in a significant increase of over 500% in crack volume (Charikinya et al., 2015). Analysis of the XCT and QEMSCAN measured images showed evidence of grain boundary fracture. These results suggest that microwave pre-treatment of crushed ore for heap leaching is a viable processing route that has the potential to improve mineral exposure to lixiviant via microwave induced cracks and hence heap leaching recovery. Following the previous study by Charikinya et al. (2015) this study aims to determine if microwave treatment of large (≥5 mm) coarse crushed sphalerite ore particles prior to bioleaching would result in improved metal extraction.

Table 1
Bulk modal mineralogy of sphalerite ore (Ghorbani et al., 2011b) and the amenability of the mineral to microwave heating according to observations made by Chen et al. (1984).

Phase	Mineral	Abundance (wt %)
Microwave absorbent	Sphalerite ($(Zn, Fe)S$)	16.0
	Pyrite (FeS_2)	33.8
	Pyrrhotite (Fe_7S_8)	1.2
	Galena (PbS)	0.2
	Chalcopyrite ($CuFeS_2$)	< 0.1
	Iron oxide (Fe_2O_3)	1.9
	Other metal sulphides	3.2
Microwave transparent	Garnet ($Fe_3Al_2Si_3O_{12}$)	0.3
	K-feldspar ($KAlSi_3O_8$)	0.4
	Chlorite ($((Mg,Fe,Li)_6AlSi3O_{10}(OH)_8)$)	1.7
	Kaolinite ($Al_2Si_2O_5(OH)_4$)	2.8
	Mica ($KAl_3Si_3O_{10}(OH)_2$)	7.9
	Apatite ($Ca_5(PO_4)_3(F,Cl,OH)$)	2.0
	Calcite ($CaCO_3$)	< 0.1
	Quartz (SiO_2)	25.5
	Others	3.1

2. Experimental

2.1. Ore characteristics

The ore consisted of HPGR-crushed sphalerite ore from the Gamsberg Zinc mine in South Africa. Table 1 presents the bulk modal mineralogy of the ore, and also qualitatively categorises the mineral according to their microwave heating response. The ore was split into the following size fractions (25 + 19), (16 + 9.5), (5 + 4.75 mm). A detailed description of the sample preparation is given in Ghorbani et al. (2011b). For this study, samples from Ghorbani et al. (2011b) were selected for use in the investigation. Representative sub-samples of each size fraction used in this study were separated from the bulk using a riffle splitter.

2.2. Microwave treatment of ore particles

A single-mode microwave heating system was used in this study to microwave treat the ore particles. A single-mode microwave cavity is one for which the dimensions support a well-defined and structurally simple electromagnetic field pattern, giving a restricted volume of high intensity electric field suitable for heating relatively small volumes of material at high dissipated power density. The microwave heating system consisted of the single-mode microwave applicator coupled to a switched mode power supply and a microwave transmission sub-system operating at 2.45 GHz. The single-mode applicator included a sliding short and stub tuners to match the impedance of the magnetron microwave generator to the impedance of the applicator, ensuring a minimum amount of reflected power (see Fig. 1 and Fig. 2).

The single-mode applicator had an internal diameter of 80 mm and a height of 120 mm. The microwave cavity contained a cylindrical 75 mm diameter microwave transparent sample holder which has a capacity for 0.4 to 1 kg of ore particles per treatment. The smaller particles packed better and yielded a higher mass in the sample. The specific microwave heating energy absorbed by the particles ranged between 2 and 5 kWh/t (Table 2). This falls within the probable economic range for microwave treatment of between 1 and 5 kWh/t (Bradshaw et al., 2007).