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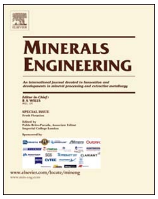

Towards large scale microwave treatment of ores: Part 2 – Metallurgical testing

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ABSTRACT

A pilot scale microwave treatment system capable of treating 10–150 t/h of material at 10–200 kW was designed, constructed and commissioned in order to understand the engineering challenges of microwave-induced fracture of ores at scale and generate large metallurgical test samples of material treated at approximately 0.3–3 kWh/t. It was demonstrated that exposing more of the ore to a region of high power density by improving treatment homogeneity with two single mode applicators in series yielded equivalent or better metallurgical performance with up to half the power and one third the energy requirement of that used with a single applicator. Comminution testing indicated that $A * b$ values may be reduced by up to 7–14% and that the Bond Ball Mill Work Index may be reduced by up to 3–9% depending on the ore type under investigation. Liberation analysis of the microwave-treated ore indicated that equivalent liberation may be achievable for a grind size approximately 40–70 µm coarser than untreated ore, which is in agreement with laboratory scale investigations reported in the literature at similar or higher doses. Flow sheet simulations further indicated that reduced ore competency following microwave treatment could potentially yield up to a 9% reduction in specific comminution energy (E_{CS}) at a nominal plant grind of P_{80} 190 µm, or up to 24% reduction at a grind of P_{80} 290 µm, for a microwave energy input of 0.7–1.3 kWh/t. Throughput could also be increased by up to approximately 30% depending on grind size, ore type and equipment constraints. To date, approximately 900 t of material has been processed through the pilot plant, approximately 300 t of which was under microwave power. Metallurgical testing has demonstrated that comminution and liberation benefits are achievable at doses lower than that previously reported in the literature, which allow high throughputs to be sustained with low installed power requirements providing a pathway to further scale-up of microwave treatment of ores.

1. Introduction

Microwave-induced fracture of ores has been widely cited as a means to address some of the challenges faced by the hard rock metalliferous mining industry, for which stakeholders have identified reducing ore competency prior to energy intensive comminution and improving liberation to enable more efficient separation closer to native grain sizes to be among potential solutions (Daniel and Lewis-Gray, 2011; Drinkwater et al., 2012; Pokrajcic et al., 2009; Powell and Bye, 2009). Investigations on microwave-induced fracture of a variety of ores (including copper sulphide, nickel sulphide, lead-zinc sulphide, gold and iron ores) over the past three decades have demonstrated many potential benefits, including reduced comminution energy, enhanced liberation and increased values recovery during flotation.

Dramatic reductions in ore competency (up to 80%), and improvements in liberation (up to 30%) and flotation recovery (up to 20%) following microwave treatment are typically reported in the literature by studies that use low power density multimode cavities at 2.45 GHz (such as a kitchen microwave oven) at low power (< 3 kW) (Amankwah et al., 2005; Amankwah and Ofori-Sarpong, 2011; Andriese et al., 2011; Andriese et al., 2012; Henda et al., 2005; Kingman et al., 1999; Kingman et al., 2000a, 2000b; Kumar et al., 2006; Kumar et al., 2010; Marion et al., 2016; Omran et al., 2015; Orumwense and Negeri, 2004; Vorster et al., 2001; Walkiewicz et al., 1993; Walkiewicz et al., 1991; Wang and Forssberg, 2005). The residence times were long ($\gg 1$ s, typically in the order of minutes) for small batch masses of ore (up to 1 kg) of typically ball mill feed size material (< 20 mm). Treatments resulted in high bulk temperatures

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(typically > 100 °C) and prohibitively high microwave treatment energy input to the ore (≫5 kWh/t, frequently > 50 kWh/t); it was widely acknowledged by the authors that such high microwave energy inputs could not justify the comminution energy savings using such microwave systems. Furthermore, the long residence times required to achieve these benefits would otherwise not support the high throughputs required by the mining industry (> 100 t/h).

The encouraging results were not universal and were highly dependent on the mineralogy of the ores tested. The efficacy of the generation of thermally-induced fractures, and thus the amenability of ores to microwave treatment, have been empirically shown to be depend on the dielectric, thermal and mechanical properties of the minerals involved, their assemblage within the ores, and the microwave energy and power density employed. Theoretical studies by several authors have confirmed these observations mechanistically (Ali and Bradshaw, 2009, 2010, 2011; Jones et al., 2005, 2007; Like and Jun, 2016; Salsman et al., 1996; Wang et al., 2008; Wang and Djordjevic, 2014; Whittles et al., 2003). In particular, the theoretical studies suggested that high power densities (typically in the order of 1×10^8 W/m^3–1×10^{11} W/m^3 in the microwave-heating phase) could yield the same amount of microwave-induced fracture at a fraction of the microwave energy input and in a fraction of the time compared to lower power density treatments due to faster heating rates and higher thermal stresses.

Experimentation using high power density single mode applicators at 2.45 GHz with higher power (up to 30 kW) enabled economically feasible microwave energy inputs (< 5kWh/t) with short residence times (< 1 s) that would support high throughputs. There are few direct comparisons between low power density multimode and high power density single mode cavity experiments in the literature. Kingman et al. (2004a) showed that Point Load Index reductions of approximately 60% could be achieved on a lead-zinc ore using a single mode cavity with < 2 kWh/t microwave energy input, which was approximately 10–20 times less energy than required in a multimode cavity for an equivalent strength reduction. Kingman et al. (2004b) and Scott et al. (2008) both tested the same copper ore investigated by Kingman et al. (2000a) in a multimode cavity and demonstrated improved liberation after high power density microwave treatments on lump fragments (> 10 mm) in single mode cavities with up to 15 kW microwave power at economically feasible energy inputs (0.1–5 kWh/t). Furthermore, Sahyoun et al. (2005) conducted flotation tests on the same ore and demonstrated a 3–6% increase in copper recovery after microwave treatment (up to 12 kW and 1.7 kWh/t on < 22 mm size material) as opposed to the 1% increase reported by Kingman et al. (2000a), attributed to the higher power density sustained in the single mode cavity. Treating coarser particles as opposed to ball mill feed size material further ensured that more of the microwave-heating phases are constrained by the non-sulphide gangue matrix, thereby promoting more microwave-induced grain boundary fracture. Other authors have also demonstrated significant reductions in ore competency (up to 40%) (Batchelor et al., 2015; Rizmanoski, 2011) and improvements in liberation and flotation recovery (~1%) (Batchelor et al., 2016) using single mode cavities under economically favourable microwave treatment conditions, though typically at microwave treatment energies > 1 kWh/t.

Potential paths to scale up were identified by researchers in the field (Bradshaw et al., 2007) and trialled during the AMIRA P879a project and during pre-piloting studies at up to approximately 30 t/h (instantaneous) and 30 kW (2.45 GHz) in batch systems. However, to demonstrate continuous microwave treatment at a scale in the order of that required by the mining industry, it was necessary to build larger single mode cavities by utilizing the 896 MHz frequency that could support even higher power output from microwave generators (up to 100 kW) to maintain the power densities used at laboratory scale.

In the first part of this paper (Buttress et al., 2017), a bespoke, laboratory-based, high throughput and continuous pilot scale microwave treatment system capable of treating up to 150 t/h of ore with up to 200 kW of microwave power was described. The paper details the integration of microwave applicators with materials handling components and ore presentation to provide a stable and reliable treatment that also meets with occupational health and safety (OHS) and electromagnetic compatibility (EMC) regulations. The aim of the facility was to understand and develop know-how surrounding the engineering challenges of microwave-induced fracture at scale, to generate large metallurgical test samples (up to 6 t batches) for subsequent analysis and to support project valuation. Following the design and construction phases of the project, commissioning tests, upgrades and metallurgical tests were conducted over a period of two years, during which time approximately 200 recorded test runs were completed on nine different ore types with a total of approximately 900 tonnes of material processed, 300 tonnes of which was under microwave power.

This second part of the paper presents the results of two campaigns of metallurgical testing (herein referred to as Phase I and Phase II) on three different ore types following microwave treatment in the pilot scale system. Phase I employed a single microwave applicator whereas Phase II employed two applicators in series following system upgrades. The pilot scale testing specifically targeted low microwave treatment energy doses (0.3–3 kWh/t) to maximise throughtput and investigate the potential comminution and liberation benefits that may be achieved at doses lower than that previously reported in the literature. The specific objectives of each campaign were as follows:

- Understand the effect of dose at fixed power density (variable throughput) using a single microwave applicator
- Understand the effect of dose and power density at fixed throughput (variable power input) using two applicators in series
- Understand the effect of treatment homogeneity by comparing the results from single and dual applicator configurations at similar dose and power density conditions
- Evaluate the potential changes in comminution circuit performance using flowsheet modelling based on laboratory test results

2. Materials and methods

2.1. Ore samples

The ore samples used throughout the piloting investigation were all sourced from a major porphyry copper mine owned and operated by the project sponsor. Three ore types of differing lithology were selected for the Phase I testing campaign, labelled Ore 1, Ore 2 and Ore 3, with Ores 1 and 2 studied further in the Phase II testing campaign. All three ore types contained chalcopyrite as the dominant copper sulphide mineral and pyrite as the dominant sulphide gangue mineral. Other microwave-heating phases included hydrated smectite clays (classified as montmorillonite) and typically poorly heating iron oxides, such as hematite. Table 1 gives the average modal mineralogy for each sample from liberation testing, discussed further in Section 2.2.4, with standard deviation to show the variability obtained across different individual samples. There was good agreement between the two bulk samples taken for Phase I and Phase II testing and little variation between individual samples.

Example texture images were captured using a Mineral Liberation Analyser (MLA) (FEI, 2016a) at the University of Nottingham and are presented in Fig. 1. All three ores typically had well disseminated heating phases with little observable association of copper and iron sulphides. However, Ore 3 contained many fragments with veined or otherwise very coarse sulphide mineralisation. Ore 1 also contained infrequent veined or coarse mineralisation.

The grain size distributions of selected minerals were extracted using the MLA and are presented in Fig. 2. It can be seen that the copper sulphides have a native grain size D_{80} of approximately 170–260 μm,