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Deriving the ideal ore texture for microwave treatment of metalliferous ores

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ABSTRACT

High power density microwave treatments on metalliferous ores have historically been shown to reduce ore competency prior to beneficiation at economically feasible energy inputs. However, the relationship between mineralogical textural features and the extent of the microwave-induced fracturing had previously been limited to qualitative descriptions or simplistic two-phase numerical models, which could not account for the complex mineral assemblages in real ores. In this paper, mineralogy, grain size, dissemination, textural consistency and mineral associations were determined for 13 commercially exploited nickel, copper and lead–zinc ores using a Mineral Liberation Analyser (MLA). The ores were subjected to high power density microwave treatments at up to 25 kW in a single mode cavity with microwave energy inputs of approximately 0.5–10 kW h/t, and the subsequent reductions in ore competency were measured by the Point Load Test. The ores that demonstrated the greatest reductions in strength typically contained between approximately 2 wt% and 20 wt% of highly microwave-absorbing minerals, with a native grain size *d*50 greater than approximately 500 μm, constrained by hard matrix minerals such as quartz and feldspar. Texturally consistent ores with a high proportion of amenable textures also demonstrated the highest average reductions in strength. These findings support the qualitative descriptions and numerical modelling results available in the literature and provide a baseline for selecting likely candidate ores for microwave treatments in the future.

1. Introduction

On the basis of current and anticipated future reserves and rates of consumption, demand is predicted to outstrip supply for many mineral commodities within the next century (Kesler, 2007; Mudd, 2010). As higher grade ore bodies are exhausted, the average grades of the remaining deposits will diminish requiring even greater volumes of ore to be milled to meet the growing demand (Crowson, 2012; Mudd et al., 2013; Northey et al., 2014; Prior et al., 2012). It is also well established that comminution is the most energy intensive stage of mineral processing and that the process is inherently inefficient (Batterham, 2011; BCS, 2007; Curry et al., 2014; Nadolski et al., 2014; Tromans, 2008). Furthermore, new ore bodies are often more complex, occurring in harder rock with finer grain sizes, which further increases the energy required to liberate the valuable minerals for downstream separation processes (Cooke et al., 2006; Norgate and Jahanshahi, 2011; Sillitoe, 2010).

This growing demand for raw materials combined with a higher embodied energy in their production, rising costs, environmental and socio-political pressures will place a strain on sustainable mining in the future. In an effort to address these challenges, the aims of energy efficiency strategies in comminution include (Daniel and Lewis-Gray, 2011; Drinkwater et al., 2012; Pokrajcic et al., 2009; Powell and Bye, 2009):

- Reducing ore competency (i.e. AG/SAG mill impact breakage and abrasion parameters, and Ball Mill Work Index),
- Improving liberation to effect separation at a coarser size,
- More efficient crushing and grinding equipment and circuit design,
- Pre-concentration or barren waste rejection, and
- Indirectly reduce the burden on energy and materials from the production and consumption of consumables, such as water, grinding media and wear liners.

Microwave treatment has been proposed as a technique to reduce ore competency prior to beneficiation and as a means of enhancing liberation through the generation of thermally-induced cracks along mineral grain boundaries (Haque, 1999;

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Jones et al., 2002; Kingman and Rowson, 1998). The efficacy of this mechanism and the amenability of ores to microwave-induced fracture depend on the dielectric, thermal and mechanical properties of the minerals involved and their assemblage within ores.

1.1. Microwave treatment of ores

Thermally-assisted liberation has been widely cited as a means of reducing the competency of ores. Differential thermal expansion of the constituent minerals within the ore occurs during heating and cooling cycles, which results in the generation of significant stresses within the ore particles leading to fracture (Fitzgibbon and Veasey, 1990; Veasey and Wills, 1991). Using microwaves as the heating source offers particular benefits in that it provides rapid volumetric heating throughout the ore of only selected mineral phases, thereby eliminating the need to rely on conduction to transfer heat, significantly increasing heating rates and reducing energy requirements for fracture.

Work on microwave-assisted fracture and liberation has been carried out since the US Bureau of Mines worked extensively in this area during the 1980s, measuring the dielectric properties and low power (1–2.6 kW, such as that used in domestic kitchen microwaves) heating rates of many common ore-forming minerals (Chen et al., 1984; Chunpeng et al., 1990; Church et al., 1988; Harrison, 1997; Kobusheshe, 2010; McGill and Walkiewicz, 1987; Nelson et al., 1989; Standish and Worner, 1991; Walkiewicz et al., 1988; Yixin and Chunpeng, 1996). These studies demonstrated that most aluminosilicates, micas, carbonates and sulphates (rock-forming minerals) showed little heating (i.e. microwave-transparent, $\varepsilon'' < 0.3$, <0.3 °C/s), whereas most sulphides and metal oxides (economically important and associated gangue minerals) readily heated when exposed to microwave energy (i.e. microwave-absorbent, $\varepsilon'' > 0.3$, >0.3 °C/s).

Studies by McGill et al. (1988) and Kingman et al. (2000b) also demonstrated that higher microwave power levels resulted in faster heating rates of many microwave-absorbing minerals. Subsequent experimental studies by Kingman et al. (2000a, 2004a,b) and Sahyoun et al. (2005) revealed that high power density treatments (typically >3 kW in single mode cavities) allowed for a similar degree of microwave-assisted breakage at significantly lower energy inputs than treatments at low power density (typically <3 kW in multimode cavities) due to the significantly higher heating rates attained.

The energy required from low power density microwave treatments (typically $\gg$10 kW h/t) outweighed any potential energy saving during comminution processes and the high residence times (typically $\gg$1 s) would prohibit processing at a scale of several thousand tonnes per hour demanded by the mining industry. These studies, therefore, demonstrated microwave treatments at economically feasible energy inputs (<5 kW h/t) and residence times (<1 s) that could potentially achieve industrially relevant throughputs.

1.2. The role of mineralogy in microwave treatment of ores

Kingman et al. (2000b) also looked at the effects different mineralogies had on the change in Ball Mill Work Index after low power density microwave treatment for an ilmenite ore, refractory gold ore and two copper ores. The authors found that the most responsive ores were those with a consistent texture with relatively coarse grained microwave-absorbent minerals constrained by a microwave-transparent matrix. In contrast, the poorly performing ores had a relatively fine microwave-absorbent phase grain size that was sparsely disseminated.

Batchelor (2013) reviewed published literature from the previous 20 years detailing experiments using high and low power density microwave treatments on metalliferous ores investigating reduced ore competency. The vast majority of the papers reported findings on single ore samples, most with limited qualitative descriptions of mineralogy, grain size and/or mineral associations. By collating the information available and accounting for the different treatment regimens the author determined that, in addition to the findings by Kingman et al. (2000b), the ores that performed best typically had a matrix comprised of hard minerals (such as quartz, feldspar, pyroxene and olivine) rather than softer minerals (such as clays, carbonates or micas) coupled with a highly microwave-absorbent phase (such as magnetite).

For complex ores it is difficult to ascertain which combinations of minerals gives rise to the most significant strength reductions through experimentation. Numerical modelling studies have illustrated the mechanism of selective heating and thermally-induced fracture by considering binary systems of two differing mineral phases with varying thermo-mechanical properties, modal abundance, grain size, grain shape and dissemination (Ali and Bradshaw, 2009, 2010, 2011; Jones et al., 2005, 2007; Salsman et al., 1996; Wang et al., 2008; Wang and Djordjevic, 2014; Whittles et al., 2003). These studies have elucidated that the two important criteria for microwave-induced fracture are microwave power density and microwave energy input. Higher power density simulations always yielded a higher degree of particle damage for a given microwave energy input. However, for a given microwave power density there existed a minimum microwave energy input to provide sufficient thermal expansion and thermal gradients to initiate and propagate significant intergranular and transgranular fractures. In summary, the higher the heating rate, the less time there is for conduction to occur between adjacent grains, the greater the "thermal shock" (or thermally induced stresses) and the lower the microwave energy requirement. The authors suggested that a power density within the microwave-absorbent grains of greater than approximately 1×10^{10} W/m^3 provided the most efficient fracture generation.

The aforementioned numerical modelling studies further demonstrated the following observations. Minerals that heat better in a microwave field and that have a high thermal expansion coefficient tended to generate fractures more readily due to higher heating rates and volumetric expansion. Finer microwave-absorbent grains, typically less than approximately 100 μm in size, have been shown to yield less fracture than coarser grains, typically greater than approximately 500 μm, attributed to a rapid loss of heat through conduction to the matrix due to the greatly increased surface area to volume compared to coarser grains. The loss of heat reduces the thermal shock and therefore requires a higher power density and/or energy input to raise the stress enough to cause significant fracture. A higher modal abundance and even dissemination of microwave-absorbent grains promoted fracture networking across the fragment, which reduced overall fragment competency; however, clustering of mineral grains helped to promote more intense localised fracturing. Finally, stronger/stiffer, or "harder", minerals (such as quartz, feldspar and pyrite, as opposed to micas and chalcopyrite for example) could not deform elastically to absorb the thermal expansion and therefore generated larger stresses leading to an increased prevalence of fracture.

In summary, it has been elucidated from the literature that coarser grains of hard and highly microwave-absorbent minerals constrained by a hard microwave-transparent matrix provide the most favourable texture for initiation and propagation of fractures. From the numerical and experimental studies reviewed it is