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Pilot scale microwave sorting of porphyry copper ores: Part 1 – Laboratory investigations

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ABSTRACT

Microwave treatment followed by infrared thermal imaging (MW-IRT) has been proposed as a potential excitation-discrimination technique to facilitate sorting of porphyry copper ores. A continuous, high throughput (up to 100 t/h), belt-based microwave cavity operating at up to 100 kW has been designed to interface directly with commercially available sorters at industrially relevant scales. In this paper, the fragment-by-fragment thermal response of 16 porphyry copper ore samples following microwave treatment in the bespoke system is evaluated to elucidate key performance criteria and identify likely candidate ores for microwave sorting. Microwave treatment energy dose was found to be the driving force behind the ultimate average temperature fragments experience, with other process variables (e.g. belt speed, power, belt mass loading, thermal equilibration time) having little effect on sortability performance. While fragment mineralogical texture and ore textural heterogeneity were shown to influence the average temperature rise of the fragment surface presented to the thermal camera, in most cases this variability did not adversely affect sortability performance. An abundance of microwave-heating gangue minerals (e.g. iron sulphides, iron oxides and hydrated clays) was shown to be the dominant source of deviation from intrinsic sortability. However, low average moisture content and co-mineralisation of copper and iron sulphides (or bulk sulphide sorting) was found to mitigate the deviation and provide better sortability performance. An attractive separation could be proposed for many of the ores tested, either to remove a large proportion of barren fragments from ore-grade material or concentrate a large proportion of copper values from waste-grade material.

1. Introduction

Recent advances in automated sorting technology has meant it has become widely cited as an emerging and potentially viable means to help address the challenges faced by sustainable hard rock mining, particularly in the forecasted low-grade and high energy demand future (Daniel and Lewis-Gray, 2011; Drinkwater et al., 2012; Lessard et al., 2014, 2016; Napier-Munn, 2015; Pokrajcic et al., 2009; Powell and Bye, 2009). During the mining process, waste-grade or barren material may be introduced to run-of-mine (ROM) ore by planned and unplanned dilution of the ore reserve as well as internal dilution from poorly mineralised regions of the ore body. Processing such material through a conventional energy-intensive concentrator is very costly, due to both increased throughput and potential value losses to tailings. It is highly desirable to remove this unwanted material prior to beneficiation so that resources are not spent on treating the material for no return. Indeed, a recent study by Ballantyne and Powell (2014) showed ore grade was the greatest determinate of specific comminution energy when compared with other factors such as circuit efficiency, ore competency and grind size. In summary, scavenging high-grade material from waste/low-grade ore or pre-concentration by early rejection of barren gangue may offer the following benefits to a mining operation:

- Extend ore reserves and/or unlock previously uneconomic ore resources
- Increase metal production by raising the head grade to the concentrator
- Reduce metal specific processing and waste handling costs, and reduce water and energy consumption
- Increase mining rate for given mill capacity or reduce plant footprint
- Support alternative processing options, e.g. direct high-grade ore to crush-grind-float circuit and low-grade ore to heap leaching
- Remove deleterious minerals prior to downstream processing

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Sorting of ores and other materials is typically performed in four to five stages, namely ore/particle preparation, presentation, excitation and/or discrimination, and separation. Fig. 1 illustrates the unit processes involved with the relationship of material and data flows in the system.

The excitation-discrimination step may be used to interrogate individual fragments or incremental lots of a bulk sample. The choice will be dependent on the methods used, the impact on throughput for the required feed presentation and the costs associated with the complexity of the separation system. Compressed air or water jet ejection systems are commonly employed for individual particle separation, whereas diverter gates/flaps are typically used for incremental lots on bulk streams.

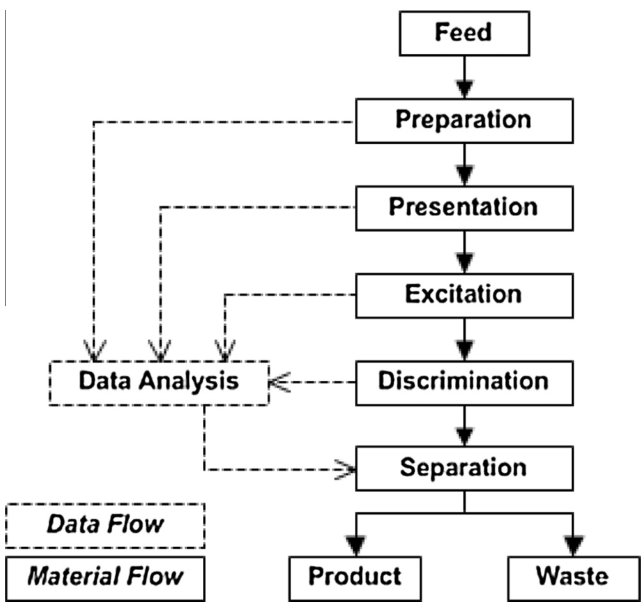

Fig. 1. Operational processes in ore sorting.

There are many excitation-discrimination techniques used in industry to measure particular properties of materials, including nuclear (e.g. radiometric), optical (e.g. colour, fluorescence), electrical and magnetic (e.g. permittivity, permeability and conductivity), and thermal (e.g. emissivity). These techniques utilise a wide range of the electromagnetic spectrum, including gamma rays and X-rays, ultraviolet, visible and infrared light, microwaves and radiowaves (Adair et al., 2013; Knapp et al., 2014; Murphy et al., 2012; Salter and Wyatt, 1991; Seerane and Rech, 2011), illustrated in Fig. 2. Whilst a number of techniques are available and have been demonstrated at industrially relevant scales for commodities such as diamonds and industrial minerals (Riedel and Dehler, 2010; Sivamohan and Forssberg, 1991), none have been proven to give the required discrimination and support the high throughputs required for low-grade finely disseminated porphyry copper ores. Porphyry copper ores are particularly important because they currently account for around 50–60% of global copper production as well as being significant sources of gold, silver, molybdenum and other by-product metals (BGS, 2007).

Microwave heating has been proposed as a technique to selectively raise the temperature of ore fragments containing valuable minerals, providing a means of distinguishing fragments with different grades (Dimitrakis et al., 2014; Dormenval et al., 2014; Harding and Wellwood, 2010). The efficacy of this mechanism depends on rapid, volumetric and selective heating of certain mineral phases within the ore matrix. In particular, highly microwave-absorbent minerals (such as nickel, copper, iron and lead sulphides, magnetite and other minerals with bound and/or free water (e.g. smectite clay)) heat far more readily than common microwave-transparent rock-forming minerals (such as quartz, feldspars, micas and many other non-sulphide gangue minerals) (Chen et al., 1984; Chunpeng et al., 1990; Church et al., 1988; Harrison, 1997; Kingman et al., 2000; Kobusheshe, 2010; McGill and Walkiewicz, 1987; McGill et al., 1988; Nelson et al., 1989; Standish and Worner, 1991; Walkiewicz et al., 1988; Yixin and Chunpeng, 1996). Infrared thermal imaging may then be employed as a means of measuring differences in the thermal response of ore fragments to provide a basis for separation using conventional

Electromagnetic Spectrum	Wavelength (m)	Sensor Type / Technology	Material Property Detected	Application
Gamma Radiation	10^{-12}	RM (Radiometric)	Natural Gamma Radiation	Fuel, Precious Metals
	10^{-11}			
	10^{-10}	X-ray Transmission (XRT) X-ray Fluorescence (XRF)	Atomic Density Visible Fluorescence, X-rays Fluorescence	Base Metals, Precious Metals, Industrial Minerals, Diamonds, Fuel
X-rays	10^{-9}			
	10^{-8}			
Ultraviolet (UV)	10^{-7}	COL (CCD Colour Camera)	Reflection, Absorption, Transmission, Shape	Base Metals, Precious Metals, Industrial Minerals, Diamonds
Visible Light	10^{-6}			
Near-Infrared (NIR)	10^{-5}	Photometric (PM)	Monochromatic Reflection/Absorption	
	10^{-4}	Near-Infrared Spectroscopy (NIR)	Reflection/Absorption	Base Metals, Industrial Minerals
Infrared (IR)	10^{-3}	Infrared Camera (IR)	Heat Conductivity / Dissipation	
Microwaves	10^{-2}	Microwave Attenuation		
	10^{-1}	**Microwave Heating with Infrared Thermal Imaging (MW-IRT)**	**Selective Heating (Metals Heat Faster than Other Minerals)**	**Base Metals (Proposed Application)**
	10^{0}			
Radiowaves	10^{1}	Radiofrequency (RF) Heating		
	10^{2}			
Alternating Current (AC)	10^{3}	Electro-Magnetic Sensor (EM)	Conductivity, Permeability	Base Metals
	10^{4}			

Fig. 2. Sensing systems for sorters in the mining industry.

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