Microwave Heating Behaviour of Ores and its Application to High-Power Microwave Assisted Comminution and Ore Sorting

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ABSTRACT

As the global demand for metal values expands, it becomes increasingly important to create more sustainable mining operations. Consequently, considerable research and technology development is required to produce processes which are both more energy efficient and have a minimal environmental impact. One potential technology is the utilization of microwave pretreatment to reduce the energy requirements in comminution. Microwaves can preferentially heat the valuable mineral phases in an ore and the resulting differential thermal expansion leads to the formation of microfractures along the grain boundaries. As a result of the preferential heating, ore competency is reduced, mineral liberation is enhanced, a coarser grind size can be employed, and plant throughput can be increased. Furthermore, microwave pretreatment can be combined with advanced ore sorting, to decrease the quantity of gangue material processed downstream and hence reduce tailings production. Previous studies on the microwave treatment of ores over the last thirty years have mainly been limited to low power bench-scale studies and there is a paucity of information on pilot and/or commercial scale studies. In the present research, the microwave heating behaviours of over forty ores have been studied at the bench-scale. These results were used to generate a database, from which a unique classification system was developed. This system was used to rank the amenability of any given ore for microwave pretreatment. This knowledge can be employed to predict the performance of the ores in the high-power pilot scale tests and thus can be used as a pre-screening tool. The effects of high-power microwave pretreatment on grindability and liberation were reported. Additionally, the ore sorting potential was evaluated using a combination of X-ray transmission (XRT) and microwave infrared (MW/IR).

INTRODUCTION

Conventional comminution circuits are extremely inefficient. A survey of three semi-autogenous grinding (SAG)/ball mill circuits by Bouchard et al. (2019) revealed that 91% of the energy input was lost, leaving only 9% available for ore breakage. Given ever-increasing costs to mine depleting ore deposits coupled with more stringent environmental laws mandated by governments, it is exigent to develop more economic solutions. One possible solution is the application of microwaves for both assisted comminution and ore sorting (Bobicki et al., 2020; Forster et al., 2021; Olmsted et al., 2021).

In general, ores contain both valuable minerals and gangue (barren rock of little to no value). Many valuable minerals, such as sulphides and some metal oxides, heat very well in response to microwave irradiation. Typical gangue minerals, especially those containing large quantities of silica (SiO_2), are transparent to microwaves and do not heat. Selective heating causes differential thermal expansion, resulting in stress and strain across mineral grain boundaries, creating microfractures. It also generates distinctive heating patterns on the surfaces of the rocks. The three main benefits of microwave ore treatment are: ore competency reduction, increased liberation, and improved sortability, with significant variables being the frequency, power, temperature, dielectric properties, magnetic properties, load size, load mass, load position, and applicator type (Peng and Hwang, 2015).

Historically, the use of microwave energy to pre-treat minerals has focused on microwave-assisted comminution (Walkiewicz et al., 1991; Amankwah et al., 2005; Henda et al., 2005; Jones et al., 2005; Rizmanoski, 2011). Henda et al. (2005) reported an uneconomical energy dose of 13 kWh/tonne from microwave pretreatment and grinding. Here, the nickel and copper grades improved by 15% and 27%, respectively, along with a recovery increase of 26%. Therefore, although microwave pretreatment and grinding alone may not be viable, downstream benefits may make a process worthwhile. The exploitation of the heat signature from microwave pretreatment for ore sorting is more recent (e.g., Van Weert, Kondos and Gluck, 2009, Van Weert, Kondos and Gluck, 2011; Ferrari-John et al., 2016; Batchelor et al., 2016a, 2016b; Naseh and Sam, 2019). Pioneering work by Van Weert and Kondos (2007) laid the foundation for this field by demonstrating that it is possible to use microwaves to readily heat sulphide ores and to use an infrared sensor as a sorting technique. However, one of their conclusions was that rocks shielded by surrounding rocks tended to heat up slowly. The authors recommended that scaling up requires the use of a belt instead of a shaft, which is contrary to a recent report from Holmes et al. (2020), which suggested that a vertical system is appropriate for commercialization. Despite the remarkable progress at the bench-scale (hundreds of studies), there is a lack of information regarding pilot and/or commercial scale studies on microwave-assisted comminution and sorting.

Three key parameters for successful application of microwave treatment at a larger scale are kinetics, penetration depth, and electronic control (Krieger, 1995). There is a trade-off between throughput and the energy input: a higher throughput reduces the energy input, but it also results in less grain boundary damage (Bradshaw et al. (2011). Recently, a study has been conducted on the development and implementation of a continuous, pilot-scale, monomode microwave applicator that could deliver very high power (>100 kW) for very short times to produce ultra-low energy dosages of <0.7 kWh/t (Batchelor et al., 2017). This is because the electric field strength increases with microwave power. With this technique, for a copper poryhyry ore, the same degree of liberation could be achieved at a grind size which was 50-60 µm greater than the untreated ore. Also the Ball mill work index was reduced by 3-9%. Olmsted (2021) reported that high-power microwave pretreatment of a gold sulphide ore improved gold recovery by 14% after a leaching time of only 6 h. Anglo American PLC announced the development of a microwave-assisted comminution project at their Amandelbult platinum mine in South Africa, as part of their FutureSmart Mining^{TM} program (Moore, 2021). In some of their preliminary test work, they reported hardness reductions of 5–25% and 8–12% for platinum and copper ores, respectively. The company is investigating installations at other facilities, starting with a pebble circuit at Los Bronces (Chile), followed by Mogalakwena (South Africa), Collahuasi (Northern Chile), and Quellaveco (Peru). This effort speaks very highly of the potential for microwave-assisted comminution in the mining industry.

The present work involves the study of the bench-scale heating behaviour of 42 unique ores to determine their amenability to microwave treatment. This test work resulted in a database, whereby a classification system was developed, which can be applied to rank any ore in one of four heating classes and determine its suitability for microwave pretreatment. Select ores from this test program were tested at the pilot-scale using a 150 kW microwave system to determine the effects of electromagnetic radiation on comminution, liberation of valuable minerals, and sorting potential.

MATERIALS AND METHODS

Materials

TABLE 1 presents the elemental analysis of the 42 ores investigated in the present study. There are many ore types including gold, silver, Ni/Cu, and Pb/Zn sulphides. Some of the oxide ores include chromite, and iron. There are also several silicate rich ores (Zn silicates, lithium, and kimberlite).

TABLE 1 - Elemental composition of candidate ores from the Crush It! Challenge determined by inductively coupled plasma – optical emission spectrometry or X-ray fluorescence.

Ore ID	Ore Type	Element (wt.%)									
		Al	Ca	Co	Cu	Fe	Mg	Ni	S	Si	Zn
CA01	Au	3.34	3.55	0.00	0.06	5.73	1.60	0.03	0.80	31.4	0.02
CA02	Ni	3.65	2.24	0.10	1.97	31.9	1.62	4.73	19.0	10.7	0.02
CA03	Ni-Cu	5.53	3.00	0.03	1.27	21.6	1.41	1.51	10.5	18.3	0.03
CA04	Ag	7.70	1.68	0.01	0.05	4.00	0.88	0.02	0.48	28.0	0.64
CA05	Chromite	6.4	0.2	<0.1	<0.01	10.9	13.0	0.2	<0.1	6.6	<0.1
CA06	Magnetite-rich Fe	0.7	0.3	0.1	–	21.3	0.9	–	–	34.9	–
CA07	Hematite-rich Fe	0.6	0.7	<0.1	–	8.6	3.1	–	–	39.0	–
CA08	Cu-Au	7.06	4.17	0.00	0.22	4.79	2.93	0.01	1.02	24.3	0.07
CA09	Ovoid low-grade Ni	0.49	0.28	0.11	2.24	55.9	0.03	2.54	33.7	0.09	0.02
CA10	Ovoid high-grade Ni	6.93	5.52	0.02	0.19	11.9	7.11	0.25	2.13	19.2	0.02
CA11	Au-Cu	7.84	2.70	0.00	0.55	3.01	1.11	0.03	0.66	31.7	0.01

CA12	Au	7.55	2.32	0.00	0.83	3.07	0.99	0.02	1.41	31.6	0.02
CA13	Au	0.42	0.34	0.01	0.02	0.37	0.03	0.01	0.19	41.8	0.01
CA14	Au	4.92	3.87	0.01	0.00	12.6	1.48	0.02	1.25	21.6	0.02
CA15	Au	7.83	4.43	0.00	0.01	4.04	1.95	0.02	1.17	24.6	0.01
CA16	Au	7.33	3.80	0.01	0.06	6.92	2.77	0.01	0.84	26.4	0.02
CA17	Ni-Cu	5.89	3.94	0.03	0.81	17.8	2.39	0.94	6.90	20.6	0.02
CA18	Cu-Ni	7.11	3.35	0.01	0.61	6.60	1.62	0.15	0.41	26.9	0.01
CA20	Ultramafic Ni	0.81	0.67	0.01	0.01	5.41	23.80	0.22	0.75	18.3	0.01
CA21	Cu-Ni	6.67	4.10	0.02	0.63	13.6	2.04	0.56	3.71	23.0	0.02
CA22	Ultramafic Ni	0.88	0.71	0.02	0.04	8.96	20.27	0.48	1.97	16.25	0.02
CA26	Zn silicate	0.56	15.70	0.01	<0.005	4.05	9.97	<0.005	0.04	3.81	7.76
CA27	Zn silicate	0.18	19.00	<0.002	<0.005	2.91	10.80	<0.005	1.10	1.95	2.84
CA28	Zn silicate	3.37	8.58	0.01	0.01	3.59	5.53	<0.005	0.02	15.0	9.32
CA29	Massive sulphide	0.62	0.84	0.13	1.92	47.0	0.36	7.28	32.50	2.20	0.03
CA30	Net textured sulphide	1.07	1.86	0.09	1.36	30.3	8.36	4.50	19.10	9.01	0.01
CA31	Disseminated sulphide	1.46	0.84	0.05	0.58	16.6	15.20	1.88	7.56	14.7	<0.01
CA32	Argilite	9.40	0.92	0.00	0.03	4.69	2.25	0.07	0.70	28.9	<0.01
CA33	Peridotite	2.26	2.41	0.02	0.15	10.5	17.7	0.62	2.44	17.3	<0.01
CA34	Gabbro	8.06	8.20	0.00	0.01	7.13	4.63	0.01	0.15	23.5	<0.01
CA36	Au sulphide	9.63	0.88	–	–	5.86	1.50	–	0.62	26.4	–
CA37	Pb-Zn sulphide	0.90	0.46	0.00	0.02	6.40	0.12	<0.005	12.2	18.2	10.3
CA38	Net textured Ni-Cu sulphide	1.1	0.6	0.1	0.9	15.2	22.1	2.5	6.7	15.5	0.1
CA40	Cu-Ni sulphide	8.0	5.3	<0.1	0.2	10.5	2.8	0.2	1.1	26.5	0.1
CA41	Ni-Cu sulphide	7.79	2.92	–	1.03	7.53	1.87	0.32	1.20	25.54	–
CA42	Porphyry Cu	8.13	1.67	–	0.15	1.39	0.22	–	0.16	34	–
CA43	Ni sulphide	4.3	5.3	0.1	0.8	15.6	12.2	0.6	3.2	19.8	<0.1
CA44	Ni sulphide	4.6	5.7	<0.1	0.4	13.3	12.3	0.3	1.9	21.2	<0.1
CA45	Lithium	7.75	0.18	–	–	0.28	–	–	0.04	30.63	–
CA46	Ovoid low-grade Ni	11.83	6.24	–	0.24	10.37	4.35	0.23	1.45	21.59	–
CA47	Au sulphide	8.98	1.20	–	–	5.02	1.34	–	0.20	28.6	0.01
CA49	Kimberlite	5.97	4.41	–	–	5.50	9.23	–	0.17	26.36	–

Methods

Elemental Composition

Inductively coupled plasma–optical emission spectrometry (ICP-OES) was used to determine the elemental composition of the head assays for the ore candidates and of selected rocks from sorting tests. For the head assays, representative crushed (2–3.35 mm) samples were pulverized into a fine powder and sent for analysis. For assays on rocks from the sorting tests, each rock was individually crushed and pulverized. All analyses were performed at XPS (Falconbridge, ON), where a subsample was split from the pulverized sample and digested via sodium peroxide fusion.

A Panalytical (Epsilon-1; 50 kV; Ag anode X-ray tube) XRF spectrometer was used to analyze the elemental composition of pulverized rock samples at Sepro Mineral Systems (Langley, BC). Each pulverized sample was riffled to between 10 and 15 g each, placed into a sample cup, and inserted into the system for analysis. The positive linear relationship with ICP-OES data was used to improve the accuracy of the XRF assays and to validate the methodology to be used for rapid XRF analysis of individual rocks in the pilot sorting tests.

Mineralogy and Liberation

The SAG and BWI products form the grinding tests were sent for analysis using QEMSCAN. This technique allows for the determination of the mineralogy and liberation analysis of a sample. The samples of interest were split, mounted in epoxy, polished, carbon coated, and imaged. This analysis calculated the number, size, mineral composition, and associations of the particles. The liberation degree of target minerals (e.g., chalcopyrite, pentlandite, pyrrhotite, pyrite, sulphides, iron oxides) was represented as an area percent, indicative of the 2D surface fraction of the target mineral in a scanned particle. The particles observed on a single scan were grouped in liberation classes based on their area percent value as follows: locked (<30%), low grade middling (30–80%), high grade middling (80–95%), liberated (>95%) and free (100%).

Bench-scale Microwave Heating Behaviour Tests

Microwave heating curves provide direct information on how a material responds to microwave radiation. For each test, a 50 g sample of crushed (1.7–3.35 or 2–3.35 mm) ore was massed into a quartz crucible and placed into a BP-211 microwave oven (53.5 cm width × 25.1 cm height × 33 cm depth; Microwave Research and Applications, Illinois, USA). A top size of 3.35 mm was selected to match the feed size for typical ball mill grinding tests. Samples were exposed to 2450 MHz microwaves at 3.2 kW with time as the independent variable. After treatment, the quartz crucible was quickly removed from the microwave oven, and a Type-K thermocouple was inserted into the centre of the sample to measure the bulk temperature. Temperature was plotted against time to generate a microwave heating curve for each ore.

Pilot-scale Microwave Tests

The 915 MHz pilot-scale microwave system was designed and constructed by Thermowave (Danvers, MA, USA). It is equipped with two 75 kW transmitters. Multiple generators can provide a better excitation of modes yielding more uniformity compared to a single feed (Metaxas and Meredith, 1983). A water circulator dissipates any reflected microwave power, thereby preventing damage to the magnetron. The system is controlled via an HMI control panel equipped with an Allen Bradley PLC. The applicator is 1 m long, with a microwave transparent polypropylene bridge and a built-in arc sensor. The conveyor belt is made of microwave-transparent silicone/polyester and can reach speeds of up to 5 m/s. For all tests, the energy dosage in kWh/t was calculated prior to the test, and the tray packing, belt speed, and microwave power were varied to meet this value (e.g., 1–4 kWh/t electrical power). Immediately after processing, a FLIR A8300sc IR camera recorded a video of the sample trays and transferred the data via a Gigabit Ethernet port connected to FLIR's Research IR software. In some of the monolayer sorting tests, the infrared videos were used to generate data for the ore sorting algorithm.

SAGDesign Tests

Following microwave treatment, the sample was prepared for the SAGDesign test. Each ore required an initial reference grind (untreated material) before the microwave treated sample could be ground. The SAGDesign test was conducted using a laboratory SAG mill (Starkey, Hindstrom and Nadasdy, 2006). The grinding energy was determined for both a SAG mill (W_{SDT}) and a Bond Ball mill (S_d-BWI), both expressed in kWh/t. The W_{SDT} value estimates the energy consumption (kWh/t) of coarse grinding - SAG mill grinding from 80% passing 152 mm to 80% 1.7 mm. The BWI test (variability of ± 9%) measured the energy required for fine grinding. The Bond mill used the ground product from the SAG mill test (T_{80} 1.7 mm) per the standard Starkey SAGDesign methodology.

RESULTS AND DISCUSSION

Bench-scale Microwave Heating Behaviour of Ores

The 42 ores tested were grouped into four classes (I–IV; TABLE 2) based on the bench-scale microwave heating behaviour (FIG 1). For the purposes of the current work, a formal definition of highly microwave amenable phases (HMAP)s is proposed. This includes the following minerals: bornite, chalcopyrite, galena, hematite, magnetite, molybdenite, pentlandite, pyrite, and pyrrhotite.

TABLE 2 - Microwave heating classes, typical highly microwave-amenable phase (HMAP) content, and minimum, maximum, and mean initial (first 30 s) heating rates for 42 ores.

Heating Class		**Typical HMAP Content (wt.%)**	**Initial Heating Rate (°C/min)**		
			Minimum	**Maximum**	**Mean**
I	Poor	0–2	13	40	23
II	Fair	2–5	21	133	76
III	Good	5–20	105	339	159
IV	Excellent	>20†	150	829	559

† excluding massive sulphide ores

Class I ores showed limited heating, reaching a maximum temperature of roughly 200°C by 8 min. Despite this, grindability improvements are still possible. For example, Hredzak and Lovas (2005) reported that that even relatively pure quartz (>99% SiO_2) exhibited reductions in grindability after prolonged microwave heating. However, heating at low power (<5 kW) for a long period allows for thermal conduction between grains and particles. This additional heating mechanism reduces the temperature differential between grain boundaries of the various phases, thereby lessening the degree to which the ore will fracture. For comminution and ore sorting benefits, high heating rates are desirable. Hence, Class I ores are not ideal. Class II ores demonstrated moderate heating: most reached 250–300°C by 8 min. Class III ores exhibited high heating rates: most heated to >400°C after 4 min. Class IV ores had very high heating rates, with all ores reaching or exceeding 400°C within 1 min of treatment. However, none of these ores could be treated for the full 8 min due to thermal runaway and fusion of the samples. Furthermore, the power, particle size and the mass of the load will all affect the heating of any material. However, to achieve the maximum possible thermal gradient, the maximum power was applied. Future work will involve the exploration of these additional parameters.

In general, Class IV ores would be excellent candidates for pilot-scale microwave treatment. The very high heating rates would both initiate fractures in the ore (reducing competency and improving liberation) and provide a distinct thermal signature for sorting. Conversely, the low HMAP content of Class I ores would result in poor heat signatures. Class I ores are generally not amenable to the process. Class II and Class III ores can be expected to realise overall benefits, except ores with very conductive surfaces, which would reflect microwaves (e.g., massive sulphide ores). To facilitate comparison among the ores, the power was fixed at 3.2 kW for all the microwave heating behaviour tests. A lower power would have helped prevent thermal runaway (Huang and Lu, 2009) in some of the tests on the ores of a higher class. One of the major findings was that most of the gold sulphides are Class I ores (CA13, CA15, CA16, CA36, CA47), except for CA08 and CA14, which are Class II and Class III, respectively. CA08 contained roughly 2.4 wt.% iron sulphides (pyrite and chalcopyrite), and CA14 contained about 11 wt.% iron oxides. This shows that just a small increase in the amount of HMAP phases is enough to shift the curves to a higher class.

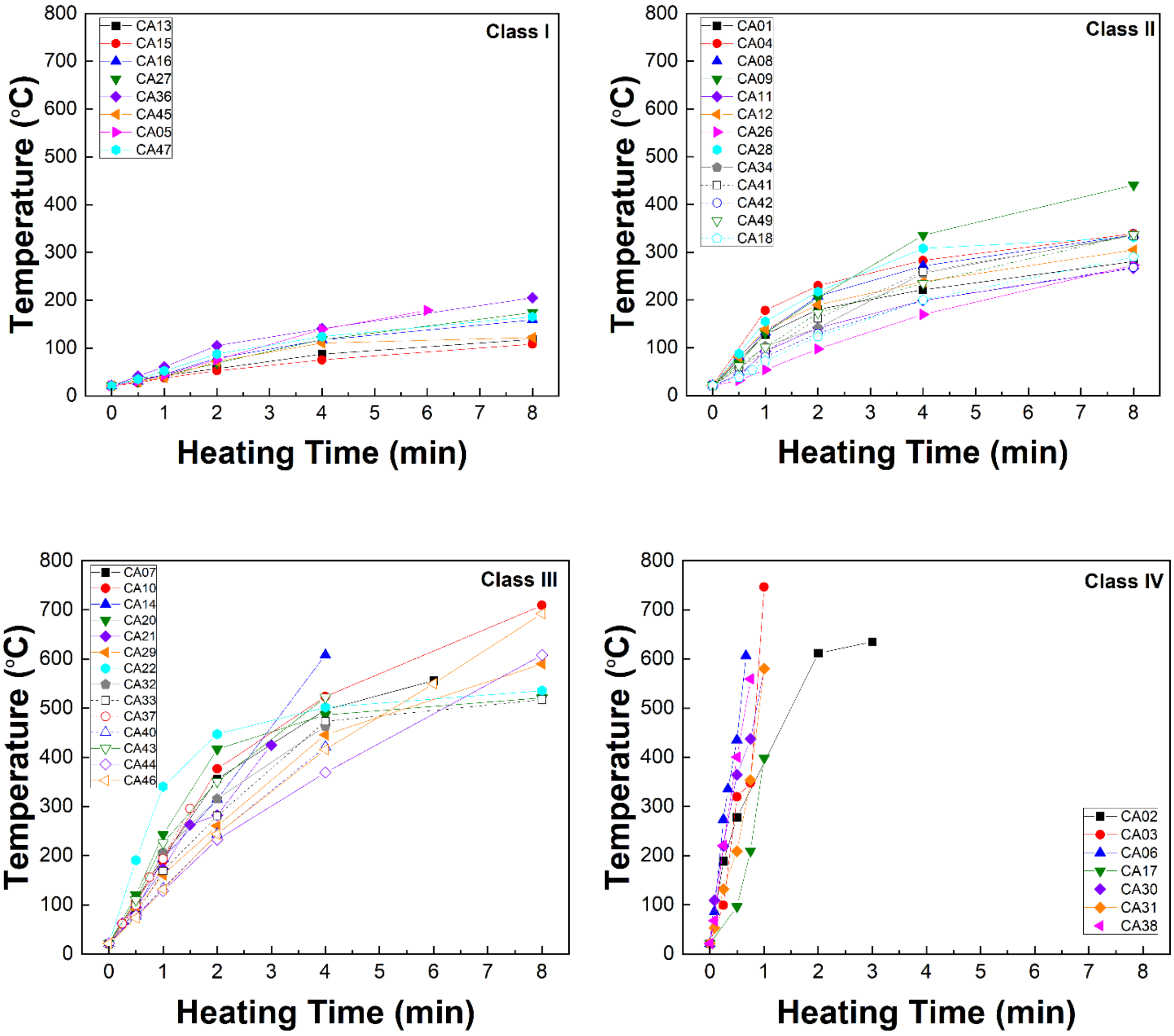

FIG 1 - Bench-scale heating behaviour curves for 50 g samples of 42 Class I–IV ores treated with 2450 MHz microwaves at 3.2 kW power; particle size 1.7–3.35 or 2–3.35 mm.

High-Power Microwave Tests, Comminution, and QEMSCAN of Select Ores

Ores CA30 (net textured sulphide ore), CA34 (gabbro rock), CA41 (Ni/Cu sulphide), and CA42 (Cu porphyry) were treated in the pilot-scale microwave system and subsequently tested using the grinding procedure according to the parameters in TABLE 3. The efficiency of conversion of electrical to microwave power was approximately 80% which is on par with that reported by Tranquilla et al. (1999). In many of the microwave assisted comminution tests, smaller particles (<25.4 mm) were added to the trays to mitigate arcing by reducing the void spacing between adjacent rocks. For the very soft copper porphyry ore (CA42), the W_{SDT} values of the microwave treated samples increased slightly after grinding, which may be indicative of improved breakage at the coarser particle size during grinding. A reduction in competency was not realised for this soft ore. Furthermore, the doubling of the electrical energy dose from 2 to 4 kWh/t did not significantly reduce the ore competency either. However, improved liberation is still possible (see next section). In many of the grindability results presented, benefits are realized in the SAG portion of the SAGDesign test, as opposed to the Bond ball mill test (closing size based off process flowsheet).

TABLE 3 - Microwave treatment parameters and SAGDesign comminution results for select ores.

Ore Class	Sample ID*	Electrical Energy Dose (kWh/t)	Power (kW)	W_{SDT} (kWh/t)	Reduction (%)	S_dBWI (kWh/t)	Reduction (%)	Bond Closing Size (µm)
II	CA34-Ref	N/A	N/A	23.2	N/A	14.7	N/A	106
	CA34-MW	2.0	150	17.6	24.1	14.0	4.6	106
	CA41-Ref†	N/A	N/A	16.7	N/A	16.5	N/A	106
	CA41-MW†	2.0	150	13.5	19.2	16.7	–1.4	106
	CA42-Ref1	N/A	N/A	7.6	N/A	16.3	N/A	106
	CA42-MW1	2.0	75	8.1	-6.6	17.0	-4.3	106
	CA42-Ref2	N/A	N/A	7.6	N/A	15.8	N/A	212
	CA42-MW2	4.0	75	8.0	-5.3	15.9	-0.6	212
IV	CA30-Ref	N/A	N/A	14.7	N/A	12.8	N/A	106
	CA30-MW	2.0	75	13.9	5.8	12.8	-	106

†Olmsted (2021); *Ref-Reference Sample; MW-Microwave Treated Sample

QEMSCAN

Ni/Cu sulphide ore (CA30)

QEMSCAN liberation analysis was carried out on the SAG test product and two size fractions from the BWI test: >106 and <106 µm. For the <106 µm products, considering the top two liberation classes (>95 and 100%), the minimal improvement in pentlandite liberation from microwave treatment was mostly due to a slight improvement for the free (100% liberated) class (FIG 2a). However, for chalcopyrite, the amount of liberated plus free material was more than 2.4 times higher for the microwave-treated (36.3%) than for the reference samples (14.9%; FIG 2b). It is possible that a greater proportion of the chalcopyrite is hosted within the gangue silicate matrix, whereas the pentlandite is preferentially combined with gangue pyrrhotite, which is a HMAP. Therefore, the chalcopyrite-silicate would experience more intergranular fracturing than the pentlandite-pyrrhotite system.

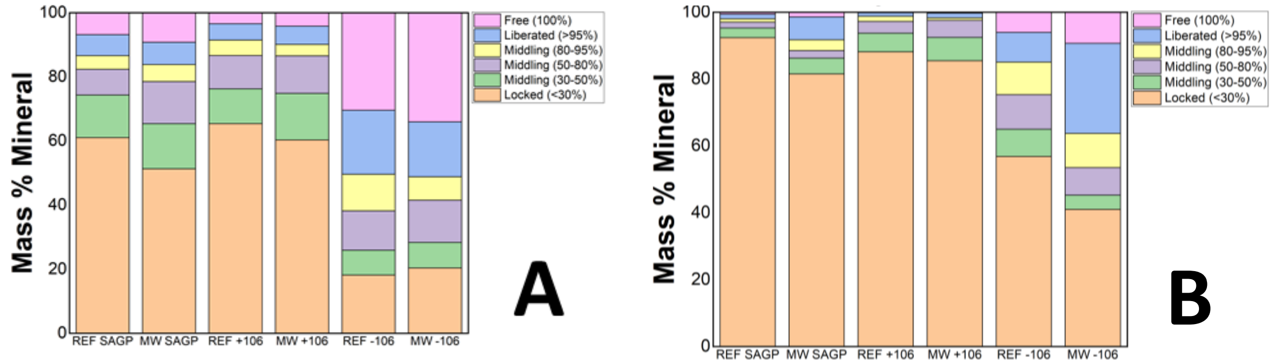

FIG 2 - Pentlandite (A) and chalcopyrite (B) liberation for reference (REF) and microwave-treated (MW) samples of CA30.

Copper porphyry ore (CA42)

Given the very low W_{SDT} for this ore (TABLE 3), microwave pretreatment followed by comminution did not yield grinding energy savings. Instead, savings are expected to be realized in downstream flotation, where an improvement in the liberation of copper sulphide species should improve overall Cu recovery. Copper sulphide liberation (>95% and 100%) from the Bond ball mill undersize products for Ref1 and 2 and MWT1 and 2 (TABLE 3) at both closing sizes showed a significant improvement after microwave pretreatment (FIG 3). For the test with a closing size of 106 µm, microwave treatment increased liberation from 25 to 58%. For the coarser closing size (212 µm), liberation was increased from 17 to 55%.

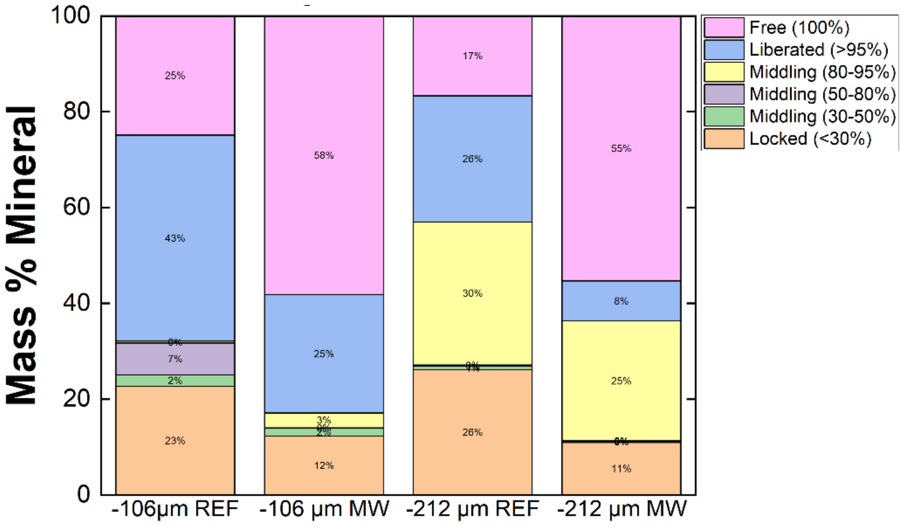

FIG 3 - Copper sulphide liberation analysis for reference and microwave treated samples at two closing sizes.

Monolayer Sorting of Nickel Sulphide Ore (CA30)/Gangue Rock (CA34) Blend

CA30 and CA34 were from the same mine site, and therefore it was of interest to carry out a sorting test on a blend of these two materials. A 25.6 kg load comprising a 58/42 wt.% blend of CA30 (48 rocks)/CA34 (36 rocks) was treated at 75 kW power (2.2 kWh/t electrical energy dose). Many of the gangue rocks (white/gray) heated up, which is likely due to the larger penetration depth (FIG 4). Certain sections of the surfaces of the valuable rocks (darker in colour) were more conductive because they contained pentlandite, pyrrhotite, and chalcopyrite. Even if surface heating was high, there was less bulk heating for these rocks, given the lower penetration depths of their constituent sulphide minerals.

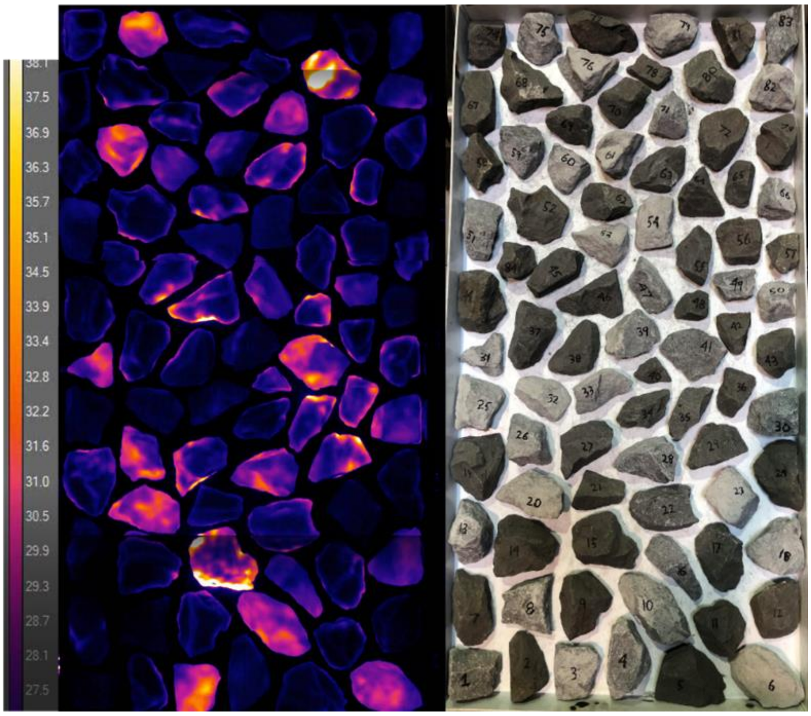

FIG 4 - Infrared and optical images of the sample tray of a 58/42 wt.% blend of CA30 (48 rocks) and CA34 (36 rocks) for the MWIR monolayer sorting test.

The infrared video was processed into multiple frames, and the pixels from the infrared heating pattern were then extracted and combined with the XRF and XRT analysis before being fed into a proprietary sorting algorithm which uses machine learning. TABLE 4 reports the mass split, recoveries, feed and product grades, and upgrade ratios for the nickel and copper. A mass rejection of 31.5% yielded a nickel recovery of 98.7%, and a corresponding upgrade ratio of 1.51. Mass rejection while maintaining high metal recovery directly translates into energy savings. A previous study by CanMicro found that the integration of ore sorting represents significant energy savings (Tian et al., 2021).

TABLE 4 – Sorting analysis results for Ni/Cu (CA30) ore.

Component	Parameters	Value	Unit
Mass Split	Mass Rejected	34.50	%
	Mass Accepted	65.50	%
Nickel	Recovery	98.70	%
	Feed Grade	3.75	%
	Product Grade	5.65	%
	Upgrade Ratio	1.51	Ratio
Copper	Recovery	97.90	%
	Feed Grade	0.76	%
	Product Grade	1.13	%
	Upgrade Ratio	1.49	Ratio

CONCLUSIONS

1. A microwave heating behaviour database comprising of hundreds of bench-scale experiments on 42 ores was developed. Ores were classified into one of four heating behaviour classes, which is directly related to the wt.% of HMAP present in an ore: (poor, 0-2; fair, 2-5; good, 5-20; excellent, >20). This is the first comprehensive study on an array of ores spanning multiple commodities, especially sulphide ores.

2. Pilot-scale microwave tests were carried out on four selected ores. This involved treatment at high power (75 or 150 kW) for very short amounts of time. Appreciable reductions in the SAG W_{SDT} values were obtained on three out of the four ores. The ore (CA42) that did not achieve a reduction in grinding energy but still demonstrated substantial improvements in the liberation of the copper sulphide mineral species. This reveals that while comminution test work may not immediately show energy savings, this loss can be reclaimed in downstream unit operations, providing sufficient liberation has been attained.

3. Monolayer ore sorting results for a blend of a nickel sulphide ore and gangue rock demonstrated that if a discrete heat signature is captured then the combination of microwave pretreatment with sorting has considerable potential.

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REFERENCES

Amankwah, R K, Khan, A U, Pickles, C A and Yen, W T, 2005. Improved grindability and gold liberation by microwave pre-treatment of a free-milling gold ore, *Miner. Process. Extr. Metall. Trans. Inst. Min. Metall. C*, 114(1): 30-36.

Batchelor, A R, Ferrari-John, R S, Dodds, C and Kingman, S W, 2016. Pilot plant microwave sorting of porphyry copper ores: Part 2-pilot plant trials, *Minerals Engineering*, 98: 328-338.

Batchelor, A R, Buttress, A J, Jones, D A, Katrib, J, Way, D, Chenje, T, Stoll, D, Dodds, C, Kingman and S W, 2017. Towards large scale microwave treatment of ores: part 2-metallurgical testing, *Minerals Engineering*, 111: 5-24.

Bobicki, E R, Boucher, D, Forster, J, Pickles, C A and Olmsted, A, 2020. Canmicro: scaling up microwave technology for the mining industry, in *Proceedings of 59th Conference of Metallurgists*, pp 1568-1581.

Bouchard J, LeBlanc, G, Levesque, M, Radziszewski, P and Georges-Filteau, D, 2019. Breaking down energy consumption in industrial grinding mills, *CIM Journal*, 10(4):157-164.

Bradshaw, S, Ali, A, Marchand, R and Barnard, A, 2011. Performance quantification of applicators for microwave treatment of crushed mineral ore, *Journal of Microwave Power and Electromagnetic Energy*, 45(1): 30-35.

Ferrari-John, R S, Batchelor, A R, Katrib, J, Dodds, C and Kingman, S W, 2016. Understanding selectivity in radio frequency and microwave sorting of porphyry copper ores, *International Journal of Mineral Processing*, 155: 64-73.

Forster, J, Olmsted, A, Pickles, C A, Boucher, D and Bobicki, E R, 2021. Multimode microwave assisted comminution of a sulfide ore: bench versus pilot-scale, in *Proceedings of 55th Annual Microwave Power Symposium (IMPI 55)*, pp 59-61.

Henda, R, Hermas, A, Gedye, R and Islam, M R, 2005. Microwave enhanced recovery of nickel-copper ore: comminution and floatability aspects, *Journal of Microwave Power and Electromagnetic Energy*, 40(1):7-16.

Holmes, T, Craig, D, Batchelor, A R, Dodds, C, Kingman, S W, Legault, E and Whetton, M, 2020. Selective heat ore treatment: shaking up the economics of mineral recovery, in *Proceedings of 59th Conference of Metallurgists*, pp 1689-1700.

Hredzak, S, Lovas, M, 2005. Influence of thermal pre-treatment on quartz crushability, *Acta Montanistica Slovaca*. 10(1): 60-66.

Huang, W and Liu, Y, 2021. Study on microwave-assisted grinding and liberation characteristics for ludwigite, *Journal of Microwave Power and Electromagnetic Energy*, 55(1): 28-44.

Jones, D A, Kingman, S W, Whittles, D N and Lowndes, I S, 2005. Understanding microwave assisted breakage, *Minerals Engineering*, 18: 659-669.

Krieger, B, 1995. Commercialization-steps to successful applications and scaleup, in *Proceedings of the Annual Meeting of the American Ceramic Society*, Cincinnati, pp 17-21.

Metaxas, A C and Meredith, R J, 1983. Industrial microwave heating. Peter Peregrinus Ltd, United Kingdom.

Moore, P, 2021. Anglo American says it is trialling insitu microwave pre-conditioning at Amandelbult platinum mine. [Online]. https://im-mining.com/2021/05/26/anglo-american-say-trialling-insitu-microwave-pre-conditioning-amandelbult-platinum-mine/. [Accessed: 26 May, 2021].

Naseh, R and Sam, A, 2019. Microwave infrared ore sorting of screen rejected rocks based on their iron and copper sulfide in Sarcheshmeh copper complex, Iran, Kerman, *Mineral Processing and Extractive Metallurgy*, 130(4): 416-424.

Olmsted, A, Forster, J, Tian, X, Boucher, D, Bobicki, E R and Pickles, C A, 2021. The effects of pilot-scale microwave pre-treatment on the cyanidation of a canadian gold ore, in *Proceedings of 60th Conference of Metallurgists, pp 507-510*.

Olmsted, A, 2021. The effects of high-power microwaves on comminution and downstream processing, Master's Thesis, Queen's University, Kingston, ON.

Peng, Z and Hwang, J, 2015. Microwave-assisted metallurgy, *International Materials Reviews*, 60(1):30-63.

Rizmanoski, V, 2011. The effect of microwave pre-treatment on impact breakage of copper ore, *Minerals Engineering*, 24: 1609-1618.

Starkey, J H, Hindstrom, S, Nadasdy, G, 2006. SAGDesign testing-what it is and why it works, in Proceedings of *SAG 2006*, *Vancouver, BC, October 2006*, pp 240-254.

Tian, X, Forster, J, Boucher, D and Bobicki, E R, 2021. Energy savings in microwave-assisted comminution: fact or fiction? *Presented at Comminution 2021, Online*.

Tranquilla, J M, Thompson, L, LaRochelle, W and Moritz, R, 1999. Advances in microwave metallurgical processes at EMR Microwave Technology Corporation: a case study in refractory gold ore, *Presented at CIM-New Brunswick Branch Annual Convention, September 1999*.

Van Weert, G and Kondos, P, 2007. Infrared recognition of high sulphide and carbonaceous rocks after microwave heating, In *Proceedings of the 39th Annual Meeting of the Canadian Mineral Processors, Ottawa, ON*, pp. 345–363.

Van Weert, G, Kondos, P and Gluck, E, 2009. Upgrading molybdenite ores between mine and mill using microwave/infrared (MW/IR) sorting technology, in *Proceedings of 41st Annual Meeting of the Canadian Mineral Processors*.

Van Weert, G, Kondos, P and Wang, O, 2011. Microwave heating of sulphide minerals as a function of their size and spatial distribution, *CIM* Journal, 2(3): 117-124.