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Microwave Ore Pre-treatment Review and Process Flowsheet Conceptualization

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ABSTRACT

The global demand for mineral commodities has increased dramatically over the years, and this is largely due to several factors, including technological advancements, industrialization, and a rise in population. Further, the demand keeps increasing because the ore being mined is becoming more complex, and the feed grade is declining over the years, prompting the need for innovative technologies to treat such ores more efficiently. Microwave ore pre-treatment is one of the potential technologies that can be employed to improve process performance. This is possible because ores are composed of both good-microwave heaters and poor microwave heaters, which creates thermal stresses through rapid and differential heating when exposed to microwave fields. As a result, fractures are formed at the grain boundaries and through the matrix, potentially improving comminution and mineral accessibility to the leach solution. Also, because of their rapid and volumetric heating, microwaves can be employed for roasting pre-treatment to oxidize sulphide minerals and natural carbonaceous materials encountered in modern gold ore deposits, making them amenable in conventional cyanidation processes after treatment. Following a thorough literature review of experimental and numerical studies to date, this article proposes several conceptual flowsheets incorporating a microwave ore pre-treatment system to improve the process performance of gold-copper ores in a crush-grind-flot-leach circuit. The literature review findings suggest that a microwave treatment system can be positioned in the comminution circuit to reduce the ore's mechanical strength and enhance mineral liberation, potentially improving the milling and subsequent metal extraction processes (e.g., flotation and leaching). The technology can also be employed in the gravity circuit for chlorination roasting of gravity tailings to reduce the amount of gold recirculating in the grinding circuit. However, more studies should be conducted using the pilot-scale continuous treatment systems to assess the technical and economic viability of the proposed flowsheets.

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INTRODUCTION

The mineral demand has increased dramatically over the years, and this is largely due to technological advancements, infrastructure development, and industrial development, all of which require various mineral commodities. The situation is aggravated by the population growth, consuming more minerals in terms of goods and services. The demand is further pushed by the gradual decline of ore grades and increased complexity of modern deposits, since higher-grade and easier-to-treat ores are mined and exhausted over time (Calvo et al., 2016). Obviously, larger volumes of low-grade ores must be mined and processed to meet the rising demand. According to Vidal et al. (2021), it is estimated that about 70 billion tonnes of material (ore and waste) are mined from the ground worldwide each year. Processing these materials using existing flowsheets is not economically attractive due to higher energy consumption and low process efficiency. To overcome future challenges in meeting the growing mineral demand, innovative processing technologies must be investigated to treat modern ore deposits more efficiently, microwave ore pre-treatment being one of the potential technologies.

Microwaves are electromagnetic waves of short wavelength ranging between 1 m to 1 mm with corresponding frequencies between 300 MHz and 300 GHz (Thostenson & Chou, 1999). In the electromagnetic spectrum, microwaves are positioned between infrared and radio waves. They are self-propagating waves carrying electric and magnetic field components oscillating in phase and perpendicular to one another, and perpendicular to the propagation direction (Metaxas & Meredith, 1983). Microwaves are non-ionizing radiation that is turned into heat energy depending upon the type of interaction with the target materials (Mishra & Sharma (2016). Since their rapid development during World War II, microwaves have been widely used in various applications such as communications, radar detection, medical, scientific, electronic warfare, navigation, as well as microwave heating (Gupta & Leong, 2008). Essentially, the microwave heating of materials is the result of direct molecular volumetric interaction with electromagnetic radiation, making it suitable for more rapid heating than conventional heating, which relies on convection, conduction, and radiation heat transfer mechanisms (Clark & Sutton, 1996; Haque, 1999). Crucially, microwave energy is transferred throughout the volume of the material (i.e., volumetric heating), reducing processing times and improving overall heating quality (Thostenson & Chou, 1999).

For over the past thirty years, many researchers have demonstrated the great potential of microwave heating technology in improving mineral processing systems, with the most notable early works conducted at the US Bureau of Mines (Walkiewicz et al., 1991; 1993). However, most of these studies were limited to lab-scale experiments and a few used pilot-scale units, treating only small batch samples of up to a few kilograms. Recently, researchers at the University of Nottingham (UK) designed, constructed, and tested a pilot plant for microwave ore pre-treatment that can operate continuously at a throughput rate of up to 10-150 tonnes per hour (Buttress et al., 2017; Batchelor et al., 2017). The aim of their study was to demonstrate the viability of a pilot-scale system that could subsequently be scaled up to a large-scale system that could be deployed for mine site operations. This article expands the knowledge by exploring several conceptual flowsheet options that incorporate such a microwave treatment system to process gold-copper ores, following a review of microwave ore pre-treatment studies on comminution and leaching conducted over the last thirty years.

A REVIEW OF MICROWAVE ORE PRE-TREATMENT STUDIES

Microwave Heating of Minerals and Ore Fracturing Mechanism

Essentially, minerals heat up differently upon exposure to microwave fields. This is due to the differences in dielectric properties, electrical conductivities, and bonding properties that exist in different minerals (Hua

& Liu, 1996). Earlier studies conducted by Chen et al. (1984) and Walkiewicz et al. (1988) showed that generally, the majority of sulphides, sulphosalts, and sulphoarsenides heat up rapidly in comparison to most silicates, carbonates, sulphates, some oxides. Later, Kingman et al. (2000) investigated the microwave heating responses of various minerals over a range of exposure times using a microwave power of 2.6 kW at a frequency of 2.45 GHz. Similar findings were reported in this later study that most sulphides heat up faster (due to their semiconducting properties) than most metal oxides and silicates. For example, chalcocite (Cu_2S) attained a temperature of 245°C after microwave irradiation for 120 minutes, as opposed to a lower temperature of 28°C attained by quartz (SiO_2) for the same irradiation time of 120 minutes.

The principal mechanism of ore fracturing (e.g., in sulphide ores) upon microwave irradiation is based on the rapid, volumetric and selective heating of sulphide minerals within a microwave non-heating gangue matrix (mostly rock-forming minerals). This type of heating results in thermal expansion mismatches between the heated and non-heated mineral phases. Essentially, the expansion of microwave absorbent phases stretches the transparent gangue matrix, causing tensile and shear stresses around grain boundaries. A close examination of stress vectors simulations reported by Jones et al. (2005) revealed that within the microwave-absorbent (e.g., pyrite) particle a state of compression exists, with the highest magnitude acting in the centre of the pyrite particle, whereas shear and tensile stresses predominate outside the particle in the microwave-transparent phase (e.g., calcite matrix). As a result, intergranular and transgranular fractures occur, particularly, when the magnitude of induced stresses exceeds the ore strength (Salsman et al., 1996; Ali & Bradshaw, 2010). Several studies have reported images that reveal this type of ore fracturing in microwave treatment studies, such as (Andriese et al., 2011; Charikinya et al., 2015; Batchelor et al., 2015), suggesting the possibility of increasing mineral liberation and improving metal recovery.

Furthermore, ore samples containing hydrated mineral phases can also exhibit significant fractures when irradiated in microwave fields. In this case, ore fracturing is attributed to the dehydration of water (an excellent microwave absorber) contained within the ore. The fractures formed are caused by one or more of the following mechanisms (Kobusheshe, 2010):

i. Internal pressure caused by steam generated when microwaves interact with hydrated phases within the ore.
ii. Expansion of hydrated clay minerals (e.g., smectite, halloysite, montmorillonite).
iii. Thermal decomposition of certain mineral phases and loss of water of crystallisation, resulting in lattice structural defects.

Studies on Microwave-assisted Comminution

Over the past thirty years, many studies have demonstrated the use of microwave energy to improve comminution or reduce ore strength. Some of the studies were carried out using higher microwave power densities (single mode cavities), whereas others used lower power densities (multimode cavities – a kitchen microwave being a familiar example). Essentially, single mode cavities support one resonant mode for maximum electric field strength, and the sample is to be placed in this region (the hot spot) to ensure maximum power delivery (Thostenson & Chou, 1999; Peng & Hwang, 2015). Multimode cavities, unlike single mode cavities, can support multiple resonant modes at the same time, forming a complex electric field pattern within a cavity. Figure 1 illustrates the electric field distributions in the single and multimode cavities. Since the microwave power is not confined within a small volume in multimode cavities, lower power densities are achieved when the treatment is performed in such cavities, necessitating longer irradiation time in comparison to single mode cavities.

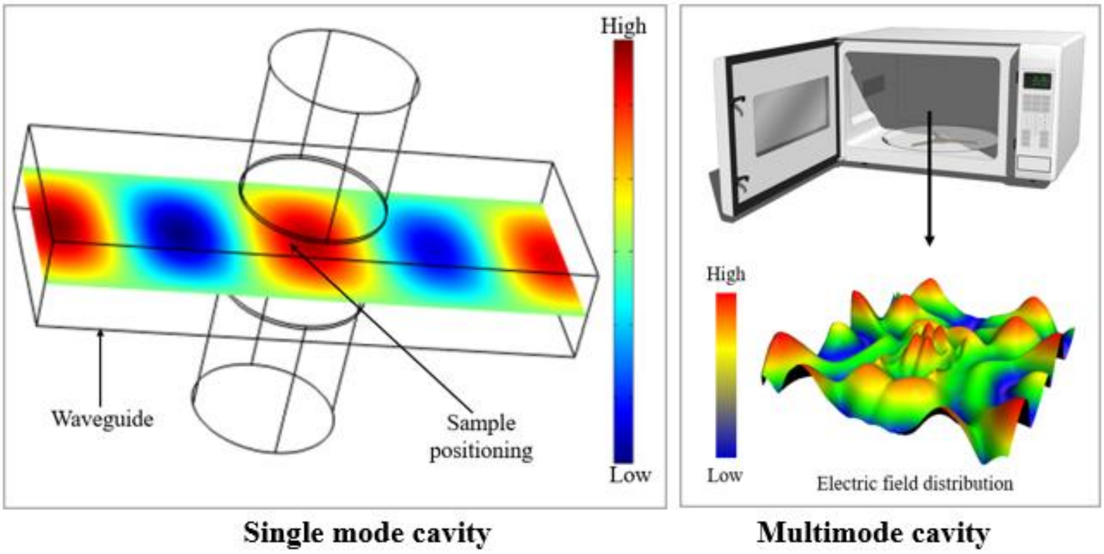

Figure 1: Electric field distribution - single mode vs multimode cavities (Giyani, 2023).

A list of the low microwave power density comminution studies includes (Walkiewicz et al., 1991; 1993; Tavares & King, 1999; Kingman et al., 2000; Amankwah et al., 2005; Vorster et al., 2001; Wang & Forssberg, 2005; Kumar et al., 2010; Koleini & Barani, 2008; Omran et al. 2015; Marion et al., 2016; Singh et al., 2017; Cai et al., 2018; Bobicki et al., 2018; Jiawang et al., 2020; Yu et al., 2021; Barani et al., 2021; Gholami et al., 2021; Pickles & Lu 2022). The findings derived from these studies generally show that microwave energy can reduce the ore's mechanical strength and improve grinding performance. For example, higher reductions of Bond rod mill work index of up to 91% were achieved due to microwave treatment of copper ores by Kingman et al. (2000). However, such results have been achieved using longer irradiation times of 10 seconds to more than 4 minutes, resulting in higher microwave energy consumption.

The earlier numerical simulation microwave treatment study by Whittles et al. (2003), using the binary ore of calcite and pyrite, showed that the microwave treatment duration can be significantly reduced when higher power densities are employed, and still achieve higher ore strength reductions. Results showed that the higher microwave power density of $1x10^{11}$ W/m^3 in a single mode cavity generates a larger reduction in ore strength (uniaxial compressive strength - UCS) of up to 55% (from 126 to 57 MPa) within a very short exposure time of 0.05 seconds.

Following interesting results by Whittles et al. (2003), many microwave treatment studies were carried out using single mode cavities to assist comminution using experimental and numerical simulation methods. Some of the experimental studies include (Kingman et al., 2004a; 2004b; Sahyoun et al., 2004; Kobusheshe, 2010; Batchelor, 2013; Charikinya et al., 2015; Ure 2017; Giyani, 2023). These studies generally show that microwave ore treatment can reduce ore strength and improve comminution performance within a very short time. For example, Sahyoun et al. (2004) reported significant strength reductions of copper carbonate ore (containing copper sulphides, magnetite, and carbonate minerals) in terms of Bond rod mill work index of up to 73-83%. These results were achieved in a short irradiation time of 0.5 seconds using a single mode cavity at a microwave power of 10-15 kW, equivalent to 1.4-2.1 kWh/t specific energy input (see Table 1).

Table 1. Rod mill grinding results after microwave treatment in a single mode cavity (Sahyoun et al., 2004)

Microwave Exposure Time (s)	Power Level (kW)	% Reduction in Bond Work Index	Reduction in Bond Work Index (kWh/t)	Energy Expended (kWh/t)
0	0	0	0	0
0.5	10	78.4	7.92	1.39
0.5	13	75.7	7.65	1.81
0.5	14	82.7	8.35	1.94
0.5	15	73	7.37	2.08

The impressive strength reduction reported in these microwave treatment studies using single mode cavities within very short durations and high microwave power inputs is attributed to high tensile and shear stresses (thermal stresses) as results of higher temperature gradient developed between the microwave-absorbing phases and the non-absorbing matrix. As a result, significant damage is induced, which can significantly reduce ore strength. On the other hand, if the ore is slowly heated with low microwave power, more heat is transferred by conduction from the microwave-absorbing phases to the adjacent gangue matrix, resulting in small thermal stresses and less ore weakening (Kingman et al. 2004). Some of the microwave ore pre-treatment studies (simulation or theoretical) include (Salsman et al., 1996; Jones et al., 2005; 2007; Ali & Bradshaw, 2009; Ali & Bradshaw, 2010; Ali, 2010; Djordjevic, 2014; Yang et al., 2020). The following findings were derived from these studies: the extent of ore pre-damage increased with the microwave power density and exposure time; the stress regime inside a heated mineral particle is compressive, whereas shear and tensile stresses predominate outside the boundary. Also, higher strength reductions are achieved if the ore possess some of these properties: coarse microwave-absorbing grains; high modal area of a microwave-absorbent phase; microwave-absorbing mineral constrained in a strong transparent gangue matrix; microwave-absorbing mineral with a high thermal expansion coefficient. Furthermore, ore samples containing a high proportion of stiffer microwave heaters (e.g., pyrite, magnetite) are more amenable to microwave-induced fractures, given suitable texture (e.g., coarse grain size).

Salsman et al. (1996) investigated the influence of sulphide content and sulphide grain size on heating response using a mixture of pure minerals: chalcopyrite (microwave-absorber), and quartz (microwave transparent gangue). The proportion of chalcopyrite in the mixture varied from 0% to 7%, and the particle sizes of chalcopyrite tested were 53, 178, 357, and 601 µm, of which each size was mixed with quartz powder. Thereafter, 100-gram samples of each mixture were exposed in a multimode cavity for 120 seconds at a microwave power of 1 kW. Results showed that the microwave energy (heat) absorbed by the sample is proportional to the mass of chalcopyrite grains present in the mixture. In addition, the heating rate decreases significantly with the decrease in chalcopyrite grain size, because the heat absorbed by the smaller chalcopyrite grains dissipates more rapidly into the surrounding quartz than that dissipated by the larger grains, and the temperature of the smaller grains does not rise as rapidly. This suggests that ore samples containing coarser grains of microwave-absorbing minerals can exhibit greater thermal gradient when exposed to microwave fields, leading to more thermal stresses and greater induced fractures.

Similarly, Ali & Bradshaw (2009) quantified the damage around grain boundaries of microwave-treated ore using numerical simulations, at a microwave power density of 1x10[10] W/m[3]. This study used a binary ore of magnetite-dolomite, with a composition of 10% microwave-absorbing mineral and 90% transparent matrix by volume, and two textures were simulated: coarser-grained (1.0-2.5 mm) and finer-grained (0.125–0.25 mm). Results showed that the damage incurred in the sample increases with microwave exposure time. Also, the microwave-induced damage decreases significantly as the absorbent-grain size decreases (Figure 2), suggesting that a higher energy input is needed for fine-grained mineralized ores than that required for the coarse-grained ores in order to achieve the same damage.

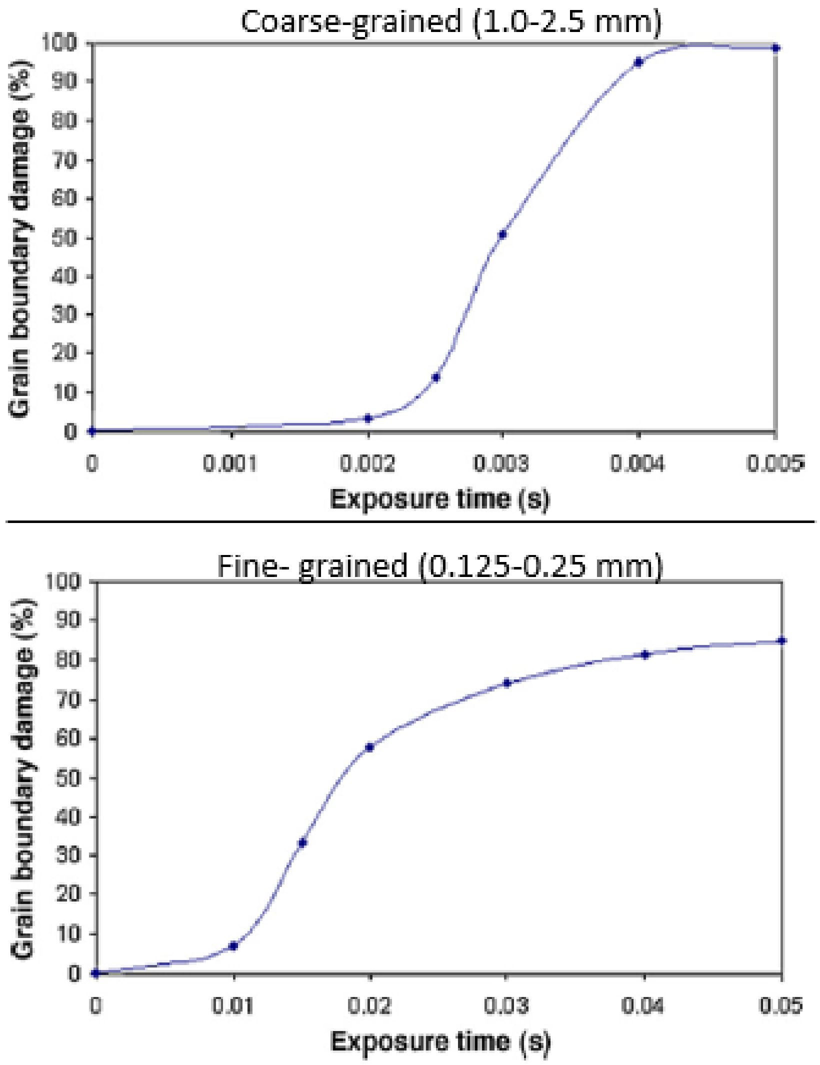

Figure 2. Microwave-damage around grain boundary regions for coarser- and fine-grained magnetite dolomite.

It is worth mentioning that most of the findings revealed in these theoretical studies were also seen in the experimental studies mentioned before. For example, Batchelor et al. (2015) conducted experimental works using 13 suphide ores of varying mineralogy and texture, which were treated at high powers (15-25 kW) in a single mode cavity with an energy input of 0.5-10 kWh/t. These authors concluded that ores that achieved higher strength reductions due to microwave treatment met the following criteria:

i. Contain the highly microwave-absorbent phases such as magnetite or sulphides of iron, lead, nickel, and copper.

ii. Consist of a high modal abundance of total good microwave heaters of 2-20 wt%. Ores with >20% microwave-absorbing phases (e.g., massive sulphide deposits) do not exhibit significant fractures at low energies because the microwave energy available to thermally expand the grains is reduced as it must be shared amongst the microwave-heating phases present. The low-grade or barren ores, on the other hand, do not have sufficient microwave heaters to induce significant fractures.

iii. Contain at least 50% abundance of hard gangue matrix (≥6 Mohs) that surrounds the microwave-absorbing phases, which supports the effective transfer of stresses and ore fracturing. The soft gangue matrix tends to undergo ductile deformation to absorb thermal shock, requiring high microwave energy to initiate and propagate fractures.

iv. Have a coarser grain size of microwave absorbent phases, with grain sizes of d_{50} >0.5-1.0 mm.

v. Have a consistent texture of microwave-absorbing phases, with a high proportion of amenable texture in most fragments.

In addition to comminution, several studies have investigated the influence of microwave ore pre-treatment on mineral liberation. Some of these studies include (Orumwense et al., 2004; Amankwah et al., 2005; Scott, 2006; Amankwah & Pickles, 2009; Batchelor et al., 2016; Charikinya et al., 2015; Omran et al., 2015; Batchelor et al., 2017; Singh et al., 2017; Huang & Liu, 2021). Like in comminution, these studies have generally indicated that microwave ore pre-treatment can improve mineral liberation to a variable degree, depending on the ore mineralogy and texture, and microwave treatment conditions employed. For example, a study reported by Batchelor et al., 2016 showed that equivalent mineral liberation can be achieved at a coarser grind size of approximately 50–60 µm than the nominal particle size due to microwave treatment, or a 2.5% increase in liberation at an equivalent grind size. In their study, they used a porphyry copper ore, which was treated at 15 kW in a single mode cavity at a microwave energy input of about 2 kWh/t. Another important finding from microwave treatment studies is that the influence of microwave ore pretreatment in mineral liberation decreases with ore particle size. This is due to reduced thermal stresses caused by a decrease in grain size of microwave-absorbing minerals, as well as a decrease in the size of gangue matrix in smaller particles, which serves as crack propagation sites for microwave-induced fractures.

Microwave Ore Pre-treatment to Assist Leaching

The kinetics of mineral dissolution is commonly described using the shrinking-core model (SCM), which assumes a particle as a sphere with an unreacted core that shrinks in size as leaching progresses (Crundwell, 1995). According to this model, the extent of mineral grain dissolution is dependent on their position within the particle, so mineral grains near the edge leach faster than those in the centre (Ghorbani et al., 2013). Fractured particles (e.g., due to microwave treatment) can provide leaching pathways to dissolve some of the mineral grains located at the core via a network of induced cracks, resulting in improved leaching kinetics and overall metal recovery. In addition, if fractures are made in large fragments that are subsequently crushed (e.g., -100+50 mm) the internal mineral grains may be exposed due to preferential breakage along induced fracture paths, thereby improving leaching performance. Since the microwave penetration depth increases with the decrease in microwave frequency and/or dielectric properties (dielectric constant and dielectric loss), the treatment performance of massive sulphide ores of such coarse fragments is expected to diminish when a higher frequency of 2.45 GHz is used, due to lower microwave penetration depth. This challenge can be addressed using the lower ISM (Industrial Scientific and Medical) frequency band, such as 433 or 896 MHz, which can penetrate deeper into such fragments.

A number of studies have been conducted to assess the influence of microwave ore pre-treatment on leaching performance, some of these studies include (Olubambi et al., 2007; Olubambi, 2009; Schmuhl et al., 2011; Amankwah & Ofori-Sarpong, 2011;

Charikinya & Bradshaw, 2017; Giyani, 2023). These studies have generally shown that microwave ore pretreatment can improve leaching kinetics and ultimate metal recovery, depending on the magnitude of induced damage, which is a function of microwave treatment conditions (e.g., energy input) and ore properties (e.g., ore mineralogy and texture). Ore samples with some of these properties: coarser/clustered, stiffer, and higher modal abundance of microwave-absorbing minerals are more suitable for microwave treatment. This type of mineralogy and texture promotes intense local heating within a non-heating gangue matrix, which creates larger thermal stresses and significant fractures, thereby increasing mineral exposure and leaching performance. In addition, given the right mineralogy and texture, coarser feed size (e.g., secondary crushed material) exhibits a greater beneficial change in terms of induced damage and leaching improvement (kinetics and ultimate recovery). This is because the microwave-absorbing phases in such particles are most likely surrounded by a large volume of microwave-transparent gangue matrix, which acts as crack propagation sites when thermal stresses are induced (Giyani, 2023). A study reported by Schmuhl et al. (2011), for example, showed the 12% copper enhancement due to microwave treatment for coarse particles (+13-19 mm) against 7% for the finer size fraction (+9.2-12.5 mm). Recently, faster leaching kinetics in multiples of four or more have been reported for ores with amenable texture, such as those with coarser, stiffer, and higher modal abundance of microwave-absorbing grains (Giyani, 2023).

The extent of leaching improvement due to microwave treatment can be delineated using the X-ray Computed Tomography (X-ray CT) imaging by comparing the post-treated and post-leached scans of ore specimens, as seen in Figure 3. This specimen sustained multiple fractures due to microwave treatment, exposing internal sulphide grains to the leach solution. It can be seen that the acid solution penetrated deeply and dissolved most of the sulphide grains located along fractured surfaces (see the disappearance of bright phases along the fractures in the post-leached scan) and obviously near the edge of the particle. It is clear that this effect is more pronounced in large fractures (wide opening) than in small fractures (narrow opening), and thus large fractures are more beneficial in terms of leaching improvement than small fractures (Giyani, 2023).

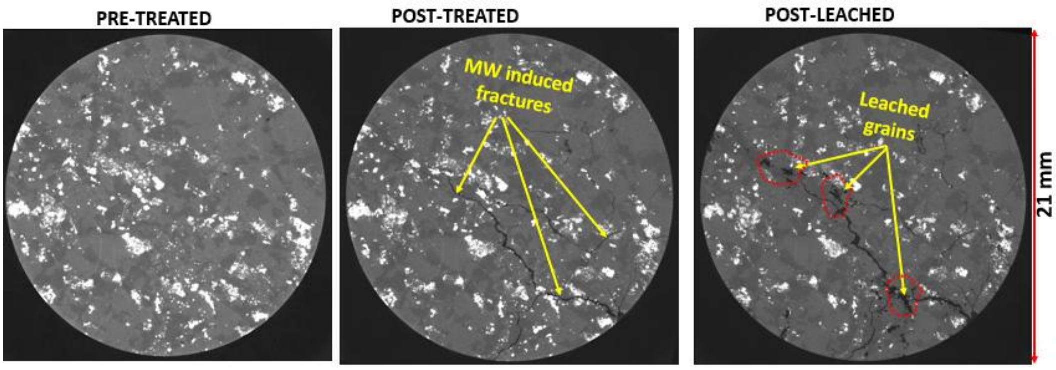

Figure 3. Leaching of sulphide grains due to microwave-induced fractures (Giyani, 2023).

Microwave Ore/Concentrate Roasting Pre-treatment to Assist Leaching

Refractory gold ores contain gold that is locked within pyrite or arsenopyrite, making it inaccessible to cyanide solution. These ores may also contain naturally carbonaceous materials that adsorb the solubilized gold cyanide complex from the leach solution. Consequently, such ores do not give economic recoveries upon the conventional cyanidation process (La Brooy et al., 1994). Roasting pre-treatment is one of the techniques used to improve leaching performance for ores that contain both sulphides and carbonaceous components. The aim is to produce a highly porous iron oxide calcine in which gold is highly liberated and free of carbonaceous materials that could otherwise inhibit gold dissolution or adsorption processes.

The microwave heating response of sulphide and carbonaceous rocks has been investigated by Van Weert & Kondos (2007), and it was found that both heat quite well when exposed to microwave fields. The higher microwave heating response of sulphide minerals and carbonaceous (graphitic) materials suggests that refractory gold ores or concentrates should heat up faster when exposed to microwave fields, producing porous calcines that can be easy to leach and potentially improving metal extraction. Several researchers have used microwave energy to pre-treat (roast) the refractory gold ores or concentrates in order to improve mineral dissolution (Haque 1987; Nanthakumar et al., 2007; Amankwah & Pickles, 2009; Hua et al., 2006; Choi et al., 2017; Wang et al., 2019, 2020; Amankwah & Ofori-Sarpong, 2020; Bai et al., 2022). These studies demonstrated that microwave roasting pre-treatment of gold ores/concentrate reduces preg-robbing materials to a variable degree, depending on ore type and applied energy. Ore samples containing excellent microwave-absorbing mineral grains (e.g., arsenopyrite and magnetite) yielded better results. Some researchers such as Amankwah & Pickles (2009) noticed the sintering effect, which formed an impenetrable coatings that render the gold inaccessible in subsequent recovery processes. This effect occurs when the material is roasted for too long at higher microwave power (over-roasting), indicating the importance of optimizing the roasting parameters. In their study, the sintering effect was addressed by re-grinding the calcine to improve mineral accessibility.

Based on the fact that gold can readily be volatilized from their ores by heat treatment (e.g., at 750-1050°C) in the presence of alkali halide salts. Some researchers have recently performed microwave chlorination roasting experiments to recover gold from gold-bearing materials, and the results were compared with those of conventional roasting. These researchers include Zhu et al. (2018), Li et al. (2020), and Li et al. (2021). Their studies involved roasting the material in the presence of alkaline salts (e.g., $CaCl_2$) to volatilize the gold, followed by adsorbing the exhaust gases from the calcine with activated carbon soaked in an alkaline solution. Their findings showed that microwave roasting is rapid and yields better recovery as compared to conventional roasting, particularly when the material contains excellent microwave heaters. For example, Zhu et al. (2018) reported higher gold recoveries of 69-96% attained by microwave treatment, as compared to lower recoveries of 35-85% by conventional roasting. Furthermore, Li et al. (2020) observed that conventional heating required more energy (i.e., twice that of microwave roasting) to obtain the same gold recovery of 85%.

Scale-up Developments - Opportunities and Challenges

As mentioned before, studies in microwave treatment of ores to assist comminution have been reported since the 1990s. Most of these studies are performed in small batches of less than 1 kg using low-intensity multimode cavities at low powers of less than 3 kW and for longer irradiation times of more than 10 minutes. For the first time in the 2000s, single mode cavities with higher power levels of up to 15 kW were used for ore pre-treatment to assist comminution (Kingman et al., 2004). The use of single mode cavities demonstrated significant comminution improvements at economically feasible energy inputs of less than 5 kWh/t by exposing the sample to high electric field intensity for less than 1 sec. Following that work, the first continuous belt-based treatment system was tested around 2006. In that system, the ore was placed in a microwave-transparent plastic tube and moved instantaneously through the applicator at an equivalent throughput of 10-20 tonnes per hour, using a microwave power of up to 30 kW at a frequency of 2.45 GHz. One of the key lessons from that work was the issue of power spread in conveyor systems and gradual warming of the load, which minimizes the thermal shock and ore fracturing, indicating the importance of confining the electric field within the applicator. One possible solution to address this challenge is to use a vertically aligned tube through which materials flow as a packed bed to interact with well-confined microwave fields.

Around 2010, a pilot-scale treatment system was developed utilizing the vertically aligned tube, whereby ore fragments were moved as a packed bed through the applicator using a belt and pulley system. The key development arising from that work was the design of circular chokes above and below the applicator, which helped to confine the electric field in a relatively small region, reducing the gradual warming of the load and maximizing the thermal shock that promotes ore fracturing. From 2010 to 2015, a large-scale continuous system capable of treating coarsely crushed ore fragments (up to 50 mm) at a throughput rate of up to 10-150 tonnes per hour in a laboratory-based environment was designed, constructed, and evaluated by metallurgical testing (Buttress et al., 2017; Batchelor et al., 2017). Unlike other high-throughput microwave heating systems that use conveyor belts to expose the sample to the applicator, this system utilized a vertically aligned tube through which materials flow as a packed bed to interact with microwave fields (see Figure 4). One of the key findings from that study was the importance of exposing more ore fragments in a region with a higher electric field strength, which results in more homogeneous and effective treatment.

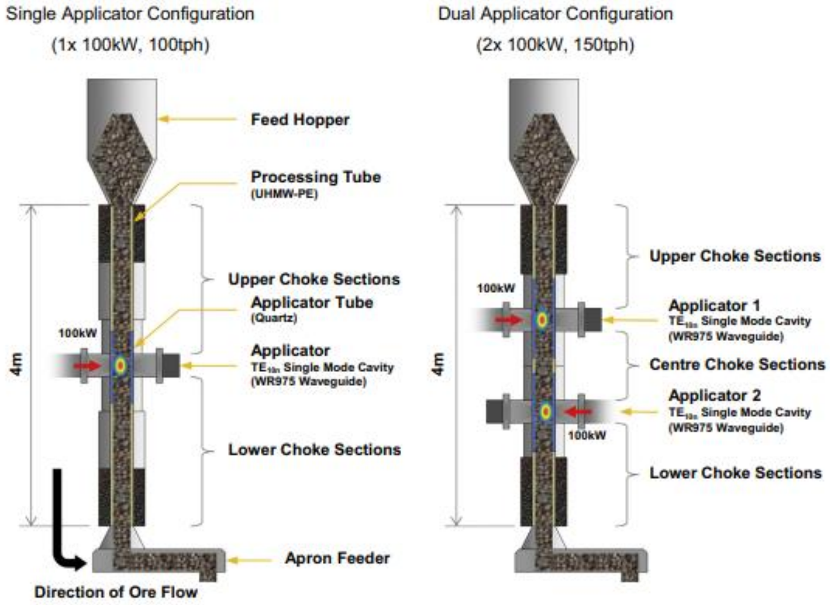

Figure 4. Vertically aligned tube microwave ore treatment system – single (left) and dual (right) applicators (Buttress et al., 2017).

Results showed that a dual treatment system consisting of two single mode applicators connected in series improved comminution significantly when compared to a single applicator system

CONCEPTUAL FLOWSHEETS DISCUSSION

Following the literature review, this section describes conceptual flowsheets that incorporate microwave heating technology to improve process performance in a crush-grind-flot-leach circuit.

A typical crush-grind-flot-leach process flowsheet is shown in Figure 5, and this is the base-case scenario (without microwave treatment). The run-of-mine ore (typically -1000 mm) is subjected to one or two stages of crushing to a top size of about 50-100 mm. After crushing, the ore is further reduced in the primary grinding mill (mostly SAG mill), which is often in a closed circuit with a pebble crusher, to produce a finer product particle size of less than 1 mm. The ground slurry is pumped to the hydrocyclone unit for classification, whereby finer particles of P_{80} of about 106-75 microns (overflow) report to the flotation circuit. The majority of the hydrocyclone underflow (e.g., 80% of the flowrate) is returned to the ball mill for further grinding to improve mineral liberation. The small fraction of the underflow (say 20%) reports to the gravity circuit to recover the liberated gold that circulates through the ball milling circuit. This is achieved through centrifugal gravity concentrators (e.g., Knelson or Falcon) followed by the intensive cyanidation process (e.g., Acacia, Inline leach reactors). The pregnant solution from the gravity circuit reports to the electrowinning cell, where gold is deposited on the cathodes, and the concentrate product from the cathode is smelted to get the gold bullion. The residue gravity solid tails product is returned to the grinding circuit for further size reduction. Essentially, the flotation process involves two key stages: roughing (to maximize recovery) and cleaning (to upgrade the rougher concentrate to improve the final concentrate grade). The flotation concentrate is thickened and dried to obtain the final copper concentrate. The flotation tails (a combination of rougher and cleaner tails) are thickened and then fed to the conventional CIL circuit to recover the gold left in these tails.

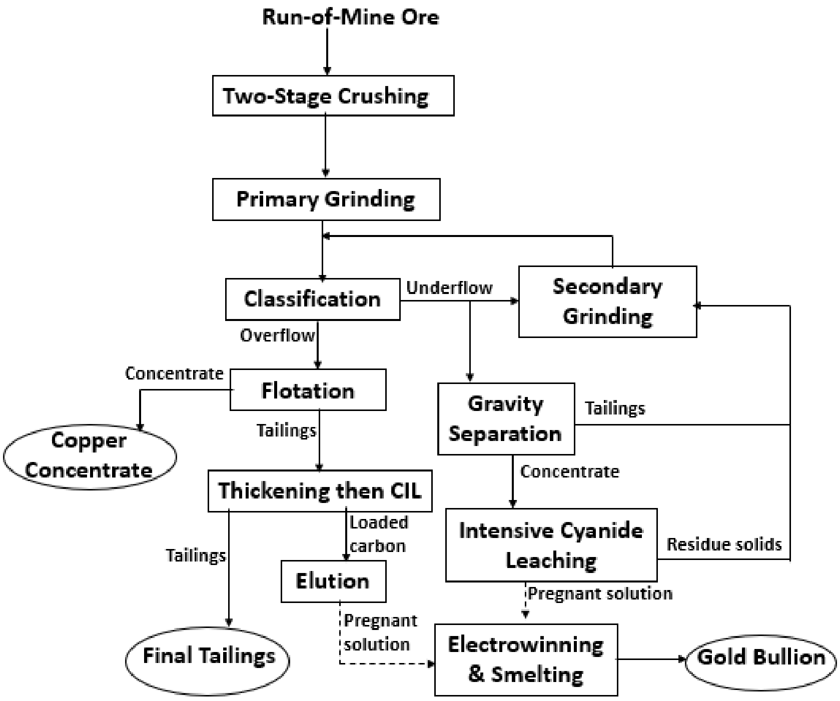

Figure 5. Crush-grind-flot-leach circuit – without microwave treatment (the base-case scenario).

Based on this conventional flowsheet, alternative flowsheets incorporating a microwave treatment unit to improve process performance are proposed. However, it is worth mentioning that metal detectors and magnetic separators be installed to detect and remove tramp metals from the ore prior to microwave treatment. This is because metallic objects from mining tools and crushers coming along with the ore can significantly reflect microwave energy and disrupt the electric field distribution within the microwave cavity, reducing the efficiency of the treatment process (Giyani, 2023). Also, the high reflected microwave power caused by metallic objects in the ore can cause electrical arcing, which can potentially damage the microwave treatment components, including the microwave generator (magnetron).

Option 1

In the first option, a microwave treatment unit can be positioned between the crushing and primary grinding processes, as illustrated in Figure 6. The aim is to reduce the ore's mechanical strength prior to grinding, as well as improve mineral liberation (at a coarser grind size) through preferential breakage along the microwave-induced fractures, which occur preferably along grain boundaries. It is preferrable to position the microwave treatment unit before the crushed ore storage bin, because the free-fall of ore fragments in the bin will promote further comminution (impact breakage) of treated fragments before reporting to the grinding stage, potentially lowering the grinding energy. Grinding results of a pilot scale microwave treatment system shown before in Figure 4 demonstrated a reduction in Bond mill grindability index of 3-9%, and a reduction in A*b values (drop weight test) of 7-14% at a microwave energy of 0.7-1.3 kWh/t, depending on ore type (mineralogy and texture) and microwave treatment conditions (Batchelor et al., 2017). Also, mineral liberation results on the treated ore showed that equivalent liberation may be achieved for a grind size of about 40–70 µm coarser than that of untreated ore. One of the possible challenges in this flowsheet is that a larger microwave heating system will be required for effective treatment, which needs to be properly designed to ensure treatment homogeneity of the whole ore.

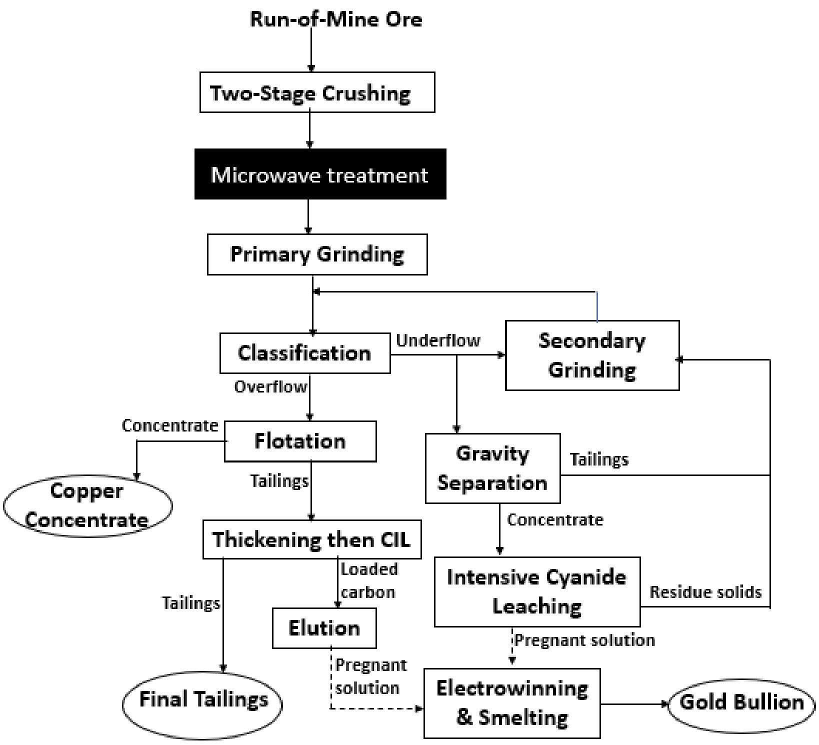

Figure 6. Option 1- Microwave treatment unit at the comminution circuit.

Option 2

In the second option, a microwave treatment unit is proposed to be positioned in the gravity circuit to treat the gravity tailings (Figure 7). The aim is to improve the gold recovery in the gravity circuit, hence reducing the amount of gold recirculating in the grinding circuit. In this case, the gravity tailings material is subjected to microwave treatment, to increase mineral exposure for cyanide leaching through a network of microwave-induced fractures. The treated material is then subjected to the intensive cyanide leaching process before returned to the ball mill for further grinding. Alternatively, the gravity tailings can be subjected to the microwave chlorination roasting mentioned before in the literature review. In this process (not shown in Figure 7), the gravity tailings will be mixed with alkali halide salts (e.g., $CaCl_2$) and then subjected to microwave roasting at a temperature of about 750-1000°C to volatilize the gold. The gold will be adsorbed from the calcine exhaust gases using activated carbon soaked in an alkaline solution. Of course, the loaded carbon will then be sent to the elution circuit, followed by the electrowinning and smelting processes to obtain the final gold product. The possible challenge in this flowsheet is that the gravity tailings product needs to be dried to reduce the moisture content prior to microwave treatment (e.g., by pressure filtration and hot air). This decision is based on the fact that water is an excellent microwave absorber, and thus, if not reduced, most of the microwave energy will be used to heat water, reducing the amount of energy available for actual ore pre-treatment.

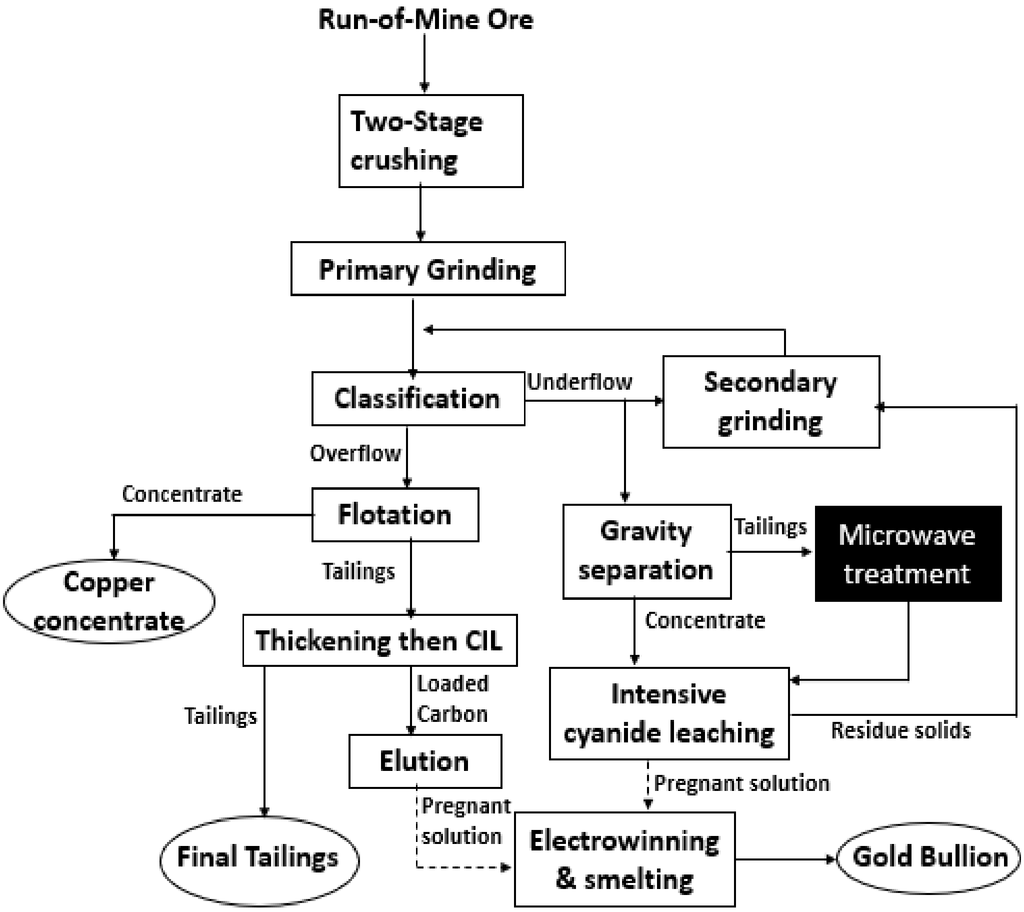

Figure 7. Option 2 - Microwave treatment unit at the gravity circuit.

Option 3

The third proposed option of utilizing microwave treatment technology to improve process performance in mineral processing operations is shown in Figure 8. This flowsheet is particularly suitable for double refractory ores. As mentioned in the literature review section, these ore types yield poor recoveries when subjected to the conventional cyanidation process, because they contain gold that is occluded within sulphide minerals and are associated with naturally carbonaceous materials that adsorb solubilized gold. One of the key differences of this flowsheet compared to others described before is that the grinding and classification processes are performed without adding water. The dry grinding and classification process is not a very common practice in most mineral processing plants but has successively been done in some large operations, such as the Barrick Goldstrike mine in the United States utilizing the double rotator mill (Krupp Polysius) in a closed circuit with a system of classifiers and conventional roasting pre-treatment, as detailed by Thomas et al. (2001). The decision to perform dry grinding and classification before microwave treatment in Figure 8 is based on maximizing the microwave energy for roasting the ore, rather than boiling the water in the wet process. Also, the microwave-roasting fluidized bed system is preferred to promote uniform distribution of heat and avoid localized heating. The calcine from the roaster is quenched and neutralized with lime to raise pH to 9.5-10 before being subjected to the flotation and CIL processes. One of the key challenges in this flowsheet is the emission of SO_2 and CO_2, meaning that flue gases from the roaster must be extensively cleaned before being released into the environment.

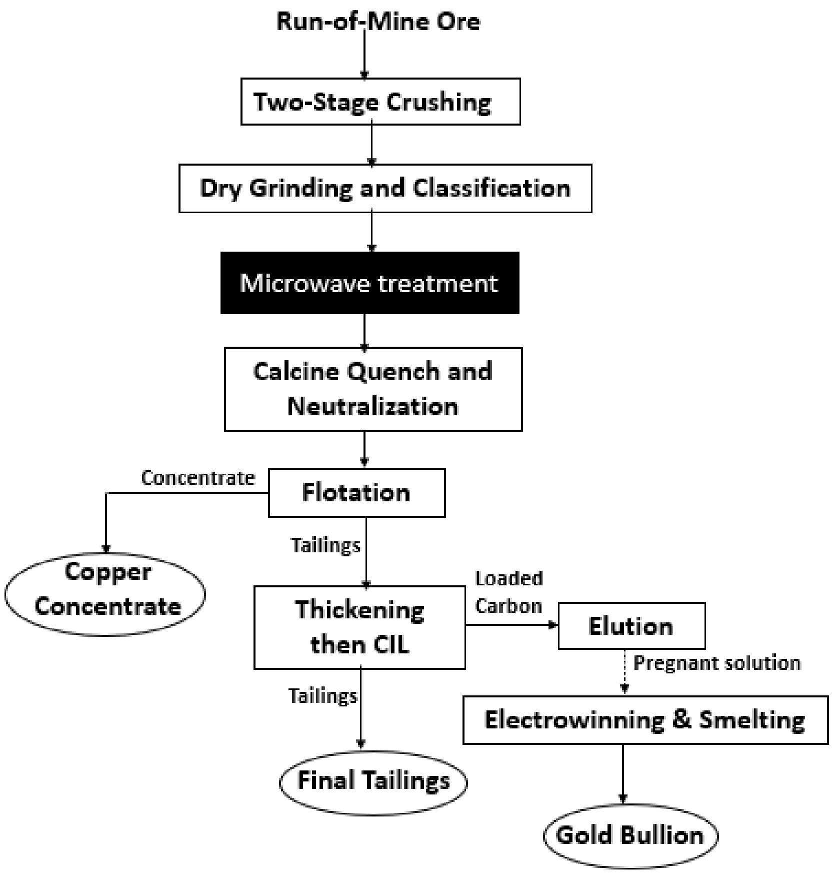

Figure 8. Option 3 - Microwave treatment unit prior to flotation and leaching.

CONCLUSION AND RECOMMENDATION

Microwave heating is a potential technology that can be utilized for ore pre-treatment to improve mineral processing performance, such as comminution and leaching. This is possible because the majority of valuable mineral phases (e.g., sulphides) heat up rapidly in comparison to most rock-forming minerals (e.g., quartz). The rapid and differential heating of mineral phases within the ore creates tensile and shear stresses, potentially reducing the ore's mechanical strength and enhancing mineral accessibility to leaching chemicals. However, the benefit of microwave ore pre-treatment is dependent on ore properties (mineralogy and texture) and microwave treatment conditions. In general, ore types with higher abundance, coarser, and stiffer microwave absorbing phases heat up faster and create more intense heating when subjected to microwave fields, resulting in more induced fractures and higher metal extraction. In addition, microwave ore pre-treatment performed in single mode cavities promotes more rapid heating within a short time because the microwave fields are confined within a small region, making it suitable to aid comminution and roasting pre-treatment.

This study proposes several conceptual flowsheets that incorporate microwave ore pre-treatment to improve the process performance of a crush-grind-flot-leach circuit. The discussion has indicated that microwave treatment technology can be used to reduce the ore's mechanical strength and improve mineral liberation prior to grinding, flotation, and leaching processes. Also, the technology can be used to roast the ore to oxidize the preg-robbers (natural carbonaceous materials) and sulphides from the double refractory ores, making them amenable to leach via conventional cyanidation processes. Furthermore, chlorination roasting of gravity tailings has been proposed to reduce the amount of gold recirculating in the grinding circuit. The possible challenges associated with the proposed flowsheets include: non-uniform heating of the material, SO_2 and CO_2 emissions into the atmosphere, and drying the ore prior to microwave treatment. These challenges can be addressed through the use of fluidized bed roaster confined within a single mode microwave cavity, extensive treatment of flue gases from the roaster before they are released into the environment, and the use of hot gases to reduce the moisture content in the ore prior to microwave treatment. It is recommended that more research be undertaken using pilot-scale continuous treatment systems to assess the technical and economic feasibility of the proposed flowsheets.

Declaration of Interest Statement

The author declares that there is no potential conflict of interest relating to this study, and that all activities pertaining to this work were performed by the author.

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