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Microwave Pre-treatment and Microstructural Evidence of Ore

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Research Article

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Microwave Pre-treatment and Microstructural Evidence of Ore

Derrick Njabuliso Dlamini[1*]

Abstract—This study seeks to investigate the effect of microwave pretreatment on the grindability of ore using single-mode and multimode configurations. Particle size distribution analysis and SEM microstructural characterization were employed to evaluate comminution efficiency. Results show that microwave pretreatment significantly enhanced size reduction, with pretreated samples achieving a P80 of approximately 80 µm after 60 minutes of grinding, compared to 400 µm for untreated ore. Multimode pretreatment produced more extensive microcrack networks and interconnected fractures than single-mode treatment, correlating with improved grinding performance. These findings demonstrate that microwave pretreatment is an effective method for weakening ore microstructure and reducing grinding energy consumption.

Keywords—Comminution, Grindability, Microwave Pretreatment, Mineral Phases, Particle-Size Distribution

I. INTRODUCTION

The efficacy of microwave processing depends on the material's complex permittivity, where the real part represents the dielectric constant and the imaginary part, or dielectric loss, dictates the ability to convert electromagnetic radiation into volumetric heat [1][2]. This dissipation of energy is driven by both polarization losses, resulting from dipole orientation under oscillating fields, and conductive losses attributed to the Joule effect [3]. These dielectric properties remain inherently dynamic, evolving significantly with fluctuations in temperature, moisture content, and the material's specific chemical composition during the irradiation process [4]. Specifically, the presence of metallic compounds and moisture acts as a coupling mechanism, facilitating the formation of localized hotspots through resonance with the oscillating electromagnetic field [5].

Thus, the heating action is fundamentally driven by mechanisms such as dipolar polarization, magnetic losses, and conductive losses, which facilitate the conversion of electromagnetic energy into thermal energy [6]. These mechanisms function collectively to enable selective heating, where disparate dielectric and magnetic properties cause varying heating rates across different mineral phases [7]. In magnetic materials, this energy conversion is further enhanced through the rearrangement of magnetic domains and modifications in electron spin states, including hysteresis and eddy current losses [8].

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Furthermore, the intrinsic heterogeneity of the ore matrix leads to non-uniform temperature field distributions, where regions containing highly microwave-amenable phases, such as sulphides and iron oxides, exhibit superior energy absorption compared to gangue minerals [9][10]. Specifically, the dielectric-loss coefficient of synthetic samples demonstrates complex, non-linear behaviour relative to mineral content depending on the electrical conductivity of the constituent species [11]. Moreover, the geometric arrangement and particle size distribution significantly influence electromagnetic coupling, with larger particles often exhibiting greater heat absorption due to enhanced volumetric interactions [12]. Consequently, the selective heating of these components is governed by the electromagnetic energy conversion principle, involving both dielectric and magnetic loss mechanisms [13]. In another study, an experimental observation confirmed that magnetic ores, such as those containing magnetite, demonstrate heightened sensitivity due to selective microwave absorption and thermal runaway phenomena [14]. This study delves in a comparison of grinding effects of microwave treated and untreated ore samples.

A. Advantages of microwave pre-treatment

The selective heating generated by microwave irradiation exploits the dielectric differences between ore constituents, inducing localized thermal stresses that promote preferential fracturing along grain boundaries [15]. This phenomenon effectively increases the liberation of finely disseminated mineral complexes, providing a distinct advantage over conventional methods that often result in excessive overgrinding [16]. Furthermore, the generation of thermal convection currents at the solid-liquid interface accelerates the removal of reaction products, which prevents the passivation of mineral surfaces and ensures continuous lixiviant contact [17]. The surface modification increases the total reactive surface area, significantly reducing the charge transfer resistance during electrochemical dissolution [18]. This intensified surface reactivity, coupled with the creation of structural microdefects, facilitates superior microbial attachment and colonization during bio-flotation processes, thereby increasing the recovery of refractory metals [19][20]. Future implementation strategies should therefore focus on optimization and calculate the ideal ratio of energy expenditure between microwave pre-treatment and subsequent grinding to minimize total emissions and processing costs [21]. Recent advancements in high flux radiation further emphasize this synergy, where precise thermal modulation facilitates efficient gangue rejection and improves subsequent grindability, particularly in complex iron ore matrices [22]. Furthermore, numerical simulations and electron microscopy have confirmed that targeted microwave

power inputs induce localized microcracking at mineral interfaces such as those between hematite and quartz thereby facilitating preferential fracturing [23]. These comminution-related enhancements align with broader strategies to integrate early gangue rejection, where controlled thermal stress significantly reduces energy consumption by decreasing the bond work index of the feed [24].

II. MATERIALS AND METHODS

A. Microwave Pretreatment

Microwave pretreatment was conducted at a reported microwave power output of 1000 W for an exposure duration of 10 min. These operating conditions were used to investigate the potential effects of microwave irradiation on the ore's mineralogical and physical characteristics.

B. Grinding profiles and P80 estimation

Grinding tests were conducted using a feed mass of 1 kg in a mill with an internal diameter of 25 cm and a length of 27 cm, operated at a rotational speed of 43 rpm. The grinding media charge comprised of 10 kg of steel balls for ball milling tests. Following grinding, the material was classified into sieve fractions ranging from 200 to 53 µm for subsequent compositional analysis. The number of experimental replicates and the associated measurement uncertainties should also be reported, where available, to establish the reproducibility and reliability of the results.

C. Ore sample and phase characterization

Mineralogical and chemical characterization of the ore was conducted using X-ray diffraction (XRD), X-ray fluorescence (XRF), and scanning electron microscopy (SEM). XRD was used to identify the crystalline mineral phases present in the sample, while XRF was employed to determine its bulk chemical composition.

III. RESULTS AND DISCUSSION

A. Mineral-phase information and XRD pattern

TABLE I: MINERALOGICAL COMPOSITION OF THE ORE SAMPLE.

Phase name	**Chemical formula**	**Content (RIR, %)**	**Mineral grade in ore (%)**
Dolomite	$CaMg(CO_3)_2$	49 ± 5	49
Sphalerite	ZnS	0.48 ± 0.07	2.12
α-Iron(III) oxide (hematite)	α-Fe_2O_3	9.8 ± 0.4	9.8
Pyrite	FeS_2	12.2 ± 0.5	12.2
Periclase	MgO	10.3 ± 0.4	10.3

The mineralogical analysis indicates that the ore consists predominantly of dolomite (49 ± 5%), accompanied by sulphide and oxide phases. Sphalerite (ZnS) which reported a grade of 2.12% represents the target mineral for zinc recovery. Pyrite (12.2 ± 0.5%) and hematite (9.8 ± 0.4%) indicate a significant iron bearing mineral that may influence separation selectivity. The presence of periclase, tenorite, hausmannite and MnO_2 further demonstrates the mineralogical complexity of the ore. The high dolomite content may influence pulp chemistry and reagent consumption during flotation. Consequently, effective grinding and mineral liberation are essential for improving selective separation and metal recovery. Microwave pretreatment may offer additional benefits by inducing microcracks and potentially enhancing mineral liberation; however, this effect requires experimental verification. Overall, the mineral assemblage highlights the need to optimize pretreatment and flotation conditions for effective beneficiation of the ore.

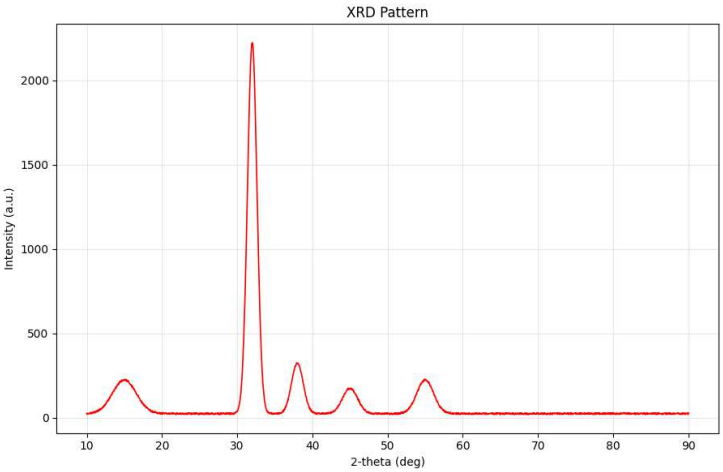


Fig. 1: X-ray diffraction (XRD) pattern of the ore

The XRD pattern (Fig. 1) indicates that the ore is predominantly dolomitic, with a pronounced diffraction peak at approximately $2\theta = 32°$ accompanied by smaller reflections across the measured angular range. These reflections suggest the presence of crystalline mineral phases within the ore matrix. The strong peak indicates a highly crystalline phase, and the pattern is consistent with a carbonate rich ore, in agreement with the reported high dolomite content [25][27]. Therefore, accurate phase identification is essential for understanding the ore mineralogy and evaluating its suitability for subsequent beneficiation.

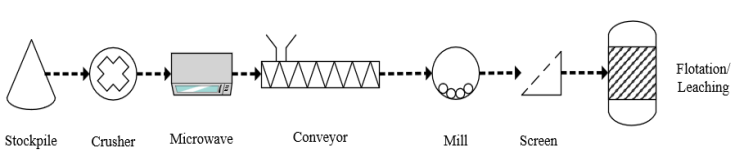


Fig 2: Schematic process flow diagram

B. Particle-size distribution with microwave pre-treatment

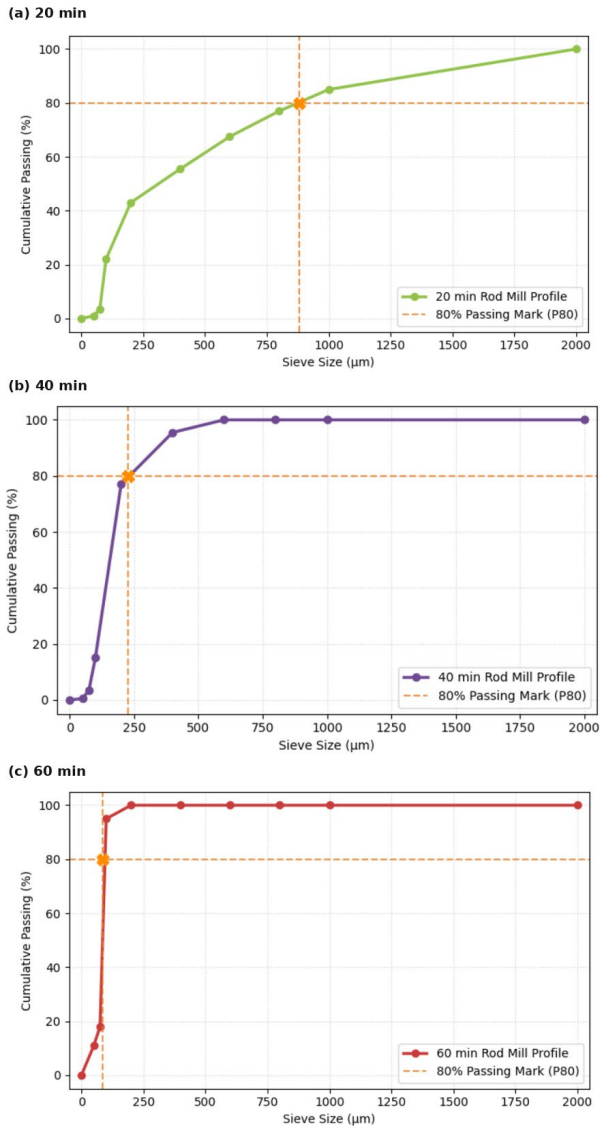


Fig 3: Cumulative particle size distribution profile after microwave pretreatment.

C. Particle-size distribution without microwave pre-treatment

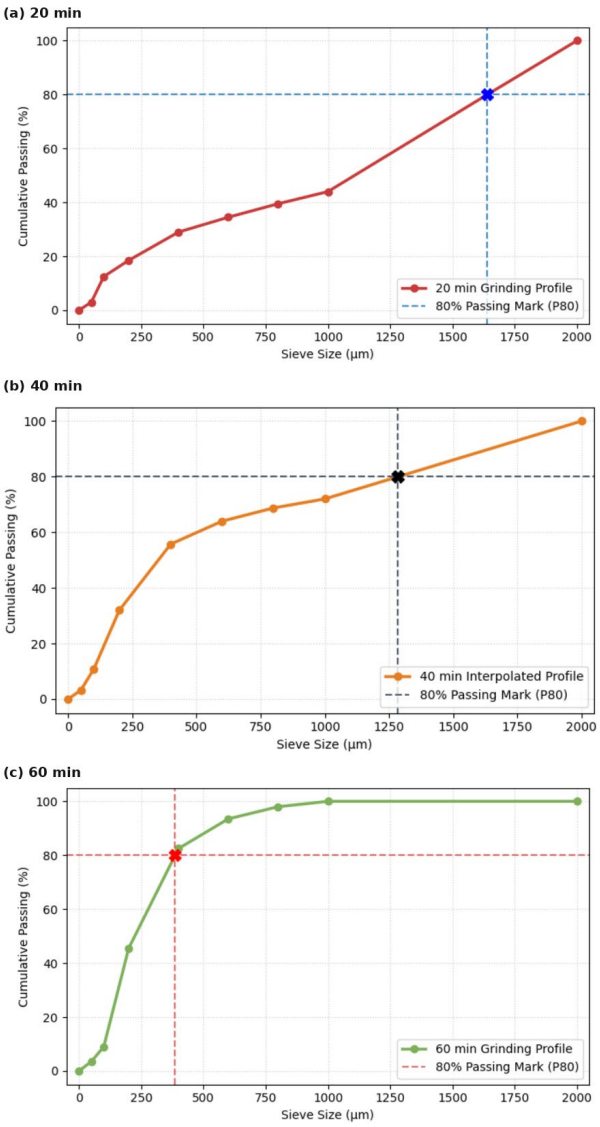


Fig. 4: Cumulative particle size distribution profile without microwave pretreatment.

After microwave pretreatment, the size fraction curves show a progressive shift towards finer sizes with increasing grinding time (Fig 3). The P80 decreased from approximately 850 µm at 20 min to 220 µm at 40 min and 80 µm at 60 min. The greatest reduction occurred between 20 and 40 min, corresponding to a decrease of approximately 74%, compared with 64% between 40 and 60 min. This trend is consistent with the evolution of particle-size distributions during comminution, in which continued grinding promotes particle breakage and the generation of finer fractions [28]. These results also confirm that microwave pretreatment significantly enhances grindability, allowing for the production of a much finer product in a shorter time frame.

The cumulative particle size distribution profiles for the untreated ore samples, presented in Fig. 4, demonstrate a clear inverse relationship between grinding duration and particle size reduction. After 20 min grinding time, the P80 was found to be 1,600 µm, the 40 min about 1,300 µm, and the 60 min about 350 µm. This trend depicts a size reduction of course particles to finer ones. Specifically, the P80 decreased from approximately 1650 µm at 20 minutes to 1300 µm at 40 minutes, before dropping sharply to roughly 400 µm at 60 minutes. The latter substantial reduction in the size fraction confirms that extended grinding times does effectively enhance the liberation of finer particles which is a critical factor for optimizing downstream mineral processing efficiency.

D. XRF composition after grinding

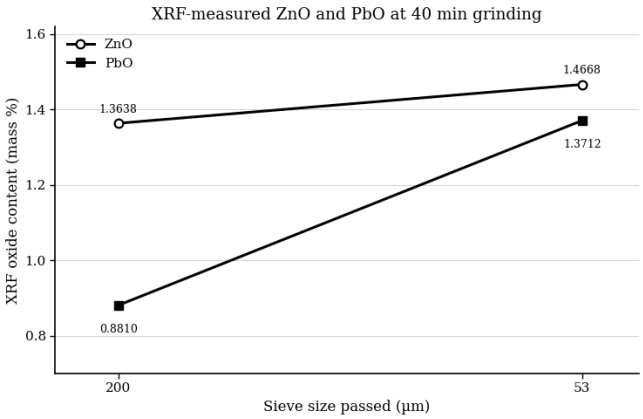


Fig. 5: XRF analysis showing ZnO and PbO oxide content vs. sieve size passed for a 40 min grinding cycle.

Fig. 5 shows an increase in the measured ZnO and PbO contents as the sieve size decreased from 200 to 53 µm following 40 min of grinding. The ZnO content increased from 1.3638 to 1.4668 mass %, corresponding to an absolute increase of approximately 7.55% relative to the initial value. A high metal content was observed for PbO, which increased from 0.8810 to 1.3712 mass %, representing an increase of approximately 55.64%. The data shows that ZnO and PbO reported the highest content at the finer 53 µm fraction**.** Therefore, grinding can promote the breakage of composite particles, expose previously enclosed mineral phases, and alter the distribution of mineral bearing particles among different size fractions.

E. SEM evidence of microstructural features

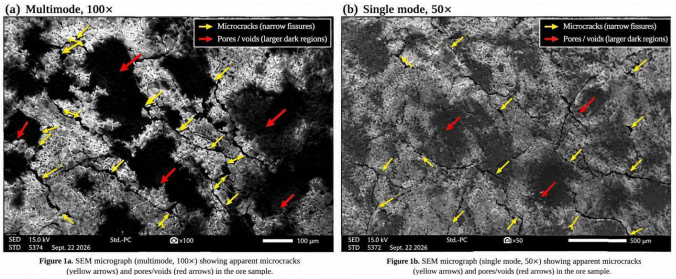


Fig. 6: SEM micrographs labelled as post-pretreatment material: (a) multimode, 100×, 100 µm scale bar; (b) single mode, 50×, 500 µm scale bar.

The SEM micrographs presented in Fig. 6 provide critical microstructural evidence of the physical changes induced by microwave pretreatment, which directly explain the enhanced grindability observed in the particle size distribution analysis. For the multimode microwave operating at a power output of 1800 W, as shown in Fig. 6a, reveals a highly fractured and porous mineral matrix, characterized by an extensive network of both narrow microcracks indicated by yellow arrows and larger pores/voids indicated by red arrows. In comparison to the single-mode microwave operating at 1000 W, the treated sample as shown in Fig. 6b exhibited a comparatively less fractured surface, characterised by fewer and more spatially isolated microcracks and pores than the multimode-treated sample. The observed fractures appear less interconnected, suggesting a lower degree of visible surface damage under the specific treatment conditions investigated. However, this qualitative observation does not establish the inherent superiority of multimode treatment, as microwave induced damage is influenced by power density, exposure duration and ore mineralogy [29].

IV. DISCUSION

A comparative analysis of the particle size distribution profiles for the microwave-pretreated (Fig 3) and untreated (Fig. 4) ore samples reveal that microwave irradiation significantly enhances grinding efficiency and promotes finer comminution. While both datasets exhibit the expected inverse relationship between grinding time and particle size, the magnitude of size reduction is markedly greater in the pretreated samples across all tested intervals. For the untreated ore, the P80 decreased from approximately 1650 µm at 20 minutes to 400 µm at 60 minutes. In stark contrast, the microwave-pretreated ore achieved a substantially finer product, with the P80 dropping from roughly 880 µm at 20 minutes to just 140 µm at 60 minutes. Notably, the 20-minute P80 of the pretreated ore (880 µm) is finer than the 40-minute P80 of the untreated ore (1300 µm), indicating that microwave pretreatment can achieve comparable or superior size reduction in half the grinding time. Furthermore, the microwave pretreated ore curves display a steeper slope at coarser sieve sizes, suggesting that microwave induced fractures along mineral grain boundaries facilitate rapid breakage and reduce the energy required for liberation. These findings demonstrate that microwave pretreatment is an effective method for improving ore grindability, potentially leading to significant reductions in grinding time and energy consumption in downstream processing operations.

These microstructural observations correlate strongly with the grinding performance data. The extensive microcrack network in the microwave sample depicted in Fig. 6 would significantly weaken the ore matrix, reducing its mechanical strength by facilitating rapid crack propagation during grinding. This explains why the microwave pretreated ore achieved a much finer P80 at shorter grinding times compared to the untreated samples. Therefore, the untreated ore sample as shown in Fig. 4 require more grinding energy to achieve comparable size reduction. The SEM analysis confirms that microwave pretreatment effectively preconditioned the ore by creating abundant microcracks and voids, thereby enhancing grindability and reducing downstream processing energy requirements.

V. CONCLUSION

This study demonstrated that microwave pretreatment substantially improves ore grindability by inducing microstructural damage in the form of microcracks and pores. Comparative analysis of particle size distribution profiles revealed that pretreated samples achieved significantly finer products compared to untreated ore. SEM micrographs confirmed that multimode microwave treatment generated more extensive and interconnected fracture networks than single-mode treatment, providing a mechanistic explanation for enhanced comminution. These findings indicate that microwave pretreatment, especially in multimode

configuration, is a promising approach for reducing grinding time and energy consumption in mineral processing operations. Future work should optimize microwave parameters and quantify energy savings at industrial scale.

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