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Research Paper

Innovative comminution strategies for optimizing mineral concentrate quality, grade, and recovery rates

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ABSTRACT

Purpose: Geological characterization preceded the essential crushing and grinding operations to facilitate effective mineral liberation. By examining breakage mechanisms including impact loading, compressive stress, shear forces, attrition, and non-mechanical disintegration pathways, this study quantifies energy consumption parameters ranging from 5 to 25 kWh per tonne, underscoring comminution's pivotal role as the primary ore dressing stage.
Design/methodology/approach: The research extensively investigates mineral liberation phenomena, particle size distribution evolution, and the downstream implications of comminution on mineral concentration and flotation performance, drawing comparisons with established methodologies such as mine-to-mill optimization frameworks.
Findings: The findings advocate for the mineral processing sector to embrace forward-looking paradigms that integrate advanced technological solutions and innovative operational approaches to ensure sustainable and efficient mineral resource exploitation.
Originality: State-of-the-art technological interventions enhance mineral separation efficiency and metal extraction yields, promoting environmental stewardship and sustainable raw material utilization.
Practical implications: This synthesis emphasizes the fundamental importance of efficient comminution practices, accounting for economic considerations, energy demands, and ore-specific characteristics, while advocating for progressive size reduction technologies.
Social implications: Technological innovations including Autogenous Grinding (AG) and Semi-Autogenous Grinding (SAG) milling systems demonstrate significant operational advancements, with contemporary studies evaluating their effects on mineral recovery kinetics.
Keywords: *innovative size reduction practices; mineral recovery rates; mineral processing; comminution efficacy; comminution strategies; comminution technologies*

1. Introduction

Mineral processing represents a fundamental pillar of the global mining industry, serving as the critical interface between raw ore extraction and valuable metal production. Within this domain, comminution the sequential reduction of particle size through mechanical crushing and grinding operations consumes the predominant share of processing energy, typically accounting for 50-70% of total operational power requirements (Matsanga et al., 2023). The efficiency and effectiveness of size reduction processes directly govern downstream separation performance, ultimately determining concentrate grade, metal recovery rates, and overall process economics. The optimization of comminution circuits has garnered increasing attention as mining operations confront declining ore grades, escalating energy costs, and stringent environmental regulations. Traditional comminution approaches, while historically effective, often fail to achieve optimal liberation characteristics required for modern high-efficiency concentration processes. Contemporary mineral processing demands innovative size reduction strategies that balance energy consumption against liberation requirements, particle size distribution specifications, and downstream metallurgical performance (de Bakker, 2014). This comprehensive review investigates cutting-edge comminution methodologies applied to ore samples derived from a significant mineral deposit. Through systematic evaluation of grinding media configurations, residence time optimization, and advanced breakage characterization, this study aims to establish evidence-based guidelines for comminution circuit design. The research integrates theoretical understanding with practical operational parameters, providing actionable insights for industry practitioners seeking to enhance processing efficiency while minimizing environmental impact.

1.1. Comminution Fundamentals and Energy Considerations

Comminution encompasses the progressive reduction of solid material particle dimensions through the application of external mechanical forces. The process fundamentally relies on the creation and propagation of microcracks within mineral grains, ultimately leading to fracture and size reduction. Bond's Third Theory of Comminution provides the foundational mathematical framework relating energy consumption to particle size reduction, expressed through the Work Index (Wi) concept that quantifies ore resistance to grinding (Aldrich, 2013). The Wi is expressed in kWh per tonne (kWh/tonne or kWh/t), representing the energy required to reduce ore from theoretically infinite size to 80% passing 100 μm.

Energy consumption within comminution circuits represents a primary operational cost driver, with published values ranging from 5 kWh per tonne for relatively soft, easily fractured ores to exceeding 25 kWh per tonne for competent, abrasive ore types (Daniel et al., 2010). These variations reflect differences in ore hardness, mineralogical complexity, feed particle dimensions (F80), and target product specifications (P80). The energy efficiency of comminution processes has become increasingly scrutinized as operations seek to reduce carbon footprints and operational expenditures simultaneously.

1.2. Comminution Breakage Mechanisms in Size Reduction

Mineral particle fracture occurs through multiple distinct mechanisms, each producing characteristic breakage products and energy consumption profiles. Impact breakage generates rapid stress application through collision events, typically producing relatively coarse fragments with minimal fines generation. Compression breakage, dominant in jaw and gyratory crushing operations, applies gradual increasing stress until fracture initiation, producing more uniform product distributions (Zhang et al., 2023).Shear and attrition mechanisms become increasingly significant in fine grinding applications, where particle-particle and particle-media interactions generate abrasion and chipping rather than catastrophic fracture. Attrition breakage selectively targets mineral grain boundaries, potentially enhancing liberation characteristics for complex polymetallic ores as shown in Fig. 1. Understanding the dominant breakage mode within specific equipment configurations enables targeted optimization of operating parameters to achieve desired product specifications.

1.3. Advanced Comminution Technologies

High-Pressure Grinding Rolls (HPGR) technology has emerged as a transformative advancement in tertiary and quaternary crushing applications. Operating through inter-particle compression between counter-rotating rolls, HPGR systems achieve significant energy savings compared to conventional tumbling mills while generating microcracks that enhance downstream grindability (Morley, 2006). The technology demonstrates particular advantages for competent ores where conventional grinding proves energy-intensive.

Autogenous (AG) and Semi-Autogenous Grinding (SAG) mills represent another significant technological evolution, utilizing the ore itself as grinding media within large-diameter rotating mills. AG mills rely exclusively on coarse ore particles for grinding action, while SAG mills incorporate supplementary steel media to enhance breakage kinetics as depicted in Fig. 2. These systems eliminate or reduce grinding media costs while accommodating large feed sizes directly from primary crushing circuits (Morrell, 2004).

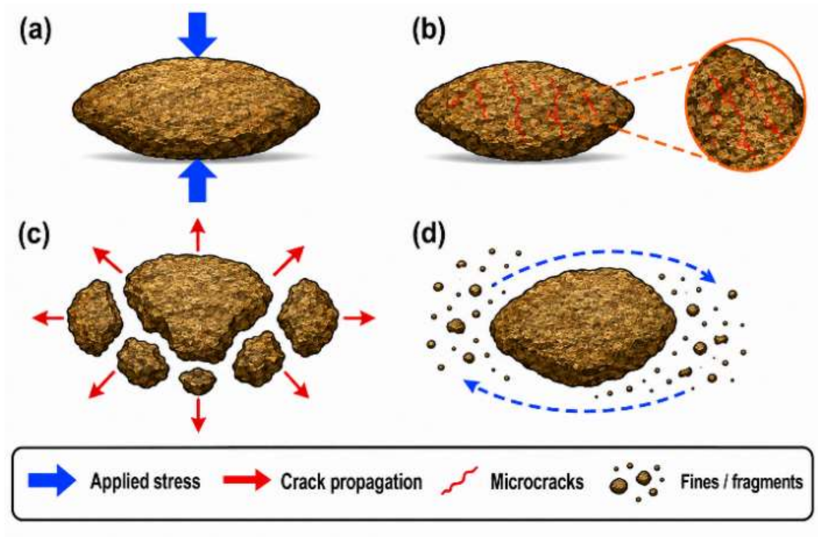

Fig. 1. Fundamental breakage mechanisms in mineral comminution: (a) Parent particle under stress; (b) Fatigue microcrack development; (c) Fracture propagation and (d) attrition/ shear (chipping) phenomena.

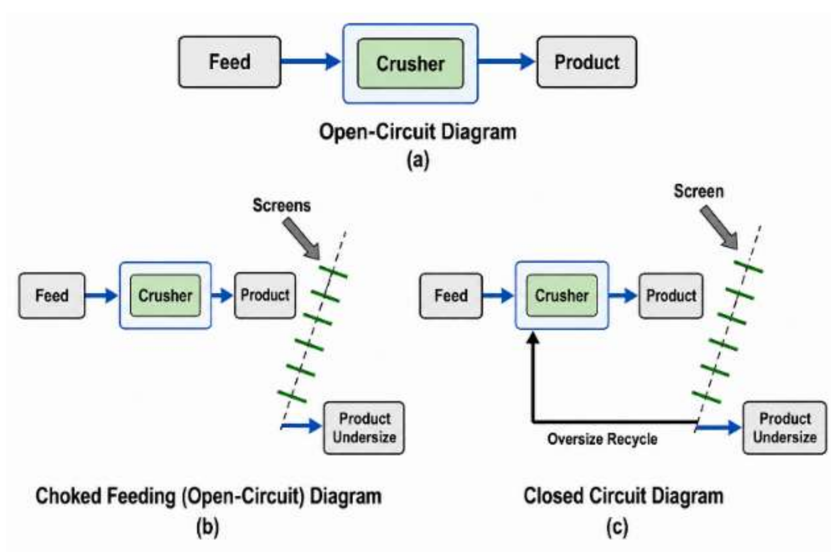

Fig. 2 - Comminution circuit configurations: (a) Open-circuit crushing; (b) Choked-feed open-circuit operation; (c) Closed-circuit crushing with screen classification and oversize recycle.

1.4. Mine-to-Mill Optimization Concepts

The mine-to-mill (M2M) optimization philosophy represents a paradigm shift from isolated optimization of individual unit operations toward holistic value chain optimization. By recognizing the interdependencies between blasting fragmentation, crushing efficiency, grinding performance, and downstream separation, M2M approaches identify opportunities for substantial energy and cost savings that remain invisible when optimizing individual process stages in isolation (Valery et al., 2019).

Optimized blasting practices that generate finer primary fragmentation reduce crushing and grinding energy requirements while potentially improving liberation characteristics. The integration of blasting parameters with comminution circuit design exemplifies the systems-thinking approach essential for maximizing overall resource utilization efficiency.

2. Methodology and Methods

2.1. Ore Sample Characterization

Representative ore samples were obtained from a mineral deposit exhibiting complex polymetallic mineralization. Initial geological characterization established the ore body composition, mineralogical associations, and grain size distributions. The ore exhibited moderate hardness characteristics with significant variability in competence across the deposit, necessitating comprehensive comminution testing to establish design parameters. Sample preparation followed established protocols to ensure representativeness while eliminating segregation and contamination. Composite samples were prepared through systematic crushing, splitting, and homogenization procedures. Mineralogical analysis provides detailed liberation characteristics and mineral association data.

2.2. Comminution Procedures

Bond Ball Mill Work Index determinations were conducted following standardized procedures to quantify ore grindability and establish baseline energy requirements for conventional ball milling circuits. The test procedures involved closed-circuit grinding at varying screen sizes, with energy consumption recorded throughout the testing sequence (Aldrich, 2013). The Wi was was calculated in kWh/tonne according to Bond's Third Theory equation.High-Pressure Grinding Roll (HPGR) testing was conducted to evaluate energy-efficient size reduction through inter-particle compression. The HPGR experimental parameters were systematically controlled as follows: (1) Specific pressing force: 3.5 to 4.5 N/mm² (tested at increments of 0.25 N/mm²); (2) Roll speed: 0.5 to 1.2 m/s (variable frequency drive controlled); (3) Feed moisture content: 3% to 7% by weight (monitored continuously); (4) Feed size (F80): 25-35 mm; (5) Target product size (P80): 3-5 mm for pre-grinding applications. Tests were conducted across varying specific grinding force levels to establish optimal operating windows for the ore sample (Wu et al., 2023). Laser diffraction particle size analysis characterized product distributions from various comminution approaches, providing detailed quantification of particle size distributions across the full size range from millimeter to sub-micrometer scales. This analytical technique enabled precise evaluation of the fine's generation characteristics associated with different breakage mechanisms as shown in Fig .3.

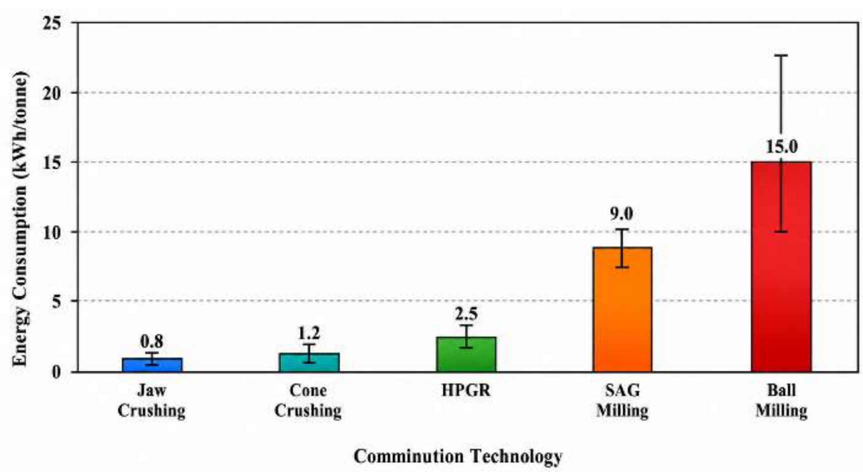

Fig. 3 - Comparative bar chart showing energy consumption values (kWh/tonne) for different comminution technologies including jaw crushing, cone crushing, HPGR, SAG milling, and ball milling.

3. Results and Discussion

3.1. Comminution Performance Evaluation

The experimental program quantified significant variations in energy efficiency across different comminution approaches. Bond Work Index determinations indicated moderate ore resistance to grinding, with values ranging from 12.5 to 18.3 kWh/tonne depending on the specific ore zone sampled shown in Fig.3. These results established baseline expectations for conventional ball mill circuit design while highlighting opportunities for alternative comminution strategies (Daniel, 2007).

HPGR testing demonstrated substantial energy advantages compared to conventional tertiary crushing and early-stage grinding. Specific energy consumption reductions of 15-25% were achieved while simultaneously generating product distributions with significantly enhanced microcracking. The microcrack networks developed during HPGR processing improved subsequent ball mill throughput by 8-12%, effectively amplifying the initial energy savings through downstream benefits (Saldaña et al., 2023).

3.2. Particle Size Distribution and Liberation Characteristics

Laser diffraction analysis revealed distinct particle size distribution patterns associated with different breakage mechanisms. Impact-dominated breakage produced relatively coarse, uniform distributions with minimal ultra-fines generation as shown in Fig.4. Conversely, attrition and abrasion processes generated broader distributions with significant sub-micrometer particle populations. These distribution characteristics have important implications for downstream separation efficiency, as flotation kinetics and selectivity are strongly influenced by particle size (Jameson, 2012).

Liberation analysis quantified the relationship between particle size and valuable mineral exposure. As anticipated, liberation increased with decreasing particle size, though the relationship exhibited significant non-linearity. A critical particle size range was identified below which liberation improved dramatically, suggesting the presence of composite particles containing intergrown valuable and gangue minerals depicting in Fig. 5. This liberation data provided essential input for optimizing the trade-off between grinding energy consumption and separation efficiency (Suyantara et al., 2018).

3.3. Metallurgical Performance Implications

The comminution optimization directly influenced downstream flotation performance through its effects on particle size distribution and mineral liberation. Optimized grinding protocols that achieved target particle size distributions while minimizing over-grinding improved flotation kinetics and selectivity. Comparative flotation testing demonstrated that HPGR-treated feed material achieved equivalent metal recovery at coarser grind sizes compared to conventionally crushed feed, translating to significant energy savings in the grinding circuit (Fosu et al., 2015).

The relationship between concentrate grade and metal recovery exhibited the characteristic trade-off pattern, with comminution optimization shifting the

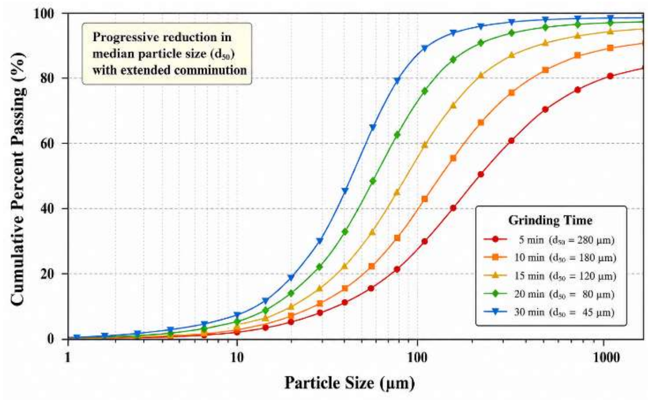

Fig. 4 - Evolution of particle size distribution with grinding time, demonstrating the progressive reduction in median particle size and broadening of the distribution during extended comminution.

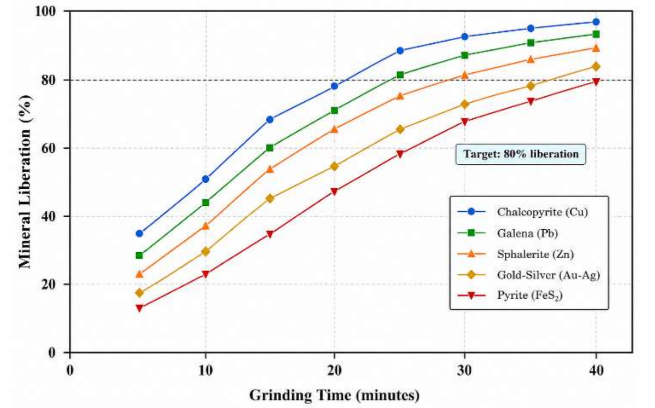

Fig. 5 - Mineral liberation progression as a function of grinding time, illustrating the differential liberation characteristics of various mineral phases within the composite ore.

grade-recovery curve toward more favorable operating positions. By achieving superior liberation at equivalent or reduced energy inputs, the optimized comminution strategy enabled operation at higher recovery levels without unacceptable grade dilution, or alternatively, higher concentrate grades without significant recovery penalties as represented in Fig.6.

3.4. Comparative Technology Assessment

Comprehensive techno-economic evaluation compared the optimized comminution circuit incorporating HPGR pre-treatment with conventional crushing-grinding configurations. The analysis incorporated capital costs, operating expenses, energy consumption, and metallurgical performance to generate holistic value assessments. Despite higher initial capital requirements, the HPGR-based circuit demonstrated superior net present value (NPV) due to sustained operational savings and improved metal recovery shown in Fig.7.

The mine-to-mill optimization potential was quantified through integration of blasting fragmentation data with comminution circuit modeling. Simulation results indicated that optimized blast designs generating finer primary fragmentation could reduce total comminution energy requirements by 8-15% while simultaneously improving feed grade consistency and downstream process stability.

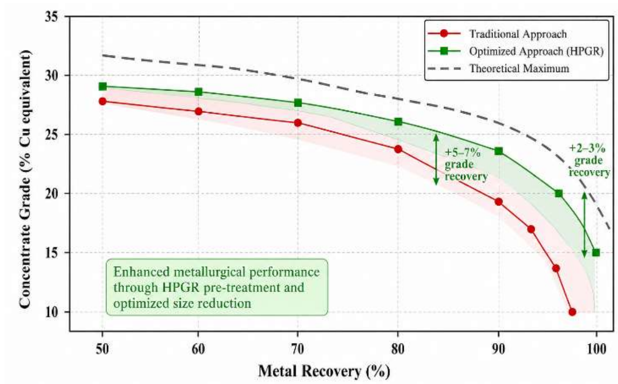

Fig.6 - Grade-recovery relationships comparing optimized comminution approaches with conventional methodologies: demonstrating enhanced metallurgical performance achievable through innovative size reduction practices.

Conclusions

This comprehensive investigation of innovative comminution strategies for ore samples demonstrates the substantial potential for optimization within mineral processing operations. The research establishes that advanced size reduction technologies, particularly HPGR systems and optimized grinding media configurations, can achieve significant energy savings while simultaneously improving metallurgical performance through enhanced mineral liberation characteristics.

Key findings confirm that energy consumption within comminution circuits can be substantially reduced from the typical 5-25 kWh per tonne range through strategic technology selection and operating parameter optimization. The integration of HPGR pre-treatment demonstrated energy reductions of 15-25% while generating microcrack networks that improved downstream grindability and flotation response. These benefits compound across the value chain, amplifying initial energy savings through enhanced processing efficiency.

The study highlights the critical importance of matching comminution intensity to liberation requirements rather than applying uniform grind sizes across all ore types. Differential liberation characteristics of valuable minerals within complex polymetallic ores necessitate tailored comminution approaches that optimize the grade-recovery relationship specific to each mineral assemblage.

Mine-to-mill optimization concepts emerge as essential frameworks for maximizing resource utilization efficiency. By integrating blasting fragmentation characteristics with comminution circuit design, operations can achieve holistic improvements that remain invisible when optimizing individual unit operations in isolation. This system-thinking approach is essential for sustainable mineral processing in an era of declining ore grades and escalating environmental expectations.

The mineral processing industry is urged to embrace a future-ready paradigm that integrates advanced technologies, innovative operational approaches, and comprehensive sustainability considerations. Cutting-edge comminution technologies contribute not only to enhanced mineral separation and metal extraction efficiency but also to environmental conservation and responsible raw material stewardship. Technological intervention and process modeling

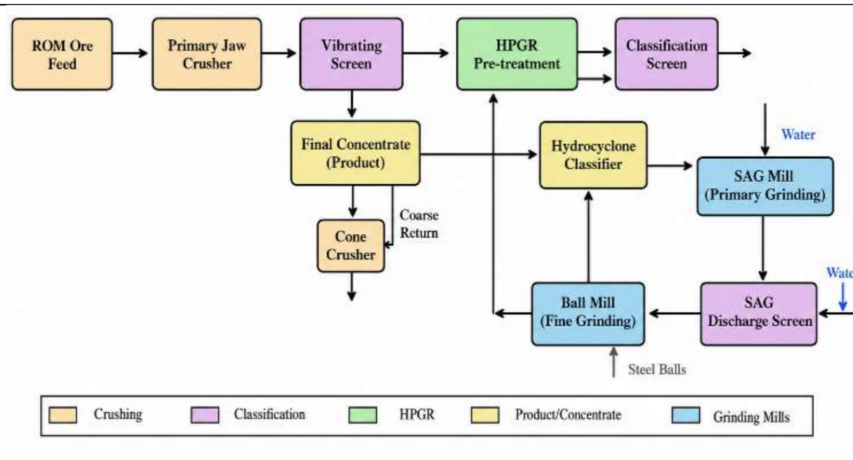

Fig. 7 - Optimized comminution circuit flowsheet integrating HPGR pre-treatment with SAG/ball mill grinding for enhanced energy efficiency and metallurgical performance.

emerge as strategic imperatives for achieving optimal grade-recovery relationships while meeting evolving environmental and social governance standards.

Future research directions should focus on intelligent comminution systems incorporating real-time ore characterization, adaptive control strategies, and predictive modeling to dynamically optimize size reduction processes. The integration of artificial intelligence and machine learning with traditional comminution engineering promises further advances in energy efficiency and metallurgical performance. The findings presented herein provide a foundation for these continued innovations, contributing to ongoing efforts to enhance mineral processing efficacy across the entire mineral value chain.

Author Contributions

Arsalan Ahmad: Conceptualization, Methodology, Writing – Original Draft, Data Curation, Software. **Farhan Ahmad:** Validation, Formal Analysis, Investigation, Writing – Review & Editing, Visualization. **Muhammad Faizan Ahmad:** Formal Analysis, Investigation, Visualization.

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Conflicts of Interest Statement

The authors declare no competing financial or non-financial interests, nor any personal relationships, that could influence the work reported herein.

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Nomenclature

AG	Autogenous Grinding
SAG	Semi-Autogenous Grinding
HPGR	High-Pressure Grinding Rolls
Wi	Bond Work Index (kWh/tonne or kWh/t)
F80	Feed size at 80% passing (μm)
P80	Product size at 80% passing (μm)
E	Specific energy consumption (kWh/tonne)
M2M	Mine-to-Mill
PSD	Particle Size Distribution
t8/5	Cooling time from 800°C to 500°C (s)

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