Minerals Engineering 204 (2023) 108419

Contents lists available at ScienceDirect

Minerals Engineering

journal homepage: www.elsevier.com/locate/mineng

Commercialisation pathway for low energy wet/dry gyratory rolls crusher comminution technology

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ARTICLE INFO

Keywords:
Comminution
Crushing
Energy efficiency
Dry processing
GRolls®
HPGR
Commercialisation

ABSTRACT

Comminution for mining and cement industries accounts for over 2 % of global energy consumption and an innovative Gyratory Rolls Crusher (GRolls®) technology has been developed in South Australia to reduce energy and water consumption, providing dry and wet crushing from ~ 20 mm to 20 µm fractions without media, replacing up to two stages of size reduction. The GRolls® is a compression based particle size reduction device, designed to generate fine and ultra-fine products from coarse feeds, by simultaneously applying pulsed compression and shear forces to a packed particle bed. The breakage mechanisms initiated by these forces include compression breakage, inter-particle compression, induced tensile failure and particle shear forces generated by a gyrating roll.

The paper presents the commercialisation pathway of the GRolls® technology, from "proof of concept" laboratory scale Alpha prototype and concept design of an upscaled Beta prototype for a pilot plant. A systematic progression of laboratory scale testing of a wide range of feed materials through the Alpha prototype was undertaken to confirm the "'proof of concept" design and identify the many design variables and operational configurations that affect the GRolls® crushing and energy performance. The test results were evaluated against currently available comminution solutions such as the High Pressure Grinding Rolls (HPGR) and Vertical Rolls Mill (VRM) in which the mining section is moving towards to provide more economical dry comminution and a progression towards partial to full dry process flowsheets.

The commercialisation pathway has confirmed the broad performance range and energy consumption of the GRolls® which could be modularised in the near future to support new and existing low grade mining operations in remote areas restricted by limited water and power infrastructure.

1. Introduction

Comminution is the reduction of solid materials from large to smaller particle sizes by crushing, grinding or milling. Comminution for mining accounts for approximately 1 % of the total global power consumption and generates similar levels of green house gas emissions (Engeco, 2021). In a typical mining operation comminution circuits may account for around 50 % of its power consumption, with power accounting for around 10 % of operating costs and grinding consumables (media) accounting for up to 30 % of operating costs. In cement production, grinding accounts for nearly 70 % of their operating power cost (ECRA, 2015), and a further 1 % of global power consumption.

Mine operators are seeking continual capital and operating cost reductions to stay competitive, increasing power efficiencies from their comminution circuits and lower water demands to meet stricter regulatory requirements, higher environmental sustainability and community expectation levels (Luukkanen et al., 2022). Mining operations are also becoming more remote as global resources are exhausted, with new lower grade mining operations generally having limited access to water and power infrastructure.

Energy efficient crushing technology currently extends down to around the 1–10 mm particle size, below which attrition and grinding circuits are used to achieve fine grind sizes below 100 µm (µm). Grinding equipment such as ball mills, semi-autogenous grinding (SAG) mills, autogenous grinding (AG) mills and stirred media mills can account for a large portion of the mine operations power requirements, are wet

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https://doi.org/10.1016/j.mineng.2023.108419
Received 13 May 2023; Received in revised form 25 August 2023; Accepted 23 September 2023
Available online 10 October 2023

processes and use media. The mining sector is moving towards greater use of High Pressure Grinding Rolls (HPGR) and Vertical Rolls Mills (VRM) to provide more economical dry comminution and a progression towards dry process flowsheets (Gerold et al., 2012). The ability to undertake mineral processing using dry circuits reduces the amount of water needed for processing and concentration, which could lead to the elimination of tailings storage facilities that cover large surface areas and reduce the risk of catastrophic failures. Dry processing can reduce energy consumption but also can result in improved mineral recovery (Katzmarzyk et al., 2019).

An example is the new flowsheet developed for the OZ Minerals West Musgrave copper nickel deposit in Western Australia, where dual VRM's replace traditional SAG and ball mill circuits prior to flotation and separation circuits. The dry flow sheet has eliminated the need for media, improved flotation recovery and reduced power consumption by 15 % sufficiently for the project to be powered by 70 % renewable energy sources (OZ Minerals, 2020).

HPGR's and VRM's were developed in the cement industry and then are progressively being applied to dry process applications in the mining industry. Any new comminution technology for application in the mining or cement industry would progress through a commercialisation pathway to validate the technology. Technology Readiness Level (TRL) index (Fig. 1, CSIRO, 2023) is a globally accepted benchmarking tool for tracking progress for new technologies from blue sky research (TRL1) to actual system demonstration and commercial applications (TRL9).

This paper presents the commercialisation pathway of GRolls® technology, from "proof of concept" Alpha prototype (TRL3) to laboratory scale testing (TRL4 and TRL5) and upscaled Beta prototype for a pilot plant (TRL6 and TRL7).

2. Concept design

In 2017 a concept design (TRL3) for a Gyratory Rolls Crusher (GRolls®) was developed in Adelaide Australia by Mr Chris Kelsey based on his over 60 years experience in the mining industry. A company CBSM Mining Services Pty Ltd was formed in 2018 to commercialise the GRolls® technology. The shareholders identified a growing industry need for comminution units capable of operating in both dry and wet conditions, and reducing coarse feed (i.e. < 20 mm) into fine and ultra-fine particle sizes (e.g. < 100 μm), appropriate for first stage beneficiation. The target for the GRolls® is to achieve less than 30 kWh/t energy consumption and greater than 30 % product (product being 80 % less than a target particle size, i.e. P80 < 75 μm) discharge in a single pass for a variety of wet or dry feed materials which will be more efficient and versatile than a wide range of current comminution industry solutions.

The GRolls® technology is a unique combination of load mechanisms designed to generate fine and ultra-fine products from coarse feeds, by simultaneously applying pulsed compression and shear forces to a packed particle bed (Fig. 2). The breakage mechanisms initiated by these forces include compression breakage, inter-particle compression, and particle shear forces generated by a gyrating roll – thus inducing and enhancing particle tensile failure. Cyclic compression stress (σ_E) is generated as the gap is closed and opened between the rollers due to the eccentric shaft, and steady compression (P) is generated as the material is drawn through the gap. The shearing stress (τ_E) are generated due to particles moving across the opposing faces of the rollers and due to the relative cyclic gyratory motion of the rollers. There is also a shear stress (τ_{RS}) acting in an orthogonal direction from the differential speed of the rollers. At most locations between the rollers all of these mechanisms can happen simultaneously and at a frequency determined by the oscillation speed.

The GRolls® technology consists of a "v" profiled main rotating roll and an opposing gyratory roll with an intermeshing "v" profile (Fig. 3). The chevron roller configuration generates multiple crushing chambers for wet and dry feed materials within a single unit, which minimises skewing and edge effects common with HPGR's and should result in wear being limited to the roller surfaces.

The main rotating roll is driven through a gearbox, while the gyratory roll is mounted on a shaft with an eccentric off-set to generate the gyratory motion which periodically varies the size of the crushing gap. The eccentric off-set is equivalent to an open and closed size setting for a cone crusher, with off-sets of < 0.1 mm targeting particle generation of < 100 μm. The gyratory roll is compressed against the main driven roller, rotates freely in mesh with the main driven roll as feed enters the crusher, and requires a relief mechanism to prevent the intermeshed rollers from jamming. The gyratory motion generates a high frequency pulsing action which initiates particle breakage, with the oscillation speed varied to achieve a target of around 100 compressions of the gyratory roller for each rotation of the driven main roller (around 3° to 4° of rotation).

3. Alpha prototype

A laboratory scale Alpha prototype (TRL4) unit (GRolls400) was designed and built (see Fig. 4 and Fig. 5) to validate the concept design and undertake multi-commodity feed material trials (real-world testing, TRL5). The unit comprised a 7.5 kW motor with belt drive linked to the main roller and 5 kW motor belt drive for the oscillating rollers, with the rollers being 400 mm in length (hence GRolls400 naming) and having a diameter of 250 mm. The oscillating roller is mounted on a pivoting table activated by pneumatic artificial muscles such that forces applied to the rollers can be applied and released as required. Discharge from the lab unit was either to a under bin or a cyclone/classifier system. The Alpha unit design was undertaken using 2D Computer Aided Drafting (CAD) methods to provide a low cost unit to undertake validation testing of the concept.

The validation testing was conducted on a dry silica sand (<400 μm) feed material under different unit configurations and operating conditions to provide essential baseline data to improve the laboratory scale unit and also to compare against existing comminution equipment. Laser sizing of feed and discharge materials via a cyclone/classification system was used to assess the Alpha GRolls® unit performance during the following varying test conditions:

- Eccentric off-set distances (0.5 mm. 0.2 mm and 0.1 mm).
- Oscillation direction (anticlockwise, clockwise and no oscillation).
- Speed (rpm) of oscillation (gyration).
- Speed (rpm) of driven main drive.
- Material feed rates (slow to fast).
- Recirculated feed (classifier oversize and full discharge).
- Roller pressure applied by pneumatic artificial muscles.

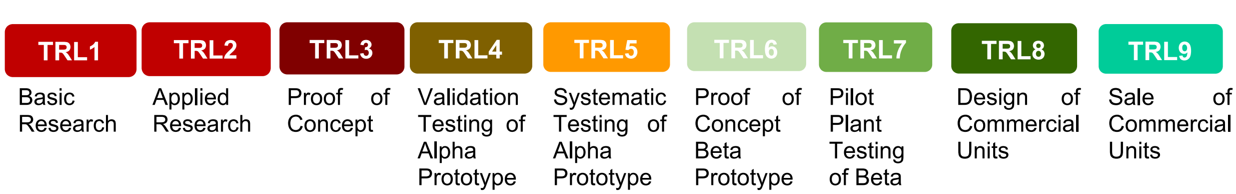

Fig. 1. Technology Readiness Levels (TRL), (CSIRO, 2023).

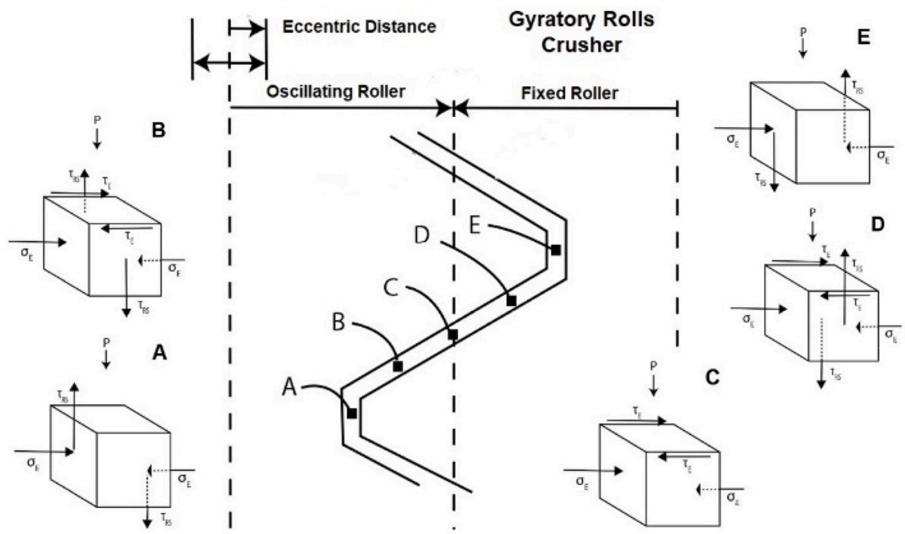

Fig. 2. GRolls® Crushing Chamber Loads.

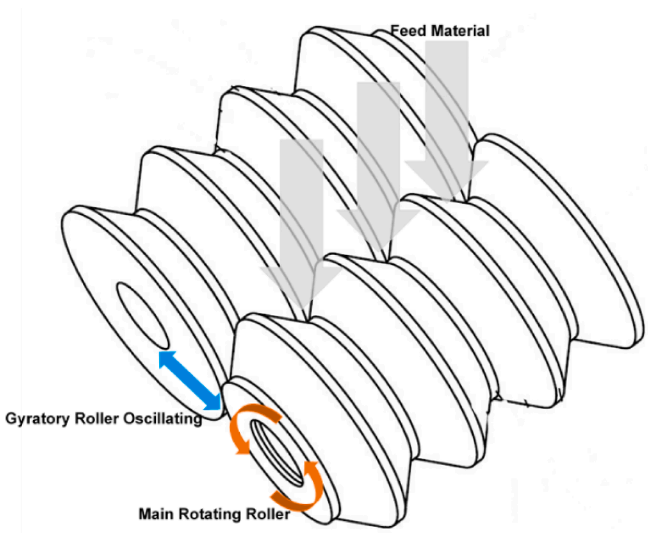

Fig. 3. Concept Design of GRolls®.

Fig. 4. Roller configuration for GRolls®.

The validation testing confirmed that the GRolls® concept can achieve size reductions in dry testing but also importantly identified weaknesses in the unit configurations and designs, resulting in modifications to the frame, bearings, drive and feed systems.

4. Systematic laboratory testing

Systematic laboratory scale testing (TRL5) of the Alpha GRolls® unit on silica sand, slag, limestone (maximum particle size 20 mm and < 10 mm) and magnetite ore (<10 mm) feed materials under different configurations was conducted to demonstrate and validate the size reductions for a range of dry feed materials. Testing conditions were documented and photographic/video recordings undertaken of all tests conducted. The feed and discharge materials were analysed using laser sizing unit and sieves to determine the size reduction performances, with independent particle size distribution testing conducted on all feed materials and validating the laser sizing data of discharge materials.

A summary of the grading performance of the GRolls® is presented in Fig. 6 which clearly demonstrates the large and consistent size reduction performance over a range of feed materials. The fines (<75 µm) generated during a single pass ranged from 19 % to 38 %. Limestone (specific

Fig. 5. Laboratory scale GRolls® GRolls400 unit.

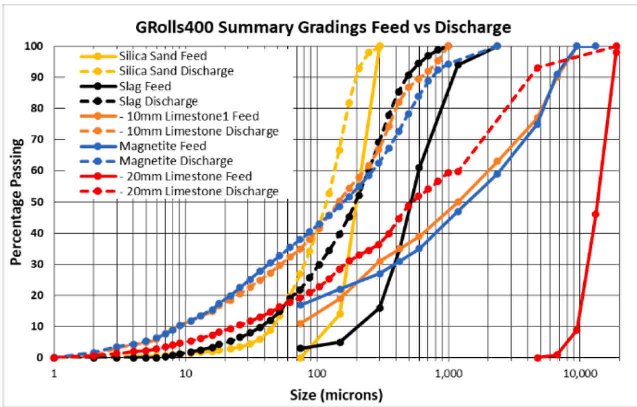

Fig. 6. GRolls® Gradings Summary Feed vs Discharge.

gravity of 2.65 g/cm^3) and magnetite ore (specific gravity of 3.38 g/cm^3) materials of a similar feed size generated similar product gradings as shown in Fig. 7, even though they have different densities and hardness properties. Given those similar results, extensive testing programs using limestone feed may replicate testing of magnetite ore feed provided by clients in small quantities.

The magnetite ore material was tested as different size fractions (<10 mm and < 3 mm) which resulted in similar discharge curves and 38 % <75 μm (Fig. 8). The < 10 mm magnetite result is further compared in Fig. 9 against published data from a similar magnetite ore processed by a HPGR presented in Baawuah et al (2020), showing fines generation of 38 % <75 μm for the GRolls® against 18 % <75 μm for a HPGR.

The limestone material was further tested varying the size fractions, with 29 % to 38 % <75 μm generated from feed with fines which ranged from maximum size of 2.36 mm to 10 mm (Fig. 10), whilst 20 % to 25 % <75 μm generated from feed with a range of fractions from − 20 + 9.5 mm to − 6.7 + 2.36 mm (Fig. 11). The − 9.5 + 2.36 mm discharge fraction was passed through the GRolls® unit a second time to simulate a closed circuit and recorded 63 % <75 μm (Fig. 11).

Another measure of the crushing performance is assessed by using reduction ratios, being the ratio of feed (F) particle size to the product (P) particle size. In this study, the 80 % reduction ratio (RR80) and 50 % reduction ratio (RR50) were used to estimate and compare the GRolls® performance over the range of feed materials. The RR80 and RR50 were estimated using Eqs. (1) and (2), respectively.

$$RR80 = \frac{F80}{P80} \tag{1}$$

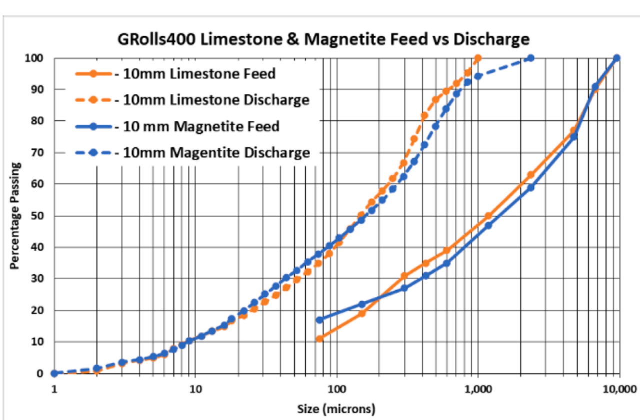

Fig. 7. GRolls® comparison Limestone vs Magnetite Feed.

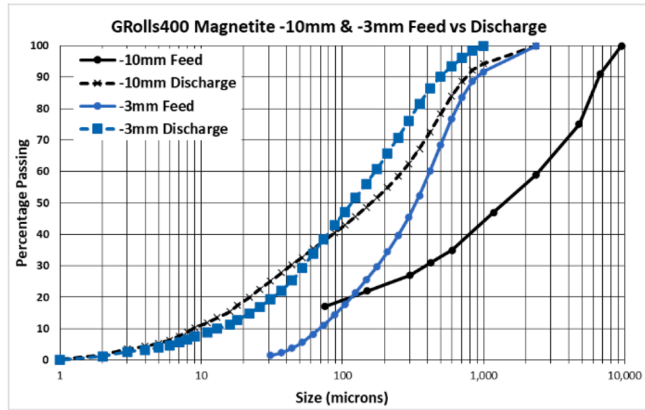

Fig. 8. GRolls® Magnetite < 10 mm vs < 3 mm comparison.

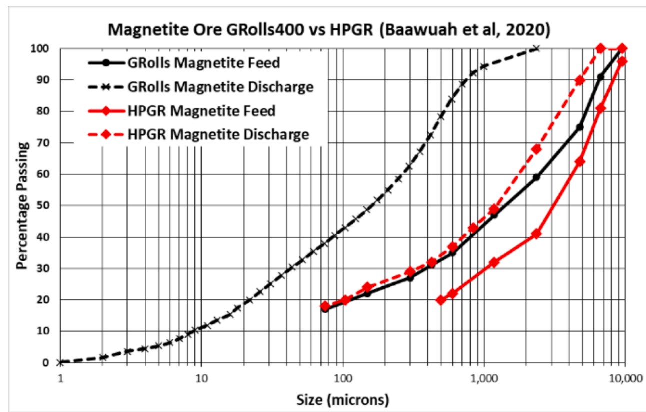

Fig. 9. Magnetite Ore Comparison GRolls® vs HPGR.

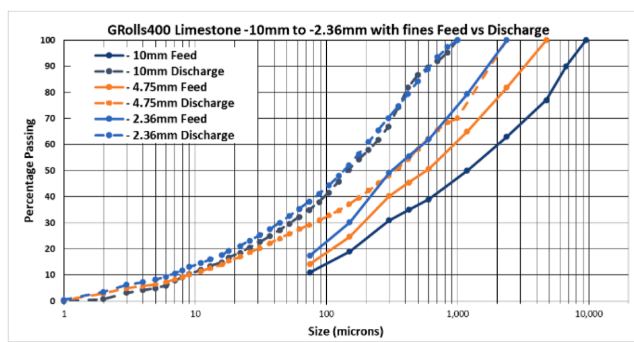

Fig. 10. GRolls® <10 mm to < 2.36 mm feed comparisons.

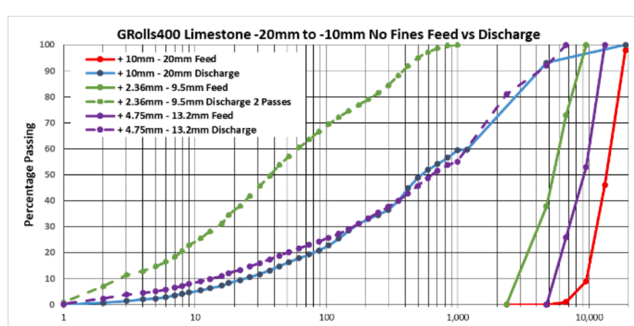

Fig. 11. GRolls® <20 mm to < 10 mm feed comparisons.

$$RR50 = \frac{F50}{P50} \quad (2)$$

Where F80 and P80 are the 80 % passing feed and product particle sizes, respectively, whilst F50 and P50 are the 50 % passing feed and product particle sizes, respectively.

Fig. 12 demonstrates that the GRolls® laboratory unit can achieve high reduction ratios (RR80 of 5 to 18) of dry coarse feed materials from 2 mm to 20 mm in size, whilst still achieving high reduction ratios for dry feed materials less than 2 mm (RR80 of 1.8 to 2). The P80 < 75 µm results in all tests were over 10 %, with the majority exceeding 30 % for both fine and coarse feed materials.

A suite of limestone materials was tested, ranging from 2 mm up to 20 mm in maximum particle size, with the highest reduction ratio RR80 of 19 achieved for a < 9.5 mm material. The testing showed lower reduction ratios when coarser feed materials greater than 10 mm were tested, but still achieved 5 to 6 times RR80. The testing showed lower reduction ratios RR80 of around 2 for feed materials < 3 mm.

The testing demonstrated that even for coarse feed materials the GRolls® was able to generate a high proportion of fines (20–40 % <75 µm) in a single pass, and around 50–64 % <75 µm after two passes, with high reduction ratios RR80 between 1.8 and 17.

5. Energy efficiency

Laboratory testing included recording the power consumption of the Alpha GRolls® unit with different baseline feed materials to determine initial energy consumption and validate the concept of the GRolls® being energy efficient.

The Net Specific Energy (NSE, kWh/t) was determined based on the difference between the no load and power draw during processing of the feed material, as per Eq. (3).

$$NSE = \frac{Grosspowerdraw - Noloadpowerdraw}{Circuittonnage} \quad (3)$$

Where power draw in kW and circuit tonnage in t/h.

The Size-Specific Energy ($SSE_{(75\mu m)}$, kWh/t) is the energy consumed in a comminution process to generate particles less than 75 µm (Ballantyne et al., 2015), as per Eq. (4).

$$SSE(75\mu m) = \frac{NSE}{\% < 75\mu m generated/100} \quad (4)$$

The Bond operating work index (Wi_o) was calculated as per Eq. (5)

$$Wio = \frac{NSE}{\left(\frac{10}{\sqrt{P80}} - \frac{10}{\sqrt{F80}}\right)} \quad (5)$$

where P80 is the 80 % passing size of product in µm, and F80 is the 80 % passing of feed in µm.

The initial energy consumption test results are presented in Table 1 and are favourable with competitor equipment, such as the HPGR reported in Baawuah et al (2020). Even though the GRolls® reported higher Net Specific Energy (NSE, kWh/t) consumption for all feed materials, the large size reductions (RR80) of the GRolls® generates nearly twice the fines content (%<75 µm) which results in significantly lower recirculation loads and more energy efficient comminution as presented in lower Bond operating work index (Wi_o) values. When considering the energy consumption of air classification (4–7 kWh/t, Jankovic et al., 2015), the lower recirculation loads of the GRolls® will result in lower overall energy consumption for tertiary and quaternary dry comminution circuits.

6. Dry vs wet feed materials

Laboratory testing of wet feed materials was undertaken to confirm the applicability of the GRolls® technology to wet mining processes. Limestone (<3 mm) was fed as a 33 % solids (w/w) slurry into the Alpha GRolls® unit to simulate a mining wet process circuit requiring tertiary/quaternary re–grind. The test conditions included processing the same feed material dry and twice as a slurry, collecting in a discharge bin and sampling the dry and two wet discharge materials for particle size distributions.

The dry processing test was (Fig. 13) conducted at a rate of around 300 kg/h which produced comparable results to previous testing using an air classification system. Due to the size of the slurry pump the wet testing (Fig. 14) was conducted at around 1,200 kg/h (4 times the dry test rate).

Results presented in Fig. 15 and Table 2 show comparative size

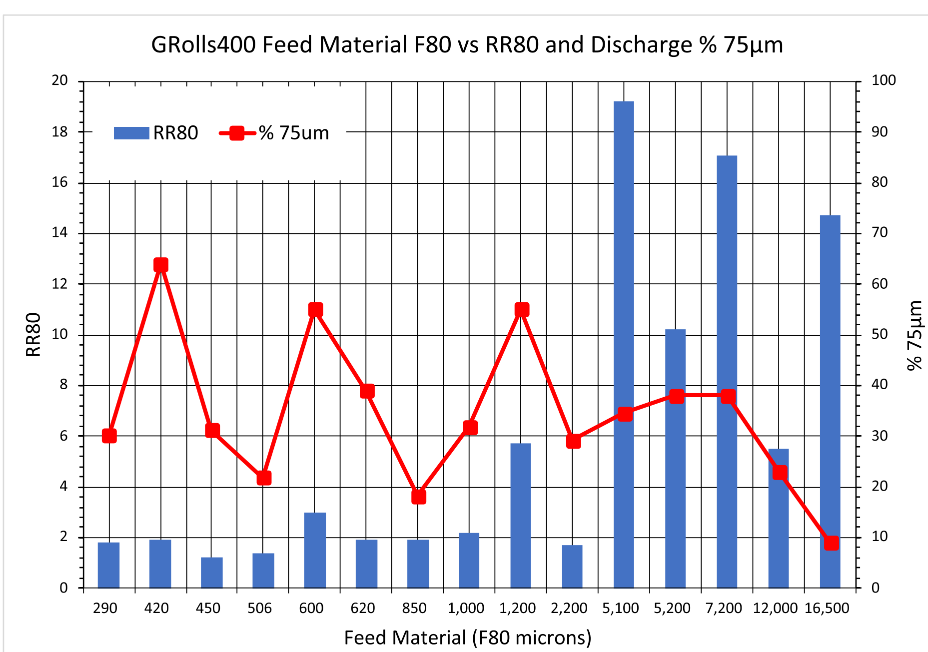

Fig. 12. GRolls® F80 vs RR80 and % 75 µm.

Table 1
Summary of GRolls® Energy Studies.

		GRolls® Dry Trials					Baawuah et al, 2020
		GRolls400					*HPGR*
Feed Material		Silica Sand	Lead Zinc Slag	Limestone	Magnetite Ore Feed	Magnetite Ore Re-Feed	*Magnetite Ore Feed*
F80	μm	290	850	5,100	5,200	620	*6,520*
F50	μm	230	510	1,180	1,400	320	*3,260*
F20	μm	184	320	160	140	110	*530*
F < 75 μm	%	0	5	11	17	11	
NSE	kWh/t	3.5	3.3	13.2	9.0	5.9	*1.6*
$SSE_{(75μm)}$	kWh/t	11.7	17.6	37.6	23.8	15.1	*10.7*
Wi_o	kWh/t	17.5	35.9	21.4	29.7	37.1	*37.2*
P80	μm	160	446	400	510	320	*3,590*
P50	μm	114	271	145	160	110	*1,270*
P20	μm	64	125	25	22	32	*100*
P < 75 μm	%	30	18.2	35	38	39	*18*
RR80	Reduction Ratio	1.8	1.9	12.8	10.2	1.9	*1.82*
RR50		2.0	1.9	8.1	8.8	2.9	*2.57*

Note F = feed material, P = product discharge single pass.

Fig. 13. GRolls® Dry < 3 mm limestone feed material.

Fig. 14. GRolls® Wet 33 % solids (w/w) slurry < 3 mm limestone feed material.

reductions (RR80 and RR50) for the slurry coarse fractions at the high feed rates. The % fines generation (<75 μm) was slightly less for slurry (23 %) compared to dry processing (32 %), however the overall rate of product fines generation was much higher due to the higher feed rates.

When compared to the flat rolls of the HPGR, the GRolls® has chevron shaped rolls which contains and directs the slurry into the crushing chamber. Similar to dry testing results, the amount of fines generation is highly dependent on the slurry feed rate, with slower slurry feed rates expected to achieve improved percentage fines (<75 μm) generation.

7. Pilot plant

The next step in the commercialisation pathway is in 2024 to design and build an upscaled GRolls® unit (Beta prototype, TRL6). A concept design has been developed for a 3–5 tph GRolls® unit which will be powered by a 55 kW motor with direct drive linked to the main roller and 37 kW motor belt drive for the oscillating rollers, with the rollers

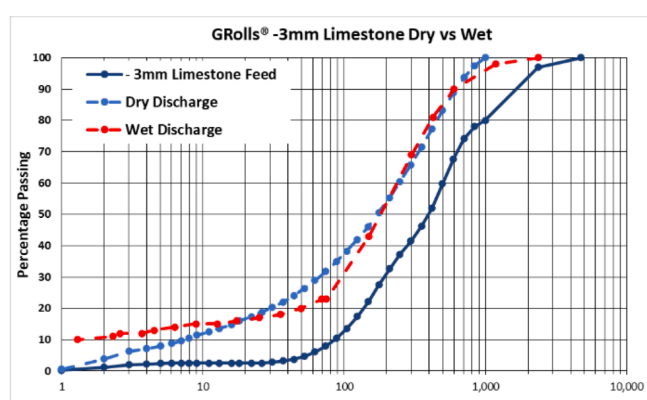

Fig. 15. Gradings of GRolls® dry vs wet 33% solids (ww) slurry test.

Table 2
GRolls® Dry vs Wet Test Results.

Wet Test Results		Dry	Wet
F80	μm	1,000	1,000
F50	μm	400	400
F20	μm	110	110
F < 75 μm	%	7.8	7.8
Rate	kg/hr	327	1,200
% solids	% w/w	100	33
P80	μm	460	420
P50	μm	175	185
P20	μm	30	50
P < 75 μm	%	31.9	23.0
	kg/hr	104	276
RR80	Reduction Ratio	2.2	2.4
RR50		2.3	2.2

being 1000 mm in length and having a diameter of 600 mm (Fig. 16). The design will utilise 3D CAD and FEA modelling to assess upscaling issues such as frame strengthening, bearing sizes, load applications and roller configurations.

The unit is estimated to weigh over 12 tonnes and is sized to be accommodated in an international size container (Fig. 17) for transport and modularization for pilot plant and small scale dry and wet comminution operations.

A pilot plant (full scale pilot, TRL7) will be progressed in 2024 to process feed material through the GRolls® over an extended period with the constant feed source providing critical data to validate the long term energy and product discharge performance, wear locations and rates, maintenance costs and operability of the pilot GRolls® unit under commercial conditions. The throughput and maximum size of the feed materials will also be explored by the upscaled unit for a range of feed materials during the testing program which will then be used to cross-reference and validate upscaling design assumptions. The pilot GRolls® unit will undertake multiple trials with different feed materials at different sites to prove the technology to mining, cement and waste materials commercial applications.

8. Development and research applications

The laboratory GRolls® unit will continue to be used in ongoing laboratory testing programs on various feed materials and applications to build a comprehensive test work database as a key element of Intellectual Property of the GRolls® technology. The testing will include assessing further modifications and improvements to frame, bearings, load applications, feed and discharge systems, different lining options, wear locations and maintenance performance.

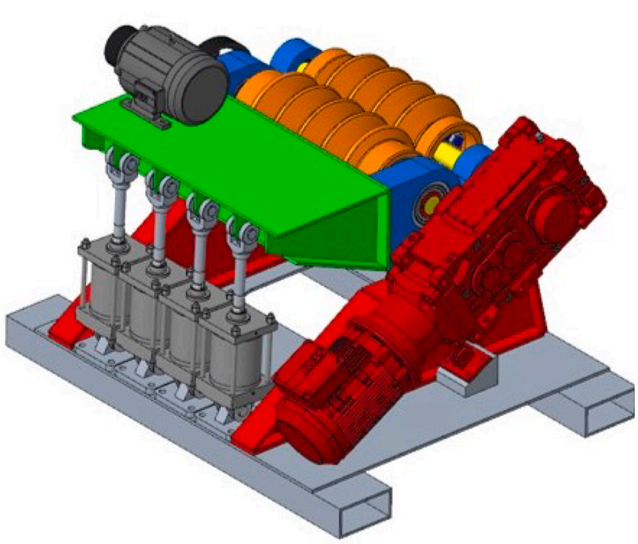

Fig. 16. Concept design 3–5 tph GRolls®.

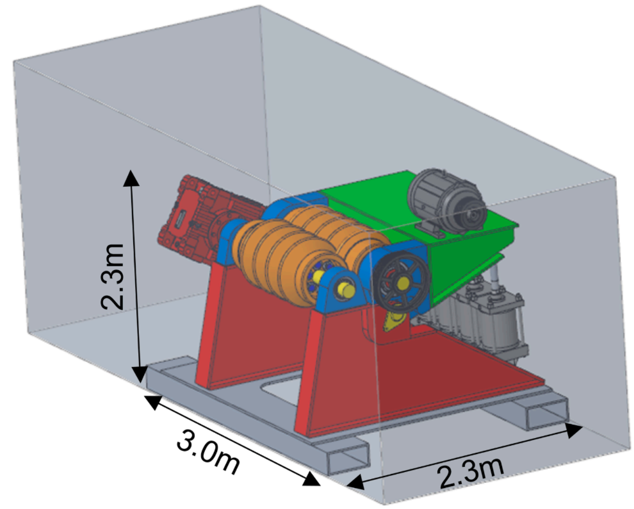

Fig. 17. 3–5 tph GRolls® inside international container footprint.

The University of South Australia will be engaged to undertake broad Research and Development (R&D) related to GRolls® energy consumption and post-comminution processing flowsheet consequences and benefits. This R&D will be led by Professor William Skinner of UniSA’s Future Industries Institute. Key research investigations will include, liberation benefits afforded by high compression and shear, subsequent impact on beneficiation (wet, dry), dry comminution chemistry benefits (e.g. avoidance of inadvertent activation, improved leach kinetics, etc.) and potential for fully dry processing of commodities. This R&D will be pursued through various engagements, including advanced analysis of products via projects within the ARC Centre of Excellence and other research programs with mining industry participants.

9. Commercial applications

Progression of the GRolls® technology through the last steps of commercialisation (TRL8 & TRL9) will small lab scale (<1 tph) and pilot plant scale (3–5 tph) units with a progression through to 25 tph units and then 75–100 tph units. The GRolls® units are targeting to replace or augment existing wet and dry tertiary/quaternary comminution units in the global mining and cement industries (Fig. 18), providing improved energy and water efficiencies and eliminate media which should result in lower capital and operating costs for operators.

There is also a small market for laboratory scale and pilot plant units, the smallest VRM and HPGR units are around 50 tph which severely limits mining companies and research facilities to test small volumes of feed materials recovered from their exploration programs, during feasibility studies or academic research programs. The lab and pilot scale GRolls® units will be mobile and able to travel to remote mineral resource locations or academic testing facilities for testing bulk, chip and drill core samples through test equipment that closely replicate operational performances and thereby reducing project risks. These small GRolls® units could also reprocess old tailings at their in situ moisture content for winning rare earths and other critical minerals.

Small mining operations are also restricted from using VRM and HPGR due to their low volumes, especially for critical mineral resources located in remote resources where power and water supplies are limited. GRolls® pilot plants could be established at critical mineral resources as part of proving the resource, with the number of GRolls® units incrementally increased as part of a staged establishment and subsequent expansion of a critical mineral operation.

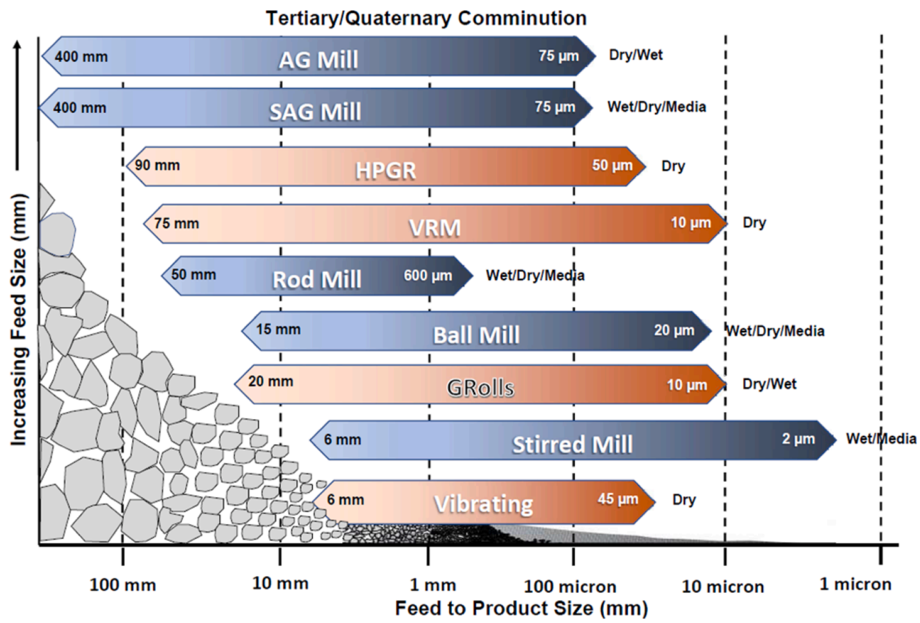

Fig. 18. Tertiary & Quaternary Comminution Technologies.

Small GRolls® units for mobile plants or small pilot/modular plant units can incrementally augment existing process flowsheets to reduce bottlenecks, improve performance of existing equipment and provide smaller quantities of specialist/niche products if needed. Opportunities may be realised in processing small, satellite deposits in brownfield operations, without transporting additional tonnages to existing concentrators. Progression from smaller units to larger units can increase augmentation or replace existing flowsheet equipment as well as be installed within new dry or wet processing circuits. Replacing re-grind with "re-crush" using a GRolls® prior to cleaning circuits engenders further energy savings, and may also further improve recovery rates.

The GRolls® can be operated dry or wet, therefore can be applied to all mineral process flowsheets, providing energy and water efficiencies, modularisation to match renewable energy sources and incremental performance improvements, from feasibility studies through to full operation. The GRolls® technology can provide significant competitive advantages to our customers as the design is simple, scalable and robust which will allow units to have low manufacture costs whilst achieving power savings, increased fines generation and flow sheet flexibility.

The GRolls® advantages outlined above for the mining industry can also be applied to the cement industry (slag, fly ash and clinker grinding) as well as the waste industry crushing feed such as concrete, glass and electronic waste for recycling and recovery.

10. Conclusions

A concept for a Gyratory Rolls Crusher (GRolls®) technology that can operate in both wet or dry process conditions whilst reducing coarse feed into fine and ultra fine particle sizes with low recirculation rates has been progressed through the early stages (TRL3-TRL5) of a commercialisation pathway. These results confirm that the GRolls® can achieve final product sizes less than 75 μm in a few passes with lower recirculation loads resulting in lower power consumption, without media and could eliminate at least one stage of quaternary comminution in a mining circuit. This would achieve a simplification of the mineral processing flow sheets for many mining operations, reduce power and grinding media consumption, dramatically reduce the amount of water used, stored and consumed during the process and eliminate high risk tailings storage.

The concept will be progressed in 2024 with the design, building and pilot plant operations (TRL6-TRL7) of an upscaled 3–5 tph GRolls® unit to finalise the validation process under semi-commercial operations. The last steps of commercialisation (TRL8 & TRL9) will result in small lab scale (<1 tph) and pilot plant scale (3–5 tph) GRolls® units becoming commercially available, with a progression through to 25 tph units and then 75–100 tph units after continued product development and testing.

The GRolls® technology will provide benefits to the mining industry for the following applications:

- Dry tertiary and quaternary comminution circuits to:
  - o reduce power and water consumption.
  - o eliminate media.
  - o improve recovery grades.
  - o augment processing capacity with smaller modular units.
- Wet re-grind circuits for lower power consumption and eliminating media.
- Crush dry, moist or wet tailings, fly ash, slags or other valuable waste materials.
- Mobile crusher for laboratory, exploration, pilot plant studies or integration into modular process trains.

CRediT authorship contribution statement

Mark Drechsler: Conceptualization, Methodology, Investigation, Validation, Visualization, Formal analysis, Resources, Writing – original draft. **William Skinner:** Conceptualization, Methodology, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

The authors wish to acknowledge Mr Christopher George Kelsey, the inventor of the GRolls® technology, who sadly passed away in

December 2022 prior to him seeing the successful completion of the commercialisation pathway for his innovative crushing technology.

The authors acknowledge the technical and financial support of CBSM Mining shareholders.

We also wish to acknowledge the support of the South Australian government through the Department of Energy and Mines and their ThinkingCriticalSA incentive program.

We also acknowledge the support of the ARC Centre of Excellence for Enabling the Eco-Beneficiation of Minerals, grant number CE200100009.

The GRolls® technology and GRolls® trademark are protected by various patent and trade mark applications and registrations.

References

Baawuah, E., Kelsey, C., Addai-Mensah, J., Skinner, W., 2020. Comparison of the performance of different comminution technologies in terms of energy efficiency and mineral liberation. Miner. Eng. 156.

Ballantyne, G., Mainza, A., Powell, M., 2015. Using comminution energy intensive curves to assess efficiency of gold processing circuits. In: World Gold. 29 Sept – 1 Oct. Johannesburg, South Africa, Southern African Institute of Mining and Metallurgy, pp. 1–10.

CSIRO. Technology Readiness Levels Definitions and Descriptions. http://www.ret.gov.au/energy/Documents/Unlocking_Australias_Energy_Potential.pdf.

ECRA, 2015. ECRA future Grinding Technologies Project – Report about Phase 1. European Cement Research Academy, Technical Report TR 127/2015.

ENGECO, 2021. Mining Energy Consumption 2021.

Gerold, C., Schmitz, S., Stapelmann, M., & Dardemann, F., 2012. Recent Installations and Developments of Loesche Vertical-Roller-Mills in the Ore Industry. 26th IMPC2012, New Delhi India.

Jankovic, A., Suthers, S., Wills, T., Valery, W., 2015. Evaulation of dry grinding using HPGR in closed circuit with an air classifier. Miner. Eng. 71 (2015), 133–138.

Katzmarzyk, J., Silin, I., Hahn, K., Wotruba, H., Gerold, C., and Stapelmann, M., 2019. Investigation on Flotation Behaviour of a Copper Sulphide Ore after Dry Grinding by Loesche Vertical Roller Mill. 58th Annual Conference of Metallurgists (COM2019), August 2019 Vancouver Canada.

Luukkanen, S., Tanhua, A., Zhang, Z., Mollehuara Canales, R., Auranen, I., 2022. Towards waterless operations from mine to mill. Miner. Eng. 187.

OZ Minerals, 2020. West Musgrave Pre-Feasibility Study – a low carbon, long life, low-cost mine. ASX release, 12 February 2020.