Will AG Milling Make A Comeback?

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Abstract

The hidden footprint of embodied energy and CO_2 emissions of steel grinding media is an overlooked, but rather obvious pathway to significant reduction in (optional) Scope 3 emissions in the energy-intensive comminution process. The embodied energy of grinding media is around 40% of the direct energy use and up to 60% of CO_2 energy emissions for SABC circuits, offering up to 40% reduction in comminution emissions. To shift from high ball load SAG milling to AG milling requires a considerable mind shift, in terms of addressing operating risk and switching from high operating cost to higher capital investment with lower Opex (lower specific energy and liner wear in addition to no steel media). Perhaps the greatest perceived risk is in terms of sensitivity to ore variability resulting in significant swings in throughput, another is the throughput limitation for highly competent ores. It is proposed that the major hurdle to uptake of AG milling is the ability to reliably predict the circuit performance, especially the dynamics with varying feed competence. This paper addresses the high value of shifting to AG milling and a pragmatic pathway to adoption through developing the ability to predict performance with confidence. This can include retrofitting as expansion options by combining with advanced blasting options, compressed bed and conventional crushing. With industry backing this can come to fruition in just a couple of years to help support a lowered emission AG milling revolution.

Keywords

AG mill, scale-up, embodied energy, energy reduction

Motivation

Although the selection of comminution technology is driven by economic considerations there is a push within the mining industry, motivated by communities, governments and investors, to include reduced CO_2 emissions as part of the evaluation criteria. Mining companies are scrambling to find low energy and CO_2 emissions processing pathways. The hidden footprint of embodied energy and CO_2 emissions of steel grinding media is an overlooked, but rather obvious pathway to significant reduction in (optional) Scope 3 emissions. The embodied energy of grinding media is up to 40% of the direct energy use and up to 60% of CO_2 energy emissions for SABC circuits, offering up to 40% reduction in comminution CO_2 emissions. To shift from high ball load SAG milling to AG milling requires a considerable mind shift, in terms of addressing operating risk and switching from high operating cost to higher capital investment with lower Opex (lower specific energy and liner wear in addition to no steel media). Perhaps the greatest perceived risk is in terms of sensitivity to ore variability resulting in significant swings in throughput, the addition of balls was originally implemented to smooth out throughput. Another is the throughput limitation for highly competent ores, that have a slow breakage rate while producing an excessively fine product. However, there are many highly successful AG circuits around the world, notably in Scandinavia.

Briefly, autogenous primary milling and pebble grinding were introduced in the beginning of the 20th century, with the well-known designs by Hedsel-Hardinge (USA) and Aerofall (Canada) being gradually introduced until the middle of the century (Lynch and Rowland, 2005). Successful applications of the technology were then found from the late 1950s in North America in processing competent iron ores (taconites), which had the additional advantages of having high specific gravity and relatively low variability in the deposit. Independently, the tube mill was developed in South Africa through a chance mis-feeding of a pebble mill (which was the preferred final fine grinding stage after rod milling), with the evolution described by Jackson (1961) and Mokken (1978). In Scandinavia the AG mill was also developed to provide fully-autogenous grinding in AG-pebble mill circuits, one of the most notable being the coupled AG-pebble mill system of Boliden mines.

From that beginning, where mills with 18´ in diameter were used, onwards until the 1970s, AG mills increased in size, reaching 38´ in diameter by the 2000s (e.g., Olympic Dam in Australia), benefiting from the economics of scale, in particular when compared to the alternative circuit that was popular at the time (3-stage crushing plus rod milling). However, the push towards higher throughputs and the growing use of these mills in grinding other commodities, such as copper, nickel and gold ores, with lower specific gravity and higher variability led to a growing shift towards SAG milling.

The authors propose that the major hurdle to uptake of AG milling is the inability to reliably predict the circuit performance, especially the dynamics with varying feed competence. This points to the uptake barriers that can be addressed. The primary barrier is the inability to predict the survival and transport of rocks through the AG mill, which includes:

- how the mill content evolves,
- the production of pebbles for a downstream pebble mill (if used), and
- the fraction of discharged pebbles available for recycle crushing.

Current models lack both the transport function, in terms of through the grinding media and out of the discharge system, and appropriate rock breakage characterisation for the dominant abrasive breakage of the rocks and progressive weakening of the autogenous media. A significant secondary barrier is the limited characterisation of variability across an orebody, which poses a substantial risk for long-term operation due to the uncertainty of operating reliability with unknown future feed competence.

Despite the risks, there is a temptation to persist with process design based off projecting performance from existing operations, under the perception that this is proven and low risk. However, this has been repeatedly proven to be a flawed approach with outcomes being different to design expectation, both positive (seen as a win) and negative. The positives with usually higher throughput than required can be a win, but can also strand an over-designed asset with constraints surrounding it. The negatives lead to loss in mine production and require ongoing upgrades to address the capacity limits. The unexpected outcome after scaling off a similar operation or a 'robust' data set will tend to be the result of a lack of understanding of the underlying drivers to the performance, which are by this approach lumped into a gross average response.

The other limitation of scaling design from empirical relationships built on databases, is that the approach intrinsically prevents development of new technology and levels of operation. For example, going to larger and longer mills is filled with risk, as these empirical models are then being extrapolated outside of the range they have been fitted to. Examples are extrapolating mill throughput and power from the almost linear data at lower mill fillings, below 25%. This is a severely flawed assumption that the Morrell (1992) power model and later mill filling work, such as the Grindcurve data of Powell, Perkins and Mainza (2011) showed to be dramatically incorrect with a strong peak and reduction above a certain filling that is condition dependent. Additionally, the Grindcurve data showed that these peaks are at different fillings. Similarly, there is an assumption in mill design that increasing discharge open area will increase discharge rate and mill throughput. This is incorrect. The slurry discharge rate reaches a peak and reduces as open area increases, as noted in the work of Powell and Valery (2006), and Hilden, Powell and Bailey (2015). The pebble discharge has an independent response, requiring far more open area to enable the large pebbles to discharge through apertures of 50 – 80 mm. The pebble discharge response and limits are possibly the most poorly understood aspect of mill modelling, with specialist consultants and designers relying on some rule-of-thumb discharge limits derived from limited data, or calculation based on the probable maximum rock population in the mill, Morrell (2000).

AG milling suffers to a greater degree than SAG milling from modelling uncertainty – with a higher sensitivity to the feed conditions and breakage modes in the mill. With a critical need to understand the pebble production rate from the potentially largest AG mills to be designed, this limitation is highlighted as a risk to new and more ambitious projects that wish to utilise AG milling.

The great sensitivity of AG milling with respect to feed size distribution and ore competence needs to be addressed through reliable knowledge of the variability of ore characteristics within the mineral deposit. That information then should be delivered in a form useful to process prediction via a sound geometallurgical program. The successful implementation then demands close coordination between mine planning, blast implementation, blending control and the process plant.

This paper explores:

- the current status of AG milling,
- future opportunities with associated design limitations and risks,
- physical limitations around rock charge content and transport,
- modelling shortfalls; recent experimental work that sheds light on transport understanding,
- dealing with dynamics, and
- perception issues that need to be addressed to enable a potential comeback of more environmentally friendly AG milling.

The paper closes with a proposed practical strategy to de-risk the increased implementation of AG milling and the outlook.

Background

Despite the propensity to shift to SAG mills with ever-increasing ball loads, there are numerous successful AG operations worldwide. A few examples are listed to illustrate the basis of successful AG mill implementation.

SUCCESSFUL APPLICATIONS

Three examples of successful applications of AG milling in Australia are presented. Olympic Dam has 38´ AG mill that operates in single-stage mode, considered advantageous in preventing contamination by steel from grinding media, which is detrimental to the response of the copper/uranium ore to acid leaching. Kambalda mine has a 24´ AG mill closed with a pebble crusher to grind nickel ores from several mines in the region. Cannington mine has an interesting circuit of an AG mill grinding sufficiently fine to directly feed stirred mills.

The 22 MW Boliden Aitik AG mill has been the largest in the world, with highly successful operation at over 3000 tph per AG milling line, as reported by McElroy et al (2019). With the Boliden direct pebble feed method, the secondary pebble mill receives its media direct from the AG mill pebble discharge via gravity feed. The entire process plant is designed to minimise energy consumption and consumables over the long life of mine, including conveying, gravity feed to tailings, screw classifiers and no steel grinding media. Stable control is achieved through use of an A-frame stockpile and distributor, to provide a blended feed. In the Aitik survey work the researchers ran the mill at 22.0 ± 0.1 MW for hours ahead of a survey. The rock is relatively soft, with an A*b of 80, a specific milling energy of 10-11 kWh/t, and SSE_{75} of around 26 kWh/t-75 µm. The survival of a substantial rock charge of grinding media for this rock that is relatively soft on average, highlights the significance of a distribution of hardness in the rock feed. The overall energy efficiency of the circuit was assessed by the Coalition for Eco Efficient Comminution (CEEC) Comminution energy curve program (Ballantyne, 2018). As shown in Figure 1, Aitik falls at the lowest end of the energy curves on energy and cost per tonne. This supports the low energy AG milling approach that Boliden has taken.

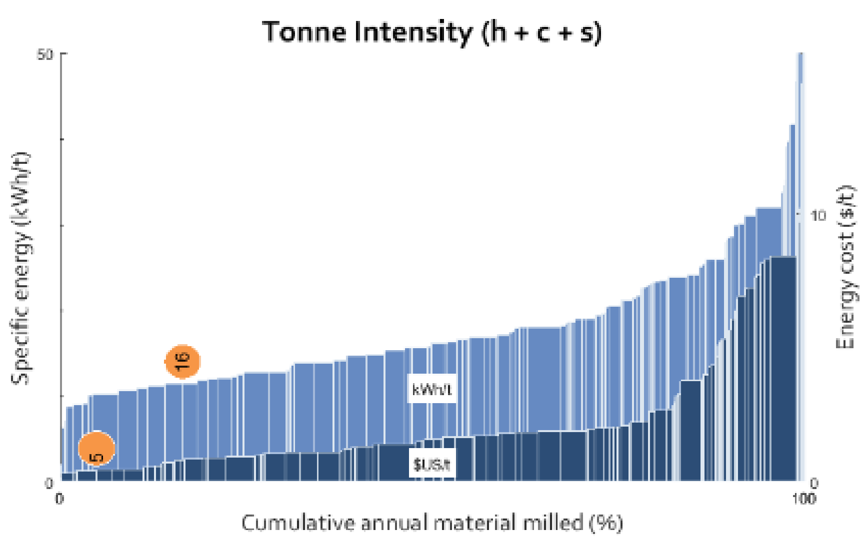

Figure 1—Aitik Energy curve benchmarking (Ballantyne, 2018)

The LKAB iron ore mine in Sweden utilises a fully autogenous circuit to process a highly bimodal magnetite ore at around 500 tph. Coarse magnetic removal is used to strip out a portion of coarse waste quartzite ahead of the AG mill, and the remaining coarse rocks are sent to a separate feed bin to act as a controlled media input. The rejection of low-grade rocks can be tuned to ensure sufficient grinding media in the mill, as the magnetite component is incompetent (A*b around 100) whereas the quartz component is competent at an A*b of 37. Detailed surveys of the milling plant conducted by Powell et al (2011) within the AMIRA P9 project provided good measures of circuit performance. The circuit is illustrated in Figure 2.

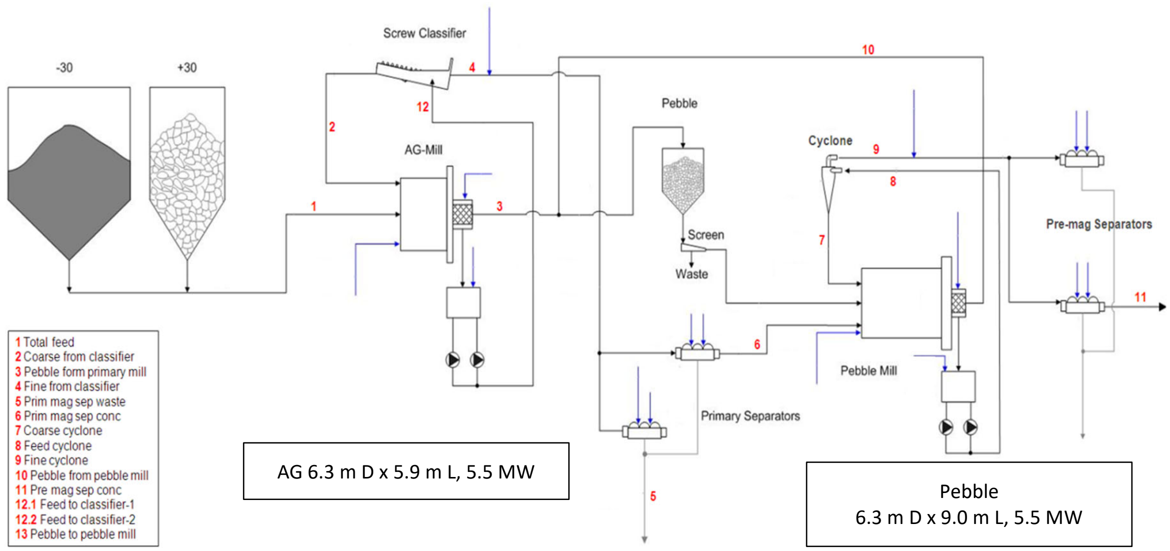

Figure 2—LKAB Magnetite AG milling circuit

Utilisation of the separate media bin allowed good mill filling control, maintained for a wide range of filling used to develop Grindcurves. Despite being the lower density, the quartzitic rock provided excellent media, and its build-up in the pebble mill was measured to completely dominate the pebble content. Bleeding of more waste into the circuit and on to the pebble mill was used to increase power and reduce a slurry pool in the mill. This highlighted the issue that the mills should be designed based of the more competent component in a multi-component feed, as there is an extremely dominant build-up of the competent component, as reported by Bueno et al (2011).

EMBODIED ENERGY

Steel grinding media are used in tumbling mills to improve rock breakage intensity due their high hardness and high density. The media wears as it grinds the rock and is consumed as either fine iron filings that find their way to the tailings dam or as ball scats that are removed and stockpiled. According to Daniel et al. (2010), the expense of replacing grinding media can be comparable to the cost of comminution power consumption. Additionally, the process of mining, smelting, casting, and transporting media requires a significant amount of energy. This embodied energy consumed during media wear is a crucial aspect that is often overlooked when evaluating energy efficiency in tumbling mills and comminution.

The media consumption rates are typically converted to the units g/kWh$_{\text{milling}}$ as opposed to g/t to normalise for the effect of mill specific energy and allow the figures for individual mills to be combined with complete circuits. Ballantyne (2019) compiled a database of media consumption rates using modern forged media (Figure 3). The majority of media consumption rates ranged between 20 and 80 g/kWh with an average around 50 g/kWh. Without including recycling, the production of steel requires 6.0 kWh/kg and creates 2.0 t CO_2 equivalent emissions per tonne (Yang and Broadbent, 2017). Including forging and transport to site, the total embodied energy of forged steel balls is approximately 6.6 kWh/kg (Ballantyne, 2019). The embodied energy of media consumption as a proportion of the electrical power is obtained by multiplying the media consumption rate (in kg/kWh) by the embodied energy (in kWh/kg). Figure 3 shows that the embodied energy of media wear is equivalent to between 10 – 50% of the electrical power draw of the mill. In terms of CO_2 emissions, an average media wear of 50 g/kWh accounts for approximately 0.1 kg CO_2/kWh. This compares to electrical power emissions which ranges from 0.2 for grid power up to 0.6 kg CO_2/kWh for diesel generators.

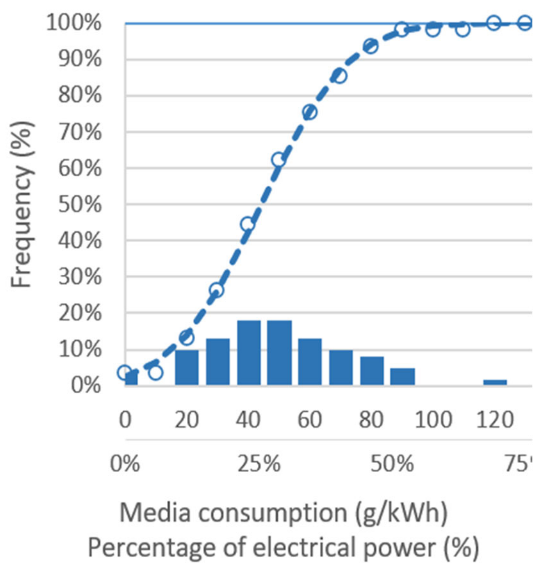

Figure 3—Media consumption rates (Ballantyne, 2019)

Future Applications

A couple of examples of assessing AG mills for future circuits are presented to highlight opportunities and design challenges.

FMI EXPERIENCE

As part of a pre-feasibility study for a 90 kt/d concentrator, Freeport-McMoRan Inc. (FMI) examined many candidate flowsheets before selecting a subset for pilot testing. Proprietary Wood Mackenzie and S&P SNL reports indicated that the lowest opex concentrators are AG/pebble mill (globally lowest) and AG/recycle crush/ball mill (in the FMI portfolio). Of course, there are many other factors at play, but it does indicate that a circuit with an AG mill is a good candidate for exploration.

The pre-feasibility study considered two important aspects: capital efficiency and operating cost efficiency. For capital efficiency, the focus was on utilising the largest available equipment, which minimizes $/MWh and maximizes capacity per plant unit area, and its corollary, which is operating as few parallel lines as possible (fewer pieces of equipment to operate and maintain), which offers better constructability and simplified layouts.

Operating cost efficiency considered reduced labor force requirements (this is not only important from an employment cost point of view but also from a lack of availability and experienced labor force point of view, which has its own costs), ease of maintainability, reduced consumables (grinding steel and liners), medium to high energy efficiency (energy costs are low in the contemplated location, and with a plan to procure green energy) and with minimal recycle (reduction of auxiliary power where possible).

Another consideration is operating stability. This is addressed by planning to have a high level of automation and control but also considering the intrinsic resiliency of the circuit (capacity to treat variable ore hardness). An example of resiliency is to use an HPGR as a recycle crusher due to its superior turndown ratio (range of throughput that it can accommodate) compared to a cone crusher. Another example is to have a variable speed mill, which provides an additional degree of freedom to mitigate the impact of ore changes.

Flowsheet selection was initially guided by a previous study (for a different site) that indicated that a single stage AG mill was the most energy efficient (Table 1). Note that the results are project specific but, in this case, there was confidence in the similarity of the performance between the two projects. The results may seem surprising at first glance since the HPGR is generally thought as being a more efficient comminution machine. The shift in ranking comes from two elements: auxiliary power (of feeders, conveyors and pumps) contributes 13.5% of the energy for an AG circuit whereas it is 19.7% for the HPGR circuit; the second element is the work performed by (the less efficient) secondary grinding circuit (either a ball mill, BM, or a high efficiency ball mill, HEBM, which is a ball mill operated at lower load and speed). The more work the secondary circuit must contribute the lower the total circuit efficiency.

Table 1—Specific Energy (kWh/t) of Selected Flowsheets

	SABC	**HPGR/BM**	**SSAG**	**HsAP**
Crushing & Aux	0.60	1.43		
HRC/HPGR & Aux		2.92	1.71	1.51
SAG/AG & Aux	6.77		7.93	4.72
BM/HEBM & Aux	9.97	9.05		4.44
Total	17.34	13.39	9.64	10.64
Improvement over SAG	0%	23%	44%	39%

Unfortunately, the single stage AG (SSAG) mill circuit was predicted to have an extremely high circulating load, which limits the amount of fresh feed to keep the flow through the mill at a reasonable level. Many parallel lines would have been required to achieve the desired plant tonnage. This was counter to the desire for the minimum number of lines (as well as the capex associated with a multiplicity of equipment) and the energy advantage is reduced due to the power pricing environment at site.

An HsAP circuit has an AG mill with an HPGR in closed circuit with a screen to handle the recycle, followed by a pebble mill in closed circuit with cyclones. The circuit was attractive from an energy efficiency point of view but, in the end, layout issues precluded closing the HPGR with a screen. This led to comparing flowsheets with an open circuit HPGR recycle crusher.

As the selection of the flowsheet progressed, several thoughts and observations came to light. The first is that the AG mill is the constraint in any single line flowsheet contemplated. With the desired tonnage, the mill size became extremely large. Attempts at shifting the load to a pebble mill failed because of restrictions to the AG mill diameter (42 ft), which forced the selection of a longer mill to draw more power. During pilot testing, several configurations were trialled— APH: HPGR product is sent to the pebble mill, AH: single stage AG with an HPGR for recycle crushing, and AHP: AG/recycle HPGR/pebble mill. It was confirmed that a longer mill would lead to some increase in throughput (Figure 4) but also to a finer transfer size (Figure 5). The finer transfer size meant that the pebble mill would not perform as much size reduction. However, the overall operating work index does not appear to be affected by the AG mill aspect ratio (Figure 6). In other words, as the AG mill length was increased, the AG mill would have a higher reduction ratio and consequently the power distribution shifted more towards the AG mill. This was counter to the desired result.

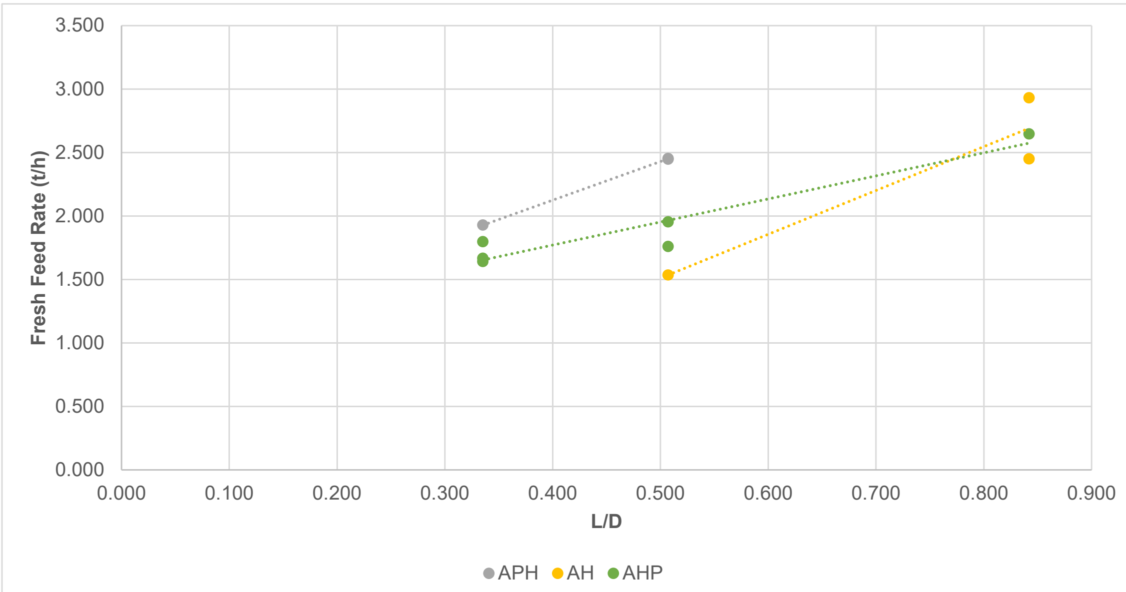

Figure 4—Impact of L/D on fresh feed rate

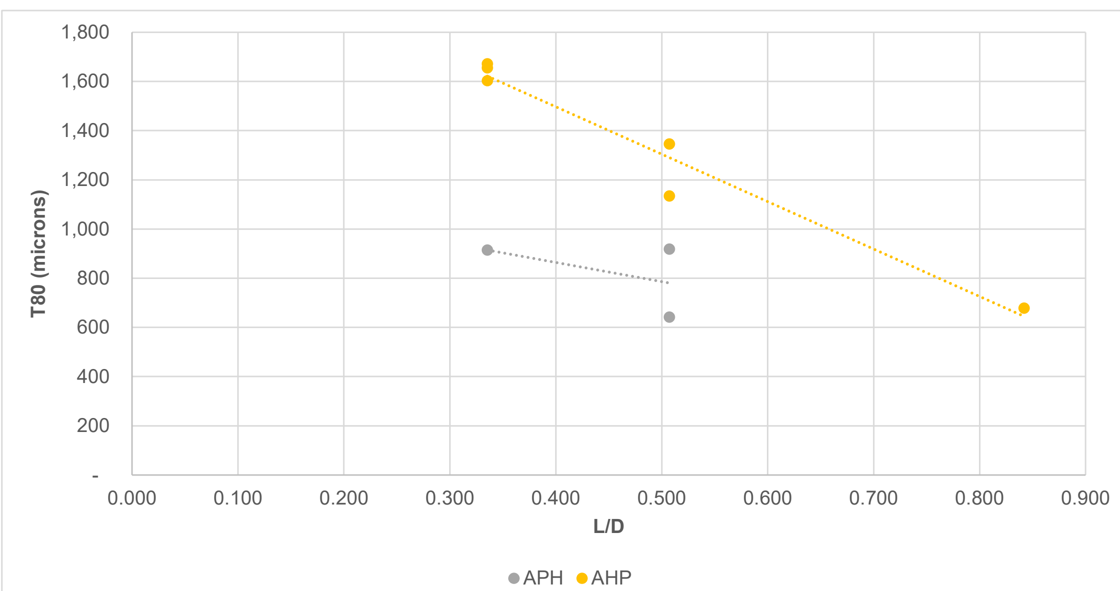

Figure 5—Impact of L/D on Transfer Size

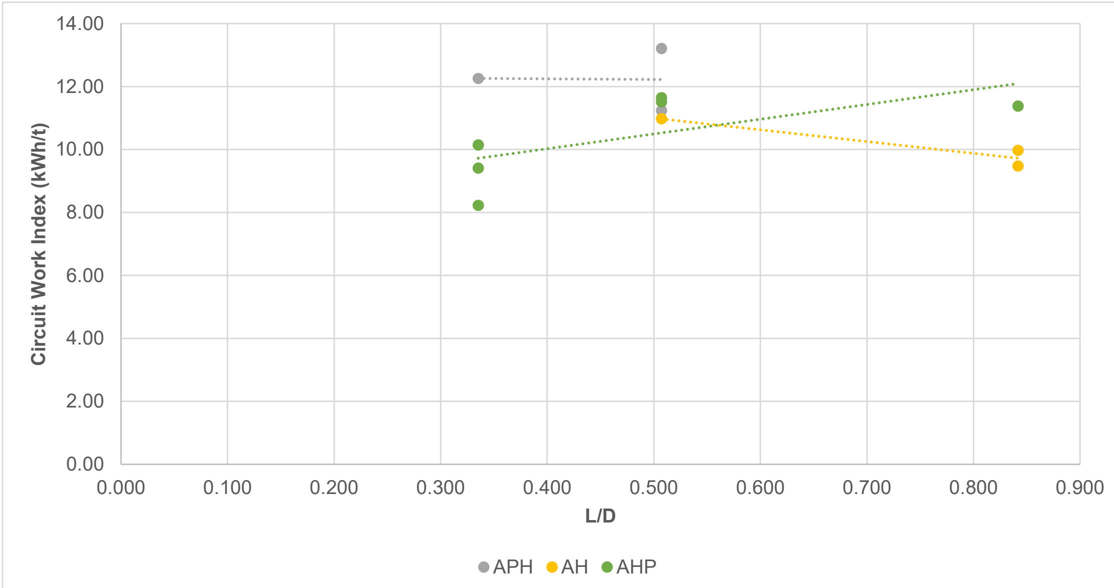

Figure 6—Impact of L/D on Circuit Operating Work Index

Another concern was the flow through the mill. As the AG mill length is increased there is more power and a higher throughput but the capacity of the mill to transport the material is reduced due to the longer travel through the mill load (Chiasson, Powell and Vien, 2023). To mitigate this, deep curved pulp lifters and even an open-end discharge were considered. The high flows also created concerns with screening the AG mill discharge. Combination of trommel and screen as well as a separate screening station with multiple screens were considered. This created material handling and layout issues that were counter to the initial objective.

In the end, the single line option was rejected in favor of a dual line. With the dual line, the flows were much more manageable, and the resulting mill aspect ratio was more in line with the existing plant. As an added bonus, the AG mill could now be powered by a dual pinion drive rather than a wraparound motor, which saves on capital costs. The project is now progressing through feasibility.

ITABIRITE IRON ORE STUDIES

One good example of potential applicability and also of limitation in applicability of AG milling is a pilot-scale study in a 6´mill carried out with a low-grade Brazilian iron ore, called itabirite (Rodrigues et al., 2021). Tests were carried out for ores with varying competence and under a variety of conditions and some results are summarized in Table 2 in comparing AG and SAG operation. When grinding the very soft and fine ore (GAL), AG operation was not attractive, evidenced by the higher SSE value than SAG, which is due to inability of the mill to hold a proper grinding charge owing to its fineness and low competence. In this case, even the addition of a small ball charge (4%) increased throughput and reduced the SSE value, thus demonstrating the benefit of SAG operation. On the other hand, operation of the mill with the more competent itabirite (JAN) resulted in nearly the same performance in AG and SAG mode with low ball charge (4% balls), with the advantage for the AG mode given the absence of grinding media, but at the expense of a 17% lower throughput. An additional test was run for JAN ore, but with a substantially higher ball load (16%). However, it showed that SAG operation became progressively less attractive, owing to the substantial coarsening of the product and increase in SSE, with the benefit of only 4% of additional throughput. For these incompetent ores either a low ball load is required or a portion of competent low-grade competent feed is required, similar to the LKAB example presented earlier.

Table 2 – Comparison of open-circuit pilot AG and SAG iron ore grinding (Rodrigues et al., 2021)

Ore	A*b	Ball Load (%)	Feed –75 µm (%)	Feed F_{80} (µm)	Product –75 µm (%)	Product P_{80} (µm)	Feed Rate (t/h)	SSE (kWh/t –75 µm)
GAL	265	0	18.7	37,777	48.6	374	4.65	9.4
	265	4	18.7	37,777	43.3	985	7.34	7.6
JAN	54	0	10.8	125,637	41.0	1,152	1.21	28.5
	54	4	10.8	125,637	40.6	1,308	1.46	26.9
	54	16	10.8	125,637	36.3	1,703	1.52	36.4

Gaps in Application

Some reasons for the limited use of AG milling circuits, despite their success in a number of applications, are noted as barriers to uptake.

The milling in AG mills is dominated by abrasion, this does not favour highly competent ores, as their abrasion rate is low and they tend to produce an overly-fine product – both factors working against high throughputs. Variability in feed results in wide swings in operation, as the rock load builds and depletes with changes in competence and feed size. The introduction of balls for SAG milling helped to stabilise the feed rate by providing a substantial portion of the grinding media. Steel media also helps address the issues with competent ores. The fully autogenous mill load can be fine and well packed, leading to slowed slurry transport and thus susceptibility to build-up of a slurry pool. This was noted in the LKAB and Aitik case studies presented above, most notably in the pebble mills. The low media density requires larger mill sizes to provide the required milling power. With mills already at 40 ft diameter, this drives operations to needing two AG mills instead of one SAG mill. The FMI study highlights the unknowns around transport, driving the decision to utilise two AG mills instead of one larger mill.

It is proposed that a key aspect to enable the uptake of more AG milling is the need for lowering the risks in design and operation. A pathway to this is confident simulation of the process, not just in average assumed stable conditions, but for the natural variability that will be experienced. This indicates that accurate, dynamic models are required within a fully-dynamic simulation platform. The predictions should deal with multiple ore components, gangue rejection, dynamic blending, superposition of control algorithms, materials handling and segregation (such as bins and stockpiles), partial crushing, and changes in blasting. They should predict: mill fillings; pebble production and competence of these for use as downstream pebble media; product size distribution in all process streams; realistic responses and lags in the circuit to feed changes and control responses; build-up of competent fractions in the mills and circuit; and response to various potential forms of crushing (partial pre-crush, mid-size crush, pebble crushing).

In order to assess this task, it is first necessary to assess the current modelling status and capability.

AG Mill Model

Current SAG/AG mill models that are in general use lack significant aspects of realistic mechanistic properties of an AG mill. They are based off body breakage, e.g., the JK SAG model has an added but fixed ‘abrasion’ term, which is actually a modifier to increase the fines production to better match reality. Breakage rates are back-fitted to match operating data, but these accommodate missing functionality of the models, such as a predictive term for rock abrasion that so dominates AG mills. They lack terms for build-up of competent rocks, which requires multi-component modelling. They are steady-state so cannot predict transport and lag times through the mill or circuit.

The best available status in models under development are summarised below.

Starting from the simplest energy-size reduction relationship to the population (size-mass) balance models, much of the success in predicting the performance of tumbling mills relies on the existence of fairly well-defined mechanical environment in the mill, which draws the required power for size reduction and transfers the energy to particles, causing breakage. In the case of AG milling, the dual role of the ore in being the object of size reduction and grinding media responsible for distributing the energy to breakage, introduces substantial uncertainties in the operation, which becomes evident in the lack of simple models available to confidently predict AG mill performance.

For autogenous milling to be successful important requirements exist. The ore should have enough coarse rock to act as grinding media, typically in the 250-100 mm size range. Also, these coarse rocks should be competent enough not to shatter immediately in the first couple of turns in the mill, neither excessively competent, resulting in their build-up in the mill and reducing capacity. This latter becomes evident from the appearance of highly rounded pebbles in the mill discharge.

The added complexity brought by AG milling requires a fresh look at its mathematical modeling, with a mechanistic approach that captures the sub-processes being favored by the authors. This new mechanistic mathematical approach relies on the coupling of detailed single-particle breakage characterization, considering both body and surface breakage and description of the mechanical environment within the mill using the Discrete Element Method (DEM) (Carvalho and Tavares, 2011, 2014). In addition, it relies on description of proper transport of slurry and ore particles through the mill and its discharge through the grates, using tools that include Computational Fluid Dynamics (CFD) and Smoothed Particle Hydrodynamics (SPH), coupled with a proper microscale formulation of the population balance model (Figure 7).

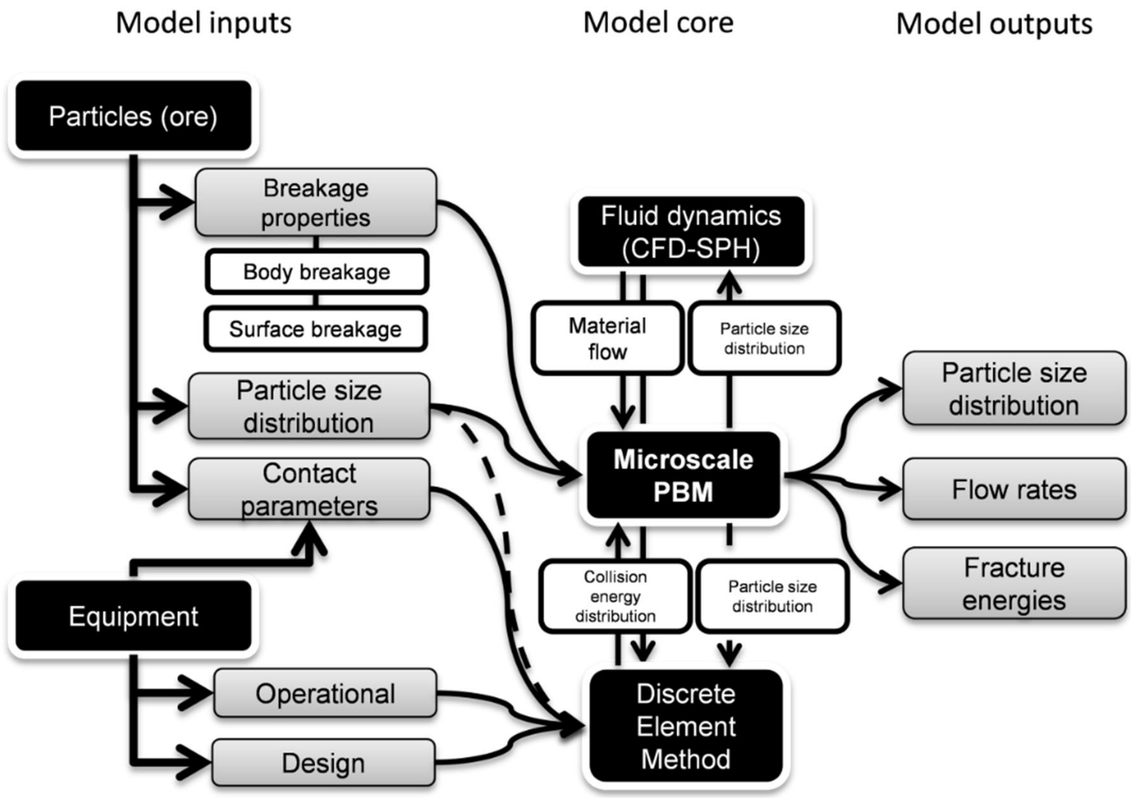

Figure 7—Mechanistic AG mill model structure (Carvalho and Tavares, 2011)

This so-called mechanistic mill modelling approach has already been successfully used to predict size reduction in ball mills (Tavares & Carvalho, 2009; Carvalho et al., 2021) and stirred mills (Oliveira, de Carvalho & Tavares, 2021), but its greatest potential impact – and challenge – lies exactly in its application to AG milling. Coupling of the detailed information on how particles break, including their distribution of particle fracture energies and their amenability to weaken (damage) as a result of repeated impacts, with the collision energies in the mill allows a proper dynamic description of the AG mill operation. From this, the charge size distribution can be predicted at any point in time, which defines the ability of the mill to produce size reduction. A preliminary application of this model has been demonstrated on a pilot-scale AG mill grinding copper ore, on the basis of an assumed discharge function from the mill and with no additional data from the pilot-scale test. A comparison between measurements and the experimental results is shown in Figure 8, which demonstrates the potential of the approach. This simulation, which relied on iteratively simulating media motion in DEM and updating the mill hold-up using the microscale population balance model, is not a simple task and still requires additional developments before it can be applied routinely. Ore characterization that is demanded for this model is not standard, as discussed in the following section.

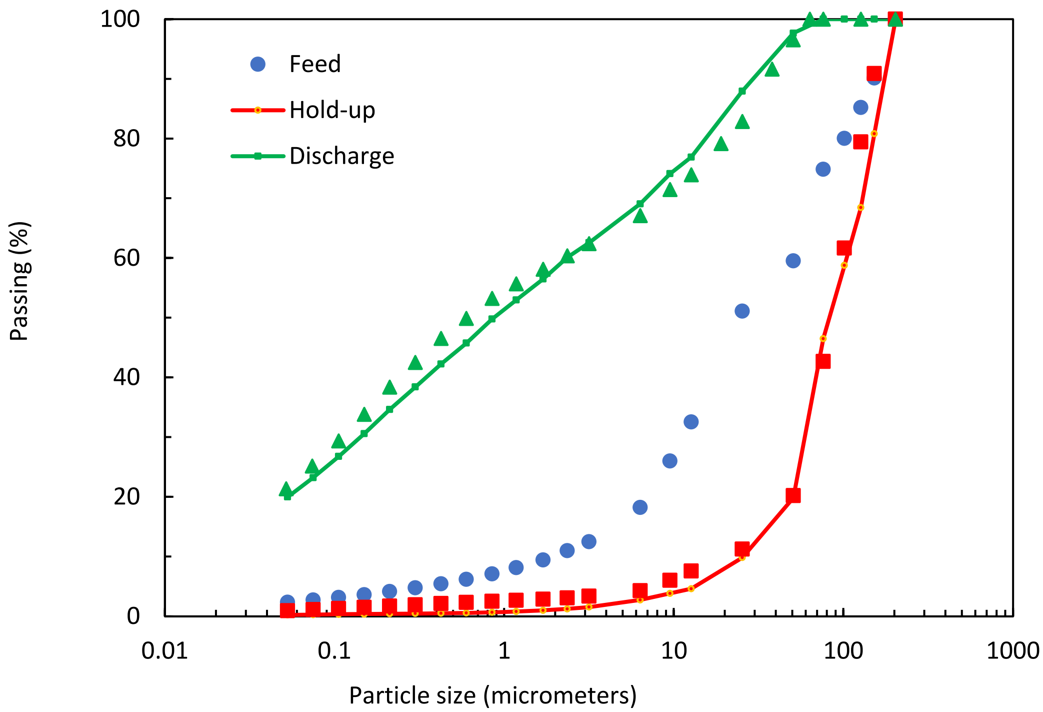

Figure 8—Comparison of measured (symbols) and predicted size distributions (lines) from milling of copper ore in a 6´x 2´ pilot-scale AG mill (Carvalho and Tavares, 2014)

The assumption that autogenous grinding media and slurry are fully mixed may be considered generally valid for high-aspect mills and particularly short in absolute length, such as the one simulated in Figure 8. However, in the case of longer mills with lower aspect ratios, transport of slurry through the charge and also distribution of the grinding charge becomes a challenge that needs to be incorporated into a successful model of the mill (Powell et al., 2023).

AG mill model for reliable design

This section highlights the aspects needed to design and scale-up AG mills with sufficient confidence.

INCREMENTAL BREAKAGE

As mentioned, the success of AG milling relies heavily on the ability of the ore in generating suitable grinding media. With the aim of giving insights into this, a few competence tests have been proposed. Bond developed a media competence test in which 100-160 mm rocks were rotated in a 1.93-0.32 m drum for a set time, sizing the product and testing the size fractions for grindability and resistance to impact (Lynch and Rowland, 2005). Variations of these tests have also been proposed, including the SGS media competency test (McPherson & Turner, 1978). Alternatively, Mörsky, Klemetti, Knuutinen, Kalapudas & Koivistoinen. (1996) proposed drop tests to compare the response of candidate ores to results from ores known to be suitable to AG. The results of these tests were used only qualitatively to scale off database references, not in predictive models.

The tests listed above attempt to capture two aspects of the ore mechanical response which are critical in AG mills, but which they lump together. One is related to the strengths or magnitude of energy required to fracture the coarse particles contained in the feed and the other is the amenability of the rock to weaken when subjected to stresses that are insufficient to cause their body breakage in the first impact event. This latter has been called damage (Tavares & King, 2002) or incremental breakage (Morrison, Shi & White, 2007). Its importance has only been recently recognized, being applied to advanced models of crushers and mills (Tavares & Carvalho, 2009). Results from drop tests of a tough copper ore (CWi = 19.7 kWh/t) are shown in Figure 9 along with the fit to a continuum damage model (Tavares & King, 2002), which show that data such as these may be adequately predicted and used within a proper model framework (Figure 7) for predicting AG milling. The specific energies depicted assume free falling conditions, corresponding to drops from 2,4 and 8 m.

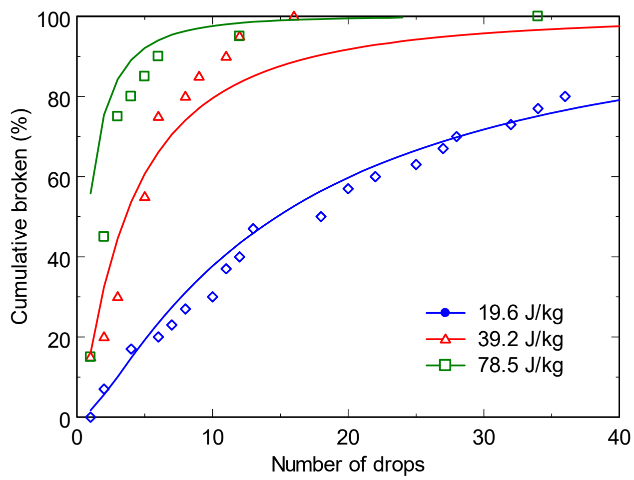

Figure 9—Cumulative breakage of 125-75 mm copper ore rocks from drop tests (Carvalho & Tavares, 2011).

ABRASION FUNCTION

The critical aspect lacking in current models is a realistic abrasion function, the removal of mass through rubbing of rocks over each other. This has been addressed through pilot-scale tests and resultant ore calibration at the JKMRC. Yahyaei, Weerasekara & Powell (2015) presented a method to quantify the production rate of abraded product and the resultant appearance function of the product. A 1.2 or 1.7 m diameter batch mill is used to tumble rocks in at a low speed and high filling to ensure an almost exclusive abrasion interaction. Wash water is used to continuously flush the fines that are produced out of peripheral ports, minimizing secondary breakage of the fine product.

Surficial breakage rate (SBR) was defined based on the concept of mass loss per applied surface specific energy (kWh/m^2). Importantly, this is not per mass or volume, so is independent of the size of the rock. Initially, when the rock is rough and angular, the abrasion rate is higher and produces a slightly coarser product, which includes chipped fragments. As the rock rounds out, the abrasion rate reduces and the product becomes uniformly fine. A plot showing the change in abrasion rate from fresh to conditioned, rounded, rocks is presented in Figure 10. This also shows a possibly linear relationship with competence for the three ores tested. The change in appearance function with rounding is shown in Figure 11.

This method is suited for populating the abrasion component of a model, but is, admittedly, rather intensive on sample requirement and testing time. A more convenient smaller-scale test has been investigated but not yet established.

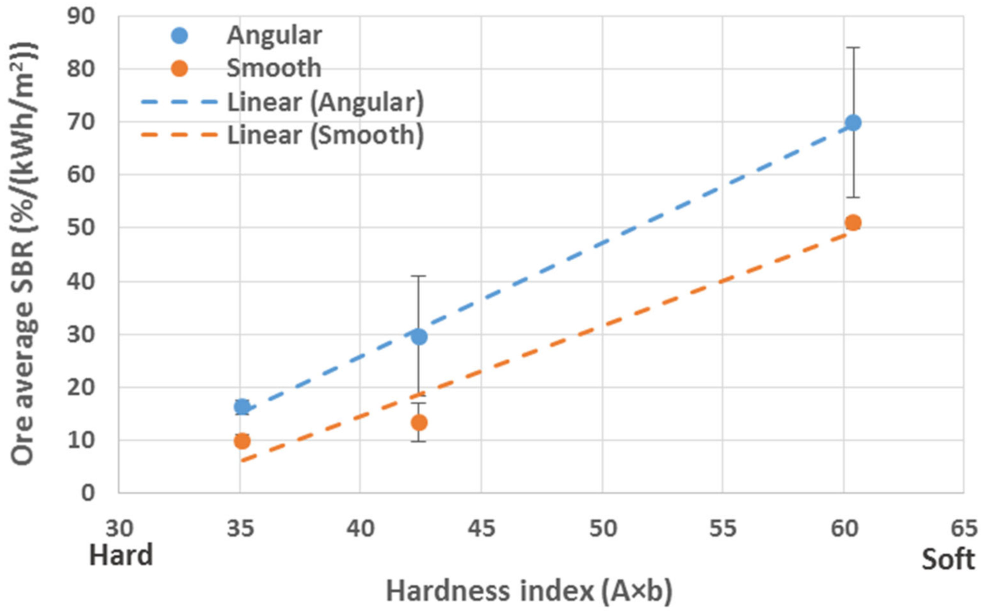

Figure 10—Relationship between SBR and ore hardness index (A×b) (Yahyaei, Weerasekara and Powell, 2015)

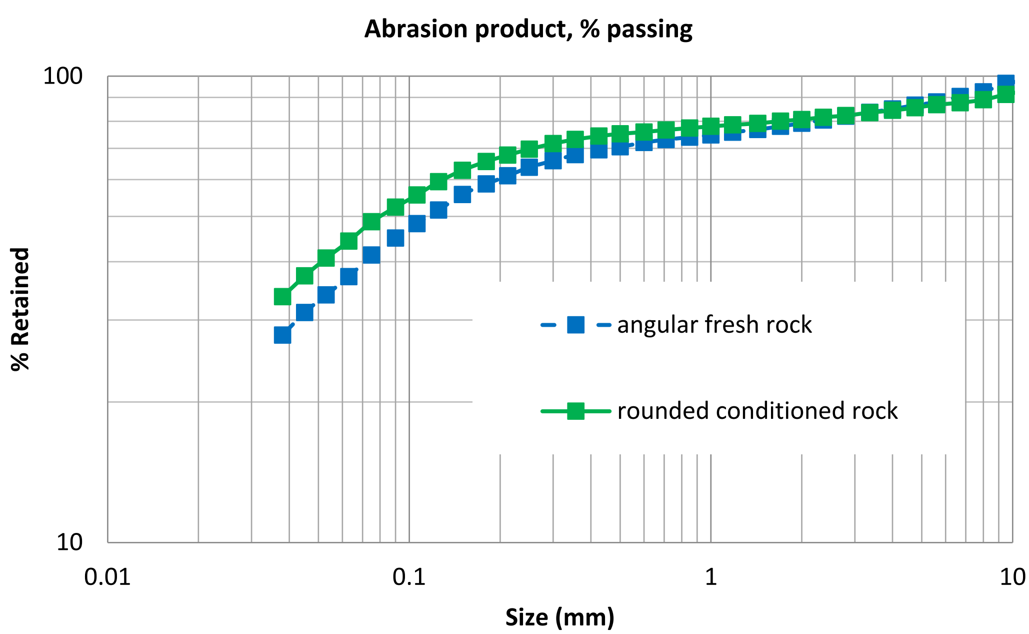

Figure 11—An example of the abrasion appearance function

MULTI-COMPONENT

The need to incorporate the build-up of the more competent pebble portion of rock in the mill is another essential component required in a predictive AG mil model.

In the same way that when a batch of particles are dropped the weaker particles are preferentially broken (Figure 9), leaving the rest of the particles unbroken – however damaged – the differential breakage of the softer components in a multicomponent ore also occurs inside an AG mill. Figure 12 compares distribution of particle fracture energies of three ore types which were found in a single iron ore deposit. It shows that differences in their distributions are significant. In a mechanical environment dominated by collisions of magnitude, for instance 50 J/kg (representing, approximately, 5 m drops on the bare mill liner), nearly all particles of Ore #3 would break at the first impact, whereas only about 12% of those of Ore #1 would. Such measures would allow both the variability between and within ore types to be captured. Such ore blends in an AG mill would result in build-up of pebbles of the more competent ore types and depletion of the softest.

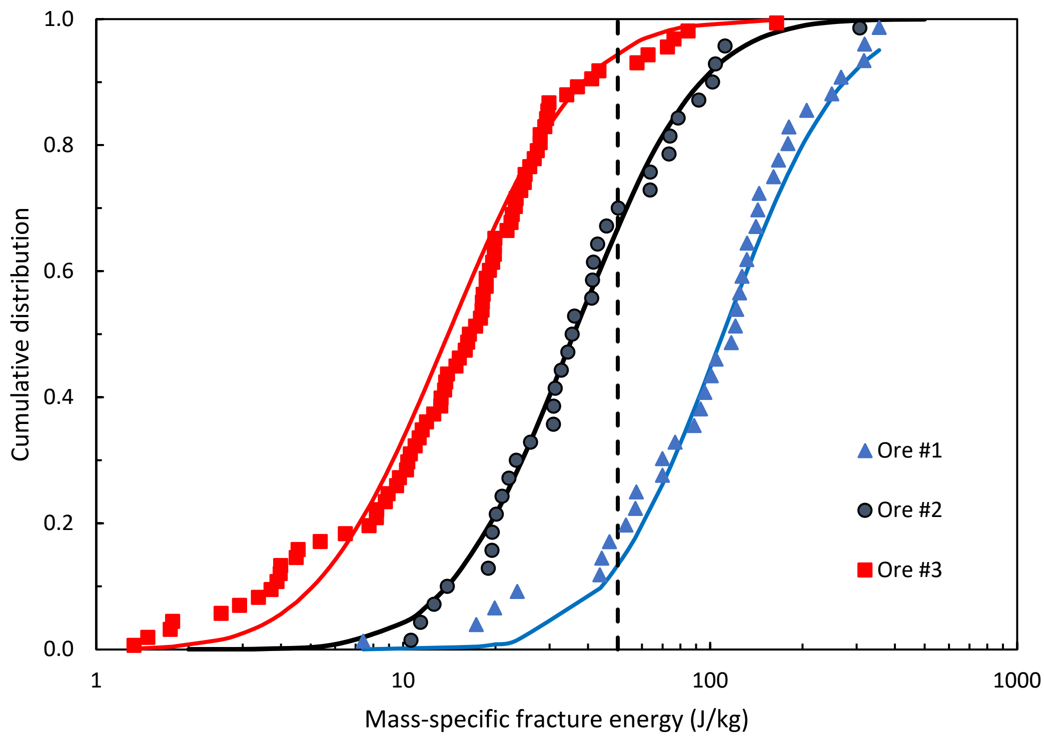

Figure 12—Distributions of fracture energies of particles of three iron ores in the size range 212-150 mm

TRANSPORT AND DISCHARGE

As noted in the FMI experience study, the inability to predict the transport rate through the mill and production of pebbles for recycle crushing, was a significant unknown from pilot-scale test work.

To this end, associated pilot transport trials were conducted at SGS labs in Lakefield, as reported on in Chiasson, Powell and Vien (2023). This graphically demonstrated the significant differences in transport rates along the mill of different size rocks, as plotted in the summaries of Figure 13. This has been taken up in the development of a mill transport model that can be incorporated into a new AG mill model, presented by Powell et al (2022, 2023). The proposed model incorporates unique rock diffusion terms to account for the large observed range in transport rates, and a discharge function that is truly only discharge through the grate, not an average of overall flow through a mill.

The importance of this development is that the build-up of competent rock and its independent rate of discharge can be captured. This can then be used to scale to any mill size with any feed type. Additionally, transport through the mill is the key to a realistically dynamic model, that will predict build-up and lag through a mill, as observed in real, dynamic operation.

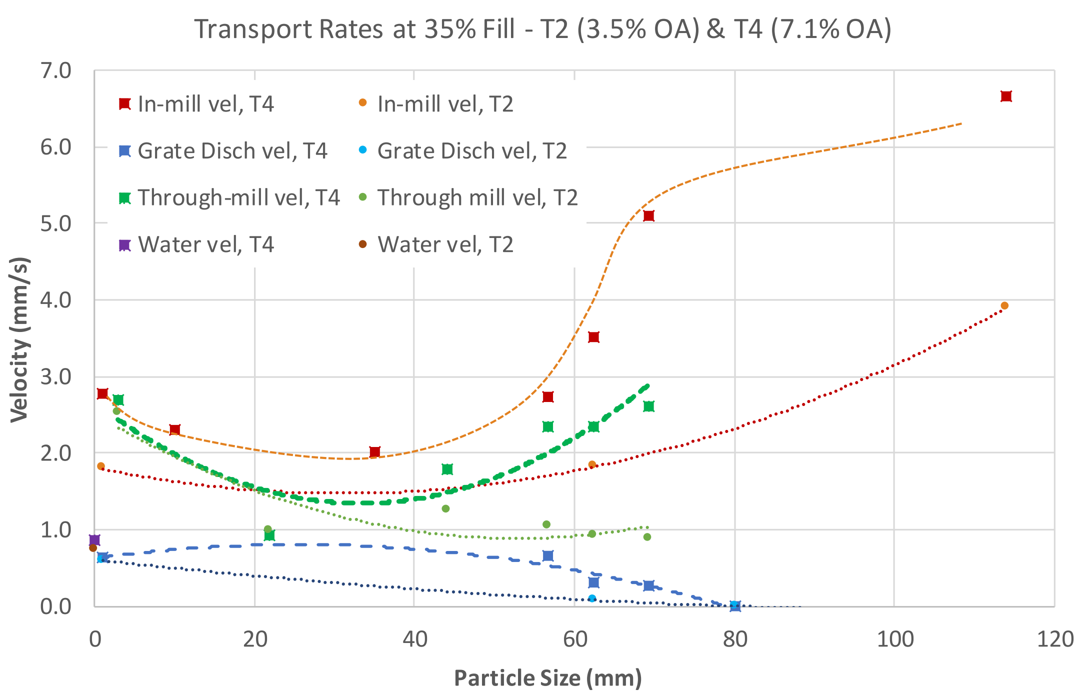

Figure 13 - Average transport rates by particle size. Chiasson, Powell and Vien (2023)

DYNAMICS

As noted earlier, a fully dynamic mill model is required to de-risk the application of AG mills. A base model has been developed that incorporates the following sub-components:

The ore was tested at the JKMRC for the extended tn breakage function and in the large abrasion mill to characterise the abrasion breakage function.

1. Size-dependent transport function incorporating three sub-processes
2. Discharge function for end slice of the mill contents that identifies the substantial difference for large particles
3. Impact breakage function applying the extended tn breakage and appearance model (Ballantyne, Bonfils & Powell, 2017)
4. Abrasion surface breakage model
5. Impact breakage energy distribution across all particle sizes as a function of mill operating conditions and contents size distribution
6. Abrasion breakage energy distribution across all sizes
7. Available breakage energy dictated by mill power draw
8. Time-stepping dynamic model applied along the discretised length of the mill
9. The mill model is closed with a circuit screen and crushing product to allow closed circuit simulation.

The majority of these items are novel or a novel implementation. The complete model has been applied to two pilot trials with recycle pebble crushing and in open circuit operation. This was partially successful. The mill content prediction was good for open circuit operation but did not capture the high breakage rate of the crushed pebbles in the test with bimodal feed. These led to the prediction of excess mid-size material (5-15 mm) in the product.

Although a full working dynamic mill model has been developed that incorporates rock transport as a function of size, several uncertainties remain that limit its application to full-scale design scenarios. The discharge function was found to vary significantly with mill content in a manner that a simple back-fitted calibration function cannot predict. The probably of capture function for impact breakage requires modification to more correctly predict the enhanced rate for mid-size particles with high coordination numbers (probability of capture and crushing between larger rocks).

The model can in principle be applied to full-scale mill prediction, but this will require calibration of some key discharge and transport functions, that may not scale to larger mills with different load contents. A significant body of work has been conducted to develop a novel dynamic mechanistic model based off the theories of Powell (2018), Bonfils & Powell (2019). A unique number density mathematical platform proposed by Weatherley & Powell (2017) that allows scaling to large mills with no computational penalty has also been applied. The mechanistic modelling of Carvalho & Tavares (2014) provides an additional proven route to simulating AG mill operation. The modelling points to the areas that require further research development.

Derisking the Design

Successful design of an AG circuit should take into consideration the unique requirements that should be met to reduce risk, by ensuring consistent and predictable performance. Some important factors are outlined, but the list is by no means exhaustive.

ENGINEERING CONSIDERATIONS

Moving toward autogenous grinding will change the power split between primary and secondary milling and increase the mill shell size relative to installed power, but does not have a major impact on the design of the circuit unless pebble handling facilities are required to enable secondary pebble milling. Pilot plant testing may be required in some cases to reduce design risks for hard ores or highly variable ores.

Comminution trade-off studies that include AG milling should include Scope 3 carbon emissions in the economic analysis to take into account the media consumption. Completing studies in this way can dramatically change the relative economic benefit of AG milling in comparison to other comminution circuit options (Ballantyne, Pyle, Foggiatto, Martin & Lane, 2023).

ORE CHARACTERISATION

A more thorough understanding of the ore characteristics over life-of-mine is required than is generally available at design stage. The range and likely blend of competence is required to provide a reliable design. For more complete ore-body characterisation the recently introduced Geopyörä test may prove to be invaluable, in providing variability data and an order of magnitude more data points across an ore body that currently achieved, as presented by Bueno (2021, 2023) and Chavez Matus (2022).

MINE PLANNING

Based off the ore breakage characteristics, the mine plan should target not just grade but also providing the ore blend range needed to ensure successful AG milling. This will apply especially to the fraction of competent rock in the mill feed.

BLAST CONTROL

Even more so than for SAG milling, the integration of blasting practice with milling is needed to ensure maximum productivity. Producing bi-modal feeds, limiting the coarse rock or producing more as required are two clear areas to be incorporated.

CLAYS AND NATURAL FINES

Incorporating early removal of fines and clays can be a great bonus to using AG milling. This can be via scrubbing as an integral part of the process.

FEED CONTROL

A blended and / or segregated split of feed by size and / or blend must be designed into the process. It is necessary to be able to control feed blend for successful and stable operation. This requires a full appreciation of segregation and materials handling issues. The stockpile modelling work of Ye et al (2022a, 2022b) provides a dynamic predictive model that includes segregation by size and source across a stockpile or bin. Buffer stockpiles can also be used to enable continuous control within a favourable blend fraction of the competent versus soft components in the ore. Buffering involves bleeding off only a fraction of the ore into a stockpile that is then used to blend in as required for stable feed blends. This minimises double-handling costs.

OVERGRINDING

The issue of excessively fine product, especially from competent ores, may best be addressed through mid-size partial pre-crush and or recycle pebble crushing. This will accelerate transport through the AG mill, reducing over-grinding, and coarsen the product due to the contribution of crushing. Crushing has the added advantage of being low energy and introducing minimal embodied energy. Incorporating fine crushing of pebbles, HPGR or similar efficient breakage of mid-size material will enhance the positive impact of grinding on circuit throughput and reducing unwanted fines.

Understanding and manipulating transport through the mill links to mill and discharge design, which can be improved to further limit over-grinding.

DYNAMICS

Designing for the dynamic operation requires a fully-dynamic simulation platform. Although this does not currently exist in mineral processing, this is being developed by the Global Comminution Collaborative (GCC) on the recently launched open-source Dyssol platform (www.dyssoltec.com). This utilises real-time stepping through a process flowsheet, incorporating transport times, lag, mixing, segregation etc. The platform also allows the inclusion of mineralised components with independent breakage properties. Control systems can be layered on top of the dynamic simulator with variable feed scenarios entered into the feed to enable simulation of the dynamic response for various process designs and control methodologies. This will guide both design and control, and provide a more realistic measure of the circuit production over time.

FLEXIBLE DESIGN

Underlying the advantageous implementation of AG milling circuits is the incorporation of flexible operation. Powell (2013) provided the following definition: “FlexiCircuits leverage ore variability to maximise resource utilisation”. The Flexible Circuit approach for process design focuses on the investigation of the benefits of customising processing flowsheets to different ore types, as an alternative to existing circuit layouts processing blended ores. The focus is to increase circuit efficiency (enhanced recovery of valuable minerals) and productivity (lower operational costs) by integrating circuit design with the knowledge of ore type characteristics, such as the distribution of value-bearing particles. The approach consists of strategies to be considered when defining circuit layouts, including staged rejection of waste and alternative processing routes for ores with different properties. The ability to fully simulate circuits such as the examples presented in by Powell, Foggiatto and Hilden (2014), in dynamic mode is the objective.

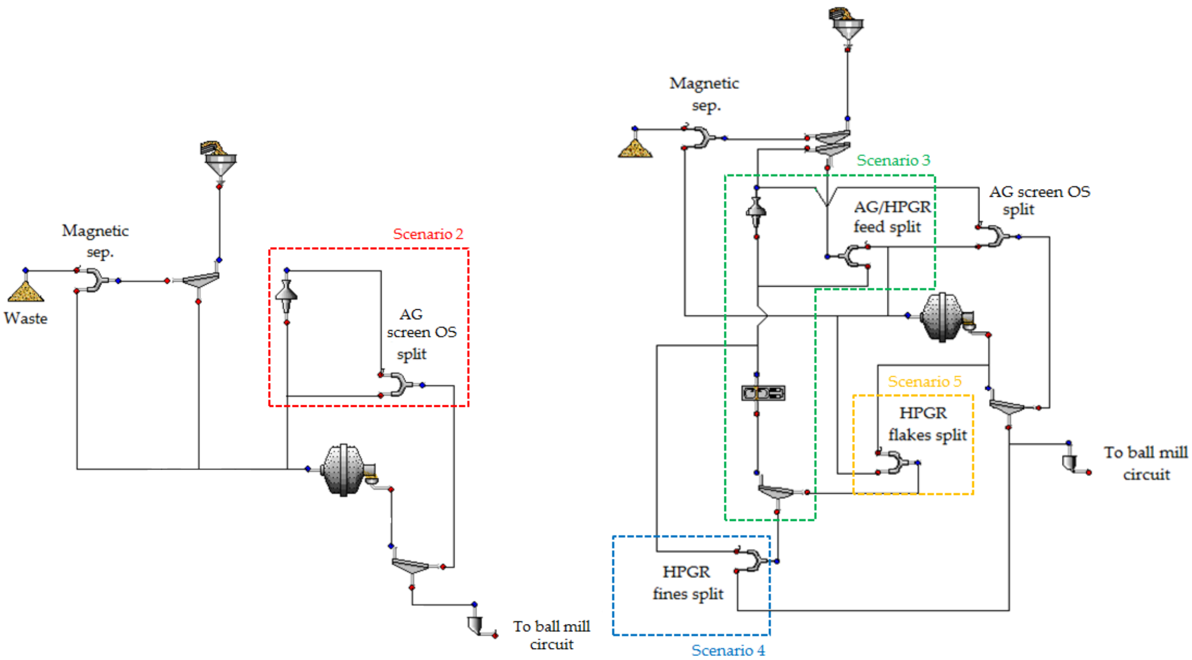

Figure 14—Flexi-circuit options (Powell, Foggiatto and Hilden, 2014)

The future?

The imperative to slash our energy and emissions footprint is a strong driver in the mining industry, with public buy-in from the major companies. With a shift to Autogenous grinding offering a route to reduce emissions by 40%, this must surely be high on the agenda of any mining company that operates SAG and ball mills.

The barriers to implementing AG milling rather than continuing the current rush to load up SAG mills to the brim with steel media are explored and a clear pathway to de-risking the renewed uptake of AG milling is presented. This involves investing in technology from ore characterisation, to model development, to engineering solutions.

Key elements to address are:

- Engineering design–plant layout
- Economically viable ore characterisation for incorporation of variability and blending over life-of-mine
- Mine planning to facilitate control over blend windows
- Control of blasting for a tunable ideal feed with different ore types
- Dealing with clays and deleterious elements
- Feed control via controlled blending, separation of rock grinding media, preventing undesired segregation, buffer stockpiles
- Limit overgrinding and slimes production through mill discharge design, content control, mid-size fine crushing

- Incorporate dynamics in process design
- Complete development of a fully-dynamic AG mill model and simulator to predict the long- and short-term operation and control

All of these factors are understood and can be tackled as a coherent push to uptake, presenting an ideal forum for cooperative research and technology development within the industry to accelerate access for rapid implementation required to meet world energy and emissions targets. The options include modification of existing circuits and repurposing of equipment with potentially comparatively low new investments based off the expected evolution of understanding and capability.

Will AG milling make a come-back? There is a strong probability it will, based on the environmental and cost drivers, underwritten by the capability, industry willing, to reliable predict and control AG mill performance. Will the viable, but untested potential circuit, featuring AG milling, as proposed by 10 years ago by Powell (2013) and illustrated in Figure 15, become a reality? Only time will tell.

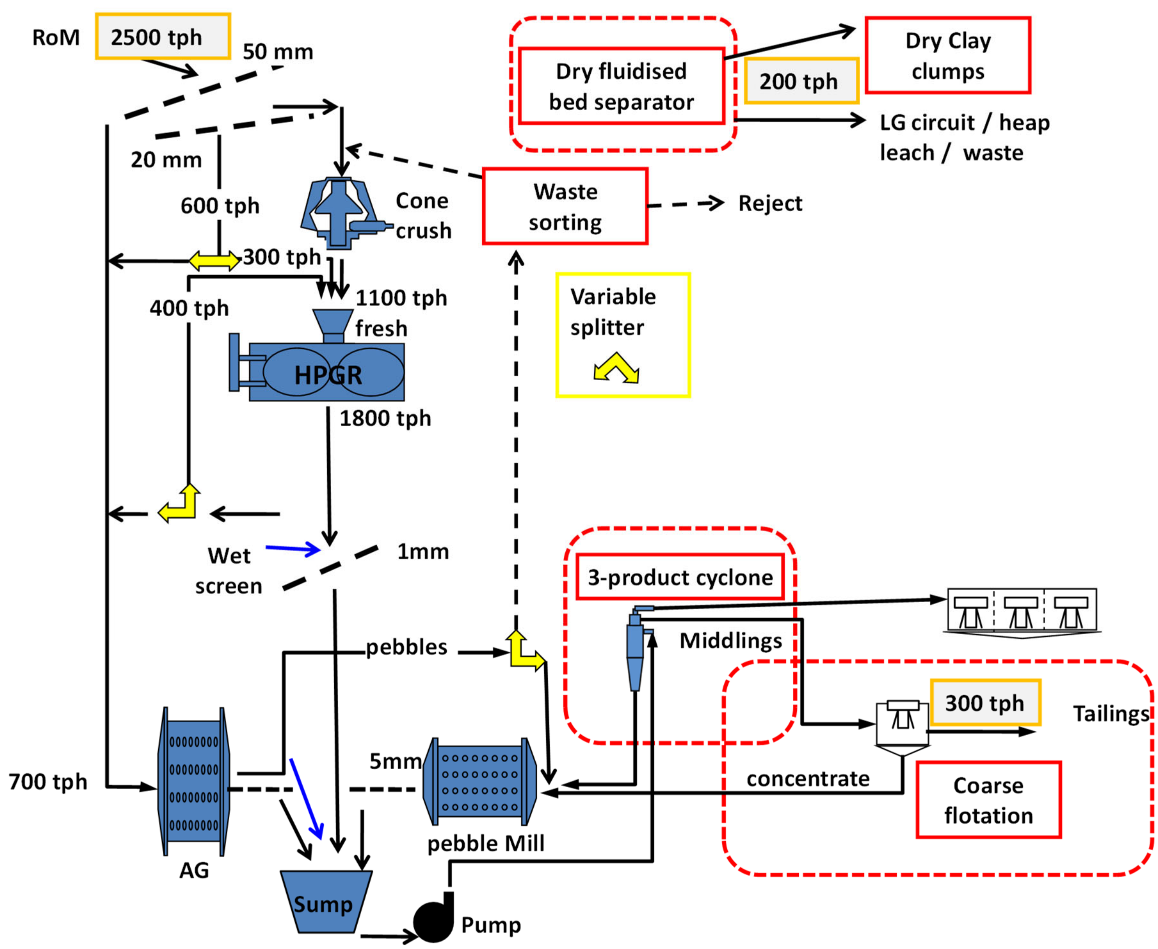

Figure 15—Flexi-circuit with AG mill, HPGR and future ore rejection options (Powell, 2013)

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