HPGR—FAQ

by C. Morley*

Synopsis

The successful commissioning of the Cerro Verde project in Peru at the end of 2006 marked the culmination of the efforts of many in the industry over many years to have high pressure grinding roll technology recognized and accepted as a legitimate alternative to the conventional approach to large-scale hard rock comminution circuit design. Other hard-rock projects that have recently adopted HPGR include Freeport (Indonesia), Boddington (Australia) and Amplats Potgietersrus (South Africa).

With the increasing acceptance of this technology, the need for technical presentations and articles exhorting the industry to adapt has diminished somewhat, and it is considered appropriate now to shift the emphasis to the provision of information for those considering embracing change.

This article endeavours to answer frequently asked questions on the subject of high pressure grinding roll technology, with particular reference to its application in the hard rock minerals processing sector.

Introduction

Contrary to popular belief, high pressure grinding roll technology is not 'new', having its genesis in the early 20th century as a method of coal briquetting (Figure 1), and being used in comminution applications since the mid 1980s. However, while HPGR is now commonplace in the briquetting, cement, diamond, and iron ore sectors, its adoption for true hard rock comminution duties has been slow and cautious, and there are still only a very few hard rock operations to have embraced this rapidly maturing technology. This article endeavours to answer questions on the subject, provide information, dispel myths, and generally demystify the technology, with a view to encouraging the more widespread understanding of HPGR as an alternative or supplement to conventional crushing and milling circuit designs.

The technology

What is HPGR?

The high pressure grinding roll machine comprises a pair of counter-rotating rolls mounted in a sturdy frame. One roll is fixed in the frame, while the other is allowed to float on rails and is positioned using pneumo-hydraulic springs. The feed is introduced to the gap between the rolls and is crushed by the mechanism of interparticle breakage. (Figure 2.)

Comminution performance is largely determined by the pressure exerted by the hydraulic system on the floating roll. Typically, operating pressures are in the range of 50–150 bar, but can be as high as 180 bar. For the largest machines, this translates to applied forces of up to 25 000 kN.

'Inter-particle breakage'—what's that?

The mechanism whereby particles are broken by compression between other particles, as distinct from single-particle breakage involving compression between the surfaces of the crushing machine.

The manufacturers

Who makes HPGRs?

There are currently three recognized manufacturers of HPGR machines, namely Polysius (a ThyssenKrupp company), KHD (KHD Humboldt Wedag AG), and Köppern (Maschinenfabrik Köppern GmbH & Co KG), all based in Germany.

Are there any differences between the makes?

No fundamental differences; however, there are some variations in design philosophies. For example, Polysius favour a high aspect ratio design—

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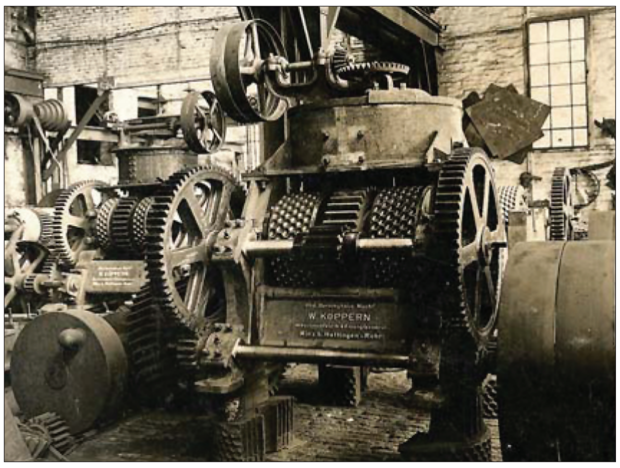

Figure 1—Early briquetting press

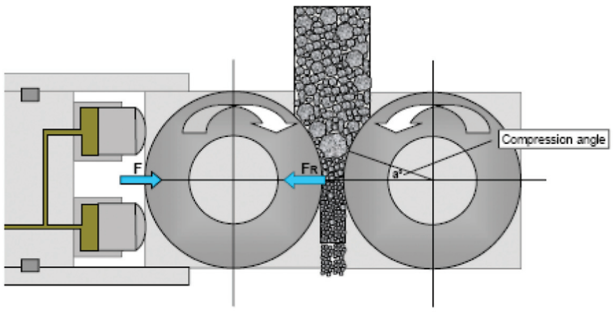

Figure 2—HPGR design principle

large roll diameter, smaller width—whereas KHD have traditionally preferred a low aspect ratio and Köppern a 'square' ratio. More recently, KHD have offered higher ratios for certain large capacity applications.

Polysius and Köppern use self-aligning spherical roller bearings, whereas KHD use cylindrical roller bearings.

All three manufacturers offer rapid roll change-out designs that minimize the turnaround time for replacing worn rolls.

Differences in wear materials are discussed later.

What are the relative merits of the different aspect ratios?

The high aspect ratio design is inherently more expensive, but also offers an intrinsically longer wear life for a given application, as the operating gap is larger and the roll surfaces are exposed to a correspondingly smaller proportion of the material processed. The high aspect ratio design also produces a coarser product due to the greater influence of the edge effect; however, the effect is relatively slight, particularly with larger units. The low aspect ratio has a higher pressure peak in the compression zone, and therefore generates a finer product. Again, however, the effect is relatively modest.

The 'edge effect'—what's that?

The pressure profile across the roll displays a tapering off of pressure toward the roll edges, leading to impaired comminution performance. The 'edge' proportion is a function of the operating gap (edge = gap x ~1.2), which is in turn a function of the roll diameter (gap = 2–2.5% of diameter), so a high aspect ratio design has a greater edge effect.

And the bearing design?

Being fully sealed, the cylindrical roller bearing design allows the choice of grease or circulating oil lubrication (although in the latter case, grease is still required for bearing seal lubrication). By contrast, the self-aligning spherical design can be only grease lubricated to accommodate the relative movement between shaft and seal.

The nature of the cylindrical bearing design is such that, for large units, multiple bearings are required to accommodate the machine's pressing forces, while for the spherical design, single bearing pairs are used.

The users

Who uses HPGR?

The great majority of the 500+ units in operation globally are in the cement sector and are too numerous to identify individually. Since their introduction in the mid-1980s, HPGRs have been widely used in the diamond and iron ore sectors where they are now considered commonplace. In the hard rock sector (typically copper and gold ores), the first application was a full-scale 15-month trial at Cyprus Sierrita in 1995/96.

More recently, HPGR was selected as the preferred technology for the Cerro Verde copper/molybdenum project in Peru (commissioned November 2006) and the Boddington gold/copper project in Western Australia (under construction at the time of writing). Freeport Indonesia (commissioned November 2006) use two units to pretreat ball mill feed, to generate a finer mill product and consequently enhance flotation performance.

Amplats Potgietersrus Division (platinum, South Africa) commissioned a single large unit in November 2007. Several other mining companies in Western Australia are considering, or are committed to, using HPGR technology in upcoming projects.

Figure 3 (courtesy of Polysius) illustrates the ready acceptance and rapidly increasing population of HPGRs following their introduction to the diamond and iron ore sectors, and also reflects the relatively slow and cautious approach in the hard rock sector—although interest here can be seen to be accelerating, albeit belatedly.

What happened at Cyprus Sierrita? I heard that it was a failure

While this application is widely considered to have been unsuccessful as it did not lead to a commercial sale, the fact that the comminution performance of the machine was impressive is not in dispute (Thompsen, 1996, Thompsen *et al.*, 1996). The difficulties experienced related to the behaviour of the wear surfaces, and many valuable lessons were learnt from this operation about the precautions

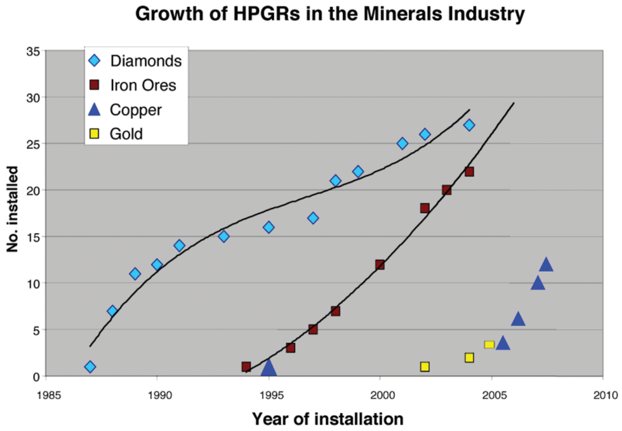

Figure 3—HPGR population growth

necessary in circuit design and unit operation for the protection of the studded roll surfaces and the successful application of HPGR technology (Morley, 2005). Bearing in mind that this was (and was intended to be) a trial, it could be argued that it was in fact a success, as the outcome now forms a large part of the foundation of current machine and circuit design practice.

The rules

What were the findings from the Cyprus Sierrita trial, and what are the rules for using HPGR in hard rock applications?

These are discussed in detail elsewhere (Morley, 2005)—the major issues relate predominantly to protection of the wear surfaces and can be summarized thus:

- Feed must be unsegregated and presented uniformly across the roll width
- Tramp metal management must be highly efficient and the system designed so that tramp metal removal does not entail stopping of feed to the HPGR
- Feed top size should not exceed the operating gap between the rolls
- For highly competent ores, very high operating pressures should be avoided
- Continuous tyres are preferred to segments as accelerated wear occurs at the segment boundaries
- Roll edge protection and cheek plate design is now well developed and this method of protection is generally preferred to edge bypass rock-boxes, although this alternative is still considered in some specialized applications.

Why so much emphasis on protection of the wear surfaces?

The machine is mechanically very reliable with availability factors typically in excess of 98%. The great majority of lost operating time relates to wear surfaces, hence the focus on this aspect in technology development. The low overall machine utilization of about 60% during the Cyprus Sierrita trial was due almost entirely to difficulties and experimentation with the roll wear surfaces. Since then, developments in wear surface design, and recognition of the foregoing rules in circuit design and machine protection, have together led to improvements in overall utilization factors giving today's values typically in the range of 92–95%.

Early roll surface designs were borrowed from the cement sector and comprised smooth NiHard and profiled surfaces that had very limited wear lives when used on hard, abrasive ores. Combined with the time involved in changing outworn rolls, this resulted in very low, often unacceptable machine availabilities.

The wear life was extended dramatically by the introduction of studded roll surfaces (which capture crushed material in the interstices to form a so-called autogenous wear layer) and edge wear blocks. Both studs and edge blocks are of tungsten carbide, which, although hard and wear resistant, is brittle and easily chipped or broken—hence the need for protective measures.

The change-out time issue was resolved with the development of rapid roll change-out designs, which reduce the turnaround time from as much as five days to about 32–36 hours.

All three manufacturers offer studded roll designs, and the proprietary Hexadur® surface is available from Köppern. This comprises hexagonal tiles of a proprietary abrasion-resistant material set into a softer matrix, which wears preferentially in operation allowing the formation of an autogenous wear protection layer at the tile joints. Hexadur's low profile makes it less susceptible to damage from oversize feed or tramp metal, and higher operating pressures are tolerable. However, at the time of writing, the population of Hexadur-clad rolls in hard rock applications was small and wear life on abrasive ores unproven. (Figures 4 and 5.)

The terminology

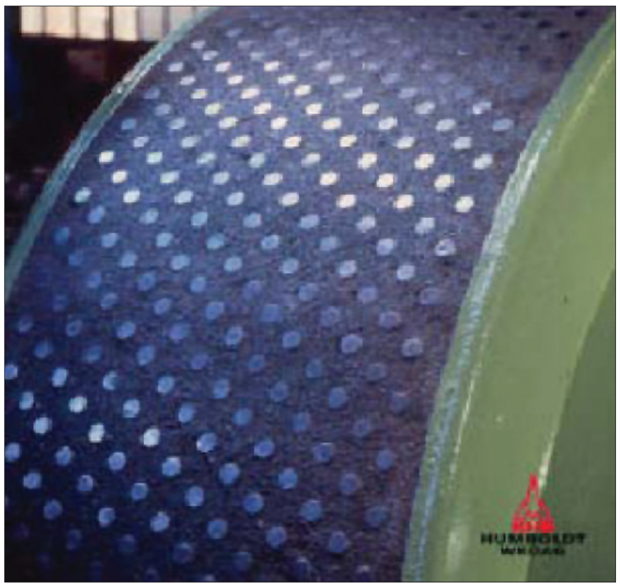

Figure 4—Studded roll

Figure 5—Hexadur

There are several unusual terms that seem predominantly to relate only to HPGRs—what do they all mean?

These terms relate to the performance of the HPGR and were formulated largely to assist in the process of scale-up from laboratory or pilot tests to full-scale machines.

- *Specific press force* (N/mm²)—the applied force divided by the projected area of the roll (width x diameter). The applied force does of course increase with machine size, but when normalized in this way becomes independent of size. Typical practical operating values are in the range of 1–4.5 N/mm² for studded roll surfaces and up to 6 N/mm² for Hexadur.
- *Specific throughput* (ts/m³h)—the capacity of a machine with a roll diameter of 1 m, a width of 1 m and a peripheral speed of 1 m/s. It is a function of the feed material characteristics and roll surface, determined by testwork and used for scale-up. It is also known as specific capacity or 'm-dot'. Typical values for studded rolls are in the range of 210–260 ts/m³h for an ore SG of 2.7. (Values are proportional to SG.) For truncated feeds—i.e. feeds with fines removed—values decrease by about 25%.
- *Specific gap* (% of roll diameter)—determined by testwork and used in scale-up. Typical values are in the range of 2.0–2.5% for full-fines feed and about 1.5–2.0% for truncated feeds.
- *Specific energy* (kWh/t)—the net power draw per unit of throughput. Also independent of machine size, and an almost linear function of specific press force for a given application. Typical operating values are in the range of 1–3 kWh/t.
- *Specific power* (kW.s/m³)—the product of specific energy and specific throughput, it is used to estimate the shaft power required for a given machine.
- *Shaft power* (kW)—the product of specific power and the diameter, width, and peripheral speed of the rolls.
- *Unit capacity* (t/h)—the product of specific throughput and diameter, width, and peripheral speed of the rolls.

The shaft power and unit capacity predicted by these formulae can be compared with the measured values of the operating unit to evaluate the accuracy of scale-up in design.

On the subject of unit capacities, what range is available?

Leaving aside the laboratory-size machines, the smallest units deployed in the field are the KHD and Polysius pilot units, rated at nominally 20–80 and 80–100 t/h respectively. The largest machine produced to date is the Polysius 24/17 (2.4 m diameter, 1.7m wide—in operation at Cerro Verde and ordered for the Boddington project). This machine has a capacity of about 2250 t/h and is driven by twin 2500 (Cerro Verde) or 2800 kW (Boddington) variable speed motors.

The manufacturers have developed a range of standard sizes between these limits, but are able to engineer machines of essentially any size. For example, the largest diameter machines to date are the 2.8 m units at Premier diamond mine in South Africa. They are only 0.5 m wide, however, with twin 600 kW drives, so are not particularly large in capacity terms—the large diameter was selected to provide a large operating gap to avoid diamond breakage. Recently, the roll surfaces were changed from smooth to studded, giving a significant increase in both capacity and wear life with only a minor impact on size reduction performance.

Operating characteristics

How does HPGR operation vary with feed characteristics?

Ore characteristics having a significant effect on HPGR operation include competency, abrasiveness, moisture and size distribution (i.e. full-fines or truncated):

- At a given operating pressure, power draw is a function of ore competency, so that a high-competency ore will give high power draw and influence bearing and motor selection.
- A combination of highly competent ore, high operating pressures and oversize feed (i.e. top size significantly larger than the operating gap) is a recipe for stud damage. High pressures and oversize feed are more tolerable with less competent ores.
- A high fines or clay content in the feed leads to impaired comminution efficiencies, although HPGR is much better able than cone crushers (for example) to tolerate such feeds.
- High moisture levels cause reductions in specific capacity.
- Very high moisture levels can cause wash-out of the autogenous layer and lead to accelerated wear.
- High ore competency and abrasiveness together lead to increased wear rates. Note that high abrasiveness alone does not necessarily lead to high wear rates—the Bond abrasion index is a poor predictor for HPGR. The manufacturers have developed standard tests using laboratory-size HPGRs for the purpose of predicting wear rates.

- Truncated feeds give reduced specific capacities, a coarser product, and higher wear rates.
- Ore type, feed moisture content and operating pressure determine flake competency.

'Flake competency'?

The product of an HPGR is discharged in the form of a compressed cake or flake with a density of about 80 to 85% of the ore SG, depending on operating pressure. The competency of the flake depends primarily on the ore type, with hard, primary ores tending to produce fragile, easily deagglomerated flakes, and softer, clayey ores (such as kimberlites) giving more competent flakes that often need intensive deagglomeration before further treatment.

Control philosophies

How does the operator control the working gap between the rolls?

In short, he doesn't. This and other HPGR myths and misconceptions are discussed elsewhere (Klymowsky, 2003). The operating gap is a function primarily of the ore characteristics and the roll diameter and surface texture, and is only a weak inverse function of operating pressure.

So if the gap can't be controlled, what can be?

There are only a few variables available to the operator, namely the hydraulic system precharge pressure, the operating pressure, and the roll speed (assuming a variable speed drive is fitted).

- The precharge pressure determines the stiffness of the pneumo-hydraulic 'spring' and the response of the machine to feed irregularities. The optimum setting is ore-dependent and determined by test work, and normally should not need changing after initial set-up during commissioning.
- The operating pressure set-point is adjusted to modify HPGR performance. Increasing pressure has the following effects:
  - Increased specific energy, proportional to the pressure increase
  - Slightly reduced capacity due to the smaller gap
  - Finer product, up to a point—the fineness curve (say, %-1 mm) approaches a plateau as pressure is progressively increased, whereafter the additional energy consumed with further increases in pressure materializes as heat and a higher flake density.
- Roll speed can be used as an operating variable to control throughput. Capacity increase is not a linear function of roll speed as higher speeds result in more slippage of the ore against the roll surface; however, the effect is only slight with studded rolls due to the inherently high kinetic friction of the autogenous wear layer.

That covers control of the machine—what about control of the circuit?

There are two important aspects of the operation of an HPGR that drive the process control philosophy:

- The HPGR must be choke-fed to maintain comminution efficiency
- The number of stop-start events must be minimized, as accelerated roll wear occurs during feed run-up and run-down.

Choke feeding can be achieved by the use of a variable speed belt feeder controlled by a level signal from the HPGR feed hopper, and stop-start events can be significantly reduced by the use of variable speed drives on the HPGR rolls controlled by a level signal from the HPGR feed bin. This allows the HPGR throughput to be matched to feed arisings. The two control loops operate independently and in parallel. (Figure 6.)

The benefits

Why use HPGR?

Commonly, the primary motivation for the use of HPGR as a hard rock comminution alternative is its energy efficiency when compared to conventional crushers and mills. Furthermore, downstream energy requirements, typically in ball milling, are often reduced due to the increased fineness of the HPGR product (compared to conventional crusher products) and to reduced work indices caused by micro-cracking of the HPGR product particles.

What's micro-cracking?

Also known as micro-fracturing or micro-fissuring, this is the phenomenon whereby internal fracturing of particles occurs due to the extreme pressures exerted by the rolls in the compression zone. Being thus weakened, such particles display a reduced energy demand in the downstream comminution process. (Figures 7 and 8.)

Are there any other benefits?

When compared to conventional SABC, HPGR-based circuits offer significant reductions in grinding media costs, as SAG

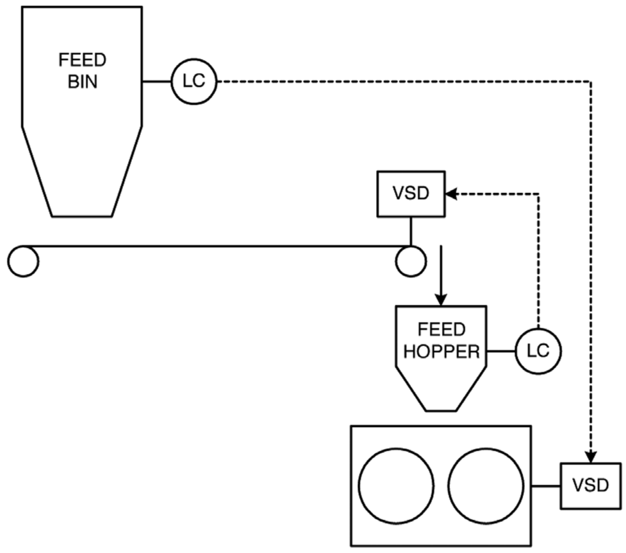

Figure 6—HPGR circuit control

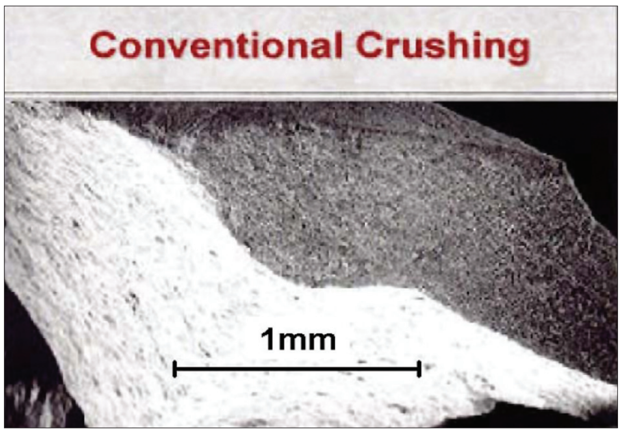

Figure 7—Conventionally crushed particle

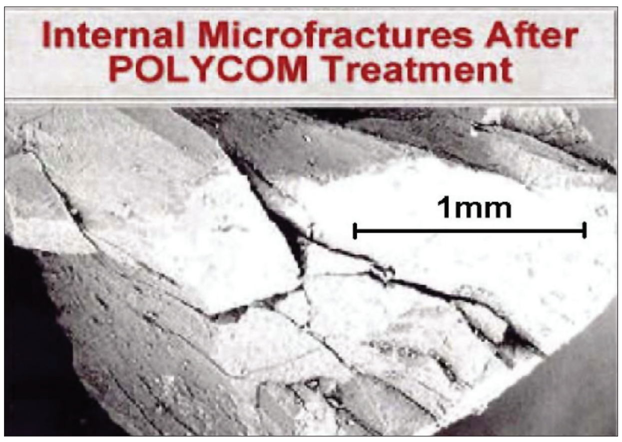

Figure 8—HPGR crushed particle

mill ball consumption is eliminated. While ball mill media consumption is typically slightly higher than in SABC circuits due to the coarser transfer size from the HPGR, there is still a substantial benefit that typically is of the same order of magnitude as the savings in energy.

But isn't this offset by the cost of the replacement HPGR tyres?

Studies have shown that, in $/t terms, the cost of HPGR tyres is about the same as that of SAG mill liners. Such studies generally make conservative estimates of HPGR tyre life, and the longer lives typically achieved in practice tend to enhance the case for HPGR. This situation has improved further with the rapid roll removal designs now available from the HPGR manufacturers, resulting in turnaround times shorter than for the equivalent SAG mill reline event.

So, there are benefits to be had in energy and grinding media, with liners about neutral—anything else?

The literature notes that improvements in downstream processing should be expected due to the reduced overgrinding experienced in HPGR-based circuits, but the benefits are relatively minor compared to those seen in the comminution process. However, substantial benefits have been reported in gold recovery when the HPGR is followed by a heap leach process (Klingmann, 2005).

A further, non-technical benefit lies in the comparative lead times for the supply of SAG mills and HPGRs. Typically, SAG mills, particularly large ones, have considerably longer lead times than HPGRs—differences in the range of six to fourteen months have been estimated for some projects—so that, if the SAG mill is on the project schedule critical path, HPGR could offer some benefit in project execution time.

HPGR also offers improved plant ramp-up times compared to SAG-based circuits, as an HPGR can operate at full throughput almost immediately, and as noted earlier has a very high mechanical availability factor.

The disadvantages

So much for the benefits—what's the downside?

At the current stage of development of the HPGR machine and HPGR-based flowsheets, capital costs are generally higher than for the equivalent SABC circuit. This is due to the need to control the HPGR feed top size, implying a closed circuit secondary crushing step upstream, and to control mill feed top size to avoid milling inefficiencies, implying closed circuit operation of the HPGR itself. It is the cost of these closed circuit facilities—crushers, screens, conveyors, bins, feeders, dust control, tramp metal management—that inflates the cost of HPGR-based hard rock comminution circuits.

Therefore, until this capital cost differential can be eliminated or reversed—by further technology innovation in the design of both machine and circuit—an HPGR-based circuit must offer sufficient operating cost benefits to offset the additional capital cost over an acceptable payback period.

Application guidelines

How can I tell if HPGR is likely to be attractive for my project?

The main drivers influencing the selection of HPGR are ore competency, electricity cost, and plant throughput. Included in electricity cost is grinding media cost as the two are linked when media consumption is expressed in g/kWh terms—and as noted earlier, grinding media cost is a significant component in the comparison. Included in plant throughput is project life, as it is rare for a high throughput to be selected for a short project life. A long life allows greater flexibility for the incremental capital cost payback period to come into effect. In Figure 9, if a project's data point is above the surface defined by these variables, then HPGR is probably worth examining as an option; if below, probably not. A fourth factor is fineness of grind—a coarser grind favours HPGR due to the skewing of comminution energy toward the (more efficient) HPGR.

Can these factors be quantified?

Not precisely, as they are project and ore specific to a degree. It is necessary to conduct the appropriate trade-off studies for each individual project, as the global database of hard rock HPGR projects is still too small to allow reliable benchmarking. However, the following can be used as a

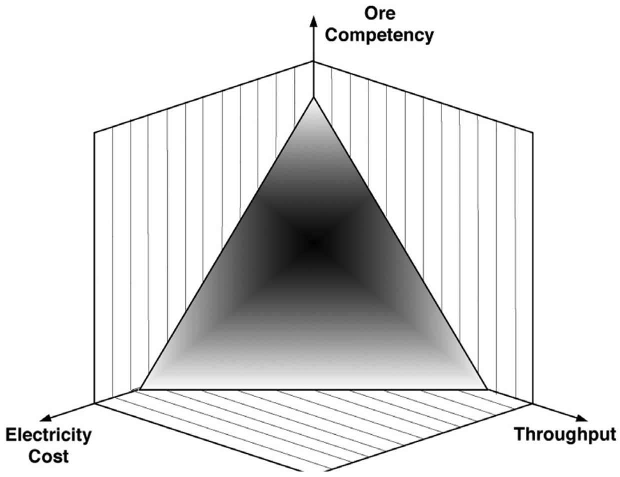

Figure 9—Application matrix

guide:

- ➤ Ore competency, as measured by the JK A^*b parameter, is the best preliminary indicator of HPGR suitability (in a project-economics sense). As illustrated in Figure 10 (courtesy of Newmont Mining), SAG specific energy rises exponentially as the A^*b value decreases (more competent ore), and HPGR becomes progressively more attractive as the A^*b value decreases below about 35–40. Above this point, SAG milling is likely to be the more viable.
- ➤ Electricity costs below, say, US3¢/kWh would be considered cheap in this context, while above about US8¢/kWh would be expensive.
- ➤ The higher the throughput, the smaller the capital cost differential—the economies-of-scale effect. Studies have shown that, for a 100 000 tpd project, the difference is about 10–12%, whereas for 25 000 tpd, this increases to around 30%, so the incremental capital payback period is longer for a smaller project.
- ➤ In this context, grind sizes of 90 m and below would be considered fine, whereas 125 µm and above would be coarse. However, this is of course a sliding scale—the coarser the better in terms of HPGR suitability and economic benefit.

Testwork

I understand the above guidelines are just that—so having decided my project might benefit from the use of HPGR, what happens next?

The three T's—testwork, testwork and testwork:

- ➤ Testwork to characterize the ore, with as many as possible of the following being measured on representative ore types:
  - – Physical properties
    - • UCS (compressive strength)
    - • Point load index (tensile strength)
    - • SG, bulk density, moisture
  - – Bond indices
    - • Crushing (CWi)
    - • Rod milling (RWi)
    - • Ball milling (BWi)
    - • Abrasion (Ai)
  - – JK Comminution Parameters
    - • A^*b (impact breakage)
    - • t_a (abrasion breakage)
    - • t_{10} (size reduction)
    - • DWi

The most important of these are the ore SG, the JK A^*b parameter and the Bond ball mill work index, which are required for circuit simulations.

- ➤ Testwork to assess the amenability of the ore to HPGR treatment, including:
  - – Specific throughput
  - – Wear rate
  - – Power requirement
  - – Product sizing
  - – Effect of pressure on:
    - • Product sizing
    - • Micro-cracking effect on:
  - – Leach recoveries

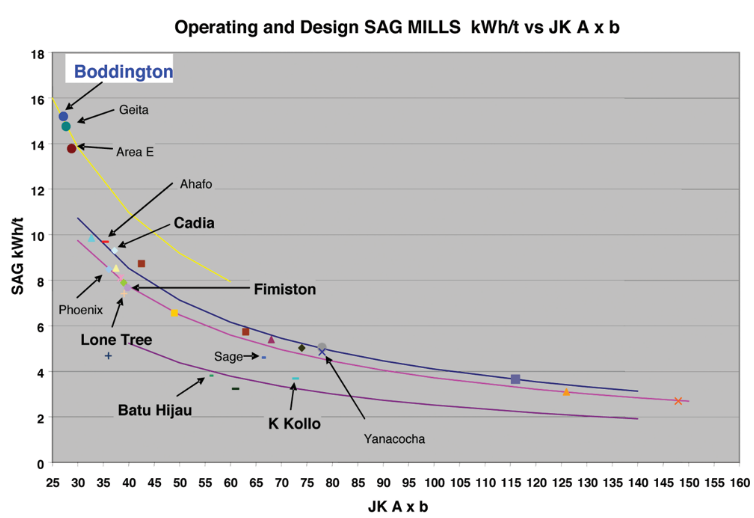

Figure 10—SAG milling specific energies

– Milling specific energy

Figure 11 (courtesy of Polysius) illustrates that, of the many ores tested by Polysius, the majority are in the low abrasive, high fines quadrant, indicating good amenability to HPGR treatment.

➤ Testwork to assess flake competency. This is an essential component of the HPGR test suite, as a competent flake would indicate the likely need for a dedicated deagglomeration step before further treatment of the HPGR product. Generally, hard competent ores produce a fragile flake that is easily broken up simply by handling on conveyors and in bins, but it is important to conduct the tests, on representative ore samples, to ensure flowsheet design errors are avoided. Note that flake competency is not a measure of an ore's amenability to HPGR treatment; rather it influences the design of the circuit handling the HPGR product.

Circuit modelling and evaluation

I now have my testwork results, which look promising. Can I now proceed with plant design?

In a technical sense, yes—but while technical feasibility has been demonstrated, commercial viability has not yet been addressed. For this, it is necessary to:

➤ Conduct simulation modelling of the HPGR-based circuit and the alternative—typically SAG-based—to determine overall comminution specific energy requirements

➤ Use the model results to size major equipment and develop circuit designs to a prefeasibility level of detail for the two (or more) options

➤ Develop prefeasibility-level capital and operating costs for each option and conduct life-of-mine financial modelling to determine to most favourable option.

If the HPGR-based circuit emerges as most favoured, then both technical and commercial justification have been achieved. If a marginal benefit (or penalty) is indicated, it might be necessary to progress the design and estimate detail to full feasibility level to improve confidence.

Note that fully developed flowsheet concepts are not essential at this stage, provided due cognizance is given to the HPGR feed and product top-size control requirements and the possible need for flake deagglomeration as indicated by testwork.

The primary focus of modelling is to determine overall comminution specific energy requirements for the various options. For hard rock applications, there is typically a significant energy saving for HPGR over SABC, but within the HPGR category, little difference between circuit options should be expected.

Flowsheet options

I have now demonstrated that my ore is amenable to HPGR treatment and that the economics of my project will benefit from the use of this technology. I am ready to start designing my plant. What are my flowsheet options?

This subject is addressed in detail elsewhere (Morley, 2006) and is too wide ranging to be covered in any depth in an article of this nature. Suffice to say that HPGR offers a considerable degree of flexibility in its application, but that, for typical hard rock applications, an HPGR-based circuit would have the general appearance of a three-stage crushing and single stage ball milling circuit, with HPGR used as the third crushing stage.

In brownfields applications, HPGR can be used to debottleneck conventional crushing/milling circuits and SAB(C) circuits. In the former, HPGR can be used to replace or supplement conventional (cone) tertiary crushing capacity, or to pretreat ball mill feed to improve milling performance (e.g. Freeport Grasberg). In the latter, HPGR can be used in a precrushing duty to increase SAG mill feed fineness, or in the pebble crushing circuit (e.g. Empire taconite) to further improve overall AG or SAG mill performance.

Conclusion

Acceptance of HPGR in the hard rock sector has been

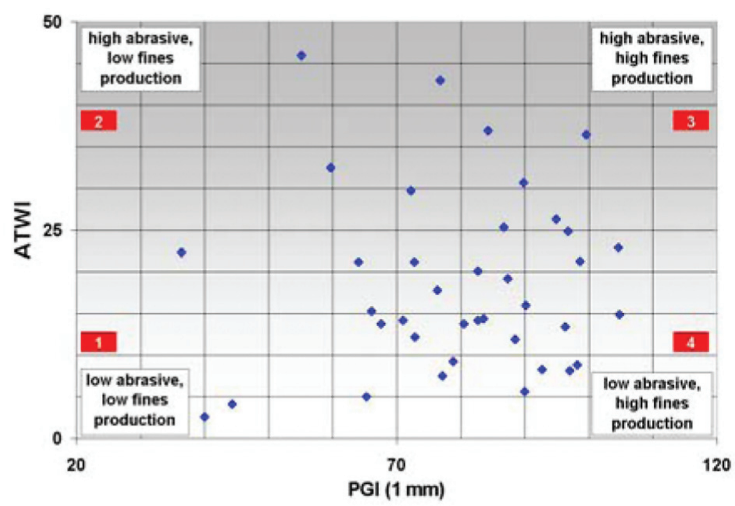

Figure 11—Polycom grindability index

relatively slow and cautious, but has come to maturity with the successful commissioning of the Cerro Verde project and recent adoption of the technology for several other major hard rock projects. The technology can now be said to be sufficiently well understood and adequately developed to allow HPGR to be seriously considered as an alternative comminution method for hard rock applications.

However, the global database for hard rock operations is still lightly populated, and project and ore specific testwork and circuit modelling are essential for prospective applications. The appropriate trade-off studies are recommended to compare HPGR technology with conventional circuit designs to ensure decision-making is well informed and the most favourable project-economics outcome achieved.

Acknowledgements

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