Real and Potential Metallurgical Benefits of HPGR in Hard Rock Ore Processing

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Abstract. Significant improvements in design and wear abatement technology combined with escalating energy and steel media costs are making High Pressure Grinding Rolls (HPGR) increasingly attractive for applicable “hard rock” ore applications relative to SAG-Ball milling. In addition, HPGR offers significant metallurgical benefits, which is the topic addressed in this paper. As early as 1988 it was shown that HPGR comminution resulted in improved gold leaching even at considerably coarser particle size distributions than the conventional minus-74 micron grind. Dramatic heap leach recovery and leach rate improvements were demonstrated in column leaching of South African gold ores also in 1988. Randol (1993) reported that Anglo American Corporation had demonstrated flotation recovery benefits of HPGR. Smit (2005) showed that grade-recovery curves can be significantly optimized by adjusting the HPGR pressure. Unfortunately, the metallurgical benefits of HPGR were not aggressively pursued in the 1990’s when it was found that wear rates and operational availability presented challenges in the treatment of “hard” ores using HPGR designs available at that time. Following improvements in HPGR wear abatement technology and design, industry was reminded of the metallurgical benefits of HPGR by Baum (1997) on the basis of photo-micrograph and petrologic observations on the product of bench-scale HPGR. Operational availability and wear-rate abatement improvements have been conclusively proven in three semi-commercial HPGR demonstrations on two gold mining and one platinum mining operations. HPGR was successfully demonstrated on extremely tough ores that are less amenable to SAG milling. Metallurgical benefits of HPGR stem from the inter-particle breaking characteristics of this type of comminution, and include: improved liberation of valuable mineral grains for better flotation and gravity recovery as well as improved and faster heap leach gold and copper recoveries. Test results suggest that mineral recovery benefits can be enhanced if HPGR-liberated sulfide particles are recovered early, i.e. by flash flotation before the HPGR product is ground in a subsequent ball mill. HPGR deserves also to be tested as a means of accelerating bio-heap oxidation of sulfide ores as well as for pretreatment benefits in the reprocessing of tailings by flotation or gravity and for fine-grinding applications, possibly in conjunction with Isamills. HPGR benefits and applicability are, as one might expect, ore-specific and every ore needs to be carefully tested.

INTRODUCTION

von Michaelis (1988) wrote*: “HPGR technology from Germany has demonstrated several advantages including reduction in comminution power consumption. Better grain boundary breakage is claimed to reduce over-grinding which is important ahead of flotation. In addition, this type of crushing is claimed to cause micro-fractures in relatively coarse mineral particles which allows better lixiviant access even without fine grinding. Esna-Ashari & Kellerwessel (1988b) show how Roller Press Crushing (i.e. HPGR) improves heap leach recovery in recent tests.”* Two decades later these benefits of HPGR are being rediscovered, only this time using proven HPGR technology and equipment that has been improved and adapted to treat even some of the hardest ores reliably and at a low cost.

Since the 1980’s High Pressure Grinding Rolls (HPGR) have become standard in the kimberlite and lamproite diamond processing industry as a means of liberating diamonds from softer gangue material with the added advantage of not breaking large stones. HPGR is also widely used in the fine-grinding of iron ore to increase the surface area of pellet feed. Odenwald et. al. (2005) showed the various ways in which HPGR is used for this growing application. Most recently, HPGR selection for projects such as Cerro Verde, Boddington and Freeport Grasberg appears to be motivated mostly by operating cost savings, particularly in energy and grinding media and/or for the ability of HPGR to handle tough ores that do not lend themselves ideally to SAG milling.

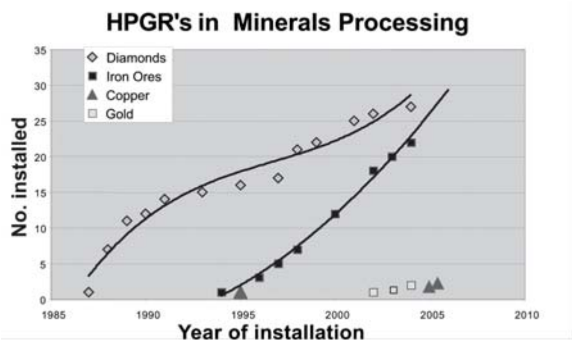

Fig 1. Growth in HPGR applications in diamond iron ore, copper and gold ore processing. Source: Knecht (2004)

Baum (1997) and Baum et al. (1996, 1997) showed on the basis of photomicrograph and petrologic examinations of HPGR product grains that HPGR promises the following benefits:

1) Micro-fractures introduced into the HPGR product would be expected to result in reduced energy consumption and lower steel consumption in downstream ball milling compared with second stage milling of conventionally crushed ores and ores processed through primary SAG mills.
2) Micro-fractures introduced into HPGR product can be expected to improve heap leach extraction recoveries. Column leach tests showed that leach rates are often also improved as indicated first by Esna-Ashari & Kellerwessel (1988b).
3) Baum (1997) showed that improved mineral liberation by HPGR indicated an expected 2.5-15% improvement in flotation recovery and 2.5 – 9% recovery improvement in gravity recoveries.

HPGR was tested at a commercial scale of around 1250 tph at Cyprus Sierrita in 1995 but this test was discontinued after the copper price dropped and expansion plans at Sierrita were scrapped. There was little incentive at that time to persist in finding solutions to operational availability challenges of the large HPGR machine with segmented tyres installed at Sierrita.

Around 2000, however, interest in HPGR was renewed when extensive pilot testing revealed that HPGR offers significant capital and operating cost benefits including significant energy savings compared with SAG-ball milling for the Boddington Gold project in Western Australia as reported by Parker et al (2001).

Three significant HPGR pilot plant demonstrations at Boddington Gold Project, Western Australia; Newmont Lone Tree, Nevada, and Anglo Platinum PPL demonstrated that HPGR can successfully and reliably be applied in the treatment of very hard and abrasive ores with acceptable, even low, wear rates and high operational availability.

In 2005 HPGR was selected for the treatment of copper ores at a new 100,000 tpd Phelps Dodge Cerro Verde project now under construction in Peru and to improve recovery through finer grinding with potential expansion of one of the three lines at PT Freeport Indonesia’s Grasberg copper operations as outlined by Mosher (2005).

Now that HPGR is finally becoming accepted as a reliable and cost-effective means of tertiary comminution of “hard rock ores”, and as an alternative for SAG mills, industry attention is focusing on metallurgical benefits

Heap Leaching Benefits of HPGR

Klingmann (2005) reported column leach tests comparing a three-stage crush (with HPGR as stage 3) with a four-stage conventional crush with a vertical shaft impact crusher as stage 4 treating two types of gold ore from Golden Queen Mining Co. Ltd.’s Soledad Mountain gold project in California. Despite the finer crush of the VSI-crushed products, (see *Fig. 2)* the HPGR-crushed products yielded leach recovery improvements ranging from 7.7% to 10.7% in absolute terms as well as significant improvements in leach rates as shown in *Fig. 3.* Bottle roll leach tests of HPGR product also showed improved gold leach recoveries. It is interesting to note, however, that although silver leach recoveries were improved by HPGR, the degree of improvement was very much less than for gold.

Klingmann (2005) also showed that heap moisture retention and saturated moisture content of HPGR ores are very much lower for HPGR product than for the four-stage conventionally crushed comparison. As a result the 60-m high heaps can be expected to be more stable using HPGR-crushed ore.

Esna-Ashari & Kellerwessel (1988b) first showed dramatic heap leach recoveries and leach rate improvements in 200 mm diameter x 100 mm high column leach tests on two different African gold ores with and without cement agglomeration. These tests showed gold leach recoveries ranging between 96.6%

and 94.9% with and without agglomeration respectively for minus 50mm ore passed through an HPGR machine compared with 74.1% - 80.7% leach recoveries for the same ores crushed to minus 20 mm (minus 3/4-in) in a conventional lab-size jaw crusher, but both agglomerated with cement.

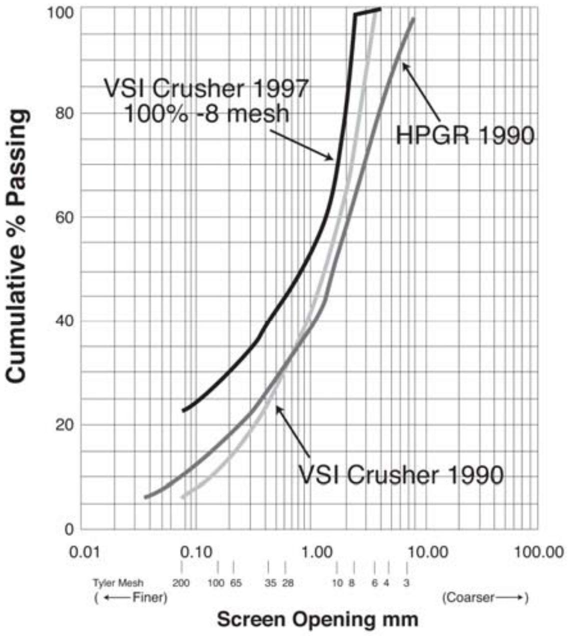

Fig. 2 Golden Queen Soledad Mountain comparison of particle size distributions of HPGR product with 4th-stage VSI product. Source: Klingmann (2005)

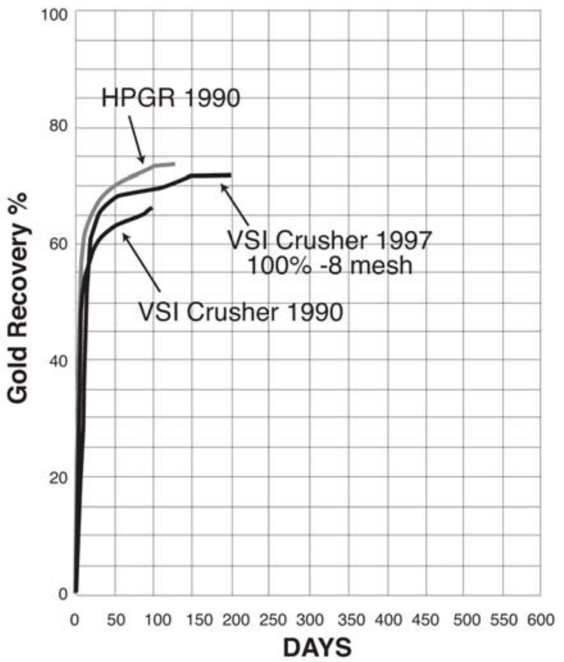

Fig 3. Comparison of gold leach rates and leach recoveries for a gold ore after three-stage HPGR crushing with four-stage conventional crushing with VSI. Source: Klingmann (2005)

Esna-Ashari & Kellerwessel (1988b) leach recovery and leach rate improvements were ascribed to the generation of more fines and also micro-fractures as a result of intense inter-particle pressures in the HPGR machine. Esna-Ashari & Kellerwessel showed that HPGR product could be agglomerated either by adding cement and 3% w/w water to the HPGR feed or in a separate agglomeration drum to the HPGR product. They commented on preferential breakage in the HPGR of particles with lower elasticity modulus. It should be noted that the very small bed height (100 mm) of the column leach tests conducted by Esna-Ashari (1988b) are unlikely to simulate real-life heap leaching recovery expectations, but they convincingly demonstrate the improved heap leach rates and leach recoveries pos-sible from this ore type as a result of HPGR.

Baum (1997) used dye-impregnation to demonstrate micro-fractures in HPGR product particles. (*Fig.4).*

Patzelt et al (1996) showed column leach test results indicating that the heap leach improvement benefits of HPGR over conventional crushing is greatest for the coarser particle size ranges probably due to the formation of micro-fractures as shown in *Fig. 5* below.

von Michaelis (2001) proposed that improvements in leach recovery and in the rate of recovery of metals as a result of HPGR should be further explored to engineer the heap leaching process as a means of treating higher-grade ores. Heap and dump leaching had hitherto been applied mostly to treat low-grade materials that did not justify the capital and operating cost of milling.

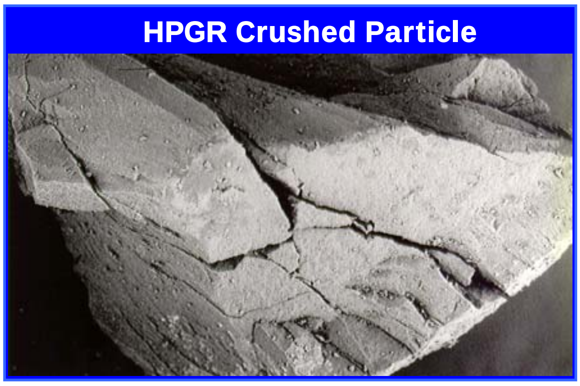

Fig.4 Comparison of HPGR-crushed particle with conventionally crushed showing micro-fractures.

Source: Baum (1997)

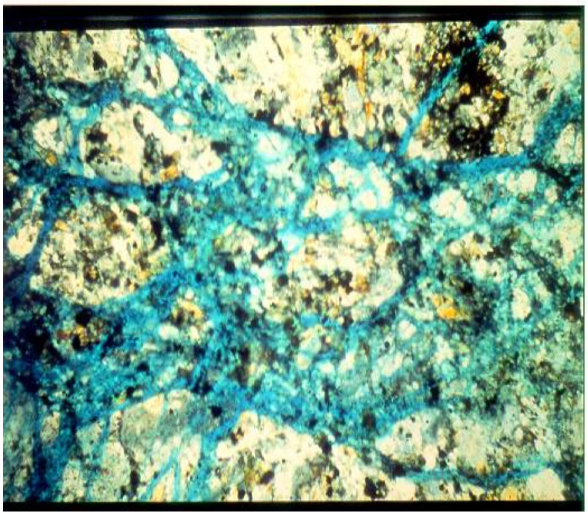

Fig. 4 Cross section of HPGR product particle after dye impregnation to illustrate micro-fractures that are beneficial to heap leach gold and/or copper leach recovery. Source: Baum (1997)

One of the most economically attractive applications of heap and dump leaching is often in conjunction with a mill. High-grade ore goes to the mill, and lower-grade ores and proto-ores are sent to the heap- or dump-leaching facility. Improving the leach recovery through the application of HPGR would raise the grade cut-off for ore optimally going to the heap or dump leach. Depending on the grade of ore and the recovery differential between milling and heap leaching, and the metal price, HPGR could even be expected to improve heap leaching economics to such an extent that, in some cases, the large capital investment in a mill might be avoided altogether.

Critics are quick to comment that heap leaching of very finely crushed material has not been successfully demonstrated in many real-life operations. Randol (1993) reports successful heap leaching of sand tailings after a sand-slime split, and Newmont's Zarafshan joint venture in Uzbekistan successfully heap leaches ore that is fine-crushed using vertical shaft impact crushers.

For pure heap leach projects, significant recovery and recovery rate improvements have been demonstrated on certain ores when HPGR is applied yielding a rapid payback on the extra capital of installing HPGR. In other cases, where an ore requires tertiary or quaternary crushing with agglomeration in order to achieve high heap gold leach recoveries, HPGR as a tertiary crusher has been shown to reduce overall capital and operating costs in addition to improving gold recovery. An excellent case of this is the Soledad Mountain described by Klingmann (2005) already referred to above.

HPGR can also be expected to offer benefits in heap leaching with pulp agglomeration. The HPGR fines if they are enriched in gold could be screened off for agitation leaching and after decantation of pregnant solution, the thickened pulp could possibly be agglomerated on to the unleached and possibly lower-grade coarse fraction for heap leaching.

In copper heap leaching the acid lixiviant reacts not only with the copper minerals, but also with the gangue. In many cases the gangue decrepitates as a result of this reaction between lixiviant and the gangue. Under the load of the overlying heaps decrepitated underlying gangue can result in reduced permeability of the lower parts at the bottom of the heaps where permeability is essential if pregnant solutions are to exit the heaps unhindered. Therefore there is often a race against time to leach copper efficiently in the overlying layers of ore before the permeability at the base of the heap starts to be seriously reduced. Also, faster leaching of copper can be expected to result in reduced reagent consumptions as there is less time for the slower gangue-lixiviant reaction to consume acid (or for cyanide volatilization losses in the case of gold and silver heap leaching.).

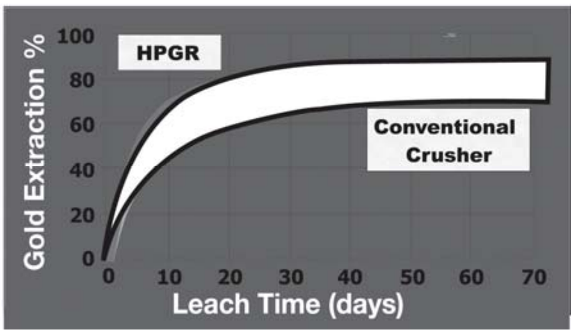

Fig. 5 Column leach test results for a highly siliceous gold ore. Source: Patzelt et al (1995)

Bio-Oxidation Benefits of HPGR

Biological oxidation of sulfide minerals in stirred reactors requires considerable capital and operating costs. Residence time of sulfide minerals undergoing biological oxidation in stirred reactors typically takes several days with expensive oxygen injection and often cooling requirements. To accelerate the biological oxidation process, very often the sulfide concentrate is subjected to fine-grinding or ultra-fine-grinding which is also expensive and energy intensive. Based on observations of micro-fissure generation by HPGR comminution, it could be worthwhile to explore the benefits of HPGR as a means of improving the overall flotation of sulfides and bio-oxidation process.

Baum (1997) showed a photomicrograph of the cross section of a sulfide particle in an ore that had been subjected to HPGR. Micro-fractures were clearly visible in the ore itself as well as in the sulfide particle. These micro-fractures would not only provide a way for leach solutions with nutrients, oxygen and bacteria to find there way to the sulfide particle within the ore lump, but also could provide a means for nutrients, bacteria and oxygen to penetrate the sulfide particle itself. This picture suggests that HPGR should provide a ready means for HPGR to accelerate heap-bioleaching processes. The same micro-fractures would also provide a means for the bioleach products to leave the particle.

Fig. 6 Cross section of a sulfide particle in ore treated by HPGR showing the micro-fractures in the sulfide particle that would accelerate bio-oxidation. Source: Baum (1997).

Sometimes, in order to efficiently produce a flotation concentrate for biological oxidation in a stirred tank, there are significant flotation recovery losses. Whole-ore bio-oxidation on aerated heaps of HPGR treated ore could prove beneficial.

It would be logical, therefore, to explore the merits of biologically oxidizing whole ore on heaps. Bio-heap leaching of sulfide-refractory gold ores was pioneered by Dr. Jim Brierley at Newmont's Carlin, NV operations. Ore was first innoculated with micronutrients and a bacterial culture before being placed on the heaps. Air was injected through the base of the heaps. On completion of the acidic bio-heap oxidation process, the oxidized heap material was picked up and washed to remove acid before milling it and leaching in alkaline cyanide or, if preg-robbing species are present, using a thiosulphate solution to leach the gold.

Brierley & Brierley (2000) presented a summary of the operational requirements and techniques of bio-heap leaching secondary copper ores. They listed ten copper bio-heap leaching operations in operation at that time together treating around 1.2 million tonnes per year of ore.

It remains for the benefits of HPGR to be explored in the optimization of bio-oxidation of sulfides especially on heaps. The idea of agglomerating (along the lines of Geobiotics' GEOCOAT® process) a base metal sulfide concentrate onto HPGR-treated low-grade ore substrate, as opposed to inert crushed rock) followed by oxidation of the sulfides on a heap has yet to be explored.

Gold Leach Benefits of HPGR

Dunne et al (1996) reported on cyanide leach testwork performed using the rolling bottle technique. For very coarse material the bottle was rolled intermittently for one minute in an hour to reduce autogenous grinding. For these tests the leach time was extended to 48 hours compared to the standard 24 hours. Gold extraction results for all leach tests are summarized in Table 1 below. Not only were insoluble gold residues reduced and leach recoveries improved significantly through the use of HPGR, but leach kinetics were also improved.

The Australian leaching test results shown below are consistent with the results reported by Esna-Ashari & Kellerwessel (1988a) on a Witwatersrand gold ore which are shown in Table 2. Esna-Ashari & Kellerwessel (1988a) produced – 1 mm screened HPGR product at 5.0 tph at an energy consumption of 4.3kWh/t which resulted in a more than encouraging 94.7% gold leach recovery.

Patzelt et al. (1995) also showed a significant gold leaching improvement at all particle sizes fractions for a semi-refractory Nevada gold ore.

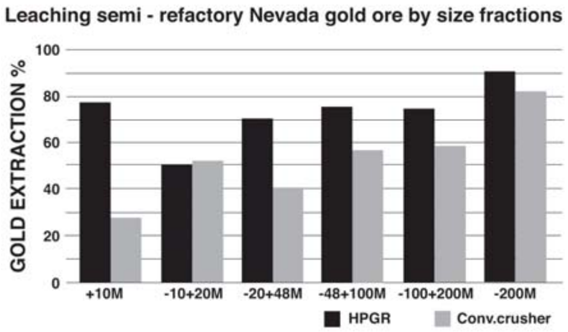

Fig. 7 Bottle roll leach results for a siliceous gold ore from Nevada showing improved gold leaching at all particle sizes, but especially from the coarser fractions. Source: Patzelt et al (1995)

Table 1: HPGR Benefits in Cyanide Leaching New Celebration Ore

Particle Size	HPGR		ORIGINAL	
(P80 microns)	Residue (g/t)	Gold Recovery(%)	Residue (g/t)	Gold Recovery (%)
4000	0.10	79.0	0.22	57.9%
425	0.12	78.3	0.17	69.0%
325	0.11	82.1	0.13	73.1%

Source: Dunne, Goulsbra & Dunlop (1996)

Table 2: HPGR Benefits in Cyanide Leaching Witwatersrand Gold Ore

Particle Size (mm)		HPGR	CONVENTIONAL GRIND
	+1.0	32.7%	33.1%
-1.0	+0.5	96.4%	28.8%
-0.5	+0.25	97.4%	46.2%
-0.25	+0.125	98.5%	93.5%
-0.125	+0.063	99.1%	99.1%
-0.063		99.0%	98.9%

Source: M. Esna-Ashari and H. Kellerwessel (1988a)

Gravity Recovery Benefits of HPGR

It would be logical to expect that HPGR can provide significant improvements in gravity gold recovery when treating ores with relatively coarse gold that is liberated better by inter-particle crushing.

Gray (2005) reported a phenomenal improvement in gravity gold recovery from around 60-percent to over 90-percent in pilot testwork on an ore from Ballarat, Victoria when HPGR is used for comminution as opposed to conventional milling.

Baum (1997) showed data from a 1989 paper by Clark & Wills in which the gravity recovery of chromite was improved when HPGR is employed compared with rod or ball milling.

Baum (1997) also showed an example in which more tin ended up in a gravity concentrate of higher grade, with lower losses to gravity tailings as a result of using HPGR compared with conventional grinding.

Dunne et al (1996) showed no HPGR benefits in gravity gold recovery tests on ores from New Celebration Gold Mine, Western Australia. This demonstrates how ore-specific HPGR benefits are.

Flotation Benefits of HPGR

Fig 8 provided by Baum (1997) shows the excellent liberation of small sulfide grains in an ore particle after treatment by HPGR.

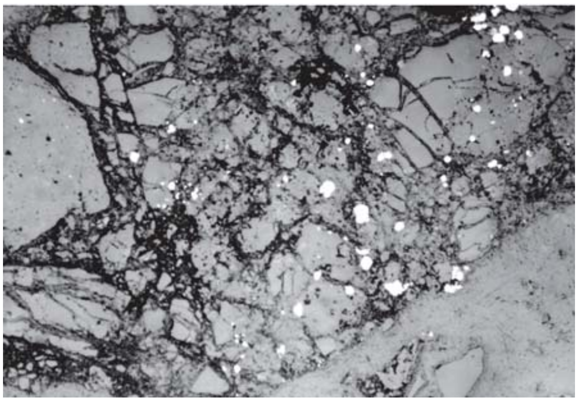

Fig 8 Liberation of sulfides by HPGR fracturing

Smit (2005) revealed important new findings about HPGR by Anglo Research, namely that the flotation benefits of HPGR can be optimized significantly by adjusting the pressure between the rolls. Copper recovery and concentrate grade increase steadily with increasing roll pressures as a result of better liberation. If too much roll pressure is applied, flotation recoveries and grade deteriorate significantly, presumably due to "over-grinding" as shown in *Fig 9*.

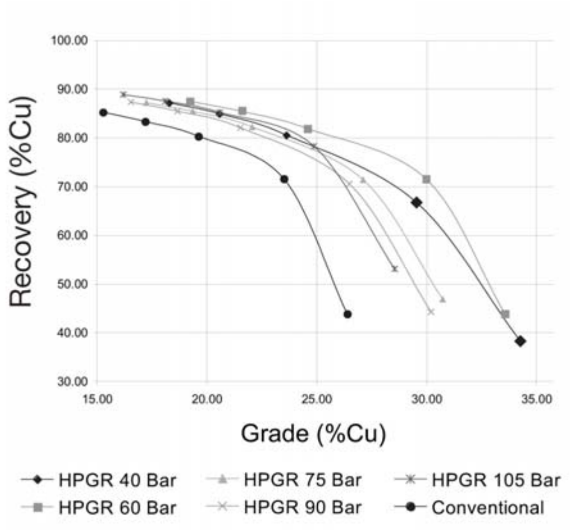

Fig 9 Optimization of the grade-recovery flotation curve for a Chilean copper ore by changing HPGR roll pressures. From Smit (2005)

Smit (2005) also showed that if the already liberated HPGR product is returned to the ball mill with the HPGR product screen oversize, then much of the HPGR flotation recovery benefits are lost, probably due to over-grinding. In his tests, the HPGR product was fine-screened and the screen oversize was sent to the ball mill, the product of which was recombined before flotation with the HPGR product screen undersize. The optimum HPGR roll pressure for the ores tested was in the range 45 – 75 Bar which is moderate compared to the pressures that HPGR is capable of delivering. Smit's (2005) observation is likely to prove very important in understanding the benefits of HPGR and for the future destiny of HPGR in hard-rock ore treatment.

It was found that if the HPGR product screen undersize were to be subsequently treated in a ball mill along with the coarser particle fractions (screen oversize) prior to flotation, then the particle size distribution of the flotation feed appears to be more or less the same regardless of the HPGR roll pressure, and the benefits of the HPGR optimization would be lost. This observation also implies that multiple stages of HPGR with screen classification between may offer significant benefits over conventional milling ahead of flotation. Also, flash flotation of HPGR product screen undersize appears likely to be especially beneficial, of course again depending on ore characteristics.

Simplistically, Flotation of sulfide minerals from gangue are challenged by three main comminution-related factors. 1) If mineral particle liberation is inadequate, then flotation recovery and concentrate grade will be lower. 2)

If the ore is "over-ground" then more of the more friable sulfides turn into "slimes" for which flotation recovery is reduced. 3) Fine steel from abraded mill media and liner steel alters the chemistry of the pulp and becomes oxidized resulting in higher flotation reagent consumptions and sulfide recovery interferences.

Since HPGR does not use steel balls as media, the third factor (fine iron in the mill product) is eliminated.

Leading comminution experts believe that HPGR (inter-particle crushing) can be tuned to generate less super-fines (slimes) than conventional milling, thereby improving flotation recovery of even friable minerals such as sulfides.

Baum (1997) showed an expected 2-15 percent improvement in flotation recoveries of sulphide minerals as a result of HPGR. Dunne et al (1996) showed that flotation recoveries and concentrate grades could be sinificantly improved (5.9 g Au/t in concentrate after HPGR vs 5.2 g Au/t and recovery of 76.8% after HPGR vs 61.9% when comminuted to P80 = 425 microns). At a grind of P80 = 212 microns, they showed a concentrate grade improvement from 4.2 g Au/t concentrate using conventional milling to 5.2 g Au/t after HPGR at about the same recovery. Even at p80 = 150 microns, the concentrate grade was improved from 4.1 g Au/t to 5.8 g Au/t following HPGR.

Mosher (2005) showed that flotation recovery losses were greatest for the coarse plus-212 micron and the ultrafine-minus 20 micron size fractions accounting respectively for 59% and 20% of the copper losses to tailings. Plus 212 micron material accounts for 30% of the mass and minus 20-micron particles account for 20% of the mass before installation of HPGR in this particular circuit. He also showed that copper liberation increases dramatically in particles smaller than 50 microns. HPGR is being installed to achieve better liberation both as a result of inter-particle comminution and by finer grinding. Within a year it is expected that real-life full-scale results will be available to demonstrate metallurgical benefits of HPGR.

Conclusions

1. Improved design and proven operational availability of HPGR even for some of the hardest and toughest ores is attracting mining industry attention.
2. Higher energy and steel prices provide a significant incentive for industry to consider new technologies such as HPGR that reduce energy and steel consumption.
3. HPGR has been selected by major companies for three large scale mineral processing operations which will soon provide living proof of HPGR performance in real life.
4. As more companies test HPGR, so more metallurgical benefits are being discovered, some of which (e.g. recovery improvements) could well prove significantly more valuable than even the significant energy savings and steel cost savings.
5. HPGR offers metallurgical benefits in flotation, gravity, leaching and heap leaching. These will become increasingly apparent as more ores are tested, and as more HPGR test facilities are located in laboratories with extractive metallurgy and flotation test facilities to test the HPGR test products.
6. Conventional mills are by their very nature notoriously energy-inefficient. For many mines, energy is the single biggest cost item. HPGR offers a way to save significant amounts of energy.
7. The jump from stamp mills to ball mills was a step change improvement in mineral processing technology. SAG mills were a major jump forward from ball mills. It is a privilege to have the opportunity to help find applications for the next step change improvement in comminution technology, namely HPGR.

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