CAN DIAMONDS GO ALL THE WAY WITH HPGRs?

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Abstract

The diamond industry is no newcomer to High Pressure Grinding Rolls (HPGR) as it has used the technology for more than 20 years, predominantly in secondary crushing and recrushing roles. In fact it could be argued that the diamond industry has led the way for the wider minerals industry to consider its application.

In existing conventional secondary cone crushing applications, large valuable diamonds are "won" through meticulously managing the recovery process within defined particle size ranges. Conventional crushers operate with relatively large closed side settings, but have the potential to damage diamonds by making direct contact with the sides of the crusher. Cone crushers also result in steep product size distributions that run a high risk of losing many of the smaller, un-liberated but more abundant diamonds from the rock. This current comminution paradigm of particle size reduction management results in recrushing processing applications or plants where HPGRs are often used.

HPGRs operate under the seemingly odd condition where the gap between the rolls is largely a function of the roll diameter irrespective of the feed size. This offers an opportunity for the diamond industry to consider using multiple HPGRs or units with high circulating loads to effectively generate a product with a very high proportion of fine material that can be rejected ahead of the beneficiation step.

This in effect results in a new paradigm, a single comminution step, where all diamonds of all sizes are liberated and preserved. The circuit product size distribution will consist mainly of barren kimberlitic fines along with some grits, pebbles, indicator minerals, as well as the prized undamaged diamonds. The HPGR product stream needs to be scrubbed, slurried and screened at 1 mm resulting in a greatly reduced volume of diamond-rich particles that progress to the dense medium concentration and/or direct x-ray separation steps.

In this application, the HPGR is viewed "outside the box", but within the context of diamond winning processes. Examples of how "HPGR can go all the way" are presented in the paper.

2.1 Introduction

The diamond industry has adopted high pressure grinding rolls (HPGR) mainly because of better liberation of large, rare, "particulate" high value diamonds. In this application, the HPGR process is able to preferentially liberate both small and large diamonds within the packed bed of particles under relatively high pressure while causing minimal damage to the gems. Under these conditions, the "strong" diamonds are liberated with a closing gap that exceeds the size of the prized diamond. This reduces the risk of inflicting damage to the diamonds. McKay (2009) has stated diamond damage can be caused by a number of semi-controllable factors such as blasting impact type crushing, pumping, cycloning etc which can reduce revenue, especially if very large diamonds are damaged. The HPGR comminution solution is therefore very attractive to those diamond mines that are classified as "large" diamond producers.

A potential innovative way in which the diamond industry could make use of HPGR in future is to consider large diameter rolls with high capacity and high circulating loads to perform all the comminution in a single step.

2.1 Motivation

The gem diamond industry "wins" diamonds, often referred to as "diamond winning" as opposed to diamond recovery. The winning concept remains as miners strive to recover the world's largest and most valuable diamond ever. To achieve this without compromising the "winning" of many of the other smaller diamonds that contribute significantly to revenue (Figures 1 and 2) is an immense challenge. HPGRs have the potential to do it, and "go all the way".

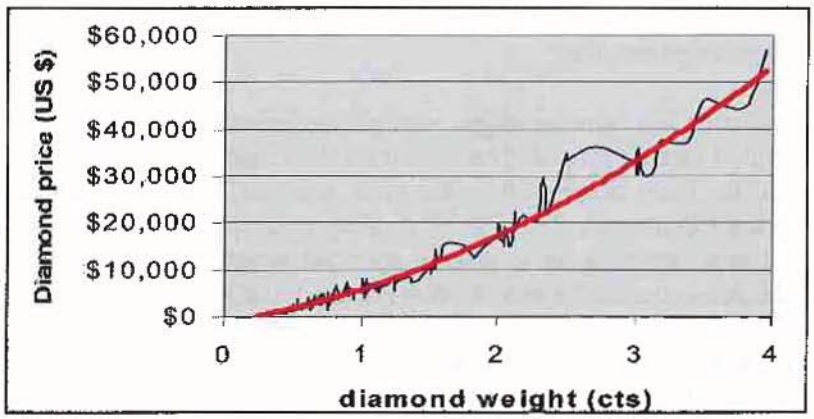


Figure 1 Increasing cut diamond value with increasing size (Daniel, 2002)

Because each mine has a different grade, each mine also has a diamond content that will vary in size and quality. This is further complicated by the fact that within the diamond retail market, diamonds as a commodity can have up to 14,000 classifications that vary in value. This results in diamonds having a unique "finger-print" property that relates diamond size, carats produced and revenue (Figure 2). Figure 2 illustrates how important it is for the diamond "winning" processes for mine "A" to recover all diamonds larger than 4 mm undamaged. Whereas mine "B" is classified as

a "large" diamond producer 4 mm –20 mm. Diamonds larger than 20 mm are uniquely classified as "rare and famous".

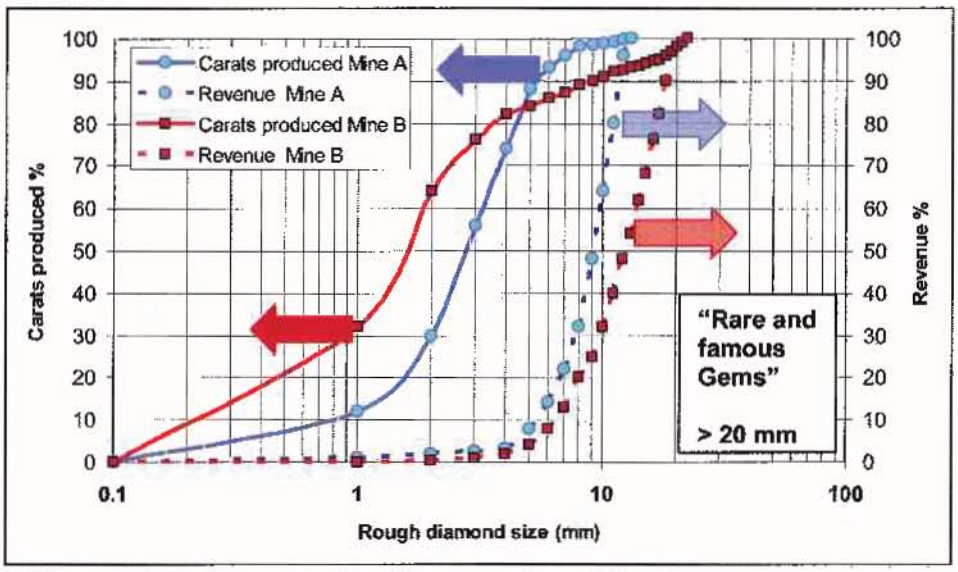


Figure 2 Characteristic diamond mine signature plot, with varied revenue vs. carats produced (illustrative))

The interim results for Gem Diamonds for the six months ended 30 June 2009 stated the following: "The Letšeng Mine continues to produce large diamonds of the highest quality. In the first half of 2009, Letšeng recovered 20 diamonds which sold at prices greater than US$20,000 per carat, achieving an average price of US$29,563 per carat".

These are extremely high value gems and have values that are much higher than the "cut" gem data shown in Figure 1 at 2002 prices. Table 1 estimates the average value of individual gems at the Letšeng mine based on size and value per carat data from the 2009 interim report. This is not strictly correct as value per carat increases as the size increases, and large gems are generally valued on a case by case basis rather than on weight. This leads to the conclusion that large gem producing diamond mines should at all cost attempt to reduce diamond damage in the crushing and liberation stages of diamond ore processing. However it would appear that the Letšeng mine (Lesotho) has the potential of producing the largest gem diamond in the world. Other large gem producers that also have this potential are the Cullinan mine (South Africa) and the Jwaneng mine (Botswana).

Table 1 shows how diamond size is related to value and carats

Diamond size mm	Diamond volume cm^3	Diamond density g/cm^3	Diamond (sphere) cts	Price 2009 US $/ct	Diamond Value US $ (000)	Comment
4	0.03	3.5	1	29,563	30	high value
6	0.11	3.5	2	29,563	59	high value
8	0.27	3.5	5	29,563	148	high value
10	0.52	3.5	9	29,563	266	high value
12	0.90	3.5	16	29,563	473	high value
15	1.8	3.5	31	29,563	916	large diamond
20	4.2	3.5	73	29,563	2,158	large diamond
25	8.2	3.5	143	29,563	4,228	large diamond
35	22	3.5	393	29,563	11,618	large diamond
70	180	3.5	3,143	29,563	92,917	large diamond

2.2 Why and how HPGRs are used in diamond processing industry

HPGRs are used in the diamond processing industry because they are capable of reducing the risk of diamond damage due to the inter-particle nature of the breakage process. This is achieved by crushing the rock under relatively high pressure between two counter rotating stud lined rolls (Figure 3). The stud lining is designed as a wear protection mechanism as opposed to "teeth" used to crush the ore. The maximum particle size ($X_{p\,max}$) can be smaller than the gap between the rolls.

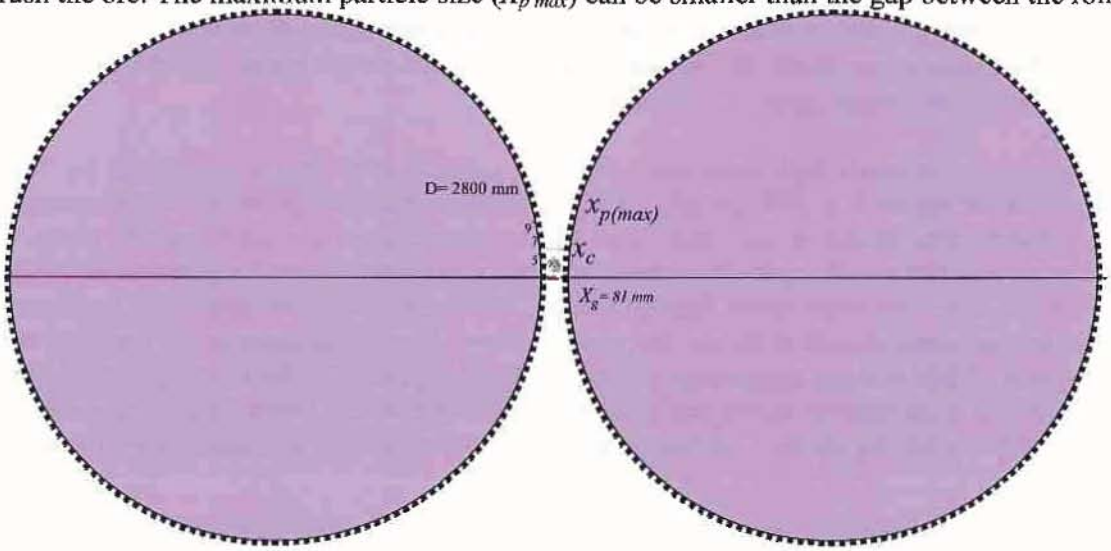
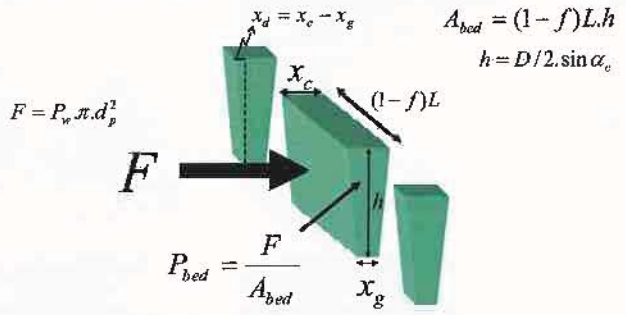


Figure 3 illustrates the concept of a 2.8 m diameter studded HPGR unit

A bed of particles is normally formed between the rolls where all particles of all sizes are selected for comminution and produce what is commonly known as "flake". Ore properties generally define the extent of breakage, and HPGR can often be described as units that facilitate a comminution process where the rock is able to break upon itself. Flake product is produced within a small zone bounded by the geometry between the rolls defined by X_c and X_g (Figures 3 and 4) and is the reason for the claim that the HPGR working gap is largely a function of the roll diameter irrespective of the

feed size. This enables the concept of using high circulating loads in the circuit design, which effectively re-processes the two edge effect fractions as illustrated in Figure 4.



$$W = \int_{x_g}^{x_c} P_w.\pi.d_p^2 dx \approx \frac{P_w.\pi.d_p^2.x_d}{2} \qquad P_{bed} = \frac{2P_w.\pi.d_p^2}{(1-f)L.D.\sin\alpha_c}$$

Figure 4 illustrates the compression zone where ore is subjected to relatively high pressures (Daniel, 2002).

Typically, a 2.4 m diameter by 1.65 m wide roll will have a throughput of 2500 t/h and a corresponding operating gap of 63 to 70 mm (Figure 5). Flake material (Figure 6) contains the liberated undamaged gems that are separated into particulates in conventional scrubber units, followed by dense medium separation and x-ray sorting to produce a diamond-rich stream for final hand sorting.

POLYCOM® HPGR SIZE	:	24/17-8	Larger POLYCOM	:	26/18-9
Roll Dimensions	:	2,4m x 1,65m	Roll Dimensions	:	2,6m x 1,75m
Press Force	:	17,000 KN	Press Force	:	20,000 KN
Motor Power installed	:	2 x 2,500 kW	Motor Power installed	:	2 x 3,300 kW
Roll Speed (nominal)	:	20.8 rpm (2.61 m/s)	Throughput (m=240[ts/hm^3])	:	3.000 t/h
Throughput (m=240[ts/hm^3])	:	2,500 t/h			
Specific Press Force	:	4,29 N/mm^2	Specific Press Force	:	3,96 N/mm^2

Figure 5 Characteristic features of two large Polycom HPGR units (Klymowsky, 2008).

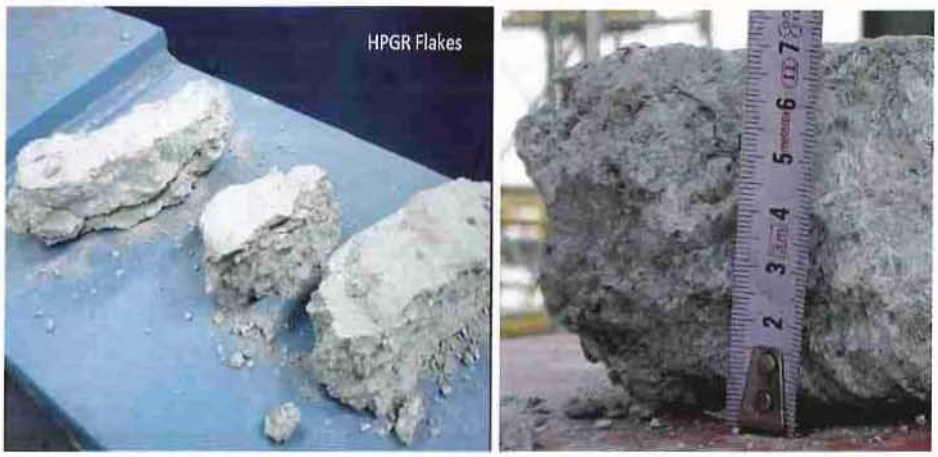


Figure 6 shows pilot scale HPGR flake on the left (Hilden and Powell, 2008) and an industrial HPGR (24/17) product flake representing an operating gap of 70 mm (Klymowsky, 2008)

Table 2 lists several different roll sizes and the corresponding expected unit throughput and operating conditions with varying degrees of circulating load. Figure 7 shows the profile of a large diameter unit that has already been built and put into production. All unit throughputs listed in Table 2 are estimated on the basis of an assumed specific throughput of 230 ts/hm^3. Specific throughput is a technical term used by the HPGR manufacturers to size and scale up equipment for a given duty.

An important new processing concept is the use of high recirculation loads in the HPGR circuit. This has the same effect as using multiple HPGRs to effectively generate a product with a very high proportion of fine material. When relatively small throughput rates are required, units with high circulating loads should produce a final scrubbed product consisting of some barren kimberlitic fines, grits, pebbles and the all-important liberated undamaged diamond gems.

Table 2 Typical HPGR throughput capacity, operational conditions and size of large liberated diamond

HPGR	Roll Diam mm	Roll Length mm	Roll Speed. m/s	Flake Density g/cm³	Ratio diam/ gap -	HPGR Unit Throughput t/h	M-dot SP t/h ts/hm³	Circulating Load %	New Feed t/h	Annual @93% Mtpa	Oper. Gap mm	Diamond size (sphere) mm	Diamond Volume cm³	Diamond density g/cm³	Diamond (sphere) cts
In use	2000	1500	2.00	2.2	34.5	1,377	**230**	65	835	6.8	58	52	74	3.5	1,301
In use	2400	1650	2.40	2.2	34.5	2,182	**230**	75	1247	10.2	70	63	128	3.5	2,249
Design	2600	1750	2.60	2.2	34.5	2,716	**230**	100	1358	11.1	75	68	163	3.5	2,859
Feasible	2600	1250	2.60	2.2	34.5	1,940	**230**	75	1108	9.0	75	68	163	3.5	2,859
In use	2800	500	2.00	2.2	34.5	643	**230**	0	643	5.2	81	73	204	3.5	3,571
Feasible	2800	1000	2.80	2.2	34.5	1,800	**230**	100	900	7.3	81	73	204	3.5	3,571
Feasible	2800	1250	2.80	2.2	34.5	2,250	**230**	200	750	6.1	81	73	204	3.5	3,571
Propose	3000	850	3.00	2.2	34.5	1,756	**230**	200	585	4.8	87	78	251	3.5	4,392
Propose	3000	1050	2.55	2.2	34.5	1,844	**230**	200	615	5.0	87	78	251	3.5	4,392
Propose	3000	1250	3.00	2.2	34.5	2,583	**230**	200	861	7.0	87	78	251	3.5	4,392

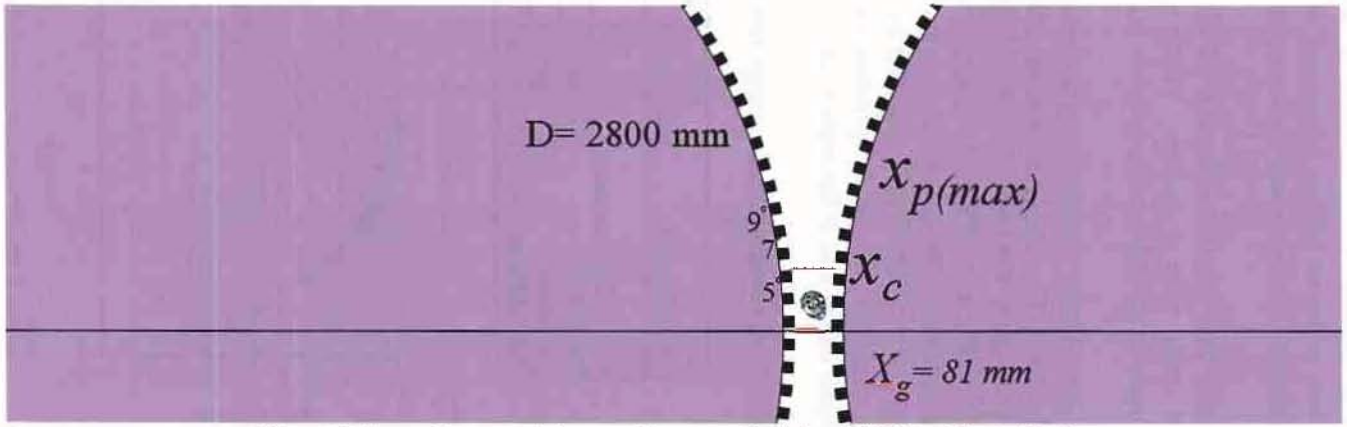


Figure 7 shows the expected operating gap of a 2.8 m HPGR with stud lining

2.3 Innovation and new flow sheet concepts and applications

Processing rates at diamond mines vary and might not be ideally suited to large diameter, large capacity HPGR units. In this event, the HPGR must be tailor-made to suit the application. For example, a large diameter machine could be selected where a large operating gap is required, but using a small roll width to suit the nominated capacity. Also, variable speed roll drives can be used to provide additional flexibility and ensure consistent choke feeding conditions.

Where very large throughput tonnages (>10 Mt/a) and high reduction ratios are required, multiple units in series could offer a solution. Plants with lower tonnages (3-7 Mt/a) may consider high recirculation loads in a single unit to achieve the same effect.

Modelling of the HPGR comminution process has matured, and validated models are available (Daniel, 2002, 2004). The validated models follow a process whereby ores are first tested in either laboratory or pilot scale test units. Test data is then used to scale up and predict the performance of larger industrial scale units (Table 3). Figure 8 shows laboratory test data and model fitting (LHS) with the model-predicted full-scale unit size distributions on the right hand side. Figure 8 represents the performance of the HPGR unit operated by BHP Billiton's Ekati diamond mine (Daniel, 2002, 2004). In this example 50% of the product passes 1 mm. Ekati is known to have softer ore that breaks upon itself easily and is the reason for the excellent size reduction.

Table 3 shows the dimensions and energy use of four operating units in industry

Data Source	Roll Surface	Roll Size (m)	kWh/t (full-scale)	kWh/t (lab-scale)
Rio Tinto (historical)	Smooth	2.2	1.8-2.5	1.8-2.5
De Beers	Smooth	2.8	4.0-4.5	4.0-4.5
De Beers	Studded	2.8	2.5-3.0	3.5-3.9
BHP Billiton	Studded	1.7	1.0-1.2	2.0-3.0

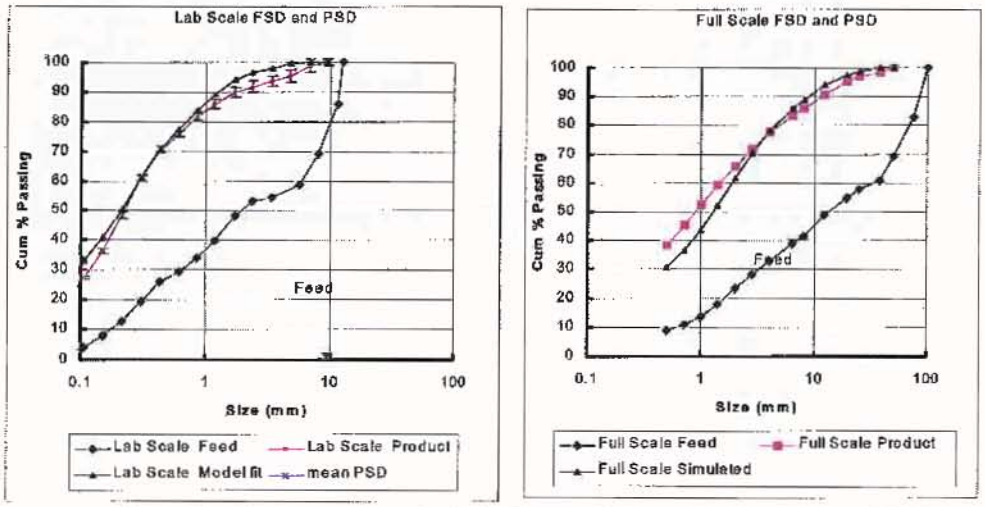


Figure 8 shows product size distributions of Ekati diamond ore in laboratory and full scale HPGRs (Daniel, 2004)

Harder copper and lead-zinc ores have recently been tested in a 750 mm diameter Koeppern pilot scale test unit located in Perth (Daniel, 2007). The competent rock was processed with multiple passes through the HPGR, with each pass producing a progressively finer product. Up to 60% of the copper ore passed 1 mm after three passes (Figure 9) and the figure was 70% for the lead-zinc ore (Figure 10).

Assuming a kimberlitic rock would behave the same as these copper and lead-zinc ores, then the entire HPGR product stream may then considered for scrubbing. Scrubbing is seen as an ideal process where the flake can be deagglomerated, slurried, and screened at 1 mm to result in a greatly reduced volume of diamond-rich particles reporting to the downstream beneficiation process.

When a smaller throughput is required, a large HPGR running with high circulating loads run the risk that the large diamonds will have to pass through the HPGR two or three times before they are separated in the scrubber and recovered downstream. This alternative comminution paradigm assumes that diamonds will not be damaged provided the gap between the operating rolls is larger than the diamond. Any mine that considers such an application will have to undergo extensive HPGR test work. The use of diamond simulants used commonly in the diamond industry should be used in these tests to assess the potential for diamond damage.

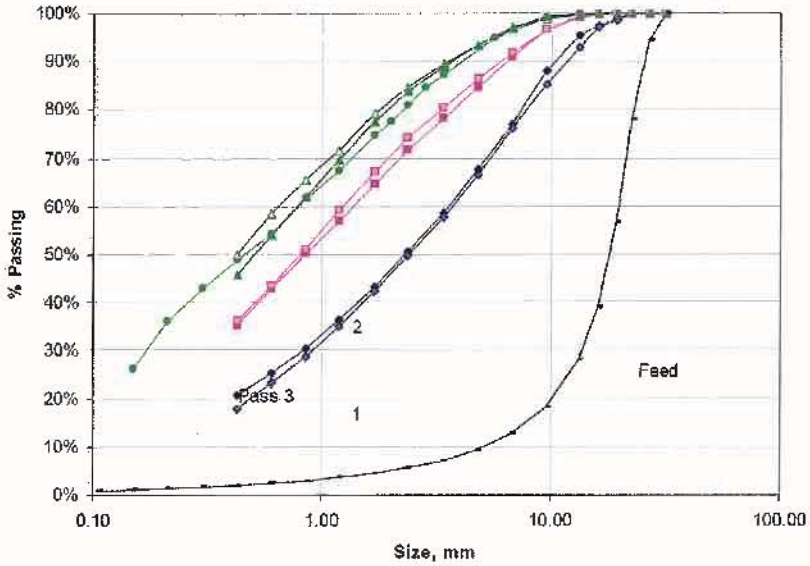


Figure 9 shows the effect of multiple passes through HPGR for a copper gold ore (Hilden and Powell 2008)

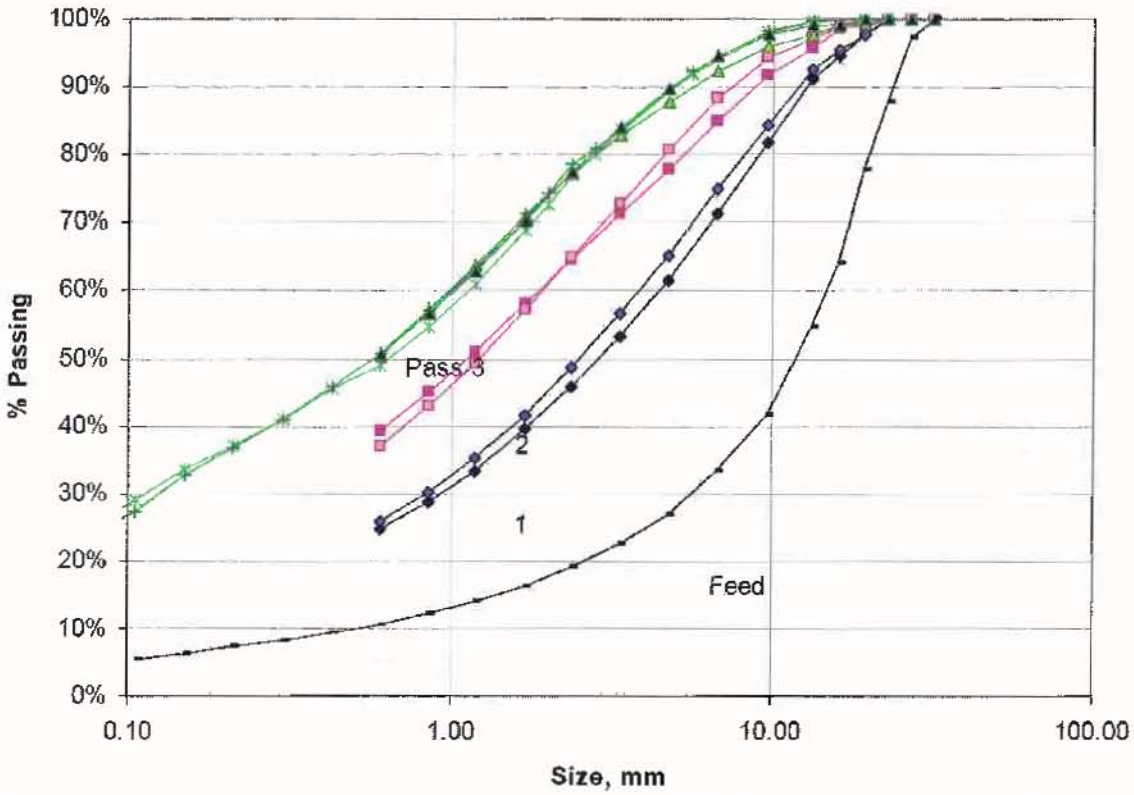


Figure 10 shows the effect of multiple passes through HPGR for a lead zinc ore (Hilden and Powell 2008)

2.4 HPGR manufacturers and growth of the technology

Knecht (2000) reported that in 2000, 450 HPGR units had been commissioned world-wide, 90% of which are operating within the cement and slag grinding industries. The remaining 10% or 45 units had been successfully implemented in the diamond and iron ore industries. Since then, the number of HPGR units installed in the minerals industry, namely diamonds, iron ore and hard rock (copper, gold and platinum) had increased to 35, 42 and 30 units respectively. This updated data (Figure 11) was presented by Klymowsky (2008) and illustrates the rapid rate of growth of HPGR applications experienced in recent years.

Today there are three German HPGR manufacturers who hold patents and licences to build HPGRs. These are Krupp-Polysius, KHD Humboldt Wedag (KHD) and Koeppern.

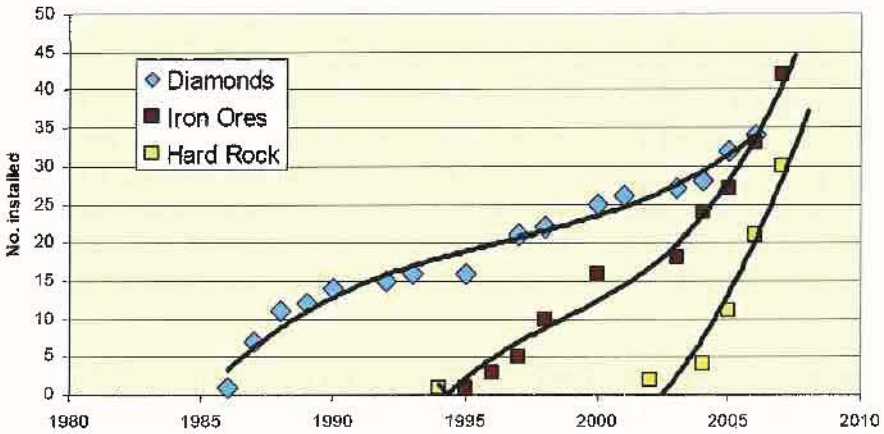


Figure 11 illustrates the grown of HPGR's particularly in the iron and hard rock applications (Klymowsky, 2008).

2.5 Increasing throughput with competent ores – Argyle case study

The Argyle Diamonds AK1 circuit, commissioned in 1985, had a nameplate capacity of 3.0 Mt/a, using a comminution circuit comprising three-stage crushing and scrubbing ahead of HMS beneficiation, with a fourth stage handling the HMS coarse floats recrush duty. Conventional cone crushers were used for the secondary, tertiary and recrush duties. The plant was designed for expansion to 4.5 Mt/a by the installation of additional scrubbing, crushing, screening and HMS modules, for which provision was made in the original layout.

The circuit was designed to handle a wide range of ore types, encompassing at one extreme the highly weathered material (Bond Work Index 10 kWh/t and Abrasion Index 0.22) predominating during the early operation, and at the other, the hard, competent and abrasive primary lamproite (Bond Work Index 18 kWh/t and Abrasion Index 0.60) (Dunne, *et al*, 2004, Maxton *et al*, 2002, 2003, 2004) encountered at depth in subsequent years. Throughput was constrained at the weathered or 'fine' end of the spectrum by the fines handling components of the circuit (degrit, desand, thickeners and water supply) and at the unweathered or 'coarse' end by the comminution and beneficiation circuits (crushers, screens and HMS). Between these limits – that is, while treating only moderately weathered or transition ores – neither the fine nor coarse constraints applied and throughputs in excess of nameplate were predicted in the design and confirmed in actual operation, with rates in excess of 4 Mt/a achieved within the first year of operation.

Within a few years of commissioning, most of the weathered ore and much of the transition material had been processed, and the coarse-end constraints were beginning to be encountered more frequently (although throughput levels were maintained generally above 4 Mt/a by plant optimisation and above-design circuit utilisation factors). By the late 1980s, expansion studies were in progress, with a view to accommodating the permanent shift towards the coarse end of the ore spectrum and also to increase throughput. The obvious method of expansion was to debottleneck the comminution and HMS circuits by the installation of additional process modules as allowed for in the initial design. However, this approach was considered a high-cost option and alternatives were examined.

HPGRs had at the time been recently introduced to diamond process plants in South Africa, and this technology became the focus of Argyle's expansion studies. The result was that, by 1990, the first HPGR in Australia was in operation at Argyle, producing the desired increase in capacity (from 4.5 to 6.4 Mt/a [Dunne, *et al*, 2004, Maxton *et al*, 2002, 2003,2004]) without the need for any of the additional comminution and HMS process modules required using the pre-planned, conventional approach to expansion. The HPGR was interposed between the secondary crushing and scrubbing stages and effectively presented the plant with a feed sizing corresponding to an ore type in the fine-to-average part of the spectrum. Thus the coarse-end constraint was removed by significantly increasing the proportion of -1 mm material in the plant feed and eliminating this ahead of the main process plant.

A second HPGR was installed in 1993, accompanied by some of the additional process modules in the downstream plant allowed for in the initial design. The target plant capacity for this expansion was 8.6 Mt/a, and this was comfortably exceeded by further plant optimisation and debottlenecking.

This example illustrates how the capacity of a diamond processing circuit can be dramatically increased by pre-treatment of the plant feed using HPGR, allowing a large portion of the feed to be reduced and rejected as unwanted fines ahead of the main process.

At the time of these expansion steps at Argyle, the studded tyre lining system had not yet been invented, and smooth segmented NiHard tyres were (and still are) used on this pre-treatment duty. HPGRs with studded tyres have an intrinsically greater specific capacity than the equivalent smooth roll machines due to the higher kinetic friction and resultant improvement in feed draw-in behaviour, and in subsequent studies in the late 1990s, Argyle examined the possibility of converting these HPGRs to studded tyre format.

The intention on this occasion was not a further increase in plant capacity but the use of the additional unit capacity to handle the HMS coarse floats recrush duty that had to that time been performed by cone crushers. (This recrush duty had always been difficult using cone crushers, with a poor reduction ratio and high operating costs, and the introduction of HPGR technology offered the opportunity to increase processing efficiency and also improve diamond liberation in the recrush size fraction.)

While the studies found the proposed circuit to be technically feasible, the conversion to studded rolls did not proceed, as the cost of converting from open to closed circuit secondary crushing upstream (for protection of the studded lining) was prohibitive. Instead, a dedicated studded roll HPGR was installed on the recrush duty with the cone crushers reduced to standby status.

The new recrush circuit, commissioned in early 2002, has a capacity in excess of 750 t/h at maximum roll speed with turn-down to 300 t/h at minimum speed. The normal operating pressing force is around 3.2 N/mm^2 with a maximum of 4.5 N/mm^2. Screens ahead of the HPGR ensure a feed top–size restriction of 25 mm; product sizing is 80% -8 mm and more importantly (from a fines rejection perspective) 36% -1.18 mm (Dunne, *et al*, 2004, Maxton *et al*, 2002, 2003, 2004).

Operationally the circuit modifications met design expectations. The first set of tyres lasted 3,764 hours and crushed 2,035,555 tonnes of ore. Downtime due to equipment failure was negligible. An evaluation of the comminution performance of the HPGR compared to that of the

conventional cone crushers was undertaken using the two standby cone crushers. The conclusion drawn from interpreting the data is revealing – as expected the cone crushers utilised low energy of around 0.5 kWh/t and generated about 8%–10% -2.3 mm material, whereas the HPGR operates at energy levels up to three times higher and generated 32-48% -2.3 mm material (Dunne, *et al*, 2004, Maxton *et al*, 2002, 2003, 2004).

2.6 Conclusions

This paper presents a modified way in which the diamond industry might use HPGR, a technology it has been using since 1986, mostly in recrush applications to liberate enclosed diamonds in tailings streams that have already undergone diamond extraction.

The new circuit concept proposes the use of very large high capacity HPGR units to generate a very fine product, a large proportion of which is rejected from the process to produce a greatly reduced volume of diamond-rich material reporting to the beneficiation step.

HPGRs are also considered in plants that produce large diamonds. As such the HPGR is considered a safe alternative to cone crushing, which is known to cause diamond damage and significant loss in revenue. HPGRs are also ideally suited to harder lamproite diamond-bearing ores.

The evolution of these larger diameter HPGRs could well pave a second path for their greater use in hard rock minerals industry applications, much as the original introduction of this technology did more than 20 years ago in the diamond sector.

It is quite possible that diamonds can go all the way with HPGRs

2.7 References

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Before joining Ausenco in 2008, Mike completed both his Masters and PhD degrees at the University of Queensland's JKMRC and specialised in the area of eco-comminution, ore characterisation and circuit energy efficiency. In particular, his knowledge of HPGR is being used by clients where more efficient processes are being considered in expansion studies. Mike initiated the triple pass HPGR concept within the Centre for Sustainable Resource Processing (CSRP) in 2007 which is ongoing. Prior to coming to Australia in 2000, Mike spent a number of years with Anglo American Corporation and six years with De Beers (DebTech) in project management and mineral resource management roles. Since joining Ausenco, Mike has worked on several SAG vs. HPGR trade off studies, including the Detour Lake and Mt Todd Projects and two confidential projects. Mike has also reviewed the performance of existing equipment at a number of Newcrest's operations including Cadia, Telfer, Mt Todd, and Gosowong and several other client confidential studies.