HPGR—The Australian Experience

R. Dunne,[*] D. Maxton,[†] S. Morrell,[‡] and G. Lane[**]

INTRODUCTION

This paper traces the application of High Pressure Grinding Rolls (HPGR) at industrial and pilot scale in Australia. The Argyle Diamond Mine installed the first of two smooth segmented HPGRs during 1990 in an open-circuit secondary-tertiary crushing application to increase throughput. In 2002 a third HPGR was added to improve liberation and so increase the recovery of smaller diamonds. The latest improvements in wear technology (tyre with tungsten carbide studs) were incorporated in the design of this machine.

Extensive HPGR pilot-plant trials were undertaken during the 1990s at both the Kalgoorlie Consolidate Gold Mine and the Boddington Gold Mine. The purpose of these trials was to evaluate HPGR as a method to increase throughput, as an alternative to SAG milling, and also to ascertain if downstream benefits existed.

One of the challenges for HPGR circuit designers is to translate what occurs at small laboratory and pilot scale into what is likely to happen in a full-scale circuit. Scale-up from pilot machine results is normally recommended by manufacturers. However, such tests need relatively large quantities of material, particularly if meaningful data on wear are to be obtained. Laboratory tests are preferable, as they need relatively small quantities of ore, but may be questioned in terms of how they relate to full-scale operation. Modelling and simulation have played a particularly important role in this respect in Australia. Models are available which have proven to be very accurate at being able to scale throughput and specific energy response from laboratory to industrial machines. More recently, work in Australia has also been done in developing a model which has the potential to scale laboratory wear data as well.

* Newmont Australia, Perth, Australia
† Argyle Diamonds, Perth, Australia
‡ SMCC Pty, Ltd., Queensland, Australia
** GDR Minproc, Ltd., Pinjarra Hills, Australia

COMMERCIAL APPLICATION OF HPGR

ARGYLE DIAMOND MINE—BACKGROUND

To date Argyle Diamond Mine is the only mine within Australia to utilise HPRC technology and now has three roller presses in operation. Argyle introduced HPGR technology in 1990 in an effort to counter the problem of increased ore hardness and also to increase throughput capacity (Hutton 1994). Prior to this, the ore supply was mainly weathered lamproite (Bond Work Index 10 kWh/t and Abrasion Index 0.22). As mining in the open pit progressed at depth, the more competent unweathered lamproite became the predominant feed source (Bond Work Index 18 kWh/t and Abrasion Index 0.60). The crushing circuit was limited by both its tertiary and coarse tailing re-crushing capacity with the harder ore. A study was carried out to see if the existing Allis Chalmers tertiary crushers could be replaced or supplemented to remove this bottleneck. Several variations of the cone crusher were considered and none appeared to offer substantial benefits. At that time the HPGR type of crusher seemed to offer a workable solution. However, it was only when the effect of placing the HPGR upstream of the tertiary crushers, and directly after the secondary crushers, was studied that the true benefit was demonstrated. This showed the potential to produce in excess of 30% minus 1 mm in the HPGR crushed product. This would remove the bottlenecks in the downstream crushing circuits and lift treatment capacity from 4.5 Mtpa to 6.4 Mtpa.

Three German crusher manufacturers held licences from the patent holder to build HPGRs. These were Krupp-Polysius, KHD Humboldt-Wedag (KHD) and Koeppern. The decision was made to purchase a single 2.2-metre-diameter by 1.0-metre-long unit with smooth rolls from Krupp-Polysius capable of treating 600 tph. KHD could only offer three 200-tph units for the duty and Koeppern had not sold a production unit. The first roller press purchased had twin 1,200-kW motors with fixed speed drives. The second HPGR installed in 1994 had twin 1,800-kW motors with variable speed drives. This machine was installed to further increase throughput capacity and so maintain diamond production. The diamond content in the feed was predicted to decrease with extended mine life.

Operation of the Smooth Roll HPGR

The HPGR crushing duty is arduous, treating a secondary crushed product with an 80% passing size of nominally 75 mm. Lumps of up to 250 mm enter the feed on occasion, due to the fact that the secondary crusher operates in open circuit.

The first few years of operation were problematical with the main issue revolving around wear on the roll tyres and check plates. The first set of tyres of solid Ni-hard failed after 6 hours in service. The second set wore out in 10 days and the time required to change out the solid tyres was around 20 days. As a result of these events, it was decided to move towards a bolt on segmented design.

Over the years various roll surface wear materials have been tested ranging from hard facing compounds to Ni-hard alloys. The process has been optimised to the point where the Ni-hard segments last around 6 weeks, treat around 475,000 tonnes and wears down the surface of the rolls by some 150 mm. The time required for a change-out has been reduced to some 30 hours and the utilisation has steadily increased from 42% to 76%.

Another issue encountered was excessive wear on the cheek plates. This was serious enough that these were replaced with a customised bypass rock box. This caused a loss in comminution efficiency due to "edge" bypass and also led to an acceleration of wear in the center zone of the roll surface. An unacceptable "bath tub" profile resulted requir- ing the roll surface to be regularly ground "on-line" to provide an acceptable wear pro- file. The additional utilisation more than compensated for the high cost associated with this procedure.

Application of HPGR with Studded Rolls

The process circuit at Argyle is essentially a large-scale crushing and screening plant pre- paring ore for subsequent diamond recovery. Comminution is undertaken down to a quaternary crushing level via conventional cone and HPGR crushers. Investigations car- ried out in the late 1990s indicated that additional diamond liberation and recovery could be achieved by decreasing the crushed size of the recycled coarse tailings (Maxton, Morley, and Bearman 2003). However this would substantially increase the recycle load in the tertiary/re-crushing circuit. A study at that time showed that the addition of a HPGR to replace two cone crushers would have the benefit of maintaining the same plant throughput capacity (i.e., no increase in recycle load). Furthermore advances had been made in the area of HPGR "studded" roll surface technology (to improve wear characteristics) to the extent that two mines in North America had installed it on their HPGR machines. In addition to improved surface wear there appeared to be throughput benefits with a "studded" roll.

Pilot-plant testwork. To quantify the benefits a detailed pilot plant, testwork was undertaken at the CSIRO Division of Minerals in Perth. The testwork program confirmed the formation of a competent autogenous layer between studs (a condition necessary to improve wear) using the primary unweathered lamproite. It was found that the through- put appeared to be a strong function of truncate feed bottom size—which is the main influence on bulk density. Also for a given feed bulk density the moisture content influenced throughput negatively. This is more pronounced at higher roller speed. An increase in specific throughput of up to 40% was predicted from the testwork using a studded rather than a smooth surface on the HPGR.

Design and operation of circuit. The new circuit was commissioned in 2002 and has a capacity in excess of 750tph at the maximum roller speed. There is VSD control to facilitate 300 tph at the minimum roller speed. The normal operating pressing force is around 3.2N/mm^2 with capacity to increase this to a maximum of 4.5N/mm^2. Screens ahead of the HPGR ensure a feed top–size restriction of 25 mm and the product particle size is 80% passing 8 mm, and more critically 36% passing 1.18 mm.

An essential part of the circuit is the removal of tramp metal to protect the HPGR. The system consists of a self-cleaning magnet to remove the majority of magnetic tramp on the conveyor feeding the main HPGR feed bin. A high-sensitivity metal detector is installed directly after the tramp metal magnet. Upon detection and after an appropriate time delay the shuttle on the conveyor discharge diverts around 10 tonnes of feed into the tertiary cone crusher bins. In addition another high-sensitivity metal detector is installed on the feeder from the main HPGR bin to the HPGR pre-bin to protect tramp entering the circuit downstream of the main storage bin. Upon detection, and after a small time increment, an air-actuated system allows bypass of the feed to HPGR.

Operating experience over the 12 months of operation revealed a serious issue that contributed to much lower machine utilisation than expected. The shoulder edges on the HPGR do not have autogenous protection and wore down to the extent that welded strips of hard facing was required to protect the edge. The hard facing buildup was carried out every 320 hours, resulting in approximately 60 hours downtime. A new design modification will address the need to weld by changing the edge design to accommodate bolt-on “sacrificial” edge segments. A preliminary trial of the concept, where relatively small edge segments were welded in place, was evaluated on the first tyre set, and the result of this trial was encouraging.

As the studs on the surface of the rolls wear down, shims are removed to bring the distance between the fixed and floating rollers to a predetermined minimum when on the mechanical stops (i.e., zero gap). This maintains the zero gap at a minimum of 15 mm to avoid diamond breakage.

The cheek plate tips are made with a 10-mm-thick tungsten carbide layer and last approximately 1,000 hours. The performance of the cheek plates in general is accept- able. Inexpensive cheek plate insert liners sit above the expensive tips and are replaced every 2 to 3 weeks.

Operationally the new circuit modifications have met design expectations. The HPGR was commissioned during February 2002 and the first set of tyres lasted 3,764 hours and crushed 2,035,555 tonnes of ore. Downtime due to equipment failure was negligible.

Cone crushing versus HPGR. An evaluation of the comminution performance of the HPGR compared to the performance of conventional cone crushing was made during one shutdown period for HPGR roll edge welding. For this evaluation two standby cone crushers were used. The conclusion drawn from interpreting the data is revealing but not considered to be definitive. As expected the cone crushers utilised low energy of around 0.5 kWh/t and generated minus 2.3 mm material in the region of 8%–10%, whereas the HPGR operates at energy levels up to three times higher and generated 32%–48% of minus 2.3 mm material.

PILOT PLANT TRIALS IN AUSTRALIA

Kalgoorlie Consolidated Gold Mine Trial

Background. In 1993 the Kalgoorlie Consolidated Gold Mine (KCGM) examined the option of installing HPGR technology as a way to increase treatment capacity from the already 4.8 Mtpa to 7.5 Mtpa (Watson and Brooks 1994). The initial phase of the study consisted of laboratory-scale testwork in Germany followed by an engineering study using parameters derived from the laboratory testwork. The study showed possible operating and capital cost savings compared to alternative processing routes by including an HPGR unit in the existing tertiary crushing circuit to reduce ball mill feed size. The study also highlighted a number of process and technical concerns that required resolution prior to commitment to the application of HPGR technology. To provide the necessary information a HPGR pilot-plant trial was undertaken during the latter part of 1993. An evaluation of the results from the pilot plant showed that there was no capital and/or operating benefit in considering HPGR technology. Two HPGR units with “smooth” rolls and an additional ball mill were required for the expansion. Smooth rolls were selected due the problems experienced during the pilot-plant trial with stud breakage on the studded rolls. Furthermore no discernible downstream ben- efits were found in flotation and cyanide leaching. Consequently it was considered that HPGR technology was not the best option for the expansion.

Pilot-plant trial. The objectives of the pilot plant were to demonstrate the technical feasibility of the HPGR process on a larger and continuous scale. It was also important to confirm the process flowsheet developed in the initial study phase and generate metal- lurgical and engineering data for the design. There was a need to refine operating cost estimates especially for component wear on the HPGR and assess any potential down- stream benefits in milling, flotation and cyanide leaching.

Both KHD and Krupp-Polysius were approached to supply a pilot-plant unit for the trial. Due to time constraints the only pilot machine available was an RPV 90/25 model supplied by KHD. This was a converted briquetting machine with upgraded drives and gearboxes. The pilot unit was supplied with both smooth and studded segmented liners.

Details of the unit are

Model Number	RPV 90/25
Roll Diameter	900 mm
Roll Width	250 mm
Motor Power	2 × 90 kW
Roll Speed	0.94 and 0.87 m/s (pulley drives)

HPGR pilot-plant trial. The gold ores at KCGM are mined from carbonate-altered basalt and dolorite lodes. The Bond rod and ball mill work indices vary respectively from 13 to 16.3 kWh/t and 14.1 to 16.5 kWh/t, while the Bond abrasion index (Ai) varies between 0.08 to 0.34. Parcels of ore for the HPGR pilot-plant program were prepared at one of the existing crushing facilities at KCGM. The ores were crushed to nominally 100% passing 50 mm using a jaw and cone crusher in open circuit. The crushed ore was stockpiled ahead of the pilot plant and reclaimed by front-end loader. The feed rate to the HPGR was controlled by means of a load cell to maintain a constant level in the feed box and ensure the HPGR was choke fed. Both a permanent magnet and metal detector were installed ahead of the HPGR for tramp metal protection. A weightometer located on the HPGR feed conveyor measured the feed rate The crushed product discharged into a bifurcated chute arrangement with internal cutters to separated edge and centre discharge material. The cutters were manually adjusted to remove anywhere from 0% to 50% of the product. The products (edge and centre) were stockpiled separately.

Unfortunately the planned pilot-plant testwork program had to be modified due to limited plant availability as a result of wear problems encountered on the HPGR. The most significant of these was excessive wear on the check plates, the first set of plates only lasting half a day. After testing numerous wear materials over many weeks some success was obtained using a two-piece plate arrangement with 19-mm tungsten carbide squares. Dust management was also an issue and additional water sprays were installed around the circuit.

The following observations were made from the pilot trial:

- Increasing the amount of fines in the feed increased the amount of flake in the HPGR product and the crushed product size was finer.
- Increasing the moisture resulted in a slight decrease in throughput and an increase in flake production. Wear also appeared to increase the wetter the ore.
- The specific power consumption increased with smooth liners resulting in an increased fines generation in the minus 106-micron fraction. The operating gap for the smooth liner configuration was less than the studded liners and consequently the throughput was 60% less than for the studded configuration.

TABLE 1

	HPGR Ore	Tertiary Crushed Ore
Feed rate to the ball mill (tph)	14.7 (3.5)	12 (1.2)
Feed size (F80 mm)	4,340 (950)	5,930 (460)
Product size (P80 mm)	101 (24)	117 (28)
Operating work index (kWh/t)	12.0 (1.1)	14.4 (0.5)

Figures in brackets—standard deviation.

A 200-tonne sample of HPGR crushed product, including edge material, was processed through a pilot-scale vibrating screening plant with deck apertures of 12.0 mm and
6.75 mm. No de-agglomeration stages were undertaken prior to screening. Screening efficiencies of greater than 90% were achievable.

Ball mill trials on HPGR product. Two ball-milling trials using a 2.4-m-diameter mill were conducted on both tertiary crushed ore and HPGR product to assess if there were any differences in grindability. Mill surveys of 30-minute duration were performed during the trials. Slurry samples from key locations around the circuit and mill feed were taken at 5-minute intervals. A summary of the data is shown in Table 1.

The Boddington Gold Mine Trial

Background. Gold production at the Boddington Gold Mine (BGM) in Western Australia commenced in late 1987 and oxide reserves provided a mine life of 14 years. In the early 1990s work commenced on evaluating the viability of treating the large low-grade gold-copper primary resource situated beneath the oxide cap. A trial pit was developed in 1996 allowing access to the ore for pilot-plant testwork. One of the options considered for the treatment of this ore, given the ore hardness, was HPGR. The primary ore is a combination of competent diorite and andesite with typical ball mill work indices of 14 to 17 kWh/t, rod mill work indices of 21 to 26 kWh/t, unconfined compressive strengths of 150 to 200 Mpa and Bond abrasion indices of 0.5 to 0.7.

At that stage, studded-roll technology was in its infancy and concerns about avail- ability and costs of maintaining the wear surfaces of the rolls led to HPGR technology not being considered for the process at that time. However, it was also concluded that HPGR technology provided a power efficient comminution process for the ore (Parker et al. 2001).

HPGR pilot-plant trial. An agreement was reached with KHD to supply the same pilot-scale unit originally used at Kalgoorlie Consolidated Gold Mines in 1993. Krupp- Polysius was unable to provide a pilot unit in the time allowed. The HPGR pilot plant was commissioned during the early part of 1996. A total of 33,000 tonnes of ore for the trials were crushed in the Boddington supergene/basement plant and the product size was nominally 100% passing 35 mm. Two separate trials were undertaken, an open circuit trial to investigate operating parameters (Hart 1996a) followed by a closed circuit trial with a vibrating screen to determine machine availability and wear issues (Hart 1996b), and to provide material for down stream treatment and evaluation (Reese 1996). The pilot-plant circuit layout was similar to that used at KCGM with choke feeding of the HPGR and tramp metal protection. Operating parameters and particle sizing data from the open circuit trials are shown in Table 2.

TABLE 2

	Range
Open Circuit Trials	
Specific grinding force (N/mm^2)	3.5–6.5
Net specific power (kWh/t)	2.2–3.2
Throughput (tph)	35–58
HPGR Product Sizing	
% minus 3.35 mm	55–70
% minus 106 microns	17–25

TABLE 3

Operating Data	Trial 1	Trial 2	Trial 3
Tonnes treated	10,676	8,308	8,868
Screen aperture	12 mm	12 mm	7 mm
Recirculating load (%)	40	28	32
Net tonnes milled (t)	6,361	5,956	5,992
Availability (%)	85.0	90.5	89.7
Net average throughput (tph)	22.3	38.1	36.3
Net specific power (kWh/t)	4.0	3.1	2.1
Specific pressure (N/mm^2)	6.6	6.47	3.65
Product sizing (% - 3.35 mm)	81.2	63.6	56.3
Product sizing (% - 106 microns)	28.1	21.9	15.9

A reduction in HPGR roll speed from 0.91 m/s to 0.65 m/s had no effect on specific power consumption. Actual throughput dropped by 15% at the lower speed for a small increase in the production of fines. Specific grinding force had a moderate effect on product size distribution with a 4% increase in fines over the range tested. The "no load" gap settings were not found to influence machine or product operating conditions.

Following the open circuit test conditions were selected for closed circuit trials using 12-mm and 7-mm screen cloths on the vibrating screen. During the trial period 28,000 tonnes of ore were treated through the HPGR (new feed plus recycle from the screen) producing 18,000 tonnes of final product. Machine availability was 90% and this included significant downtime for temporary repair to the roll surface. Increasing the fines present in HPGR feed by recycling final product had a minor overall benefit in the production of fines. The recycle of 33% product increased throughput by the same amount and resulted in a 3% improvement in fines generation. Operating data from the trials are shown in Table 3.

Material wear rates were monitored closely during the trials. Cheek plate wear was significant at the start of the trial (lasting only 70 to 90 hours); however, movement of the plates away from the rolls (up to 10 mm) resolved this issue without an adverse effect on the integrity of products generating wear. Wear rates on both cheek plates and roll surfaces were considered the greatest risk leading to the decision to consider other process routes over HPGR. Dust management around the circuit was also highlighted as requiring attention in future studies.

TABLE 4

Operating Data	Trial 1	Trial 2	Trial 3	Crushed Ore
Tonnes milled	6,042	5,891	6,222	
Average feed rate (t/h)	71	68	76	63
Mill feed (F80 micron)	5,700	6,850	2,950	8,400
Grind size (P80 micron)	105	92	93	105
Operating ball mill Wi(kWh/t)	13.7	13.2	13.0	14.4

Ball-milling trials on HPGR product. The HPGR product were processed through the Boddington supergene /basement plant that had a ball mill and cyanide leaching circuit. The purpose of this was to determine the ball mill specific power and related calculated work indices as well as any improved leach performance compared to conventional crushing of the feed. During the ball trials routine both the ball feed conveyor and the ball mill cyclone overflow samples were collected for particle size analysis. The results from the ball mill trials are shown in Table 4.

Examination of continuous cyanide leach data on the ball mill cyclone overflows showed no statistical significant difference between the ore that was ball milled after HPGR treatment versus conventionally tertiary crushing.

HPGR TEST FACILITIES AND MODELLING

Test Facilities in Australia

HPGR test facilities within Australia are limited to those at CSIRO (Brisbane and Perth), Ammtec's recently commissioned facility in Perth and the HPGR located at the Independent Metallurgical Laboratory (IML) in Perth.

Laboratory Facilities

Laboratory facilities exist at CSIRO and IML in Australia. The CSIRO machine is a 250-mm diameter by 100-mm wide Krupp-Polysius machine fitted with smooth rolls. The "IML" machine is a Krupp-Polysius "Labwal" machine, 250-mm diameter by 100- mm wide fitted with studded rolls.

Pilot-Plant Facilities

For many years the only pilot-plant facility in Australia was located at CSIRO in Perth. The HPGR is an RPSR 2-80/25 KHD machine that is able to operate with roll speeds between

0.4 to 1.2 m/s. Treatment rates are typically between 20 and 70 t/h. The machine is usu- ally used in a batch treatment mode. Oversize is removed by batch screening and recycled in the form of a "locked cycle" test to simulate plant operating conditions.

Ammtec has recently obtained a pilot HPGR unit supplied by Koeppern. The unit is 750 mm diameter by 220 mm wide and is fitted with a variable speed drive (to 1.55 m/s) and a Hexadur® wear surface allowing a maximum specific pressing force of 8.5 N/mm^2. This unit provides an alternative facility to the CSIRO facility for "pilot-scale" testwork and is capable of being relocated to site for more extensive and continuous evaluation.

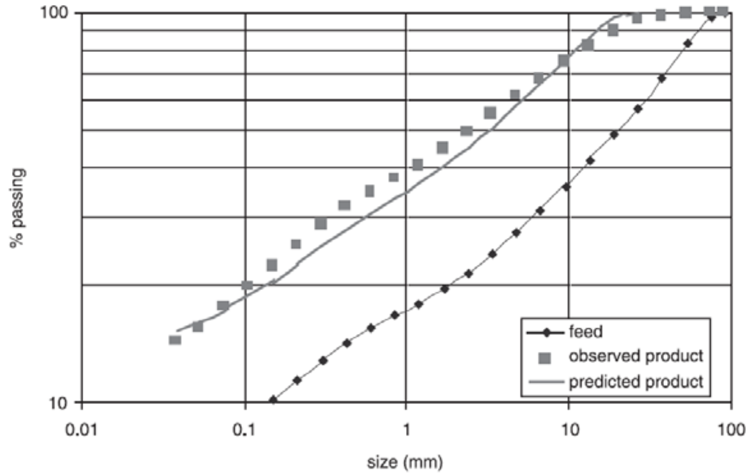

FIGURE 1 Observed versus predicted full-scale HPGR product size distribution

Modelling and Simulation

Modelling and simulation of HPGR performance is commercially available via the JKSimMet® software package. HPGR models based on general comminution principles have been developed over many years in AMIRA research projects that were/are sup- ported by the mining industry. The JKSimMet® model caters for edge effect modelling and may be set up to model rock box by-pass.

Underlying the structure of the size reduction model are three assumptions about the inherent breakage mechanisms that occur in a HPGR (Morrell et al. 1997), namely:

- If particles are bigger than a certain critical size they will be broken directly by the roll faces as would occur in a conventional rolls crusher.
- Breakage at the edge of the rolls is different to that at the centre and conforms more to that experienced in a conventional roll crusher. This is the so-called "edge effect" which defines the proportion of relatively coarse particles usually seen in HPGR products.
- At some point away from the edges of the rolls, and extending upwards from the area of minimum gap, is a compression zone where breakage conditions are those experienced in a compressed packed bed.

The model contains three breakage processes and one splitting process between the edge and compressed bed zones. For the breakage processes a conventional crushing model (Andersen 1988; Whiten 1972) is employed to describe the size reduction. The model has been validated under a range of conditions by calibrating it using laboratory- scale HPGR data then comparing its predictions of pilot- and full-scale performance with observed data. A typical result is given in Figure 1.

Recent data (Parker et al. 2001) has shown the HPGR performance is impacted by the porosity of the feed (i.e., bulk density/feed particle size). Other modelling issues

TABLE 5 Observed versus predicted wear on studded roll surface

Roll Speed, m/s	Stud Wear, mm	Predicted, hours	Observed, hours
0.91	3.6	455	443
0.65	1.4	234	298

such as screen efficiency (ability to deagglomerate flake) are both ore dependent, mois- ture dependent, machine dependent and circuit dependent.

Wear Model

A Brisbane-based company, SMCC, has developed an HPGR roll surface wear model. The approach relates the rate at which metal is removed from the roll surface as a function of its speed and surface area. This model uses data from laboratory-scale tests such as those carried out by Krupp-Polysius using their 100-mm diameter “Atwal” machine. The model fits a wear parameter to these data which is subsequently used in the model to predict roll life of operational machines. As a test of the model, data from the pilot programme undertaken at BGM in 1995 were used. Atwal wear tests were also carried out on a sample of feed ore. The model was therefore fitted to the Atwal data and then used to predict how long it would take for the studs to wear to the measured lengths during the various operating periods of the programme. The resultant predictions and the observed values are shown in Table 5.

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