PEBBLE CRUSHING BY HPGR

F.P. van der Meer
Weir Minerals.

Minerals Processing and HPGR Technology
Egtenrayseweg 9
5928 PH Venlo
The Netherlands

T: +31 (0)77 3272955
E: f.vandermeer@mail.weir
W: www.global.weir

R. Fernandez
Weir Minerals South America

Manager Comminution Division
San José 0815, San Bernardo,
Santiago Chile

T: +56 (2) 27542115
E: rfernandez@mail.weir
W: www.global.weir

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ABSTRACT

AG or SAG milling frequently becomes a bottle-neck in an operation as the generation of critical size pebbles and the subsequent required re-crushing of these results in an extra burden for the (S)AG mill in the form of a recirculating load of harder and more abrasive material.

HPGRs are high capacity crushing units providing a high reduction ratio, especially in terms of the generation of finer particle size fractions than conventional crushers. HPGR crushing can provide a profitable alternative or addition to a grinding circuit, allowing the crushed pebbles to be bled to the subsequent downstream ball mill grinding and beneficiation stages, thus freeing desired capacity for the (S)AG mill stage and enhancing overall plant throughput. In addition, the low operating cost and low specific energy consumption of HPGR allows the installation of this technology with a remarkably short payback time.

Adapted wear parts design and dedicated maintenance procedures guarantee very high HPGR availability and low operational downtime.

This publication summarises some of the features and experiences for HPGR application in pebble crushing and includes an example case study of pebble crushing in a copper minerals processing project.

KEYWORDS

HPGR, Pebble Crushing, SAG, Energy, Capacity

INTRODUCTION

Where Autogenous or Semi-Autogenous milling is applied, the generation of material consisting of a critical particle size fraction often poses a restraint in achieving the efficient throughput of the circuit's grinding section. The critical particle size material, referred to as pebbles, is oversize material from conventional grinding by fully autogenous grinding (FAG) or semi-autogenous grinding (SAG) mills. These ore particles are critical in the sense of being too coarse for being crushed by the ore lumps (in FAG grinding) or steel balls (in SAG milling), and too fine to act as grinding media, being of a too low mass and size to crush the finer particles present in the mill load.

The critically-sized pebble material generally ranges in size between about 25 mm and 90 mm (1"-3½"). In (S)AG mill circuits, pebbles and other oversize material are recycled back to the mill, either by subsequent classification (screening, hydro-cyclones), by trommel screen on the mill outlet, or through a system of pebble ports and separate discharge of a fine product to a downstream pebble mill.

When returned to the mill, because the pebble material is too coarse for being crushed and too fine to act as grinding media, it presents an unavoidable inefficiency in the grinding process, and leads to an increased circulating load and therefore a lower effective throughput and plant throughput restriction. The higher recycle load at the maintained power input to the mill leads to a higher specific energy consumption. Also, given the higher load of critical size material in the mill, the grinding process shifts from an impact breakage environment to an attrition and abrasion dominated size reduction. This leads to the generation of more (ultra-) fines and over-grinding of fines.

In many cases, it is measured that pebble material survives the milling due to either specific milling conditions (e.g. ball size population, pulp density) or due to the fact that the pebbles consist of a harder ore mineral composition, such as harder (gangue) minerals, with higher compression strength and possibly a higher abrasion wear character.

Current practice is to remove the pebble material from the mill load by product classification and / or pebble ports in the mill discharge diaphragm and trommel screen. The pebbles are then crushed separately by cone crushers and fed back in with the mill feed. This has the effect of minimising the accumulation of critical size material in the mill load end, thus improving the grinding result in terms of product generation with a reduced proportion of slimes from over-grinding. In effect, additional grinding capacity is thus set free, and plant capacity benefits. A feed-forward of the crushed pebbles in the case where the (S)AG mill is followed by ball milling is seldom possible, as the crushed pebbles exceed the feed size specifications of the ball mill operation. As an alternative, a two-stage fine crushing is sometimes proposed, to reduce the crusher pebbles further to meet the ball mill feed specifications [Clemens 1992].

Nevertheless, the presence of pebbles implies a bottleneck in the circuit, and additional ways are sought to alleviate this in order to maximise plant operational effectiveness in terms of throughput and energy.

HPGR AS A PEBBLE CRUSHING TOOL.

The application of HPGR to further crush the pebble material, either by treating the cone crusher pre-crushed material or directly as received from the (S)AG mill, presents an attractive option to alleviate bottlenecks in grinding. HPGR offers a much finer product size as compared to conventional crushers in pebble crushing applications. The particle size of the pebbles however is generally considered too coarse for a direct feed to the HPGR.

Direct crushing of pebbles as received from the mill is not generally advisable. Feed material to a HPGR unit should preferably be smaller than the roller gap, which on average is between 2% and 3% of the roll diameter to minimise roll surface wear and to promote full inter-particle crushing. For a coarser feed, the feed top size depends on nipping angle, similar to what is common practice in conventional rolls crushers. Due to nipping constraints, but also due to considerations of minimizing roll surface wear, the accepted top feed size generally is kept at about. 1.5 times the operating gap for a full particle size distribution, with about 80% of the feed having a particle size passing the operating gap size. [Van der Meer, 2010]. For pebble crushing, where a truncated feed is present and is void of fines and with a narrow particle size distribution, a lower oversize factor (e.g. 1.2 or less) would be advisable.

Physically, material at a top size of about 90 mm could well be handled by nowadays larger diameter (3m) HPGRs. As a rule of thumb, and generally supported by data from testing, the operating gap scales to about 2.5% of the roll diameter. Thus for a roll diameter of 3m, and having a modest oversize factor, a top size of 100mm would be acceptable, with 80-90% passing the operating gap of about 75mm. For some HPGR's, the diameter and thus the pebble port size may be adapted to make optimum use of the HPGR crushing facility.

Additionally, due to wear rate considerations, a coarse feed with excessive material larger than the operating gap would thus not be acceptable.

A truncated feed as with untreated pebbles would also have other draw-backs in HPGR crushing [Van der Meer & Maphoso 2011]. Depending on the initial fines content in the feed, the product particle size for a truncated feed in many cases is relatively similar (though slightly coarser) to that from a full feed crushing. This implies that the size reduction from a truncated feed might at least be as efficient as that from a full feed, with a higher net fine product generation.

A truncated feed generally results in a significantly reduced specific throughput, as a lower bulk density of the pebbles and fewer fines to fill the void space in-between the ore grains results in a decrease in specific throughput. Depending on the narrowness of the feed size distribution, the HPGR specific throughput may drop by up to 35-40% compared to a full feed size distribution. In many cases, pebbles do display relatively smooth rounded surfaces. The downward material transport for a more or less smoothly rounded pebble particle shape, especially in the compaction zone above in the operating gap, may need to be reduced due to a less effective compaction. Net specific energy consumption at a maintained specific press force will increase, in some instances by up to 50%, as compared against a full feed situation, as it is more or less inversely proportional to the lower, less dense, mass processed. The table below illustrates this for a sample of taconite iron ore pebbles as when comparing between a 1.5 inch top size pebbles material and a same top size pebble material including crushed material.

	Specific Throughput ts/hm³	Net Specific Energy kWh/t
Pebbles 1.5“ as received	215	2.1
Pebbles 1.5“ with added crushed oversize	267	1.8

Table 1. Comparison of HPGR parameters for pebbles with and without crushed oversize material.

Another phenomenon occurring with a truncated feed (or narrow size distribution of pebble material) is that a relatively high roll surface wear rate may be encountered. A truncated feed, with a presumed more ”mobile” particle population, generally generates a weaker “autogenous wear layer”, where contact with the relatively coarse entering pebbles fragments do tend to break-away the coating on the roll surface, and where material slippage may play a role. Thus operating cost (from a more frequent replacement of worn grinding rolls) may increase for a truncated feed. On the other hand, a lower grinding media wear may potentially result from the bleeding off the harder, higher-silica-content pebble material from (S)AG mills, and from removing the abrasive slow grinding part of the mill charge.

The above suggests that processing a feed of uncrushed pebbles may be less advantageous, unless more fines can be added to the feed. This can be achieved by bleeding a part of the plant feed to the HPGR, or by modifying the mill outlet to produce more middle-sized particles to the pebble crushing circuit. Also operating the HPGR in closed circuit, either by applying a partial product recycle or classification of the HPGR product could provide a wider particle size distribution, facilitating better wear life and size reduction.

SENSITIVITIES

A number of sensitivities do exist when arranging a HPGR after an AG mill, but even more so after a SAG mill. These are due to the presence of oversize material or tramp metal in the (S)AG mill discharge. As in any operation, tramp metal originates from material introduced in upstream operations such as mining, and from broken or worn parts of upstream equipment. In the case of SAG mills, these tramp objects ado also include spilled balls, broken balls or scats exiting the mill or bypassing safety screens (Figure 1).

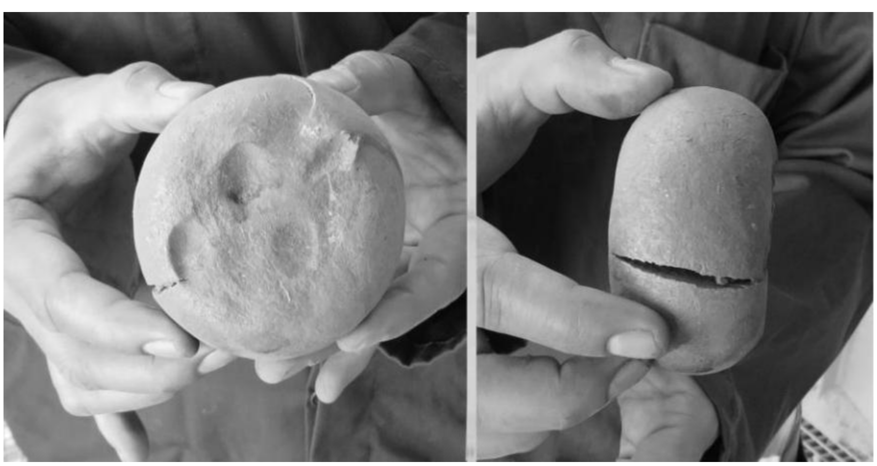


Figure 1. Example of Aerofall ball retrieved after HPGR passage, cracked and dented by HPGR rolls.

Tramp metal objects in HPGR feed will increase wear. Oversize objects, near or in excess of the operating gap size, will lead to high point loads on the roll surface [Morley 2008]. For an average HPGR operating at press force of 20.000kN focused on a contact surface area of 2 x 2cm, will result in a local pressure of 50,000Mpa. This is well in excess of the compressive strength of steel (400Mpa). Thus the introduction of metal objects near or larger than the HPGR operating gap will result in forces damaging the HPGR roll surface or the studs applied to the rolls.

To avoid tramp metal introduction in HPGR units, a well-designed detection and removal system should be applied. This would consist of a tramp magnetic separator, a metal detector, and a subsequent tramp metal rejection facility. Such a system should preferably be installed as close as possible to the HPGR, ideally directly ahead of the HPGR feed chute.

Oversize rock larger than the operating gap will also burden the HPGR roll surface and, depending on the surface's proportion, lead to a higher wear rate and operating cost. If possible, a safety screen or a strict control of the CSS of the preceding crusher should be applied. In addition, the design of a HPGR unit with a suitable L/D ratio could allow larger rock sizes.

The mineralogical or geophysical composition of ores is seldom fully homogeneous. The proportion of harder and softer materials and thus the proportion of pebbles may vary significantly, such as with transition gold ores or coarsely banded iron ores. A variable capacity therefore is requested for a pebble crushing circuit. For HPGR this is most easily achieved by installing a variable speed drives to allow for adapting the roll speed to the required throughput rate.

Conventional pebble crushing could be considered a compromise between throughput and product fineness. As the feed rate of pebble material increases, the pebble crushers are forced to operate at a coarser CSS to allow a higher throughput [Clements 1992]. This increases the load in the SAG mill due to additional recycling of coarser crusher product. HPGR, mainly by virtue of a variable roll speed, provides a higher capacity without generating a coarser product and consequently allow increasing the SAG mill throughput by 15-30%.

An appropriate control system should be selected to monitor and maintain the material level in the HPGR feed chute or associated bunker level, and control the roll speed or apply a more suitable operating pressure level in tune with the presented pebble feed rate and quality.

In addition, attention should be given to the design of the feed system ahead of the HPGR, to ensure a homogeneous material distribution over the rolls' width and length. Segregation of material, either over the width or length of the rolls, is often a cause of uneven wear of the roll surface, and an off-spec product size distribution can necessitate early roll replacement.

Moisture can also have a pronounced effect on the HPGR process [van der Meer, Dicke 2008]. Pebbles generally have a relatively low moisture content, even after wet upstream processing. By consequence of the relatively large ratio between volume and surface area for pebble material, free surface moisture readily redistributes to the crushed product.

The biggest advantages of HPGRs, are the high unit capacity and low energy consumption. For pebble crushing the advantages foremost lie with the size reduction achieved to produce an adequate ball mill feed material, with a high proportion of finished product which can be allowed to bypass the ball mills by a pre-classification (reverse circuit). In addition, though maybe of less consequence for the modest mass proportion in relation to the further feed, downstream benefits like a reduced ball mill work index and potential preferential liberation have been be observed.

Analysis of breakage rates [Klymowsky 2003] for a characteristic SAG mill breakage rate distribution was done considering a critical size between approximately 20-90mm. It was indicated that conventional pebble crushers generate a product with a significant amount of material still in the critical size range. The HPGR product however has a wider size distribution with a peak occurring below the peak of maximum breakage, and many fines occurring in the "fines low breakage" region. Screening would remove the fines, and concentrate the remaining material in the region of maximum breakage. Simulation studies have shown that the capacity of a SAG mill can be increased by up 30% in this way.

The introduction of HPGR into the circuit allows a boost of (S)AG capacity. Either a finer recycle material could be established to the SAG mill from crushed pebble, or no recycle at all, with HPGR product sent to downstream processing or ball milling. Added advantages often include a reduced ball mill work index, enhanced liberation for beneficiation, and a high proportion of finished product that could bypass subsequent ball mill grinding. As example of the work index reduction, analysis of a copper ore sample indicated that the pebbles did partly stem from harder ore components, which was supported by comparison of Bond ball mill work index measurements. The average work index (125 µm) for the ore was 11.9 kWh/t, whereas the pebble material before HPGR show an average work index of 13.5kWh/t. After HPGR the work index for the crushed pebbles reduced by about 16%, to 11.3kWh/t.

A further aspect of HPGR for crushing untreated pebbles would be that, as the roll diameter of modern HPGRs are generally large enough to accept the pebble particle sizes of up to 90mm, the pebble production rates from the (S)AG mills generally would be relatively low, and thus far below the rated capacities of the standard HPGR units. For example, most HPGRs with a roll diameter of 2.4-3.0m diameter have roll widths of 1.7-2.2m. Assuming a specific throughput for pebbles of about 225 ts/hm^3, capacities of these units, at nominal roll speed, would be between 2000 t/h and 4500 t/h. Envisaged capacities for pebble generation however generally lie in the vicinity of maximally 600 t/h. Thus either the HPGRs are required to run at a very low rotational speed, or the width of the rolls must be reduced to match the pebble feed rate. This would then result in a HPGR width at a roll diameter of 3.0m of for instance a near 0.4m. This would pose a high strain on the equipment design and material. Also, considering the inherently large edge effect, the wear rate profile and product size would be severely affected.

For this reason, operations generating only a relatively small pebble mass production rate do presently rely on reducing the pebble size prior to HPGR by pre-crushing.

EXISTING EXAMPLES

As an example, the Empire Iron operation applies a HPGR with a roll diameter of 1.4m and a width of 0.8m to treat pre-crushed pebbles [Dowling et al, 2001, Rose et al, 2002].

The hard ore and the fine particle size required resulted in a high specific energy consumption for the autogenous grinding of up to about 24kWh/t [Cordes 2003]. An increase in the throughput in the two existing grinding stages could only be achieved with an additional crushing or grinding stages. For the autogenous mill lines 22-24 the integration of an HPGR for the re-crushing of the surplus pebble material downstream of a 7' Symons short-head cone crusher proved effective. The crushed pebbles are returned to the primary mills, where the smaller material proves to be easier to grind to target size range and therefore horsepower consumption is reduced and the throughputs can be increased.

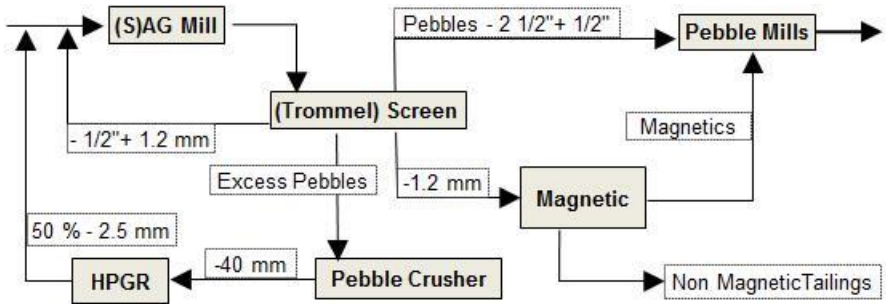


Figure 2. Empire Concentrator Flow Sheet around HPGR. Lines 22-24.

For generating a product of 50% passing 2.5mm from a crushed feed of 40mm, the required energy input was 1.7kWh/t. A mass rate of up to 400t/h (80% of the Empire IV pebbles) is treated by the HPGR, and the results do show an average increase in primary milling of at least 20%, with double the effect being achieved for some ores. Corresponding primary milling specific energy usage has reduced also, effectively reducing the primary milling input at a significantly enhanced capacity.

This way Empire successfully integrated high pressure grinding roll technology into an autogenous grinding circuit treating high tonnages of magnetite iron ores. As part of a study on extending the use of high-pressure grinding throughout the Empire flow sheet, grindability tests were performed on Empire 4 crushed pebbles before and after passing through the roll press. The results on this material indicated significant increases in grindability, with the effect increasing with more difficult to grind ores.

For operations with a larger installed HPGR the possibility exists to supplement the HPGR feed with fresh/scalped material [Dixon, Olson, Wipf. 2010]. At Penasquito the ore processed in the upstream semi-autogenous (SAG) mill is not hard enough to produce the amount of pebbles the circuit is designed for. Thus the HPGR, which is operated in open circuit following a pebble (cone) crusher, is under-utilised.

This also provides the opportunity to enhance plant throughput, where the HPGR van effectively process material in parallel to the existing installed (S)AG mill, as well as crushing the excess pebbles generated.

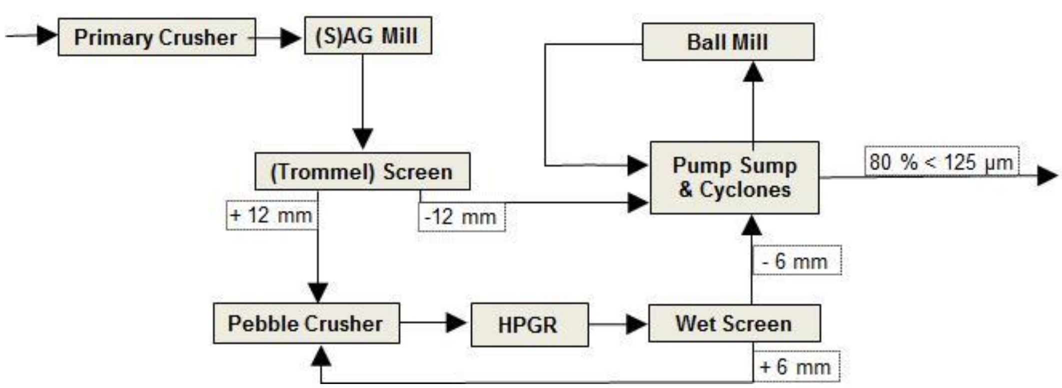


Figure 3. Penasquito Flow Sheet around HPGR.

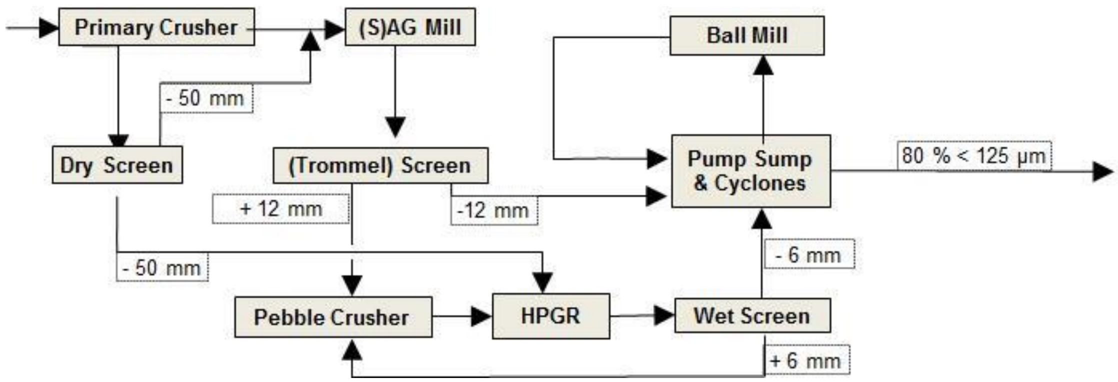
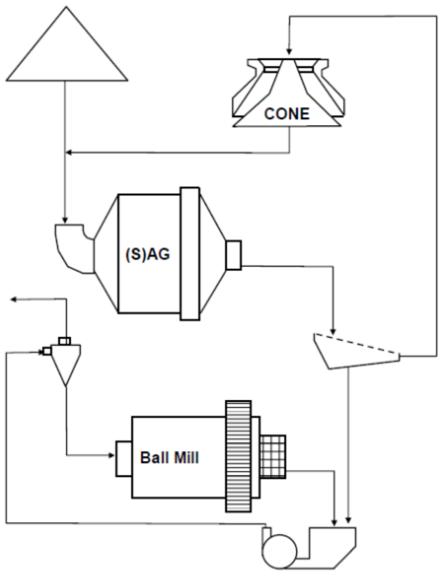


Figure 4. Penasquito Flow Sheet around HPGR, adapted.

CASE STUDY

A calculation case study was carried out for a South-American copper ore, comparing the various flow sheets as sketched below. The standard situation involved crushing of a SAG mill pebble material between 50mm and 15mm by conventional cone crusher, at a CSS of about 12mm. The crushed pebbles were then fed back to the SAG mill. For the 5,200t/h plant throughput, the pebble mass flow was about 600-900t/h, and the SAG mill processed average about 6,000t/h at a power consumption of 14,000kW (Figure 5). The SAG product is sent to the subsequent ball mill, operating as reverse circuit, with hydrocyclone classification ahead of the ball mill to bypass the final product size fraction to the downstream rougher flotation. Considering a production increase from an average 5,200t/h to 6,000t/h, it was considered that this increase in plant throughput could be achieved by alleviating the load on the SAG mill, by redirecting the crushed pebble material directly to ball milling (Figure 6).



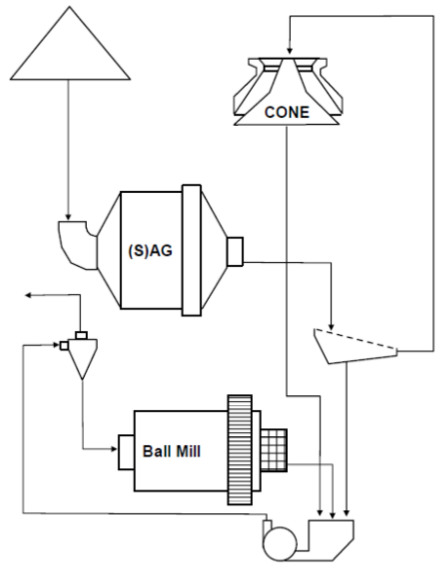
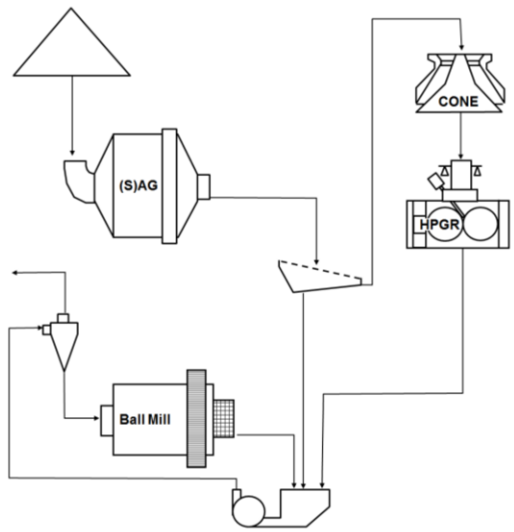


Figure 5 (left side). Pebble crushing by Cone crusher, product back to (S)AG.
Figure 6 (right side). Pebble crushing by cone, product forward to downstream ball mill discharge pump sump.

In addition, it was considered to introduce HPGR treatment of the pebble material, assuming that this would generate a finer ball mill feed containing less intermediate particle sizes. This would allow a higher SAG throughput at potentially a similar or lower overall energy consumption and possibly improved metallurgical performance due to micro-cracking of HPGR product particles.

In this, two possible arrangements were considered: pebble pre-crushing by cone crusher and subsequent HPGR in open circuit, with the product being sent forward to the downstream ball mill discharge pump sump (Figure 7), or crushing by cone crusher followed by HPGR in closed circuit with a 6mm screen aperture (Figure 8).



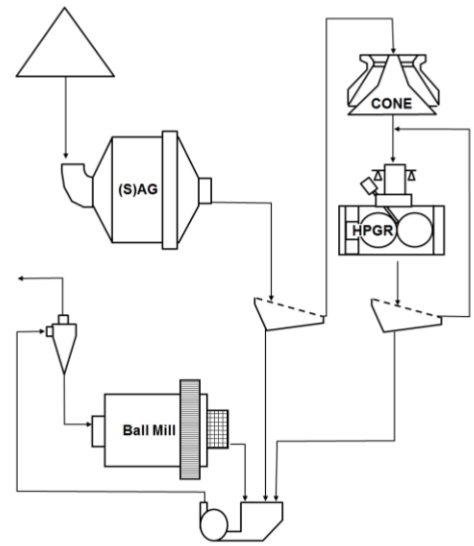


Figure 7 (left side). Pebble crushing by cone and subsequent HPGR in open circuit, product forwarded to downstream ball mill discharge pump sump.
Figure 8 (right side). Pebble crushing by cone and subsequent HPGR in closed circuit (with 6mm screen aperture), product forwarded to downstream ball mill discharge pump sump.

The current situation was indicated at a plant feed of 5200t/h, with the expansion aiming at 6000t/h. With pebble generation representing 15% of the SAG throughput, a comparison between the arrangements indicated above could be made (as shown in table 2). Early removal of the harder pebble material from the SAG load suggested a reduction of the SAG overall energy consumption from about 2.35kWh/t to 2.25kWh/t. Furthermore, assuming a cone crusher specific power of 1.0kWh/t and a HPGR specific energy consumption of 1.2kWh/t, the flow sheet arrangement options as calculated indicate a reduction in overall plant specific comminution energy from 11.5kWh/t to 10.1kWh/t, while allowing a plant capacity increase from 5,200t/h to 6,000t/h.

Arrangement of cone crusher product	Present: to SAG	to Ball Mill	to HPGR Open Circuit	to HPGR Closed Circuit
Plant Feed, t/h	5,200	6,000	6,000	6,000
SAG Mill Feed, t/h	6,000	6,000	6,000	6,000
SAG Mill Power Consumption, kW	14,100	13,500	13,500	13,500
Pebble Crusher Feed, t/h	900	900	900	900
Pebble Crusher Power Consumption, kW	900	900	900	900
HPGR Feed, t/h	0	0	900	1,260
HPGR Power Consumption, kW	0	0	1,080	1,512
Effective Ball Mill Feed, t/h	4077	4758	4650	4542
Ball Mill Power Consumption, kW	44,773	53,773	48,298	44,553
Total Power Consumption, kW	59,773	68,173	63,778	60,465
Total Specific Power Consumption, kWh/t	11.5	11.4	10.6	10.1

Table 2. Comparison of pebble crushing options by cone crusher and HPGR.

CONCLUDING REMARKS

Analysis of existing circuits and study cases does indicate that the application of HPGR in pebble crushing circuits does presents benefits in boosting plant capacity, and making a more efficient use of (S)AG mills, crushers and ball mills. The treatment facility for pebbles or excess ore does alleviate bottle-necks in the operation and provides room for a higher flexibility in with respect to fluctuations in ore hardness, process conditions and capacity.

One could infer that the application of pebble crushing by HPGR directs the hard ore to where it can be treated best, considering that HPGR is especially suitable for the harder components and pebbles, and allowing the average or softer ore to be treated by (S)AG.

In this, it must be part of the assessment to deal with tramp and oversize material, and consider the relationships of ore feed size and shape to HPGR roll dimensions, as well as feed quality in terms of moisture content and feed size distribution.

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