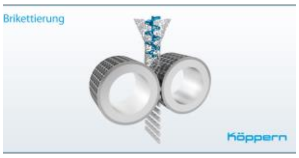

Quantification of HPGR energy efficiency effects on downstream grinding process

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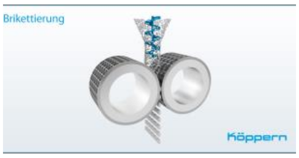


ABSTRACT

HPGRs (high pressure grinding rolls) have been developed within the last decades for energy efficient processing of a wide variety of ores. Special interest has been raised by projects increasing the capacities of processing plants by installing HPGRs prior to ball mills. Bond ball mill tests have been used for decades as a base for ball mill dimensioning in mineral circuits. For final Capex-Opex considerations of the processing circuit, one key question is about the level of grinding energy split between HPGR and downstream grinding stages. This is especially interesting if the downstream process comprises multiple grinding stages combined with separation steps.

The paper presents investigations on grinding energy consumption, size distribution and microfracturing of HPGR products, which affect the efficiency of the whole comminution and sorting process.

INTRODUCTION

The comminution process of High Pressure Grinding Rolls (HPGR) was discovered in the 1980s by the research work of the German Professor Schönert. Its main advantage is the high energy efficiency in comparison to ball mill grinding which has been the benchmark process in the cement industry by then (Schönert, 1988). Since then, a worldwide trend towards HPGR application has been established (Klymowsky, 2002), first in the cement industry but soon after also in ore processing.

Nevertheless, it has to be noted that the technology has its roots much earlier. Köppern, as one supplier of HPGR, has been working for more than 120 years on roller presses, starting with the formation of coal briquettes between two rollers. Subsequently, other fields of application, e.g. for fertilizer compaction, emerged (Schönert, 1966).

Even based on this history, it was a large step to transfer this process principle to minerals applications due to the much higher wear caused by the higher abrasivity of those materials. The first applications started in iron ore concentrate grinding. Meanwhile, with the optimization of the roller surfaces using studs (Morely, 2006), the service life of the rollers substantially increased and the technology has been well established for ores and hard rock applications.

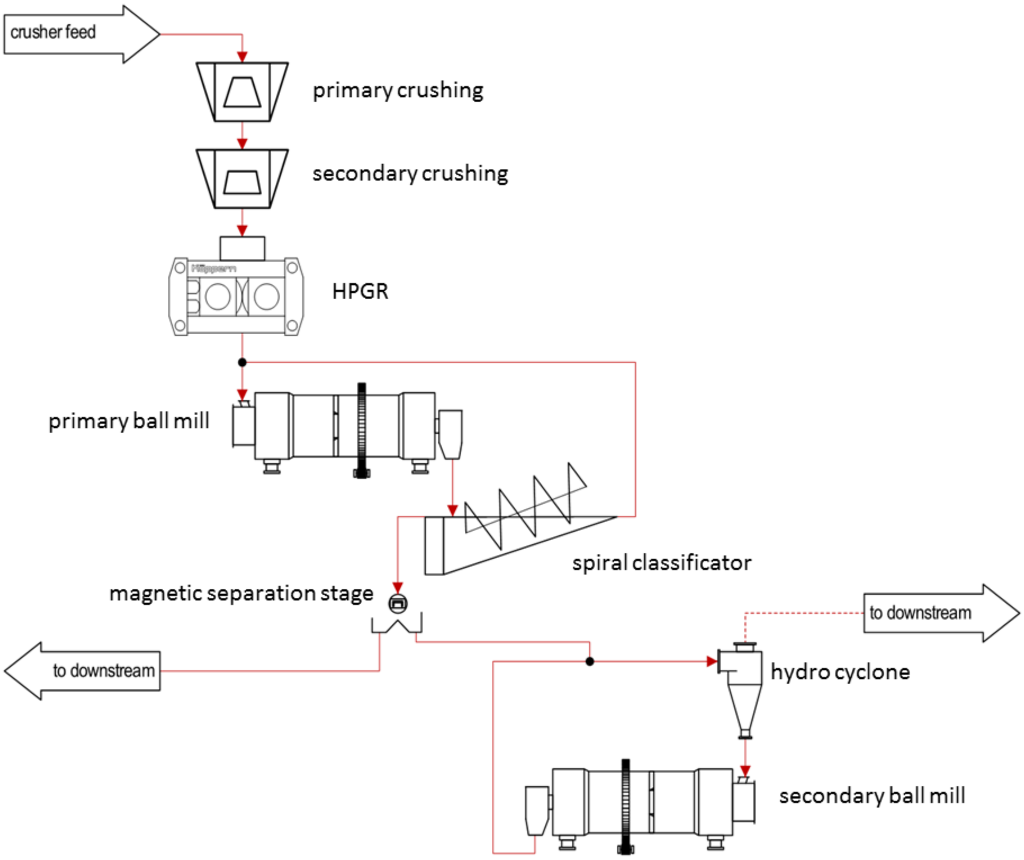
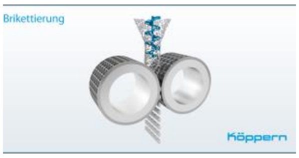


Figure 1 – Typical Flowsheet of HPGR processing in front of ball mill

Figure 1 refers to a common installation of a HPGR for iron ore. Other set ups with primary ball mills in circuit with cyclones which are prevalent in non-ferrous industries shall not be addresses in this paper. The material is pre-crushed to a feed size of 25 mm and then processed by HPGR within a pregrinding application in front of a primary ball mill (Morely, 1995). The HPGR is designed to work in open circuit in this case, with the transfer size to the ball mill being in the range of 80 % passing 7 mm. The primary ball mill is operated in a closed circuit with a screw classifier, followed by a magnetic separation stage. Tailings of this stage are reground in a ball mill hydrocyclone circuit for further processing.

To achieve the best grinding efficiency, HPGR are available in a wide size range. **Fehler! Verweisquelle konnte nicht gefunden werden.** shows a state-of-the art Köppern type HPGR. The key questions for sizing of such a machine are:

1. What throughput is to be processed by the machine?
2. What is the desired transfer size to the downstream process?
3. Which energy input shall be achieved?
4. How does the downstream flowsheet look like?
5. Which downstream effects shall be fostered, especially with regard to the subsequent ball mill grinding stage?



All those questions need to be answered in the process design phase, prior to selecting and sizing the key equipment.

Figure 2 – Typical example of a state of the art HPGR

SIZING KEY EQUIPMENT

The performance of HPGR primarily depends on the ore and its characteristics (Morley, 2006). Grinding tests are still indispensable to determine those characteristics and to predict the operational behaviour of the machine comminuting a certain material. The most important parameters are the specific throughput and specific energy consumption which allows selection of the appropriate HPGR for the required material and process parameters (Heinicke, 2016). The specific energy consumption is a mass rate normalized value to describe the amount of energy transferred to the material in one single grinding pass.

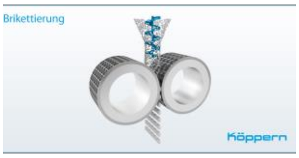
$$W_{Sp,HPGR} = \frac{(P_{t,HPGR} - P_{i,HPGR})}{\dot{M}_{HPGR}} \tag{1}$$

with:

	$W_{Sp,HPGR}$	mass specific energy consumption of HPGR
	P_t	total power draw under load
	P_i	idle power draw
	$\dot{M}_{HPGR}$	total HPGR throughput equals fresh feed rate in open circuit operation

The BOND ball mill test (Bond, 1952) is a proven method to predict the performance of a ball mill. The power draw can be calculated respectively, using the following formula:

$$W_{Sp,BM} = W_i * k * \left(\frac{10}{\sqrt{P_{80}}} - \frac{10}{\sqrt{F_{80}}}\right) \tag{2}$$



with:	$W_{Sp,BM}$	power draw of ball mill
	W_i	Bond work index as material specific parameter
	k	product of correction factors according to Bond
	P_{80}	80% product size passing of ball mill
	F_{80}	80% feed size passing of ball mill

If the formula is analysed in an analytical way there are three influences to reduce the energy consumption which have different level of effect:

- reduce F80 at low impact,
- reduce P80 at medium impact,
- reduce work index at highest impact.

Figure 3 shows those effects on the throughput of a ball mill (varied parameters as per table 1):

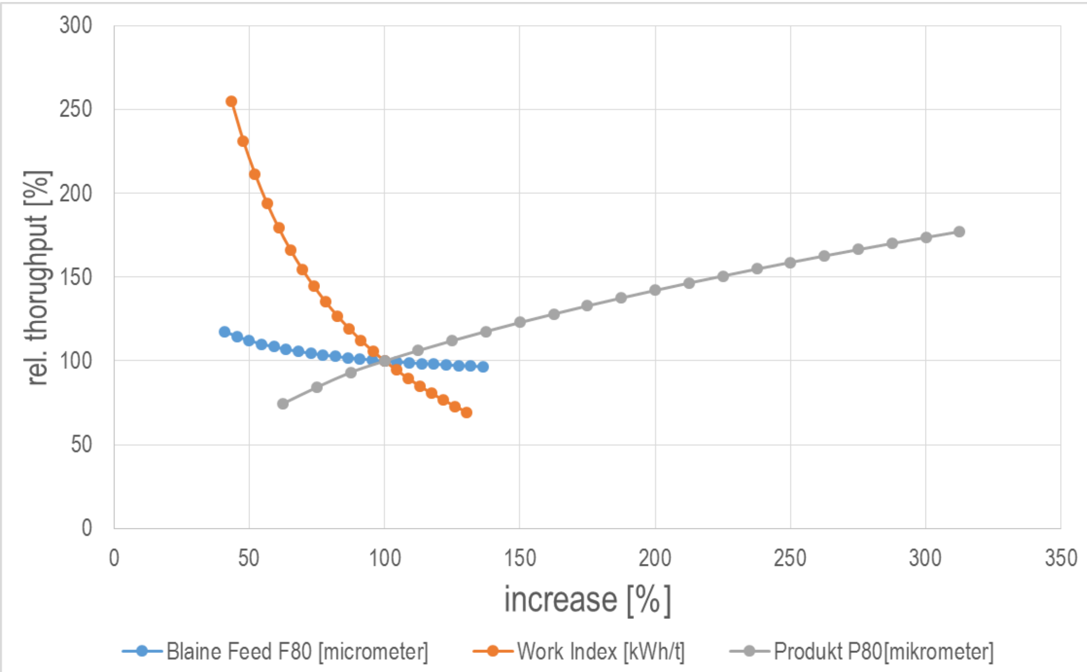


Figure 3 – Effect on throughput of Bond parameters

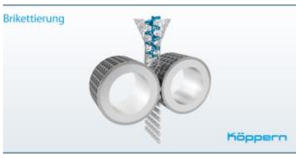


Table 1: Input parameters for Bond variation graph of a brown field plant (see also Povey, 2019)

Feed rate	466 t/h
Feed size F80	11 mm
Product size P80	0,181 mm
Mill power effective	3575 kW
Estimated Bond Wi	11,5 kWh/t

The total grinding energy according to the flowsheet shown in Figure 1 can be calculated as follows:

$$P_{TOTAL} = P_{HPGR} + P_{BM,1} + P_{BM,2} \tag{3}$$

with: P_{Total} total grinding power consumption

P_{HPGR} power consumption of HPGR

$P_{BM,1/2}$ power consumption of primary (1) and secondary (2) ball mill

The combination of (1) and (3) results in (4):

$$P_{TOTAL} = W_{Sp,HPGR} * \dot{M}_{HPGR} + W_{Sp,BM,1} * \dot{M}_{BM,1} + W_{Sp,BM,2} * \dot{M}_{BM,2} \tag{4}$$

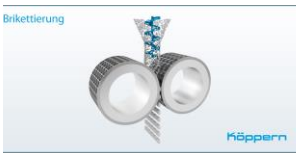
with: $\dot{M}_{BM,1/2}$ total primary (1) and secondary (2) ball mill throughput

$W_{Sp,BM,1/2}$ primary (1) and secondary (2) ball mill work index

If a mass split of 50 % is assumed in the magnetic separation stage, the masses are related as follows:

$$\dot{M} = \dot{M}_{HPGR} = \dot{M}_{BM,1} = \dot{M}_{BM,2} * 2 \tag{5}$$

with: $\dot{M}$ fresh feed rate



Thus, the combination of (2), (4) and (5) results in (6):

$$P_{TOTAL} = \dot{M}\left\{(P_{t,HPGR} - P_{i,HPGR}) + W_{i,1} * k * \left(\frac{10}{\sqrt{P_{80,\mathrm{BM1}}}} - \frac{10}{\sqrt{P_{80,\mathrm{HPGR}}}}\right) + W_{i,2} * k * \left(\frac{10}{\sqrt{P_{80,\mathrm{BM2}}}} - \frac{10}{\sqrt{P_{80,\mathrm{BM1}}}}\right) * 0{,}5\right\} \tag{6}$$

with: $W_{i,1/2}$ Bond ball mill work index as material specific parameter of primary (1) and secondary (2) ball mill

k product of correction factors

In a given brown field application, the installed power of the ball mills is fixed which means that the product of specific energy and maximum attainable throughput has to be the same for each mill at all times. Also, the transfer size to the downstream process after second ball mill is defined by the material characteristics and respective specifications of the downstream process such as liberation size and throughput. The product size of the HPGR, however, can be adjusted by increasing the hydraulic piston pressure in the machine. Thus, also the feed size to the primary ball mill can be controlled. An increase of the hydraulic pressure in the HPGR leads to an increased power draw of the HPGR roll drives as well (see Figure 4).

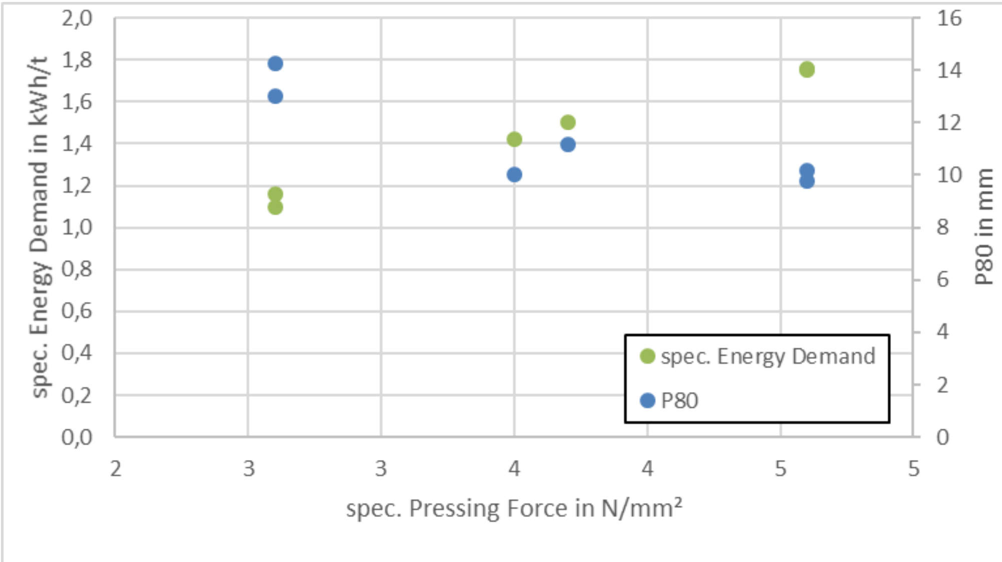
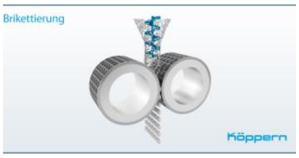


Figure 4 – Correlation of specific hydraulic pressure and specific energy demand from a test series with iron ore

Moreover, the high pressure grinding regime leads to micro-fractures within the product as shown in Figure 5. Those micro-fractures reduce the strength of the ore fed to subsequent comminution machines. In the presented flow chart, they reduce the Bond ball mill work index of the material transferred from the HPGR to the primary ball mill.



Thus, the throughput or the size reduction degree of the primary ball mill can be increased to fully exploit the installed power of the ball mill. It became clear that there is an optimization potential between energy efficient grinding in the HPGR and downstream ball mill grinding.

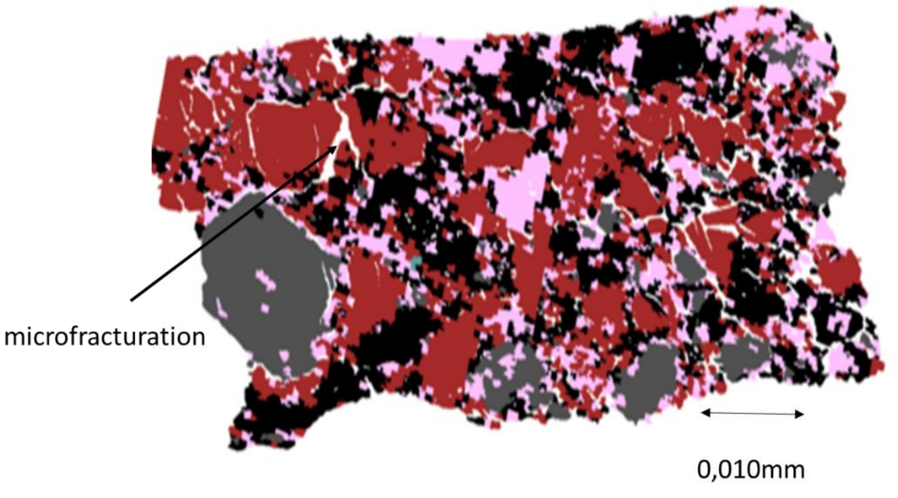
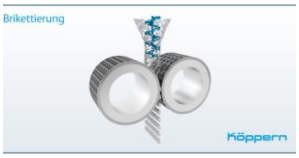


Figure 5 – Example of a micro-fractured particle of a HPGR

Such an optimization has to include the whole downstream process. An simple increase of the throughput in the primary ball mill would mean that the second ball mill would receive a higher feed rate as well. It can be assumed that the mircro-fracturing initiated by the HPGR will be exploited in the primary ball mill. Therefore, the secondary ball mill has to be designed considering a higher Bond ball mill work index than the primary one. The best way to avoid a potential overload of the secondary ball mill is to reduce the transfer size from primary ball mill. This affects the sorting behaviour and impacts the optimum process as well. The micro-fracturation of the particle is known to increase the liberation degree and therefore can influence the magnetic separation (Michaelis, 1995). Again the design of mass flows is influenced and need to be optimized. For this optimization, it is essential to understand of the differences between ball mill grinding and HPGR grinding in view to the downstream energy efficiency effects.

INFLUENCES ON BOND WORK INDEX USING HPGR

To assess the energy efficiency effect of HPGR, various Bond ball mill test series were performed (see also Brüggemann, 2019), all of them following the stipulations of Bond. The feed material for the Bond tests was a medium grained granodiorite from Kindisch (Germany) with a compression strength of σ_D = 176 MPa, produced by a hammer mill with grate (HAZEMAG Unirotor 490/380), a single toggle jaw crusher (Retsch BB 250 XL) and an HPGR (Köppern HPGR 60/10-230 and HPGR 22/3), see Figure . In those three machines, the material is stressed in different ways, merely by compression in the jaw crusher and the HPGR or by blow and shear in the hammer mill.



Despite the upper limit of the feed size of the material for the tests was always the same (-3150 µm), the particle size distributions PSD vary significantly. The first mayor difference is the slope of the particle size distribution curve (see Figure). While the particle size curves distribution curves of the jaw crusher and hammer mill product in the respective size range show only minor differences, the slope of the HPGR product size distribution is shallower, which is a common observation for HPGR grinding (Heinicke, 2007).

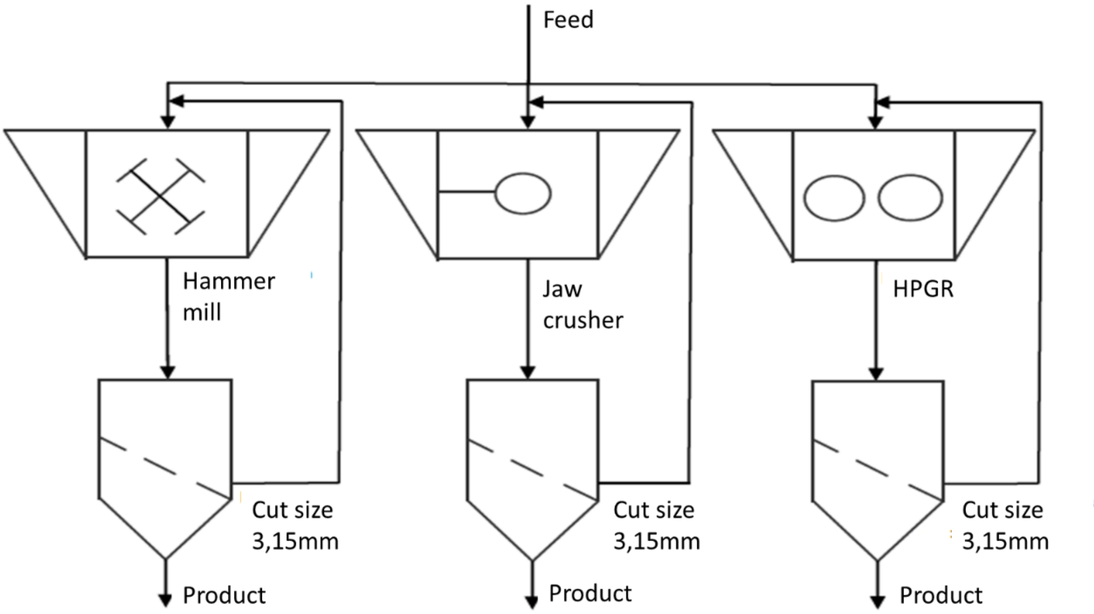


Figure 6 – Test work set up for preparation of sample

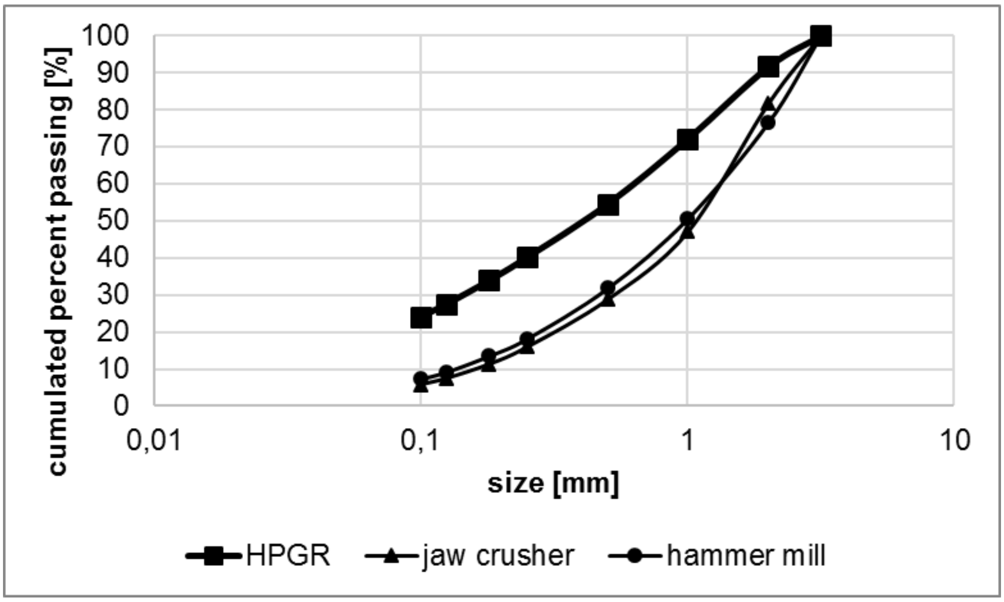
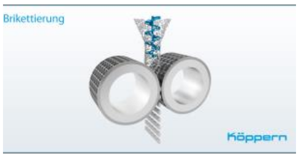


Figure 7 – Particle sizes for different preparations



It has been well established, that among others the preparation of the feed material influences the results of the Bond test (Gonzàles 2019, Weier 2018, Vizcarra 2019) but the experimental error is usually small (Ballantyne 2019). The small experimental error was also confirmed in our own tests with the scatter of three repeated tests being around 0.4 % (+/-0,07kWh/t of a medium 18,08kWh/t). Therefore, the Bond test is used also in this paper to assess the influence of micro-fractures generated by HPGR onto the grindability. Initially the W_i values were assessed for the PSD of the materials as obtained by just screening at a cut size of 3150 µm, see Figure . The resulting values of the BOND test are given in Table 2. They showed a reduction of the Bond work index of up to 8 % for the material ground by the HPGR.

TABLE 2 – Overview of Bond work index for different feed preparations

Preparation aggregate	**W_i [kWh/t]**
Hammer mill	17,89
Jaw crusher	18,09
HPGR	16,79

This reduction included potential effects of micro-fractures caused by HPGR as well the difference of the three feed materials. To reduce the influence of the differing PSD distributions, the product materials of jaw crusher and hammer mill were screened and classified into eight size fractions between 0 and 3150 µm. For comparison, the same procedure was also conducted for the original fresh secondary crushed material from the quarry (fraction -3150 µm directly separated from original feed size -32000 µm without further comminution). Afterwards, the mass per each fraction was adjusted to the shear of the respective fraction in the HPGR product. The modified fractions of each feed material were combined again and thoroughly blended and homogenized, finally well matching the particle size distribution of the HPGR product.

With the 3 modified feed materials, the Bond tests were repeated. The results are presented in Table 3. The reduction of the Bond work index increased even further to 15 % which indicates a remarkable effect for the power draw of a ball mill installed after the HPGR.

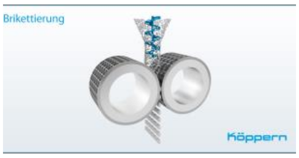


TABLE 3 – Overview of Bond index for different feed preparations at same feed PSD

Preparation aggregate	**W_i [kWh/t]**
Hammer mill screened to match HPGR	19,34
Jaw crusher screened to match HPGR	18,34
Fresh feed screened to match HPGR	18,32
HPGR	16,79

A further effect of an HPGR installation prior to ball milling in ore processing can be seen in the high comminution selectivity, as shown in Figure (Heinicke, 2022; Kühnel, 2022). During size reduction in the sample preparation for the Bond tests deploying different machine types, the coarser particles report to the finer classes depending on their mineral content and the type of stressing introduced by the comminution machines. While selectivity in comminution is generally limited with machines such as jaw or cone crushers, machines deploying the confined bed comminution principle such as HPGRs may support such selectivity as shown in Figure 8. Here, the fine fractions (-1 mm) exhibit a remarkable reduced quartz content while the iron is enriched.

A sample collected from such material for the Bond test by just classifying the -3150 µm fraction would simply reflect the increased content of the softer iron containing minerals. Assessing such a sample in a Bond test may again result in overdesigning mills for a production process which do not account for the special comminution characteristics with an HPGR. This effect has not been quantified so far as the preparation method of material for the BOND tests is not further specified and typically does not reproduce the real production conditions appropriately for HPGR.

Those effects have to be carefully analyzed for HPGR test work design. Typical vendors of HPGR have this ability and knowledge and will consult the individual clients accordingly for the individual ore type of the project (Heinicke, 2015).

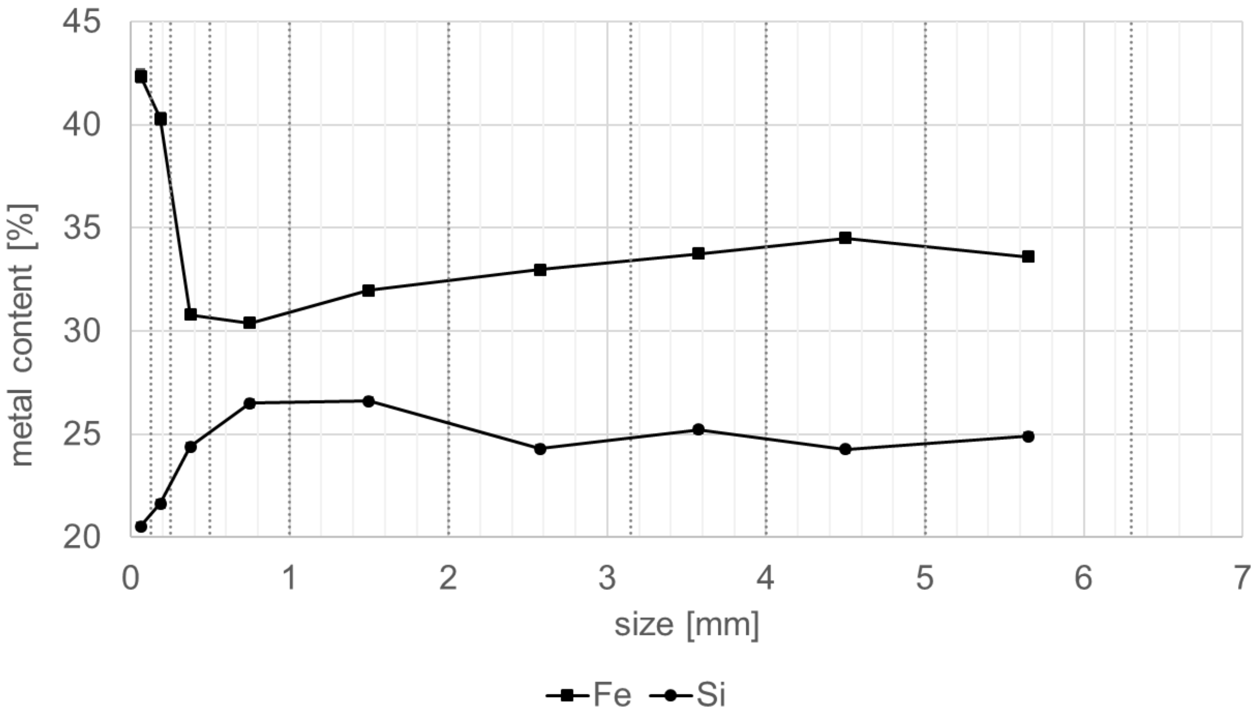


Figure 8 – Selective comminution effects in feed material processed by HPGR for an ore with high quartz and low iron contents

CONCLUSIONS

The grinding with HPGR showed remarkable effects on the downstream energy efficiency in ore processing. To quantify those effects, common test routines according BOND may be oversate the actual specific energy consumption as they are influenced by size distribution, particle weakening and selective grinding effects of HPGR. A careful planning of HPGR test series has to be done to balance the effect to downstream processes correctly. As the ores will differ from project to project this procedure shall be addressed by client and vender for each individual project.

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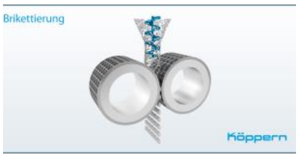

REFERENCES

Ballantyne, G and Giblett, A, 2019. Benchmarking comminution circuit performance for sustained improvement. SAG Conference, Vancouver

Bond, F C, 1952. The third theory of comminution. Mining engineering, p. 484-494

Brüggemann, J, 2019. Diskretisierung des Bondtest für GBWM Anwendungen. Masterarbeit. Technische Universität Bergakademie Freiberg

Gonzáles, G G, Coello-Velazquez, A l, Fernandez, B, Menendez-Aguado, J, 2021. Multivariate Analysis of the Ball Mill Bond's Standard Test on 2 Tantalum Ore. Metals, 11, 1606

Gruendken, A, Matthies, E, vanderMeer, F D, 2008. Flowsheet considerations for optimal use of high pressure grinding rolls. Proceedings of Comminution08 in Falmouth, p. 1-37

Heinicke, F (2012) Beitrag zur Modellierung der Zerkleinerung in Gutbettwalzenmühlen. Dissertation. Rheinisch-Westfälische Technische Hochschule Aachen

Heinicke, F, Guenter, H, Kamptner, A, 2016. How to avoid errors in HPGR product characterization. Proceeding of Procemin in Santiago de Chile, p. 1-11

Heinicke, F, Lieberwirth, H, Guenter, H (2016). Modelling of HPGR Edge recycling data with progressive gridning data. Proceeding of Comminution, p. 1-11

Klymowsky, R, Patzelt, N, Knecht, J, Burchardt, E, (2002). Selection and sizing of High Pressure Grinding Rolls. SME Handbook, p. 1-40

Kühnel, R (2021). Untersuchungen zur trockenen Aufbereitung von Magnetiterzen unter besonderer Berücksichtigung des Trennverhaltens im Luftstrom. Dissertation. Technische Universität Bergakademie Freiberg

Michaelis, H (1995). Real and potential metallurgical benefits of HPGR in Hard Rock Ore Processing. Randol Conference , p. 1-9

Morley, C (1995). The case for High Pressure Grinding Rolls. Randol Conference, p. 1-16

Morley, C (2006). Flowsheets for HPGR. SAG Conference, p. IV172-IV189

Povey, B C, Nol, Lifanov, D (2017): The introduction of HPGRs to the SGOK magnetite plant in Russia. Proceedings of Metplant, p.1-19

Schönert, K, (1966). Einzelkorn-Druckzerkleinerung und Zerkleinerungskinetik. Untersuchungen an Kalkstein-, Quarz-, und Zementklinkerkörnern des Größenbereiches 0,1-0,3mm. Dissertation. TH Karlsruhe

Schönert, K, (1988) A first survey of grinding with high-compression roller mills. International Journal of Mineral Processing 22, p. 401-412

Weier, M L, Chenje, T, (2018). Accuracy of the Bond ball mill test and its implications. *14th International Mineral Processing Conference & 5th International Seminar on GeoMetallurgy.* Santiago, Chile, Procemin-Geomet

Vizcarra, T, Wong, B (2019) Testwork variabililty – implications for grinding circuit design. SAG Conference, Vancouver