DOI: 10.53660/CLM-3832-24Q45

Aspects of roller press for the comminution of crushed iron ores

Aspectos da prensa de rolos na cominuição de minérios de ferro

Received: 10-07-2024 | Accepted: 12-08-2024 | Published: 16-08-2024

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ABSTRACT

Mining industries have faced a huge challenge to reduce cost, especially, in ore comminution that can reach more than 60 % of the total power consumption of mineral beneficiation plants. High-pressure grinding rolls (HPGR) has been used as an alternative when combined with the traditional autogenous or semi-autogenous (AG/SAG) grinding mill in the comminution of run-of-mine iron ores. Four similar pilot scale runs were performed in a closed circuit in order to evaluate the impact of HPGR processing on subsequent grinding for different lithologies. A considerable decrease in power consumption for the grinding process was observed after HPGR comminution. Furthermore, a good coefficient of determination ($R^2 > 0.84$) was observed between the Bond work index (*WI*) of the fresh feed and the *WI* of the HPGR product. This leads to a significant decrease in operational and capital expenditures (OPEX and CAPEX). Since the energy consumption has impact on carbon dioxide emissions, adopting this unit operation prior to conventional grinding reduces greenhouse gas emissions.

Keywords: Grindability; carbon footprint; compact itabirites; roller press

RESUMO

As indústrias de mineração enfrentam um grande desafio para reduzir custos, especialmente na cominuição de minério, que pode representar mais de 60 % do consumo total de energia das plantas de beneficiamento mineral. Os rolos de moagem de alta pressão (HPGR) têm sido utilizados como uma alternativa quando combinados com os tradicionais moinhos autógenos ou semi-autógenos (AG/SAG) na cominuição de minérios de ferro bruto. Quatro testes em escala piloto semelhantes foram realizados em circuito fechado para avaliar o impacto do processamento por HPGR sobre moagem subsequente para diferentes litologias. Uma considerável redução no consumo de energia para o processo de moagem foi observada após a cominuição por HPGR. Além disso, um bom coeficiente de determinação ($R^2 > 0,84$) foi observado entre o índice de trabalho de Bond (*WI*) do material de alimentação fresca e o *WI* do produto HPGR. Isso leva a redução significativa nas despesas operacionais e de capital (OPEX e CAPEX). Como o consumo de energia tem impacto nas emissões de dióxido de carbono, a adoção desta operação unitária antes da moagem convencional reduz as emissões de gases de efeito estufa.

Palavras-chave: Moabilidade; pegada de carbono; itabiritos compactos; prensa de rolos

INTRODUCTION

Comminution employing high-pressure roller press (HPGR) has been used since the 1980's decade, especially in the Portland cement industry (Kellerwessel, 1990). This kind of equipment normally has a low specific energy consumption, and it is increasingly used as an alternative application for conventional tertiary and quaternary crushing and grinding, with particle size ranging from 0.025 mm to 100 mm. It can be applied to moist or dry ores, both under open circuit arrangement and closed circuit (Meer & Leite, 2018).

In short, HPGR has one of the rollers with a shaft in fixed bearings, while its other roller is movable and can move against springs or, more commonly, against a hydraulic piston system, which applies force to the movable roller, consequently compressing the particulate bed against the surface of the fixed roller (under pressures greater than 50 MPa, according to Daniel and Morell, 2004) and leading to the autogenous comminution of the constituent particles of the bed (in transit). Alternatively, and simultaneously, instead of actual fragmentation of the bed particles, this type of equipment generates microcracks that will progress to fractures, in subsequent comminution equipment, resulting in a significant reduction in energy required for a given degree of reduction, that is to say: reducing the operational work index (*WI*) of the comminution circuit (Michaud, 2020; Ghorbani *et al.*, 2013; Saramak and Leśnia, 2024).

To clarify the distinction between conventional roller crushers and HPGRs, roller crushers primarily fracture individual particles through compression between rotating cylinders. In contrast, high-pressures grinding rolls (HPGRs) operate on a bed of particles, utilizing a combination of compression and shear forces to achieve finer sizes and induce intraparticle microcracks. In accordance with this reasoning and by virtue of to their characteristics HPGRs are widely applied in regrinding of iron ore pellet feed concentrates to increase the bulk specific surface area (Abazarpoor *et al.*, 2018; Meer & Leite, 2018). Lately, this process has been upgraded with the development of new techniques of control, materials, and devices (Oliveira *et al.*, 2016). This has favored studies on other applications within the mineral industry. Just to give an example, a low-grade hematitite comminution was tested by Xinran *et al.* (2022).

The mining industry has been facing a challenging scenario for the increasingly need for hard rock processing. This issue is mainly due to the high energy consumption of traditional AG/SAG milling processes. Thus, it is becoming required to find alternatives to reduce power consumption (Kodali *et al.*, 2011), and consequently, lessen high operational expenditure spent with traditional comminution processes. As a final point, a decrease in carbon emissions is becoming mandatory for general industries (Morrell, 2022). In line with this approach, the use of HPGR in the comminution of iron ores has been explored in several studies. Several authors have provided a comprehensive overview of HPGRs in the ore and minerals industry, highlighting their efficiency and positive impacts on downstream process steps.

Ribeiro *et al.* (2010) found that HPGR application in the Minas-Rio Project led to process stability and potential financial gains. Amiri & Abadi (2022) compared the effects of HPGR and ball mill grinding on pelletizing and reduction stages, with HPGR resulting in improved pellet quality. Jiang (2016) proposed a technique for recovering iron from hematite-rich diasporic-type bauxite ore, which could potentially be applied in the context of HPGR comminution of iron ores.

Some authors (Kodali *et al.*, 2011; Sadangi & Das, 2022) have found results that indicate a decrease in power requirement in circuits including rock comminution step after a previous HPGR processing. The effect of HPGR processing has been explained by the embrittlement of rocks due to internal microcracks formation. Furthermore, this process has another advantage because of irregularly shaped particle formation, which increases superficial area and therefore increasing the Blaine index (Abazarpoor *et al.*, 2018). Even though many studies were carried out on this subject, there is no further information about the lithology effects in the comminutions processing at HPGR.

Concerning mathematical modeling of this operation, Campos *et al.* (2019) have modified the Torres and Casali model for high-pressure grinding rolls (HPGR). Their improvement succeeds in prediction of power, throughput, and product size distribution in roller pressing iron ore concentrate.

Within this context, this paper investigates the impact of lithology on circulating load within an HPGR comminution circuit. It compares the power consumption of a traditional ball milling process with and without upstream HPGR integration. The data and analysis of the pilot-scale HPGR processing campaign are presented in the following sections.

MATERIALS AND METHODS

Preparation of Samples

The four tested iron ore samples were sourced from industrially mined hematites originating from the Iron Quadrangle geological district (in Minas Gerais State, Brazil). For a comprehensive idea of the geochemical aspects of the hematites and/or itabirites of the banded iron formations of the Iron Quadrangle, see Selmi *et al.* (2009).

All types of samples studied in this work break down into the following major categories: compact ore: *C*, friable ore: *F*, undefined ore: *U*, and blended ore: *B*. The blended material was composed of 74 % in mass of compact, plus 5 % of friable, and 21 % of undefined lithology. The amount of iron ore used for the experimental campaign was 6.0 tons of samples *C*, *F*, and *U* and 15.0 tons of sample *B*.

HPGR circuit configuration

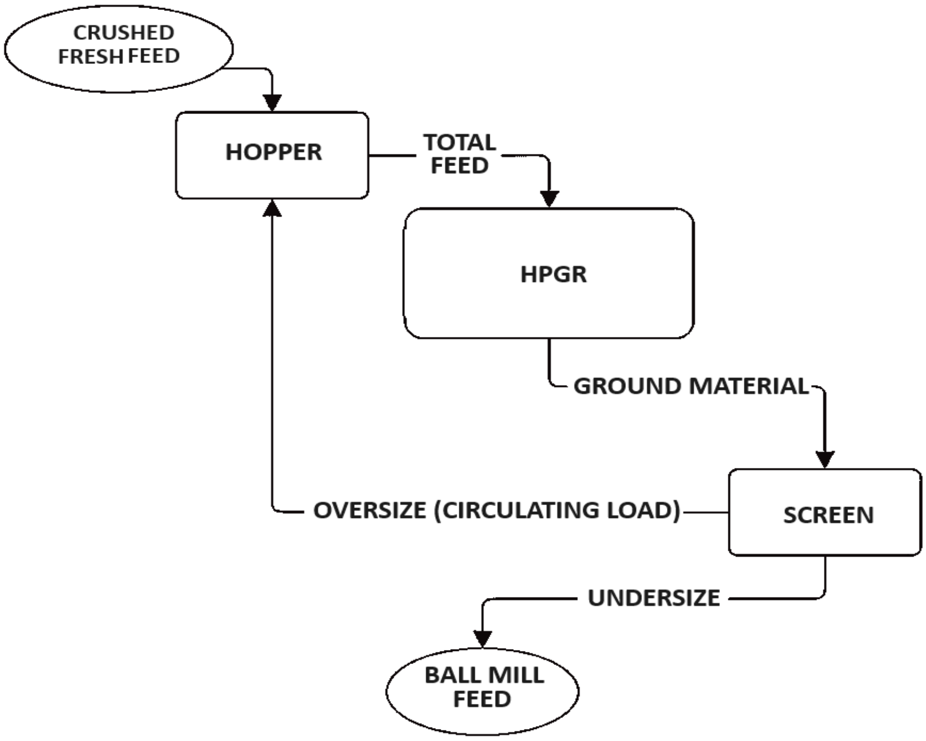
All the samples were crushed in a jaw crusher until D_{90} = 19 mm, and then, they were ground in an HPGR pilot plant, from 19 mm to 1mm. The HRC 300 model (from Metso) was the roller press used, with a roller diameter of 300 mm. Figure 1 shows the processing route tested in this work. As shown (***Figure*** 1), the materials were ground and classified in a continuous circulating load. The flow rate of the HPGR's feed varied from 1.06 t/h to 2.68 t/h, depending on the tested sample.

All the data parameters from the HPGR process are shown in Table 1. Note that, some information such as flake density, and ores moisture is also listed. An overview of the tested pilot plant can be seen in Figure 2.

With regard to the pressure used, for comparison with another type of rock, Alves *et al.* (2015) carried out an experimental campaign with HPGR for the comminution of an ore containing phlogopite (its ideal formula is $KMg_3AlSi_3O_{10}(F,OH)_2$), in which the initial hydraulic pressure range used was between 1.0 MPa and 6.0 MPa (under 1.591 rad/s or 15.2 rpm).

In turn, Schneider *et al.* (2009) investigated HPGR comminution for the same type of rock (compact itabirite). They tested the process using two different initial particle sizes: below 10 mm and between 10 and 3.4 mm. The oil pressure applied ranged from 1 to 6 MPa, and the rollers rotated at an angular velocity of 2.64 rad/s (25.2 rpm).In the present study, a slightly lower angular velocity of 2.408 rad/s (23.0 rpm) was employed.

Figure 1– Closed HPGR tested circuit



Source: Authors' elaboration (2024)

Table 1– Summarized main parameters of the HPGR process

Parameters	**Samples**				**Unit**
	B	**C**	***F***	***U***	
Pressure operation	4.20	4.20	4.10	4.10	MPa
Net power (fixed roller)	7.33	7.18	5.71	8.59	kW
Gap operation	7.00	7.40	6.14	8.60	mm
Bulk density	2,65	2.60	2.99	2.67	t/m³
Moisture	0.74	0.34	1.16	0.05	%
Roller diameter	300				mm
Roller angular speed	2.408				rad/s
Motor power	2 x 15.0 = 30.0				kW
Nominal amperage	30.5				A
Initial pressure	4.00				MPa
Initial gap	2.0				mm
Required product	Below 1 mm				
Circuit	Closed in 1.2 mm screen				

Source: Authors' elaboration (2024)

For each lithotype, samples were taken from jaw crusher product (HPGR fresh feed) and ground material to quantify the effect of introducing a roller press comminution stage ahead of the traditional ball milling stage. The goal was to measure how this inclusion would impact both energy consumption and the amount of circulating load.

Figure 2 – Overview of the pilot plant used for the tests.

Source: Authors' elaboration (2024)

After sampling, the materials were prepared to be processed in a ball mill, to calculate the required comminution energy. For that, the fresh feed was crushed till to 80 wt.% passing size through 2.8 mm. For HPGR products, since it was previously ground below 1 mm, the F_{80} established was 0.72 mm. Both samples, fresh feed and HPGR's products were ground by the ball mill to the 80 wt.% size passing through 100 µm.

The work index (*WI*) was calculated by the following equation (Man, 2002; Doll & Nikolić, 2022):

$$WI = \frac{48.95}{\mathrm{P1}^{0.23} \mathrm{x}\ \mathrm{Gdb}^{0.82}\ \mathrm{x}\ [\left(\frac{10}{\mathrm{P80}^{0.5}} - \frac{10}{\mathrm{F80}^{0.5}}\right)]} \quad (1)$$

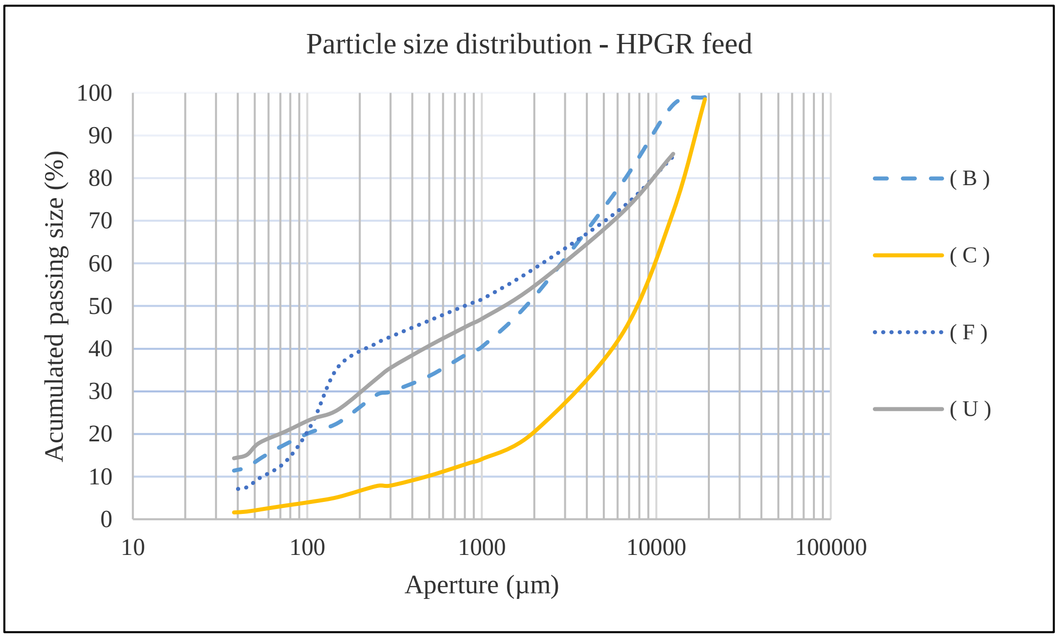
Where: P1 — closing screen size [µm] (in this case P1 = 149 µm); Gdb — Grindability [g/revolution]; P80 — 80 % passing size of product [µm]; F80 — 80 % passing size of feed [µm].

RESULTS AND DISCUSSION

Characterization of the ore types

Figure 3 shows, for fresh feed, the overall circuit product size distribution for each of the tested lithologies. Moreover, the ground product size distribution can be seen in Figure 4. An evident coarser particle size distribution can be noticed for compact lithology (D_{80} =15 mm). Otherwise, friable lithologies presented a finer particle size distribution (D_{80} = 6.3 mm). It can be explained by the behavior of each lithology in the jaw crusher used as a previous comminution of HPGR feed, that is, soft minerals generate more fines than hard minerals.

Figure 3 – Particle size distribution of all tested fresh feed

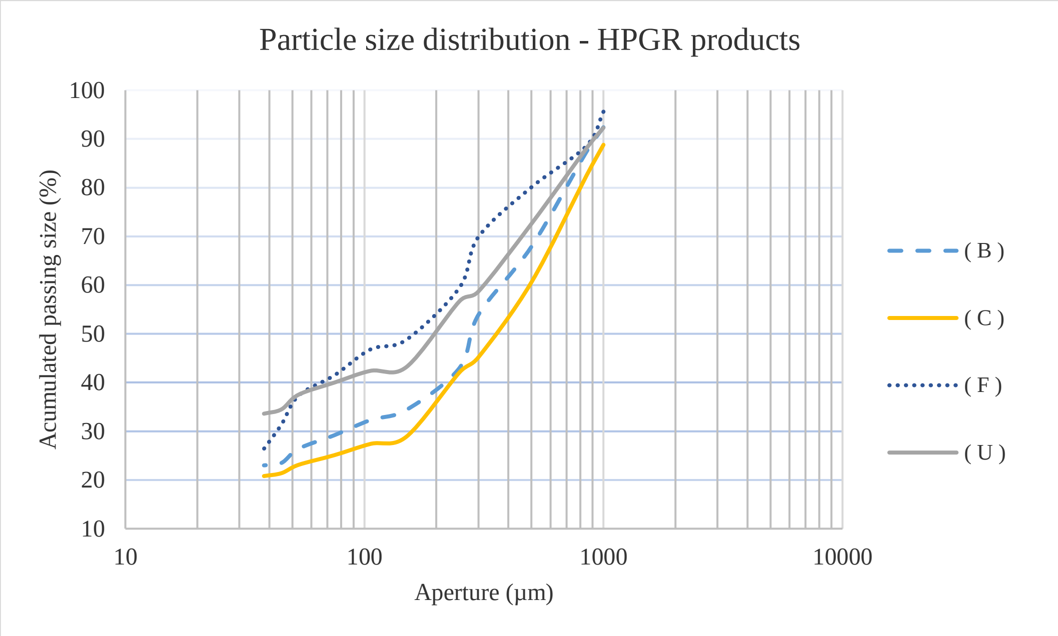


Source: Authors' elaboration (2024)

Since the final target for this study was 90 % in mass passing size through 45 µm, the samples *F* and *U* present over 30 % in mass of passing through 45 µm. In contrast, hard rocks such as C and B achieved less than 23% in mass of passing through the same aperture (Figure 4). Besides fines (below 45 µm) generation, the particles from the HPGR process present an irregular shape (Abazarpoor *et al.*, 2017, which is an advantage for the pelletizing process since it increases the roughness of the superficial area, and consequently, can improve the characteristics of the pellets, giving high integrity for it (Podczeck & Newton, 1995). That is, non-round particles can generate pellets with high compression resistance (Meer *et al.*, 2018).

As can be seen (Table 2) the chemical composition of all samples is composed of iron oxide and silicon oxide, and a minor amount of other components are also present. These samples represent banded rocks from Brazil's southeast region, also named iron quadrangle. For the sake of conceptual correctness, it is worth mentioning that the chemical composition table, though expressed in terms of oxides and volatile components (LOI stands for "loss on ignition"), is a simplified formalization that doesn't reflect the actual crystallographic structure of the mineral constituents.

Figure 4 – Particle size distribution of all tested (ground) products



Source: Authors' elaboration (2024)

Table 2 – Chemical assays of major components in mass concentration

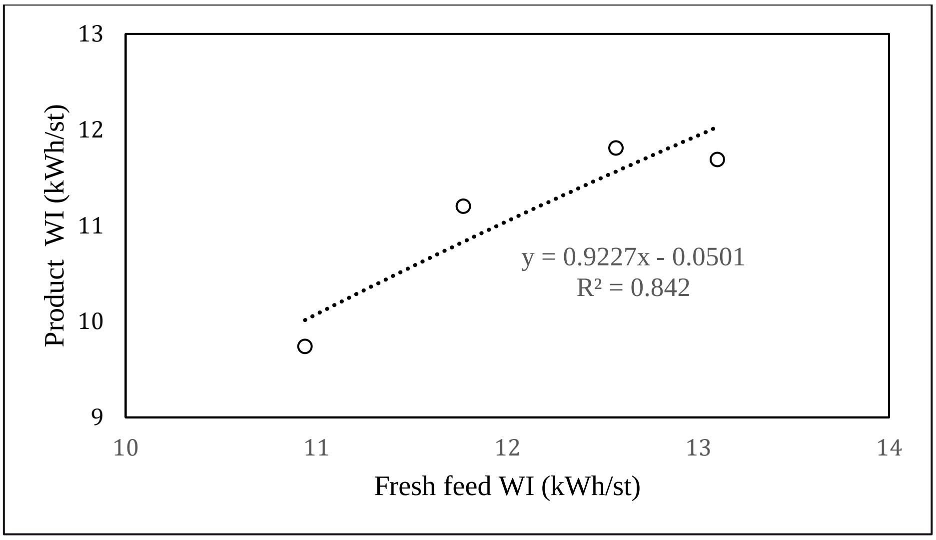
Sample	Fe_2O_3 [%]	SiO_2 [%]	Al_2O_3 [%]	Mn [%]	P [%]	CaO [%]	MgO [%]	TiO_2 [%]	LOI [%]
B	58.48	39.73	0.48	0.04	0.03	0.19	0.13	0.02	0.64
C	59.02	39.95	0.13	0.02	0.01	0.04	0.04	0.03	0.18
F	59.00	37.48	1.10	0.60	0.04	0.15	0.23	0.04	1.26
U	54.66	42.24	1.19	0.08	0.07	0.08	0.05	0.08	1.13

Source: Authors' elaboration (2024)

Work Index of fresh feed versus HPGR product

For each material, the data from *WI* were compared and the variations were calculated. Figure 5 shows the results of *WI* from fresh feed and ground products. As can be seen, all the samples presented the same tendency of *WI* decreasing after the HPGR processing. The energy reduction for tested rocks varies from 4.8 to 11 %, showing a considerable reduction in power consumption. In addition to the reduction of power consumption in the milling process, a good correlation between the results of *WI* from feed and product was observed (Figure 5). For preliminary project phases, it can lead to a better prediction of power consumption once known *WI* of the fresh feed of the HPGR.

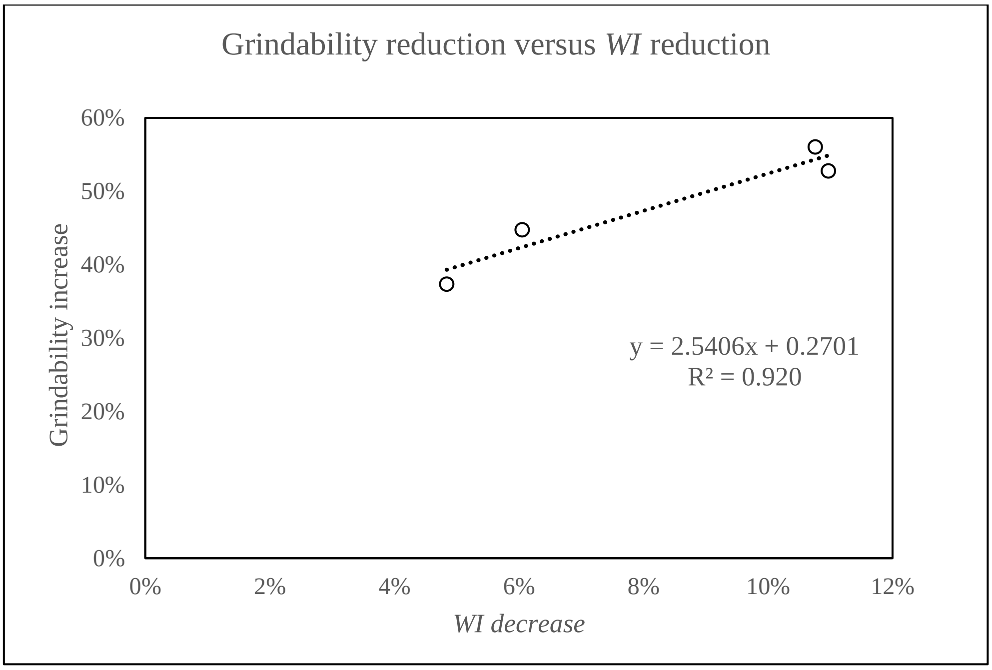
Figure 5 – Comparison between work index of fresh feed and ground product



Source: Authors' elaboration (2024)

Firstly, it can be explained by the reduction of grindability. As mentioned before, in equation (1), grindability (*Gdb*) has a fundamental importance since the growth of this parameter leads to a decrease do *WI*. Figure 6 shows a good correlation (with coefficient of determination: $R^2 = 0.920$) between grindability growth and *WI* reduction, i.e., it indicates that the regression prediction well fits the data, so it corroborates the *WI* formula

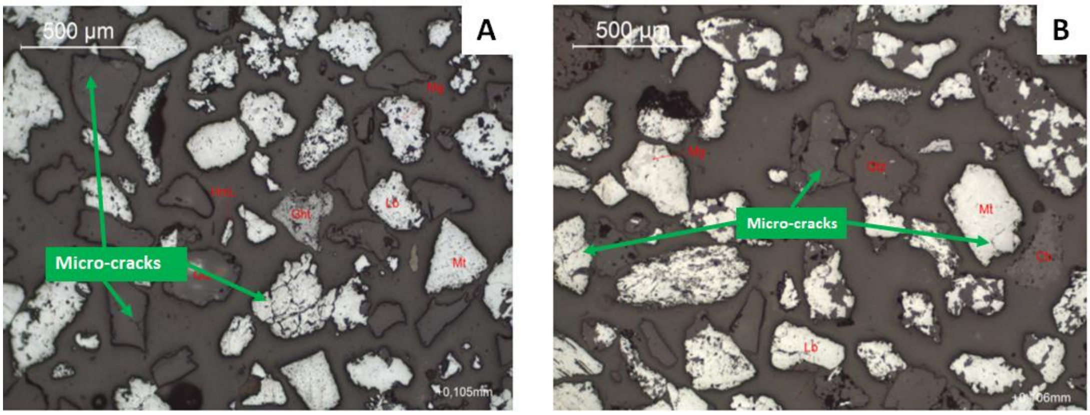
Figure 6 – Correlation between grindability and *WI*



Source: Authors' elaboration (2024)

Secondly, it can be explained by microcracks generated during the HPGR process (Kodali *et al.*, 2011; Sadangi & Das, 2022). Even though the microcracks formation is more common inside the particle, as can be seen in Figures 7A and 7B, some cracks are visible even on the surface of the particles. The two ore micrographs shown in that figure are of the friable lithotype (left) and the compact lithotype (right). Note that the fissures are observed in quartz (black) and also in iron oxide particles (white).

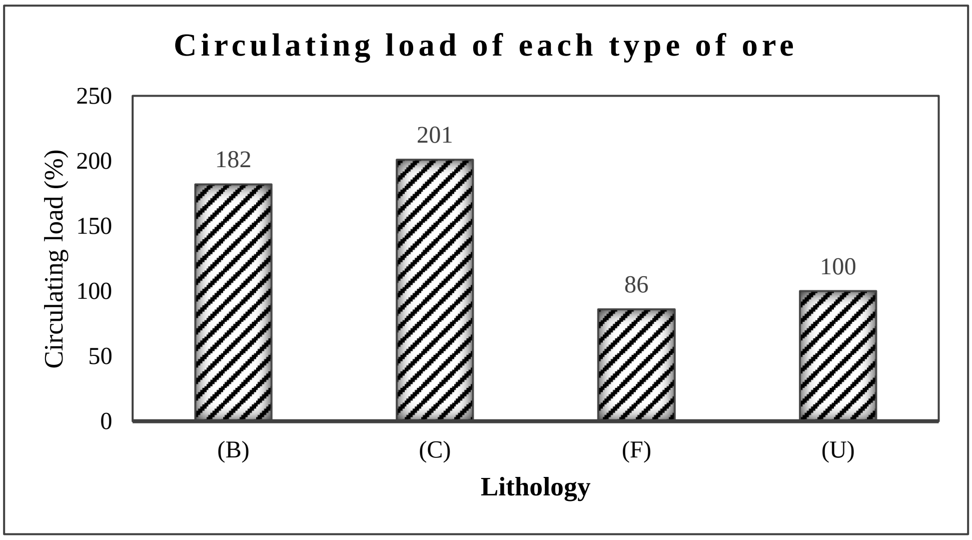
Figure 7 – Optical microscopy images of HPGR product A) Friable B) Compact



Source: Authors' elaboration (2024)

The results of circulating load for each studied lithology are shown in Figure 8. As can be seen, the increase of compact material leads to an increment of circulating load. As illustratedThe circulating load goes from 86 % for friable ore to 201 % for hard rock in terms of mass percent. This information is very important for the development of new processing sizing.

Figure 8 – Circulating load

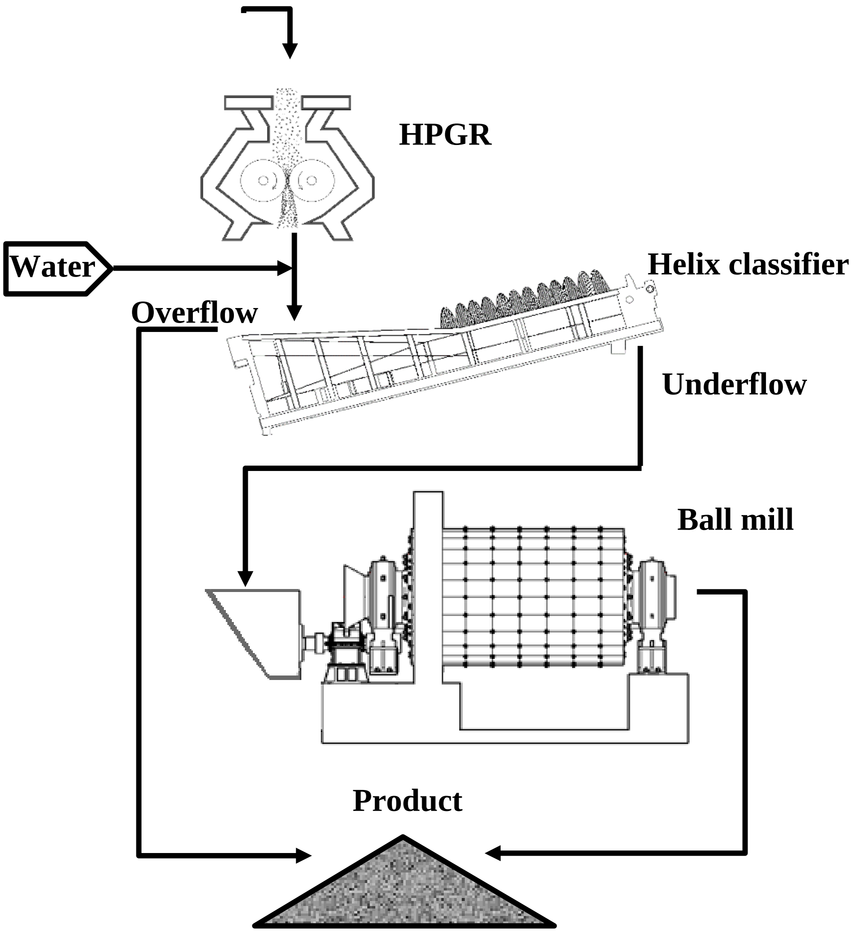


Source: Authors' elaboration (2024)

Figure 9 summarizes the key benefits of introducing HPGR before the ball mill for iron ore comminution. Notably, the HPGR process leads to a substantial increase in the specific surface area of the rigid granular system (Abazarpoor & Halali, 2017). This increased surface area is critical for the strength of iron ore pellets, since the industry standard typically employs a minimum apparent specific surface area of 180 m^2/kg (as estimated by the indirect Blaine permeametry method).

The crucial induction of microfractures in mineral grains and their benefits are indirectly supported by the conceptual route shown in Figure 9. Furthermore, the scalping step was applied to reduce fines from ball mill feed, it can also reduce significantly power consumption and consequently reduce OPEX, since it can lead to a *WI* decrease (Ferreira *et al.*, 2015). Moreover, this arrangement requires less CAPEX once fines are removed from mill feed. Nevertheless, it must be studied for each type of ore since it can affect the rheological properties of the ore inside the mill.

Figure 9 – Mainly characteristics and advantages of using the HPGR process, before ball mill.



Source: Authors' elaboration (2024)

CONCLUSIONS

The results showed that high-pressure grinding roll (HPGR) is a suitable process for being used for run-of-mine (ROM) comminution. Nevertheless, the only correlation found between lithology and process was the increase in circulating load and mineral hardness. Considering that no correlation with lithology or size distribution was noticed, it shows that each material from any deposit must be tested before processing route definition.

The HPGR process, microcracks within particles play a crucial role by promoting embrittlement, which in turn improves grindability. This can lead to significant reductions in power consumption, production costs, and carbon dioxide (CO_2) emissions for the mineral processing industry.

Despite the high circulating load found for the four types of lithology tested, the HPGR process was shown to be an alternative to reduce the power consumption and flow rate of the ball mills process. For this study, the target for particle size distribution was to reach a final product of a ball mill with P_{90} of 45 µm. However, depending on the tested material, the HPGR process achieved from 13 to 45 % (in mass) of passing through 45 µm. As a final remark, it is important to note that, using HPGR before ball mills, a classifier process can be required to reduce over-grinding and avoid problems in flotation processes due to fines and ultrafine excess, for instance.

ACKNOWLEDGMENTS

The authors are thankful to Conselho Nacional de Pesquisa —CNPq, Fundação de Amparo à Pesquisa de Minas Gerais — FAPEMIG, and Coordenação de Aperfeiçoamento de Pessoal de Nível Superior — CAPES for their financial support. The authors also take the opportunity to declare that there is no conflict of interest regarding the publication of this article.

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