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Comparing strategies for grinding itabirite iron ores in autogenous and semi-autogenous pilot-scale mills

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ABSTRACT

High grade iron ore resources are becoming depleted in Brazil, with relatively low-grade ores requiring more intensive comminution for proper liberation of iron minerals, followed by upgrading. Comminution circuits that have been frequently used in the Brazilian iron ore industry in preparation of high-grade iron ores consist of multiple crushing stages followed by ball milling and are known for being highly complex and capital-intensive installations. This work assesses the potential suitability of autogenous (AG) and semi-autogenous (SAG) milling through an extensive pilot plant campaign carried out with itabirite iron ores. The effects of ore type, feed size distribution, circuit configuration (open or closed-circuit and two-stage or single-stage), mode of grinding (AG or SAG), ball load, use of pebble crushing as well as of full secondary pre-crushing have been investigated. The results demonstrate both the technical feasibility and energy efficiency of such an alternative for itabirite comminution circuits.

1. Introduction

High-grade iron ores from Brazil were frequently processed via multistage crushing/screening followed by magnetic separation and flotation. Progressive depletion of high-grade iron ore reserves resulted in the need to process the lower grade iron ores. Typical lower grade iron ores are represented by itabirites, which are metamorphic banded-iron formations (Hagemann et al., 2016), and consist basically of iron oxide (predominantly hematite), with quartz as the main gangue mineral. Such dilution of the ore fed to the plant has demanded the inclusion of grinding stages to liberate the valuable iron oxides from the gangue, typically to sizes below about 0.15 mm (França et al., 2020; Rodrigues, 2014).

Circuits that are currently in operation dealing with the low-grade itabirite ores rely typically on four crushing stages, followed by grinding in ball mills and concentration by flotation. This size reduction strategy requires several pieces of equipment, both for processing and handling the ore in several parallel lines for the case of high capacity plants, resulting in significant operating and capital costs (Segura-Salazar et al., 2018). Adoption of autogenous or semi-autogenous grinding (AG/SAG) would lead to a significant simplification alternative to such plants.

Within the scope of AG/SAG grinding, several approaches can be used in size reduction. For instance, the mill may be operated in the absence of steel grinding media (AG) or with steel balls (SAG) (Gupta and Yan, 2016). In the case of SAG operation, different ball fillings can be used (Napier-Munn et al., 1996). Circuits can operate in open circuit or in closed circuit with a classifier. Further, either SAG or AG mills can be operated in a stand-alone mode (single-stage) or coupled to a ball mill in FAB or SAB configurations (Gupta and Yan, 2016). The size distribution of the fresh feed as well as the ball size distribution are also known to have important effects in the process (Napier-Munn et al., 1996). Finally, more recently, the full secondary pre-crushing of the fresh feed to the mill has also been considered a valid alternative to improve throughput of SAG mills (Siddal and Putland, 2007).

Their low competence, with drop weight A*b indices of over 100, has led to some doubts regarding the suitability of itabirite ores to AG/SAG milling. However, the presence of different types of itabirites with

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different levels of competence results in a wide variability of competence in this type of ores (França et al., 2020; Rodrigues, 2014), which may provide sufficient competent material to build up a suitable rock charge in the mill, thus allowing successful AG/SAG milling. An example is magnetite iron ore with a bulk A*b of over 100, but an A*b of 37 for the waste silica content that is successfully milled in AG mode in Sweden by LKAB mines (Bueno et al., 2011a).

In spite of the important advances in modelling and simulation of autogenous and semi-autogenous grinding made in recent decades (Napier-Munn et al., 1996; Morrell, 2004), risks exist in designing a circuit adopting AG/SAG mills for low-grade itabirite iron ores from bench-scale information. This is especially due to the multi-component nature of the ores, as addressed in modelling and test work of Bueno et al. (2011b, 2012). As such, pilot-plant testing remains a valid method to gain insights into the use of this alternative in size reduction for ores with which only limited experience exists with the technology. The present work investigates several variables that influence the performance of AG/SAG grinding through experiments conducted at a pilot-scale. Different ore types, feed size distributions, modes of operation (open/closed circuit, AG/SAG, single/two-stage), ball loads and size distributions, as well as the use of secondary pre-crushing or pebble crushing have been investigated, with the aim of assessing the effect of the various variables as well as the technical feasibility of processing such low-grade ores in AG/SAG mills.

2. Experimental

2.1. Ore samples

Samples of four ore types were collected from the Run-of-Mine product of three Brazilian mines operated by Vale and located in the Iron Quadrangle of the state of Minas Gerais: Galinheiro (GAL), Sapecado (SAP) and Jangada (JAN). In the case of Galinheiro mine, two samples were collected, named GAL-IC and GAL-IF, the former presenting a coarser particle size distribution and, supposedly, also a more compact itabirite, than the latter which is known as friable. Fig. 1 shows images of typical itabirites at the mine sites, thus demonstrating the widely different competences of the ore types. Samples containing a total of 625 tons were collected for both bench-scale and pilot plant tests.

2.2. Bench-scale tests

Comminution properties for all samples were determined according to the Bond ball mill work index (BWi), Bond crushability work index (CWi), JK Drop Weight Tests (DWT) and JK Abrasion testing (Napier-Munn et al. 1996). The BWi was determined following the standard test, using a closing sieve of 150 μm.

The DWT consists of dropping a weight under gravity to crush individual particles placed on a steel anvil (Napier-Munn et al., 1996). Important parameters extracted from the DWT are the t_n values where t is defined as the percentage passing each nth fraction of the original particle size. The value of t_n that is more often used is t_{10} which can be described as the percentage passing in one tenth of the original particle size. The breakage index (t_{10}) is related to the specific comminution energy as follows:

$$t_{10} = A\left(1 - e^{-b\mathrm{Ecs}}\right) \tag{1}$$

where Ecs is specific comminution energy (kWh/t), t_{10} is the percentage passing 1/10th of the initial mean particle size tested and A and b are ore impact breakage parameters. The product $A{*}b$ is regarded as an index of the amenability of the ore to breakage by impact.

2.3. Pilot-scale tests

The pilot plant process equipment consisted of a 1.83 m diameter by 0.61 m length SAG/AG mill, a pebble crusher, two spiral classifiers and a 0.91 m diameter by 1.22 m length ball mill. Two circuit configurations were adopted in pilot plant testing as shown in Fig. 2. For the single-stage (SS) configuration the AG/SAG mill operated in a closed circuit with a spiral classifier, so that the product was nominally below 0.4 mm. The two-stage configuration included AG/SAG milling with optional pebble crushing followed by ball milling, the latter in a closed mode with a spiral (screw) classifier. The coupling of the SAG or AG mill with ball milling is known as SAB (C) or FAB (C) circuit respectively, where C denotes the use of pebble crushing. A total of 21 SAG/AG tests, four of which included ball milling, were conducted at different configurations and conditions. Fig. 3 shows the pilot-scale AG/SAG mill configurations, and Table 1 summarizes the apertures of grates, pebble ports and trommel used in the tests. It is worth mentioning that there were no open pebble ports in most tests.

The ball size distribution used in the SAG mill tests is presented in Table 2. The one designated as "standard" was used in nearly all SAG tests, whereas the one identified as "finer" was used for a particular test involving the JAN sample.

The system adopted for feeding the AG/SAG mill consisted initially in screening the ROM feed size distributions, separating into five individual size fractions: −203 + 152 mm; −152 + 76.2 mm; −76.2 + 25.4 mm; −25.4 + 12.7 mm and −12.7 mm. The weight of each size fraction was calculated in order to reconstitute 100 kg sub-samples according to a predefined size distribution. The sub-samples containing 100 kg were prepared using wheelbarrows and a platform scale. The contents of each wheelbarrow were then discharged onto the ground for shovelling on the SAG/AG mill fresh feed conveyor belt. The rate of ore addition was dictated by the need to maintain the mill at a constant total weight, which was measured by the loadcell mountings and shown on a large display in the pilot plant area. In order to shorten the period required to stabilise the mill, the desired weight of ore was loaded into the mill prior to each test. This procedure was successful in maintaining the mill charge volume within a narrow range for all tests. Mill power was measured during the tests and the mean power during steady-state operation recorded.

Stability of the circuit operation was assessed by monitoring

Fig. 1. Images of itabirites at the mine site during sample collection (modified from Rodrigues, 2014).

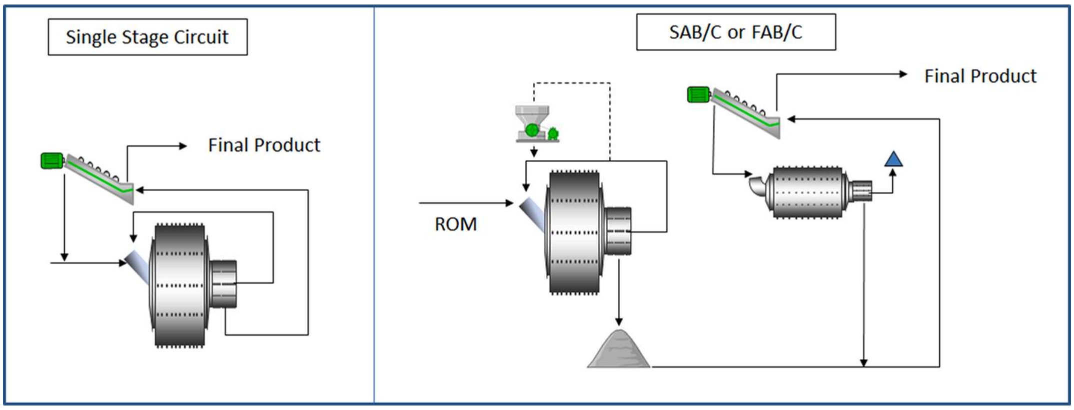

Fig. 2. Circuit configurations adopted in the pilot-scale tests.

Fig. 3. Overview of the pilot SAG mill, with the spiral classifier on the left (Rodrigues, 2014).

Table 1
Apertures of grates, pebble ports and trommel.

Feature	Aperture (mm)
Grate	12–14
Pebble ports	63.5 × 63.5
Trommel	12.7

Table 2
Ball size distributions used in the SAG mill tests (percent in weight).

Ball size (mm)	% retained	
	Standard	Finer
101.6	50	12
88.9	32	17
76.2	18	18
63.5	–	24
50.8	–	29

variables such as mill feed rate and power draw. After a period of steady-state operation, ranging from 2 to 7 h, sampling started. In order to reduce the stabilization period for some tests, a blend of new and conditioned charge from previous tests with the same ore was loaded into the mill at start-up. Sampling increments were collected throughout the duration of the test for each stream selected. At the end of each test the entire mill charge was emptied and both the ball and the rock charges were carefully screened. All data from the tests were mass-balanced. Percentage of solids in the feed to the AG/SAG mill was maintained at 78 ± 2% (w/w) in all tests.

Different feed size distributions were prepared. Besides the Run-of-Mine (ROM) size distribution, which emulated the product of primary crushing, in the case of JAN, a finer size distribution was prepared for testing, whereas in the case of GAL-IC, a coarser size distribution was prepared, by controlling the proportions of the different size fractions contained in the tested sample. This was carried out in order to isolate the effects of feed size distribution and ore competence in the tests. In addition, in the case of JAN, an additional feed was prepared, emulating the application of secondary crushing of the feed, so that the sample contained a top size of 102 mm, which contrasts with the 203 mm of the primary crusher product.

More detail on the experimental procedures may be found in the thesis of Rodrigues, 2014.

3. Results and discussion

3.1. Feed ore characteristics

Table 3 presents the chemical assays, which confirm that grades were reasonably low in comparison to richer Brazilian iron ores, being in the range from 42 to 50% Fe. Fig. 4 shows the particle size distribution of the Run-of-Mine samples, as well as additional feeds prepared for the pilot-scale tests. The Fig. 4 shows that the ROM size distributions varied significantly for the different ores, with GAL-IF, GAL-IC and SAP presenting bimodal size distributions, shown by the 'steps' in the size distribution, with a significant proportion of already fine material contained in the feed, in the range of 40 – 60% finer than 150 μm. On the other hand, JAN sample presented a smoother size distribution which is more typical of the feed to SAG mills in hard rock applications (Napier-Munn et al., 1996).

Table 4 summarizes results of the bench scale tests. Values of $A{*}b$ and ta for the ores studied are also strongly correlated, as commonly observed for other ores (Napier-Munn et al., 1996; Tavares and Silveira, 2008). Apart from JAN, all other samples may be classified as very soft, when values of the $A{*}b$ breakage index are considered (Napier-Munn et al., 1996). Also, values of crushing work index (CWi) increased

Table 3
Sample assays.

Sample	Fe (%)	SiO_2 (%)
GAL–IF	47.4	29.5
GAL–IC	42.2	37.9
SAP	46.4	33.1
JAN	49.8	26.4

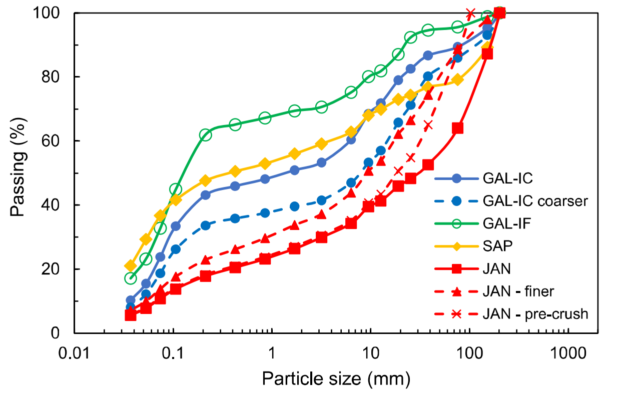

Fig. 4. Particle size distributions (PSD) of the samples of the feed to the pilot-scale tests. Solid lines represent the "as received" samples, whereas the dashed lines represent size distributions that were prepared for particular pilot-scale tests.

Table 4
Summary of bench scale test results.

Sample	JK Abrasion t_a	JK DWT			Bond crushing CWi (kWh/t)	Bond Ball mill BWi (kWh/t)*
		A	*b*	*A*b*		
GAL-IF	4.21	63.1	5.86	370	4.1	6.5
GAL-IC	3.42	58.8	4.51	265	6.4	6.2
SAP	2.04	56.7	3.06	174	9.6	7.7
JAN	0.55	38.8	1.40	54.2	15.5	10.8

* Calculated for 150 μm

inversely with the *A*b* breakage index, as commonly observed (Napier-Munn et al., 1996; Tavares and Silveira, 2008).

In order to demonstrate the exceptionally low competence of these ores in comparison to those usually subjected to SAG/AG milling, data from Table 4 has been plotted in the diagram proposed by Bueno and Lane (2011), which originally consisted of sets of *A*b* (DWT) and BWi from 134 SAG/AG pilot plant tested samples. Fig. 5 compares the original results from that work to the results of the four itabirite samples, indicating that the latter are much softer than any of the former as described in the figure.

3.2. Pilot-scale trial results

3.2.1. Effect of ore type

Typical results from the tests are presented in Fig. 6, which shows the size distributions of the various product streams measured in a particular test. It is evident that in closed-circuit operation the return of the oversize (coarse product) from the screw classifier is responsible for a less bimodal feed size distribution to the mill relative to the fresh feed, shown by the smoother size distribution.

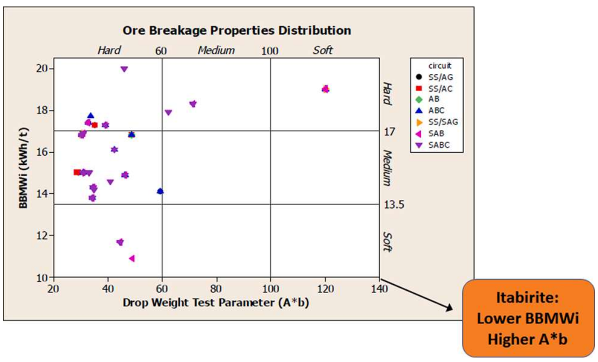

Fig. 5. Values of BWi and A*b from 134 tests in pilot-scale AG/SAG mill (Bueno and Lane, 2011) showing the region of Itabirite ore samples from the present work is off the scales of the data base of ores.

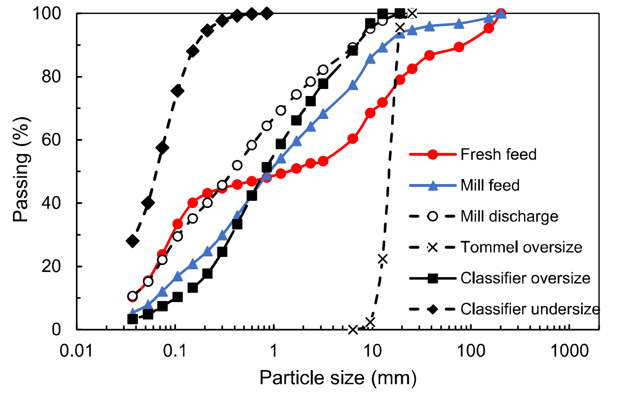

Fig. 6. Size distributions from SAG test with GAL-IC in closed-circuit mode.

Table 5 presents results from tests for the four itabirite ore types that are the object of the present work. The tests have been conducted under the same conditions, namely in single-stage (SS) SAG mode, with 4% ball charge, with the mill total filling varying from 21.4 to 26.6%, and the mill operating in closed circuit with the spiral classifier. It shows that product fineness was relatively consistent, whereas feed rates and specific energies varied an order of magnitude from the test with the softest (GAL-IF) to the toughest (JAN) ore sample. Given this variation, which is partially due to the significant differences in feed size distribution (Fig. 4), results from the tests have been analysed on the basis of two indices, namely the size-specific energy and the fSAG. First, the size-specific energy (SSE) (Ballantyne et al., 2015) is given by

$$SSE = \frac{100 * SE}{\% < 75\ \mu m\ \text{in product} - \% < 75\ \mu m\ \text{in feed}} \quad (2)$$

where *SE* is the specific milling energy, given in kWh/t.

The SSE was used throughout the present work to assess the AG/SAG milling tests, being a useful index of grindability. In addition, results have also been analysed on the basis of the fSAG (Siddal et al., 1996; Bueno and Lane 2011), which is given by

$$fSAG = \frac{\text{SAG circuit specific energy}}{\text{Bond crushing} + \text{Bond ball milling circuit specific energy}} \quad (3)$$

where the SAG circuit specific energy is given by the sum of the energy in the SAG/AG pilot mill, added to the ball mill and the crusher specific energies (when applicable). Whereas the ball mill energy was measured in the pilot plant, the crusher energy (either secondary or pebble) was estimated on the basis of the Bond model and the Bond crushing work index (Table 4) (Bueno and Lane, 2011). The crushing-ball milling circuit specific energy was estimated on the basis of the Bond equation and the relevant Bond work indices (Table 4), with the crushing energy given from the SAG/AG F80 to a nominal product with P80 of 8.0 mm being added to the ball mill energy from F80 of 8.0 mm to the actual P80 of the pilot test, given either by the SAG/AG or the ball mill, depending on the circuit configuration (Fig. 2). No correction factors were used in the Bond equation, so that these may be regarded only as a rough estimate, valid for comparative purposes.

Table 5 shows that GAL-IF and SAP demanded the lowest energy per tonne of fine (−75 μm) material, GAL-IC demanded about 1 kWh/t more, whereas JAN demanded more than four times that amount to produce the same tonnage of fine material. These results are in qualitative agreement with results from both A*b of the JKDWT and t_a values

Table 5
Effect of feed ore in closed-circuit single-stage (SS) SAG operation.

Sample	Feed		Product		Fresh feed rate (t/h)	Specific energy (kWh/t)	SSE (kWh/t −75 µm)	fSAG (–)
	−75 µm (%)	F80 (µm)	−75 µm (%)	P80 (µm)				
GAL-IF	32.8	9,449	55.5	128	8.39	1.41	6.2	0.28
GAL-IC	23.8	20,708	57.5	121	5.48	2.49	7.4	0.48
SAP	36.7	80,798	77.6	82	5.40	2.61	6.4	0.31
JAN	10.8	125,637	70.9	95	0.93	13.60	22.6	1.22

from the JK abrasion test (Table 4). The value of fSAG was significantly lower for the tests with the three softer materials, suggesting that the energy demanded in size reduction using the SAG mill would be significantly lower than that estimated for the traditional crushing-ball milling circuit when used in the same task. The value of fSAG above one in the case of JAN demonstrates the challenge in the SAG mill operating with such a tough ore.

3.2.2. Effect of feed size distribution and mode of circuit operation

Due to the large variations in particle size distribution (PSD) of samples, it was decided to prepare additional PSDs for selected samples (Fig. 4) in order to assess the influence of feed size distribution on SAG milling. Table 6 summarizes the results for tests conducted in two different configurations, that is, open and closed circuit, for GAL-IC and JAN ores.

It is observed that the throughput increased as the PSD of the feed became finer in all tests. In the case of GAL-IC sample the SAG mill open circuit throughput obtained for the coarser PSD was 38% lower than the figure observed for the finer PSD. Accordingly, the throughput reduction resulted in 17% increase in SSE, from 6.5 to 7.6 kWh/t–75 µm. The same occurred with the JAN sample i.e. the SAG mill circuit throughput obtained for the coarser PSD was 30% lower than the figure observed for the finer PSD. Accordingly, in this case the throughput reduction resulted in 13% increase in SSE. All these results were obtained for SAG milling open circuit configuration. The finer feed size distribution for the GAL-IC ore resulted in almost halving the fSAG index, thus demonstrating an improved advantage in comparison to the traditional crushing-ball milling circuit.

Table 6 also shows the SAG milling results obtained for samples GAL-IC but in this case in closed-circuit configuration. Here too the SAG mill circuit throughput was reduced as PSD was changed from finer to a coarser sample. The reduction was thus 25% which is smaller than the 38% figure obtained for the open circuit configuration. Interestingly, the change in SSE and fSAG were also smaller than for the open circuit, indicating that the variation of the feed PSD has a higher influence in open-circuit than in closed-circuit operation for the ore in question.

A comparison between open and closed-circuit operation is also possible by examining Table 6 for GAL-IC. Evidently, closed-circuit operation resulted in significant reduction in circuit throughput, while producing much greater proportion of fines in the product. Comparisons normalizing the results on the basis of fineness of the product suggest that the SSE either increased marginally (GAL-IC finer sample) ore was unaffected by mode of operation (GAL-IC coarser sample).

Fig. 7 shows photographs taken from the charge upon crash-stopping the SAG mill. The relatively dry charge obtained for the mill when operating in open circuit contrasts with the slurry pooling conditions observed for the closed circuit (single-stage) operation. The presence of the slurry pool could have been a result of a small delay in stopping the recirculating flow or/and the pulp flowrate exceeded the capacity of the mill to remove the pulp. The incapacity of the mill to remove the pulp would have been responsible, at least in part, for the higher SSE in the closed-circuit operation. Thus, the design of grate profile and pulp lifters must be carefully addressed in the case of single-stage industrial operations.

3.2.3. Effect of mode of mill operation (SAG or AG) and ball load

Additional tests were carried out to compare SAG and AG milling, the former with 4% steel ball load. The comparative tests comprised both operation in open and closed circuit, as well as in single- and two-stage configurations. In this case the coarser PSDs from GAL-IC and JAN were used, together with a GAL-IF as a third sample. Tables 7 and 8 show the summary of the results.

Table 7 and Table 8 show that AG operation resulted in lower throughput than SAG milling. The largest reduction in throughput in AG milling (45%) was observed for the softest ore (GAL-IF) operating in closed circuit, which could be explained by the inability of the ore to perform as autogenous grinding media, given its fineness (Fig. 4) and low competence (Table 4). This was also the ore associated with the largest increase in SSE. This points to the need to blend in a more competent component if this were to be milled autogenously, as successfully trialled for an incompetent ore by Powell et al (2019). With the exception of JAN (Table 8), AG operation resulted in much larger production of fines (Table 7) than SAG milling and has the added benefit of not requiring the use of steel grinding media. In single-stage operation the fSAG increased from SAG to AG mode, further confirming the smaller attractiveness of the autogenous mode of operation in terms of energy demand.

The influence of ball load on SAG milling performance was also evaluated. Table 8 shows the summary of open-circuit SAG milling tests for JAN ore with 0%, 4% and 16% ball charge. It shows the increase, although modest, of mill throughput with ball load. It also shows that operation with the 4% ball load led to the most energy-efficient operation, as evidenced by the lower SSE and fSAG values, thus demonstrating that the modest increase in capacity using higher ball loads for this particular ore occurs at the expense of significant reduction in energy efficiency.

Table 6
Effect of feed size distribution and type of circuit in single-stage SAG milling (open/closed).

Sample	Circuit	Feed		Product		Fresh feed rate (t/h)	SSE (kWh/t −75 µm)	fSAG (–)
		−75 µm (%)	F80 (µm)	−75 µm (%)	P80 (µm)			
JAN finer	Open	13.8	44,216	40.1	1,570	2.09	23.4	2.45
JAN	Open	10.8	125,637	40.6	1,308	1.46	26.9	2.60
GAL-IC	Open	23.8	20,708	41.7	714	11.87	6.5	0.61
GAL-IC coarser	Open	18.7	37,777	43.3	985	7.34	7.6	1.12
GAL-IC	Closed	23.8	20,708	57.5	121	5.48	7.4	0.48
GAL-IC coarser	Closed	18.7	37,777	62.1	108	4.13	7.7	0.59

Fig. 7. Typical mill loads as observed in pilot scale tests: open circuit (left) and closed-circuit (right) SAG operation (modified from Rodrigues, 2014).

Table 7
Effect of AG/SAG mode for selected samples.

Sample	Circuit	Feed		Product		Fresh feed rate (t/h)	SSE (kWh/t –75 µm)	fSAG (–)
		−75 µm (%)	F80 (µm)	−75 µm (%)	P80 (µm)			
GAL-IC	SAG	18.7	37,777	43.3	985	7.34	7.6	1.12
	AG	18.7	37,777	48.6	374	4.65	9.4	0.97
	SAG*	18.7	37,777	62.1	108	4.13	7.7	0.59
	AG*	18.7	37,777	68.4	94	3.00	8.9	0.73
GAL-IF	SAG*	32.8	9,449	55.5	128	8.39	6.2	0.28
	AG*	32.8	9,449	67.0	99	4.60	8.0	0.47

* Single-stage (SS) operation

Table 8
Effect of ball load for JAN sample in open-circuit grinding.

% Balls	Feed		Product		Fresh feed rate (t/h)	Specific energy (kWh/t)	SSE (kWh/t –75 µm)	fSAG (-)
	−75 µm (%)	F80 (µm)	−75 µm (%)	P80 (µm)				
0	10.8	125,637	41.0	1,152	1.21	8.61	28.5	2.63
4	10.8	125,637	40.6	1,308	1.46	8.00	26.8	2.60
16	10.8	125,637	36.3	1,703	1.52	9.28	36.4	3.43

3.2.4. Effect of number of grinding stages

Operation of the AG/SAG mill in single-stage and two-stage mode was then compared, both in closed-circuit operation. The two-stage circuit was configured as SAG/AG grinding followed by ball milling (SAB or FAB) (Fig. 2). These comparisons have been made for GAL-IC with a coarser PSD sample (Fig. 4) and results are summarized in Table 9.

Two-stage circuits presented consistently higher throughput than single-stage, which is not a surprise, given the higher installed power. Indeed, SAB mill circuit throughput was 78% greater than the figure observed for single-stage SAG milling. Besides the throughput increase, SSE and fSAG demonstrate the lower energy efficiency of the two-stage circuits, which is associated to the large power demanded in ball milling. The same occurred with AG milling i.e. AB mill circuit throughput was 53% greater than the figure observed for AGSS milling. Here too, all grinding parameters showed a reduction in the efficiency of the two-stage circuits.

The amount of material finer than 10 µm in the product, namely slimes, is one of the critical issues when dealing with Itabirite grinding. Prior to flotation the ore needs to be deslimed, since the presence of such fines would negatively impact flotation performance. Comparing the two-stage to the single-stage circuits, no clear pattern was identified in terms of generation of this material. This demonstrates that slimes generation would not be a relevant criterion for selection either circuit confirmation, at least for the ore in question.

3.2.5. Effect of pebble crushing

The effect of using a pebble crusher was also evaluated. Table 10

Table 9
Effect of double/single stage in closed-circuit grinding of sample GAL-IC.*

Primary/ Secondary mill	Final Product			Fresh feed rate (t/h)	Specific energy (kWh/t)		SSE (kWh/t −75 µm)	fSAG (–)
	P80 (µm)	75 µm (%)	10 µm (%)		SAG/AG	Ball mill		
SAG/Ball	102	63.0	6.4	7.34	1.87	3.56	12.3	0.93
SAG/ -	108	62.1	6.7	4.13	3.34	–	7.7	0.59
AG/Ball	97	67.2	7.9	4.65	2.81	3.58	13.2	1.07
AG/ -	94	68.4	7.4	3.00	4.44	–	8.9	0.73

* Fresh feed: F80 of 37,777 µm, 18.7% –75 µm and 1.2% – 10 µm.

Table 10
Effect of pebble crushing for sample JAN* for mill operating in open-circuit SAG mode.

Pebble crushing	Product		Fresh feed rate (t/h)–75 µm (%)	Circulating load (%)**	Specific energy (kWh/t)		SSE (kWh/t −75 µm)	fSAG (–)
	P80 (µm)	−75 µm (%)			SAG	Crusher ***		
With	1,645	36.8	1.73	10.83	6.52	0.06	25.1	2.39
Without	1,308	40.6	1.46	6.04	8.00	–	26.9	2.60

*Fresh feed: F80 of 125,637 µm and 10.8% −75 µm.
** Ratio of trommel oversize divided by trommel undersize flowrates.
*** Calculated pebble crusher specific energy with Bond crusher Wi and multiplied by the percentage of circulating load.

shows the results obtained in a test carried out with a combination of pebble ports and pebble crusher as opposed to a test with no pebble crushing, both using JAN sample. It shows that the use of pebble crushing was responsible for an increase in SAG mill circuit throughput by 18% in comparison to the figure observed for the circuit with no pebble crushing. Pebble crushing had the additional benefit of reducing the SSE by 7%, i.e. from 26.9 kWh/t–75 µm to 25.1 kWh/t–75 µm. However, energy consumed in pebble crushing was not included in calculation of SSE. On the other hand, estimates of fSAG, which incorporated the crushing energy consumption, attested to the energy benefit, however modest, of use of the pebble crusher.

3.2.6. Effect of secondary crushing

An alternative recently used to increase throughput in SAG mill circuits has been to include a secondary crushing stage in the circuit, therefore resulting in a finer fresh feed to the SAG mill (Siddal and Putland, 2007). A sample with a truncated PSD was prepared to assess the response of the circuit grinding JAN sample of such an alternative, already shown in Fig. 4. The summary of test results is shown in Table 11, which indicates that the SAG mill circuit throughput decreased by 18% for the truncated feed (secondary crushing) as compared with the original PSD. No substantial change was observed in SSE, whereas the fSAG increased 53%. This substantial increase in fSAG may be explained by the reduction in autogenous grinding media and increase in proportion of critical size in the mill, a deleterious effect that has been associated with feeding fully crushed secondary crushing material to the SAG mill (Powell et al., 2015).

3.2.7. Effect of ball size distribution

One of the key operating aspects of AG/SAG single-stage configuration is the circulating load, which tends to be relatively high due to the high reduction ratio required for this kind of circuit, demanding handling and classifying high flowrates. As very high circulating loads are deleterious to the circuit performance, a SAG mill test with a modified ball charge was designed to assess such issue. Table 2 compares the two ball size distributions used in testing SAG milling. The one referred as “standard” was used throughout the entire campaign, while the one identified as “finer” was prepared specifically for the test whose results are listed in Table 12. In both cases the JAN sample was used in tests in single-stage SAG circuit configuration (SAGSS).

Table 12 indicates that the SAG circuit throughput for finer ball size distribution test decreased by 2% as compared to standard ball size distribution test. The exceedingly high circulating load of over 800% was successfully decreased to nearly half, for the finer ball size distribution test, but the benefit would need to be balanced against the 10% increase in SSE and a 9% increase in fSAG.

4. Conclusions

A wide range of SAG and AG milling tests were conducted, with circuit configurations covering single and two stage, with and without pebble and pre-crushing, in order to assess the viability of grinding low grade itabirite ores in these circuits compared to the current approach of multistage crushing and ball milling.

The relative efficiencies of the alternative circuits were assessed using the size specific energy (SSE) measured at 75 µm. The fSAG parameter was also used as an alternative measure to provide a rough comparison to expected crushing-milling production values, where values below one indicate a greater efficiency than expected.

The following conclusions were derived from the extensive pilot plant campaign with three different itabirite ores:

- For SAG mill open circuit configuration, coarser feed size distributions resulted in significant reductions in circuit throughput, accompanied by a systematic increase in SSE and fSAG;
- Comparisons with SAG mill closed circuit configuration showed the same trends in throughput and energy efficiency with coarser feed sizes observed for open circuit mode, but the magnitude of changes was smaller;
- SAG milling allows significantly higher circuit throughput compared to AG milling, ranging from 25% to 83% depending upon circuit configuration (open/closed) and grinding mode (AG/SAG). The energy efficiency of AG milling was lower, however, this should be balanced against the benefit of AG milling not requiring the use of steel grinding media;
- AG milling produces a finer product;
- It is possible that in autogenous mode the more competent components, richer in silicates, were ground far finer – due to the greater abrasion component in autogenous milling, leading to the unexpected rise in SSE. Unfortunately, component-by-size data was not generated by which this hypothesis could be tested. It is recommended that this is assessed in future work, as finer grinding of the silicates is not a favorable outcome, from both an energy and recovery perspective.
- Single stage AG/SAG milling required significantly less energy than two-stage circuits;
- Pebble crushing increases throughput and energy efficiency when incorporated in the circuit for the tougher itabirite ore tested;
- Increased SAG mill ball charge from 4 to 16% resulted in only a modest increase in circuit throughput, but a significant reduction in

Table 11
Effect of secondary crushing in SAG milling of JAN in open circuit.

Secondary crushing	Feed			Product		Fresh feed rate (t/h)	Specific energy (kWh/t)		SSE (kWh/t −75 µm)	fSAG
	Top size (mm)	F80 (µm)	−75 µm (%)	P80 (µm)	−75 µm (%)		SAG	Crusher *		
Without	203	126,637	10.8	1.308	40.6	1.46	8.00	–	26.8	2.60
With	102	51,550	11.1	1.535	52.4	1.19	11.10	0.25	26.9	3.99

* Estimated using Bond CWi.

Table 12
Effect of ball size distribution of JAN* in closed-circuit single-stage grinding.

Ball size (Table 2)	Product		Fresh feed rate (t/h)	Specific energy (kWh/t)	Circulating load (%)	SSE (kWh/t −75 μm)	fSAG (–)
	P80 (μm)	−75 μm (%)					
Standard	90	72.8	0.95	12.8	836	20.6	1.12
Finer	95	70.9	0.93	13.6	476	22.6	1.22

* Fresh feed: F80 of 125,637 μm and 10.8% −75 μm.

energy efficiency, demonstrating that a high SAG mill ball load is unfavourable for these ores;

- A truncated feed, mimicking secondary crushing of the SAG feed, was detrimental to the operation, resulting in reduction in both circuit throughput and efficiency;
- Finer ball charge size distribution was beneficial for single stage SAG mill operation, being responsible for 43% reduction in the circulating load in milling, with only a 2% reduction in circuit throughput.
- Based on energy efficiency in terms of fSAG values, values lower than one achieved for three of the softer ores (GAL-IC, GAL-IF and SAP) demonstrate, however roughly, the attractiveness of AG/SAG milling in comparison to multiple stages of crushing following ball milling. The opposite conclusion could be drawn from the tests involving the tougher ore (JAN), since values of fSAG were all higher than one, so that the attractiveness of AG/SAG milling could only be potentially justified on the basis of other criteria, such as circuit simplicity and CAPEx.

In summary, the results of this comprehensive set of pilot test work show that AG/SAG milling is technically feasible and generally an attractive alternative from the standpoint of energy efficiency, for grinding itabirites. Among the circuit configurations/variables studied, the closed single-stage tests were the most attractive in terms of grinding efficiency. However, evidence of slurry pooling, associated with the substantial proportion of fines in the feed, suggest that great care must be exercised on mill discharge design when deploying this circuit configuration at industrial scale.

CRediT authorship contribution statement

Armando F. da V. Rodrigues: Conceptualization, Methodology, Data curation, Writing - original draft. **Homero Delboni Junior:** Writing - original draft, Writing - review & editing. **Malcolm S. Powell:** Supervision, Writing - review & editing. **Luís Marcelo Tavares:** Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Ballantyne, G.R., Peukert, W., Powell, M.S., 2015. Size specific energy (SSE) – Energy required to generate minus 75 micron material. Int. J. Miner. Process. 136, 2–6. https://doi.org/10.1016/j.minpro.2014.09.010.

Bueno, M., Lane, G. 2011, A review of 10 years of AG/SAG pilot trials. In: Proc. 5th Int. Conf. on Semi-Autogenous and High-Pressure Grinding Technology, Canadian Institute of Mining and Metallurgy (CIM), Vancouver, BC, Canada, pp. 1–16.

Bueno, M.P., Kojovic, T., Powell, M.S., Shi, F., 2012. Multi-component AG/SAG mill model. Miner. Eng. 43–44, 12–21. https://doi.org/10.1016/j.mineng.2012.06.011.

Bueno, M., Niva, E., Powell, M.S., Adolfsson, G, Kojovic, T., Henriksson, M., Worth, J., Partapuoli, Å., Wikström, P., Shi, F., Tano, K., Fredriksson, A., 2011a. The dominance of the competent. In: Proc. 5th Int. Conf. on Semi-Autogenous and High-Pressure Grinding Technology, Canadian Institute of Mining and Metallurgy (CIM), Vancouver, BC, Canada, pp. 1–12.

Bueno, M. Powell, M.S., Kojovic, T, Shi, F. Sweet, J., Philips, D., Durant, B., Plint, N., 2011b. Multi-component autogenous pilot trials. In: Proc. 5th Int. Conf. on Semi-Autogenous and High-Pressure Grinding Technology, Canadian Institute of Mining and Metallurgy (CIM), Vancouver, BC, Canada.

França, J.R.O., Barrios, G.K.P., Turrer, H.D.G., Tavares, L.M., 2020. Comminution and liberation response of iron ore types in a low-grade deposit. Miner. Eng. 158, 106590.

Gupta, A., Yan, D., 2016. Autogenous and semi-autogenous mills. In: Mineral Processing Design and Operations, 2nd ed. Elsevier, pp. 263–285. https://doi.org/10.1016/B978-0-444-63589-1.00009-5.

Hagemann, S.G., Angerer, T., Duuring, P., Rosière, C.A., Silva, R.C.F., Lobato, L., Hensler, A.S., Walde, D.H.G., 2016. BIF-hosted iron mineral system: a review. Ore Geol. Rev. 76, 317–359.

Morrell, S., 2004. A new autogenous and semi-autogenous mill model for scale-up, design and optimisation. Miner. Eng. 17, 547–445.

Napier-Munn, T.J., Morrel, S., Morrison, R.D., Kojovic, T., 1996. Mineral Comminution Circuits: Their Operation and Optimization. Julius Kruttschnitt Mineral Research Centre, Brisbane, Australia.

Powell, M.S., Mainza, A.N., Hilden, M., Yahyaei, M., 2015. Full pre-crush to SAG mills – the case for changing this practice. In: Proc. 6th Int. Conf. on Semi-Autogenous and High-Pressure Grinding Technology, Canadian Institute of Mining and Metallurgy (CIM), Vancouver, BC, Canada.

Powell, M.S., Bozbay, C., Kanchibotla, S., Bonfils, B., Musuniri, A., Jokovic, V., Hilden, M., Young, J., Yalcin, E., 2019. Advanced mine-to-mill used to unlock SABC capacity at the Barrick Cortez mine. In: Proc. 7th Int. Autogenous and Semi-Autogenous Grinding and High Pressure Grinding Roll Technology, Canadian Institute of Mining and Metallurgy, Vancouver, BC, Canada.

Rodrigues, Armando F.d.V., 2014. Grinding of Itabirite Iron Ore in Autogenous and Semi-Autogenous Mills. MPhil thesis. JKMRC-SMI, The University of Queensland, Australia.

Segura-Salazar, J., Souza, N., Tavares, L.M., 2018, A holistic pre-feasibility study of comminution routes for a low-grade Brazilian iron ore. In: Proc. 11th Int. Comminution Symp., MEI International, Cape Town, p. 1–11.

Siddal, B., Putland, B., 2007. Process design and implementation techniques for secondary crushing to increase milling capacity. In: SME Annual Meeting. Feb. 25-Feb. 28, 2007, Denver, CO, USA.

Siddal, B., Henderson, G., Putland, B., 1996. Factors influencing sizing of mills from drillcore samples. In: Proc. 2nd Int. Conf. Autogenous and Semi-Autogenous Technology, Vancouver, UBC, p. 463–480.

Tavares, L.M., da Silveira, M.A.W., 2008. Comparison of measures of rock crushability. In: Yekeler, M., (Ed.), Fine Particle Technology and Characterization. Research Signpost, pp. 1–20.