A SCALE UP MODEL FOR HPGR HARD ROCK GRINDING[1]

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Abstract

Vale, one of the largest mining companies in the world, has prioritized the development of HPGR technology for practical application in its current projects. An existing population balance model for the HPGR has been evaluated under distinct grinding conditions for one feed material. The effect of grinding pressure, feed size distribution and the presence of water was investigated. The population balance model response showed a clear dependency of product size distribution with specific grinding pressure. As a result, specific grinding pressure was incorporated into the PBM, allowing for predicting product size distribution at practical values of this important parameter. Based on this result, a characterization procedure was envisaged so as to produce PBM and scale-up parameters for the model. The procedure does not require slow compression tests, and all of the testing can be carried out in an expedited form in an instrumented bench scale HPGR, using small samples of about 10 kg. The only analyses required are size distributions. The PBM model was implemented in the Modsim™ plant wide simulator, with facilities for scaling-up HPGR operations.

Key words: Simulation; Modeling; Comminution; Iron ores; HPGR.

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1 INTRODUCTION

Scaling up an HPGR mill is fairly easy and the technology is well established. However, in hard rock applications, it is only logical to use HPGR grinding in closed circuit with a vibrating screen. This pre-scalps the material that is already sized to specification, usually ball mill feed, avoiding the extra tonnage through the HPGR, with better utilization of capacity. At the same time, the screen closing the circuit with the HPGR guarantees product top size, which cannot be accomplished with the HPGR operating in open circuit, unless under very special circumstances. In order to scale up an HPGR operation in closed circuit with a vibrating screen, it is necessary to determine the size distribution in the feed stream to the HPGR, as well as the tonnage. This will be a function of the grinding properties of the material, and the only sensible way to make the required calculations is by simulation. In turn, simulation requires a model for HPGR grinding that is capable of predicting the size distribution in the product given the operational conditions (grinding pressure, machine dimensions) and the size distribution in the feed. In other words, simulation requires a population balance model for the HPGR.

A suitable population balance model for HPGR grinding has been developed, and calibrated against pilot scale grinding tests.[1,2] The model includes the capability of predicting the size distribution that is produced at varying levels of grinding pressure.[3] The nature of HPGR grinding is such that capacity and grinding power vary with grinding pressure as well. This implies that the operating grinding pressure must be specified in order to simulate the HPGR unit, and to scale up for power and capacity. This imposes an additional problem. The amount of circulating load is controlled by the product size distribution that is produced in the HPGR unit, so it is necessary to match the capacity of the unit by changing other operational variables such as roll diameter and length or roll speed. Power calculations follow once capacity is properly matched. This system works well in a simulation environment. The technical details involved in the characterization of an ore for HPGR grinding scale up are described here.

2 SCALE UP OF CAPACITY AND POWER

Austin and Trubelja[1] discussed a scale-up procedure based on a dimensionless specific capacity factor. The alternative to this is Seebach and Knobloch specific throughput rate.[4] The preferred method here is the use of a dimensionless specific capacity factor. In fact, the scale-up of capacity is described in detail in a joint paper by Austin, Trubelja and Seebach with all the relevant details such as the calculation of the critical angle of nip, assumed to remain constant between the industrial mill and the bench scale mill.[5] There are two methods available for scaling up power. The first method is based on a dimensionless specific power factor. The method, credited to Guevara and Menacho, is described by Austin et al.[5] The alternative is to assume that the force acting angle remains constant in the test and in the industrial scale HPGRs, as described in Klymowsky et al.[6] This is a good assumption, and it should hold when the critical angle of nip is machine independent. There is one advantage of the Guevara and Menacho method: they provide a correction factor based on the F80 (80% passing size) of the feed material in the test and the industrial mills. This is important because the industrial feed size distribution cannot be tested in the bench scale mill, with a feed top size usually < 12mm. Unless pilot scale tests of the larger feed sizes can be performed, the recommendation is to use the Guevara and Menacho dimensionless specific power factor and their correction for feed size.

The dimensionless specific capacity factor here is **not** defined as the traditional $\dot{m}$ found in the literature and adopted by the manufacturers. For this model, the specific capacity factor is defined as the dimensionless *m*:

$$m = \frac{Q}{\rho u D L} \tag{1}$$

Where:

m = specific capacity factor
Q = production in kg/s
ρ = sample density in kg/m^3
u = roll peripheral velocity, in m/s
D = roll diameter
L = roll length

The specific power factor is defined as

$$p = \frac{\Psi}{uDLP} \tag{2}$$

Where:

p = dimensionless specific power factor
Ψ = grinding power, in Watts
P = Grinding pressure, in Pascal

The grinding power is the power used for grinding only. To calculate grinding power, simply subtract no-load power from the total power measured in a given grinding test. No-load power should be constant for a given test mill. The grinding pressure is defined as the grinding force divided by *DL* so the specific power factor is in fact only a function of the grinding force applied, the peripheral roll velocity, and the observed grinding power.

The values of p and m vary with grinding pressure. If a set of HPGR grinding experiments is carried out at several grinding pressures, the values of p and m can be plotted against grinding pressure, and the trend can be easily modeled using an empirical function with few parameters. This can be easily accomplished in an Excel® spreadsheet, for example, using the trend line graph function. Capacity and power can therefore be calculated for any roll size and speed given the desired operating grinding pressure. Guevara and Menacho's power correction can then be calculated if the values of P80 are known for both, the test material and the simulated mill feed.

There is one additional operating variable that is required in order to simulate the industrial mill. This is the value of the operating gap, and it is required because it controls the probability of breakage by direct roll contact for particles that are larger than the operating gap. In order to estimate the value of the operating gap in the industrial mill, a set of equations that can be derived from geometrical consideration can be used.

The critical angle of nip is assumed constant for the industrial and the test roller press. It is defined as

$$\cos\alpha_c = \frac{x_g \rho_g}{\bar{\rho} x_c} \tag{3}$$

Where:

x_g = grinding gap
ρ_g = apparent density of particle bed at the gap
x_c = gap at the critical angle of nip
$\bar{\rho}$ = feed apparent density

The critical angle of nip can be measured for a given grinding test, and the values plotted against the specific grinding pressure. This allows for calculating the critical angle of nip in the range of grinding pressures obtained in the experiments, using the same strategy to model p and m. In order to calculate the critical angle of nip, it is necessary to measure the bulk density of the feed material used for the test machine. The grinding gap can be measured directly for each grinding test. The gap at the critical angle of nip is calculated from the following expression:

$$x_c = 0.5\left\{\left(D + x_g\right) - \left[\left(D + x_g\right)^2 - \frac{4\rho_g D\, x_g}{\bar{\rho}}\right]^{0.5}\right\} \tag{4}$$

Finally, the apparent density of the particle bed at the gap can be calculated from:

$$\rho_g = \frac{Q}{uLx_g} \tag{5}$$

To simulate the industrial mill, one must define the grinding pressure. This is usually a value between 1 and 6 MPascal for most operations. The critical angle of nip, as well as the scale-up factors *m* and *p* are a function of grinding pressure, so whenever the grinding pressure is changed, these parameters must be correspondingly adjusted.

3 EXPERIMENTAL

A series of six grinding tests were carried out with compact Itabirite from Conceição as feed at the Vitoria grinding laboratory using the Polysius™ bench scale 250mm x 100mm rolls roller press. The tests were designed to produce increasing specific grinding pressure. Table 1 shows the initial test conditions.

Table 1 Test conditions for all samples

Feed sample dry weight, g	10000
Water content, %	0
Feed sample density, kg/m^3	4133
Feed sample bulk density, kg/m^3	2480
Feed method	Choke feed
Roll diameter (D), mm	250
Roll length (L), mm	100
Factor for converting oil pressure into grinding pressure (*)	2.0
Initial gap, mm	1.0
Rolls surface	Studded, worn
Stud height, mm	0.8
Fraction of roll surface covered by studs	0.45
Roll speed (u), m/s	0.33
Roll speed (ν), rads/s	2.64
No load power, kW (**)	2.02

(*) Oil pressure is usually given in BAR, as this is the unit used by the data acquisition system. This is readily converted to MPascal by

$$P^{Oil}_{MPascal} = 10 \times P^{Oil}_{(BAR)} \tag{6}$$

as 10 BAR = 1 MPascal. Specific grinding pressure is defined as the force, produced by the hydraulic system per unit area of roll face. That is:

$$P = \frac{F}{DL} \tag{7}$$

were D is roll diameter and L is roll length. As P is usually given in MPascal, and F in kN, Eq. (7) has to be converted from straight S.I. units to

$$P = \frac{F}{1000DL} \tag{8}$$

As the hydraulic system is particular to every machine design, a conversion factor must be provided by the manufacturer for converting oil pressure from the hydraulic system into specific grinding pressure. For the Polysius™ bench scale machine, the factor is 2.0 as shown in Table 1. Therefore, oil pressure can be converted into specific grinding pressure by:

$$P_{(MPascal)} = 2 \times 10 \times P^{Oil}_{(BAR)} \tag{9}$$

Polusius™ frequently uses N/mm^2 when referring to specific grinding pressures and MPascal when referring to hydraulic pressures. These are equivalent, and 1 N/mm^2 = 1 MPascal. In this work, the convention adopted is to use MPascal for all pressures, and to indicate hydraulic pressure with the *Oil* superscript.

(**) No-load power is defined as the power, in kW, required to turn the two rolls at the roll velocity specified for all grinding tests, with no feed. Under these conditions, bearing pressure is minimal, and grinding force is null. For this test mill, each roll consumes about 1 kW of power to turn at 0.33 m/s (roll peripheral velocity u). The resulting no-load power is about 2 kW.

The compact itabirite from the mine was crushed to below 150 mm at Vale's Mariana Center of Technology. This was a large sample of several tons of ore. A 30 ton portion was separated for HPGR testing in Vitoria, for both pilot and bench scale testing. The maximum feed size for pilot scale HPGR testing is 32mm so the entire lot was further crushed below this size using a 32mm screen in closed circuit with a jaw crusher. A smaller portion of the resulting feed, about 500 kg, was then crushed below 10mm for bench scale HPGR testing.

The objective of this test work in particular is to design a roller press to partially replace secondary crushers, and completely replace the tertiary crusher stage, producing -10mm feed for a ball mill circuit. Running the industrial roller press in open circuit does not guarantee top size, so it is clear that the industrial roller press, would be in closed circuit with a 10mm vibrating screen. If one designs such circuit, it becomes immediately clear that the feed to the industrial roller press should be scalped, thus increasing capacity and power draw and probably increasing performance. If the application calls for scalped feed, then the samples to be tested should also be scalped. There are no criteria to decide how the samples for testing in the bench roller press should be scalped, so a decision was made by common sense to use a similar top size/scalping size ratio for both industrial and bench scale machines. For the industrial roller press the top size of the feed material should be at least 30 mm and the scalping size is, by design, 10 mm, because this is the top size of the feed to the ball mill circuit. The top size of the sample for the bench scale machine is 10mm so the feed test samples should be scalped at about 3.4 mm in order to maintain a constant ratio.

It is not required to scalp the test feed samples very precisely, and in fact the industrial screening operation is designed for a screening efficiency of about 90%. This is the type of efficiency that is required for scalping the test feed samples. Besides a better emulation of the industrial conditions, it is much easier to prepare scalped samples with a higher level of contamination of fines.

The test program consisted of six identical scalped samples of compact itabirite prepared in a size range of -10+3.4mm, to be ground at initial oil pressures of 10, 20, 30, 40, 50 and 60 BAR, in order to produce a sequence of product size distributions at increasing grinding pressures.

4 RESULTS

The measured operating variables, grinding power, specific grinding pressure, grinding time and operating gap resulting from each test are shown in Table 2.

Table 2 Measured operating variables.

Initial oil pressure, BAR	Grinding power, kW	Specific grinding pressure P, MPascal, eq. (4)	Grinding time, s	Grinding gap, mm x_g, eq. (5)
10.74	1.96	1.34	9.49	8.95
20.06	2.61	2.09	10.10	8.82
30.11	3.18	3.04	10.69	8.44
40.74	3.69	3.71	11.94	8.01
50.79	4.08	4.48	12.32	7.89
60.06	4.66	5.13	12.72	7.82

In Table 2 Table 2 **Measured operating variables.**the initial oil pressure is not to be confused with hydraulic grinding pressure. The initial pressure is manually set prior to the tests, and it is difficult to get exactly the designed pressure for each test. The actual values of initial oil pressure are listed so that the increase in pressure can be calculated, although this is not really necessary here, and the important result is the operating grinding pressure that is achieved from each initial hydraulic pressure setting.
The trend lines that describe the variation of m, p and α_c with grinding pressure are shown in Figures 1 to 3.

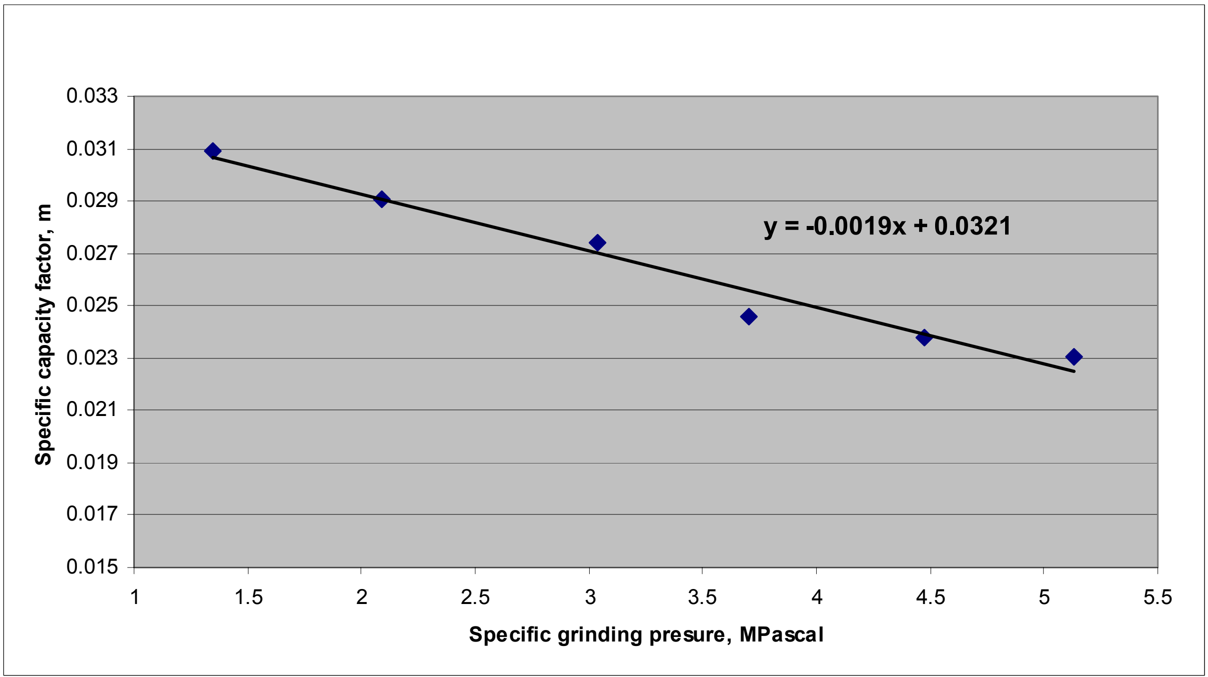

Figure 1: variation of the specific capacity factor with grinding pressure and calculated trend line.

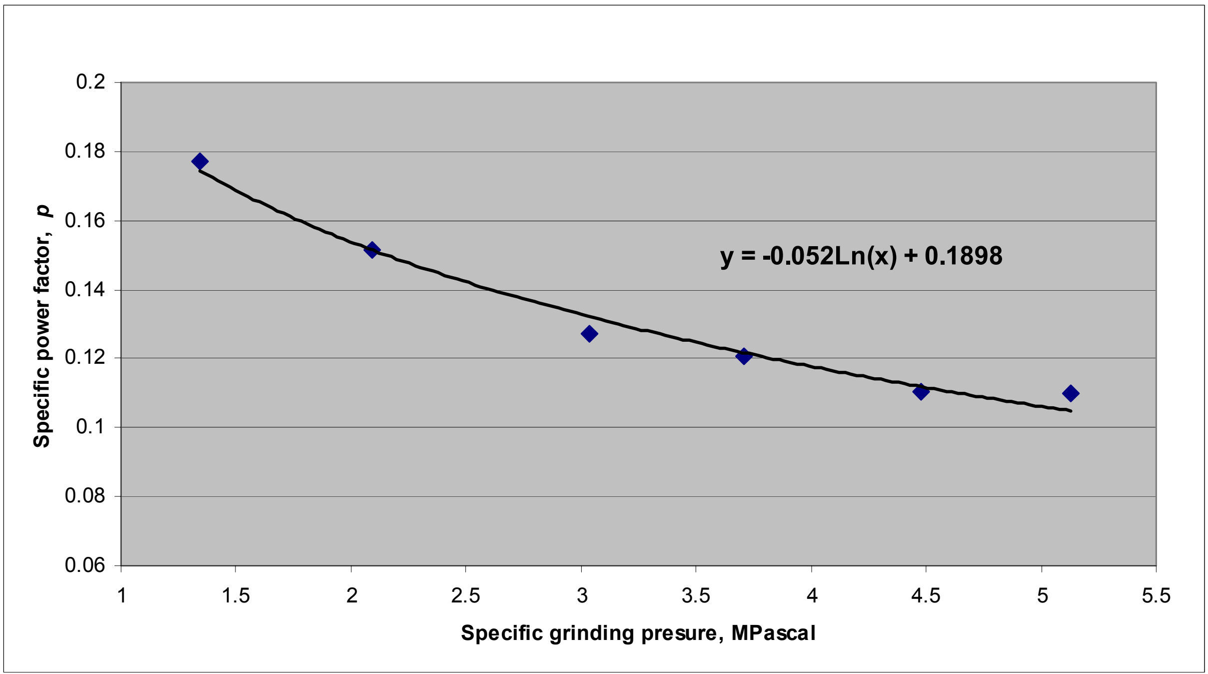

Figure 2: variation of the specific power factor with grinding pressure and calculated trend line.

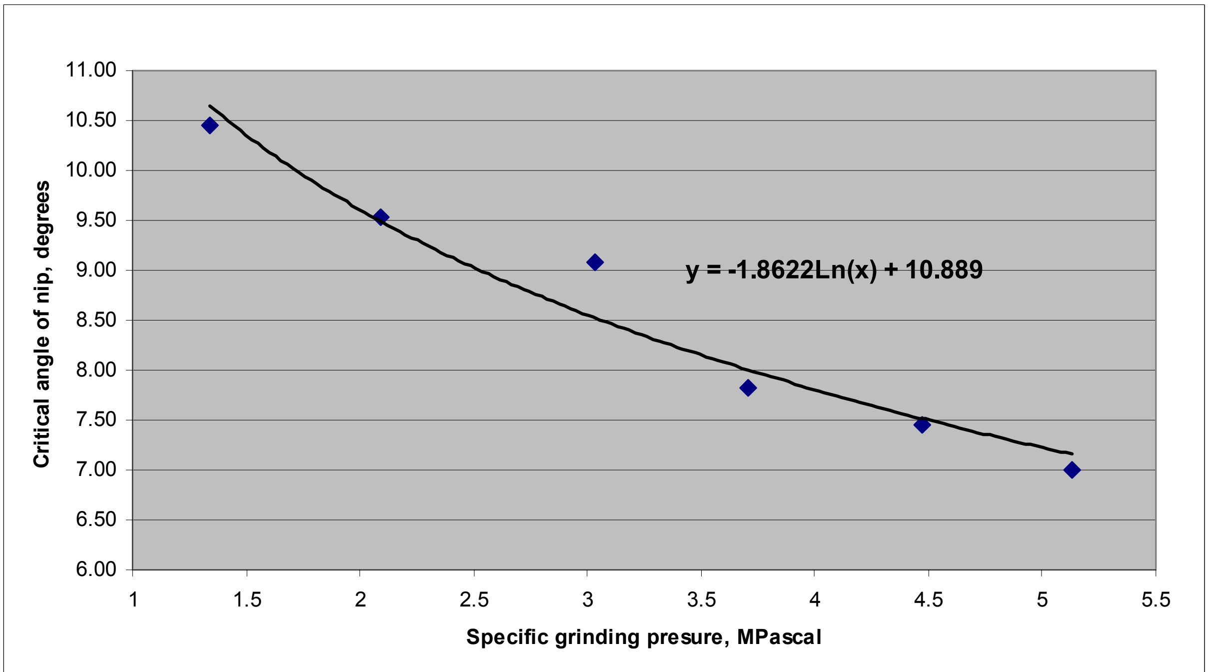

Figure 3: variation of the critical angle of nip with grinding pressure and calculated trend line.

The values in Figures 1 to 3 can be calculated from the data provided in Tables 1 and 2 and equations (1) through (5). The model trend lines do not need to be of any pre-specified form, and in this case it turned out that the capacity is best described by a linear regression while power and nip angle are best described by logarithmic functions. The important aspect of the results is that the two scale up parameters and the critical angle of nip can be calculated for any grinding pressure in the range of 1 to 6 MPascal. The critical angle of nip is required to estimate the operating grinding gap for the industrial mill, which in turn is a model parameter for direct roll breakage of large particles.

5 DISCUSSION AND CONCLUSIONS

A set of six grinding tests in a bench scale HPGR have been used to demonstrate how the data produced in each grinding test can be organized in terms of specific grinding pressure. If an arbitrary grinding pressure is defined for the operation of an HPGR machine of any size, scale up parameters can be calculated as well as the operating gap that is going to be produced, provided that:

1. The roll surface characteristics of the industrial machine are similar to that of the test mill.
2. The sizing of the feed particles to the industrial machine is similar to that used in the test machine, especially with respect to the top size considered and if scalping prior to grinding will take place.

As particle size distribution changes, bed cohesion changes accordingly. This is sometimes referred to as internal friction factors and is an important property that influences the grinding forces that are produced, the gap and consequently power, capacity and size distribution in the product. In cases where the feed contains significant amounts of fines, adding water can change bed cohesion significantly, resulting in completely different grinding and scale up parameters.

In addition to the scale up factors and critical angle of nip, population balance parameters are required for simulation. These can be derived by analyzing the size distributions that are generated in each grinding test. Fortunately, the population balance model parameters do not vary with grinding pressure[3].

A user interface has been implemented in Modsim™. The simulator calculates the capacity of the industrial roller press, and reports the number of units required to attend the simulated feed rate. If this number is smaller than one, a smaller press is required, or, alternatively, the rolls speed can be reduced, or both. If the calculated number of presses is larger than one, a larger press is required, or the roll speed is increased or both. Increasing rolls speed increases power and has the undesired side effect of reduced liner life. Attention should be paid to the maximum roll speed recommended by the manufacturer. Also important, liner life should be taken into consideration when scaling up. The procedure is complete when the number of presses required is equal to one. This is usually achieved in less than five simulations.

Grinding power is reported but care should be taken when specifying motor power as grinding power does not include no-load power. Power transmission efficiency factors and power factor for a given installation may vary significantly. Currently, there is no model to predict no-load power implemented in the simulator.

This system is not limited to hard rock grinding and closed circuit grinding. The procedure should be general enough so that it can be applied in most configurations, including open circuit and pellet feed grinding, as well as other ores and materials. Research and development should continue with a few case studies in order to confirm the model, and to determine the most appropriate sample preparation procedure for each case.

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