Evaluation of the Operational Parameters during the Start-up of the Neves-Corvo AG/SAG Mill

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Abstract

Being the Mining Industry one of the main industry sectors responsible for the development of societies since the beginning of time to the present day, the need to have available resources for a constantly growing world population is increasingly important.

In order to meet the constant needs of essential metals for society, it is increasingly necessary to have more efficient mines with greater production capacity. This efficiency and greater production capacity involves the installation of larger equipment and also the reduction of downtime. One of the equipment's used in the largest mines in the world and which allowed significant increases in production and shorter downtimes due to other equipment, are the AG/SAG mills.

This document aims to analyze the data obtained during the commissioning and start-up of the AG/SAG mill in Neves-Corvo and to verify correlations between operational parameters in order to optimize its operation.

With the completion of this Dissertation, it was possible to verify that the best way to verify correlations between operational parameters is the use of multiple regressions, due to the complexity of the operation of an equipment such as an AG/SAG mill.

Finally, it is concluded that a good knowledge of the operational parameters of an AG/SAG mill is extremely important for the optimization of a circuit.

It is also important to mention the importance of the continuation of this study for future operating campaigns of the mill.

Keywords: AG/SAG Mill; Optimization; Correlation; SOMINCOR; Zinc

1. Introduction

Being the Mining Industry one of the main sectors responsible for the development of societies from the beginning of time to the present day, the need to have available resources for a constantly growing world population is increasingly important.

In order to meet the constant needs of essential metals for society, it is increasingly necessary to have more efficient mines with greater production capacity. This efficiency and greater production capacity involves the installation of larger equipment and also the reduction of downtime. One of the equipment used in the largest mines in the world and which allowed significant increases in production and shorter downtimes due to other equipment's, are the AG/SAG mills. The size of these equipment's allows to increase production in a way that other mills would not allow. The fact that this type of equipment allows the removal of other equipment upstream, such as crushing circuits and other mills, considerably reduces operating costs and downtime for maintenance of other equipment. The versatility of AG/SAG mills, allowing them to function both as Autogenous and Semi-Autogenous grinding, are another factor that makes this one of the most used equipment in the mining industry worldwide.

As SOMINCOR is part of one of the world's largest mining groups, Lundin Mining, as a strategy to increase its zinc production, decided to install an AG/SAG mill and expand its mining facilities and the existing Zinc Processing Plant. This expansion consists of the installation of new conveyor belts with a total length of about 3 km and a new crushing station. In the surface, beside the addition of the new mill, new flotation cells were also installed.

As the new AG/SAG mill is the new heart of the Neves-Corvo Zinc Processing Plant, this work was intended to seek relationships between operating parameters in order to better understand its operation and in the future optimize its operating parameters, helping to obtain of better results.

1.1 Grinding Circuits with AG/SAG Mills

AG/SAG mills are applied to competent ores, that is, ores that do not degrade easily and that guarantee reasonable energy consumption considering that consumption in this type of milling is higher than in conventional milling. The option for semi-autogenous mills is due to the fact that they are less susceptible to variations in the ore. (Beraldo, 1987)

These mills are applied in single-stage milling or as a primary mill preceded by a ball mill or a vertical mill to perform secondary milling.

The main grinding circuits currently used in the industry are shown in Table 1.

Table 1: Principal Grinding Circuits. Source: Adapted from (Beraldo, 1987)

Circuit	Description
Rod Mills in Open Circuit	Applied to coarse grinding with the product's particle size in the order of 1 mm or more
Single Stage Ball Mills	Very common in copper ore, efficient only when preceded by fine crushing (10 to 15 mm)
Single Stage AG/SAG Mills	Not very common due to not being energy efficient
Open circuit Rod Mills preceded by closed circuit Ball Mills	It is the most energy-efficient circuit, however, the one that requires the greatest investment. Its control is easy and allows feeds with grain sizes from 25 to 30 mm
AG/SAG mills followed by closed circuit ball mills	They represent a low investment, as it avoids the costs inherent to fine crushing, energy consumption is reasonable and metal consumption is lower, however, they are conditioned by the ore's characteristics.
A-B-C Circuit: AG Mill, Crusher and Ball Mill	The crusher is used to crush the critical sizes of the autogenous mill. This option makes it impossible to use SAG mills as the grinding load would damage the crusher

1.2 Advantages of Autogenous Grinding

Circuits consisting of SAG mills / high-capacity ball mills predominate for their contribution to substantial savings in capital and operating costs, which, in turn, enable low-grade, high-tonnage operations, such as copper and gold ores.

In addition, these types of circuits have several advantages over conventional circuits, namely greater versatility, in the case of AG mills, less wear on the linings, since no grinding load is used, lower operating costs, as it is not It is necessary to purchase grinding load or this quantity is smaller compared to conventional mills, allows the processing of larger tonnages and, since crushing/milling steps are eliminated, it avoids maintenance costs. (Markstrom, 2020)

1.3 AG/SAG Circuits Optimization

The search for optimization of AG/SAG circuits must be a constant process that aims to maximize efficiency whose criteria vary from circuit to circuit, however, it is imperative to optimize the following points regardless of the circuit:

• Knowledge of the mechanical and electrical characteristics of the mill:

o Dimension: both the interior of the shell and the liners that must be regularly measured in order to monitor their wear;

o Discharge liners parameters: grates opening, open area and location of openings in order to control pulp discharge; grates opening must also be monitored as it is subject to wear;

o Motor capacity: verification of the maximum power admitted by the motor to monitor mill overloads;

o Instrumentation: the most effective method of monitoring the performance of the mill, which allows obtaining operational data for momentary actuation and/or acquisition of a database that allows the study and prediction of the mill's behavior. The most used instruments are scales, load cells or pressure sensors in bearings, power indicators, flow meters, density meters and particle size analyzers.

• Feed: the feed rate is limited by the volume and power of the mill and is also influenced by the mill speed which, in case the load is to be kept constant, when it increases, it requires an increase in the feed rate.

• Product particle size: the manipulation of all the parameters including the opening of the discharge screens, the quantity and size of the grinding charge, the speed and power of the mill and the feed rate contribute to a certain particle size of the final product that will be the purpose of the process in question. An efficient classification of the product is also crucial as it avoids the return of unwanted particles and by manipulating the particle size distribution it is possible to obtain different feeds and consequently different products. When dealing with a circuit consisting of two fragmentation stages, the optimization of the feed in the AG/SAG mills and of the product in the second stage must be privileged.

• Energy consumption: The specific energy consumption (kWh/t) is a measure of process efficiency because, despite being dependent on the type of ore, it is also influenced by the feed particle size, load, mill speed and grinding load that the higher it is, the lower the energy consumption, having as a negative consequence the wear of the liners.

The optimization of process parameters should be seen as a set because there are relationships between them, which largely affect the final result. Simulation techniques also allow studying the behavior of the ore and predicting the characteristics of the final product. (Napier-Munn, 1996)

2. Zinc Expansion Project (ZEP)

The Zinc Expansion Project (ZEP) arose from Somincor's need to increase its Zinc production with the discovery of the North and South Lombador deposit.

Several prospecting campaigns were carried out in order to characterize the discovered deposit, which showed high levels of Zinc, although located at a depth of 1000 to 1200 meters.

Once the studies for the characterization of the Lombador deposit were concluded and the economic and financial analysis of what would become the ZEP had been carried out, it was decided to proceed with it. ZEP not only includes modifications at the level of the mine's bottom structure, but also at the level of modification and construction of new surface installations.

The main modifications at the bottom level of mine included:

• A new crushing at level 260 to accommodate the increased production of Lombador.

• A new conveyor belt system, responsible for linking the new level 260 crushing to the current system. This new conveyor belt system consists of 3 conveyors, each approximately 1 km long.

Regarding the necessary surface modifications, the PEZ includes:

• Construction of a new building for the installation of an AG/SAG Mill (object of study of this Dissertation);

• Construction of a new building for the installation of new flotation cells (100 m3) (Figure 12);

• Installation of new Float cells (100 m3) in the Existing Zinc Processing Plant;

• New Tailing Cyclones installation;

• Installation of a new Tailings Thickener at the Cerro do Lobo plant;

• Installation of new concentrate filters.

2.1 Zinc Processing Plant – ZEP Configuration

With the conclusion of the Zinc Expansion Project (ZEP) the zinc processing plant will undergo some changes, not in relation to the products obtained (Zinc and Lead Concentrate) but in its configuration and treatment capacity.

In its final configuration, the Zinc Processing Plant will have the capacity to process 2.5 mtpy. The circuits will be divided as follows: Main Circuit for Lead and Main Circuit for Zinc. At the time of writing of this dissertation, the RZ circuit is not considered and only half the amount of lead that enters the processing palnt is considered, called “Half Pb”. Lead that is not processed is directly sent to final tailings.

For planning reasons, it was decided to divide the Project into several phases: Phase 1A and 1B, Phase 2 and finally Phase 3. The differences between the 3 phases are predicated on the equipment that is put into operation as its construction and commissioning are completed. Phase 1B (Figure 1) focus of this dissertation, is characterized by the operation of the AG Mill fed by Zinc ore, with a feed in the order of 140-150 t/h feeding the Zinc Processing Plant in its current configuration, with one of the existing Vertimill functioning as secondary milling. During this phase, the maximum tonnage is limited to the aforementioned 140-150 t/h, as there is a limitation on the treatment of the Zinc Plant in the current configuration. This limitation ceases to exist once the new flotation cells installed by ZEP are in operation. In addition to the fluctuation limitation, there is also a limitation at the Tailings Cyclones level, which will be overcome with the entry into operation of the new ZEP Tailings Cyclones Facility.

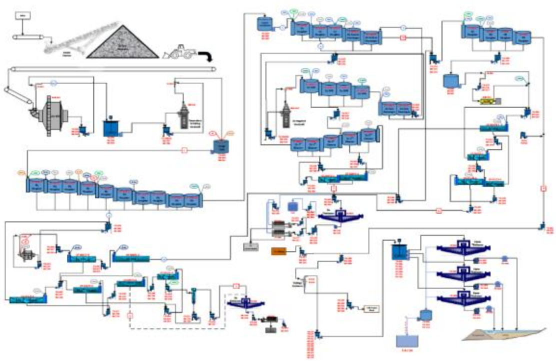

Figure 1: ZEP Phase 1B flowsheet

2.2 Grinding Circuit – ZEP Configuration

With the start of ZEP, the Zinc ore from the mine, crushed by Primary Jaw Crushers to granulometries <200 mm, is placed through a Stacker Radial in a new ore park, with a capacity of 30,000 tons of Zinc Ore.

The Zinc ore stored in a pile in this new ore park is transported through a Loader to the Feeding Hopper of the AG/SAG Mill Feeding Conveyor (Figure 2). This hopper is equipped with an Apron Feeder which serves as a buffer against the impacts of the ore discharged into the hopper, in addition to controlling the discharge to the AG/SAG Mill Feed Conveyor.

Figure 2: AG/SAG Mill Feeding Hopper

The AG/SAG Mill Feeding Conveyor discharges the zinc ore into the mill (Figure 3), where it will be autogenously ground, without recourse to grinding load. As mentioned above, the maximum feed size (F100) is 200 mm and an F80 of 150 mm. In the case of AG mills, the feed size and the particle size distribution curve are of great importance for the correct and better performance of the mill. If there is not a good particle size distribution, efficient grinding will not be achieved, as there will not be ore with the necessary size to grind the rest.

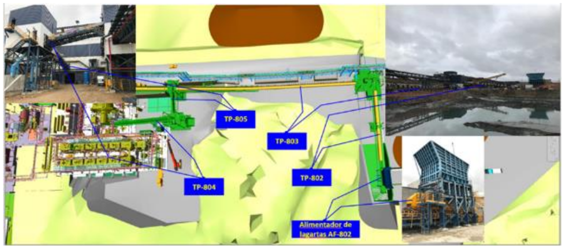

Figure 3: AG/SAG Mill Material Handling Circuit

2.3 AG/SAG Mill Control Philosophy

Changes in ore composition (hardness and/or particle size) in the mill feed have a major impact on the efficiency of autogenous grinding. The composition of the ore has a direct impact on the processing capacity and also on the size of the mill product.

Controlling the mill load is essential for stabilizing the flow and particle size of the mill product. The mill load can, within some limits, be mostly controlled via the mill rotation speed or else via the feed rate. The addition of water to the mill and the circulating load (underflow of cyclones) also significantly influence the mill load.

1. Mill load control by varying the rotational speed.

a) Feed rate in manual operation mode (auto);

b) Mill load is controlled by automatically varying the mill rotation speed;

i. Manual set-point of the mill load;

ii. The mill load set-point must be adjusted in order to obtain the desired particle size in the overflow of the primary cyclones or the specific desired energy consumption (kWh/t);

c) If for any reason the grinding process is unstable:

i. An operating range for speed can be defined through a maximum and minimum value (OutHigh and OutLow);

d) Mill feed control cycle activated in order to reduce fresh feed if load or torque on the motor is close to reaching their maximum values, see point 3 below.

2. Mill load control by varying the feed rate;

a) Feed rate in automatic operating mode;

b) Mill rotation speed in manual mode;

c) Manual set-point of the mill load;

i. The load is controlled by changing the feed rate;

ii. The rotational speed and mill load set-points will be adjusted in order to obtain the desired particle size in the overflow of the primary cyclones or the specific milling energy consumption (kWh/t).

d) Mill feed control cycle activated in order to reduce fresh feed if load or torque on the motor is close to reaching their maximum values, see point 3 below.

3. Mill feed control cycle activated in order to reduce fresh feed if motor load or torque is close to reaching their maximum values;

a) Torque limit set-point for equipment protection, it is normally not changed;

b) Max/High torque set-point, can be changed by the operator;

c) Load limit set-point for equipment protection, normally not changed;

d) Max/High load set-point, can be changed by the operator;

e) Logic selector for Min. value for load and torque in order to provide external set-point to mill feed control.

4. Torque control, the aim is to control the torque through power variation (in theory power control, but through the torque set-point);

a) Torque set-point defined by the operator;

b) Feed rate in automatic operating mode;

c) Mill rotation speed in manual mode.

5. Feed rate and mill rotation speed in automatic operating mode;

a) Feed rate and mill rotation speed vary depending on established limits;

i. Maximum limit value for torque is defined, see 3a;

ii. Maximum limit value for mill load is set. See 3c;

iii. An operating range for the load is defined with a maximum and a minimum value;

iv. A maximum set-point is defined for motor torque and mill load respectively;

v. The mill will ramp up and run at its full speed when torque or load is limiting the feed rate;

saw. The mill will operate with variable speed in order to control the load when the feed reaches its maximum value.

3. Results and Data Analysis

The data collected for the development of this work, comprise the period of operation of the AG/SAG Mill during phase 1B of ZEP. The operating period is between the 14th of January and the 25th of March. Since the mill's operating period was not continuous in this date range, having only worked about 8 full days, it is these full operating days that will be considered for this work. Another consideration for the analysis and discussion of results was the decision to perform only the analysis of data referring to the operating days in January, since it includes the largest number of days, about 5.

The parameters analyzed in this dissertation are as follows:

• AG/SAG Mill Current (A);

• AG/SAG Mill Power (kW);

• AG/SAG Mill Rotation Speed (% critical speed);

• Dilution and washing water flows (m3/h);

• Primary Cyclone Feed Flow (m3/h);

• Percentage of Solids from Primary Cyclone Feed (%);

• Specific Energy Consumption of AG/SAG Mill (kWh/t);

• AG/SAG Mill Fresh Feed Flow (t/h);

• Pebbles recirculation (t/h);

• Interior Load of AG/SAG Mill (t);

• AG/SAG Mill Torque (N.m);

• D80 Primary Cyclones (µm);

• D80 Feed Mill AG/SAG (µm).

Of this vast set of parameters for which data were collected, only a few will be used, since making an exhaustive analysis of all would make this work too extensive.

In order to better organize the analyzed parameters, they were divided into 3 categories: manipulable variables, controllable variables and even monitorable variables.

It is also important to point out that the data collected were collected during the commissioning and start-up phase of the AG/SAG mill, that is, much of the instrumentation was still in the calibration phase, another was not operational yet and the circuit did not reach stability.

3.1 Torque vs. Internal Load Regression Model

The simple regression curve between Torque and Internal Load can be seen in . According to the theory, torque should increase whenever certain conditions are met: if the load center is further away from the mill center, if the mass of the charge increases and if the mass increases due to the increase in density of the ore.

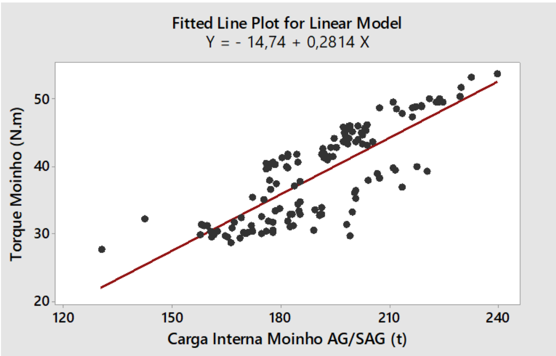

Figure 4: Simple Regression Curve for Torque vs. Internal Load

Figure 5 shows that there is a clear statistical relationship between Torque and Mill Load, with a p-value less than 0.05, more specifically 0.001.

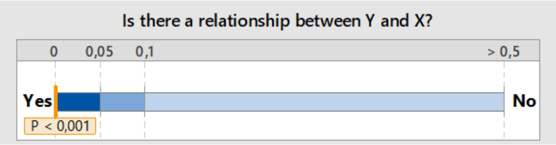

Figure 5: Statistical Significance of the Relation between Torque and Internal Load

Figure 6 shows that the R^2 of the regression model is equal to 63.96%, meaning that 63.96% of the torque variation in the mill can be explained by the internal load.

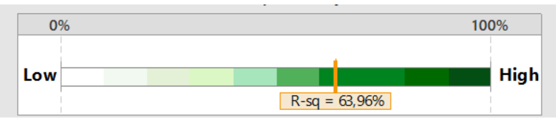

Figure 6: Variation % Explained by the Regression Model

It is also possible to observe through Figure 7 that there is a clear positive correlation between Torque and Mill Internal Load (r=0.80). This means that when the internal load of the mill increases, the torque also tends to increase, corroborating what the theory claims.

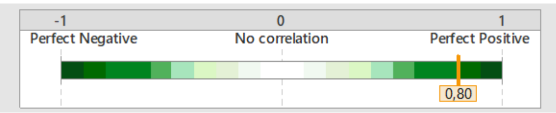

Figure 7: Correlation between Torque and Internal Load

3.2 Torque vs. Internal Load, Pebble Recirculation, Primary Ciclones UF Dilution Water and AG/SAG Mill Feed Chute Water Multiple Regression Model

Figure 8 shows the statistical relationship between Torque and the other variables considered for the regression model. With a value of p<0.001, there is a statistically significant relationship between Torque and the other variables used.

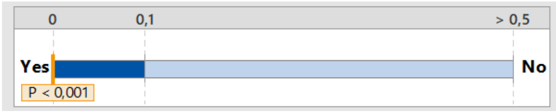

Figure 8: Statistical Significance of the Relation between Torque and the other variables

Observing Figure 9, it is possible to conclude that a high percentage (85.99 %) of the variation in the Mill Torque value can be explained by the obtained regression model.

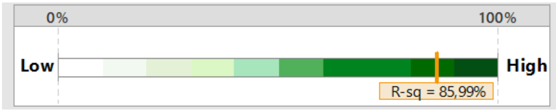

Figure 9: Variation % Explained by the Regression Model

In Figure 10, it is possible to observe the individual impact of each variable used, on the mill torque value. As can be seen in the figure, the variable that most influences the mill torque value is the internal load, something that can be confirmed in Figure 11, where the mill load is the most responsible for the increase in the percentage of R^2.

The multiple regression presented here, confirms what had already been obtained through the simple regression between Torque and Internal Load, where it was clearly observed that the increase in the mill's internal load had a considerable influence on the Torque value.

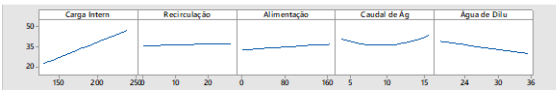

Figure 10: Influence of the considered variables in mill Torque

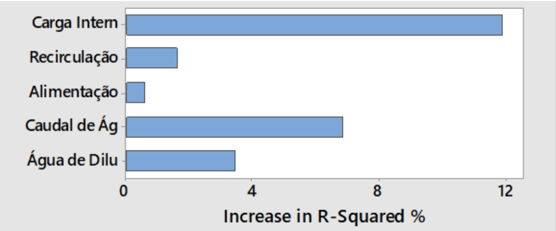

Figure 11: Incremental Impact of the considered variables in Mill Torque

Through this multiple regression model it was possible to obtain the following equation (1).

$$\begin{aligned} Mill\ Torque = {} & 90.3 - 0.0276\,X1 \\ & + 1.925\,X2 \\ & - 0.4432\,X3 \\ & - 5.660\,X4 - 1.606\,X5 \\ & + 0.1609\,X4^2 \\ & - 0.00974\,X1 \times X2 \\ & + 0.002466\,X1 \times X3 \\ & + 0.1122\,X4 \times X5 \end{aligned} \quad (1)$$

Being:

X1: Mill Internal Load (t)

X2: Pebbles Recirculation (t/h)

X3: Fresh Mill Feed (t/h)

X4: Mill Feeding Chute Water Flow (m3/h)

X5: Primary Cyclones UF Dilution Water (m3/h)

4. Conclusions

This dissertation had as its main objective the analysis of data from the operation of the Mill AG/SAG installed in the Neves-Corvo Mine and the search and verification of correlations between the various variables observed and recorded.

Although this was not the initially defined objective for this work, as the theme says would be the Optimization of Operational Parameters during the Start-up of the Mill AG/SAG in Neves-Corvo, the fact that this work was developed exclusively in an environment industrial and more specifically in a project environment, led to the need to rearrange the subject due to the observed operating conditions.

From the consulted bibliographical research, it was verified that although Autogenous and Semi-Autogenous grinding mills are very common in several places of the world and have been in use for several years, the AG/SAG mill of Neves-Corvo, will be the first of its type in operation in our country, being therefore a unique opportunity in Portugal to monitor its operation with ore from the Iberian Pyrite Belt.

It is possible to conclude with this work that in order to explain the operation of equipment with the complexity of an AG/SAG mill, it is necessary to take into account several variables and not just a small set. The way in which this equipment works requires it, and since it is so dependent on variations upon entry, taking into account several parameters will certainly help to better understand its behavior.

Although it is possible to find reasonable correlations between pairs of variables through regression models, it will certainly be more favorable to resort to multiple regression models in order to explain the functioning of the mill.

A good example that shows the advantage of considering multiple regression models compared to models between pairs of variables is Torque. In the case of a regression between a pair of variables Tap vs. Internal load, an R2=63.96 % was obtained compared to an R2=85.99 for a multiple regression. The fact that several variables are being considered for the model significantly increases the correlation percentage.

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