Optimization of mill performance by using online ball and pulp measurements

by B. Clermont* and B. de Haas*

Synopsis

Ball mills are usually the largest consumers of energy within a mineral concentrator. Comminution is responsible for 50% of the total mineral processing cost.

In today's global markets, expanding mining groups are trying to optimize mill performances. Since comminution is concerned with liberating valuable minerals for recovery in the separation process, it is crucial to run the mills at the best operating conditions which lead to good liberation at competitive throughputs with minimum costs (energy and wear). The high availability of the equipment is also essential to maximize production and profit.

To reach this key objective, continuous and reliable information about the mill operation is vital. An innovative tool which can deliver information about in-mill dynamics has been developed by Magotteaux. It can provide online and accurate measurements of the degree of grinding ball fill and pulp position for timely decision making and actions. This tool could be used on its own or linked to an automatic grinding ball loading system named Magoload. Therefore, ball load could be kept constant by using direct measurement.

This article describes the Sensomag and presents some of the major improvements that can be achieved with it. Some other promising avenues are still to be explored.

Keywords: Comminution, process control, process optimization, process instrumentation, online analysis.

Introduction

The performance of tumbling mills is sensitive to the volumetric mill filling which influences grinding media wear rates, throughput, power draw, and product grind size from the circuit. Each of these performance parameters peaks at different filling values. In order to continuously optimize mill operation, it is vital to obtain regular measurements of the ball load and pulp position.

The current way to measure the charge filling degree

Crash stops and grind-out

Generally, crash stops are performed to obtain measurement of charge filling and slurry loading. The crash stop involves running the mill under steady state then cutting off all feed streams to the mill as it is being stopped. Sufficient time is required to obtain all the important measurements correctly during the crash stop. The mill filling should be measured at a minimum of 3 points along the mill. Excess of slurry could also be estimated.

To get rid of pulp and rocks in the charge, a mill grind-out (no ore feed) of 10 to 20 minutes is also performed before mill inspection or relining. The complete grind-out is required to obtain the accurate ball load measurement or the percentage by volume of balls in the mill. This is usually performed soon after a crash stop.

The basic principle is to measure the height 'H' from the charge to the shell and the internal mill diameter 'D_i'. By calculating the ratio 'H/D_i' and using the graph below (Figure 1), the charge filling degree in volume could be estimated. The number of visible plates on the shell liner could also be counted and an angle could be calculated (α) but the accuracy of this method is far lower than the measurement of the vertical height from the charge to the roof.

Although crash stops and grind-outs provide important information, they have several disadvantages:

- They do not provide the milling internal dynamics and therefore, the changes in charge motion due to operating parameters. There is no data related to liner design such as the toe and shoulder regions.
- Production is disrupted for the duration of the procedure: grind-out, mill stoppage, mill start-up and the transition period to steady state.
- Stresses, generated in the ball charge, increase, which may result in spalling of balls and blocking the grate discharge.

* *Magotteaux International, s.a.*

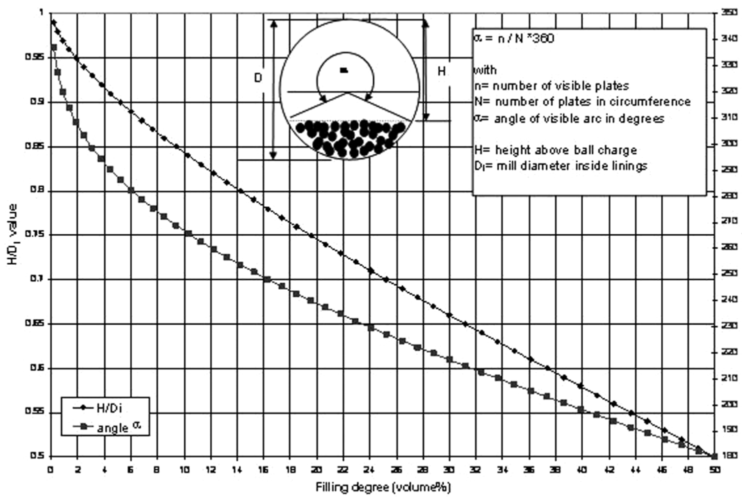


Figure 1—H/D_i and ange α as function of filling degree

➤ Soon after a stop, a mill is a dangerous place to enter for the personnel tasked with taking measurements or samples.

➤ Crash stops are difficult to handle. The mill and all feed streams should be stopped simultaneously but, often, they are stopped around about the same time. Slurry could still be pumped out of the mill during a few rotations. The accuracy of the measurement could suffer from the procedure that is followed by the operator.

Mill power

Usually, plant operators use mill power readings as an indicator of ball filling degree and, often, try to keep it at the maximum level.

It is well known that the mill absorbed power depends on operating parameters other than ball level, such as pulp density and liner configuration.

Figure 2 shows that there is no linear relation between mill absorbed power and ball filling degree. As indicated on the graph, a small variation in power could be the result of a significant variation of balls filling degree.

As the ball wear rate depends directly on the surface of the media charge, a small variation in power will lead to an important increase of wear rate. The risk of underloading or overloading the mill is an additional factor.

A direct measurement of the ball level in the mill, more accurate than power readings, as well as a control of it, is therefore highly important.

Load angle as an indicator of milling efficiency?

Toe and shoulder angles of the charge are always used for liner design purposes. Many simulation tools exist to obtain the necessary information about media trajectories. Data are used to avoid the risk of liner and ball damage by projecting balls directly on the shell liner. Figure 3b illustrates this issue. Obviously, a good liner design and the right operating conditions such as mill speed or balls filling degree, should limit the risk of projection.

The purpose of this paper is to further explore the issue related to the grinding efficiency. There is probably more to be gained from media angle than a risk of breakage only.

Table I illustrates or quantifies the media charge angle for different liner designs at different mill speed but with constant filling degree (30%). Indeed, as explained previously, at a mill stop, the measurement of ball charge filling degree could be undertaken and will provide the static media charge angle (β_{static} = 143°). An online measurement of the similar angle ($\beta_{dynamic}$), when the mill is running, provides information about the dynamics of the charge. The ratio between the dynamic and the static media angle is calculated and gives a value of the load 'expansion'. (Figure 4.)

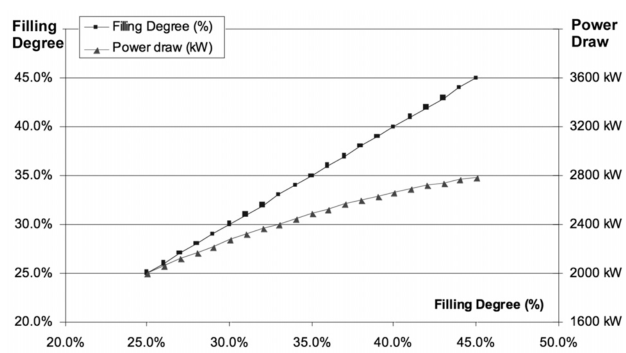
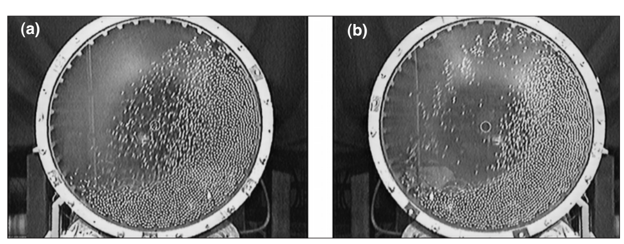


Figure 2—Nonlinear relationship between power draw and filling degree



Soft (30°) attack angle; 75% CS; J=30%

Aggressive (5°) attack angle; 75% CS; J=30%

Figure 3—(a) Lab-scale test with low lifting angle, (b) high lifting angle

Table I

Influence of speed and liner design on load dynamics

Mill speed	Soft design		Aggressive design	
	Media charge angle ($\beta_{dynamic}$)	Ratio $\beta_{dynamic}/\beta_{static}$	Media charge angle ($\beta_{dynamic}$)	Ratio $\beta_{dynamic}/\beta_{static}$
65% CS	178°	123%	179°	125%
75% CS	179°	125%	187°	131%
85% CS	192°	134%	197°	138%

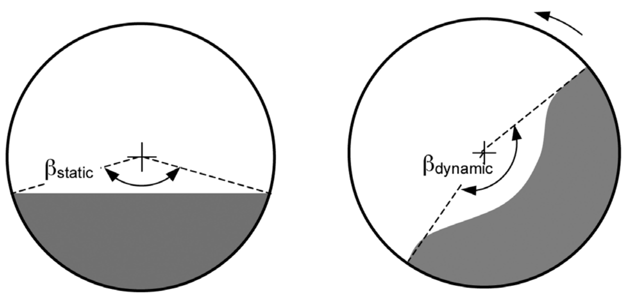


Figure 4a and 4b—Definition of static and dynamic load angles

Many authors have highlighted in previously published papers that the ore breakage is closely linked to the ball charge motion. It is well known that ball milling efficiency varies during the lifetime of the shell liner. For instance, the mill performance could become worse or better by putting in a new shell liner. Data from pilot plant test work illustrates the influence of the shell lifting effect on the grind for a primary grinding duty. Figure 5 shows the evolution of the mill discharge product size in relation to the lifting effect of the liners.

In this specific case, it is obvious that a certain load expansion is needed to allow the coarse particles entering the media charge to be reduced.

Therefore, at this stage, a direct measurement of the dynamics in the mill gives very valuable information to the operator. The evolution of media angle (β_{ynamic}) could probably help the operator to optimize the mill efficiency (plan a liner change and/or change mill speed if possible). Studying the complete evolution of the media angle (β_{ynamic}) through the liner lifetime can lead to an improved liner design.

However, the example of liner design and grinding efficiency uses the media charge angle only. Other examples will explore the interaction between the pulp and the media load.

Influence of slurry properties and load behaviour in tumbling mills

In 1988, Professor Moys, from the University of the Witwatersrand in South Africa, published articles about the effect of slurry rheology and flow rate on mill behaviour. He had already highlighted the interaction between slurry and media in the mill by looking at the mill grinding efficiency. At that time, it was difficult to acquire a lot of valuable information as robustness in an aggressive environment was not assured.

Twenty years later, the Sensomag is able to show this interaction by looking on the pulp position angle and media angle. The Sensomag has been developed to continuously measure both ball load and pulp slurry positions inside a running mill. The main data are provided in terms of toe and shoulder angles. (Figure 6.)

The pulp density is an important parameter which influences the grinding efficiency. In iron ore, for instance, a variation of 2 to 3% solid content in the slurry could lead to a difference up to 10% on the energy (kWh/T) for a similar grind.

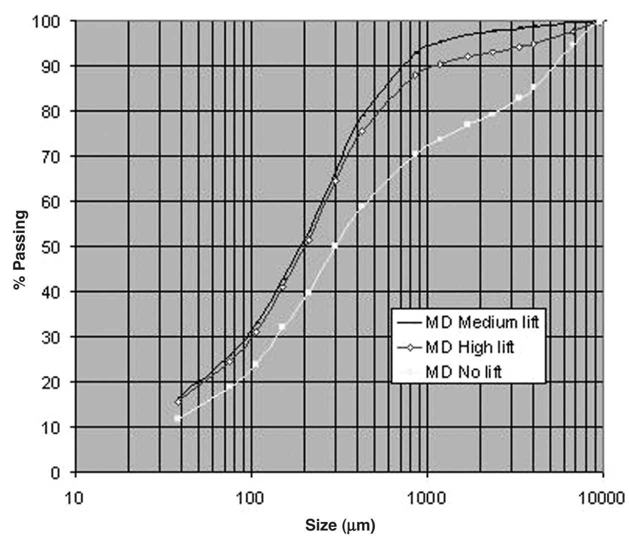


Figure 5—PSD–mill discharge, primary mill

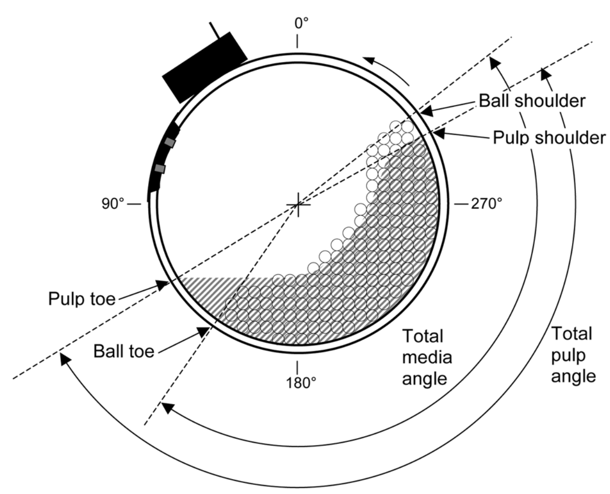


Figure 6—Cross-section of the mill with angular references

In the platinum industry, by increasing the solid content in the slurry, the product becomes finer. At a higher percentage solid than 73 to 74%, the product becomes coarser again. At this level, a drop in grinding efficiency occurs. (Figure 7.)

For a better understanding of the decrease in the grinding efficiency, the media and pulp angles are recorded by the Sensomag®. From 69 to 73% of pulp solid content, the media angle keeps a constant value (184°) and the grinding zone fills up but remains unsaturated (media angle > pulp angle). From 74% the media angle exponentially increases with pulp solid content. Unstable milling conditions starts to occur. The Sensomag® clearly detects the load expansion. (Figure 8.)

This test also shows that by feeding the mill with a too dilute pulp, the grinding zones between the media are not saturated, leading to high media wear rate.

A variation in total ball angle can be detected and linked to grinding efficiency and charge expansion. This could help the operator to make the right decision and keep the mill running in such a way as to be close to the optimum pulp density (73% in the above example). It must be kept in mind that the optimum is always very close to the unstable zone.

Influence of balls filling degree

The performance of ball mills is very sensitive to the volumetric mill filling which influences grinding media wear rates, throughput, power draw, and product grind size. A pilot plant investigation with an overflow mill discharge has been conducted. For a given throughput, it seems that the pool size has a major influence on the product grind. Further investigation will be conducted in an industrial mill to determine the optimum media filling degree for a specific application.

This paper illustrates this point for a grate discharge mill. For a specific production rate in the pilot plant, an increase in the balls level from 25% to 30% leads to an increase in product fineness. But, adding balls from 30% to 35% does not mean that the final product will go finer than 78% passing on 75 µm as already achieved at 30% of ball filling degree. By plotting on a graph the energy needed to produce particle sizes less than 75 µm as a function of balls filling degree, the curve shows the optimum filling degree for this specific case (Figure 9).

If the operator is working with a ball filling degree higher than the optimum, a waste of energy occurs. As the ball wear rate is proportional to the surface of the media charge, an extensive wear of balls occurs as well.

By measuring the angle position of both the pulp and ball charge, further information is revealed. For each ball filling degree, the grinding zones are not saturated with pulp.

It means that a certain number of balls are just rolling without pulp and therefore, those balls are just wearing each other without doing any grinding work.

At 35% of filling degree, by increasing the throughput step by step, the grind does not change. By following the pulp angle and ball angle during the increase of throughput (Figure 10), we could conclude:

- ➤ Those measurements could be an indicator of throughput restraint.
- ➤ For a given throughput, the right ball level for an economic operating condition, wear and energy could be determined and kept.

Figures 8 and 10 show the interaction between ball and pulp angles. It is now time to show how to obtain those values and prove their reliability. The last part of this paper will describe the Sensomag® in detail and illustrate its operation with a few examples.

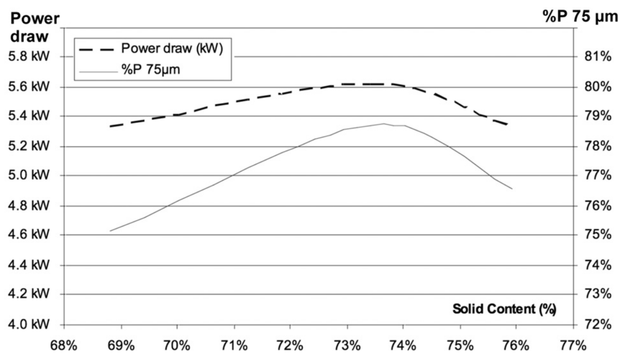


Figure 7—Mill efficiency evolution with pulp solid content

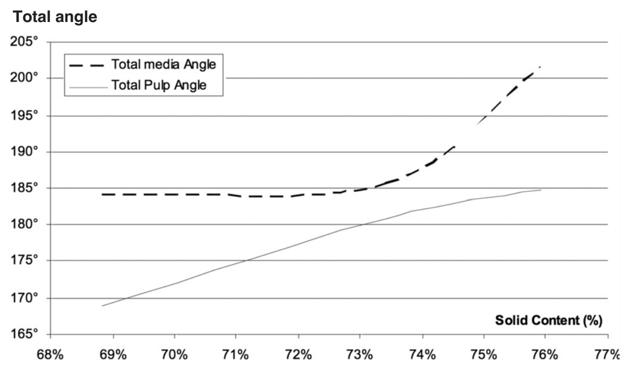


Figure 8—Grinding zone progressive filling with pulp solid content until load expansion

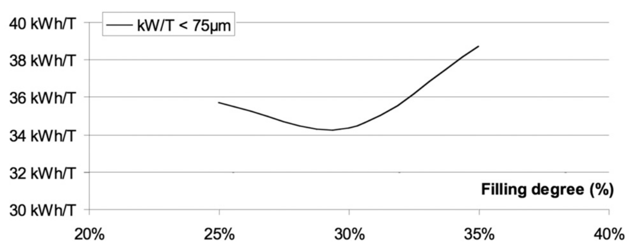


Figure 9—kWh/t <75 µm as a funciton of milling filling degre—constant feed rate, grate discharge

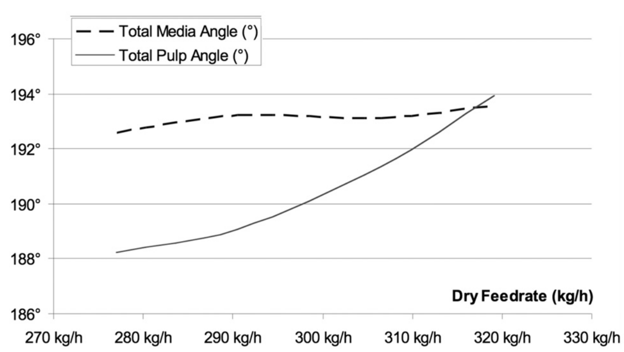


Figure 10—Grinding zone progressive filling with feed rate

A description of the Sensomag®

The Sensomag® has been developed to continuously measure both ball load and pulp slurry positions inside a running mill. The main data are provided in terms of toe and shoulder angles. Refer to the reference angles in Figure 6. (Angles are counted in the same direction as the mill rotation).

The principal element of the Sensomag is a standard polyurethane beam, installed inside the mill, and containing sensors, which perform direct measurements of ball and slurry presence. There is no complex interpretation of any indirect signal of any kind such as noise, shell vibrations or mill power drawn. (Figure 11.)

The ball load and pulp slurry detection is performed, on a mill section, at every revolution. Those raw signals are sent through a wireless link to a central unit where they are processed.

The four angles are then computed and made available online to the customer supervision system via a standard OPC link or 4–20 mA electrical signals. (Figure 12.)

As described in the first part of this paper, the knowledge of ball load and pulp slurry positions, inside a running mill, is a unique opportunity to optimize equipment usage, leading to quality and throughput increase as well as energy and media cost reductions.

The Sensomag can also provide a ball load filling degree (in percentage volume) based on the various angles and mill absorbed power. This requires at least one mill shutdown to perform a manual ball filling degree measurement in order to calibrate the mathematical model.

Once calibrated, the Sensomag can be used to finely monitor steel ball consumption, manage ball additions (top ups), reduce shutdown periods (required for grind-outs and crash stops) and increase safety by reducing the number of mill internal inspections.

Example of industrial results

The Sensomag has been installed on several industrial grinding mills. Various validation tests have been conducted and others are still under investigation.

Pulp level controller

The experiment was performed on a 4.8 m diameter grate discharge mill, equipped with a Sensomag. The customer has built a special moving plug that can partially block the outlet trunion in order to keep more slurry inside the mill. When fully in the trunion, this device is able to keep enough pulp inside the grinding chamber to change the mill discharge to an overflow one, with an 8 to 10% power drawn reduction. When fully out, it has no effect at all. The mill is back to its original grate discharge conditions.

The experiment consists in moving the plug fully in and measuring the effect on the pulp level with the Sensomag. Then, after stabilization, the plug is moved fully out to go back to the original grate discharge conditions. All the angles measured by the Sensomag are displayed in Figure 13a–d.

As shown in Figure 13a–d, the pulp toe angle decreased by about 10°, while all other angles remained almost unchanged. A pool, typical of an overflow discharge mill, appeared. After the plug was driven out from the trunion, all angles recovered their original values. (Figure 14.)

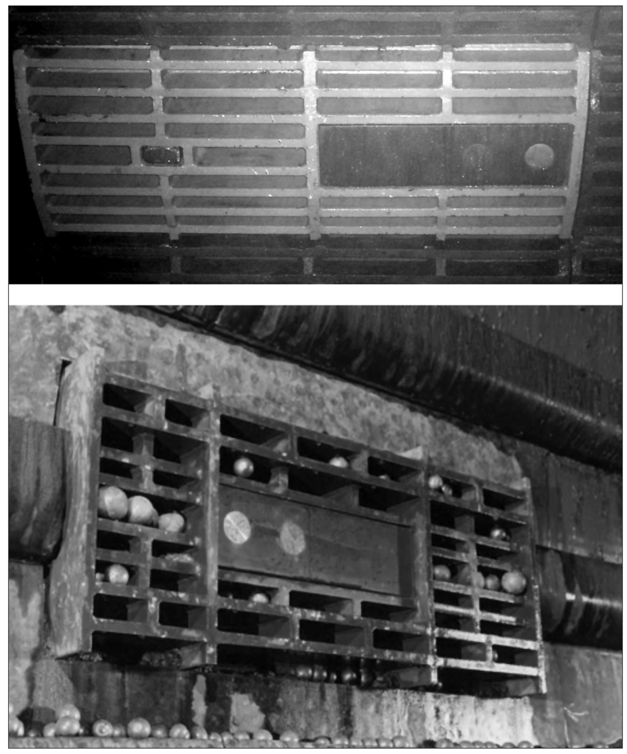


Figure 11(a) and (b)—examples of polyurethane sensor beams

Figure 12—Example of Sensomag® installation on the mill shell

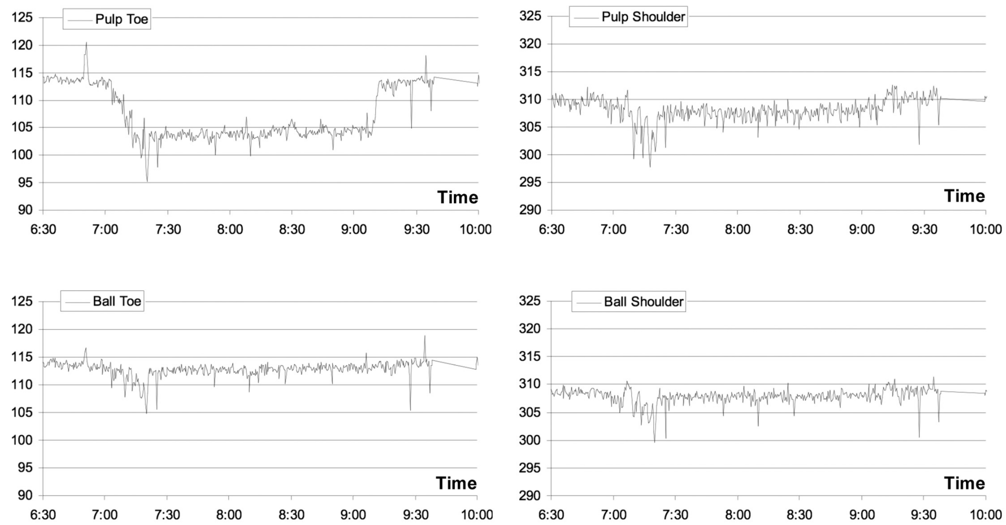


Figure 13a–d—Sensomag® angles during the plug in/plug out

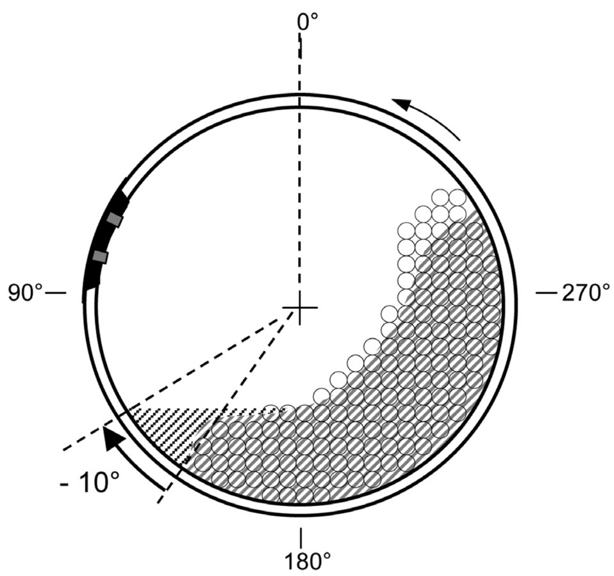


Figure 14—Cross-section of the mill during the plug in/plug out experiment

This experiment demonstrates that the Sensomag is able to continuously follow the evolutions of the pulp level inside a running ball mill. Other intermediate plug positions (different from fully in and fully out) could then be chosen in order to finely adjust the pulp level, leading to optimal grind for minimum power consumption.

What should also be pointed out in this specific case (in grate discharge conditions) is that both toe angles display very similar values (around 115°). This is also the case for both shoulder angles (310°). The conclusion may be that the grinding zone is just saturated with pulp (optimal situation).

Ball wear without addition

The experiment was performed on a 7.3 m diameter overflow mill, equipped with a Sensomag. The mill was left to run for 42 hours without any ball additions. All the angles measured by the Sensomag are displayed in Figure 15a–d.

As shown in Figure 16, the pulp toe angle did not move. It remained constant at 86° (overflow discharge). Both ball and pulp shoulder angles decreased, in parallel, by about 1.5°. The ball toe angle increased by around 1°. The filling degree, computed by the Sensomag, decreased from 31.6% to 30.9%. This signal fits correctly with a filling degree estimation, based on ball additions and a ball wear rate of around 40 g/kWh.

This demonstrates that the Sensomag is able to continuously follow the evolutions (wear) of grinding media level inside a running ball mill.

Ball additions

The experiment was performed on a 7.3 m diameter overflow mill, equipped with a Sensomag and a Magoload. The Magoload is an automatic grinding ball loading system developed by Magotteaux. At about 6:30 am, the filling

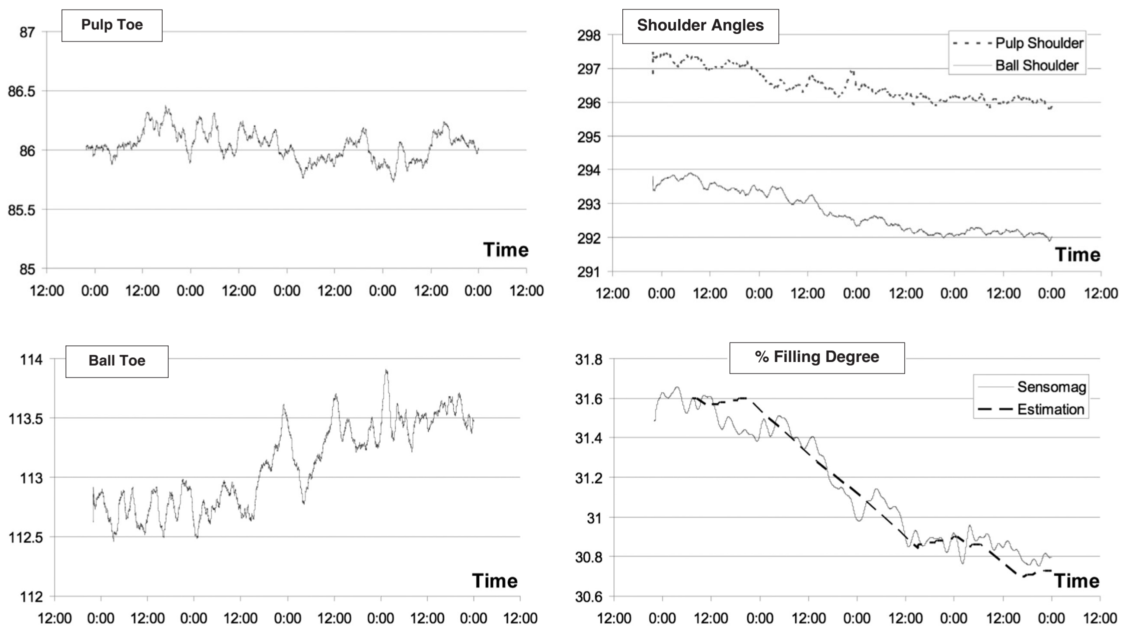


Figure 15a–d—Sensomag® angles during the ball wear experiment

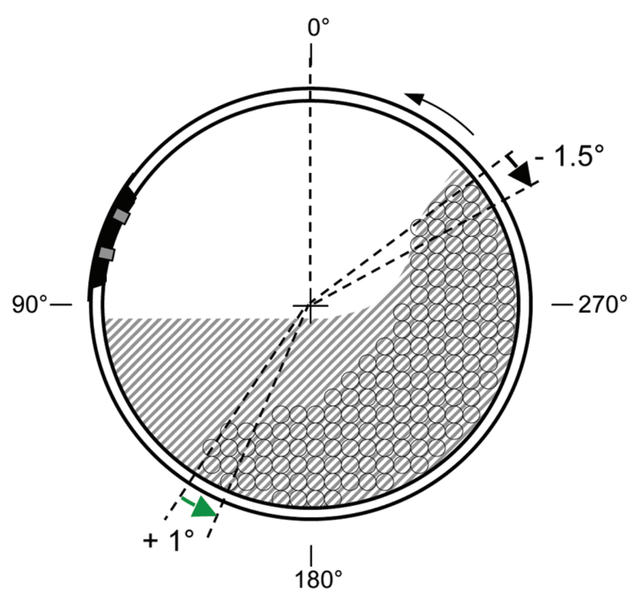


Figure 16—Cross-section of the mill during the ball wear experiment

degree setpoint on the Magoload was increased by 0.2% (from 30% to 30.2%). To reach this new setpoint, 4 tons were added by batches of 225 kg every 2 to 3 minutes. The final target was reached at 7:30. All the angles measured by the Sensomag are displayed in Figure 17a–d.

As shown in Figure 18, the pulp toe angle did not change very much as the mill is in a overflow discharge configuration. Both ball and pulp shoulder angles increased, in parallel, by about 0.5°. The ball toe angle decreased by around 0.5°. The filling degree, computed by the Sensomag, increased from 30.0 % to 30.2 %. Again this signal fits correctly with a filling degree estimation, based on ball additions and a ball wear rate of around 40 g/kWh.

Again, this demonstrates that the Sensomag is able to finely and continuously follow the evolutions (additions) of grinding media level inside a running ball mill.

The last two experiments show the joint evolution of both pulp and ball shoulder angles. This was always observed in other situations, not illustrated in this article. This has two outcomes: the information content of both angle signals is almost identical and the global lifting of the total mill load is due to a combination of balls and pulp. In other words, the balls help to lift the pulp and the pulp helps to lift the balls.

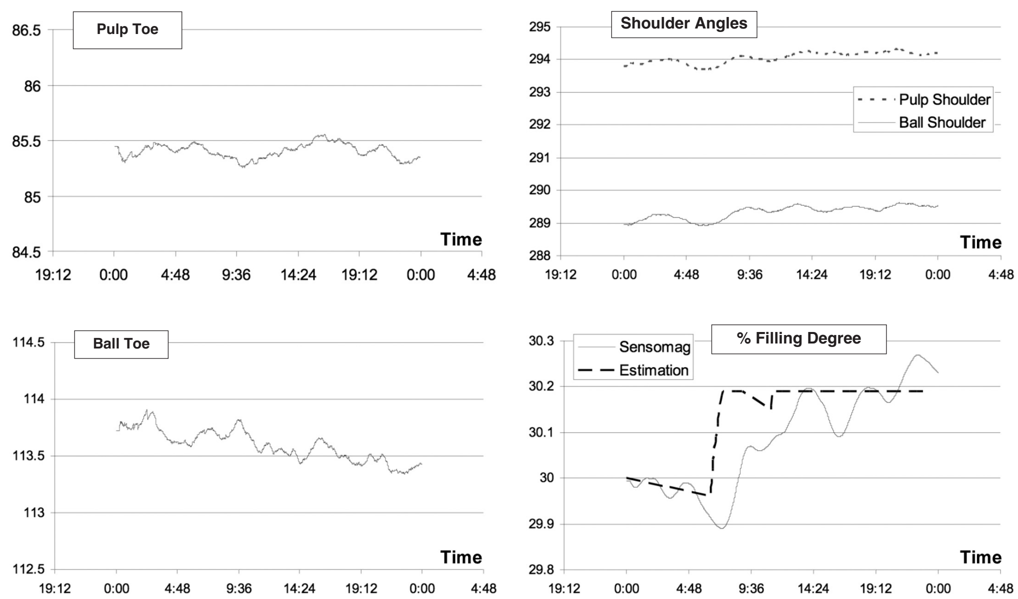


Figure 17a–d—Sensomag® angles during the ball addition experiment

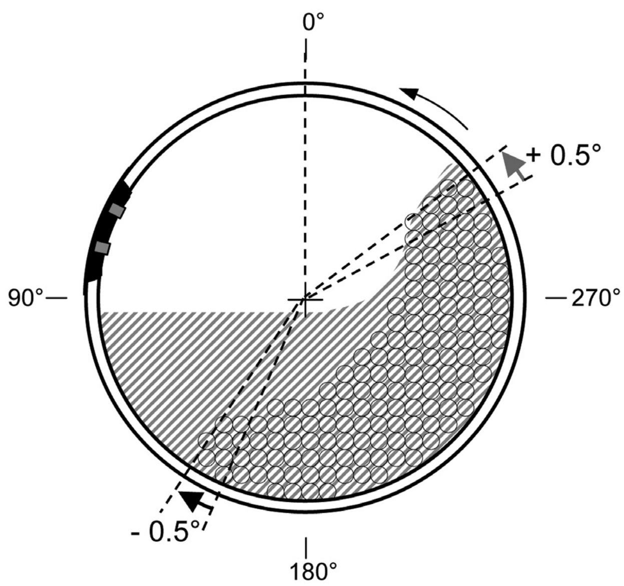


Figure 18—Cross-section of the mill during the ball addition experiment

Conclusions

The Sensomag is a unique tool that can continuously provide valuable information of what is really happening inside a grinding mill. It opens up a wide variety of avenues to explore in order to optimize mill running conditions.

It is able to finely follow, independently, pulp slurry and ball load levels evolutions inside the mill and provide this key information, online, to the plant engineers.

Sensomag® physically measures critical mill parameters and turns them into valuable information for timely decision making and action.

Knowing the mill internal dynamics in terms of grinding balls and pulp slurry angular positions given by the Sensomag will enable the mill manager to:

- Optimize liner design to obtain good relative movements of grinding media and pulp as well as avoid ball projection and liner breakage
- Monitor liner wear and efficiency changes in order to optimize liner replacement
- Improve grate discharge design to keep pulp level constant all through the mill length
- Monitor interactions between pulp angles and media angles to detect load expansion due to pulp density change and to run the mill with the grinding zone properly saturated
- Optimize and control the mill media filling degree to reduce production costs while keeping the same grinding performance.

Other optimizaton possibilities are still to be explored.

The mill filling degree is one of the last critical measurements that still require a mill shutdown and it is performed manually every few months. The Sensomag® also represents a solution for this essential issue.

References

Moys, M.H. Measurement of slurry properties and load behaviour in grinding mills. *First IFAC Workshop in Applied Measurements in Mineral and Metallurgical Processing*. Sabi-Sabi Game Reserve, October , 1988.

Powel, M. and Valery, W. Slurry pooling and transport issues in SAG mills. *International Autogenous and Semiautogenous Grinding Technology*. Vancouver, September, 2006.

Napier-Munn, T.J., *et al. Mineral Comminution Circuits, Their Operation and Optimisation. JKMRC* Monograph Series in Mining and Mineral Processing, 1996. ◆