Here's the Key

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Introduction

When the cement market stagnates, or worse, falls drastically, the focus moves to reducing production costs. The kiln process is usually the primary target since it is considered to be the heart of the cement plant. However, what is surprisingly true, is that 65% of power consumption comes from the grinding department that is comprised of 42% grinding cement and 23% grinding raw materials. Grinding, as it turns out, is a very power hungry process that makes the cement industry one of the largest consumers of power when compared to any other modern industrial activity. The goal of this article is to describe how specific power (KWh/t) can be dramatically reduced in the grinding department by 6% or more. Specifically, a new solution is described that employs vibration sensors (MillScan) on a typical ball mill, coupled with an easy to use expert system (MillExCS) in the control room. Benefits from this technology include the ability to predict the volumetric fill level of the mill that can then be used to reduce both specific power consumption and 'over-spill' situations, as well as provide reductions in output standard deviation fineness yielding increased productivity.

Understanding ball mill power consumption

In the quest to reduce specific power consumption on a ball mill, it is important to review the constraints of the problem and understand how more efficient loading can actually decrease mill motor power consumption.

Per Fred Bond's early work on ball mill power consumption, the amount of horsepower required for a given mill is a function of the following parameters: mill diameter, length, speed, mill type and percent loading.[1] Of these parameters, percent loading is the only available variable for tuning, whereas all other parameters are fixed, usually at the time of

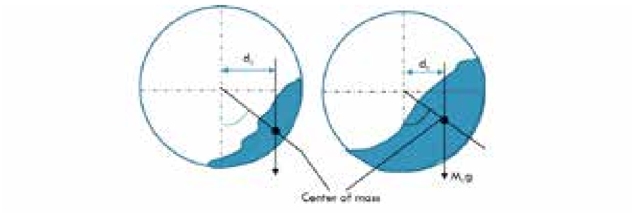


Figure 1. Center of Mass (Mc) vs. Mill Load.

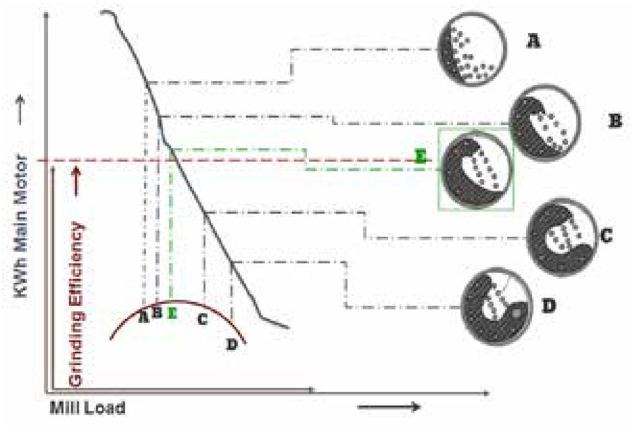


Figure 2. Mill Motor Power (KWh) vs. Mill Material Loading.

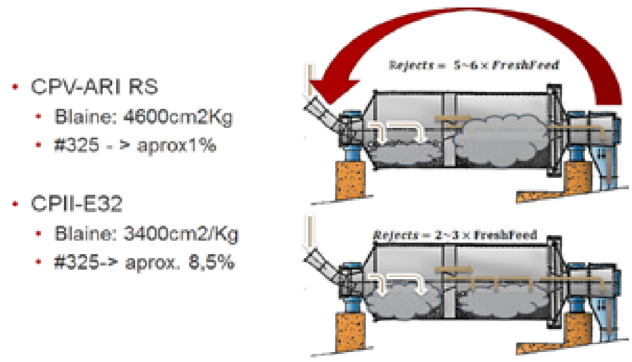


Figure 3. Material flow differences according to cement type.

commissioning. Percent loading is comprised of the ball charge and the amount of material in the mill. Of these two components, the amount of material input to the mill is controlled and altered in a real-time manner, while ball charge is typically designed to be kept constant throughout time, with balls only added to replace those with wear. The amount of material in a mill is therefore the variable available for real-time control and can be shown to affect motor power as follows. Power $\mathbf{P=2\pi \times N \times T}$ where T is torque and N is rotational speed. Torque $\mathbf{T=M_c \times g \times d_c + T_f}$ where M_c is the center of mass of the ball charge and material being ground, g is gravity, d_c is the distance between the gravity vector and the point of rotation. T_f is the constant torque required to overcome initial friction. From these two equations, P is seen to be linearly proportional to d_c, the distance between the rotational axis and the center of mass. Figure 1 illustrates this for a ball mill. When a mill becomes more full, the center of mass M_c begins to shift towards the vertical axis of rotation. This, in turn, decreases d_c which lowers the power consumption.

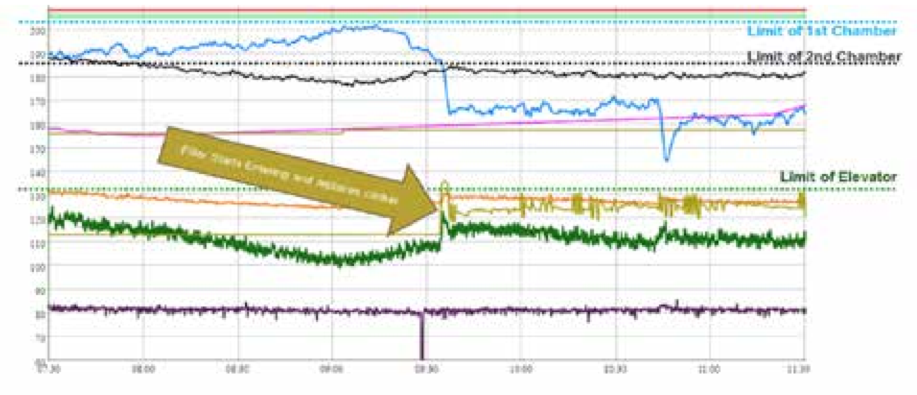
Increasing mill load and decreasing mill power is a common ball mill phenomenon. In Figure 2, power consumption is plotted as a function of mill load. Ball trajectory A shows a high power consumption condition where the mill is severely under loaded and power consumption is high. B shows that, as more material is added to the mill, the power decreases some proportional amount. C and D are instances where there is low power consumption but the point of efficient grinding (E) has been passed. In C and D, the balls are no longer striking the actual material, but instead are striking the mill liners. In case D there may also be the phenomena where a significant portion of the charge begins to 'free wheel' or spin around the axis of rotation and not strike either the material or mill liner. This can lead to an out of control situation, which may result in a spill at the inlet.

In Figure 2, E is the point of optimal grinding. Here, the desired output quality is being met, along with sufficient material being produced as well as low power consumption when compared to A and B. E is the peak of the grinding efficiency curve, which is shown in red under the power vs. load plot. Thus we can observe that, as the mill is filled, power begins to drop, but we are restricted to a maximum load in the mill that yields the highest grinding efficiency. This optimal point of operation therefore equates to an optimal load of material in the mill. To achieve this optimal load, fresh feed at the inlet needs to be added to the mill. Additionally, the feed rate set point will need to be controlled in a real-time manner to maintain the ideal mill load for operation at a point that is slightly above or equal to point E on the power curve. Unfortunately, this is not an easy task as changes in fresh feed density, hardness and increasing rejects can cause the mill load to change, resulting in non-optimal conditions.

Real-time mill load measurements using vibration sensors

From the previous discussion, it was observed that some type of quick response mill loading signal is required for fresh feed control. Traditionally, this has been done with sound based systems (microphones) and load cell sensors. Microphones are notoriously susceptible to sound from nearby mills/equipment and particularly poor at measuring the sound coming from the mill outlet chamber. Microphones also have maintenance issues with dust and therefore generally unreliable. Load cells, on the other hand, are more reliable but tend to be noisy and slow reacting to changing conditions in the mill chamber, thus rendering them unsuitable for instantaneous fresh feed control.

It has been found that vibration sensors employing modern signal processing techniques are best suited for measuring the volume of material in a mill. The amount of vibration energy generated from the balls striking the inner liner is directly proportional to the volume of material in the mill. Two sensors are used on each end of the mill such that a fill level can be accurately monitored in both the first and second chamber of a two chamber mill. These signals can be used for real-time feed control as well as to observe how well both chambers are operating. For example, if material is constantly observed to be filling the second chamber, while the first chamber is empty, the grinding media or diaphragm between the two chambers may require maintenance or re-design. Filling/emptying trends from these sensors can also be used to determine whether or not to shorten, lengthen or widen the chambers for better material flow.



Then slowly increase production.

Figure 4. Injection of filler at the elevator.

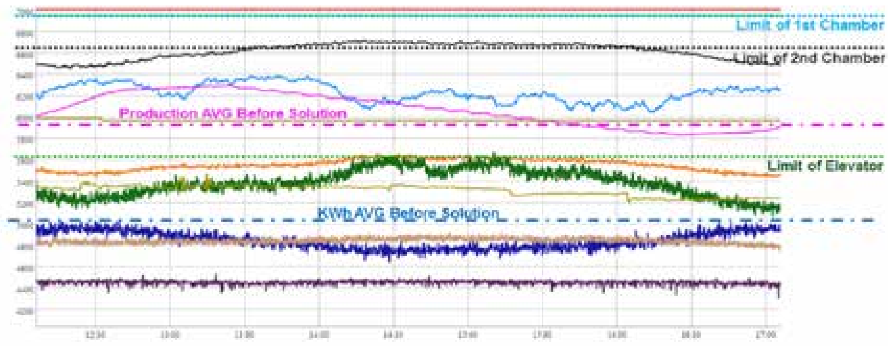


Figure 5. Typical mill operation (5 hour duration).

Vibration sensors and expert system control

A MillScan G4 fill level monitoring system was used that has one magnetically mounted vibration sensor on each end of the mill. The vibration is then analysed by a main unit that can differentiate grinding vibration from mechanical vibration through frequency domain analysis. Because each sensor is attached directly on a bearing housing or support structure, the system is immune to external interference that can affect a microphone. Each sensor then measures the ball impacts occurring at a distance of 1.5 – 2 m from their corresponding mounting points. Two highly accurate 4-20 mA volumetric fill level signals are then generated by the main unit that correspond to readings taken from the two vibration sensors. These 4-20 mA signals are then used with an expert control system, known as MillExCS. The benefit of having the expert system is that one is able to transfer the knowledge and experience of the best operators and process control engineers into a reliable and automatic controller. The system runs on a typical Windows PC and is very easy to setup, maintain and change.

After installation, the strategies of control are passed to the system, similarly to how a new operator would be taught how to react to events governing the mill process. There is no need for mathematical models or exhaustive and intensive training sets. Instructions are written semantically what the system must do for a particular situation. An example is shown below:

If InMillScan is 'optimal range' and,
If InMillScan is 'not increasing fast' and,
If OutMillScan is 'below Optimal range' and,
If OutletElevator is not high,

The advantage of this is that the rules can be can easily browsed to understand the control system strategy.

Case study: material flow and bottlenecks

MillExCS has been successfully implemented in several plants spanning Europe, North Africa and South America. Here are the results from a 2014 Brazilian installation that was part of a small cement group facing great difficulties with a failing cement market. While there are other examples of installations with better results, this particular installation is of interest because the local cement market declined 21% in 2016, versus sales the previous year, and the price of electricity doubled during this period. Also, in addition to falling sales and increasing energy costs, this plant also had a very difficult to control, unbalanced mill chamber filling problem that was limiting efficiency.

Beginning with the mill and material produced, a typical two chamber ball mill was used to produce cement with a required fineness of 3%, 2% and even 1% residue in #325u mesh. The manufacturing conditions also dictated that this mill must be able to switch from producing very fine cement to a much coarser type and vice versa at any given point in time. Figure 3 shows these two cement types known as CPV-AR1 and CPII-E32.

In Figure 3, the material flow, as well the bottleneck, changes from one chamber to another, depending on cement type. For the coarser material, CPII, the diaphragm between the mills becomes the bottleneck where material is retained in the first chamber. However, for the finer CPV materiall, the material sweeps through the first chamber and ends up in the second chamber and the bottleneck is at the discharge end of the mill.

Because the fresh feed set-point for material entering into the first chamber is controlled, any change in fresh feed has an immediate effect on the first chamber fill level. Thus, for a coarse material like CPII, where the reject rate is only 2 – 3 times the fresh feed rate, the filling/emptying of the first chamber tends to respond well to changes in fresh feed. However, when producing the finer material (CPV), a significant amount of time is required before any changes in the fill level are seen in the second chamber when changes are made to the feed rate. This is due to the large amount of fine material in the second chamber resulting from rejects sweeping through the first chamber, and from the fact that amount of reject material returning is 5 – 6 times greater than the current fresh feed rate.

To summarise, CPII is ground in the first chamber, while CPV is mainly ground in the second chamber. When grinding CPII, the first chamber is responsive to feed changes because of close proximity to the feeder and the lower proportion of returning material (rejects) compared to fresh feed in the first chamber. On the other hand, when grinding CPV, the second chamber has a much slower response to changes in feed because the bulk of the grinding is occurring further away from the feeder, and also because the fresh feed is proportionally much smaller to the total material (rejects) in the second chamber. Because of these differences in material flow and bottleneck locations, it is very important to have a good reliable volumetric fill level sensor on both the first and second chambers.

Case study: further complication from pre-ground filler

When grinding CPV vs. CPII there is added complexity due to the distance from the feed source and because of a larger proportion of reject material. Another additional complexity at this plant is that limestone is replaced occasionally with a fine pre-ground silica material called filler. The filler material is a low cost additive that is directly added to the outlet elevator and can be substituted at any time for 15% of the fresh feed (limestone portion).

Figure 4 shows the effect of adding filler to the elevator; the first chamber fill level drops drastically. This drop is due to the feed being deprived of limestone (a wet coarse material) while filler is injected into the elevator. The fresh feed is reduced, while the filler sweeps through to the second chamber. During this same period of time, the outlet fill level sensor shows the second chamber fill level remaining constant. For this situation, the expert system has been programmed to ignore the drastic drop in fill level from the first chamber and instead use the fill level signal from the second chamber. This is done via the following expert rules:

If InletMillScanGradient is falling fast and,
If InletMillScan is not overloaded and,
If OutletMillScan is not high,
Then increase setpoint fast.

In Figure 4, because the OutletMillScan fill level (black signal) is high, the fresh feed set-point is not rapidly increased but instead allowed to continue at its current value to maintain the optimally high level of material in the second chamber. For this control, the Outlet_MillScan signal is kept slightly under its maximum fill level point, which was determined to be the optimal efficiency of the second chamber. This is called the 'limit of second chamber' in Figure 4 and it was determined at the time of installation by studying lab quality results and other process variables.

Thus, if the outlet fill level signal for control is not used when grinding filler or other fine material, the drastic reduction in vibration (sound) at the inlet chamber will cause the controller to increase fresh feed. This, in turn will dramatically increase the inlet chamber fill level and destabilise the process by over filling the second chamber. This was the case at this plant, previous to this solution, where fresh feed would then need to be cut for 5 – 10 mins to bring the process back under control. This over filling/cutting feed operation occurred several times per day and has been observed at many other plants that are tasked with grinding very fine cement.

Figure 5 illustrates typical operation under expert system control. During this time, the Inlet_MillScan vibration signal can be observed to react very differently to fresh feed than the other process variables due to the large amount of rejects sweeping through to the second chamber. The second chamber is the bottleneck, with a fineness goal of 1%. In this case, the elevator and mill power signal response times are very long and the fastest signal for control is the second chamber Outlet_MillScan (black) vibration signal.

In the beginning of Figure 5 we can also see that both the inlet and outlet chamber fill levels are below optimal and so the expert system significantly increases the fresh feed set point (pink) in the first hour of the trend. Then when the Outlet_MillScan starts to rise as a result of increased fresh feed, the expert system begins to slowly cut the fresh feed set point to reduce the Outlet_MillScan signal and bring the mill back in control. Of particular interest is the hour of operation beginning at 13:30 at the start of the fresh feed being cut. Here the continuing slow build-up of fine material in the second chamber is shown by the slow increase in the Outlet_MillScan signal from 13:30 to 14:00 hours. However, during these 30 minutes, the elevator amps (green) stay relatively flat and do not trend up until after 14:00 hours. Here the vibration signal is in advance of the elevator signal by at least 30 mins and this allows the expert system to react faster than previous operation based on elevator amp control. Because of this enhanced control, the expert system is able to keep the chambers fuller than in previous operation. This results both in increased production and reduced power when compared to the previous averages.

When grinding CPII-E32, the primary variable for control is the Inlet_MillScan signal and the first chamber is pushed to a level slightly under the dashed line 'limit of first chamber' in Figure 5.

Results and conclusions

The average reduction in specific power consumption was computed to be 14.95% over the three-month period immediately following the MillExCS installation. During this period, a 6.23% production increase was also observed. The savings in specific power alone for the 3-month period after installation paid for the entire solution. Additional benefits were that ball wear and average standard deviation for cement fineness also decreased over this period of time. Thus, by maintaining a fuller mill, the plant was able to produce more material for less power with less ball wear with a higher quality end product. After several months of operation with reduced fineness standard deviations, the output quality fineness targets were allowed to be slightly increased, such that even more production increases should be possible in the future.

In conclusion, it is essential that an expert system be used for control when multiple types of cement fineness are produced. This is due to the significantly different material flow of each material being produced and where primary grinding is occurring: the first chamber for coarse material and the second chamber for finer material with larger proportions of rejects. Equally essential is the requirement for a fast responsive and accurate volumetric fill level signal for each chamber in a two chamber mill. The control strategy needs to monitor both chambers in real-time and have the ability to quickly decide which vibration signal should be used for primary control.

References

1. "Crushing and Grinding Calculations, Part I-II.", Fred C. Bond, Br. Chem. Eng., 6: 378–385, 543–548, 1961.