Stirred Milling Technology – A New Concept in Fine Grinding

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ABSTRACT

Nowadays, the demand for a finer grind in minerals processing has set new challenges within the industry, particularly for grinding technology. Apart from a finer grind, energy efficiency is also a key driver in optimising comminution technology.

Stirred milling technology, already proven in many other industries, delivers a modern, sophisticated, flexible and energy efficient grinding solution for fine and ultra fine grinding in minerals processing. Fine grinding technology is utilised particularly in concentrate regrinding to complete the liberation of valuable minerals after the first stage of concentration. Maintaining the correct particle and particle size distribution of the regrind product is crucial for downstream process performance. Stirred milling technology offers the unique possibility for online control and optimisation of the regrind product particle size.

This paper describes the basis of this online control possibility and discusses the implementation of stirred milling technology in minerals processing, particularly in regrinding applications. The paper will also outline management and control of fluctuations in feed rate tonnages as well as particle size fluctuations in concentrate regrinding.

INTRODUCTION

The implementation of fine and ultra-fine grinding technology in the mineral process industry has increased over recent decades, predominantly due to the need to process finer grained ore bodies for valuable mineral liberation.

In April 2012 Outotec launched the HIGmill™ (High Intensity Grinding) for fine and ultra-fine grinding of metallic ores and concentrates. The stirred milling technology has been utilised for more than 30 years in paper filler and coating carbonate ultra-fine grinding. Further development backed by intensive test work has advanced this technology for wider use within the minerals processing industry. The following information illustrates this new approach to fine grinding control philosophy and summarises the recent test work, demonstrating the effectivity of fine grinding technology across a range of ore bodies.

STIRRED MILLING TECHNOLOGY

Mill structure

The vertical stirred media grinding mill uses a grinding chamber filled with small beads whereby comminution takes place by attrition between the beads. The stirring effect is caused by rotating discs mounted on a shaft. There are also stationary discs on the mill body positioned in between each rotational disc. The mill structure and its main components are presented in Figure 1.
Main components are:

- Motor
- Gearbox
- Grinding chamber
- Rotating shaft
- Hydro classifier for bead return
- Rotating grinding discs
- Static counter discs
- Feed inlet

**Principle of operation**

The mill feed is pumped to the grinding chamber via the feed inlet at the bottom of the mill. During continuous operation, the slurry flow transfers upwards and passes through the rotating discs and into the free space between the static counter discs and the wall lining (Figure 2). Depending on the application, the mill may be constructed with up to 30 sets of rotating and static discs. The ground product is discharged from the top of the mill by gravity as overflow.

Space around every rotational disc can be regarded as a classification stage where coarser particles move towards the chamber walls while finer particles move faster upwards through the disc openings. Due to the vertical arrangement of the mill, classification is conducted simultaneously throughout the grinding process with larger particles remaining longer at the peripheral, while smaller particles move upwards. The grinding beads stay in the mill by gravity however, as added insurance there is a hydro classifier positioned at the top and attached to the mill cylinder to ensure no beads are lost.
The process is typically an open single pass process and there is no need for an external classifier. Instead there is typically a scalping cyclone in front of the mill. This cyclone removes the ready fines and controls the slurry solids content to the targeted mill requirement. The combined cyclone overflow and mill discharge are the circuit product.

Gravity keeps the media compact during operation, ensuring high intensity inter-bead contact and efficient, even energy transfer throughout the volume. The disc configuration and the whole chamber geometry have been optimised for efficient energy transfer to the bead mass, internal circulation and classification. With the grinding media evenly distributed, the ore particles remain in constant contact, significantly increasing grinding efficiency.

Unlike tumbling mills, where comminution occurs from both impact and attrition grinding, in stirred media mills the particles suffer almost entirely attrition breakage between the beads. (Napier-Munn et al., 2005). In stirred mills there are no free-falling possibilities for grinding media, meaning that impact action does not occur. The bead size is small, typically 1 to 6 mm which means a large amount of contacts and high grinding efficiency especially in the finest range, where ball mills are not effective or cannot reach P80 10 to 40 µm.

The standard bead materials are ceramics, with a specific gravity (S.G.) of 3.8 to 4.2 kg/dm³ and bead filling is 50 to 70 % of the mill volume. The mill has a variable speed drive that makes it possible to adjust the power draw in a very wide range.

**FEATURES**

**Largest ultra-fine units**

The HIGmill is based on proven technology which has been developed over the past thirty years. There are more than 260 units installed, including over 10 mills with installed power of 5 MW, which makes the mills the largest ultra-fine grinding units in operation to date. The stirred media mill comes in various drum diameters and the mill height can be varied to optimise the media load and power.
input for specific applications. Chamber volumes range from 400 to 27,500 liters with corresponding drives from 132 kW to 5 MW.

**Operational flexibility**

All mills are equipped with a variable speed drive. Shaft rotational speed is the main on-line control parameter for the power draw of the mill. This enables a wide range of grinding applications to be addressed as the mill has excellent flexibility to adapt to fluctuating process conditions. In practice the power draw can easily be adjusted in a 1:3 ratio by controlling the shaft speed. If the specific grinding energy (SGE) target is permanently changed, the bead charge should be optimised to better fit the optimal operation of the motor.

Typical applications are the regrinding of concentrates (e.g. magnetic, flotation), iron ore tertiary grinding, precious metal ores, and fine grinding for hydrometallurgical processes. Particularly with rougher concentrate, re-grinding concentrate flow rates can vary a lot based on ore characteristics and up-stream process conditions.

There are a few options for grinding media namely ceramic beads at medium density (4 kg/dm³) or high density ceramics (>6 kg/dm³) and steel beads. Ceramics have very low wear and are more cost effective compared to small steel beads. Depending on the application, an additional benefit of ceramic media is prevention of iron contamination on the sulphide mineral surface, which would otherwise result in poorer flotation results.

A wide range of grinding media size can be used with typical bead sizes between 1-6 mm. Grinding applications can be classified as fine grinding and ultra-fine grinding:

- **Fine grinding:** F80 < 200 µm and P80 < 40 µm
- **Ultra-fine grinding:** F80 < 70 µm and P80 < 20 µm

Media sizes are chosen according to application. A rough estimation of the media top size required is 30 x F80 of the feed.

**Simple process design**

External classification is not needed for the mill product because the mill speed can be adjusted to control the product size. The product particle size distribution is narrow due to the vertical mill design coupled with the internal classification effect of the discs. If the incoming feed from the upstream process is diluted or already contains already significant amounts of product size material, a scalping cyclone (pre-classification) can be utilised. A simplified process flow sheet is presented in Figure 3.
High power intensity and energy efficiency

In stirred media grinding, the energy intensity (kW/m³) is very high versus tumbling mills. In the HIGmill the power intensity (installed) is typically 180 to 330 kW/m³. This means a very “packed” process: i.e., high throughput and/or high SGE in a small unit.

Energy efficiency/fineness vs. SGE is far better in fine grinding than in tumbling mills (Figure 4), as the finer the product, the greater the energy saving.

![Figure 4 - Fine grinding versus tumbling mills (Outotec, 2012)](image)

TEST WORK

Pilot mills

After launching a new fine grinding technology for the mineral processing industry, an intensive testing campaign was initiated using two pilot mills in Austria. The pilot mills were designed and built in co-operation with Swiss Tower Mills (STM) minerals and Kärtner Machinenfabrik (KMF). These units are available for laboratory and pilot scale test work.

The test units HIG5 (7.5 kW) and HIG25 (30 kW) are fully equipped small scale stirred media mills designed also for on-site campaigns. There are different sets of rotors available for both mills - “standard” internals are used for the finest applications and “coarse” internals for coarse feed applications up to about F80 of 300 µm, enabling the use of coarser beads of up to 6 mm.

In both pilot mills power draw is measured directly from the mill shaft by a torque sensor unit connected on the main grinding shaft. Both mills are equipped with variable speed drives.

The main values which are measured, displayed and recorded are:

- Torque of the main grinding shaft (Nm)
- Power draw of the motor (W)
- Speed of the grinding shaft (RPM)
- Calculated power from torque and RPM (W)
- Speed of the pumps (Hz)
- Speed of the mixers (Hz)
- Load of the mixing tank (kg)
Test procedures

There are two base line test procedures, continuous run and semi-continuous run. In many cases the available sample size is very limited especially in the case of green field projects. Continuous tests are easier to perform but it requires much more test material. The minimum amount of feed material needed for a semi-continuous HIG5 test is 30 to 50 kg which allows one set of test parameters to be tested. Ideally 200 to 300 kilos of sample is required to optimise the process parameters.

Continuous test run

A continuous test can be performed with both test units. The sample is mixed in a mixing tank to the appropriate milling density. The milling density is chosen according to the feed material S.G., with the target to maintain the volumetric density within set limits. Before the test the slurry is pumped in a closed circuit and the density in checked. If the density is not close enough the target, it is corrected.

The feeding pump is a peristaltic pump that gives a linear discharge vs. pump speed (RPM). The pump speed is adjusted based on pump calibration curves.

Other operational parameters are chosen and adjusted according to the test plan, which is based on experience to produce an SGE range that should cover the target particle size (P80 and/or P50 µm).

Before the first sampling round, milling density (%w/w solids) and flow rate (m³/h) are measured from mill discharge. The pump speed setting is not adjusted if the measured flow rate is within ±5 % from target and measured data is used for calculation. The mill power draw is recorded to the data logging system. Both torque and motor based data are recorded but the report is based on torque.

It is essential that the sample for particle size distribution (PSD) measurement is representative. Hence the minimum acceptable amount of slurry is four times the free volume of the mill. After each sampling point, operational parameters are changed according the test plan. Normally only tip speed is adjusted for the new SGE point, but milling density or flow rate can also be adjusted. Samples will be marked and stored for particle size analysis based on either laser or wet screening.
**Semi-continuous test run**

In a semi-continuous test run, the sample is fed several times (steps) through the mill with one set of parameters and a constant SGE. This procedure needs two mixing tanks for a slurry. The mill discharge is stored in mixer 2, which is used as a feed material in the next grinding step. The SGE is increased cumulatively in steps, and sampling is performed during each grinding step. So far this procedure is used only with the smaller HIG5 test unit. If a larger sample is available, the next choice is the continuous HIG5 test and with even larger samples, the HIG25 continuous test is preferable.

In both test types the results are shown as a performance graph where the SGE (kWh/t) is expressed as function of PSD (i.e. P80 µm as shown in Figure 6. As there are some fluctuations in individual measurements (flow rate, solids, power, PSD) needed for each test point, a regression fit is calculated. This formula can be used to interpolate SGE for any target fineness.

![Performance graph](image)

**Fig. 6 - Performance graph (Outotec, 2012)**

**Main operational parameters**

Test parameters are slurry milling density, feed flow rate / retention time, tip speed, mill internals, media filling rate, bead size/distribution and bead material.

Typical process parameters used in test work are:

- Milling densities 45 to 70 %w/w solids. (20 to 30 % v/v)
- Grinding media filling rate about 50 to 70 %v/v
- Ceramic beads (zirconium aluminum silicate) with density 3.8 to 4.2 kg/dm³. Also higher density ceramics and steel media can be used
- Bead sizes between 1.2 to 6 mm
- Wide range of tip speeds; from 1.5 to 9 m/s
- Retention times between 1 to 5 min
- Specific grinding energies from 2 up to 100 kWh/t

**Test material**

The basic test work was performed mainly with a NFQ (Nilsíä Fine Quartz) 0 to 0.2 mm, produced in SP Minerals Oy Ab Quartzite production plant in Finland. Other basic test material was NFQ 0.05 to 0.2 m from the same plant. Material selection was based on the homogenous mineralogy and PSD,
easy availability and easy handling. In this work the target was to gain a basic understanding of the mill performance and the influence of different adjustable parameters.

In parallel to the basic test work, pilot scale test work has been performed on a wide range of customer samples (ores and concentrates).

**SUMMARY OF MAIN TEST RESULTS**

A summary of the main outcomes is presented from an energy efficiency (EnEff) perspective. Energy efficiency is described simply as SGE (kWh/t) vs. P80 (µm). According to test work carried out with fine quartz the following can be summarised from the data obtained:

- Different Tip speed / flow rate combination produces same EnEff.
- Different density grinding media produces same EnEff.
- Different grinding media filling rate produces same EnEff.
- Continuous and Semi-continuous testing procedure produces same EnEff.

**Influence of tip speed and retention time**

In this test series tip speeds for each flow rate were 2.5, 4.5, 6.5 and 8.5 m/s. The retention times varied from 1 min (high flow), 2 min (medium flow) and up to 5 min (low flow). It can be seen that energy efficiency is constant on a wide range of product size and SGE as shown in Figure 7. The beads were 2.4 to 2.6 mm ceramics with 4.0 kg/dm³ density.

![Fig. 7 - Constant energy efficiency (Lehto et al., 2013)](image_url)

**Influence of grinding media density**

The influence of bead density was tested with three different materials: 4.1 g/cm³ (ceramic), 5.0 g/cm³ (HD ceramic) and 7.8 g/cm³ (steel). The beads were about the same size, a narrow fraction around 2 mm and retention time was the same in all tests.

The power draw is directly related to the bead density (bead mass with same volumetric filling), so tip speed was adjusted to produce similar power draws and SGE for each bead type.

Results are shown in Figure 8. It can be seen that EnEff stays the same regardless of the bead density. Thus using heavier beads does not bring any efficiency benefit. It only makes it possible to “pack” more energy into the same grinding chamber.
Influence of bead filling rate

The influence of bead filling rate was examined in a series of tests where all parameters were the same apart from the filling rate.

It can be seen that the same energy efficiency is achieved with different grinding media filling volumes, (Figure 9). Power draw is directly related to the volumetric filling. Volumetric filling does not, according to these results, affect the EnEff, but it can be used to optimise the power draw level. The beads were 2.4 to 2.6 mm ceramics, with 4.0 kg/dm³ density.
Comparison of continuous and semi-continuous tests and scale-up to industrial unit

Continuous and semi-continuous test work has given practically similar results in comparison (Figure 10). This means that both test procedures can be used in evaluating SGE. Also in this test 2.4 to 2.6 mm ceramic beads with 4.0 kg/dm³ were used and the feed material was fine quartz.

Typically, HIG25 gives about 20% better energy efficiency than the HIG5 if all the process parameters are the same (Figure 11). Operational practice from the carbonate industry shows that the scale-up factor from 25 liter size to industrial size is 1:1. So the sizing of an industrial mill based on a pilot trial is reliable and easy.
GRINDING CONTROL PHILOSOPHY

The flow from upstream processes can vary remarkably due to fluctuations in ore grade, quality and upstream process performance. According to the main results presented in the previous section, a new concept for on-line particle size control in regrinding can be presented.

The high intensity fine grinding concept offers a unique opportunity to measure and control product fineness on-line through the use of online control expert systems and particle size analysers. This is due to the mill’s a variable speed drive controlling the grinding shaft speed, which in turn controls the specific grinding energy (kWh/t) input into the grind material. The tip speed will be used to control power draw rapidly over a wide range. Feed rate fluctuations in upstream process can occur very quickly, however this fine grinding concept is fast enough to respond to these fluctuations. The power of the mill motor increases exponentially when the tip speed is increased (Figure 12) and vice versa i.e. if the shaft speed is doubled, the power draw is tripled.

![Fig. 12 - Power draw vs. tip speed in HIG25 (Outotec, 2012)](image)

**Control concept**

In the suggested control regime a set point for the specific grinding energy (SGE) is given in order to achieve the target product fineness. The expert control system, (such as Outotec ACT) uses feed forward and feedback control principles (Figure 13). The feed forward control principle is used by measuring scalping cyclone dry feed quantity utilizing flow and density measurements and adjusting the mill shaft speed to reach target SGE per total fine grinding feed flow. This principle ensures the target SGE is reached at all times even in fluctuating feed rate conditions. The feedback control principle is used by measuring the particle size distribution on-line by using particle size analyser technology. On-line particle size measurement will be used to control the particle size of the slurry flow to downstream processes. If the product size is out of the target set (coarser or finer), the upper level control (ACT) gives a new set point to the SGE. If there is no PSD on-line measurement utilised, the changing of the SGE set point is based on laboratory analysis.

If the texture of the ore and thus the acceptable liberation fineness changes, a new set point for PDS is given. The SGE set point is then gradually changed to reach the target PSD set point.

If the power draw demand permanently changes, the bead load is amended so that motor speed is close to the optimal. The make-up grinding beads are fed continuously to the mill along with the
slurry feed. The addition of make-up beads is controlled by an ACT algorithm based on power draw profile and previous data on real bead consumption.

CONCLUSIONS

Outotec’s stirred milling technology (HIGmill) is based on well proven technology, which can be applied to mineral processing applications. The stirred milling test work has given principles for parameter selection, industrial unit scale-up and a basis for on-line control of the entire grinding process. The process has been shown to be simple and robust, and have excellent energy efficiency through a wide operational range of process parameters. Since the energy efficiency is consistent, it is possible to control the specific grinding energy and product particle size by adjusting the shaft speed using the variable speed drive. The machine configuration allows for internal classification, whereby the coarser particles move towards the chamber walls while finer particles move faster upwards through the disc openings, reducing the potential for over grinding, allowing excellent energy efficiency. The stirred milling test work has also shown decreased energy consumption compared to conventional tumbling mills. The small bead sizes used in the grinding chamber result in a large amount of contacts and high grinding efficiency in the fine product size range (P80 10 to 40 µm).

REFERENCES

