GRINDING TEST FOR IRON ORE TERTIARY GRINDING CIRCUIT*

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Abstract
This paper presents a unique stirred milling technology, Outotec HIGmill™, a modern, flexible and energy efficient grinding solution for fine and ultra fine grinding being tested in an industrial scale level. The test was performed at an iron ore pellet producing plant in Sweden (for confidentiality reasons, it will be referred to only as “the client”) where a pilot HIGmill™ unit (HIG25) was installed parallel to a conventional regrind circuit to compare its performance to the existing ball mill. By using a continuous test run procedure and evaluating the parameters of F80, P80, mill shaft rotation speed and power drawn it was determined its grinding capabilities, operational flexibility and energy efficiency. Outotec HIGmill™ outperformed the existing ball mill in the plant proving its capabilities to grinding finer, with steeper particle size distribution (PSD) and much higher energy efficiency. The tests performed showed that, with further refining of its operation, it is capable of consistently deliver the required PSD with up to 30% higher grinding efficiency.
Keywords: Energy efficiency; Fine grinding; Vertical mill; Grinding mills.

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1 INTRODUCTION

In April 2012 Outotec launched a new fine grinding technology for the mineral processing industry. The technology has been utilised for more than 30 years in the calcium carbonate industry only, until recently when Swiss Tower Mill Minerals (STM) acquired rights for it for mineral processing. Further development backed by intensive test work has brought this technology to the minerals processing industry. Outotec, which sells and services the technology worldwide, is proud to present an update of this technology and show summary of the recent test work of this fine grinding technology on an iron ore application.

1.1 Equipment Description

1.1.1 Mill structure

Outotec HIGmill is a “stirred media” grinding mill, in where the stirred effect is caused by rotating grinding discs together with static counter discs. Mill structure and its main components are presented in Figure 1.

Figure 1. Outotec HIGmill™ [1].

The main components are:

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

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1.1.2 Operational description

60-75 % of the mill free volume is filled with grinding media (beads) that is typically 1-6 mm ceramics, with a density of about 4 g/cm3. The slurry enters a grinding chamber via the feed inlet from the bottom of the grinding chamber. The combination of slurry concentrate, grinding media (beads) and rotating discs provides momentum to stir the charge against a series of stationary counter discs. In a traditional ball mill grinding two main size reduction processes exists, impact and attrition. Impact is caused by lifting the balls with the help of liner and shell lifters up to a shoulder position from where they fall against the toe where the impact breakage process mainly takes place. Within the ball charge there is relative motion where balls are sliding and rolling against each other, and the attrition breakage occurs. In the stirred mills, like Outotec HIGmill™, there are no free–falling possibilities for grinding media, meaning that impact action does not occur at all or is very insignificant. The particles are ground practically entirely by attrition breakage between the beads [2].
During constant and continuous operation the slurry flow transfers upwards, the ore slurry passes through the rotating discs and the free space between the static counter discs lining the wall (Figure 2).

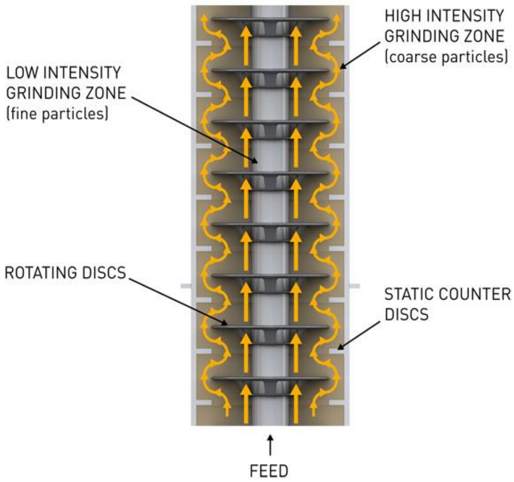

Figure 2. HIGmill™ operation principle [1].

Depending on the application there may be up to 30 sets of rotating and static discs. This one stage can be regarded also as one classification step where coarser particles move towards the chamber walls while finer particles move faster upwards through the disc openings close to the shaft. 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. This phenomenon enables simple process design. The process is typically a single pass with no external classification necessary.
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 optimized for efficient energy transfer to the bead mass, internal circulation and classification.
Make-up grinding media is fed to the mill together with feed slurry. With the grinding media evenly distributed, the ore particles remain in constant contact, significantly increasing grinding efficiency. The product discharges at atmosphere at the top of the mill. The combined cyclone overflow and mill discharge are the circuit product.

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1.2 Previous Test Work

Outotec has performed pilot scale test work on a wide range of minerals and process variables which enabled Outotec to gain a better understanding of the process variables effect on process design. Basic test work was performed mainly with a NFQ (Nilsiä Fine Quartz) 0-0.2 mm, produced in SP Minerals Oy Ab Quartzite production plant in Finland. Other basic test material was NFQ 0.05 – 0.2 m from the same plant.

1.3 Previous Test Work

Summary of the main outcomes is presented from Energy efficiency (EnEff) perspective. Energy efficiency is described simply as SGE (kWh/t) vs. P80 (µm). According to test work performed [3,4] we can summarize the following:

- Different Tip speed / retention time combination produces same EnEff.
- Different density grinding media produces same EnEff.
- Different grinding media filling rate produces same EnEff.

Continuous and semi-continuous test work has given practically similar results, as shown by Junnola [6]. This result is essential for mill sizing when there is not enough test material for continuous tests. This gives a reliable scale-up from semi continuous tests also to industrial size units.

2 MATERIAL AND METHODS

2.1 Test Period

Outotec and the client were operating the HIG25 container for the pelletizing tests between weeks 48/2013 – 9/2014. After that wear tests for the beads and the discs were made. Latter testing period was between weeks 13/2014 - 16/2014.

2.2 Test Setup

The HIGmill™ grinding test unit is built inside a container which makes it easy to transport. It is a standalone unit which carries all the necessary equipment inside including accuracy scales, tools, maintenance equipment etc. In order to start operating the unit, only electricity needs to be coupled. In the following picture (Figure 3) there is an overall view of the container.

Figure 3. HIG25 container unit [5].

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It’s preferred to be connected to an existing grinding circuit. The product from the mill can be fed back to the process and no loss of material will occur. At the same time it is easy to compare the analyses between the existing circuit and the circuit with the HIGmill™. For this particular test the grinding mill was set up parallel to the main ball mill. From the slurry stream heading to tertiary grinding ball mill the material was pumped to the HIGmill™ feed tank. When samples were not taken the product was directed back to the circuit.

2.3 Test Procedure

The tests followed the continuous test run procedure and were executed as follows:

1. Slurry from the process is fed to the mixing tank with SP40 hose pump provided by the client for appropriate milling density. Milling density is adjusted according solids density by adding water to the feed tank. The test is done batch wise.
2. The slurry is pumped through the mill chamber with a SPX15 hose pump.
3. Other operational parameters are adjusted according to the test plan; mill speed, pump speed, feed tank mixing etc. The test plan is made in order to produce performance graph which covers the target SGE (Specific Grinding Energy, kWh/t) range producing target particle size (P80 and/or P50, µm).
4. Before the first sampling round the mill is operated with higher rpm’s for 10 minutes and then dropped to the desired rpm. With the correct rpm’s the mill is operated for 8 minutes before sampling; four times the retention time. Higher revolutions at start will mix the mill thoroughly and result in better energy efficiency.
5. Sampling sequence is five minutes – each sample is about 1dl, samples are combined to give overall picture of the barrel material.
6. All sample analysis is made by the client.

2.4 Basic Operational Parameters

- Minerax ceramic beads, SG 3.9 (bulk weight 2.5 kg/l)
- Coarse liners and standard discs (12 pcs) installed in Lappeenranta
- Feed properties
    - SG 5.1
    - F 80 ~130 µm
    - Target product P 80 ~70 µm
    - Benchmark SGE 9 - 9.5 kWh/t
- Bead charge: filling rate 70 % (31.5 kg), see Table 1.

Table 1. Bead division inside the HIGmill™.

Bead size (mm)	3.5	4-5	Total
%	50	50	100
kg	15.8	15.8	31.5

2.5 Parameters and Sampling

Test parameters are according to Outotec’s experience and preliminary on-site testing. During the first weeks the operating parameters and bead charge setting were evaluated by testing different setups. Different ore types behave on their

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peculiar way and it's crucial that every ore type will be calibrated separately. The calibration is also important for the customer because the target can be different: depending on the customer, steepness of the PSD curve, energy saving or e.g. maximum particle size (P100).
The density of the feed material was decided by testing at which densities the mill transfers the most power to the material.
It was evaluated by testing during the week 5 which mill speeds will be used when producing material for pot furnace test. Two different mill speeds 375 and 425 rpm were chosen and 10 barrels of each speed was collected, altogether 20 barrels.
Density of the slurry and pumping speed stayed the same for the whole time. Only variable between the two tests was the mill speed. In the results week 5, 8 and 9 are examined.
Operating the HIGmill™ container efficiently needs two people's presence. Usually the container was operated with one Process Metallurgist from Outotec and at least one Process Metallurgist from the client. The client provided also additional help when some special tools or manpower was needed.
The samples were taken and analyzed by client's Quality Department. This was to ensure the transparency and reliability of the testing to the customer. The Quality Department arranged all the sample scoops, barrels and identification data to the sample barrels and bottles. The process reference samples were taken by the client. Generally the client supervised all the sampling inside the container. Sometimes the Quality Department did also the sampling inside the container.

3 RESULTS AND DISCUSSION

3.1 Results

The aim was to minimize the energy usage for tertiary grinding circuit. As important was to achieve the best possible PSD curve for the produced material, so that the pellet quality won't suffer. Important indicator for the material is the surface area which affects the pellet quality.
HIGmill™ material feed curve averages are in the Figure 4. In the Figure 4 HIGmill™ feed, HIGmill™ product and process reference PSD curves are combined with their average value. With the barrel number 11, new laboratory equipment was tested and therefore two different samples were taken.
The average feed and product material values for the 375 rpm (barrels 5 - 10) were F80 = 143.9 µm, P80 = 78.1 µm and for the 425 rpm samples F80 = 130.6 µm, P80 = 58.8 µm.
Reference product curves are taken from the actual process by the client in the tertiary grinding circuit. The sampling was organized by the client Quality Department. Density was measured with a Marcy scale. Flowrate was monitored using a stop watch while filling up two liter overflow vessels especially made for this purpose.

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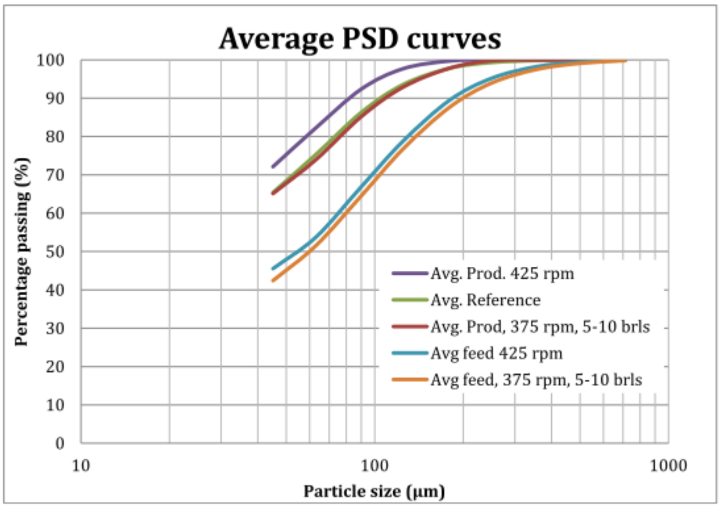

Figure 4. Average PSD curves in two different speeds, feed and process reference PSD curves.

During the week 5, performance tests were driven with different mill speeds. This was done was done to evaluate the best possible mill speeds for the pot furnace tests. The most suitable result gave SGE 5.4 kWh/t with feed size F80 = 131 µm and product size P80 = 74 µm, other results: see Table 5. All the performance trial points are plotted in the figure below (Figure 5). In the Figure 6 are all the SGE points recorded. Some of the test points done during week 5 gave significantly finer product. These points are just to show that finer product produced with HIGmill doesn't mean high power consumption. With about same power consumption as the existing grinding circuit P80 = 50 µm product is reached.

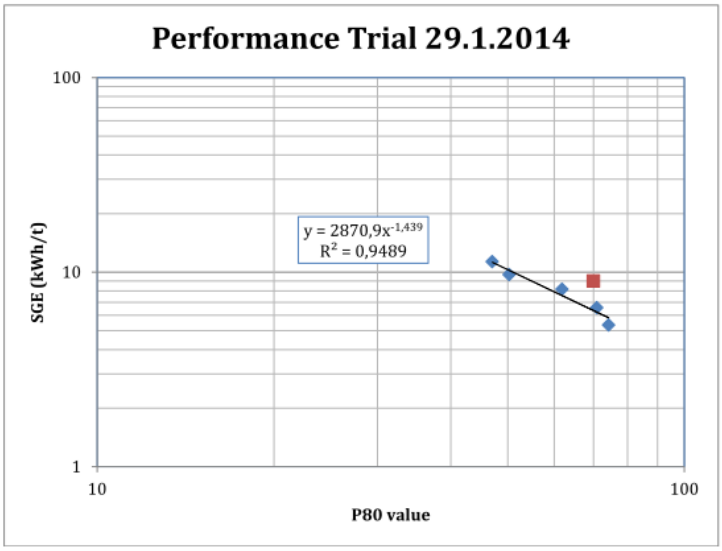

Figure 5. Performance trial results: P80 vs. SGE. Red is a reference point 9 kWh/t, 70 µm.

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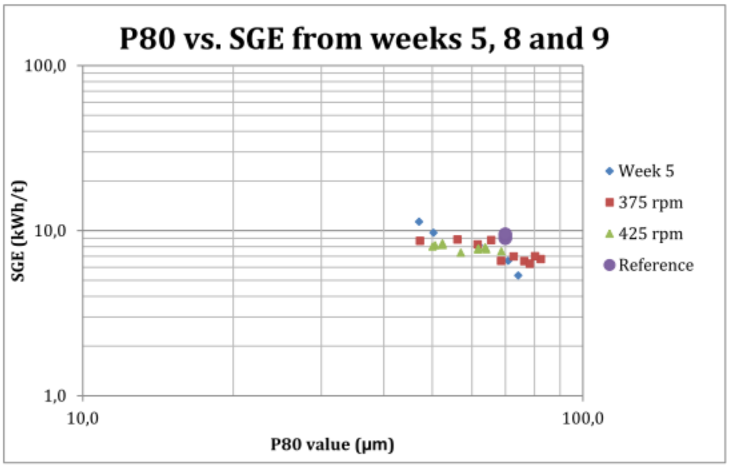

Figure 6. P80 vs. SGE from the weeks 5, 8 and 9.

One way to compare the power intakes is to back-calculate the Bond Work Index which is internationally used formula. Bond-formula has been used for decades and it is still valued high in the minerals processing area (Equation 1). The following Bond indexes are calculated from the barrels 5 to 20 and week 5 (Table 2, Table 3 and Table 4). The comparable process references are 9 and 9.5 kWh/t, F80 = 130 µm and P80 = 70 µm. The reference power intake with the existing tertiary grinding circuit was 9.6 kWh/t; in the week 5 performance test drives. In the tables 9.0-9.5 kWh/t value is used.

$$E_G = 10 \cdot W_i \cdot \left[\frac{1}{\sqrt{P_{80}}} - \frac{1}{\sqrt{F_{80}}}\right] \text{ kWh/t} \quad (1)$$

Table 2. BWi for the barrels 5-10 with 375 rpm and reference power intakes.

Barrel	5	6	7	8	9	10	Ref 9.0	Ref 9.5
BWi	23.4	22.5	22.3	20.4	24.5	22.4	28.3	29.9

Table 3. BWi for the barrels 11-20 with 425 rpm.

Barrel	11	12	13	14	15	16	17	18	19	20
BWi	19.7	17.7	16.9	17.9	15.9	19.5	20.2	17.6	19.3	17.1

Table 4. BWi for the week 5 performance tests.

Barrel	1	2	3	4	5
BWi	18.2	18.6	17.2	16.4	18.7

3.2 Result Analysis

According to the test results there is a significant drop in the power consumption. Existing tertiary ball mill circuit SGE is 9 - 9.5 kWh/t. According to these tests the power consumption with HIGmill™ could be as low as 5.4 kWh/t. In overall the feed was coarser and the product finer, which will further improve the efficiency. When the circuit is balanced the best possible power consumption can be reached.
The average feed and product material is described in the following table (Table 5). Standard deviation is included for feed and particle size. With the 375 rpm samples only the barrels 5-10 were used. Barrels 1-4 were disregarded due to the high fluctuation in the feed size. According to the test personnel it was difficult to adjust the density of the material to the correct level. Therefore the material was not as dense as the control samples. In those less dense material barrels (1-4), which were excluded, the grinding energy would have been even better.

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The latter (425 rpm) sample has smaller feed size and standard deviation is also smaller. This is cause of more intensive screening and large particle removal while filling the feed tank. Better screening was done due to the blockages inside the hoses. Metal fibers from the mine and “over size” particles from the process tend to block the test unit hoses. With production size mills this problem doesn’t exist because of larger diameter of the slurry piping.

It is also notable that the material passing for all the HIGmill™ test points <45 µm is 5 - 10% higher every time. Also the feed size has been coarser for the test mill unit.

In the Table 5 the operating BWi value is calculated across the tests. It is another way of showing that the power consumption is about 1/3 lower than with the existing grinding mill circuit. With the best one, week 5, the energy saving with the HIGmill™ could be almost 40% when comparing the BWi values. For the week 5 the average and maximum values are not recorded due to the reason that optimal points for the pot furnace tests were searched. This means that some of those week 5 values are outside of the optimal limit. SGE is calculated from the actual torque located in the shaft.

Table 5. Average F 80 and P 80 values with standard deviations.

	Week 5	**375 rpm**	**425 rpm**	**Reference**
F80 (µm)	131.0	139.8	130.6	129.3 (wk5)
STD deviation	-	12.2	10.3	2.7
P80 (µm)	74.3	69.0	58.8	73.3
STD deviation	-	11.4	6.5	2.2
SGE avg	-	7.5	7.9	9.3
SGE min	5.4 (P80 74 µm)	6.3 (78 µm)	7.4 (57 µm)	9.0 (70 µm)
SGE max	-	8.8 (56 µm)	8.4 (52 µm)	9.5 (70 µm)
<45 µm (%)	71	68	72	65
Operational BWi	17.8	22.6	18.2	29.1

Changes in the mill speed causes significant difference in the power intake and fineness, two different speeds were used according to the week 5 tests. Also the feed curves had variation. The variation is hard to exclude because the test is made as a batch wise and the material screening is made by hand. Small changes in the process, segregation inside the feed tank, feeding hose segregation (from the process) and changes in the operator’s way of keeping the suction hose cause inevitably differences. It was also noted that the final 1/3 of the feed tank density is lower. It indicates that the mixing is not sufficient for this kind of heavy material and heavy particles, considering the whole volume of the feed tank. Bottom of the feed tank was never used. Density of the material inside the feed tank was constantly monitored while filling the sample barrels. Sampling inside the container may play a small role also.

It was also indicated in the week 5 tests (Figure 3) that when the process conditions are in optimal level it is possible to reach very low power consumption values. With those results it was shown that when the feed and product material are similar to the process reference the power intensity for the mill can be 5.4 kWh/t.

In the Figure 4 product values are plotted against energy need. These points indicate that the working range as energy wise of the HIGmill is clearly below the existing one. Therefore the production size mill could even perform better with stabilized conditions.

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The fineness of the product is important. We need to wait for the pelletizing tests in order to decide whether the product is grinded too fine or not. It can be also possible that the finer product give better quality for the pellets.

Blockages during the operation may have effect to the final product variation. The blockages occurred usually after the mill feed pump at the point where there was the first reduction in the slurry hose. When the sample production, filling the barrel, had been started, few times the hoses got clocked. Then the sample collection was stopped and the procedure was started all over again by using higher revs for 10 minutes and then correct revs for about 8 minutes, four times the retention time, before starting. This was done to minimize the effect of the blockages and to retain as constant as possible conditions.

As stated before only two mill speed points and one variable mill speed point were chosen. All the HIGmills come with VSD (test and production size). With constant product flow and steady state operation the grinding circuit will be further developed as energy wise but also as PSD wise. With longer continuous run the bead charge inside the mill will become seasoned and include all size of beads. The test runs were operated only with two bead sizes, 3.5mm and 4-5mm which didn’t have time to wear. In order to reach optimal conditions inside the mill the bead charge should be seasoned.

4 CONCLUSION

Taken into account all the above Outotec HIGmill™ performs really well with the iron ore concentrate of this plant. Grinding efficiency with the test unit is 10 - 40% better compared to the existing circuit. With balanced continuous conditions the power saving can be closer to the high percentages indicated in the tests, meaning about 1/3 reduction in the grinding energy.

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