RECENT DEVELOPMENTS IN COARSE GRINDING USING VERTICAL STIRRED MILLS

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ABSTRACT

Vertical stirred mills have become a recognized solution for secondary, regrind and fine grinding applications in the mining industry due to their energy efficiency, small footprint and cost savings. This technology has further potential as the number of comminution circuits where the vertical stirred mills are paired with other energy efficient size reduction devices, such as HPGRs or crushers, is growing.

STM Minerals introduced the VPM^{TM} (Vertical Power Mill), which is a further development of the industry leading VRM^{TM} technology. The VPM^{TM} has a wider grinding chamber with increased spacing between grinding rotors, liners and stator rings allowing usage of larger grinding media suitable for coarse feed up to 6 mm top size.

An extensive test campaign has been performed to support promotion of the VPM^{TM} technology. Various feed materials have been used for testing at different grinding conditions.

This paper provides a detailed analysis of the VPM^{TM} test work performed including the energy efficiency benefits observed against conventional ball mills.

KEYWORDS

Stirred mill, coarse grinding, vertical mill, energy efficiency

INTRODUCTION

Vertical stirred milling is a well-recognized technology for the secondary, regrind and fine grinding applications and are increasingly replacing coarser ball mill applications in secondary and tertiary field. The driving force behind this trend is the higher energy efficiency obtainable for the vertical stirred mill.

Media size one of the most important variables for grinding efficiency (Brissette 2009). While the finer media has drove to increase efficiency for stirred milling technology for fine grinding technologies, we now look to the use of coarser media within a stirred mill for coarser feed size applications. Due consideration must be given to the grinding density and media size selection for the feed size and final product size. To enable use of the vertical stirred mill, the transfer size must be controlled by closing the upstream with a screen, this allows other energy efficient upstream technologies to be utilized such as HPGR or crushers. Another important consideration when comparing technologies is the scaleup factors of the technology for sizing up the full-scale operation and for making comparisons to the ball milling unit operations.

BACKGROUND

Vertical stirred milling technology has been shown to be more energy efficient than conventional ball milling. There have been various papers over the last 20 years examining this topic, some of which are highlighted below.

A comparison of different stirred milling technologies against ball milling was presented by Nesset et al in 2006. The feed size was approximately 70um and both the laboratory ball mill and laboratory vertical mill utilized 5mm steel shots as the grinding media. The energy efficiency benefit to the vertical mill at a grind size of 30um was calculated as approximately 37% from the figures provided. This may represent the more efficient use of grinding energy in the device (Nesset 2006).

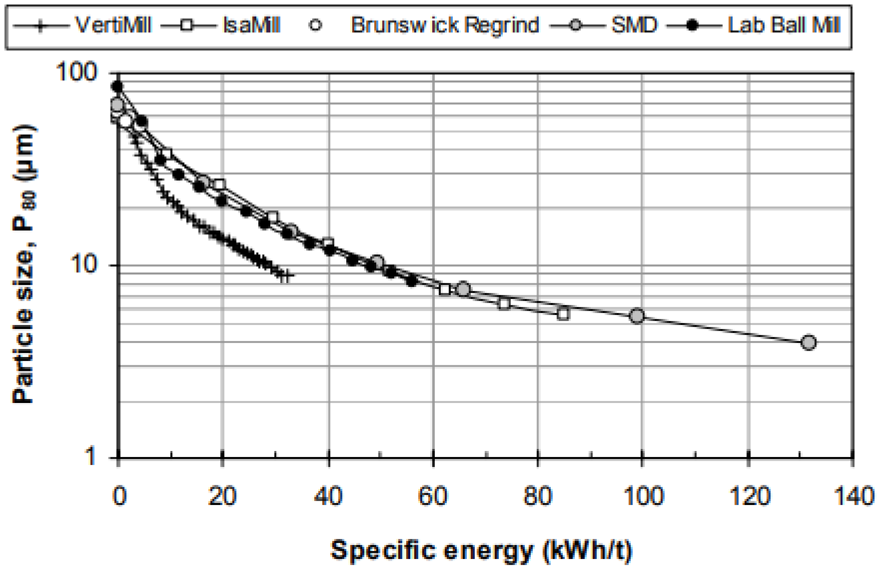

Figure 1: Energy Performance Graphs for Various Technologies studied (Nesset 2006).

Brissett (2010) reviews several industrial cases of stirred milling against ball milling. Vertical mills can operate at higher volumetric load (60-85%v/v) than ball mills (35-45%v/v), which then leads to higher productive throughput capacity (tph/m3). Fig 2 shows that that savings for a vertical mill can range from +44% utilizing the same 25mm media size and up to 60% energy savings with finer mill pleb media (Brissette 2010). The potential for Vertical milling technology for energy efficiency gains over ball milling is substantial.

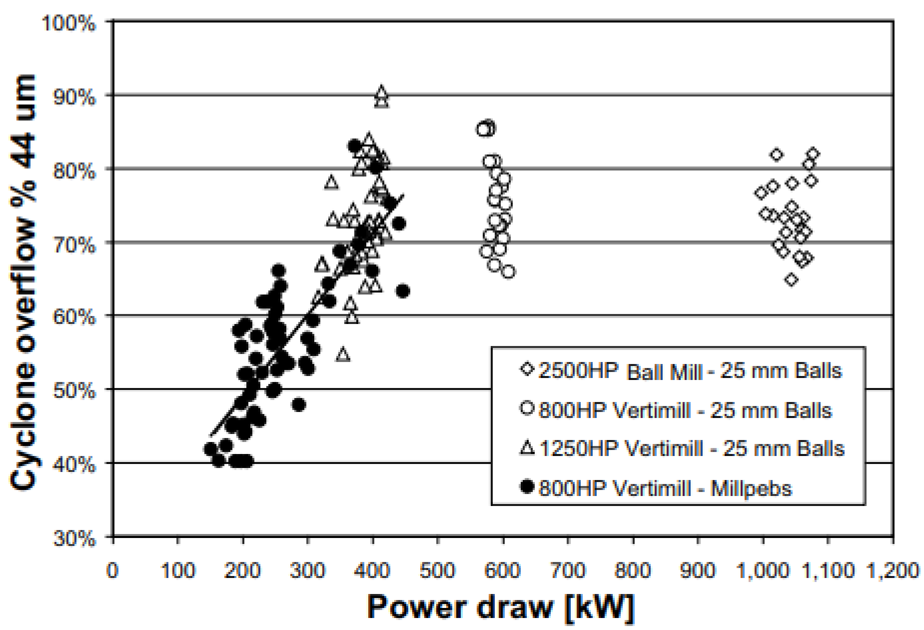

Figure 2: Power Comparison between mill technology and media size (Brissette 2010).

Pena et al (1985) presented operating data describing the how the energy efficiency of a vertical mill is better than a ball mill in a SAG mill circuit. The energy efficiency was grind size related, such that targeting a P80 of 1.19mm resulted in a 22% energy efficiency and on the fine end the P80 of 105um resulted in a 35.1% energy efficiency.

Houde et al (2019) reported on a vertical mill installed in a HPGR-VTM circuit at the Bougou mine in Burkina Faso in which two surveys where reported together with the efficiency factor relevant to ball milling The first survey had an F80 of 2.04 mm and produced a P80 of 63um for an efficiency benefit of 11% (Houde 2019). The second survey had an F80 of 3.22 mm and produced a P80 of 59um for an efficiency benefit of 17% (Houde 2019). These energy efficiency factors were later been disputed by Ballantyne (2021) due to the requirement that the analysis method not considering the steepness of SAG feed size distribution.

Pilot test work was carried out by Mazzinghy et al (2015) on a batch ball mill and pilot scale vertical mill to assess the energy efficiency factor. The results shows that the scaling factor of 1.35 was required to adjust the ball mill energy-specific breakage rates to match the breakage rates in a vertical mill. The vertical mill was found to have 35% efficiency gain over a batch ball mill with feeds up to P80 1.57 mm.

Technology scaleup is an important consideration when comparing the test work to the full scale and comparison to each technology. Both the fluidized stirred mills, the Horizontal Stirred Mill (IsaMill) and the Vertical Stirred Mill (VRM^{TM}) have a scaleup of factor of 1:1 when applied to test work (Larson M 2011, Paz 2019, Paz 2021, Harbort 2016, Gurnett 2019). The reason that the scaleup is 1:1 is that the same feed size and media size distribution is utilised in a miniature scaled mill.

The vertical gravity induced mill is sized based on Bond formula (Bond 1952) with applicable Rowland and Kjos (1980) efficiency factors. These factors are presented as a function of feed size F80 versus the Bond efficiency factor (Huang et al 2019) and reproduced below in figure 3. It shows that the parity of vertical mills equalling the ball mill efficiency could lie in the region of F80 = 3 to 4mm. The vertical gravity induced mill has a recommended efficiency factor to 0.80 (i.e 20% energy benefit) or higher when feeding the Vertimill with coarse feed F80 = 2.6mm (Hounde 2019). Ballantyne (2021) determined that the scaleup could be closer to 1.00 due to the consideration of the slope of the particle size distribution curve of the feed and products.

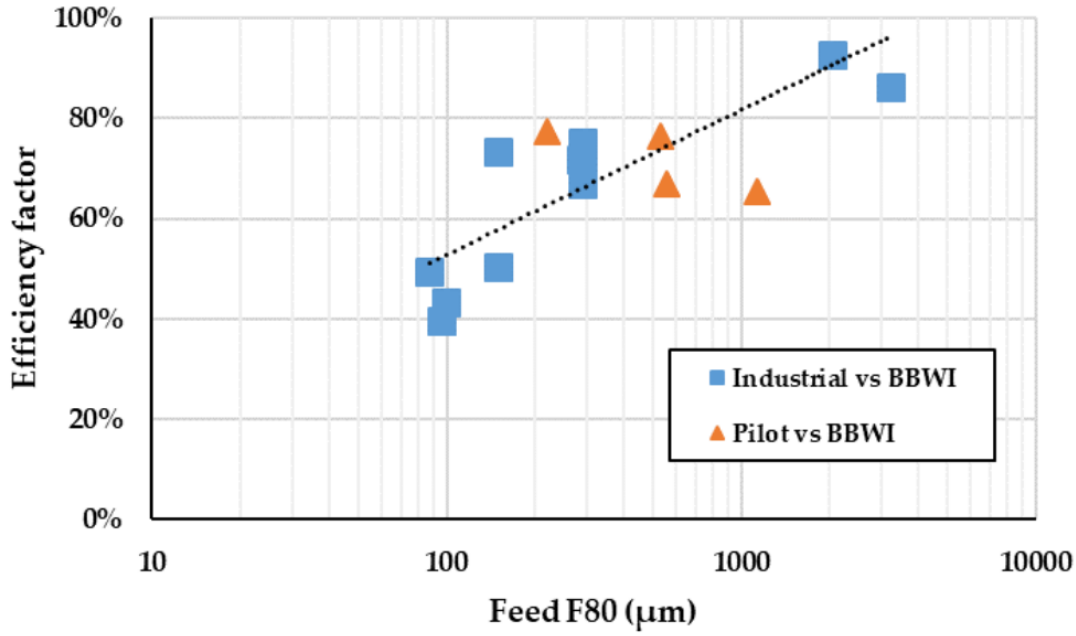

Figure 3: Relationship between feed size (F80) and Bond efficiency factor (Huang et al, 2019)

VERTICAL POWER MILL (VPM) – PRINCIPLE OF OPERATION

Declining ore grades and more complex ore bodies, as well as waste management and global net zero initiatives, lead to a clear trend for high tonnage yet energy efficient grinding. Introduced to the market in 2012 by Swiss Tower Mills Minerals AG, this unique grinding technology soon became the top-tier solution for the mineral processing industry. Designed for energy efficient fine/ultrafine/regrind/tertiary (VRM™) and primary/secondary (VPM™) grinding, the technology provides significant advantages.

Grinding in the STM mills is achieved by attrition, during interaction between feed particles and grinding media. The VPM operation is shown in figure 4. The feed slurry is pumped from the bottom through the stirred bed of media, which typically occupies up to 60% of the mill volume. Gravity prevents overflow of media from the mill and ensures it is evenly distributed across the grinding chambers. Rotating grinding rotors apply energy only in radial direction; therefore, no power is wasted for lifting the mill charge.

Feed and discharge are located at the opposite ends of the grinding chamber. Fixed stator rings on the mill shell and rotating grinding rotors create separate compartments around each rotor and make the slurry move through the mill similar to a plug flow reactor eliminating short-circuiting or dead zones.

Due to centrifugal force created by the rotors, coarser particles and grinding media are pushed out into the high intensity grinding zones on the periphery of the grinding chamber, while finer particles travel upwards closer to the mill shaft reducing grinding effect. This design feature prevents overgrinding and makes sure the energy is applied mainly to coarser particles helping maximize energy efficiency.

The slurry flow path together with the selective grinding mechanism result in a steep product particle size distribution where the target grind size is achieved in one pass through the mill with no recirculation needed.

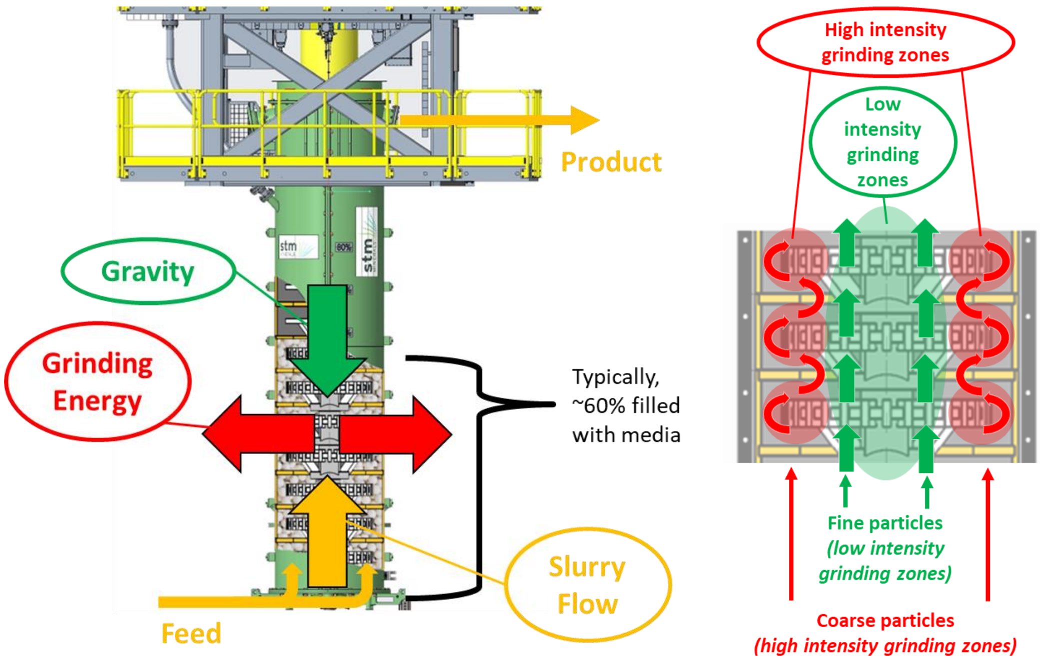

Figure 4: Principle of VPM mill operation

The mills are equipped with a variable speed drive to enable control of the applied specific grinding energy and thus management of the product size, compensating for possible fluctuations of the feed characteristics. This feature provides consistent and uniform product which feeds the downstream processes, maximizing recovery.

The VPM vertical stirred grinding mill, which has recently been introduced by STM, is a further development of the well-known and industry leading VRM milling technology. The VPM mill has a wider grinding chamber with increased spacing between grinding rotors and stator rings to allow usage of larger grinding media suitable for relatively coarse feed with the top size up to 6 mm.

EXPERIMENTAL SETUP

STM uses advanced testing methodology ensuring 1:1 upscaling accuracy from lab testing to production mill. The same grinding mechanism, media size, media type and slurry density are used in the test and production size mills, therefore no additional special scaling factor is required.

The VPM mill is the main piece of the test equipment (figure 5), which is also consist of:

- Feed bin for dry material
- Feeder with weight meter and variable speed
- Feed conveyor
- Continuous mixer (ploughshare)
- Feed pumps
- Discharge barrels
- Feed tank with impeller for slurry
- Control cabinet for mill and auxiliary equipment

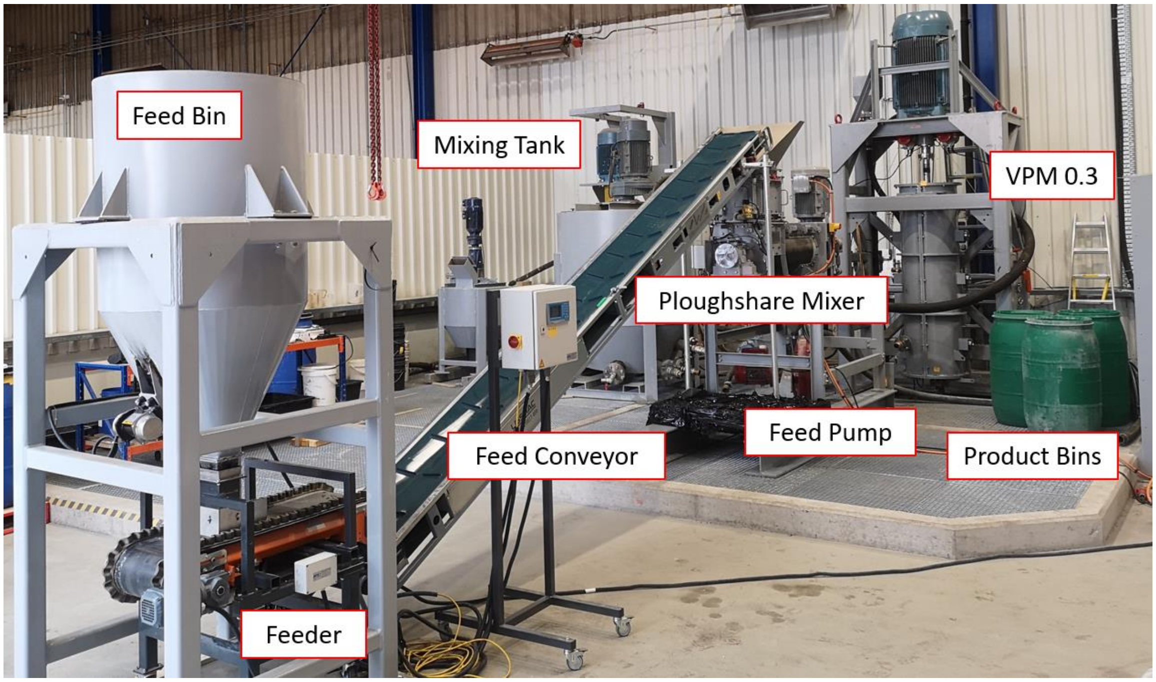

Figure 5: VPM0.3 at STM Test Center in Villach

There are two types of tests on VPM mill – semi-continuous and continuous, which assess a single stage grind using the VPM.

During the semi-continuous test (SCT) the slurry passes through the VPM mill multiple times. During the first pass the feed material will be fed from a feed bin into a continuous mixer (ploughshare) via conveyor at a certain feed rate. Water will be added to the mixer with a specified quantity to achieve required slurry density. The slurry is pumped through the VPM mill with a hose pump at a constant flowrate. The VPM motor power is kept constant and recorded. The mill discharges by gravity into a product tank or barrels from which the slurry after each pass is pumped into the feed tank with impeller. The product slurry is then used as feed slurry for the next run. The feed tank is used during the second pass and onwards. After each pass a sample of the mill product is collected and analyzed for particle size distribution. Each semi-continuous test will result in the performance plot describing dependence of the product size (P80) on the grinding specific energy (SGE).

During the continuous test (CT) the slurry passes through the VPM mill only once. Operational parameters are chosen to reach the target product size in just one pass through the mill. The feed material will be fed from a feed bin into a continuous mixer via conveyor at a certain feed rate. Water will be added to the mixer with a specified quantity to achieve required slurry density. The slurry is pumped through the VPM mill with a hose pump at a constant flowrate. The VPM motor power is kept constant and recorded. The mill discharges by gravity into a product tank or barrels and not used anymore. A sample of the mill product is collected and analyzed for particle size distribution.

A schematic process flow diagram for semi-continuous and continuous tests performed with VPM0.3 is given in Figure 6.

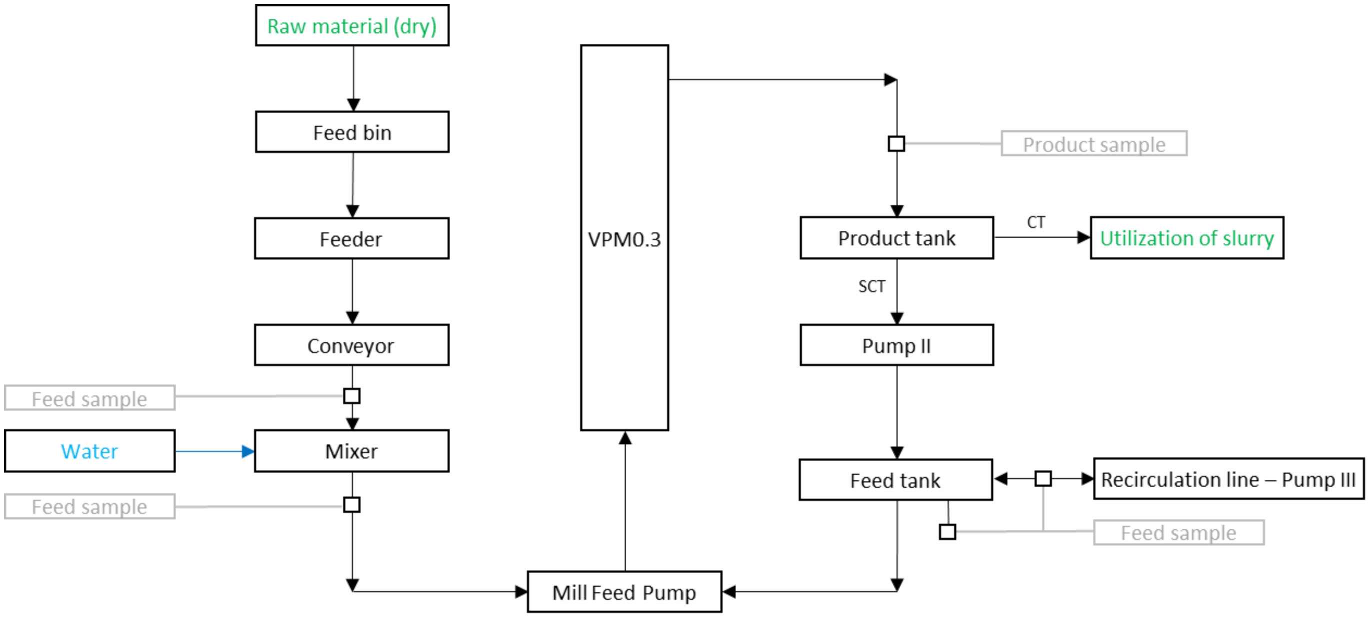

Figure 6: VPM0.3 SCT / CT Process Flow Diagram with sampling points

Main setpoints and process parameters to be followed during test work are:

- Feed material size F80, F50
- Feed material specific gravity
- Media size distribution
- Slurry density %w/w

The measured variables were:

- Shaft Speed
- Power
- Throughput (from flowrate and density)
- Product size distributions

In addition prior to testing the sample, the Bond ball work index was each sample prior to test work.

RESULTS AND DISCUSSION

An extensive test campaign has been performed to support promotion of the VPM^{TM} technology. Various feed materials have been used for testing at different grinding conditions. The samples tested included copper, gold and platinum ores in the top size range from 1 mm to 8 mm, represented by HPGR and cone crusher products. The variation of particle size distribution curves is given in Figure 7.

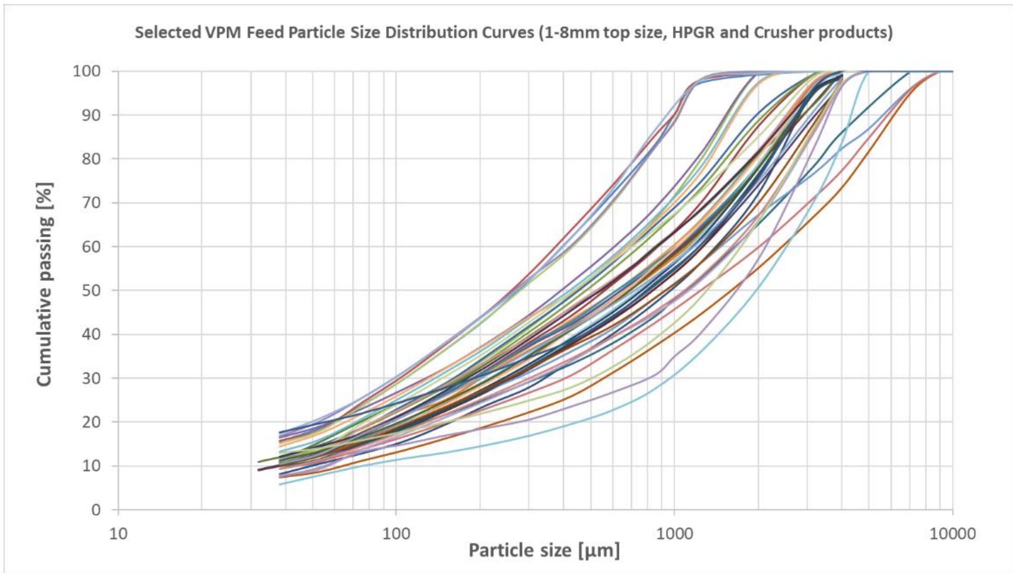

Figure 7: Selected VPM Feed Particle Size Distribution Curves

For each feed sample a suitable grinding media top size and media distribution was selected. Media size for each material tested is given in Table 1.

F100, um	F80, um	Media Top Size Range, mm
1000	700-800	12-22
2000	1200-1400	12-22
3000	1500-2000	24-32
4000	2000-3000	24-32
6000	3000-3500	24-32
8000	3500-5000	38-40

Table 1: Media Size Selection

Media distribution was selected as close as possible to a seasoned charge distribution inherent in a continuous stirred mill operation. A typical "seasoned" media size distribution (mass) should be negatively skewed in shape (figure 8), this is because of the higher mass associated with the larger diameter "fresh" beads." The wear law selected for the calculation of the seasoned media charge distribution was the Davis wear law or a constant mass wear law. Its essentially the general model of ball wear in a mill proposed by Austin and Klimpel (1985) with the constant defining the ball wear law set to 1.0.

$$\frac{dM_b(t)}{dt} = -k.r_b^{2+\Delta}$$

where Mb(t) is the ball mass after time t
rb is the ball radius
k is a constant whose dimensions depend on the value of Δ
Δ is a constant defining the ball wear law.

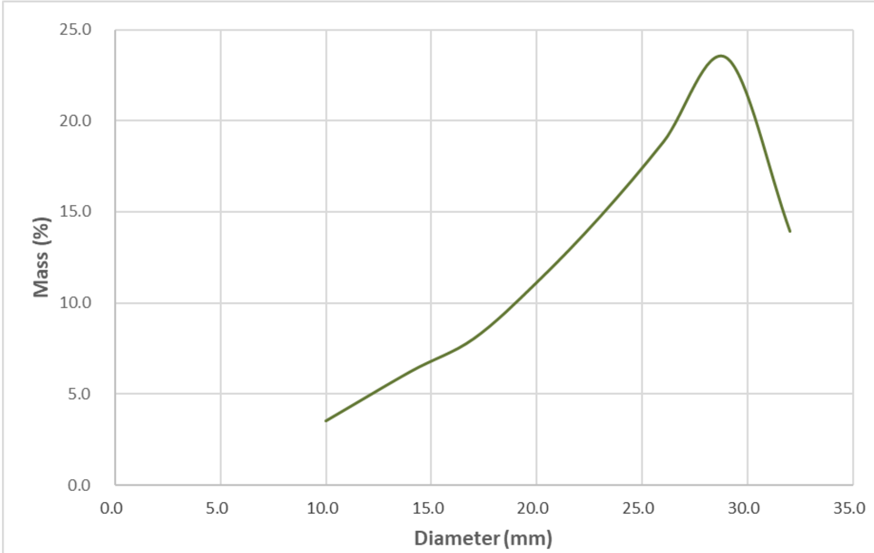

Figure 8: Example of Media Size Distribution Curves

The VPM grinding mechanism can be successfully applied to a wide grind range of coarse materials and produce uniform product size distribution curves shape (Figure 9). Regardless of the feed size the VPM produced a consistent product is achieved and it's only a question of the energy we need to apply. Figure 10 shows a few selected product size distribution curves (P80 close to 150 um) obtained when processing the same ore type with differing feed size from 1 to 8mm. We see clearly that the slopes of the product curves are very similar around the 150um, indicating that the VPM could handle fluctuations in feed size and achieve the similar product PSD curve.

Furthermore we can see that the slopes of the product PSDs are steeper than the feed PSDs (Figure 9,10). This proves that our VPM design with multi-compartment and selective grinding, minimizes any overgrinding of products, and contributes to maximizing energy efficiency.

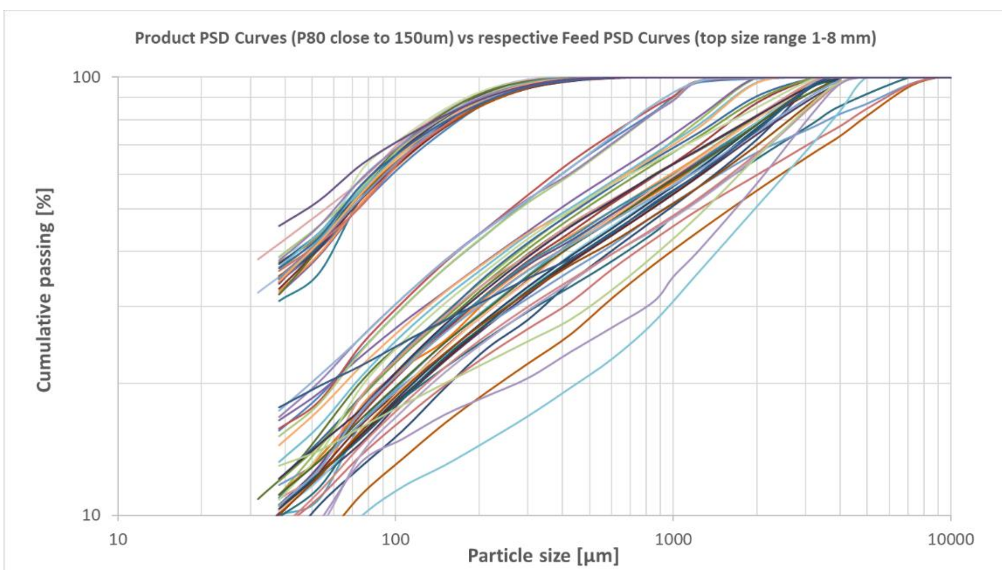

Figure 9: Product PSD curves vs respective Feed PSD

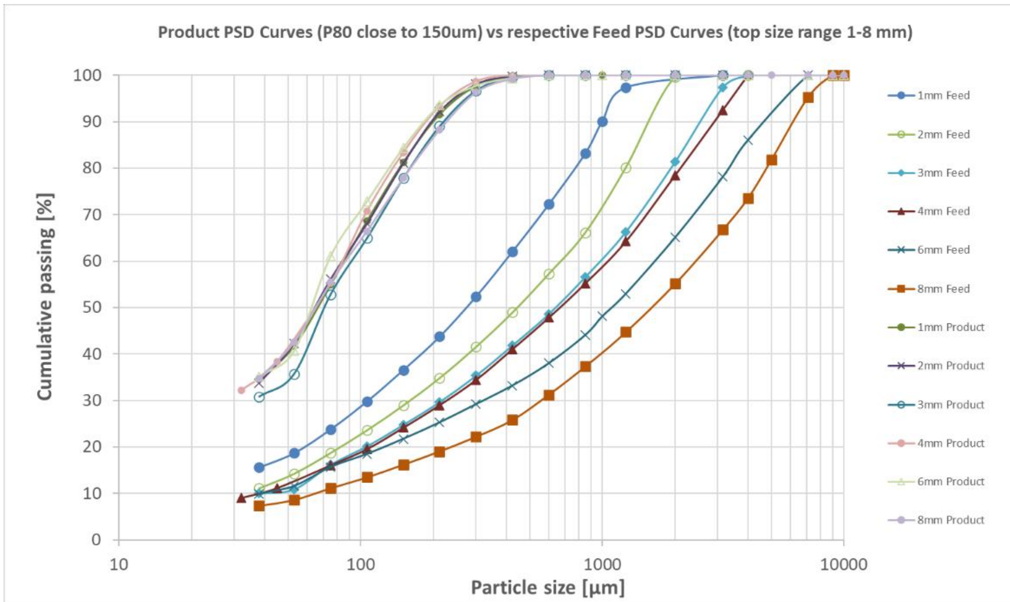

Figure 10: Product PSD curves vs respective Feed PSD for a HPGR project

Effect of Feed size

Feed size determines the required specific energy consumption to produce a certain product size. For both HPGR and cone crusher product, as expected, as feed size increases more energy is required to achieve a grind size. The HPGR product dependance is given in Figure 10, where the 1 and 2mm topsize utilized 22mm media diameter and 3mm topsize utilized 32mm media diameter. The slope of the line of best fit for the 3mm topsize was slightly more that the other lines with smaller topsize. Further media size optimization work is required in this area. The cone crusher product example is shown in Figure 11, both the 3 and 4mm topsize utilised 32mm media diameter. Both figures 10 and 11 exhibit good lines of best fit which validates the accuracy of the test work.

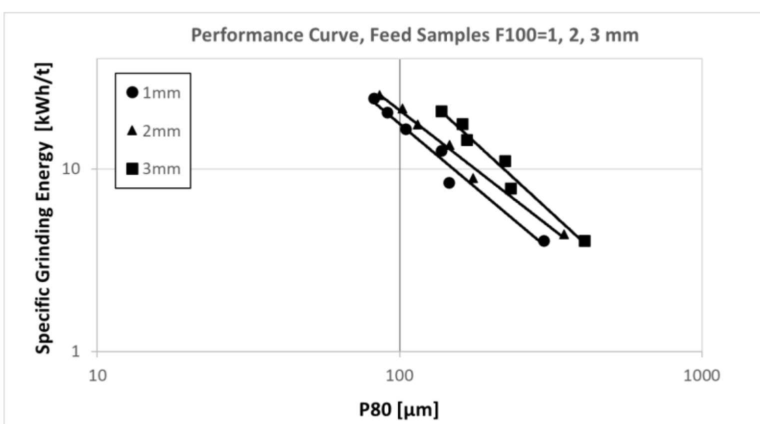

Figure 10: Tested material: HPGR product, slurry density 1.40-1.45 kg/L or 43-47% solids

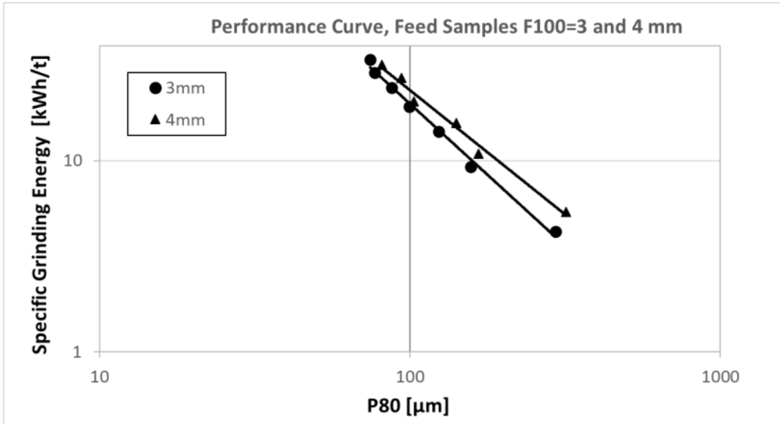

Figure 11: Tested material: Cone crusher product, slurry density 1.40-1.45 kg/L or 43-47% solids

Effect of Slurry Density

The ability to process slurries with low solids content could be an advantage for processing in HPGR circuits, since no additional dewatering stage would be required after wet screening (necessity when producing <4mm HPGR product). Figure 12 illustrates results of the tests conducted at 1.23 kg/L and 1.44 kg/l slurry density or 28% and 46% solids content. The energy efficiency is similar around ~110um, with the higher grinding density higher energy efficiency is observed at sizes less than ~110um, however this in just one grinding density test and further verification test work is needed. The typical grinding density range tested across the bulk of the tests was in the range of 40 to 50%w/w, which indicates the VPM can process this material. With regards to defining the lower density limit operating the aspects of wear rates needs to be considered, as low slurry density may result in higher media on media contact and higher media wear rates.

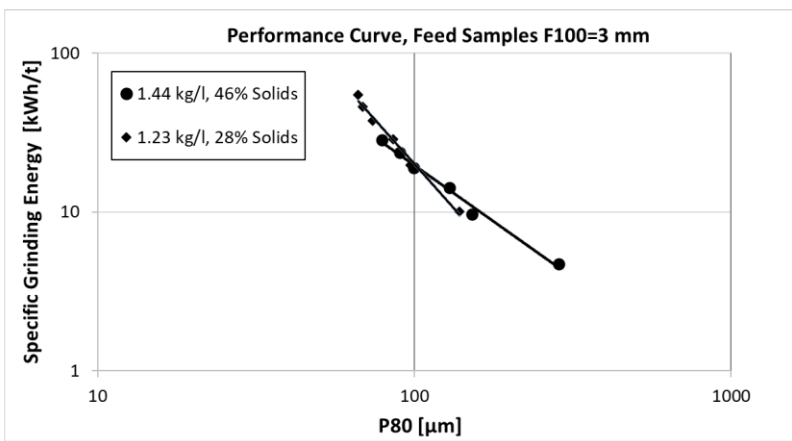

Figure 12: Effect of slurry density on grinding efficiency. Tested material: HPGR product

Specific Example

An important aspect of the test work was to compare efficiency of VPM with alternative grinding technologies such as conventional ball mills. As mentioned above every sample tested was subject to the

Bond Test to obtain the Ball Mill Work Index. Using the Bond/Rowland equation and applying the standard efficiency factors, it was possible to determine a theoretical ball milling energy and compare it with the VPM specific energy obtained during test work.

A worked example for the calculation of the efficiency factor EF factor for a target grind size is provided below.
The bond ball work index measured on the head sample prior to HPGR crushing was 16.5 kWh/t.
The test work was conducted on a HPGR product material with a measured F80 of 790 µm.

Target Grind Size = 167.8 µm

Calculation of ball milling energy:

F80 = 721.0 µm
P80 = 167.8 µm
Bond SGE = 6.59 kWh/t
EF 4 (coarse feed) = 1.000
EF 5 (fine grind) = 1.000
EF 7 (low reduction) = 1.044
Ball mill specific energy = **6.88kWh/t**

Calculation of VPM milling energy:

From the line of best fit the specific energy was calculated as **5.50 kWh/t.** Compares to **5.86** kWh/t in the test.

VPM Efficiency (EF) Factor:
Based on line of best fit => VPM milling energy / Ball mill specific energy x 100 = 5.50/6.88 x 100 = **79.9%**
Based on raw result => 5.86/6.88 x 100 = **85.1%**

Preliminary VPM Efficiency Factor

Based on this study we have preliminary defined the VPM energy efficiency factor. A considerable amount of VPM test work results (Figure 13) shows, that a single stage VPM could be more efficient over a theoretical ball mill in the order of 0-30% . Figure 12 can be expressed as this efficiency factor versus feed size range:

- 0.7 to 0.95 for sizes < 1mm
- 0.8 to 1.18 for sizes < 4.5mm >1mm

These preliminary efficiency results are comparable to other vertical regrind technology's as presented in figure 3. Our work continues in investigating how the VPM milling efficiency can be increased subject to the optimisation of media size and, grinding density etc. Further grinding media size optimisation is required to finalise these findings below. A side by side comparison between a production ball mill and pilot VPM is planned where in addition to SGE, the PSDs to be analyzed.

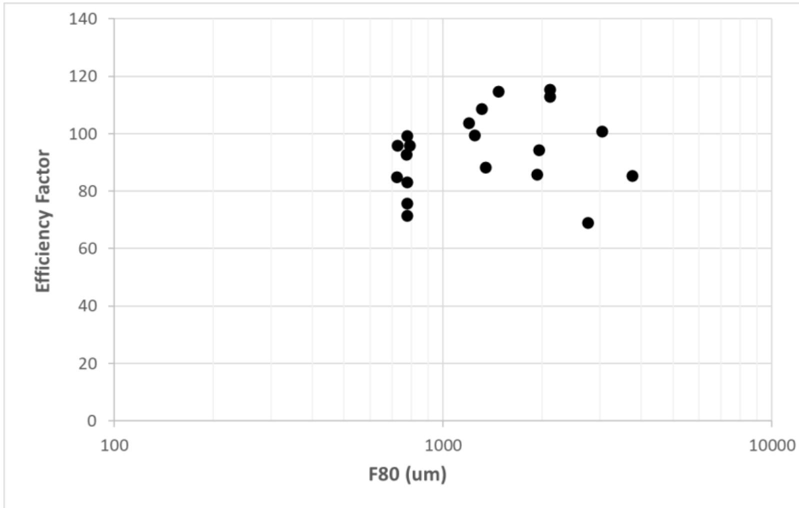

Figure 13: Feed Size (F80) Vs. VPM efficiency Factor (%)

CONCLUSIONS

Vertical stirred mills have become a recognized solution for secondary, regrind and fine grinding applications in the mining industry due to their energy efficiency, small footprint and cost savings. This technology has further potential as the number of comminution circuits where the vertical stirred mills are paired with other energy efficient size reduction devices, such as HPGRs or crushers, is growing.

STM Minerals introduced the VPM^{TM} , which is a further development of the industry leading VRM^{TM} technology. The VPM^{TM} has a wider grinding chamber with increased spacing between grinding rotors, liners and stator rings allowing usage of larger grinding media suitable for coarse feed up to 6 mm top size. An extensive test campaign has been performed to support promotion of the VPM^{TM} technology. Various feed materials have been used for testing at different grinding conditions. The materials tested included copper, gold and platinum ores in the top size range from 1 mm to 8 mm, represented by HPGR and cone crusher products.

The test work has proven that the grinding mechanism of the VPM mill can be successfully applied to grind coarse materials. The mill is able to produce a consistent product P80 given variations in feed size and it's only a question of the energy we need to apply.

It was found that a single stage VPM could be efficiently applied to feed sizes F80 < 4.5mm.
The VPM is 0-30% more energy efficient than a conventional ball mill.

NEXT STEPS

Our work continues in investigating how the VPM milling efficiency can be optimised for the parameters of media size and, grinding density etc, which will them allow finalisation of the VPM energy efficiency factors.

A side by side comparison between a production ball mill and pilot VPM is planned where in addition to SGE, the PSDs to be analyzed to study all aspects of application of both technologies.

Close attention to the test work procedure of the bond ball work index with respect to feed PSD shape.

The first large scale VPM mill for industrial application is currently being commissioned. It will give a lot of valuable information especially about scalability in coarse grinding.

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