A review of regrinding and fine grinding technology - the facts and myths

Dr Alex Jankovic, Metso Minerals Process Technology Asia-Pacific, alex.Jankovic@metso.com

ABSTRACT

Stirred milling technology is used extensively for fine grinding in the ceramic, paint and pharmaceutical industrials. It has been recently adopted by the mining industry. Specific conditions in the mining industry require somewhat different operation of this technology. However, the basic principles of operation are the same and the accumulated knowledge and experience developed in these other industries could be used to assist mining operations to get the most benefit from the stirred milling technology.

This paper presents some of the important aspects of stirred milling operation discussed in the literature and not commonly known within the mining industry: grinding media motion, active grinding volume, wear of grinding media and energy transfer, stress intensity, scale-up issues and flow limitations. The intention is to introduce a “different perspective” of stirred milling technology, in particular highlighting its potential benefits and limitations.

HISTORY

Stirred milling technology may be regarded as relatively new in minerals processing, however it is a mature and extensively used technology in the ceramic, paint and pharmaceutical industries. The latest development of this technology is in the area of “Nano-grinding” for grinding down to nano-sizes. One may say that stirred mills used today in mining and minerals processing are equivalent to the early models of stirred mills used in parallel industries.

The most commonly used stirred mills in mining and minerals processing are the VERTIMILL®, STIRRED MEDIA DETRITOR (SMD®) and ISAMILL® and a brief history of their development is given below.

VERTIMILL®

The predecessor of today’s VERTIMILL® is the Tower Mill which was introduced in 1953 by the Nichitsu Mining Industry Co., Ltd. It was invented by a chemical engineer, Iwasaki Iskoichi, and developed further with input from others. In the beginning, different stirrer designs were tested, with the screw type stirrer being chosen as the standard for use as a consequence of this testing. After Iwasaki’s death in 1954, a new company Nippon Funsaiki (Japan Crushing Mashines) in Tokyo was founded to exclusively produce the Abrasive Toushiki (steeple-like) Crusher. Hereafter, as the crusher become widely used, it was named “Tower Mill” and in 1965 the Japan Tower Mill Co., Ltd was established. In 1983, Kubota Ironworks Co. purchased the Japan Tower Mill Co., Ltd, and it supplied the technology as Kubota Tower mills . The latest “owner” of Tower mill is Nippon-Eirich.

In 1979, two Tower mills were supplied to the American Hoosier Power station, sparking interest in the technology by various American grinding equipment manufacturers. The Koppers Company, Inc. located in York Pennsylvania adopted the new fine grinding technology in the early 80’s (Hively and Jons, 1983) after which the Tower mill was manufactured by MPSI under a license agreement with the Japanese. In 1991, the license expired and Svedala Industries, Inc obtained all rights to the technology, except the name which was changed to VERTIMILL®. Svedela Industries (now trading under the banner of Metso Minerals Ltd) have installed over 250 of these units around the world.

STIRRED MEDIA DETRITOR (SMD®)

English China Clays developed an attrition stirred sand mill during the 1960’s and in 1969 the first production scale machines were installed in a kaolin plant. Currently ECC, now Imerys, operate more than 200 attrition sand mills in their kaolin and calcium carbonate plants around the world.

In 1996, Svedala and ECC signed a license agreement enabling attrition sand mills to be supplied for the Century Zinc Project. In the following year, this licence was expanded, enabling Svedala (and now Metso Minerals Ltd) to manufacture and supply the STIRRED MEDIA DETRITOR (SMD®) globally for all applications other than the white pigment industry.

After extensive testing, four SMD® mills were insalled at Pasminco's Elura operation in 1998 and 18 machines were installed in the Century Zinc concentrator in July 1999. Since 1998, 45 units have been installed in base metal concentrators all around the world.

ISAMILL®

The ISAMILL® was developed by Mt Isa Mines Limited and Netszch- Feinmahltechnik GmbH in the 1990s. By the end of 1994, this technology had become an integral part of the Lead/Zinc concentrator flowsheet. During 1995, the concentrator at McArthur Mining Limited commenced operation with a large 3 m^3 volume 1.1 MW ISAMILL® (Enderle et all, 1997).

ISAMILL® is in fact a large version of the Netszch horizontal stirred mill which was being used for various ultrafine grinding applications in various chemical processing industries. To make this horizontal mill suitable for use in the mining industry, the mechanical engineering challenges involved in expanding the volume by a factor of 6 (the largest mill at that time being 0.5 m^3 in volume) were addressed. The most distinctive feature of the ISAMILL is its media separation system that enables slurry to exit the mill but prevents the grinding media from leaving the mill (Enderle et all, 1997).

Since this time, the ISAMILL® technology has been implemented at several mining operations and undergone further development. The latest development is a 2.6 MW, 10 m^3 unit installed and operating in the Merensky Platinum Tailings retreatment process (Buys et all, 2005)

FUNDAMENTALS OF STIRRED MILLING

For development and refinement of any technology, an understanding of its fundamental processes is required. The fundamentals of fine grinding were established by Profesor Klaus Schonert in the 1980s and the fundamentals of stirred milling where developed in the 1980s and

1990s by German researchers, Steier, Schwedes, Stehr, Kwade and others. This work led to the development of a new generation of stirred mills capable of grinding finer and finer.

Stirred milling development work in the mining industry up until this time has been limited to that related to simply adopting the technology and making it work in high throughput, low value product conditions: larger mill sizes, low cost grinding media, wear protection, etc. Only limited work on the fundamentals has been undertaken and there therefore remains many important issues of stirred milling operation which are not well understood by the industry. A purpose of this paper is to review some of the findings of the fundamental work performed thus far.

MEDIA MOTION

The complex motion of the media and fluid in stirred mills is still not understood in detail. Several studies, both theoretical and experimental, have been conducted on different aspects of this subject and the results reported in the literature (Novosad, 1963, Rydin, et all, 1993, Blecher and Schwedes, 1994, Duffy, 1994, Zheng et all, 1995, Lane, 1999, Scot and Gutsche, 1999, Conway-Baker et all, 2002). The most comprehensive study was published by Theuerkauf and Schwedes in 1999 which explored the operation of both horizontal mills with disk stirrers and vertical pin mills. Media velocities were measured using a light-sheet technique. Figure 1 shows the comparison between the measured and calculated (using CFD) radial-axial fluid velocities. In general, good agreement was obtained, although it was found that numerical solution overpredicted the liquid velocity close to the stirrer shaft.

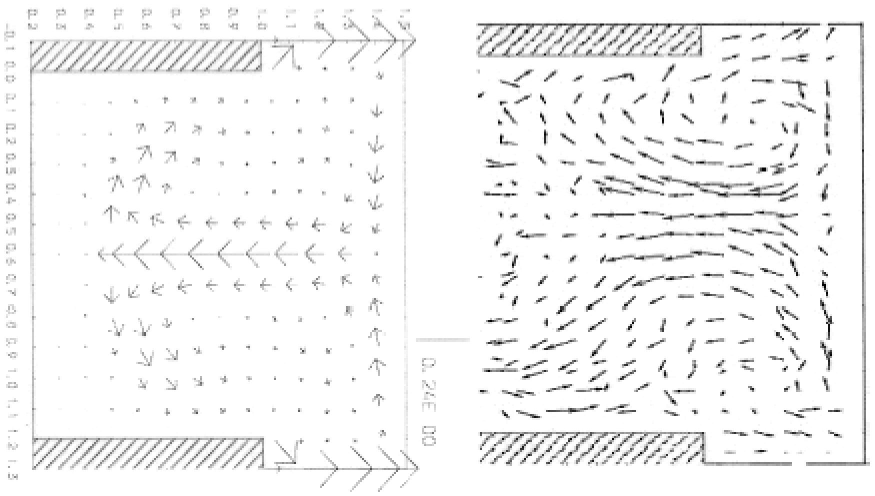


Fig. 6. (a) Calculated radial–axial velocities; normalized with $V_{tip} = 2.6$ m s^{-1}. (b) Measured radial–axial velocity; distribution for $V_{tip} = 2.6$ m s^{-1}.

Figure 1. Comparison between the measured and calculated (using CFD) radial-axial fluid velocities (Theuerkauf and Schwedes, 1999)

In the gap between the tip of the stirrer disc and the mill wall, grinding beads move in circular rings of different circumferential velocities. Figure 2 shows that these relative velocities decrease with increasing radius.

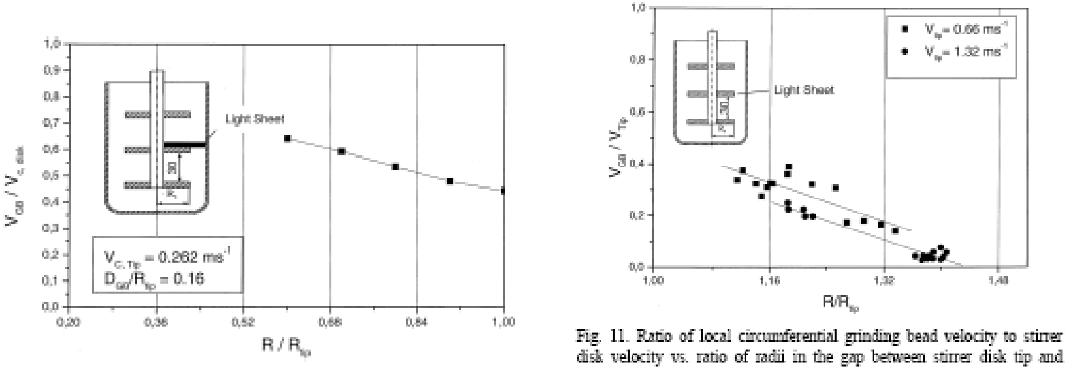


Fig. 10. Relative circumferential grinding bead velocity on a stirrer disk.

Fig. 11. Ratio of local circumferential grinding bead velocity to stirrer disk velocity vs. ratio of radii in the gap between stirrer disk tip and grinding chamber wall.

Figure 2. Relative circuferential grinding bead velocity on a stirrer disc (Theuerkauf and Schwedes, 1999)

When comparing the mixing achieved by disc and pin type stirrers, it was found that the flow field resulting from the pin stirrer was more mixed. The pin type stirrers exhibited higher and more fluctuating circumferential fluid velocities than the disc stirrers. It was therefore confirmed that to achieve intense mixing, a stirrer with pins should be used.

ACTIVE GRINDING VOLUME

The active grinding volume in a stirred mill was first determined by simulation and later investigated by measurements. Grinding is a consequence of the velocity gradient between the grinding media and the particles in the slurry which generate stress events. The different gray shades in Figure 3 indicate the different stress energies (dark zones=high stress energies) present within the volume of a stirred mill. The distinct stress energy regions in the mill are as follows:

V_1 – Media tangential velocity drops from a high velocity at the disc surface to about 50% of the tip speed over an axial distance of 2.5 mm, independent of disc size and disk spacing, but dependent on grinding media size.
V_2 – Media tangential velocity drops from almost tip speed to almost zero.
V_3 – Small stress energies are acting within about 60% of the mill volume.
V_4 – The grinding media and particles are interacting with almost the same velocity thus resulting in negligible stress energies. This region comprises about 25% of the mill volume.

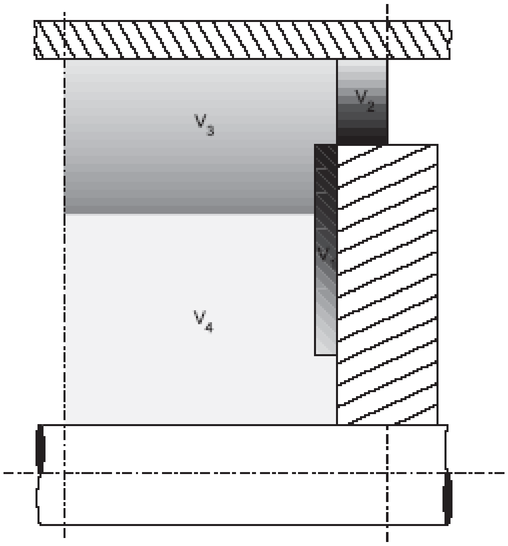


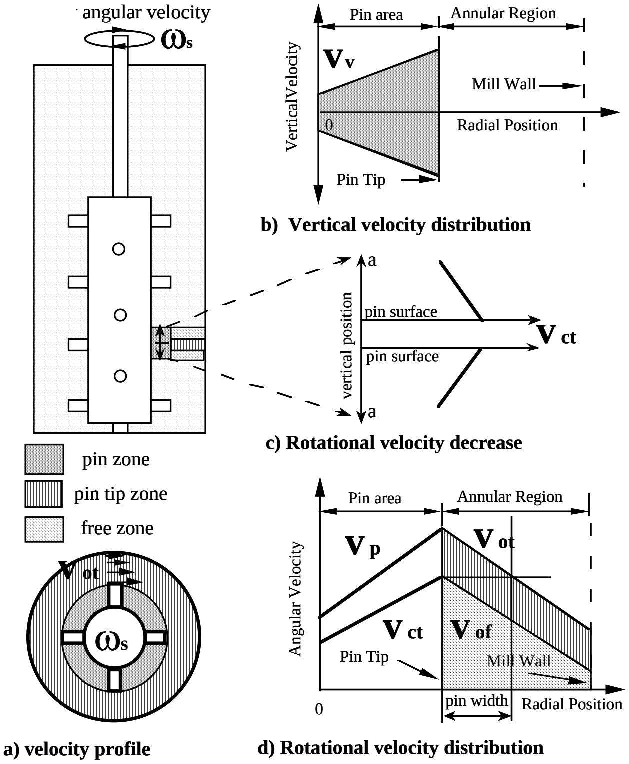
Fig. 9. Different stress energy regions in the grinding chamber.

Figure 3. Different stress energy regions in the grinding chamber (After Stender et all, 2001, 2004)

For typical fine grinding minerals processing applications (feed size about 30 to 50 microns and product size 7 to15 microns), it is estimated that only 10 to 15 % of the mill volume has stress energies higher than the 0.01 Nm required for active grinding. At coarser feed and product sizes, the required stress energy increases and the active volume decreases.

In 1997, Jankovic and Morell introduced the concept of separate grinding zones within the Tower mill and pin mill. Figure 4 and 5 shows the grinding zones and the grinding media velocity profiles assumed in these regions. This concept was used to create media motion and power models. A qualitative assessment of the areas where grinding may take place and the “dead volume” was also presented..

The active grinding volume of VERTIMILL® and STIRRED MEDIA DETRITOR (SMD®) is currently under investigation by Metso Minerals in an internal research program.



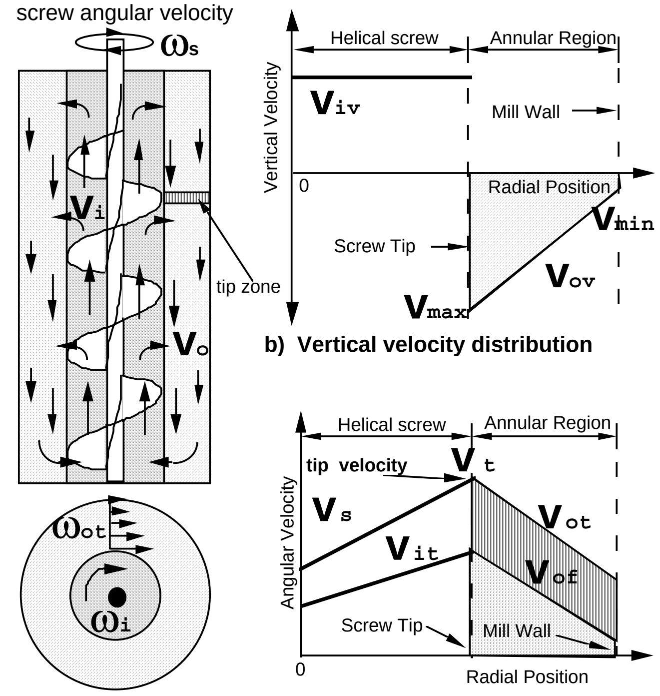
b) Vertical velocity distribution

c) Rotational velocity decrease

a) velocity profile

d) Rotational velocity distribution

Figure 4. Zones and media velocity profiles in a pin stirred mill (After Jankovic and Morrell, 1997)



a) velocity profile

b) Vertical velocity distribution

c) Tangential velocity distribution

Figure 5. Zones and media velocity profiles in the Tower mill (After Jankovic and Morrell, 1997)

GRINDING MEDIA WEAR AND ENERGY TRANSFER

Cost and performance are the primary considerations when selecting grinding media. Almost half of the operating costs of the SMD® mills at Century is the cost of grinding media (Burgess et al, 2001). Properties that affect the choice of grinding media include:

- Size
- Type
- Competency
- Hardness

A wide range of grinding media types are used in stirred mills, however in the minerals industry the decision is usually driven by cost which has led to the use of coarse sand , granulated slag and sized ore. A common problem with low grade sand media is that it has internal flaws and tends to break rapidly. This leads to high consumption of grinding media and high wear of mill internals.

Experimental investigation performed using fused corundum and silicon carbide as the grinding media in comminution show that the wear of these grinding beads is affected by structural constitution. The wear of grinding beads is determined by structure and hardness (Vicker hardness) of beads as well as the hardness and shape of ground material (Becker and Schwedes, 1999).

Figure 6 shows the effect of relative bead hardness (ratio between the hardness of grinding beads HVgb to hardnes of the product, HVp) on the wear of grinding beads for energy inputs of about 278 kWh/t. The wear decreases with increasing hardness of the grinding bead material.

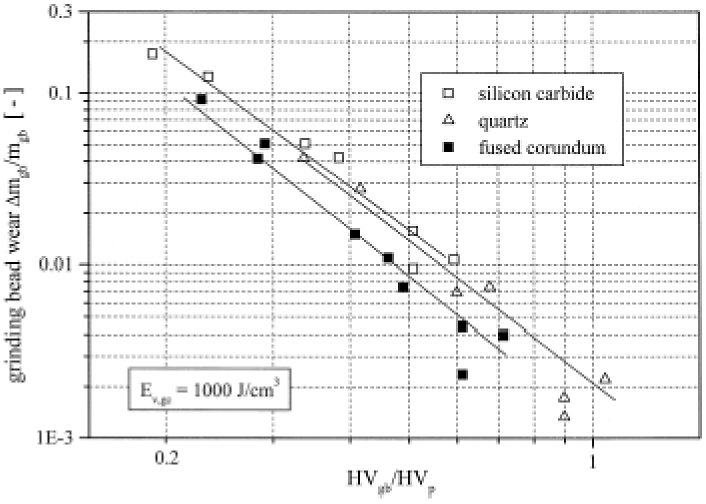


Fig. 6. Effect of hardness of grinding beads and product particles on grinding bead wear.

Figure 6. Effect of hardness of grinding beads and product particle on grinding bead wear (After Becker and Schwedes, 1999)

Although fused corundum and silicon carbide have the same hardness, higher grinding media wear was obtained when grinding with silicon carbide than with the fused corundum. It was found that the ground particle shape also had an effect on wear. When the relative bead hardness multiplied by the shape factor was plotted against wear (for a constant energy input) all results could be fitted by one line (see Figure 7).

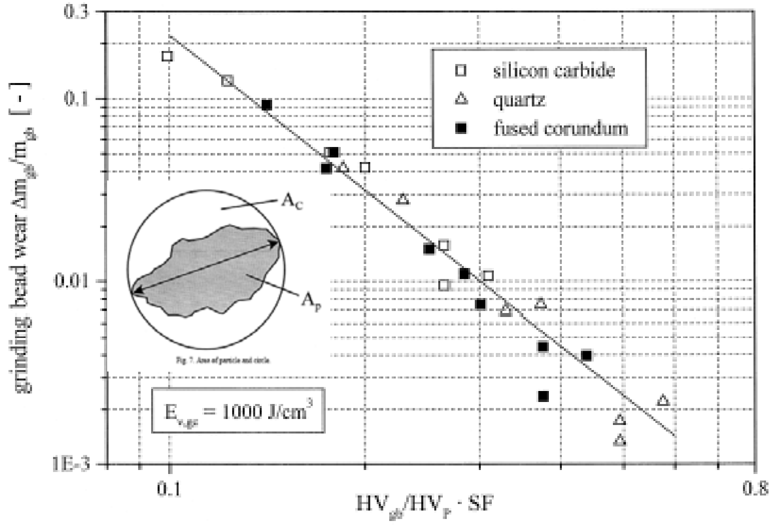


Fig. 8. Effect of hardness of grinding beads, hardness of product particles and shape of product particles on grinding bead wear.

Figure 7. Effect of hardness of grinding beads hardness of product particles and shape of product particle on grinding bead wear (After Becker and Schwedes, 1999)

Media hardness is acknowledged to have a significant effect on grinding performance (Lichter and Davey, 2001). Figure 8 shows test results from batch grinding tests performed for the same duration but with different media. This graph intends to show that harder media (Mohs scale) gives a finer product. However note that there is also a density effect which results in a higher power input with denser media. Therefore the effect shown in the figure is not only due to hardness.

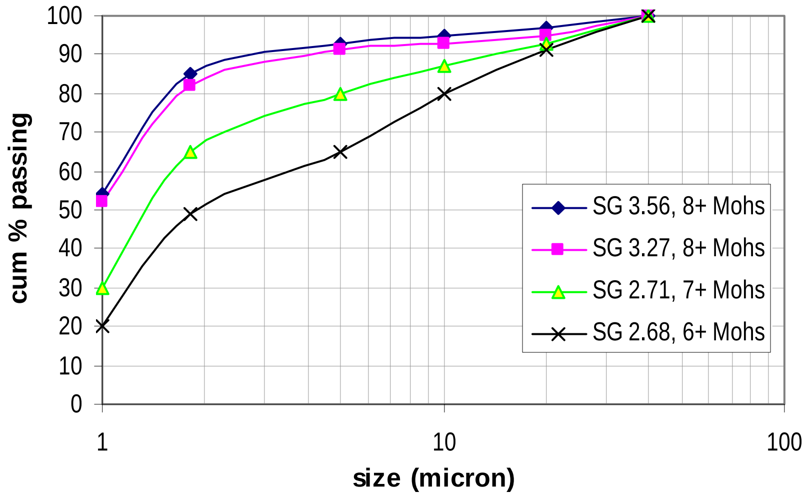


Figure 8. Grinding media hardness effect on grinding (After Lichter and Davey)

The effect of grinding media hardness on grinding efficiency was investigated by Becker et al, 2001. The energy transfer from grinding media to the product particles was represented as a single spring-mass model without damping, as shown in Figure 9. It was found that the portion of the energy which can be transferred to the product particle can be described by the following relationship:

$$E_{p,\,rel} = \frac{Ygm}{Ygm + Yp}$$

Where: $E_{p,\,rel}$ - portion of the energy which can be transferred to the product particle

Ygm - Young’s modulus for the grinding media

Yp - Young’s modulus for the product material

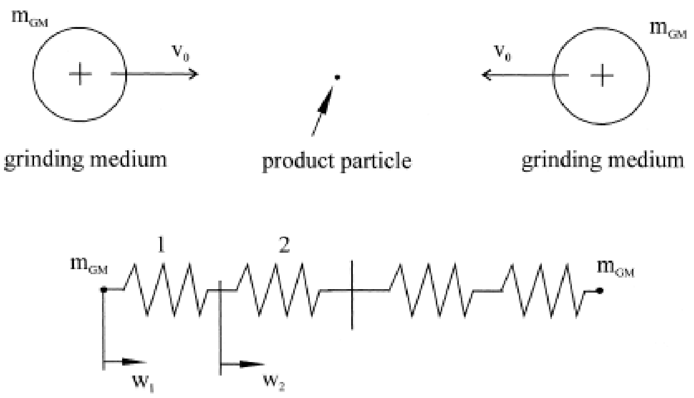


Fig. 6. Model of energy transfer from grinding media to product particles.

Figure 9. Model of energy transfer from grinding media to the product particles (After Becker et all, 2001)

Figure 10 shows the fraction of energy which is transferred to the product particle as a function of the Young’s modulus of the grinding media and the product particle. The higher the ratio, the more energy that can be transferred to the particle during one stress event. Since limestone has a relatively low Young’s modulus (30 Gpa), the amount of energy that can be transferred does not change significantly if the grinding media is glass (63 GPa) or steel (240 Gpa). Therefore, the Young’s modulus of the grinding media does not have a big effect on comminution of soft materials such as limestone or galena concentrates. However, for grinding harder products such as fused corundum or pyrite concentrates with a high silica content, choice of grinding media type is important as ineffective grinding media (softer than product) would result in inefficient grinding.

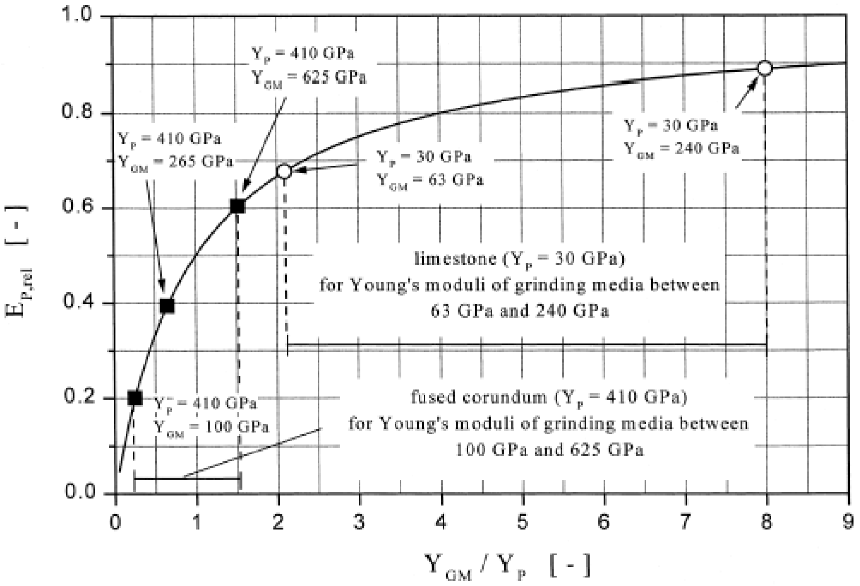


Fig. 7. Energy, transferred from grinding media to product particles.

Figure 10. Fraction of energy transferred from grinding media to product particles (After Becker et all, 2001)

At present, there has been no procedure published on how to select the appropriate grinding media for mineral processing applications. Usually, extensive testwork is recommended to assess and compare different options. Usually plants undertake industrial trials which are often expensive. The above examples show that there are fundamental properties of materials that can be related to performance in stirred milling applications. Prior to commencing an extensive testwork campaign or industrial testing, it is recommended that the fundamental properties of the potential grinding media and material to be ground be determined. This may significantly reduce the size of the testing program required and prevent costly unnecessary plant trials.

STRESS INTENSITY

There is a large number of parameters which can affect the grinding in stirred mills. Up to 44 parameters of influence were identified by Molls and Hornle (1972). A significant number of these parameters may be classified as unimportant but nonetheless the complexity of the subject is evident. Figure 11 shows that the specific energy describes the influence of mill size, tip speed of stirrer, solid concentration and density of grinding media on comminution results over a wide parameter range. As a first approximation, there is a straight line correlation between the specific energy and the produced particle size on a log-log diagram. However, there is a variation of more than +/- 20% from the fitted curve. It is estimated that measurement error amounts to +/- 8% only and the remaining variation is therefore a consequence of the effect of the process variables.

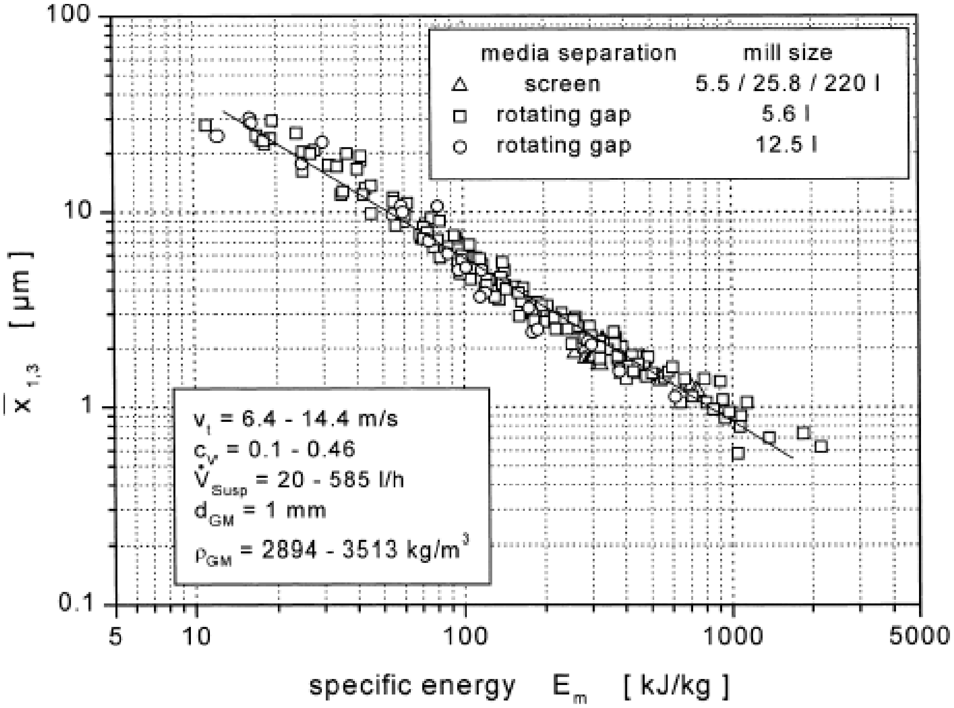


Fig. 1. Product fineness as a function of specific energy input for comminution of limestone (Stehr, 1982; Stehr and Schwedes, 1982; Weit, 1987; Weit and Schwedes, 1987; Weit et al., 1986).

Figure 11. Product fineness as function of specific energy input for comminution of limestone (Stehr, 1982; Stehr and Schwedes, 1982; Weit and Schwedes, 1987, Weit et al., 1986)

Numerous studies conducted in the last ten years have shown that stirrer speed and grinding media density and size have a significant influence on comminution results. Work published by Kwade and Schwedes (1996, 1999) indicates that in high speed stirred mills the effect of mill tip speed, media size and density can be evaluated simultaneously using the grinding media “stress intensity” approach:

$$SI_m = D_m^3 (\rho_m - \rho)\ v_t^2 \qquad (1)$$

where: D_m - grinding media size (m)

ρ_m - grinding media density (kg/m^3)

ρ - slurry density (kg/m^3)

v_t - stirrer tip speed (m/s)

SI_m - stress intensity of the grinding media (Nm)

For different specific energy inputs, different relationships exist between the stress intensity and product fineness. In Figure 12, the curves for six different specific energies are presented. Each curve has a different optimum value of stress intensity. With increasing specific energy and therefore increasing product fineness, the optimum stress intensity decreases because with decreasing particle size, less stress energy and smaller forces of pressure are required to break a product particle.

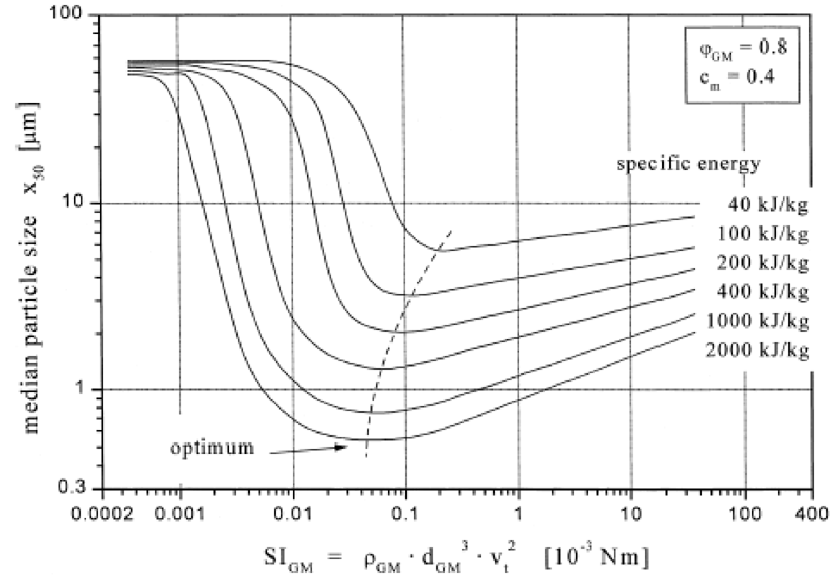


Fig. 9. Product fineness as function of stress intensity and specific energy (comminution of limestone).

Figure 12. Product fineness as function of stress intensity and specific energy input for comminution of limestone (After Becker et all, 2001)

The stress intensity concept was originally developed for high speed horizontal stirred mills and later studies conducted by the author (Jankovic, 2001; Jankovic, 2003) have shown that this concept is also valid for vertical stirred mills such as a pilot Tower mill and SAM mill as well as a laboratory pin mill (see Figures 13 and 14). This work also suggests that the stress intensity analysis from one mill design cannot be applied directly to a different type of mill.

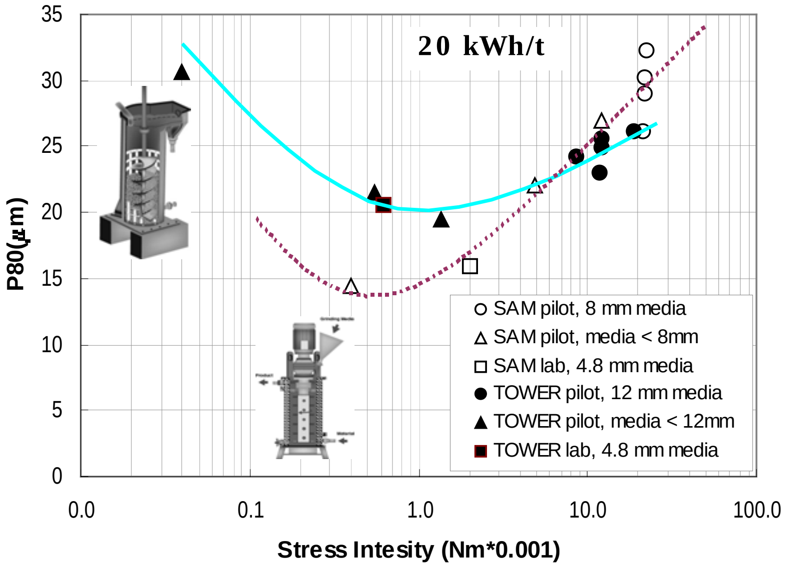


Figure 13: Grinding product size at 20 kWh/t energy input as a function of stress intensity (After Jankovic, 2001)

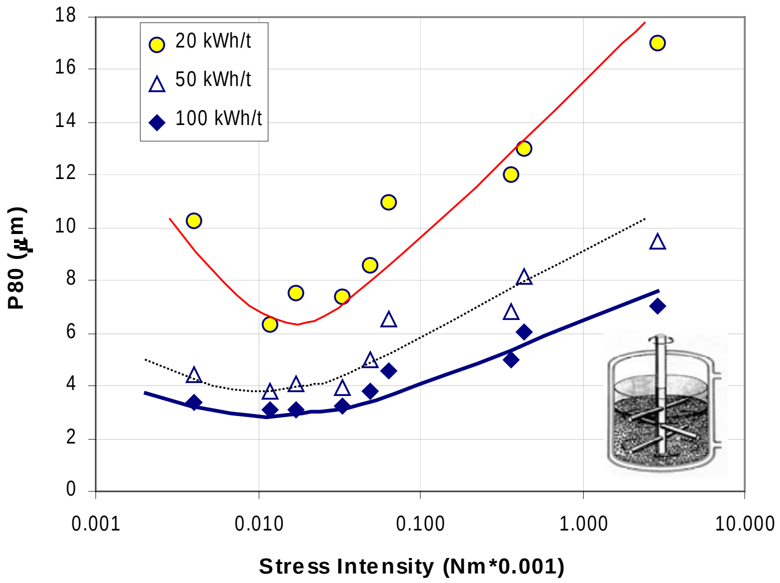


Figure 14: Stress intensity plot for zinc concentrate ground in a pin mill (After Jankovic, 2001)

Stress Intensity can be used for optimization of stirred milling operations as it effectively describes the effect of the most important variables. Once the optimum stress intensity is determined with one grinding media type, alternative media types need only be compared at this optimum stress intensity, thus reducing the amount of testwork to be performed.

APPLICATION

There are a number of important issues which should be considered when applying stirred milling technology in the mining industry: unit size, availability, operating cost, grinding range, scale-up and flowrate limitations.

SCALE-UP

The performance achieved from a full scale mill can be estimated directly from the relationship between specific energy and product size obtained at laboratory scale for both the STIRRED MEDIA DETRITOR (SMD®) and ISAMILL®. Figure 15 shows the laboratory 1.5 liter variable speed Netzsch mill used for ISAMILL® scale-up and comparison between the lab and full size unit grinding results. Energy consumption is measured directly using a power meter.

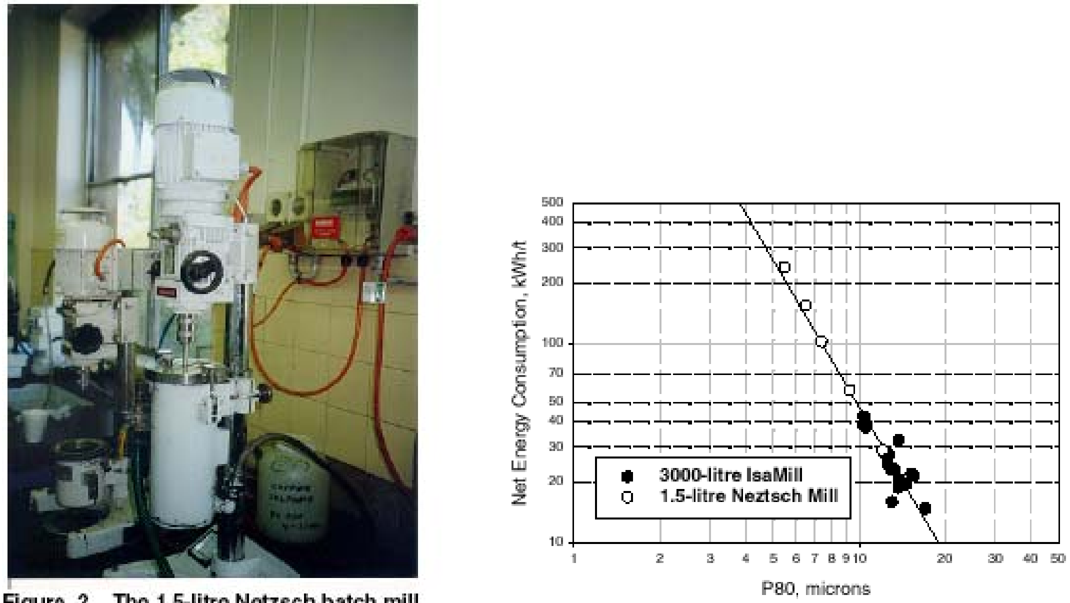


Figure. 2. The 1.5-litre Netzsch batch mill.

Figure 9. IsaMill scale-up with HMPR medium

Figure 15. Laboratory 1.5 l Netzsch batch mill and ISAMILL® scale-up example – (After Gao et all, 2002)

Figure 16 shows a picture of the laboratory Metso Minerals STIRRED MEDIA DETRITOR (SMD®) test mill which can be fitted with 1.4, 6.5 and 15 l capacity cylindrical grinding chambers. The grinding vessel is mounted on a near frictionless table which has a protruding torque arm and is free to rotate. The energy consumption is measured indirectly, by measuring torque reaction by a load cell. Metso Minerals also have two sizes of pilot units (7.5 kW and 18 kW) which can be used for continuous testing in the plant.

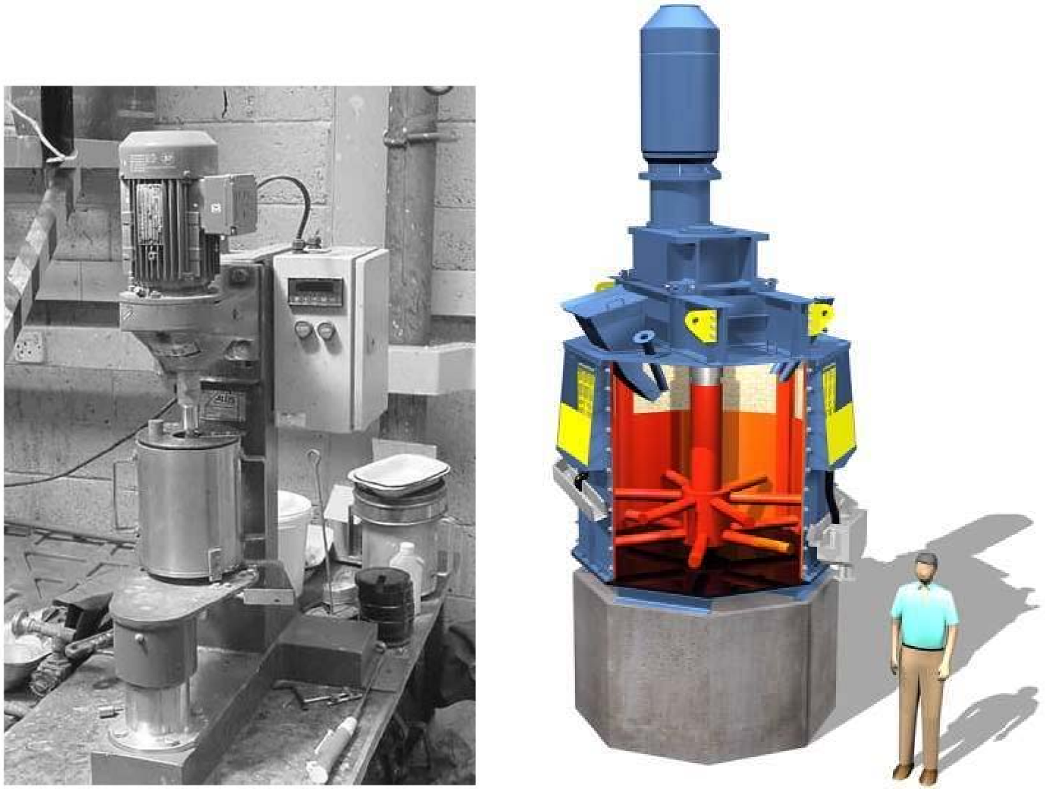


Figure 16. Laboratory and industrial size STIRRED MEDIA DETRITOR (SMD®)

Work published by Karbstein et al, 1996 shows that there is a limit in the size of laboratory units that can be used for direct energy based scale-up. Figure 17 shows the grinding results obtained with four different mill sizes. It can be observed that similar grinding results were achieved in 1 l, 4 l and 25 l mills while about double the energy was required in a 0.25 l unit. From this work it appears that the minimum mill volume for direct scale up is around 1 l. The grinding media used in this work were ceramic beads, 0.6 – 0.8 mm in size.

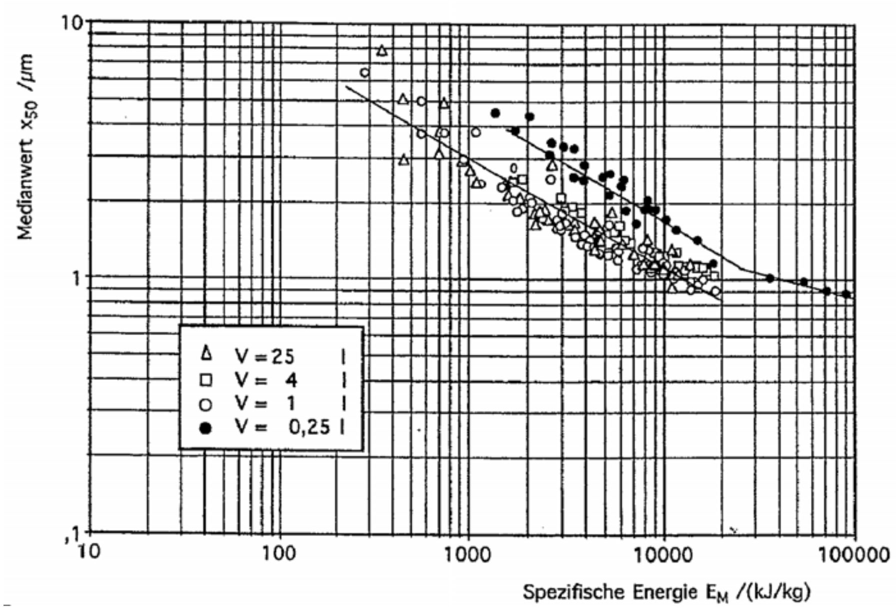


Figure 17. Effect of mill size on milling efficiency – After Karbstein et all, 1996

The influence of the grinding chamber size on specific energy requirements is also presented in Figure 18 (Stender et al, 2004). In this work a wide range of stirrer speeds, media densities and sizes were tested. It can be observed that there is a significant difference between the three mill sizes (0.73 l, 5.54 l and 12.9 l), with larger mills being more efficient. This graph is different from the graph in Figure 17 because it dos not indicate the “minimum mill size” appropriate for direct scale-up. Much larger media (up to 4 mm) was tested in this work compared to that used by Karbstein et al, 1996 (0.6 – 0.8 mm). This indicates that the minimum mill size for direct scale–up is dependant on the size of grinding media used. For smaller grinding media, below 1 mm, the minimum size of mill which would allow direct scale-up seems to be 1 liter. This does not seem to be the case for larger grinding media. More research is required to address this issue. Therefore, care should be taken when scaling up lab test results to full size mills especially when feeds coarser than 100 microns and products coarser than 25 microns are tested with grinding media larger then 2-3 mm. Pilot testwork is recommended to confirm the lab test results.

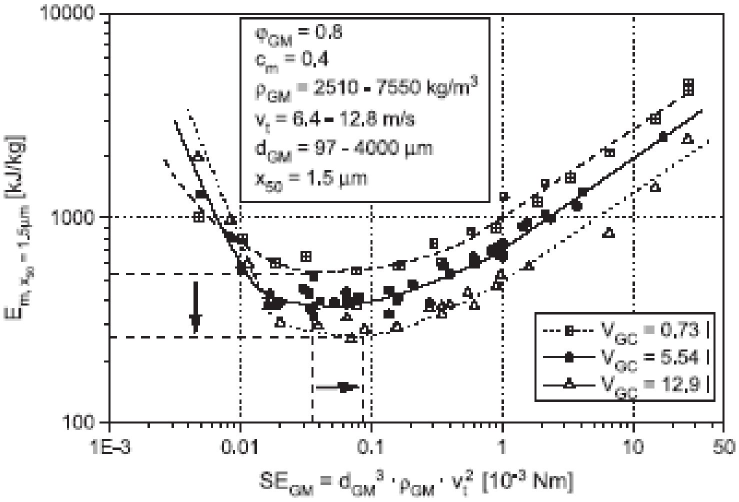


Fig. 6. Influence of grinding chamber size on the specific energy required to produce a product fineness of x_{50}=1.5 µm.

Figure 18. Effect of mill size on milling efficiency – After Stender et all, 2004

FLOWRATE LIMITATIONS

When considering the use of STIRRED MEDIA DETRITOR (SMD®) mills or ISAMILL®, it should be kept in mind that these mills are primarily designed to grind to very fine produce sizes (e.g. -20 microns at Mt Isa, Thalanga, Cadia and -10 microns at McAuthur River and Century). To produce these fine sizes, energy consumption in the order of 10-50 kWh/t is often required and therefore flowrates through the mills are relatively low (10-100 t/h) compared to that achieved in the primary grinding circuit. Theoretically, these mills can be used for grinding to coarser products, however flowrate constraints may in some situations be the limiting factor. This is especially important for the horizontally stirred ISAMILL® where the phenomenon of “hydraulic packing” has been observed (Roelofsen, 1991). The axial flow of slurry at high throughput tends to drag the grinding media towards the exit. This floating of grinding media result in inhomogeneous media distribution over the length of the milling chamber, with lower concentration at the feed end and higher concentration at the exit. As concentration of the media at the exit increases, the media motion near the mill wall becomes stagnant and at high flowrates heat generation increases. As mill size increases, tendency for hydraulic packing increases (Roelofsen, 1991).

Considering that hydraulic packing is observed in fine grinding operations where flowrates are low, it is expected that for coarser grinding applications with relatively low energy inputs (kWh/t), high flow rates would not be treatable in the horizontally stirred mills.

High flow rates and high slurry densities can cause fine grinding media discharge from the VERTIMILL® as observed in an industrial trial in Cannington's lead regrind circuit where 5-10 mm grinding media was used. Conversely, there have been no media discharge problems reported for the VERTIMILL® VTM1500 operation in the Cannington primary grinding circuit with very high flow rates (around 600 m3/h) through the mill. The ball size used is 20-25 mm and it appears that the upward slurry velocity is not sufficient to fluidise and lift this coarse grinding media to the mill discharge level. Operational data confirm that VERTIMILL® VTM1500 at Cannington works efficiently (operational and energy wise) at low (2.5 kWh/t) specific energy inputs and therefore low reduction ratios.

FUTURE TRENDS

There has been a clear trend of increased usage of stirred mills in the mining industry over the last 10 years. Stirred mills are now considered standard equipment for regrinding and fine grinding duties and there are indications that they are being considered for use in primary grinding circuits. This is certainly true for VERTIMILL® grinding mills which have already been used in typical ball mill applications (e.g. Chino and Cannington).

LARGER UNITS

As demand for stirred mills increases, the ability to increase the size of the mills becomes imperative. The largest VERTIMILL® is VTM1500 with 1.1 MW installed motor power and Metso Minerals also offers 1.1 MW STIRRED MEDIA DETRITOR (SMD®) stirred mills. The latest development in ISAMILL® technology is a 2.6 MW, 10 m^3 unit installed and operating in the Merensky Platinum Tailings retreatment process (Buys et all, 2005). The industry's principal of "the larger, the better" will force development of even bigger units in the years to come. There are design, mechanical and operational issues associated with an increase in size that will require addressing.

GRINDING MEDIA

The quality of grinding media is an important factor influencing the efficiency of operation of stirred mills, STIRRED MEDIA DETRITOR (SMD®) and ISAMILL® .. The highest quality of media available is manufactured beads which are used widely in other industries, however to date it has been cost prohibitive for use in the mining industry. Granulated slag from Mt Isa Mines and Colarado sand are the best quality of media used currently in the mining industry. Both are competitive, regular shaped and have a relatively smooth surface which minimizes the consumption of media and wear of mill internals. There are several other cheaper "local" alternatives which have been tested (and used) by the industry. However operational efficiency is significantly lower.

The only way to further improve the performance of the stirred mills is to use quality grinding media. Grinding media selection should be based on the compromise between cost and the value of improved performance. With the price of manufactured media trending downward, mills operating with manufactured beads are likely to become a reality.

CONCLUSIONS

Stirred milling development work in the mining industry up until this time has been limited to that related to simply adopting the technology and making it work in high throughput, low value product conditions: larger mill sizes, low cost grinding media, wear protection, etc. Only limited work on the fundamentals has been undertaken and there remains many important issues of stirred milling operation which are not well understood by the industry.

In this paper, some of the important aspects of stirred milling operation, not commonly known within the mining industry have been discussed: grinding media motion, active grinding volume, wear of grinding media and energy transfer, stress intensity, scale-up issues and flow limitations. It is the author's opinion that a knowledge of the fundamental processes occurring inside the stirred mills can be used to further optimize their operation.

REFERENCE AND BIBLIOGRAPY

Shibayama, A. and Mori, S., 1999. A History of the Tower Mill Pulverizer. Journal of Resourcess Processing Society of Japan, vol 46, No 1, pp.24-30

Kawabata Shigekatsu, 1955. On the Tower Abrassion Mill. Chemical Industry, July Edition, p. 620-622. (in Japanese)

Tsuchiya Shigeo, 1955. On the subsequent performances of the steeple-like crusher. Flotation, Autumn Edition, Vol.3, p. 28-34. (in Japanese)

Kawabata Shigekatsu, 1956. On the new type of abrasion mill (1st report). Compilation of theses from the Machinery Society of Japan, Vol.22, No 118, p. 443-449. (in Japanese)

Kawabata Shigekatsu, 1958. On the abrasive steeple-like crusher. Chemical Industry, March Ediction, p. 36-37. (in Japanese)

Kawabata Shigekatsu, 1958. On the theory of grinding and the design of the Tower Abrasion Mill. Journal of the Mining and Metallurgical Institute of Japan, Vol.74, p. 293-296. (in Japanese)

Kawabata Shigekatsu, 1959. On the dry type of steeple-like abrasive crusher. Journal of the Mining and Metallurgical Institute of Japan, Vol.75, p. 563-565. (in Japanese)

Kawabata Shigekatsu, 1959. New trend of the grinding machine (2nd report) – the Tower abrasion Mill. Chemical Industry, Supplement to Workshop Operation (Grinding), p.54-57. (in Japanese)

Kawabata Shigekatsu, 1959. The chemical apparatus and the “Tower abrasion Mill” equipment. Chemical equipment, July Edition, p. 97-100. (in Japanese)

Kawabata Shigekatsu, 1959. On the Tower Abrasion Mill. Lecture on grinding and classification delivered at the Powder Technology Committee’s meeting sponsored by the Kansai branch of the Chemical Engineering Society of Japan. (in Japanese)

Kawabata Shigekatsu, 1961. The Tower Abrasion Mill as a Pulverizer. Chemical Engineering, Special Issue, June Edition, p. 617-626. (in Japanese)

Kawabata Shigekatsu, 1966. Rationalization of grinding in the cement industry. May Edition, p.26-27. (in Japanese)

Kawabata Shigekatsu, 1968. Scale-up of the Tower Mill. Journal of the Mining and Metallurgical Institute of Japan, Vol. 84, p.37-39. (in Japanese)

Hively E.E., Jones S.M. Jr., 1983. Ultrafine Grinding in a Tower Mill, SME-AIME Annual Meeting Atlanta, Georgia, March 6-10

Buys, S., Rule, C., Curry, D., 2005. The Application of Large Scale Stirred Milling To The Retreatment Of Merensky Platinum Tailings. In Proceedings of the Canadian Mineral Processors, pp 649-663

Stender, H.-H., Kwade, A., Schwedes, J., 2004. Stress energy distribution in different stirred media mill geometries. International Journal of Mineral Processing, 74S S103-S117

Blecher, l., Schwedes, J., 1994. Energy distribution and particle trajectories in grinding chamber of a stirred ball mill. Procc. XIII Europian Comminution Conference, Stocholm. pp 686-697.

Novosad, J., 1964 a. Studies on Granular Materials I. Collection of Czechoslovak Chemical Communications, Vol.29, pp 2681-2696

Novosad, J., 1964 b. Studies on Granular Materials III. Collection of Czechoslovak Chemical Communications, Vol.29, pp 2703-2709

Novosad, J., 1965. Studies on Granular Materials IV. Collection of Czechoslovak Chemical Communications, Vol.29, pp 3247-3262

Rydin, R.W., Maurice, D., Courtney, T.H., 1993. Milling Dynamics: Part 1: Attritor Dynamics: Results of a Cinematographic Study. Metallurgical Transactions A, volume 24A, January

Duffy, S. M., 1994. Investigation into the Performance Characteristics of Tower Mills. *Master thesis. University of Queensland, JKMRC*

J. Conway-Baker et all, 2002. Meaurment of the motion of grinding media in a vertically stirred mill using emission particle tracking (PEPT), Minreals Engineering 15, pp 53-59

Lane, G.L. 1999. CFD modeling of a stirred bead mill for fine grinding. Proceedings of Second International Confererence on CFD in Minerals and Process Industries, CSIRO, Melbourne, Australia, 6-8 December

Scott, D.M. and Gutsche O.W., 1999. ECT Studies on Bead Fluidisation I Vertical Mills. 1st World Congress on Industrial Process Tomography, Buxton, Greater Manchester, April 14-17.

Theuerkauf, J. Schwedes, J. 1999. Theoretical and experimental investigation on particle and fluid motion in stirred media mills. Powder technology 105, pp 406-412

Zheng, J., Harris, C.C., and Somasundaran, P., 1995. Power consumption of the stirred media mills. Minerals and Metallurgical Processing., February., pp. 34-40.

Jankovic, A and Morrell, S., 1997. Power Modelling of Stirred Mills, Proceedings of the Second UBC-MCGILL BI-Annual International Symposium on Fundamentals of Mineral Processing and the Environment, Sudbury, Ontario, Canada,

Kalra, R., 1999. Overview on Alternative Methods for Fine and Ultra-Fine Grinding., IIR Conference, Crushing & Grinding ‘99, Perth

Stief, D.E., Lawruk, W.A. and Wilson, L.J., 1987. Tower mill and its application to fine grinding. Miner. and Metall. Process., Vol. 4, No. 1, Feb., pp 45-50.

Lofthouse, C.H., and Johns, F.E., 1999. The Svedala (ECC international) Detritor and Metals Industry. Minerals Eng, Vol 12, No 2, pp. 205-207

Underle, U., Woodall, P., Duffy, M., and Johnson , N.W., 1997. Stirred mill technology for regrinding McArthur River and Mount Isa zinc/lead ores. Proceesings of XX IMPC – Aachen, 21 –26 September, pp. 71-78

Jankovic, A., 2003. Variables Affecting the Fine Grinding of Minerals Using Stirred Mills, Minerals Engeneering vol 16, pp 337-345,. paper presented at MEI Conference 02, Perth – Australia.

Jankovic, A., 2001. Media Stress Intensity Analysis for Vertical Stirred Mills, Minerals Engeneering, vol 14. Special issue from MEI Conference Comminution 01, Brisbane - Australia, pp. 1177-1186

Jankovic, A., 1997. Power Modelling of Stirred Mills, Proceedings of the Second UBC-MCGILL BI- Annual International Symposium on Fundamentals of Mineral Processing and the Environment, Sudbury, Ontario, August, pp. 463-470

Jankovic, A., and S, Morrell., 2000. Scale-Up Of Tower Mill Performance Using Modelling And Simulation, Proceedings of XXI IMPC, Rome – Italy, pp. A3 1-8

Jankovic, A., 1999. Mathematical Modelling of Stirred Mills, Phd Thesis – University of Queensland, JKMRC, Brisbane, Australia

Kwade et all., 1995. Motion and stress intensity of grinding beads in a stirred media mill. Part2: Stress intensity and its effect on comminution. Powder Technology vol. 86, pp. 69-76
Kwade, A. and Stender., H. H., 1998. Constant Grinding Results at Scale-up of Stirred Media Mills. Aufbereitungs-Technik 39, pp. 373-381

Becker. M., Schwedes. J., 1999. Comminution of ceramics in stirred media mills and wear of grinding beads. Powder technology 105, pp 374-381

Burgess, F., McGuire, I. and Willoughby, R., 2001. Operation of Sand Mill Detritors at Pasminco Operations. Fine particleProcessing and Tailing Summit, July, Perth, Australia.

Ellis, S., Gao, M., 2002. The Development of Ultra Fine Grinding at KCGM. SME Annual Meeting. Feb. 25 – 27, Phoenix, Arizona, preprint 02-072

Davey, G., 2002. Ultrafine and fine grinding using the METSO Stirred Media Detritor (SMD®)). Proceedings of 34th Annual Meeting of the Canadian Mineral Processors, Ottawa, Canda

Karbstein, H., Muller, F., and Polke, R., 1996. Scale-up for Grinding in Stirred Ball Mills, Aufbereitungs-Technick 37, No. 10. pp 469-479

Molls, H.H., and Hornle, R., 1972. DECHEMA – Monography 69, Tl 2, pp.631-661

Hess, W., and Schonert, K., 1981, Brittle-Plastic Transition in Small Particle Processing. Preprints of the Powtech Conference on Particle Technology, Birmingham, EFCE Event No.214, D2/I/1-D”/I/9

Hoffmann, N., Flogel, F., Schonert, K., 1976. Bruchstück-Größenverteilungen bei der Zerkleinerung von binären and ternärn Mischungen. VDI-Bereichte, 260

Roelofsen, D.P., 1991. Developments in dispersing technology. Europian Coatings Journal, 3. pp 128-144.

Schonert, K., 1990. Aspects of very fine grinding. in: Sastry, K.V.S., and Fuerstenau, M.C., (editors) Challenges in Mineral Processing, Soc. Min. Engrs., Bookcraft, Chelsea, pp 155-172.

Schonert, K., 1991. Advances in comminution fundamental, and impacts on technology. XVII Inter. Nat. Miner. Process. Cong., Dresden, Vol 1, Sept., pp 1-21.

Stehr, N., and Schwedes, J., 1983. Investigation of the grinding behaviour of a stirred ball mill. German Chem. Eng., No. 6, pp 337-342.

Steier, K., 1972, PhD Thesis, University Karlsruhe