CHAPTER 3.11

Grinding Technologies

Aidan Giblett

Major grinding technologies in use in mineral processing today can be broadly categorized into tumbling mills, stirred mills, and compressive grinding mills. The term *mill* is ubiquitous and defines an extremely wide variety of mechanical devices that grind material to an equally wide range of product sizes. Perhaps the most widely recognized technology is the tumbling mill, where the action of a rotating steel drum promotes the grinding of mineral ores. Common types of tumbling mills include autogenous grinding (AG) and semiautogenous grinding (SAG) mills, rod mills, ball mills, drum scrubbers, and pebble mills. In tumbling mills, the primary distinction between mill types is the type and size of media used to promote comminution, and to a lesser extent the size and dimensional aspect ratio of the mills themselves.

Stirred mills employ a stationary drum and rotating shaft fitted with a helical screw, pins, or discs to agitate the mill contents and are commonly used to grind particles to fine sizes in concentrate and tailings regrind or ultrafine grinding (UFG) duty. They may be vertically or horizontally configured, reflecting either upward or horizontal flow of material through the grinding chamber. In addition to the orientation of the mill and variations in stirring mechanisms, stirred mills can also differ in energy intensity. Grinding media is commonly screened silica sand, solid steel cylinders, steel balls, or ceramic spheres.

Compression mills employ grinding wheels or rolls to grind particles under compression without the use of grinding media. Vertical roller mills (VRMs) and high-pressure grinding rolls (HPGRs) are technologies extensively used in industrial mineral processes to generate final comminution circuit product material. These are dry grinding technologies in contrast to stirred and tumbling mills, which are more commonly associated with wet slurry systems, although dry applications of those technologies in specific industries are not uncommon.

The range of application and degree of size reduction of the major grinding technologies applied in mineral ore processing are illustrated in Figure 1, progressing from the autogenous/semiautogenous milling of large particles up to 500 mm (20 in.) down to the sub-15-µm range (UFG).

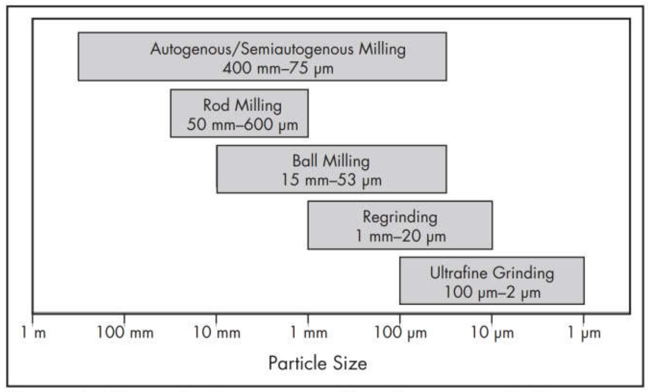

Figure 1 Size reduction ranges of mainstream grinding technologies used in mineral processing

A summary of mill installation data provided by major global grinding mill suppliers (Metso, FLSmidth, ThyssenKrupp, CITIC HIC, and Outotec) is shown in Figure 2, reflecting the applications of the major conventional tumbling mill technologies. Technology selection is influenced by the suitability for the grinding duty, ore characteristics, and the range of mill sizes available. The higher-capacity unit technologies, AG, SAG, and ball mills, are well suited to processing low-grade ore at high volumes. These technologies have the versatility to operate as single-stage mills producing final product material and are all suited to use as primary grinding mills receiving suitably prepared feed material. Ball mills have the additional flexibility of being suited to secondary, tertiary, and regrind milling duties. Because of unit capacity limitations, the use of rod mills has declined as a percentage of total mill sales terms since the 1990s, although they remain a viable technology selection in specific applications. Sales volume data indicate a similar number of rod mill sales in the 1970s and in the 2000s, defying the often-quoted status of the rod mill as an expired technology. A more pronounced decline in the number of pebble mill installations has been observed since the 1980s, although

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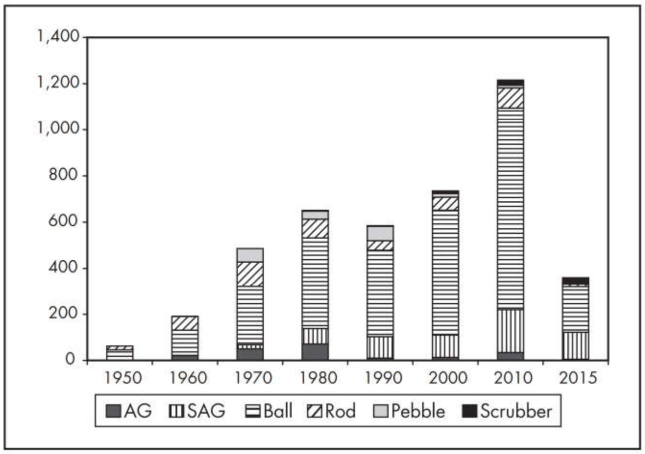


Figure 2 Tumbling mill installation trends (1950–2015)

pebble mills are still used in the grinding of ores in several industries. There are far fewer scrubber installations than the other tumbling devices; however, scrubbers are a frequently used grinding technology in the processing of diamond-bearing ores and iron ores, among others. While the general dominance of SAG and ball mills in the tumbling mill market in recent decades is clear, the other tumbling mill technologies remain relevant in mineral processing.

Stirred milling technologies include the tower mill, Vertimill, IsaMill, pin mill, stirred media detritor (SMD), VXPmill, and HIGmill. These technologies are primarily used in mineral processing for the regrinding and fine grinding of concentrates; however, a growing number of stirred mills are employed in secondary and tertiary grinding duties. The adaptation of stirred milling technology, particularly in very fine grinding applications (sub-15–20 µm), has increased significantly since the mid-2000s based on several successful installations, increasing mineral resource complexity and the availability of larger-capacity mills.

Compressive grinding technologies, most notably VRMs and HPGRs, are extensively used in the cement industry for the dry grinding of limestone, cement clinker, and slags. These technologies are not widely used in mineral processing applications to generate final ground product material, although they have significant appeal based on well-documented energy efficiencies over ball milling. Dry grinding is not immediately compatible with the wet downstream recovery processes typical of the extraction of precious and base metals but may be viable where minimal energy is required for the drying of mineral ores. The significant reductions in energy consumption that these technologies have demonstrated in the cement industry warrant consideration for more widespread application, subject to suitable wear performance. Wear performance in abrasive minerals applications has been demonstrated for HPGRs in tertiary and quaternary crushing duties, although the VRM technology has not been tested to the same extent in this industry and has found more limited application to date.

AUTOGENOUS GRINDING, SEMIAUTOGENOUS GRINDING, AND PEBBLE MILLING

This section adopts conventional definitions for autogenous and pebble milling, which in concept are primarily distinguished by the size of the media in use and the feed size processed. Crow and Lipphardt (1985) defined *autogenous grinding* as the action of a material grinding on itself, as occurs when pieces of ore of different sizes are rotated together in a tumbling mill, and observed that this action is the same in AG mills as in pebble mills. The distinction is in the media size used. AG mills are then further defined as mills that receive primary crushed or run-of-mine (ROM) ore. Mills operating in this duty, which have some part of the mill charge composed of steel grinding media, are called SAG mills. *Pebble milling* is defined as the use of tumbling mills that use rock particles of a specified size class as grinding media. In pebble milling, the grinding media may come from the sizing of crushed or milled ore particles, or from an external source, such as prepared flint or gravels.

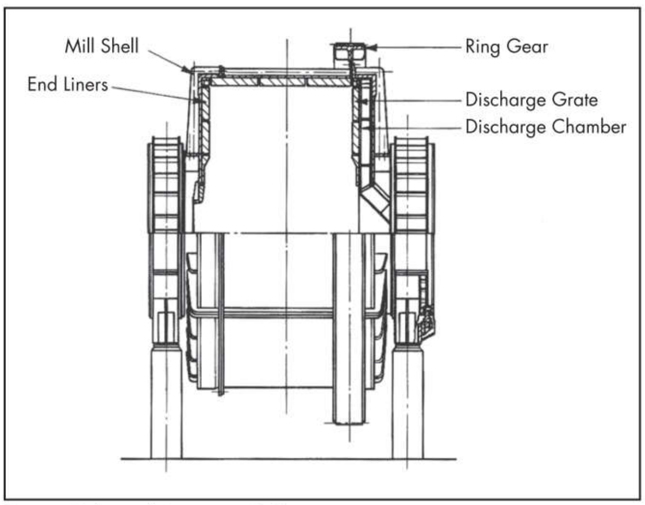
Autogenous and Semiautogenous Milling

Autogenous and semiautogenous milling are performed in tumbling mills and in predominantly wet grinding environments. Slurry densities in wet grinding typically range from 60% to 84% solids and can vary considerably from one operation to another based on the rheological characteristics of the ore. The mills are of grate discharge design, meaning that the slurry flows through the mill and is classified by discharge grates with slotted apertures ranging from 25 mm (1 in.) up to approximately 90 mm (3.5 in). Large aperture slots greater than 38–50 mm (1½–2 in.) are known as pebble ports and are intended to allow the ejection of critical size material from the mill. Material passing the grates enters the discharge chamber where pulp lifters convey the material to a central discharge cone and out of the mill. Another less common variation is to have the mill end open after the grate, such that the discharging slurry is immediately free to fall into a sump or be further classified by a screen.

AG and SAG mills (Figures 3 and 4) are most commonly operated as the primary stage of grinding before ball milling, although single-stage semiautogenous milling and multistage AG mill/pebble mill circuits are common flow-sheet variations. Feed material may be ROM but is typically primary crushed to 80% passing 100–150 mm (4–6 in.) The AG or SAG mill will discharge through a trommel screen and/or a vibrating screen to protect the secondary grinding circuit from excessively coarse particles and large mill balls. The screening stage allows oversize material discharging the primary mill to be recirculated, commonly via a pebble crushing circuit, to reduce the oversize to a suitable feed size for the secondary grinding stage. In single-stage AG/SAG applications, the mill will operate in closed circuit with hydrocyclones or fine screens to regulate the final product size.

Mill diameters up to 9.8 m (42 ft) have been constructed, although mill diameter varies significantly by application as a function of design grinding circuit capacity. Mill aspect ratio—the ratio of the mill diameter (D) to the length (L), expressed as D/L (Napier-Munn et al. 1996)—varies from high to low. High-aspect mills have greater diameter than length and may have aspect ratios of 3:1 (D/L); low-aspect mills may have a D/L ratio up to 1:2½. Generally, a high-aspect mill is preferred where high mill unit throughput is required; a low-aspect mill is preferred where a fine grind size is required, particularly if the mill is not operating in closed circuit with hydrocyclones. When the mill is closed with hydrocyclones, the aspect ratio is of no clear significance, although low-aspect mills are often favored in such applications.

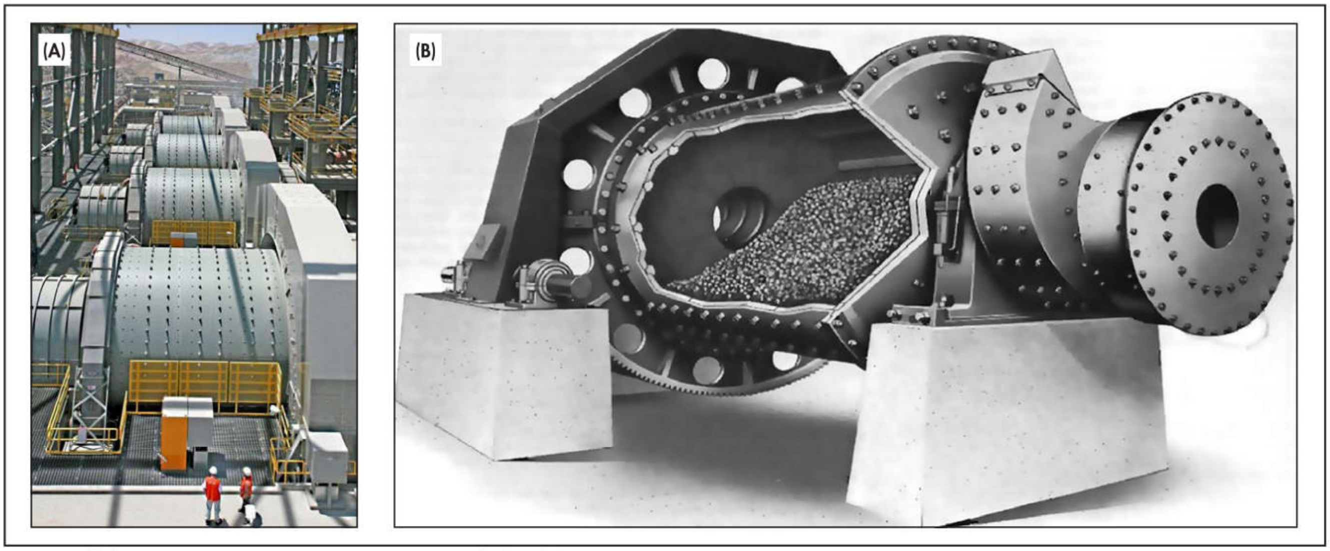
Courtesy of ThyssenKrupp
Figure 3 Prominent Hill SAG mill in Australia



Source: Mular and Jergensen 1982
Figure 4 AG/SAG mill components

When autogenously milling primary crushed or ROM ore in the absence of steel grinding media, the ore must contain some material of sufficient size and strength to effectively perform as autogenous media. Ideally, the feed material will comprise material that has strength at larger sizes but also grinds easily at finer sizes. These characteristics avoid the accumulation of material in the mill that is too small to effectively act as autogenous media, yet not fine enough to be classified as product from the mill. Excessive accumulation of such material is detrimental to grinding performance. It will result in a loss of mill capacity and is subsequently known as critical size material. Critical size material is likely to be in the 15–75 mm (⅝–3 in.) range, coarser than the discharge screen aperture and exhibiting low grinding rates in the mill. Where critical size accumulation is predicted or observed to be an issue, the use of larger grates known as pebble ports and the implementation of pebble crushing are demonstrated means to increase mill capacity. An advantage of autogenous milling is the elimination of costs associated with steel grinding media consumption, and any contamination of final products or reduced recovery because of deteriorated mineral surface condition that results from the presence of grinding media corrosion products or tramp iron. Alternatively, AG mills will have lower power draw, and lower mill capacity than an equivalent mill operating in SAG mode. Autogenous milling will produce more fines than semiautogenous grinding, which can be detrimental to downstream recovery depending on the separation process applied. Ores of higher specific gravity, such as iron ores, are known to be well suited to autogenous milling.

As a result of the potential impact of critical size buildup in AG mills, and the increased mill capacity that comes with the introduction of steel grinding media, the practice of semiautogenous grinding has become the more common application of the semiautogenous milling concept. Grinding steel balls of 100–125 mm (4–5 in.) diameter, steel charge levels ranging from 4% to 15% by volume, and total operating mill charge levels of 25%–35% by volume are traditional characteristics of semiautogenous grinding. Over time the use of steel balls up to 150 mm (6 in.) has become more popular, particularly in copper porphyry operations. The use of up to 18%–20% steel charge by volume has also become necessary to maintain high mill power draws when processing less competent ores, and highly fragmented or secondary crushed SAG mill feed. In these instances, the feed contains an insufficient number of particles of adequate size and strength to serve as autogenous media, and subsequently the mill will often operate at lower total mill filling levels in the 20%–25% by volume range. SAG mills have the added cost of grinding media consumption in comparison to AG mills; however, higher mill capacities are achieved for comparable mill sizes. SAG mills



Courtesy of ThyssenKrupp Courtesy of Allis-Chalmers

Figure 5 (A) Cerro Verde ball mills in Peru and (B) overflow ball mill cutaway

are more prone to liner breakage because of the weight of steel grinding media used, and rubber mill linings are not considered a viable option for the larger-diameter (>34 ft [>10.4 m]) SAG mills, although composite shell liners have been successfully used on small- to medium-diameter mills.

Pebble Milling

As previously described, pebble milling implies the use of screened rock particles as grinding media. These particles may be externally sourced, produced by screening of the primary crushed ore, or generated in the primary milling stage. Where the pebbles are generated from the crushed ore, the process is often termed *secondary autogenous grinding*, and this is largely the focus of this section.

In this secondary form of autogenous milling, grinding is usually performed wet and in closed circuit. Pebble mills typically are used in secondary and tertiary grinding duties after AG or rod mills. The broad range of application of pebble milling is defined by Crocker (1985) as receiving feed material up to 9.5 mm (⅜ in.) and grinding down to as fine as 10 µm. Pebble mills receiving crushed material up to 9–10 mm in size are termed *primary pebble mills* or *lump mills* and would be charged with pebble media ranging from 125 to 250 mm (5–10 in.). Where the pebble mill is a secondary mill receiving rod mill product passing 2–2.5 mm (8–10 mesh), the pebbles are taken from primary crusher product in the –100 mm (4 in.) to +25 mm (1 in.) size range. Pebble size is specific to the grinding duty to be performed, with smaller pebbles required for finer grinding, and the optimum pebble size is defined by Crocker (1985) as the equivalent weight of a steel ball that would be applied to achieve the same grinding duty in a ball mill. Pebble mills operate at high media loads (35%–40%) to maximize mill power draw and are exclusively grate discharge mills to effectively retain the grinding media in the mill at those high load levels. In some instances, combinations of pebble and steel ball grinding media have been applied.

BALL MILLS

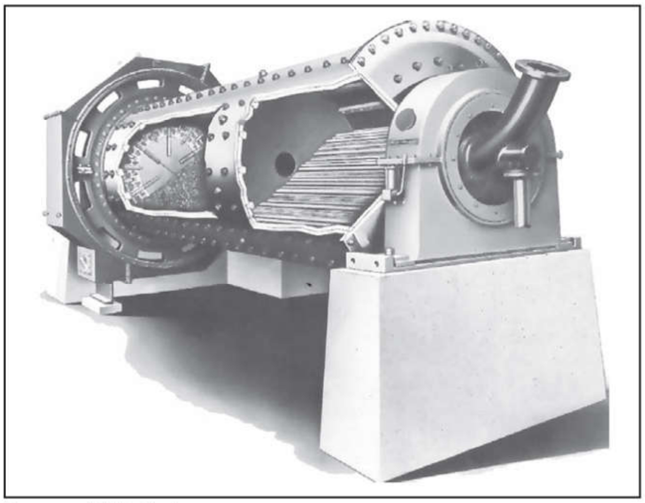
Ball mills are the most widely used form of tumbling mill where the ore is ground with a charge of cast or forged steel balls as the grinding media (Figure 5). Ball sizes from 25 to 100 mm (1–4 in.) are used, varying as a function of feed size, ore grindability, and target product size. Ball mills may receive secondary or tertiary crushed feed ranging from 80% passing (F_{80}) 6 to 15 mm (¼–⅝ in.), or classified product from a primary grinding stage producing typically finer than 6 mm (¼ in.) feed F_{80}.

While suited to wet or dry grinding, ball mills are most commonly used for the wet grinding of mineral ores and routinely generate the final product for separation or extraction at product sizes under 80% passing (P_{80}) 300 µm (50 mesh). Dry grinding using ball mills historically has been standard practice in the cement industry, although more recently VRMs have become the dominant dry grinding technology in that industry. Wet grinding overflow discharge ball mills are usually operated at 74%–76% of critical speed, 60%–80% solids, with ball loads between 25% and 35% by volume, although in smaller-diameter, grate discharge or shell supported mills, the ball load may approach 40% by volume.

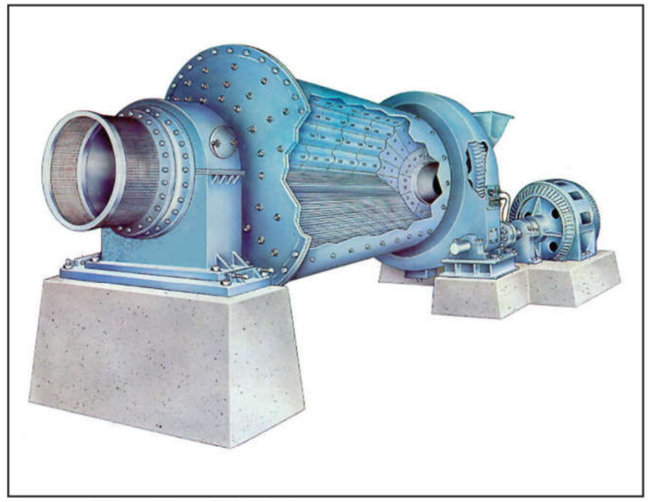
Ball mills may be of grate or overflow discharge design; however, the overflow ball mill is the most common. The aspect ratio of ball mills is highly variable with no fixed and firm rules governing the optimum aspect ratio for a given application. However, Rowland (2002) did observe that the potential for grinding media charge segregation increased with decreasing aspect ratio (D/L) when using grinding balls larger than 64 mm (2.5 in.) in diameter.

MULTICOMPARTMENT MILLS

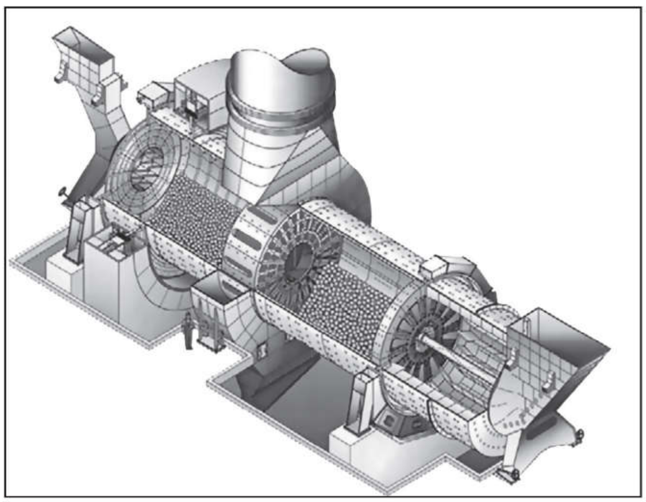
Multicompartment mills employ two or more grinding chambers to allow grinding stages to be combined in a single mill. Ground material can pass directly from one chamber to the next through a grate arrangement, or material can be removed for classification in between grinding stages. Multicompartment mills can have high length-to-diameter aspect ratios up to 5:1. Combination rod/ball mills (Figure 6) are used in many applications including bauxite grinding at Australian Alumina operations at Gove (Gouma and Bhasin 1993) and Gladstone (Singh and Sisley 2013; Skiba 1993) and grinding cement raw materials as described by Rowland (1985).



Courtesy of Allis-Chalmers
Figure 6 Combination rod and pebble mill



Courtesy of Metso Minerals Industries
Figure 8 Rod mill cutaway



Source: Thomas et al. 2001
Figure 7 Double-rotator ball mill

The double-rotator ball mill is a specialized multicompartment ball mill that was developed for the cement industry, and it has been successfully used for many years to dry-grind refractory gold ores of the Carlin Trend in Northern Nevada, United States. The selection and use of this technology for gold ore grinding has been discussed in detail by Tempel (1993) for the Newmont Carlin operation, and by Thomas et al. (2001) for the Barrick Goldstrike operation in Nevada. In both instances, secondary crushed ore is ground to final product size to provide feed material for oxidative roasting and subsequent hydrometallurgical extraction of gold. Figure 7 shows a cutaway drawing of a double-rotator mill. ThyssenKrupp mill installation data reflects almost 50 double-rotator ball mills in use, primarily in iron ore, gold, and base metals applications.

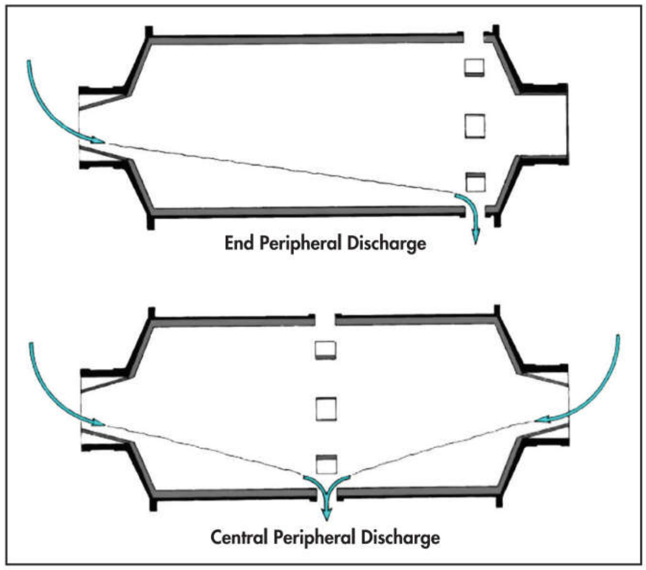
The double-rotator ball mill consists of four main sections: drying chamber, primary grinding compartment, central discharge chamber, and secondary grinding compartment. The incoming ore is dried by hot air, generated by a gas burner, in the drying chamber prior to migrating to the primary grinding chamber. Ground ore from both the primary and secondary grinding chamber enters the central discharge chamber through diaphragms. The grinding circuit is operated under negative pressure, and fine particles generated in the mill are air swept through the discharge chamber and report to the static classifier. Finished size material from the static classifier, representing approximately 30% of the feed, is collected in a baghouse cluster and transferred into fine ore storage silos. Near-size particles in the air-swept stream are captured in the static classifier and rerouted to the bucket elevators. Coarse particles are discharged from the mill outlet into air slides that feed dual-bucket elevators, which transport the coarse mill products into the feed inlet of a dynamic classifier. Most of the oversize product from the dynamic classifier is returned to the fine grinding chamber of the mill with a small portion being returned to the drying chamber. Finished size product enters a second four-baghouse cluster and is subsequently transferred into the fine ore storage silos.

ROD MILLS

Prior to the widespread application of semiautogenous milling, rod mills (Figure 8) were the favored technology for primary wet grinding applications. While still in use in many operations, dimensional constraints on rod mills typically limit their suitability in new projects to low single-line milling capacity applications or applications where downstream mineral recovery is substantially affected by fines produced in grinding.

As the name implies, rod mills use steel grinding rods as grinding media. Rod mills typically serve in primary grinding duty in wet grinding applications but have also been used as the final stage of grinding. Rod mills have been reported to receive feed as coarse as 50 mm (2 in.), although for optimum performance a feed size of 19 mm (¾ in.) is more often targeted. Grinding rod diameters range from 38 to 115 mm (1½ to 4½ in.), with rod mill operating charge levels of 35%–40% by volume being typical. The upper limit on rod length of 6.1 m (20 ft) provides the upper limit on maximum rod mill length to approximately 6.5 m (21½ ft). Rowland (2002) defined this as the length that rods will stay straight in the mill and will break into smaller pieces that will discharge from the mill when worn. Rod mills are unique in that they need to be stopped to charge the mill, and a rod storage table is required adjacent to the discharge end of the mill. Rowland further specified an optimum aspect ratio of 1:1.4–1:1.6 (*D/L*) to minimize potential for dangerous rod tangling, which then reflects the practical maximum rod mill size of 4.6 m × 6.5 m (15 ft × 21½ ft). Rod mills are commonly overflow discharge mills but can also be configured as end peripheral discharge or center peripheral discharge (Figure 9).

Rod mills have a higher charge packing density than ball mills, which results in higher energy intensity and more effective breakage of the coarsest particles in the mill feed. Rod mills will therefore have an efficiency advantage over ball mills when there are excessive oversize particles in the feed and may be selected where top size control to the next process is essential.



Courtesy of Metso Minerals Industries
Figure 9 Rod mill configuration

SCRUBBERS

Scrubbers are a specialized low-aspect-ratio mill used in applications where the physical separation of a soft component in the ore, often clays, is required before downstream processing (Figure 10). Scrubbers are associated with processing of bauxite, phosphate, iron, laterite nickel, and diamond-bearing ores. Mill diameter-to-length aspect ratio is typically 1:1.5–1:2.5, and mill diameters are commonly 5 m (16.4 ft) or less. A requirement for effective scrubbing is that the feed contain particles large enough and competent enough to act as media. Mill speeds and installed motor power are lower than for similar sized ball mills, and scrubbing is normally performed in the absence of steel grinding media. Scrubber specific energy consumption is low (typically 0.1–0.5 kW·h/t), as the duty is effectively washing rather than grinding; however, high energies can be required when processing tenacious clays or moderately competent feed material (saprock). Scrubbers are configured with either a simple overflow weir or a combination of weir and internal discharge screen. The weir retains a volume of slurry to ensure washing occurs, and the internal screen retains rocks to act as scrubbing media. The scrubber discharge is classified by fixed trommel or external screens.

Courtesy of ThyssenKrupp
Figure 10 Scrubber in a diamond application

STIRRED MILLS

Stirred milling technology has demonstrated increased energy efficiency over ball milling in fine and UFG duties, with quoted energy reductions of 30%–50% for a comparable task. This has given rise to the increasing application of stirred milling technology in mineral processing flow sheets. Stirred mills are horizontal or vertically aligned and use pins, discs, or a spiral screw fixed on a main shaft to transfer energy to the mill charge. Steel balls, steel cylinders, silica sand, and ceramic beads are common forms of grinding media. Lichter and Davey (2002) defined two classifications of stirred mills based on the impeller speed. Low-speed mills stir the media, without fluidizing it. These mills use coarser, high-density grinding media such as steel balls and cylpebs and are better suited to the fine grinding of coarser feeds. Higher-speed mills fluidize the grinding media and use lower-density sand or ceramic media.

Specific energy consumptions for stirred mills 30%–50% lower than ball mills have been demonstrated in fine grinding (<50 µm or 270 mesh) and UFG to <15–20 µm (635 mesh). Fine grinding systems achieve superior grinding efficiencies compared to ball milling because the media size can be well matched to the grinding duty. Fine and UFG mills are constructed in a way that media cannot easily leave the mill with the discharge slurry flow. This allows media as fine as 1 mm to be used in some mills when appropriate. Conversely, overflow ball mills allow particles in the ideal fine grinding media size range (1–15 mm) to leave the mill with the slurry flow and are only suited to media diameters of 20 mm or larger.

Depending on the technology, a stirred mill can accept a feed size up to several millimeters, and as a result, the technology has been applied in secondary and tertiary grinding duties in addition to the more conventional concentrate regrind and UFG applications in which they dominate. The wide range of stirred mills and mill motor sizes is summarized in Table 1.

Tower Mills

As reported by Jankovic (2005), the original tower mill was released in 1953 and has been produced under several owners since that time. The most widely recognizable tower mill brand is the Metso Vertimill (Figure 11), which came into production in 1991. Tower mills are composed of a vertical cylinder with a relatively slow speed screw media agitator, as represented in Figure 11. Because of their vertical arrangement, footprint reductions can be substantial compared to those for horizontal grinding technologies.

Table 1 Stirred mill sizes for mineral processing applications

Installed Motor Capacity, hp	Vertimill	SMD	IsaMill	VXPmill	HIGmill
0–499	VTM-15 VTM-150 VTM-20 VTM-200 VTM-40 VTM-250 VTM-60 VTM-300 VTM-75 VTM-400 VTM-125	SMD-0.75 SMD-7.5 SMD-18.5 SMD-90 SMD-185 SMD-355	M100 M500	VXP250 VXP500	HIG132 HIG300
500–999	VTM-500 VTM-650 VTM-800		M1000	VXP1000 VXP2000 VXP2500	HIG500 HIG700
1,000–1,999	VTM-1000 VTM-1250 VTM-1500	SMD-1100	M3000	VXP5000	HIG900 HIG1100
2,000–2,999			M5000		HIG1600
3,000–3,999	VTM-3000				HIG2300
4,000–4,999	VTM-4500		M10000		HIG3000 HIG3500
5,000–9,999			M15000 M50000		HIG4000 HIG5000

Courtesy of Metso Minerals Industries
Figure 11 Metso Vertimill and feed tank

Courtesy of Metso Minerals Industries
Figure 12 Metso stirred media detritor

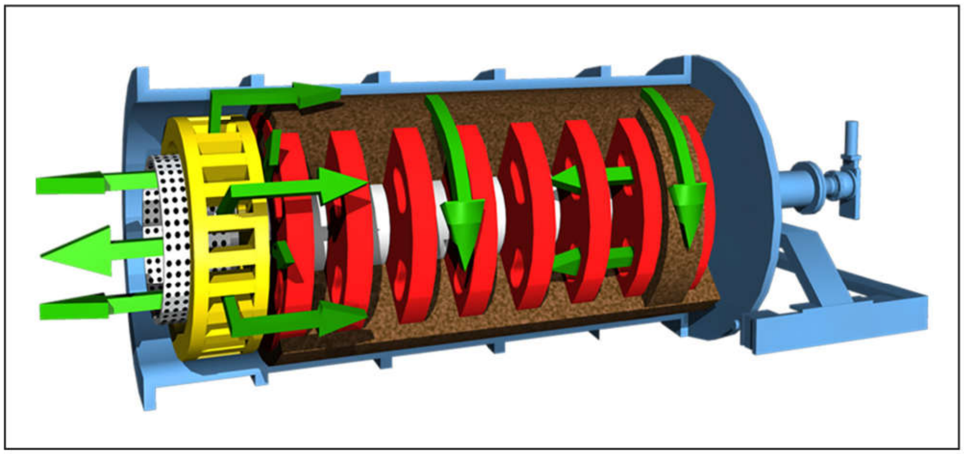
Tower mills are commonly used in flotation concentrate regrind applications and are a frequent fixture in base metals flotation circuits. Concentrate regrind duties have a typical feed size of around 100–300 µm (140–50 mesh) and products of 100–15 µm (140 to <635 mesh.) The finest grinds in commercial Vertimill applications achieve approximately 80% passing 12 µm, with finer grinds having been obtained in pilot installations. Energy savings relative to conventional ball mills in regrinding applications can exceed 35%. Media savings relative to ball mills can be 30%–50%, resulting from lower energy consumption and predominance of the attrition grinding mechanism.

The technology has also been extensively used in lime slaking applications, as the grinding mechanism increases the available surface area for reaction and the large mill volume provides sufficient retention time to output a very fine, highly reactive hydrated lime product.

With the advent of 4,000-hp and larger units, Vertimills have also been successfully used in high-capacity secondary and tertiary applications with feed sizes as large 6 mm (¼ in.). In this duty the mills typically use 6–40 mm (¼–1¾ in.) diameter steel balls as grinding media or cast steel cylinders such as cylpebs.

Stirred Media Detritor

The Metso SMD, shown in Figure 12, uses a vertical shaft equipped with pins to provide agitation of the mill charge. The grinding media is ceramic spheres or alluvial silica sand in the range of 1 mm (18 mesh) to 6 mm (¼ in.) in diameter. The agitator speed is high enough to fluidize the media but operates at lower energy intensity when compared to other fluidized media mills to produce lower wear rates at comparable grinding efficiency. Screens are fitted to the upper circumference of the mill body to retain the mill media but otherwise



Courtesy of Glencore Technology
Figure 13 IsaMill cutaway schematic

perform no classification of the product material. Feed size is in the range of 100 µm (140 mesh) to <15 µm (635 mesh), and products down to 80% passing 2–6 µm can be produced. The Metso SMD has been applied in lead, zinc, copper, and platinum group mineral flow sheets.

IsaMill

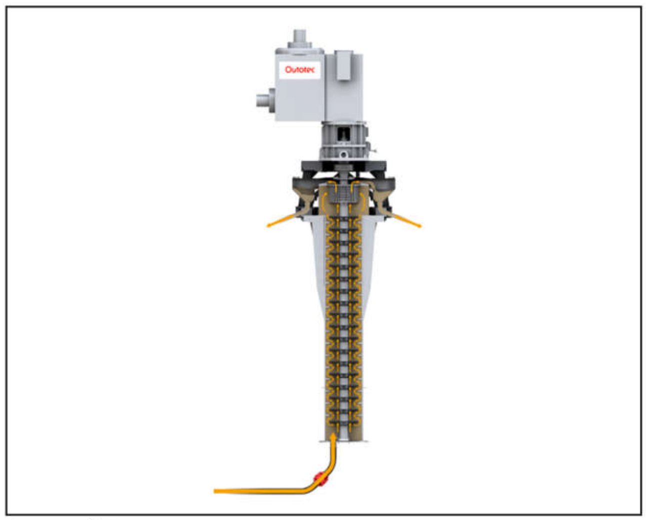
The IsaMill is a horizontal stirred media grinding mill that uses small ceramic grinding media for common regrind and UFG applications (Figure 13). Ceramic media size can range from 1.5 to 6.5 mm (18 mesh to ¼ in.) and accept feeds of up to 80% passing 350 µm in some regrind duties and discharge products as fine as 80% passing 5 µm for UFG duties.

The basic principle of the IsaMill is that it fluidizes a charge of small ceramic grinding media. Media and coarse particles are centrifuged to the outside of each disc where backflow from the product separator keeps them in the mill until the ore is ground enough by attrition and compressive forces to pass down the middle of the mill and discharge. Because of this process, external classification is not always required, but cyclones or thickeners may be required ahead of the mill to achieve a suitable operating density.

The IsaMill comes in a variety of sizes, with the mill model denoted by the chamber volume in liters. For example, the M10000 has an internal volume of 10,000 L or 2,640 gal. IsaMills are installed in several regrind and UFG duties in copper, lead/zinc, platinum, gold, molybdenum, nickel, and iron ore duties, and have been used in mainstream grinding duties at McArthur River mine in Queensland, Australia.

HIGmill

The HIGmill comprises a vertical mill body and shaft fitted with grinding discs (Figure 14). The grinding chamber is filled up to 70% with grinding beads. Rotating discs stir the charge and grinding takes place between beads by attrition. The number of discs is application specific with as many as 30 discs used. Feed slurry is typically processed by a scalping cyclone for the removal of product size material. The scalping cyclone underflow is then pumped into the base of the mill with the slurry flowing upward, through the consecutive grinding stages. Final product discharges at open atmosphere at the top of the machine. In typical cases, the process is single



Courtesy of Outotec
Figure 14 Outotec HIGmill

pass and no external classification of the mill discharge slurry is required.

The HIGmill was initially developed for the calcium carbonate industry and has more than 200 installations to date in the industrial minerals area. The technology has been adopted for mineral processing applications by Outotec, which has provided mills for base metal and platinum concentrate regrinding duties.

VXPmill

The FLSmidth VXPmill was originally developed in South Africa for the manufacturing industry and marketed as the Deswik mill before finding application in the gold industry for fine grinding applications (Figure 15). The VXPmill is a vertically oriented stirred mill that is open to the atmosphere. It is designed with a modular impeller that allows the energy distribution within the mill to be varied by changing the disc configuration. The general process flow for the VXPmill is for the slurry to enter at the bottom of the mill, traveling upward through the grinding chamber where the grinding discs agitate the media to induce attrition breakage. The slurry then overflows through a media retention screen at the top of the mill. The mill is also equipped with a variable-speed drive, which allows the mill to be operated over a wide speed range.

The VXPmill uses ceramic grinding media that is selected based on the properties of the mill feed and discharge. The mills are often used in flotation concentrate regrind and precious metals tailings retreatment where the feed size is typically <200 µm. In these applications, a media size of 2–4 mm (5–10 mesh) is commonly used to produce product sizes ranging from 50 µm (270 mesh) to as low as 10 µm (1,250 mesh).

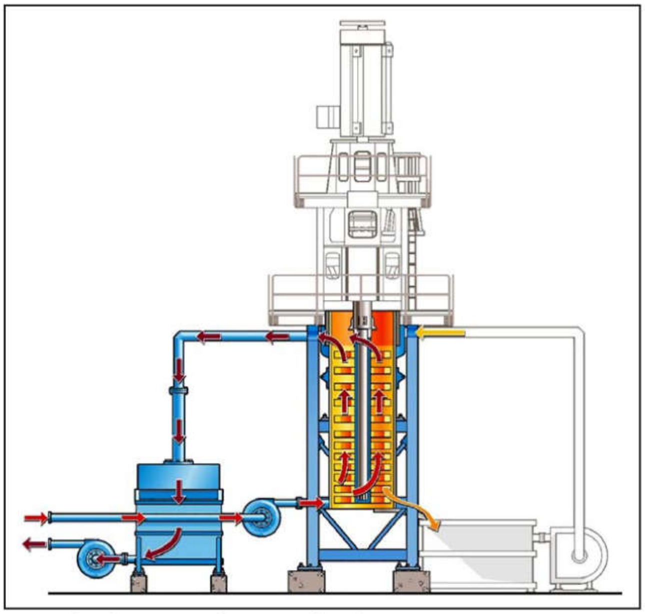


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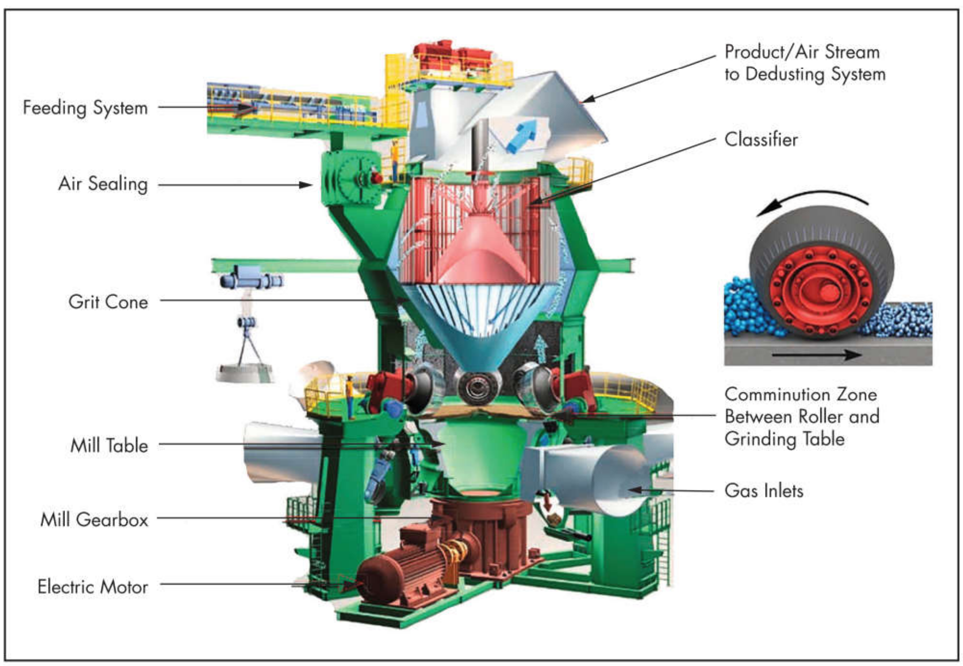
Figure 15 FLSmidth VXPmill

COMPRESSIVE GRINDING TECHNOLOGIES

Compressive grinding machines are extensively used in the grinding of cement raw materials, cement clinker, slags, coal, coke, electrode materials, paint pigment, clay, intermediate pyrometallurgical products, and industrial minerals. Considerable energy savings have been demonstrated by comparison to dry ball mills operating in these applications, and the high reduction ratios achieved can allow multiple comminution stages to be replaced by a single unit. The abrasive characteristics of the materials ground are low, and demonstrating suitable service life of major wear components in hard-rock grinding applications remains an issue limiting adaptation in mineral processing flow sheets. The successful development of wear lining strategies for HPGRs in tertiary and quaternary hard-rock crushing duties provides reason for optimism that a suitable wear solution can be found for the finish grinding of similar ores. The energy efficiency benefits of dry grinding mineral ores ahead of wet separation or leaching processes can be eroded by the energy requirements of hot gas generation and the power associated with material transport. Therefore, dry grinding technologies of this nature are best suited to ores with low moisture contents and limited abrasiveness, and where subsequent processing stages require a dry product.

Vertical Roller Mills

Grinding occurs by compressive force applied to a grinding bed between fixed grinding rollers, with adjustable shear forces and a rotating horizontal grinding table. Depending on grinding duty and unit capacity, the VRM may employ two, three, four, five, or six grinding rollers. Figure 16 depicts a three-roller Loesche VRM. Ground material flows outward,



Courtesy of Loesche GmbH
Figure 16 Loesche vertical roller mill

over the edge of the grinding table where the rising gas flow carries finer material to the high-efficiency classification system while allowing coarser, heavier particles to be returned to the grinding table. Very coarse particles leave the mill as reject against the gas flow and are recirculated mechanically by conveyors or bucket elevators. The use of hot gas (recycled or direct heated) can be employed to promote drying of the particles within the grinding chamber. The material ground to specification passes the classifier and is conveyed from the mill with the gas stream to the dedusting process via a baghouse or cyclone baghouse combinations. Classifier coarse fraction or grits are directed back to the grinding table by an internal grit return cone. The whole grinding-classifying circuit is maintained under negative pressure produced by a fan at the end of the process that draws air through the mill and the dedusting process. The ability to combine comminution stages and classification stages results in a significantly reduced plant footprint over conventional crushing and tumbling mill circuits.

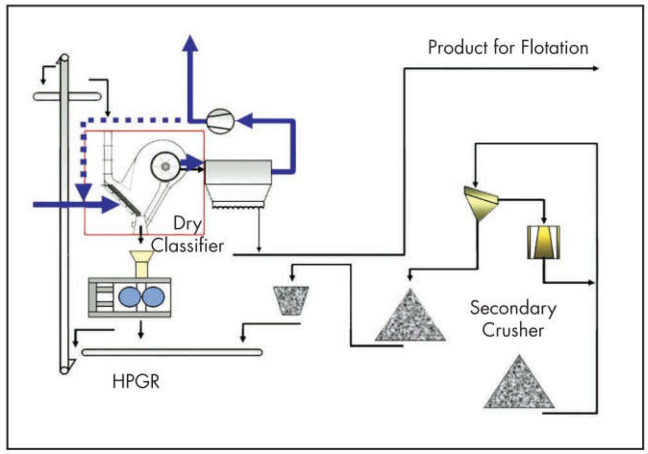
Modern VRMs are characterized by a very high reduction ratio. The larger mills can be fed with –150 mm (6 in.) material, and medium sized mills can be fed with –90 mm (3½ in.) material. Grinding down to final product sizes of 80% passing 20 µm (635 mesh) or even finer is possible, although most installations generate product sizes around 80% passing 90 µm (170 mesh). Product size requirements in practice have ranged significantly from 80% passing 600 µm (30 mesh) to 30 µm (450 mesh). A wide variety of machine sizes is available for a given application, with installed power up to 17,400 hp and unit capacities greater than 2,000 t/h.

The Foskor operation in the Phalaborwa region of the Republic of South Africa is a notable application of the VRM technology in finish grinding duty ahead of phosphate flotation. A Loesche LM 50.4 VRM was installed in place of conventional wet rod and ball milling technology in 1999 (Creamer 1999) to dry grind pyroxene ore from a secondary crusher P_{80} of 54 mm (~2 in.) to 80% passing 425 µm (40 mesh). The VRM processes on average more than 500 stph of hard pyroxene ore, of Bond ball mill work index 30 kW·h/t, and operates in parallel with a rod/ball mill circuit receiving tertiary crushed feed at 80% passing 16 mm (⅝ in.).

HPGR Finish and Semifinish Grinding

Burchardt (2014) described the use of HPGRs in the cement industry to grind slag, clinker, and limestone to product sizes of 80% passing 30 µm (450 mesh) to 90 µm (170 mesh), at energy consumptions 30%–50% lower than ball mill grinding systems. This fine grind is reportedly achievable in minerals applications. In case a coarser grind size is required in minerals applications, the "coarse end" of feasible finish grinding products may in fact be as coarse as 80% passing 250–300 µm (nominally 50 mesh). Semifinish grinding can be used to generate an intermediate product sizing less than 1 mm (18 mesh) for grinding in a ball mill or stirred mill. In both finish and semifinish applications, the feed size to the HPGR is around 80% passing 38 mm (1½ in.). Factors that need special considerations in these grinding circuits are feed moisture, material abrasiveness, and throughput capacities. Feed moisture content dictates the need for external dryers and impacts the energy consumption and capital cost of the installation.

A typical finish grinding flow sheet is shown in Figure 17. The key components of the flow sheet are the HPGR, two-stage air classifier (separators), system fan, deduction cyclones, and bucket elevators. New feed containing typically 2%–3% and up to 10% moisture is dried by hot gases in the air classification system, which consists of a static and a dynamic separation stage. The static stage generates an intermediate product that is then classified in the dynamic stage. Rejects from both stages are fed to the HPGR. Finished product is removed via dedusting cyclones or alternatively in a baghouse system. Airflow through the entire system is achieved by the system fan. Bucket elevators, or conveyor belts for high-capacity applications, convey the new feed and HPGR product material to the classification stage. Burchardt (2014) cites the example of the Newmont Minahasa (Indonesia), Newmont Carlin, and Barrick Goldstrike dry grinding applications as evidence that the air classification systems can stand up to the abrasive characteristics of gold ores.



Courtesy of ThyssenKrupp

Figure 17 Finish/semifinish HPGR grinding flow sheet

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