Chapter 4
Beneficiation of Gold and Silver Ores

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This chapter provides an overview of various innovation and technology developments in mineral processing that have shaped the current gold and silver industry. A glimpse of the present and future challenges in mining is also presented. A holistic approach to problem solving involving various stakeholders is gaining momentum, and this has been reflected in this chapter. Various developments that are being pursed in mineral processing focusing on a change in the existing mining paradigm are also presented in this chapter.

4.1 Introduction

Traditionally, a gold and silver operation is segmented into distinct core disciplines, viz., geology, mining, and processing from a technical perspective with a focus on extracting an ore body to produce marketable concentrates or metal. There are various support roles that are critical to the success of these technical disciplines such as administration, maintenance, IT, supply chain, safety, environment, and community relations.

Mining companies have started to look at their mining business holistically and also from different points of views. An integrated approach to mining is gaining prominence not just from an economic perspective but also allows them to take into account the needs of various stakeholders. Mining companies are slowly tapping

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into some successful concepts that have transformed other industries such as manufacturing, chemical, and pharmaceuticals along with oil and gas.

Some mining companies are already looking beyond the traditional disciplines of geology, mining, and processing to focus on the key value drivers that tend to integrate these disciplines and their interfaces. This is allowing mining companies to innovate, and the focus is on step change in their cost structures and productivity.

Though this chapter is about innovation in mineral processing, the authors strongly feel that this has to be seen in the light of other disciplines and the mining value chain as a whole. Any innovation focusing on mineral processing alone will only provide part of the solution and will miss big opportunities. The question then is "What are these big opportunities that will allow a step change in profitability of a mining operation in a safe and sustainable manner?"

This chapter will emphasize on the following three key focusing questions related to the innovation in mineral processing in the present mining context:

1. What innovations are required to address the existing mining challenges?
2. What are the various mineral processing innovations that have already shaped and advanced the mining industry?
3. What can be done to bridge any innovation gaps for realizing the full potential?

4.1.1 Innovations in Mineral Processing

To understand the various innovations in mineral processing, we will need to understand the various challenges the mining industry has handled so far. In the early days, high-grade ores and ore bodies were exposed on the surface. To extract these ores required minimal generation and treatment of waste. One could say, this was close to the ideal situation of "zero waste mining" scenario.

As head grades started to deteriorate with ore bodies located at a considerable depth, the need for overburden removal and therefore the generation of mining waste started to increase. With industrialization and the growth in demand of metals, the urgent need to treat low-grade ores at much greater depth intensified. Innovation focused on how to mine higher throughputs and then process them mainly to meet the immediate needs. This paved the way for mass open pit mining and larger mining machineries. Open pit mines and unfavorable terrain resulted in building concentrators that are far away from mining. Also, the consideration for a large tailings facility added to the complexity, resulting in a large mine footprint which increased in proportion with mill throughput.

In the early days when the environmental regulations were not as stringent and the access to power or energy sources was relatively easier, the main focus of innovation activities was to build larger and more efficient equipment to treat the large amount of mined product (containing mostly waste) to meet the needs of metal production targets. Hence, there was not much incentive to challenge the existing mining paradigm of mass scale waste generation, processing, and storage. This situation is still ongoing, although there is now a strong realization that this cannot continue for very long due to mounting energy costs, stringent environmental regulations, and lack of water and other resources along with an ever-increasing opposition by local communities.

The mining industry is now facing a dilemma, and there is a strong push by companies, some governments, and stakeholders to focus on innovation to address the challenges. The following are the main areas that have attracted serious attention for innovation in the area of mineral processing:

- Energy consumption and GHG reduction
- Economy of scale (capital cost)
- Efficient use of consumables (media, liner, reagents)
- Instrumentation, control, and automation
- Use of alternative water sources
- Environmental management of tailings and waste
- Modeling and simulation tools (to reduce risk in design and operations optimization)
- Seamless integration with value chain
- Continuous improvement along with training and education to improve productivity
- Breakthrough technologies (focus on step change such as dry processing, in situ mining, etc.)

4.2 Comminution

This chapter will focus on the key mineral processing innovations that have already resulted or have the potential to make a significant contribution to the mining industry. Principles of operation and design of unit operations will not be the main focus of this chapter as they are readily available for reference in various publications.

Comminution costs are typically one of the largest cost items in a gold milling operation. Since the advent of Autogenous Grinding (AG) and Semi-Autogenous Grinding (SAG) milling technologies in the late 1950s, they have established themselves as the present standard and are commonly used in the gold industry now. These technologies have replaced the previous "conventional" comminution circuits involving crushing-ball mill or rod mill-ball mill circuits. It is estimated that over 90% of the gold ounces are produced by milling operations, and the majority of these ounces come from high aspect ratio SAG circuits with significant contributions from low aspect SAG circuit such as in South Africa (Mosher 2005). The main reasons for the attraction for SAG milling are circuit simplicity and typically lower capital and operating costs to meet the needs for operations with higher throughput. SAG mills work well for handling clay rich sticky ores, which is a challenge for multistage crushing circuits requiring washing plants.

4.2.1 Crushing

Crushing is an important step in comminution that prepares the ROM ore for primary grinding and other downstream processes such as heap leach. The selection of the right crushers and crusher flow sheet is dependent on the upstream mining method and blasting characteristics and the downstream process requirements. As process plant throughputs are increasing, the need to reduce operating costs and capital cost per ton of ore processed is critical. Both crusher and circuit design have evolved with larger crushers employing more horsepower and speed to treat higher throughputs at a reduced cost.

With the advent of SAG milling, cone crushers are now more or less eliminated from comminution flow sheets. Instead, the cone crushers are employed in an SABC circuit to crush the recirculating pebbles. These pebbles tend to be more resistant to impact breakage in the SAG mill, and crusher creates ore surfaces more conducive to breakage in the grinding mills (Major 2002).

During the last 20 years, the size of gyratory crushers has not changed significantly, though their installed horsepower has increased allowing these crushers to treat higher throughputs. An example of the largest gyratory crusher is FLSmidth's 60′ × 113″ UD design with an installed power of 1 MW. Another feature of the new design of gyratory crushers is the development of top service gyratory crusher which appears to enhance safety, reduce maintenance downtime, and lower cost of crusher installation (Erickson 2014).

4.2.2 Mine to Mill

Mine to mill optimization in various operations over the years has shown significant benefits such as high mill throughput rates from reduced top-size from mining through increased powder factor or blast energies (Gillot 2006; Kanchibotla 2014). New blasting technologies are emerging that have the potential to significantly increase powder factor through innovative blasting practices such as dual blast layers within a single blast event (Brent et al. 2013).

Differential blasting for grade (DBG) involves conditioning of sub-volumes of material at bench or stope scale using customized blast designs that generate imposed size distributions with higher grade, concentrated in the finer fractions. This is referred to as differential blasting as it leverages the application of differential charge energies to different blast holes to achieve the desired result (Rutter 2017)

4.2.3 Classification of Comminution Method

4.2.3.1 Existing Technologies

- HPGR
- AG/SAG mill
- Ball mill
- Vertimill™
- IsaMill™

4.2.3.2 Emerging Technologies

- Stirred Media Detritor (SMD)
- HIGmill™
- Superfine IMPTEC crusher
- Horomill®
- Vibrocone™

4.2.3.3 New Technologies

- EDS multishaft mill
- Conjugate anvil-hammer mill (CAHM)
- HPGR—in closed-circuit with air classifiers
- HPGR-stirred mill combined
- Multi-pass HPGR circuit
- Jet micronizer (air jet mills)
- Rotary collider mill (RCM)—DevourX.
- Hicom mill
- Vertical roller mills
- Selfrag

4.2.4 HPGR

The use of HPGR technology has been extended significantly over the past 10 years. When initially introduced to the industry, HPGRs were considered to be a high capital cost and applicable to projects with high throughputs and harder ores. The benefits of the technology are now established, and the impacts on recovery and longer-term operating costs are well proven. HPGR technology is now used in a range of duties, including crushing operations in heap-leach circuits, as an alternative to SAG mills and for recycle crushing. In SAG, mills, however, are less energy efficient in handling harder and abrasive ores. As the ore bodies are steadily becoming more competent along with increasing energy costs, the industry has been looking for alternatives to SAG. It is interesting to note that the traditional crusher and ball milling technology has returned with a more innovative approach to crush rocks using high-pressure grinding rolls (HPGR).

HPGR application continues to expand. AngloGold Ashanti's Tropicana Project commissioned in 2013 treats 5.8 Mtpa of moderately hard free-milling gold ore. The comminution circuit is identical to that of Boddington, with HPGRs utilized as tertiary crushers to produce a P80 2-mm ball-mill feed. A combination of HPGR technology coupled with high-intensity cyanidation (Pyke et al. 2006) was used to recover coarse gold from the quartzitic ore processed by Bendigo Mining. The flow sheet also entailed flotation of auriferous sulfides that were subjected to high-intensity cyanidation. The tailings from the two recovery steps were not subjected to cyanidation.

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Recent successes of HPGR in hard rock application such as at Freeport's Cerro Verde in Peru (Vanderbeek et al. 2006; Koski et al. 2011) and Newmont's Boddington in Western Australia (Dunne et al. 2007; Hart et al. 2011) with a key target of significant grinding energy savings of 15–20% are reported. Both these operations have two stages of coarse crushing using gyratory and cone crushers followed by the third stage of crushing involving HPGR and a single-stage ball milling circuit.

4.2.4.1 HPGR: In Closed-Circuit with Air Classifiers

The application of HPGR technology in comminution circuits is already well established for the processing of hard ores in precious and base metal operations. Of the many possible flow sheets that have been proposed for HPGRs, those using HPGRs as tertiary crushers, in closed-circuit with wet screens (apertures in the range of 6–10 mm), and feeding ball mills seem to have become the standard for these applications.

Although these circuits provide reduced operating costs with a relative increase in energy efficiency and the elimination of steel grinding media when compared to SAG-based circuits, the overall energy reduction of the circuit is compromised by the requirement of complex material handling systems. In addition, the total capital cost is usually higher than for a traditional SABC circuit.

Several different circuits have been proposed to better utilize the HPGR by applying it for higher reduction ratio and therefore the elimination of the less efficient ball mill, e.g., the multistage HPGR. However, the one circuit/application that seems to be the most promising in terms of energy reduction, allied with relatively low capital cost requirements, is one with a single-stage HPGR in closed-circuit with air classification. This dry circuit has already been used in the cement industry for a reliable pre-mill grind or final product grind, reducing power and steel consumption cost and increasing throughput capacity while operating to make a high-quality product as fine as 25 μm (Jankovic et al. 2015).

Weir (KHD HPGR) is advocating this new circuit and has reported on recent project studies, and a few operations (iron ore and limestone processing), with final product sizes of 75 μm or as low as 15 μm, are feasible and enable significant energy reduction (more than 50% overall if compared to traditional circuits with tumbling mills).

This dry HPGR circuit usually is designed with a combination of static and dynamic air classifiers, and a schematic of its flow sheet is shown in Fig. 4.1. It is also interesting to note that "dry ground feed for flotation shows superior performance in pilot testing to wet milled product" (Aidan Giblett—Newmont TS Processing).

4.2.5 Selfrag

Selfrag is an emerging technology showing some promise in pre-weakening of mineral ores by high-voltage pulses. This was pioneered in the 1950s, but it is attracting some serious attention during the last few years. The key benefits of this technology

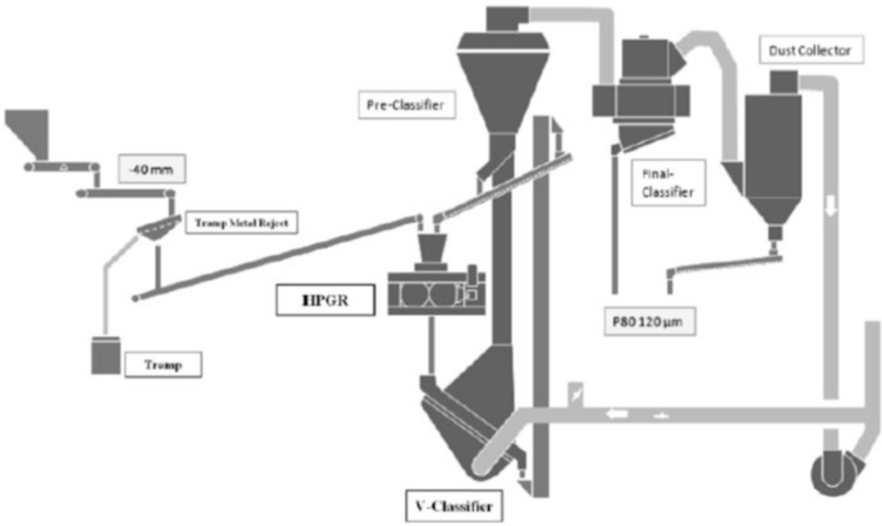

Fig. 4.1 HPGR in closed-circuit with air classification (Van der Meer and Strasser 2012)

compared to conventional comminution machines are that this is highly selective and its ability to weaken the ore with a potential for significant energy savings in further comminution (Shi et al. 2003). Studies on a Newcrest's Cadia East Cu-Au ore samples by JKMRC showed an energy reduction of 5 kWh/ton, along with a potential to remove two MP1000 pebble crushers and one 10 MW ball mill. Simulation studies showed that Selfrag has the potential to reduce the operating cost by $19 M (Shi et al. 2014). Though this study showed some potential, a detailed capital cost estimate is needed to better evaluate the potential of this technology.

4.2.6 IMP Superfine Crusher Technology

The "IMP" superfine crusher technology is presently evolving and has the potential for developing a broad range of application options as the technology matures. This "IMP" superfine crushing concept evolved from the simple premise that the probability of particle breakage increases as the number and intensity of forces simultaneously contacting the particles increase. This is quite different from conventional comminution machines where breakage rate decreases with increased energy inefficiencies as feeds become finer and harder. The IMP superfine crusher is designed to provide a mechanism that could effectively deal with fine hard feeds by maintaining high breakage rates as hard particle became finer and single-particle population rapidly expands (Kelsey and Kelly 2014).

4.2.7 Ultrafine Grinding

Global ore grades are declining. In addition, orebodies are getting increasingly complex, with the valuable minerals often more finely disseminated and therefore more difficult to liberate from the associated gangue. As gold mining companies deal with more complex, refractory, and lower-grade orebodies, the need for fine and ultrafine grinding increases. The main reason for this is that in order to extract value minerals from the ore, the ore needs to be ground in such a way as to achieve maximum liberation. As a result, fine and ultrafine grinding processes are becoming more common in the mineral processing industry. Many of the new greenfield projects involve orebodies that were historically too complex to process efficiently. However, the demand for finer grinding has set new challenges for grinding technology; new technological advancements in mineral processing, including stirred milling, have opened the door for many new opportunities. Lower-grade ore and finely distributed ore require finer grinding than the traditional mill circuit product size (P80) of 75 μm.

Ultrafine grinding (UFG) has continued to evolve in terms of equipment development. A number of specialist machines are commercially available including

Xstrata's IsaMill, Metso's Vertimill and Stirred Media Detritor (SMD), Outotec's High-Intensity Grinding (HIG)_mill, and the Metprotech mill. UFG equipment has been developed with installed powers of up to 5 MW. Compared with conventional ball or pebble milling, the specialist machines are significantly more energy efficient and can economically grind to 10 mm or lower, whereas the economical limit on conventional regrind mills was generally considered to be around 30 mm. Coupled with improvements in downstream flotation and oxidation processes, the rise of UFG has enabled treatment of more finely grained refractory ores due to a higher degree of liberation.

The application of ultrafine grinding to refractory gold ores has proven to offer a viable alternative to conventional oxidative processes in particular cases. Its application to a hydrometallurgical extraction route for other metals beyond gold is open and likely to lead to alternative process routes for these metals also.

As an example, Kalgoorlie Consolidated Gold Mines (KCGM) has successfully operated an ultrafine grinding (UFG) circuit to supplement its roaster capacity for the treatment of the refractory gold flotation concentrate. The capacity of UFG circuit for grinding to 11–12 μm is over 20 tph and achieving over 90% gold recovery (Ellis and Gao 2002).

4.2.8 IsaMill

The IsaMill™, as patented and distributed by Glencore technologies, is a high-intensity, horizontally mounted stirred mill that uses fine (2–6 mm) ceramic media for grinding in fine and ultrafine applications.

The IsaMill™ is a closed mill. Slurry travels through the mill in a "plug" -ow pattern through consecutive grinding disks. Media recirculates between the rotating disks distributing grinding action throughout the IsaMill™. Grinding is by attrition and abrasion of the particles in contact with the high-speed, small, circulating media.

At the discharge end of the IsaMill™, slurry and media reach the patented product separator. Media is centrifuged out to the shell and is pumped back with some of the slurry to the feed end of the mill. This action retains media in the IsaMill™ without the need for fine screens, while the ground discharge slurry exits the center of the product separator. The high efficiency of the IsaMill™ comes from its ability to use small media, with high surface area and high media/particle collision frequency. Small media can still grind coarse feed because of its high speed up to 22 m/s. Figure 4.2 shows a detail schematic of a large IsaMill. The high-power intensity results in a small mill with short residence times less than a minute which avoids overgrinding. This, together with the eight consecutive stages of grinding and product separator, produces a sharp size distribution without external classification (Lakshmanan et al. 2016; Gleencore 2015) (Fig. 4.3).

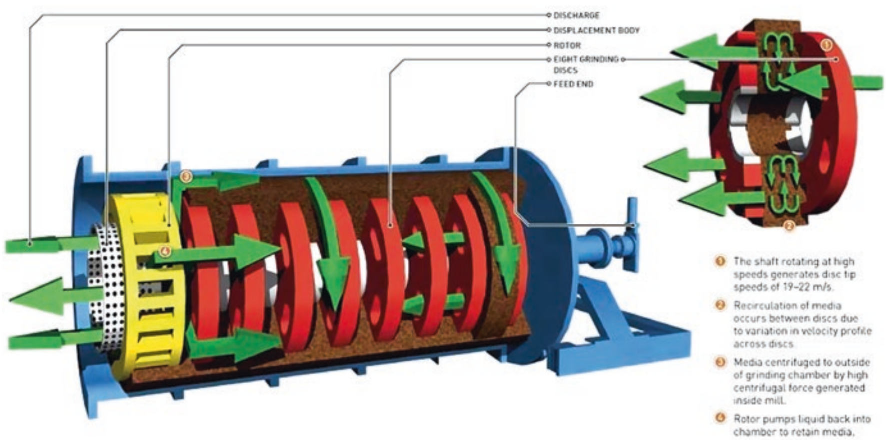

Fig. 4.2 IsaMill schematic (Gleencore 2015; Lakshmanan et al. 2016)

4.2.9 VertiMills

Vertical mills were first designed in the 1950s for applications in fine and ultrafine grinding in Japan. Lately, the vertical mill is making progress toward primary grind application and shown promise in energy reduction relative to ball mills, typical to what is normally seen in regrinding applications (Mazzinghy et al. 2014). This vertical mill would be in series with either an AG or a SAG mill grinding circuit. The vertical mill, or Vertimill™ by Metso® Minerals, has since seen many installations worldwide in regrind applications, noting a significant decrease in energy consumption compared to typical tumbling mill like a ball mill (Palaniandy et al. 2014) (Figs. 4.4 and 4.5).

4.2.10 Stirred Media Detritor (SMD)

The Stirred Media Detritor (SMD) is a fluidized, vertical stirred mill designed for optimum grinding efficiency for fine and ultrafine grinding products. The SMD utilizes the rotational energy of the impeller arms to impart a high-energy motion to the media/slurry mixture inside the mill. This results in particle-to-particle shear and compressive forces which produce the desired grinding mechanism for fine grinding. The vertical arrangement allows the drive train to be entirely supported by the mill body which leads to a small foot print and simple foundation. Also, the vertical arrangement does not require any slurry seals or inlet feed pressure. The SMD is a fluidized media mill, which means the stirrer speed is high enough to distribute the media throughout the slurry regardless of media density, forcing particle and media contact. The SMD power intensity is optimized to achieve efficient

Fig. 4.3 Industrial IsaMill (Gleencore 2015)

grinding, limit wear, and allow for heat dissipation in the case of a high-energy grind. The power intensity (kW/m^3) is relatively high compared with the other mill types but is required to generate a vortex of the media and slurry during operation and to bring the particles in contact with one another for efficient grinding. However, the power intensity is not so high that a cooling system would be required to dissipate the heat generated during a high-energy grind. Also, limiting power intensity limits the sheer force of the media/slurry on the liners and impellers and improves wear life (Fig. 4.6).

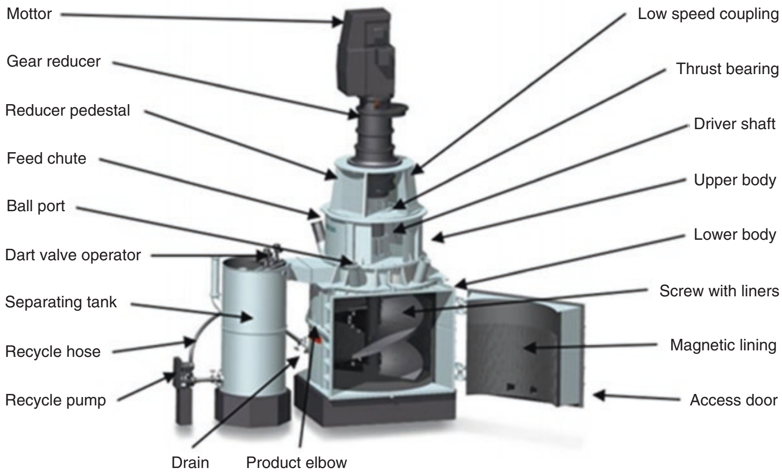

Fig. 4.4 Metso® Vertimill™ schematic (Allen 2013)

Fig. 4.5 Industrial Vertimill (Allen 2013; Lakshmanan et al. 2016)

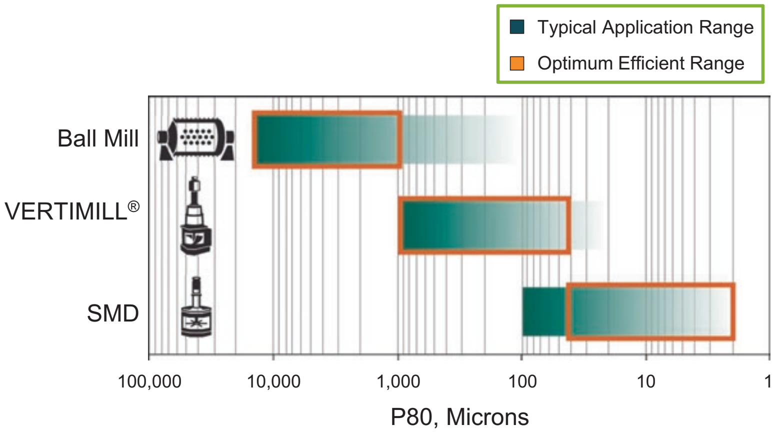

Fig. 4.6 Typical grinding ranges of ball mill, Vertimill, and SMD (Metso Minerals Industries Inc. 2016)

4.2.11 Tower Mill

The tower mill is a vertical stirred grinding mill which can be used in both dry and wet grinding applications. It has provided a means of size reduction in an area where conventional tumbling mills become inefficient (Morrell et al. 1993). The major advantage of the tower mills over the ball mills in regrinding and fine grinding operations is an efficient utilization of the fine grinding media. The normal top-size of media used is 10–25 mm, but for very fine grinding even smaller media can be used. Tower mills were first introduced in the 1950s as an alternative to the ball mills in a regrinding application. Since then, they have been used to grind a range of materials from limestone to coal to sulfide concentrates (AMIRA 1993).

The principal method of grinding in tower mill is attrition, with the possibility of some shearing and compression breakage taking place due to the motion of the media charge created by the rotation of helical screw enhancing the media pressure. The tower mill is filled to a level with the grinding media until developed power equals 80% of motor name plate rating. The tower mill will show a power saving of up to 50% over the conventional tumbling mill. The tower mill has a definite use in comminution and it can also be used for:

- Secondary grind following by ball or rod mill
- Regrind circuit.
- Grinding and leaching, as in gold cyanidation circuits
- Ultrafine grinding
- Given the proper feed and the requirement for a fine grind (Table 4.1)

4.2.12 HIGmill (High-Intensity Grinding Mill)

With installed power up to 5000 kW, the HIGmill™ is the largest fine grinding unit in the marketplace to date. This technology comes in various drum diameters, and the mill heights can be varied to optimize the media load and power input for specific applications. Chamber volumes range from 400 to 27,500 L with the corresponding drives from 132 to 5000 kW. The HIGmill is the only ultrafine grinding technology in commercial use that has the capability to use small-size high-density grinding media in mill sizes above 3000 kW. Over 260 HIGmills have been commissioned (Figs. 4.7 and 4.8).

Table 4.1 Comparing power intensities at different mills

	Typical lower grind size P80 (μm)	Power intensity (kW/m^3)
Ball mill	75	20
Tower mill	20	40
UFG mill	5	280

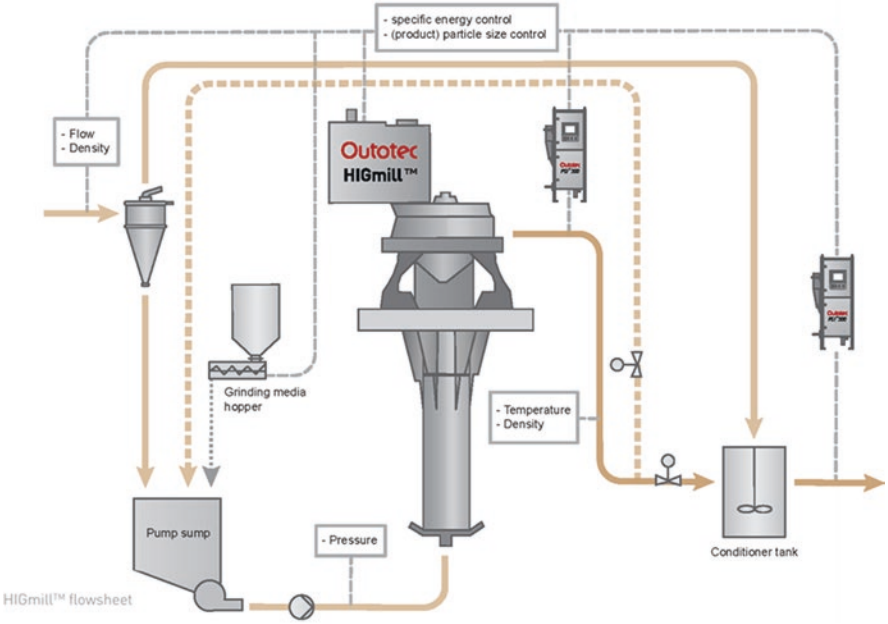

Fig. 4.7 HIGmill flow sheet (Letho et al. 2013)

4.2.13 Comminution Circuit in Large Gold Operations

The most common gold production plants comminution circuit are described in Table 4.2 (Fig. 4.9).

Crush-for-leach includes any number of stages of crushing. *SS-A* single-stage AG mill, *SS-S* single-stage SAG mill, *SS-AC* single-stage AG mill (with pebble crushing), *SS-SAC* single-stage SAG mill (with pebble crushing), *AB* AG mill-ball mill, *SAB* SAG mill-ball mill, *ABC* AG mill (with pebble crushing)-ball mill circuit, *SABC* SAG (with pebble crushing)-ball mill circuit

4.3 Classification

Classification is an important aspect of any comminution circuits. It is well known that a closed-circuit grinding circuit with a classification device results in significant benefits to the comminution process. In the early days, mechanical rake and spiral classifiers were used in closed-circuit grinding circuits. Due to capacity limitations and high operational costs because of wear and tear, these technologies are not commonly used in the present comminution circuits. Hydrocyclones became popular since the early 1950s as they are high-capacity devices that allowed the industry to

Fig. 4.8 Outotec industrial HIGmill (Letho et al. 2013)

meet the demands of increasing throughputs to treat low-grade ores. Since hydrocyclone separation is a function of both size and density, a sharp size separation is not always possible for many ore containing high specific gravity minerals and metals such as gold, PGMs, and lead. This results in building of these small heavies, which are mostly liberated, in the recirculation stream in cyclone underflow leading to unnecessary grinding with poor gravity and flotation responses. The inefficiency of the hydrocyclone separation requires the use of high circulating loads to minimize the mill residence time. High circulating loads increase the power requirements per ton of ore (Albuquerque et al. 2008).

4.3.1 Derrick Stack Sizer™

The key for major improvements in capacity and in energy consumption in closed-circuit grinding is improved sharpness of classification (Hukki and Allenius 1968). This is where screen separation has a significant advantage because of its sharp

Table 4.2 Largest gold-producing operations in 2014 (Adams 2016)

	Operation	Country	Comminution circuit(s)	2014 Production (tons of Au)
1	Muruntau	Uzbekistan	SS-S Crush-for-leach	61
2	Grasberg	Indonesia	SABC Crush-HPGR/grind	35
3	Pueblo Viejo	Dom. Rep.	SABC	35
4	Yanacocha	Peru	Crush-for-leach single-stage SAG	30
5	Carlin	USA	Crush-for-leach SAB Dry crush/grind	28
6	Cortez	USA	SAB Run-of-mine leach	28
7	Goldstrike	USA	SABC Dry crush/grind	28
8	Olimpiada	Russia	SAB	23
9	Veladero	Argentina	Crush-for-leach	23
10	Boddington	Australia	Crusher/HPGR-ball mill	22
11	Kupol	Russia	SAB	21
12	Lihir	PNG	SABC	23
13	Kalgoorlie (KCGM)	Australia	SABC	20
14	Cadia Valley	Australia	SABC	19
15	Oyu Tolgoi	Mongolia	SABC	18
16	Lagunas Norte	Peru	Crush-for-leach	18
17	Driefontein	South Africa	SAB, SS-S, crush-for-leach, crush-rod mill-pebble mill, SS-A/S	18
18	Penasquito	Mexico	SABC (with HGPR)	18
19	Kumtor	Kyrgyzstan	SAB	18
20	Tarkwa	Ghana	SABC	17

separation. Derrick Stack Sizer™ is a recent innovation in fine screening which allows for high separation efficiency and high tonnage capacity on a much smaller footprint that is possible using conventional screens (Lakshmanan et al., 2016; Clark 2007).

4.3.2 Cavex Recyclone™

Cavex Recyclone™ is a double classification unit in one stage, which seems to increase the sharpness of separation and reduces the bypass of fines to the underflow. This technology uses wash water injection mainly to rupture the viscous layer to release the trapped fines for proper classification. Recent trials and installations in grinding circuits have shown to significantly reduce fines misreporting to mill

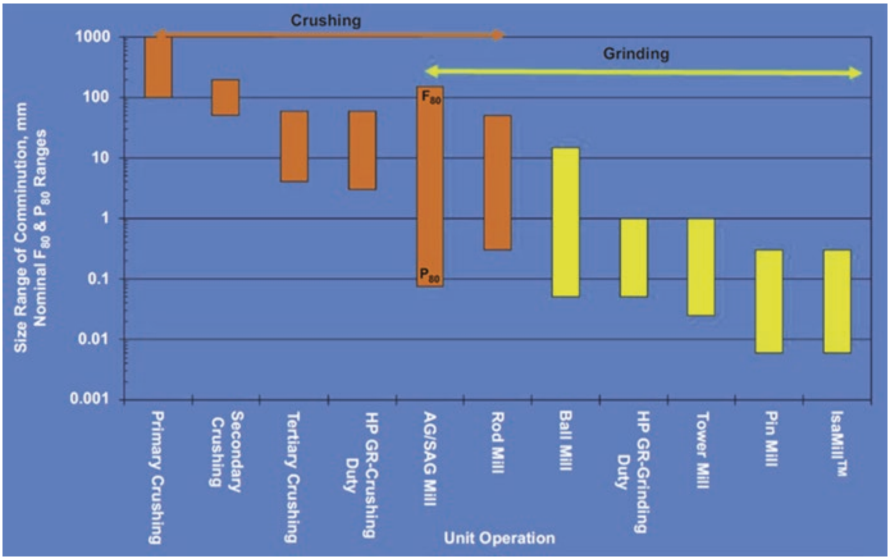

Fig. 4.9 Applicable size range for comminution unit operations (Adams 2016)

from 30 to 15% resulting in reduction in circulating load by around 50–60% (Castro et al., 2009).

4.3.3 Grade Engineering®

Grade Engineering® is an integrated approach to coarse rejection that matches a suite of separation technologies to ore-specific characteristics and compares the net value of rejecting low-value components in current feed streams to existing mine plans as part of a system view (Rutter 2017).

Grade Engineering is focused on extracting metal more efficiently by separating ore from waste before it enters comminution. Early physical rejection of non-valuable material through pre-concentration techniques before processing decreases processing costs and importantly can significantly increase the life of a mine.

Grade Engineering® is the first large-scale initiative to focus on integrated methodologies to deliver maximum operational value (Pease et al. 2015).

4.4 Pre-concentration

Removal of some waste as early as possible after blasting has the potential to reduce haulage costs to the mill in many situations. In addition, this provides an opportunity to upgrade the ore resulting in reduced energy and operating costs per unit of metal input to the plant. A higher head grade to the process plant typically results in better concentration ratio and better unit recoveries as well as the process now has to handle lower gangue content. This concept of pre-concentration is not new with application such as Dense Media separation and sorting on the surface since the 1930s (Munro et al. 1982), also applied underground (Lloyd 1979). It is worthwhile to note that not all ores are amenable to pre-concentration especially when the minerals are finely disseminated in the ore body, resulting in high losses of valuables in the waste product.

Ores types that are amenable to pre-concentration can add significant economic benefit, such as at the Kroondal platinum mines in South Africa, where about 50% of bulk mining feed of UG2 ores to the mill is rejected with a PGM recovery of 95% (Holloway et al. 2009). The value of pre-concentration has now been demonstrated for a wide range of ore types at a coarse-size range (Mohanty et al. 2000; McCullough et al. 1999; Mohanty et al. 2000; Schena et al. 1990). The value of pre-concentration should be looked in a holistic way involving integrated mining, processing, and waste disposal. Bamber has concluded based on his studies that the exploitation of a deposit with ore pre-concentration and waste disposal technologies integrated into the mining process prior to beneficiation on surface is superior to the conventional approach (Bamber 2008).

The following pre-concentration technologies appear to have a significant potential and are slowly finding applications in different mining applications:

- Size classification
- Ore sorting
- Dense media separation
- Coarse particle flotation

4.4.1 Size Classification

Concentration by comminution and size classification alone has been found to be effective for some ore types (Burns and Grimes 1986; Sivamohan and Forssberg 1991; Logan and Krishnan 2012). Size classification presents a low-cost option for rejection of waste, with maximum economic benefit at coarse particle sizes either at naturally arising ROM particle size distribution or at a coarse crush size, as close as possible to the mining face (Klein et al. 2002).

4.4.2 Ore Sorting

Ore sorting in the mining industry has evolved from manual sorting in the early days to basic optical sorting first used in mining in the 1970s using camera technology and digital image processing for industrial minerals. Arvidson and Wotruba (2014) have provided a review of the various applications of ore sorting technologies (Arvidson and Norrgran 2014). The importance of ore sorting in improving economics of marginal deposits is increasing, being realized by the mining industry (Lessard et al. 2014; Foggiatto et al. 2014).

At present, majority of automated ore sorters, outside of the diamond industry, are color or conductivity sorters (Bartram and Kowalczyk 2009). This is a significant innovation in mineral processing with an ability of pre-concentration with significantly improved economics. The optical sensors have quite a few applications, but as the optical properties differ relatively little, laser-based sensors could be useful. If the primary surface properties are distinct, NIR sensors are normally used. Novel sensor technologies are now necessary to extent the application to ore types beyond optical sensors that exploit material properties such as electrical conductivity, magnetization, molecular structure, and thermal conductivity. Combination of sensors also have potential such as optical/NIR, optical/inductive, or XRT/inductive (Arvidson and Norrgran 2014).

The recent development of LIBS (laser-induced breakdown spectroscopy), focused on pattern recognition, appears to have the potential for mass ore sorting. SonicSampDrill and IHC Mining have been working on the development of the LIBS Ore Sorter (Sonic Samp Drill 2014). Though there is potential, much work is required to make this technology commercial for large throughputs.

Normally 10–90% of the mass can be rejected in an early stage of the process at the primary, secondary, or tertiary crushing stage. Also, low-grade waste rocks don't need to be transported, crushed, milled, or further treated.

Ore sorting is applicable for precious metals, gold, base metals, diamonds, coal, ferrous metals, copper, platinum, slag, industrial minerals, and gemstones. The method which has used for ore sorting was shown is Tables 4.3 and 4.4.

4.4.3 Dense Media Separation (DMS)

Dense media separation is widely used in coal, diamond, chromite, and iron ore industries since its introduction by Dutch Sate Mines (DSM) in 1947. Though used occasionally in other industries, its application in precious and base metals, viz., PGMs, gold, copper, and zinc, is slowly gaining some momentum.

Napier-Munn et al. (2014) have provided a review of the various DMS technologies, with a focus on technologies that have been implemented by the industry. Tati nickel plant in Botswana uses DMS to reject 70% of mass with recovery of ~2/3 of the contained nickel and has allowed the mine to target a zero cutoff grade, thus allowing bulk mining and simplifying the mine plan with increased resources. Another impressive application of DMS has been in recovery of fine-grained gold from waste rock dumps at the Witwatersrand gold fields in South Africa. Despite a low feed grade (0.2–0.3 g/ton), DMS was successful in recovering 70% of the gold into 30% of the mass (Napier-Munn et al. 2014).

Table 4.3 Ore sorting methods and mineral application

Industrial mineral	Gems	Ferrous metals	Nonferrous metals	Fuel	Slag
COLOR, XRT, NIR	COLOR, XRT, XRL, NIR	XRT, EM, NIR	COLOR, XRT, NIR	XRT, RM	XRT, EM
Lime stone Dolomite Quartz Rock salt Talc Calcite Feldspar Magnesite	Diamond Emeralds Rubies Sapphires Tanzanite	Iron Manganese Chromite	Gold Silver Zinc Copper Nickel Tungsten PGMs	Coal Oil shale Uranium	Stainless steel slag Ferro silica slag Ferro chrome slag Nonferrous slag

Table 4.4 Sensor ore sorting segmentation

Sensor/technology	Material property	Segment
RM (radiometric)	Natural gamma radiation	Fuel, precious metals
XRF/XRL	Visible and X-ray fluorescence	Diamonds, base metals
XRT (X-ray transmission)	Atomic density	Base metals, precious metals, industrial minerals, fuel, diamonds
COLOR (CCD color camera)	Reflection, absorption, transmission	Base metals, precious metals, industrial minerals, diamonds
PM (photometric)	Monochromatic reflection/ absorption	Base metals, industrial minerals
NIR (near-infrared spectrometry)	Reflection, absorption	Base metals, industrial minerals
IR (infrared cam)	Heat conductivity, heat dissipation	Base metals, industrial minerals
(electro-magnetic sensor)	Conductive magnetic	Base metals

Typically, DMS processes are compact processes with high throughput of 300–1000 ton/h. Holloway et al. have concluded that DMS seems to be well-positioned with tremendous growth potential to address the need for reducing energy costs, improving mine-mill integration, and simplifying tailings handling through coarse ore pre-concentration (Holloway et al. 2009). Bamber has carried out various studies and has highlighted the significant potential of DMS in underground applications (Bamber 2008) (Fig. 4.10 and Table 4.5).

4.4.4 Coarse Particle Flotation

Flotation of ore at a top-size of 3 mm, followed by gravity concentration of the flotation tailings, has been applied previously in South Africa to treat Witwatersrand gold ores resulting in the production of a 40% mass pull at an overall gold recovery

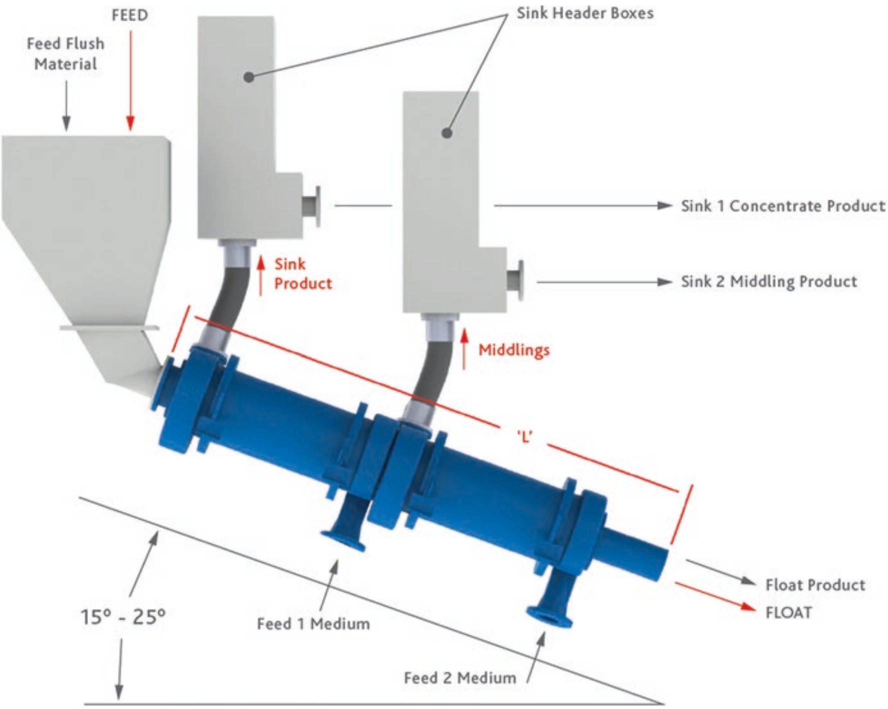

Fig. 4.10 Dense media separator schematic (Sepro Mineral Systems 2019)

Table 4.5 Application of DMS in a variety of minerals

Metals, oxides, and sulfides	Industrial minerals and silicates
Gold	Barytes
Antimony	Coal
Bauxite	Diamond
Chromite	Feldspar
Copper	Fluorspar
Iron	Limestone
Lead	Phosphate
Manganese	Potash
Nickel	Quartz
Tin	Petalite
Zinc	Spodumene

of 98% (Lloyd, 1979). Coarse particle flotation of particle ranging from 3 to 5 mm is common in the potash industry. For many base metals and precious metals applications, coarse flotation is challenging in conventional and flash flotation machines for pre-concentration purposes.

Jameson (2014) has developed a fluidized bed flotation technology for coarse flotation focusing on pre-concentration at a coarse size (600–800 μm) with an estimated reduction in operating cost of 10–20%. Though this is in experimental stage, nevertheless the concept has merit and deserves further attention (Jameson 2014). The HydroFloat® technology from Eriez also uses fluidized bed for coarse particle flotation with commercial applications in grinding circuits similar to flash flotation, also with the possibility of producing a throwaway tails (Franco et al. 2015). These are interesting developments with implications for pre-concentration at a relatively finer-size fraction. There are numerous benefits not just in reducing capital and operating costs but also for improving sustainability and environmental efforts. With the HydroFloat, it is no longer necessary to grind 100% of the ore to complete liberation. The HydroFloat can recover minerals at a coarse size needing only a minimal hydrophobic surface expression to effect a separation. As a result, maximum recovery is achieved at the coarsest possible size such that a larger portion of the ore is rejected from the plant at the coarsest possible size. The savings are enormous considering that comminution energy and media consumption represent a large portion of the plant's operating cost.

Compared to other pre-concentration technologies, flotation offers the most potential especially for fine-grained mineralogical complex ores as other technologies at a coarser grind will incur significant metal losses. A potential flow sheet involving HPGR product of 1–2 mm or SAG product of 800–1000 μm could be subjected to coarse particle flotation to reject a significant amount of feed, and the coarse flotation concentration could then be ground to a finer size for conventional flotation.

4.5 Flotation

Flotation has been used as a means to pre-concentrate refractory ores even before the 1930s in Canada, Australia, and Korea using oils as flotation collectors to produce bulk low-grade gold concentrates (Richart 1912; Taggart 1925). Until the late 1960s, most of the flotation activity was centered in Canada with gold production coming from flotation treatment of refractory, copper-gold and other complex ore types (Dunne 2005). During the late 1960s flotation of pyrite was a key focus in many South African gold operations to meet the needs of sulfuric acid market from the booming uranium industry. The gold boom in the 1980s and 1990s led to the processing of several refractory gold and copper-gold deposits in Australasia, Africa, and the Americas using flotation to produce concentrates with further treatment using bacterial and pressure leaching.

A review of the reagents used in gold flotation is presented elsewhere (Kappes et al. 2011). Flotation using xanthates as the primary collector is common for liberated, placer gold and even for many refractory ores. Dithiophosphates are widely used as secondary collectors along with xanthates in various operations. Monothiophosphates are normally more stable and selective for gold minerals with a high silver content. In acidic flotation circuits, mercaptobenzothiazole (MBT) is often preferred for gold-bearing partially or sometimes fully oxidized pyrite.

Modified thionocarbamates are used in copper-gold ores, which allow some selectively against iron sulfides even at a pH value less than 10. Many gold plants use a blended collector or separate collectors as needed based on mineralogy and ore chemistry.

Copper sulfate is commonly used as an activator of gold-bearing iron sulfides in flotation plants. The dosage, the addition point, and the slurry pH range are critical parameters for maximizing the benefits from copper sulfate. Addition of copper sulfate before collector appears to be important to improve kinetics of iron sulfides. Addition of copper sulfate at pH values ranging from 7 to 10 may slow down floatability of iron sulfides. Excessive addition of copper sulfide may result in lower recovery due to oxidation of xanthate into dixanthogen in solution, thus reducing the effectiveness of collection. Copper sulfate addition also appears to impact froth stability. There is an optimum dosage below which results in high slime recovery with a tenacious froth, whereas a higher dosage leads to a fragile froth behavior.

Sulfidization is also used for naturally oxidized or tarnished iron oxides due to unfavorable milling environment. Solution potential control at −450 mV using sodium sulfide or sodium hydrogen sulfide is typically used prior to flotation. Use of NaHS and silver ions has been reported to improve gold recovery at the Los Pelambres mine in Chile (Chryssoulis 2001). Sulfide ions appear to act as flotation activators at low concentrations less than 10^{-5} M, whereas at concentration above 10^{-5} M, it acts as a depressant (Aksoy and Yarar 1989).

Flotation of Carlin-type double-refractory sulfide ores is considered as challenging (Bulatovic 1997; Kappes et al. 2010). Refractory gold ores commonly contain free gold, submicroscopic gold, carbonaceous material, base metals, pyrite, marcasite, arsenopyrite, and pyrrhotite, with clays and graphitic carbon known to inhibit flotation behavior (Swash 1925). The Carlin refractory gold ores are mainly associated with arsenian pyrite, which is known to oxidize quickly resulting in reduced flotation kinetics. Newmont has developed the N_2TEC process to provide a reducing environment during grinding and flotation mainly to prevent oxidation of arsenian pyrite (Simmons 1997).

Mineralogy and gold deportment studies clearly suggest that an ultrafine grind (sub 10 μm) is necessary to maximize recovery of gold-bearing pyrite. A finer grind, however, results in slower flotation kinetics and poor selectivity against carbonaceous matter resulting in a very high concentrate mass pull. Novel technologies are needed to address this challenge. Newmont has developed the N_2TEC process to float arsenian pyrite in a reducing environment to minimize oxidation of sulfides, and this technology is presently used in (Simmons 1997).

The deleterious preg-robbing organic carbon can also be removed by flotation and either discarded, if the gold content is negligible (Taggart 1925), or separately treated with kerosene prior to cyanide leaching (Beer 1994).

With the trend of declining head grades requiring high throughputs to improve economics, the need for water has increased significantly over years. In temperate and equatorial latitudes, there is no shortage of water in general, although the disposal of used water is a significant issue. In other arid parts of the world such as in Chile, Western Australia, and Southwest USA, water is scarce or unavailable requiring the need to use the sea, hypersaline, or brackish water for mining.

Desalination of seawater is expensive as new desalination plants and associated pumping and pipeline systems can easily have a capital cost exceeding $500 million along with high operating costs (Blin and Dion Ortega 2013). Barrick Gold has developed a new process, air-metabisulfite treatment (AMBS), which allows use of seawater or brackish water for pyrite depression in copper flotation with minimal metallurgical impact compared to that with the conventional lime-based process (Gorain 2012). The AMBS treatment has also resolved the issue of molybdenum flotation in copper-molybdenum ores using seawater.

A holistic approach to reagent selection is becoming more important (Nagaraj and Farinato 2014) due to increased ore complexities and also the advent of quantitative mineralogy tools and better understanding of flotation cell hydrodynamics. In addition, due to stringent environmental regulations, there is a focus on developing greener flotation reagents to meet sustainability goals. More recent application of electrochemical and surface analytical techniques has allowed better understanding of the fundamentals of flotation mechanism and chemistry (Smart et al. 2007). This is an important development that is already helping in better understanding of flotation behavior of complex ores and in developing solutions to complex flotation problems (Ralston et al. 2007; Fuerstenau 2007; Gorain 2013).

4.6 Other Physical Separation Processes

4.6.1 Magnetic Separation

There are tens of thousands of low-intensity magnetic separation (LIMS) and thousands of high-intensity magnetic separations (HIMS) used in the minerals industry today. A significant magnetic separation development that had made a major impact in the mineral industry was the drum separator for magnetite ores, mainly to treat fine-grained and low-grade magnetite ores for producing high-grade concentrates for sinter feed, pellets for blast furnace feed, and also for direct reduction iron processes (Arvidson and Norrgran 2014). The Wetherill separator type is still in use today in various forms for separating precious metals, typically after calcination of ore feed. Use of magnetic separator to recover gold-bearing iron oxides from roaster leach tails is also practiced such as at Barrick's Goldstrike operation (Douglas and Semenyna 2013).

Due to declining grades, the need for sophisticated high-capacity magnetic separators is becoming important. Drums for low-intensity magnetic separators in iron ore processing are becoming larger, with drum diameters around 1.5 m and widths exceeding 4 m. Other than the trend of increasing size, the use of cryogen-free superconducting coil system is also becoming prevalent, which is the most recent technology for superconducting magnetic separators using a niobium-titanium conductor to generate the magnetic field without the need for helium to cool the coil (Norrgran et al. 2009).

4.6.2 Electrostatic Separation

Electrostatic separation (ESS) is mainly used for mineral sands application, though earlier patents suggest applications in iron ore and phosphate separations. The relative electric conductivity property of the mineral surfaces is exploited to make the separation. For example, conductive minerals such as ilmenite, monazite, and rutile are separated from nonconductive silica and zircon present in mineral sands. ESS works best on clean surfaces, and in many cases the feed needs to be washed and classified for efficient separation. ESS was also successfully implemented at several precious metals smelters recovering metal prills from slag, typically after the Merrill Crowe process. In addition, this technology has been successfully applied in gold mines to recover gold and silver from slag (Hearn 2014). Dry grinding is typically used to liberate metal prills, de-dusting and then ESS to recover these prills for direct smelting, rather than the conventional wet milling and gravity tabling followed by drying before sending these materials for smelting (Maki and Taylor 1987).

4.6.3 Magnetic Pulse Treatment

The process of magnetic impulse treatment applies for refractory gold ores in ferriferous quartzite and can provide higher recovery at low-energy consumption. The process is conducted by transporting ore or pulp through a section of dielectric pipe where a series of electromagnetic coils is mounted and generates regularly impulses of an electromagnetic field with a frequency of 50 Hz. The ideal application is ahead of grinding and enhancing iron ore grinding and gold recovery.

4.6.4 Nanosecond High-Power Electromagnetic Pulses (HPEMP)

Nanosecond HPEMP treatment has been investigated in Russia since 1997. It has shown two important effects: first, the loosening of the mineral structure due to electrical breakdown mechanism and, second, the development of thermomechanical stresses at the boundary between the dielectric and conductive mineral components.

The nanosecond HPEMP treatment showed promising results in the treatment of gold refractory ores due to high efficiency and selectivity in the disintegration of mineral complexes.

The application of high-power electromagnetic pulses (HPEMP) irradiation in dressing of resistant gold-containing ores appears attractive as this technique provides for a significant increase in precious metal recovery (30–80% for gold and 20–50% for silver), therewith helping reduce both energy consumption and the cost of products (Chanturiya et al. 2001).

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