Fine and Coarse Iron Ore Beneficiation – An Evaluation into Global Technologies and Techniques

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ABSTRACT

The mining of iron ore is a high volume low margin business because the value of this commodity is significantly lower than that of base metals. The main metallurgical challenges in most of the iron ore projects proposed for treatment nowadays have been in finding the optimum flowsheet for the treatment of magnetite ores, mixed magnetite-hematite ores and even ores that have banded ironstone formations (BIF). The associated plant designs incorporate very high capacity milling systems to grind the ore down prior to magnetic separation and in being highly capital intensive requires substantial investment in mega processing plants with associated infrastructure to mill down the run-of-mine ore to the desired treatment size for upgrading.

To minimise the cost of infrastructure, better beneficiation techniques and technologies are being sought to assist in reducing upfront ROM feed to allow for reduction in overall treatment plant footprint necessary in extracting the desired downstream product. This paper discusses such beneficiation techniques and advancement in technologies for the upgrading of coarse and fine iron ore utilising dense media separation (DMS), jiggling, wet magnetic separation, dry magnetic separation, flotation and x-ray processing.

Another group of iron ore projects involve the mining of hematite ore below the water table. Often the mined ore is wet and sticky. This combination requires high capacity processing of feed material utilising large scrubbers or attritioning units to effectively remove the slimes component present in the feedstock. The fines removed, usually below 1 mm, are then discarded in large tailings storage facilities. Approaches to recovering the saleable material contained within these fines will also be investigated in this paper. This not only implies possible reduction in slimes discard footprint, but also holds potential benefit in augmenting overall yield and recovery of hematite product.

FLOWSHEET CONSIDERATIONS

The selection of a flowsheet typically begins with the selection of a beneficiation method (Anderson and Richter, 2011). Where possible, the primary beneficiation step should be performed at the highest possible particle size. This reduces the need for further comminution of waste material and also simplifies waste dewatering and disposal. Figure 1 gives a snapshot of commonly considered beneficiation techniques relative to the particle size at which they can be applied.
For hematite, the standard technologies are DMS for high grade orebodies and jig beneficiation for lower grade orebodies. DMS can also be used on lower grade material at higher cut densities but cut points at an SG of greater than 4.0 can present engineering difficulties due to the pumping of high slurry densities. Magnetite operations typically make use of low intensity magnetic separation (LIMS) or wet high intensity magnetic separation (WHIMS). Below 1 mm, spirals and teeter bed separators (TBS) or mineral density separators (MDS) have some application, and below 250 μm, reverse flotation can be applied. SLon™ technology also seems to be popular for magnetite and dry magnetic recovery in areas such as South and West Africa where water consumption is an issue.

The final choice of particle size and beneficiation technique is highly dependent on the ore mineralogy, and it is essential that a proper ore characterisation is performed to determine the types of minerals present and their relationships. This characterisation should also identify the liberation size of both valuable and gangue material to provide information on the optimum primary and secondary beneficiation steps. Bench scale testwork is typically undertaken to determine the achievable yield and grade for each beneficiation technique, and testwork is performed at a variety of particle sizes. The final choice of beneficiation technique is highly dependent on the orebody mineralogy, and each orebody needs to be considered on its merits.

Once the beneficiation technique is selected, it is possible to prescribe the desired particle size to feed beneficiation. This, together with energy efficiency considerations, typically guides the selection of a comminution circuit. For example, in hematite, it is common to apply jig beneficiation to material less than 25 mm. This leads to the widespread application of 3-stage crushing in hematite operations. In magnetite, however, it is often required to grind to less than 2 mm before any liberated gangue material can be rejected. In this case, the application of multiple stages of crushing followed by a high pressure grinding roll (HPGR) may be more cost effective than the traditional semi-autogenous grinding (SAG) milling flowsheet due to the savings in energy and grinding media. In recent years, many new technologies have become available for inclusion in comminution circuits. Many of these have shown significant potential in reducing both energy and grinding media consumption. These include the VertiMill™, IsaMill™, and the Stirred Mill Detritor (SMD). The sizing of such equipment typically requires specialised bench scale testing and this needs to be considered in the test work phase prior to commencing the cost calculations.

Representivity of samples tested is critical to all of this work and this is vitally so if new technologies are to be included in the investigations. Typically, there are several possible flowsheets which could fulfil a given process requirement. During the concept phase, it is important to investigate and
eliminate a range of options in order to arrive at an optimised list of options for the pre-feasibility study. The common approach is to select a base case option consisting of proven technology. Various options and opportunities for the inclusion of new technologies are then identified and evaluated relative to the conservative base case option. Typical selection parameters are factors such as capital cost, operating cost, safety, and technical viability. The preferred option for each step in the process is then evaluated to yield an overall optimised flowsheet for the conceptual study business case.

GLOBAL IRON ORE PLANTS

Typical examples of a variety of Iron Ore treatment plants can be viewed in Table 1. These plants are found all over the world (Australia, Brazil, Sweden, South Africa and Mozambique) and range from mining and treating banded iron formation (BIF) deposits to Precambrian, Penge and Tenge iron deposits.

Table 1: Typical examples of global iron ore plants

<table>
<thead>
<tr>
<th>Plant</th>
<th>Location</th>
<th>Process</th>
<th>Deposit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paraburdoo (Stump and McPherson, 2011)</td>
<td>Australia</td>
<td>Crushing, screening, blending (lump and fines) and fines treatment (primary and secondary hydrocycloning)</td>
<td>Banded Iron Formation</td>
</tr>
<tr>
<td>Mount Tom Price (Infomine, 2013)</td>
<td>Australia</td>
<td>Crushing, screening, gravity separation (heavy medium drum, heavy medium cyclones, spirals), lump and fines blending</td>
<td>Brockman and Marra Mamba Bedded Iron Deposit</td>
</tr>
<tr>
<td>Roy Hill (Clout and Fitzgerald, 2011)</td>
<td>Australia</td>
<td>Crushing, scrubbing, screening, fines gravity concentration (up-current classifying and spirals), lump and fines blending</td>
<td>Banded Iron Formation</td>
</tr>
<tr>
<td>Samarco Mineracao's Alegria (Mining technology, 2013)</td>
<td>Brazil</td>
<td>Crushing, screening, grinding (pre-primary and primary), hydrocycloning, flotation, re-grinding and column flotation, fines concentrate pumping (long distance)</td>
<td>Banded Iron Formation</td>
</tr>
<tr>
<td>Vila Nova (Eldorado gold, 2013)</td>
<td>Brazil</td>
<td>Crushing, screening, hydrocycloning (primary and secondary), fines gravity concentration (spirals), lump ore and fine sinter blending</td>
<td>Banded Iron Formation</td>
</tr>
<tr>
<td>Kaunisvaara (Northland resources, 2013)</td>
<td>Sweden</td>
<td>Crushing, blending stockpiles, primary milling, primary magnetic separation (cobbing), secondary grinding, secondary magnetic separation (LIMS), reverse flotation, concentrate dewatering and filtration, coarse tails classification, fine tails thickening</td>
<td>Precambrian Iron Ore (Tapuli and Sahavaara ores)</td>
</tr>
<tr>
<td>Sishen (Exxaro resources, 2013)</td>
<td>South Africa</td>
<td>Crushing, screening, gravity concentration (coarse and medium heavy medium drum, Larcodems, coarse and fines heavy medium cyclones, jigs, fines up-current classifying), dewatering, thickening, blending beds</td>
<td>Banded Iron Formation (Transvaal Supergroup)</td>
</tr>
<tr>
<td>Thabazimbi (Exxaro resources, 2013)</td>
<td>South Africa</td>
<td>Crushing, screening, gravity concentration (coarse and medium heavy medium drums, fine heavy medium cyclones, dewatering, thickening, lump and fine ore blending beds</td>
<td>Penge Iron Formation (Transvaal Supergroup)</td>
</tr>
<tr>
<td>Khumani (<a href="http://www.saimm.co.za">www.saimm.co.za</a>)</td>
<td>South Africa</td>
<td>Crushing, blending stockpiles, on and off grade washing and screening, HPRC, gravity concentration (super fines and jig), water clarification, products (lumpy, fines and medium size), coarse discards and paste</td>
<td>Banded Iron Formation (Transvaal Supergroup)</td>
</tr>
<tr>
<td>Boabab Resources (Tete Pig Iron Project)</td>
<td>Mozambique</td>
<td>Crushing, scalping, screening, dry magnetic cobbing, pre-reduction classification, pre-reduction (future wet rod milling and wet LIMS)</td>
<td>Tenge Iron Deposit</td>
</tr>
</tbody>
</table>
Beneficiation characteristics

The following beneficiation characteristics considered essential to any metallurgical investigation are as follows (Du Toit and Langenhoven, 2011):

- **Recovery**
  - characterisation of the different density layers in the iron ore deposit thus relating various areas of ore categories in the pits which will give density cut points to yield a saleable grade,
  - determine the occurrence and quantity of near-density material in the various orebodies/ore types,
  - ore types described and categorised with their geological, mineralogical and morphological features,
  - mineral composition of orebodies in particular occurrence of (Fe, SiO₂, Al₂O₃, P, Ca, K, Na₂O, TiO₂, Mn)
  - fingerprinting the ore categories to enable real-time process interventions,
  - density and porosity of the ore,
  - expected yield per ore type (DSO mass and grade but excluding beneficiation),
  - expected yield per ore type (mass and grade including that from beneficiation) and
  - size distribution curve of product, discard and tailings product ratios (lumpy/medium size/fines/discard/tailings).

- **Crushability**
  - broken ore density of ore types,
  - bond work index (BWI),
  - compression ratio,
  - reduction ratios,
  - uniaxial compressive strength (UCS),
  - power and crushing force limits and
  - volumetric throughput limits.

- **Product stability**
  - degradation and abrasiveness index (AI) of products,
  - flakiness index of crusher products,
  - size distribution (or PSD) curve of crusher products,
  - intermediate size fraction and
  - transport (TML) and shipping index.

- **Mass flow characteristics**
  - clay and moisture (agglomeration, dispersion and rheology),
  - particle shape,
  - segregation,
  - homogenisation and
  - settling, filtration and water recovery characteristics (if applicable).

Conventional jigging

Jigging technology as a highly flexible gravity separation process making use of water and air pulsation as the separating mechanism, has been deemed a viable beneficiation process for processing off-grade +0.8 mm –32 mm ores (Du Toit and Langenhoven, 2011). Throughput typically ranges from 30 to 650 t/h with semi-skilled operators able to perform process changes if required. The process reaction time is usually very quick. It was found that jigs can easily be changed over a wide range of densities, typically 3.3 – 5.0 g/cm³. Redistribution of plant feed is sometimes required to balance feed to a particular jigging application and this suggest optimising the material feed envelope presented/fed
to the jig(s) (Mokebe, 2011). Sometimes, this necessitates the changing of bottom deck panels to achieve the desired results.

A recent example describes an increased feed to the plant’s medium (size fraction) jigs (from 126 t/h to 149 t/h) on average by changing bottom cut-point from 3.5 mm square to 3.0 mm square panels. Reducing the amount of near-sized 3 x 2 mm fraction in the coarse (size fraction) jigs, increased the retention time in the fine jigs. The narrower feed PSD to the fine jigs also increased beneficiation efficiency. The benefit of redistributing the feed split between the medium and fine jigs has been achieved, with the percentage of -3 mm +1 mm material decreasing from 14.41 % to 12.71 %. This is a 1.7 % decrease in fine jig feed distribution. The potential gains are a narrow fine jig PSD, increased ore retention time, and better beneficiation efficiency. Although the test work for the sample above example’s test work proved to be successful, there were additional factors identified that also have an effect on the screening efficiency and beneficiation in the jigs. These were:

- particle size distribution and stratification,
- aperture shape,
- angle and speed of particles relative to screening surface,
- bed thickness,
- retention time and screen vibration and
- spray water.

Ragging on fines jigs (-3 +1 mm) was another opportunity previously investigated to improve the grade of fines jig product as well as yield (Motlhame, 2011). Based on the iron feed grading, jig throughput (t/h) per meter and ragging placed in some or all chambers of the jig, an opportunity exists to improve the grade of fines jig product as well as yield. Aforementioned is also largely dependent on the fines material’s beneficiation potential to be upgraded using jigging technology.

Other investigations (Myburgh, 2010) into the efficiency of the stratification of iron ore in jigs also found that it depends on the correct pulse characteristics such as shape, amplitude, and frequency but in this case, to be able to control the pulse, the mechanical equipment used must also function correctly. The stroke needed on the jig ore bed must be taken into consideration while setting the pulse. The pulse must also be set so that the stroke on the ore bed is at least three times the top size of the ore fed to the jig. If the stroke on the ore bed is less than the needed minimum value, the separation efficiency will not be optimal. By regularly monitoring the condition of the equipment responsible for the pulse form, optimum separation efficiency will prevail.

**Centrifugal concentrators**

Gravity concentrators have been developed during the last twenty years based on the use of centrifugal forces that create large “apparent gravitational gradient” seeking to overcome the limitations associated with fine particle size distribution (e Silva et al., 1999). Traditional gravity concentrators (conventional jigs, spirals and dense medium cyclones) lose efficiency (i.e. sharpness of cut and recovery) when the mean diameter of particles are lower than 0.05mm and the difference among densities are smaller than one. The Kelsey centrifugal jig and Mozley multi gravity separator (MGS) are two examples of centrifugal concentrators particularly used in the treatment of (Richards and Jones, 2004):

- fine mineral recovery from leach tailings
- mineral removal from concentrates
- high grade recovery from waste fines

The Mozley MGS (which essentially wraps a shaking table into a cylinder and rotates it) operates at significantly lower ‘g’ force (Mular et al., 2002) than that of the Kelsey jig (8 to 22g). The MGS with capacity rates of up to 40 t/hr has truly pushed the envelope in terms of ultrafine particle recovery, reducing the bottom size of effective recovery to as low as 3-4 microns. The Kelsey jig (as the name implies) has combined a Harz type jig with an intermediate centrifugal force (approximately 60 to 80g) and can treat material at a rate of between 50 – 80 t/hr. In addition, the fine-grained jigging may
act partially as a heavy medium. Considering the high rotational speeds and consequent centrifugal forces, these types of separators require a high level of engineering including balancing of the rotational unit and careful selection of materials of construction. Other drawbacks also counting against the use of centrifugal separators include:

- throughput capacity and number of machine units required (especially with mine treatment applications processing in excess of 10mtpa ROM material and the associated fines/ultrafines portion requiring upgrade treatment),
- maintainability of units and the high OPEX required for the machines to run,
- operability of units, if not fully automated and if potential challenges are experienced with regards to the level of skills required in running of these units.

Nevertheless, properly maintained and properly fed machines (used in the right application) can provide good long-term reliability and performance.

**DMS**

With direct shipping ores (or DSO’s), as the quality of mined iron decreases and because mining below the water table has associated clay impurities, beneficiation is required to achieve the desired target iron grade. This can be a phased approach with the inclusion of a beneficiation module later on in the flowsheet (or mine execution) design. Cash flow also plays an integral part of any project and when that becomes stronger during operation of the mine, the opportunity presents itself financially to pursue a beneficiation plant (as is the case with the McPhee Creek project). Historically, DMS has been a highly efficient and proven technology application in upgrading low grade ores – if the ore is amenable to dense media separation. Due to the high volume mining of iron ore and the main metallurgical challenges associated with it, most of the work on the iron ore deposits proposed for treatment nowadays have been in finding the optimum flowsheet for the treatment of magnetite ores, mixed magnetite-hematite ores and even ores that have banded ironstone formations (BIF).

In some cases, the associated plant designs incorporate very high plant capacity including crushing, screening or grinding systems to reduce the ROM ore down to the desired treatment size for magnetic (or alternative) separation and this is highly capital intensive. This type of plant design requires considerable investment in mega processing facilities with associated infrastructure to grind down the run-of-mine ore to the desired treatment size for upgrading. Based on their successful track record in base metal and PGM plant operations already seen elsewhere, DMS as a pre-concentration tool should also be considered for reducing the amount of feed going to downstream grinding circuits to minimise plant footprint and associated CAPEX. It should however be noted that DMS as a pre-concentration step should only be considered if the orebody to be treated allows said pre-concentration and if there are no issues envisaged or identified with regards to the occurrence of near-density material.

**FeSi cone**

Previous investigations (Van Wyk and Van Schoor, 2010) into this field/application were to design and build a cone that could successfully cut at all densities within the iron ore washability range. It was possible to get some good indications with the mineral density separator (or MDS) but these units have some concerns. Test work done up to now on the cone proves that it is possible to cut at densities up to 4.5 g/cm³ but there are still a number of issues to be addressed. Some of these are listed below:

- optimise new cone modifications as per previous tests,
- influence of viscosity,
- different FeSi options,
- FeSi losses,
- comparison/evaluation between MDS and FeSi cone,
- comparison TBE (tetrabromoethane) and FeSi cone densities 3.4 – 4.0 g/cm³,
- comparison LST (lithium polytungstates) and FeSi cone,
- different ore samples,
- size distribution,
- shape distribution,
- scale-up factor and
- partition curves.

**Dry magnetic separation**

The magnetic processing of the Sishen low grade and high grade ores, using the DebTech MagRoll units (Fofana and Masango, 2011), covered materials in the size fractions of -1.18 mm +0.6 mm to -25 mm +12 mm. Tests were conducted by adjusting the key variable of the magnetic susceptibility cut point of the MagRoll units, while maintaining a low throughput. The results indicate that feeds with variable initial iron content can generally be upgraded to comply with product specifications, including low impurities (SiO2, P, and K2O). Two possible operating set points for the MagRoll units were identified as cut-point 80 x 10^-6 cm^3/g or 100 x 10^-6 cm^3/g. Hence, yields values of 50 % to 96 % were achieved for the two ore types while iron grades between 60 to 66 % were obtained for the Sishen low grade ore only.

Additionally, grade values of 63 % to 67 % iron were yielded when the Sishen high grade ore was treated. In the end, the final cut point choice will be determined by trade-off considerations between product yield and grade. In spite of the remarkable separations achieved, the throughput requirements in a typical iron ore production environment proved excessive for the machine tested with a width of 500 mm. Alternatively, small iron ore mining operations with low tonnages can potentially take better advantage of the possible benefits of these DebTech MagRoll units. Furthermore, the moisture content requirements for the ROM (run of mine) ore are size dependent, with the finer sizes (i.e. < 8 mm) needing to be free-flowing. Moisture in the fines fractions leads to agglomeration and hence entrainment into the magnetic fraction. This could be detrimental to the quality of the final products due to the collateral entrainment of impurities. For coarser fractions (+8 mm) however, surface moisture up to 2 % can be tolerated during dry magnetic processing.

**Cobbing**

Cobbing (which is essentially another form of LIMS) of ores (Metso minerals, 2013) covers quite a large particle size range and in order to treat the ore most effectively, the separators are designed with different magnet configurations and pole pitches. Cobbers utilise the belt drum separator design in order to present the material to the magnetic field as evenly distributed as possible. The rubber belt is supported by rubber idlers at the feed origin in order to absorb the material feed impact. The adjustable splitter under the magnetic drum is rubber covered for wear protection and is easily changed. The drive unit is mounted at the rear drum and is comprised of a speed reducer, V-belts, pulleys and motor. If required by process conditions or type of ore, a variable speed drive can be supplied to allow belt speed variation from 0.5 m/s up to 2.5 m/s as an option to the standard fixed speed arrangement.

**Using XRT in operations and its potential**

Some of the collaborative efforts that Kumba Iron Ore, in partnership with Springer Technology and Anglo Technical Services Research investigated were to pursue the development of a novel density determination technique exploiting X-ray transmission (XRT) and optical imaging (Shamaila et al., 2011). This technique is being developed with the aim of determining sample density distributions that apply to washability characterisation of ores, as an alternative to the traditional sink and float method. For certain applications, sink and float has required the use of tetrabromoethane (TBE) solution – a chemical that has been classified as harmful and environmentally unfriendly.

The commissioning and validation of the X-ray monitor were successfully carried out, and lessons learned from the challenges encountered. The commissioning also showed that the concept of density determination by the XRT washability monitor (or WAMON) is achievable. The validation exercise demonstrated that the WAMON is highly capable of producing reproducible results. However, for
now the WAMON remains an instrument in development as improvements are implemented as part of ongoing planned staged developments. These include the planned incorporation of an automated particle sorting capability and sample chemical analysis by X-ray fluorescence. The implementation of this monitor is aimed at computing washability curves in matter of minutes, thereby delivering real time analysis.

FINE BENEFICIATION

Fine wet sizing

Screening is the process of separating particles by size (Barkhuysen and Jain, 2011). Fine screening refers to the efficient size separations from 10mm down to 38µm. Fine screening is normally accomplished with high frequency, low amplitude vibrating screens employing either elliptical or straight line motion. In fine wet sizing, the undersize particles are transported through the screen openings by the fluid. After the free fluid is removed from the slurry through screen openings, the sizing process stops and the remaining material on the screen surface is conveyed to oversize until additional water is added to remove more near-size particles from oversize product. Wet screening can be accomplished with a relatively short screen length because most of the fluid passes through the screen openings rather quickly. This is especially true with screen surfaces that are not prone to blinding. Therefore screen width, rather than screen area, is a more important design criterion for fine wet screening.

Hydrocyclones have historically been the most common classification device used in the closing of grinding circuits. Earlier, the use of hydrocyclones made sense due to their space requirements and relatively low initial capital cost. The introduction of economically viable fine screening technology made industry review the long term economics (compared with initial capital costs) of using hydrocyclones. The inherent inefficiency and ‘black box’ technology employed by hydrocyclones inevitably led industry into developing replacement technology utilising size separation only. Hydrocyclones separate particles based on specific gravity, particle size, and specifically settling velocity in a fluid. Liberated high specific gravity particles tend to report to the hydrocyclone underflow.

These particles are generally the valuable minerals that are to be recovered and are typically ground to sizes finer than required for liberation. The presence of misplaced coarse material in a hydrocyclone overflow product can be the source of middling particles which can lead to grade and/or recovery problems. Typical efficiencies for a hydrocyclone range from 40 % to 75 %. The screen separates particles based on their size only, thus efficiencies for the Derrick Screen Stack Sizer™ classification range from 85 % to 95 % depending on the application. With an efficient classification screen, the coarse fractions (source of middlings) in a milled ore can be minimised without producing excessive amounts of over-milled material, or slimes. The main economic advantages of screens versus hydrocyclones in grinding circuits are:

- reduced energy consumption due to reduced circulating loads,
- typically require less water for operation,
- reduction in slimes generation,
- increased production rates (typically between 10 to 30 %),
- reduce grinding media consumption,
- reduced mill maintenance costs,
- increased efficiency in downstream equipment (particularly flotation),
- increased mineral recovery rates and
- reduced concentrate dewatering costs due to coarser liberation and reduction of slimes.

Three case studies for fines screening replacing hydrocyclones were also evaluated and the findings were as follows:
A subsidiary of LaiGang Company, LaiWu separation plant, required an increase in their production rate to meet the needs of the expanding steel market in China. For years, the LaiWu facility used hydrocyclones in line with chute screens to close their secondary grinding circuit. A single 5-deck Stack Sizer™ fitted with 100 µm urethane screen panels was installed into the existing plant to replace the hydrocyclones. As a result, the production of final concentrates increased from 0.5 million tonnes per year (Mt/a) to 0.8 Mt/a. The Stack Sizer™ installation paid for itself in less than a month. In addition, LaiWu was able to shut down one of two of its secondary ball mills which resulted in huge power savings (a 25 % reduction in power consumption). The tailing grade dropped from 12 % to 8 %, providing verification of increased recovery. Consequently, LaiGang decided to upgrade their other plants in the same manner.

KMAruda in Russia conducted plant trials with the Stack Sizer™ to improve the classification at its magnetite concentrator. The run of mine ore contains about 34 % total iron. The concentrator flowsheet includes two stages of grinding and three stages of magnetic separation. The primary grinding circuit on each line consists of two ball mills in parallel, operating in closed circuit with spiral classifiers. Similarly, the secondary circuit has two balls mills in parallel, operating in closed circuit with hydrocyclones. All four mills are identical in size. The hydrocyclones were fed by primary magnetic separators and the hydrocyclone underflow was distributed to the two secondary mills. The mill discharge was fed to the second stage magnetic separators, and the magnetic concentrate was circulated back to the hydrocyclones. The hydrocyclone overflow product was sent to the third stage magnetic separation. Two Stack Sizer™ screens fitted with 100 µm opening urethane screen surfaces were incorporated to replace the hydrocyclones on one concentrator line. Consequently, one of the two ball mills was shut down as a result of improved classification with the screen. The screen circuit resulted in highly efficient classification and increased grinding capacity, with significant power reduction due to one mill being shut down. The circulating load in the screen circuit decreased considerably. While the goal was to maintain the same final product grade, the final concentrate from the screen circuit was coarser, 82 % minus 71 µm compared with 92.5% minus 71µm with hydrocyclone classification. KMAruda observed that hydrocyclone underflow was normally around 65 % iron and the screen oversize ranged from 36 to 45 % iron, indicating a large increase in non-liberated material in the recirculating stream. The screen undersize was also coarser which improved downstream operations, including an increased iron recovery in the next stage of magnetic separation.

KIOCL is located in Mangalore, India and produces iron ore pellets for steelmaking. The flowsheet incorporates six Stack Sizers™ in closed circuit with ball mills. The circulating load with screening has been reduced to about 50 %, with overall separation efficiency around 90 %. KIOCL recently added four additional Stack Sizers™ to enable operation of two ball mills at the same time. They also intend to expand the plant capacity by adding a third line of grinding mills and screens. KIOCL was the first hematite iron ore producer to install Stack Sizer™ technology in India. The success of fine screens in the grinding circuit for classification at KIOCL has caught the attention of the Indian iron ore industry. Consequently, a great number of iron ore producers are now converting to Stack Sizer™ technology and replacing hydrocyclones.

**Spirals**

Spiral concentrators are gravity separators usually separating particle sizes between 0.1 and 2.0 mm in a water carrier medium (Ramsaywok et al., 2010). The capacities of the spiral concentrators range between 1 and 3 t/h dry solids and now in excess of 7 t/h in the case of high capacity spirals when treating deposits typically associated/amenable to fine ore beneficiation. The spiral concentrators are usually configured in 5 to 7 turns and can accommodate up to four starts per column.

Spiral concentrators have been part of the minerals processing industry for the past 50 years. The technology is fairly simple, relatively inexpensive, moderately high in efficiency, and well established for pre-concentration and concentration application in various mineral industries for treating fine ores. Developments over the years in improved materials of construction, improved feed box and splitter...
designs, trough design, wash water addition, capacity improvements, re-pulpers, and product boxes are among some of the improvements. Some disadvantages of spiral concentrators are:

- low throughput per unit (requiring a large banks of spiral concentrators, requiring large footprint, resulting in high capital processing plants),
- operation difficulties (especially cleaning the troughs and setting the splitters),
- sensitivity to feed fluctuations (the splitters need to be adjusted as feed conditions change) and
- fairly large water usage and large recycles due to inefficiencies.

Recent trends nowadays also include looking at high capacity units and automate splitter adjustments.

**Magnetic separators: description and application**

The use of magnetic separators in the minerals industry is mature with various types of magnetic separators used in various applications (Ramsaywok and Vermaak, 2011). Magnetic separators will typically separate a flow of material into two or more products. Magnetic separation is widely recognised as being commercially effective at mineral recovery. The primary aim when using magnetic separators for mineral beneficiation is to obtain the most applicable type of magnetic separator that will selectively separate magnetic particles from other or unwanted minerals. Magnetic separation is also particle size dependent. Table 2 summarises and classifies the most widely used magnetic separators. The intensity of a magnet is usually classified by the magnet’s surface intensity, with low usually below 1 500 gauss, medium intensity magnets up to 8 000 gauss, and high up to 15 000 gauss. Capacity is classified as low (2 tonnes per hour per lineal metre magnet), medium (10 tonnes per hour per metre magnet) and high (40 tonnes per hour per unit). Typically, particles are classified as fine (< 2 mm), medium (< 8 mm > 2 mm), and coarse (< 25 mm > 8 mm).

**Table 2: Classification of most widely used magnetic separators**

<table>
<thead>
<tr>
<th>Common name</th>
<th>Type</th>
<th>Intensity</th>
<th>Wet/dry operation</th>
<th>Capacity</th>
<th>Feed particle size</th>
</tr>
</thead>
<tbody>
<tr>
<td>LISS</td>
<td>Low intensity magnetic separator</td>
<td>Low</td>
<td>Wet/dry</td>
<td>High</td>
<td>Fine</td>
</tr>
<tr>
<td>WHIMS</td>
<td>Wet high intensity magnetic separator</td>
<td>Medium</td>
<td>Wet</td>
<td>Very high</td>
<td>Fine</td>
</tr>
<tr>
<td>VPHGMS</td>
<td>Vertical pulsating high gradient magnetic separator</td>
<td>Medium to high</td>
<td>Wet</td>
<td>Very high</td>
<td>Fine</td>
</tr>
<tr>
<td>RED</td>
<td>Rare-earth drum magnetic separator</td>
<td>Medium</td>
<td>Dry</td>
<td>High</td>
<td>Fine</td>
</tr>
<tr>
<td>IRMS</td>
<td>Induced roll magnetic separator</td>
<td>Low to high</td>
<td>Dry</td>
<td>Low</td>
<td>Fine</td>
</tr>
<tr>
<td>RER</td>
<td>Rare-earth roll magnetic separator</td>
<td>Medium to high</td>
<td>Dry and recently wet application</td>
<td>Low</td>
<td>Fine and recently medium to coarse</td>
</tr>
</tbody>
</table>

The low intensity magnetic separator (LIMS) is a rotating drum magnetic separator which can be employed in a dry or wet application. The dry applications are usually top fed, while the wet applications are usually bottom fed with either a co-current, counter-rotation or counter-current feed arrangement. The rotation direction of the drums is also optional. WHIMS is a wet magnetic separator where slurry is fed through a magnetic field through salient plates causing the magnetic fraction (mags) to be held up while the nonmagnetic fraction (non-mags) are washed through. The salient
plates are situated in a rotor which rotates past magnetic poles. When leaving the magnetic field, the mags are washed out of the salient plates.

The SLon™, like the WHIMS is an electromagnet. Magnetic particles are held up in a matrix which consists of metal rods within a rotating carousel. Pulsing occurs in the separation zone to aid with non-mag entrapment. When the carousel is out of the magnetic field, the mags are washed off (Outotec, 2013). SLon™ VPHGMS also possesses the advantages of large capacity, low operation cost and high beneficial efficiency for treating low-grade oxidising iron ores (Dahe, 2011). The cooperation flowsheet of SLon™ VPHGMS and SLon™ centrifugal separators possesses the advantages of lower operational cost, more environmentally-friendly and easier to manage. These new technologies have been successfully applied in several oxidising iron ore beneficiating plants in China namely Da Hong Shan and An Shan.

Kumba Iron Ore’s Sishen Mine is currently investigating processes to beneficiate DMS slimes to a saleable products (Skosana, 2011) – prompted by the current high demand for iron ore products as well as the iron grades in the Sishen thickener underflow of approximately 53 % iron. Initial laboratory scale test work indicated that a 66.5 % iron concentrate could be produced from the Sishen thickener underflow through a process of oversize protection screening, three-stage vertical pulsating high gradient magnetic separation (roughing, cleaning and scavenging), concentrate and tails thickening and concentrate product dewatering via filtration. Not only will the VPHGMS technology assist in reducing slimes footprint and augmenting overall iron product yield, but the opportunity also exists to expand the technology to other slimes sources at the mine, i.e. jig and existing tailings storage facility (or slimes dam) material. This however requires confirmatory test work results to qualify, quantify and confirm if aforementioned sources are acquiescent to VPHGMS upgrading.

The rare-earth drum magnetic separator (RED) consists of a rotating drum enclosing a fixed magnet arrangement (Ramsaywok and Vermaak, 2011). Feed is passed over the top of the drum. Mags are attracted to the drum and non-mags are thrown off due to the rotation of the drum (centrifugal forces). Majority of use is dry, but wet units are also available. The induced roll magnetic separator (IRMS) consists of a roll between two induced magnets with the feed arrangement on the top of the roll (Ramsaywok and Vermaak, 2011). The magnetic field induced causes the mags to be attracted to the roll, and they are removed at the back of the roll with the use of a brush. The non-mags are thrown off the roll due to roll rotation. The rare-earth roll magnetic separator (RER) is a permanent roll magnet usually covered by a belt (Ramsaywok and Vermaak, 2011). Material is passed on the belt over the magnet. The non-mags are dropped off due to the rotation of the belt and magnet and the mags are released from the belt when the belt moves away from the magnet (Outotec, 2013).

Most iron ore concentration processes are wet, utilising traditional methods of jigging and dense medium separation, among others. Dry magnetic separation in general is sensitive to particle size and similar to most other beneficiation processes, a narrow size distribution benefits the separation and concentration. Magnetic separator efficiencies are also limited by feed temperature. Normally feed is dried at temperatures in excess of 100 °C but high temperatures in excess of 130 °C can cause damage to the magnets. However, some superconducting magnets can withstand temperatures in excess of 700 °C (Outotec, 2013). Some other design limitations also associated with dry magnetic separation are:

IRMS are limited with regards to particle size:

- as the field arrangements do not allow for the separation of large particles and
- RERs have a high magnetic strength but low field depth – limiting particle sizes that can be processed. New developments claim high field depth, thus enabling larger particles (>20 mm) to be treated (Outotec and DebTech, 2013). RED’s are usually medium to somewhat high magnetic field strength, and are also limited to field depth and particle size.

**Fine grinding**

Another example of reduction in tails and unlocking the value in the waste stream is at Ernest Henry Mining (northwest Queensland). The magnetite plant there is divided into three circuits (Siliézar, 2011). The extraction (magnetic separation) and dewatering (filters) form the base plant. The regrind
circuit (using IsaMill™ technology) is utilised to liberate the magnetite. IsaMill™ technology (typically used in the base metals and PGM processing industries) not only simplifies circuit design but also improves grinding efficiency and therefore reduces downstream processing costs. Additional benefits are the IsaMills™ inherent tight product size distribution, together with the effect this has on minimising energy consumption while still ensuring adequate liberation to produce high quality magnetite concentrates (Walstra et al., 2011).

**Flotation**

Hematite banded iron ore formations (BIFs) are found in deposits throughout the World (Silva et al., 2011). Enrichment of BIFs has resulted in the development of high grade hematite iron ore bodies in Brazil, South Africa, India, and Australia. To economically concentrate these ore bodies, one must evaluate the ore mineralogy, particle size distribution, plant throughput, chemistry, kinetics, etc. in order to select the proper equipment, chemical conditioning, and concentrator configuration. The mineralogy of the iron-bearing and gangue material can determine whether flotation will be applicable. Furthermore, a wide particle size distribution could indicate that a mixed flotation circuit, using both forced and induced air flotation is optimum. A mixed flotation circuit utilises the hydrodynamic differences of these two flotation technologies to maximise selectivity and recovery of both coarse and fine particles.

The presence of clays or unliberated silica can require the addition of other types of equipment in the circuit, such as hydrocyclones or fines screening (if not too fine) to deslime the feed and grinding mills for mineral liberation. The presence of magnetite even as crystal relics in the hematite may require the addition of a combination of magnetic separators and flotation in the concentrator circuit. In some cases, where there are significant amounts of gibbsite and kaolinite, the selection of a magnetic separation circuit alone would be the best option. An in-depth knowledge of a deposit’s mineral composition and how the mineralogy of its various components is distributed is essential for proper design of a flotation circuit. If the deposit consists of a heterogeneous ore composed of small quartz particles bound with a hydrated iron material, a pre-magnetic or a density separation step would be suitable as part of the flotation circuit. Impurities within the mineral matrix can determine the grinding circuit’s design or the maximum final concentrate grade. Where there are variations between the size class of the silica and iron-bearing minerals, mixed flotation circuits may be the optimum choice.

Reverse flotation for the removal of gangue minerals away from an iron concentrate is commonly practised. By this means deleterious amounts of the gangue minerals can be brought back to meet strict iron concentrate penalties for certain elements. Particle size distribution plays an important role in determining the flotation circuit and the type of flotation equipment to use. More effective circuits could be designed if the unique hydrodynamic characteristic of each flotation machine was considered and/or enhanced to process various size distributions more effectively. The use of mixed circuits could also improve the concentrator’s metallurgical performance. Advanced design tools such as CFD models, in addition to empirical equations, should be used to change the hydrodynamic characteristics of these machines to accentuate design features that improve the flotation cell’s metallurgical performance.

In a recent evaluation, the collector performance of four different Brazilian iron ore mines (Cassola and Pedain, 2011) was evaluated. What this evaluation achieved was the effective demonstration that the currently used collector regimes of three concentrators can be precisely adapted to the requirements of the particular mine. Opportunities to improve the metallic recovery and maintaining the concentrate quality by meeting the requirements of silica grade could be outlined. It also demonstrated that maximum collector efficiency can result from achieving the optimum balance between chain length hydrophobicity – and that the degree of neutralisation can be achieved with respect to silica. For these collectors, sufficient conditioning times had to be assumed. The impact of other factors in the chemical regime of iron ore concentrators, i.e. iron ore depression and pH modification, was not subject of this specific investigation but offered space for future developments.
Upflow classifying

The AllFlux® Classifier exploits differences in density and particle size to effect separation (Sibiya, 2011). Beneficiation water is supplied from the bottom of the unit in order to fluidise the bed of material within the unit. Lower density material, as well as fines and slimes, are carried via the upward flow of water to the overflow outlets at the top of the unit. The product is discharged from the base of the unit via a modulating pinch and dart valve, which controls the rate of removal of product material to maintain bed level.

Multistage extraction, which is the normal mode of operation for the AllFlux® separator in mineral sand classification duty, was found not to be applicable to iron ore (South African iron ores in particular). This was due to the fact that the product grade was achieved only in the first stage at a yield of 26 % by mass considering the feed PSD (-1 mm +0.53 mm). The low yield was due to the -0.25 mm fraction short-circuiting the first stage beneficiation and reporting to the second stage, which means indirect classification. This fraction could not be upgraded to product specification on the second stage, and ultimately counted as waste. The teeter water rise rate of 197 m³/h contributed to achieving the product specification of 61.5 % iron consistently in stage one and this specification consequently determines the teeter water requirement.

The teeter water requirement to achieve a split velocity at the second stage was far too high and could not be achieved in the process set sighting. Furthermore, the material of construction for the unit base screen was also found not to be mechanically compatible with this application resulting in increased wear. Signs of material wear and tear were observed and the water supply (470 m³/h) was also not available to trigger the required product split rise rate velocity. A reconstituted feed PSD (-1 mm +0.25 mm) proved to increase the yield remarkably from 26 % to 43 % at the quality specification. A minimum ROM quality > 51.89 % iron, with a variance of 1.4 % iron led to consistent results by this process. When treating a slurry containing particles in the size range -1 mm generally used in mineral processing classification applications, many other factors and variables can also be significant with the most important influencing performance and operation being:

- volume concentration of solids,
- particle size,
- particle shape,
- the control loop for the opening discharge valve and
- the configuration of the inlet feed pipe.

For example for the feed inlet pipe, it was positioned deeper to introduce the feed in the region near the high density product which was ready for extraction but this configuration resulted in feed entrainment thus contaminating the product. The AllFlux® separator therefore had potential to produce a higher quality product with suitable modifications. Other Australian trials with regards to the Allflux® Classifier suggested its use in conjunction with other technologies (e.g. spirals) to best ensure overall efficiency of fine iron ore beneficiation for specific applications. Reflux Classifier® (Ludowici, 2013) is the latest addition to the art of fine particle technology (gravity based) separation and offer advantages in capacity, adaptability and efficiency. This technology type has also already been proven with operating units applying the latest in gravity-based separation engineering in Africa, Asia, Australia and North America.

The Reflux Classifier® incorporates the new ‘laminar high shear rate’ mechanism. This, along with advancements in channel spacing and width, mean that Reflux Classifiers® are very efficient and more compact than other associated fine coal and mineral processing equipment. Trials currently underway with regards to a local Australian Iron Ore Mining company includes evaluation of the Reflux Classifier® technology’s viability to upgrade the -1mm natural arising fraction which would have been otherwise rejected to waste in their existing proposed process flowsheet. The aim is also to produce a product grade that is consistent or higher than 60 % iron (previously unachievable through spirals technology and with a SiO₂ and Al₂O₃ specification of < 10 %) and to define the mass recovery associated with this desired product specification and the percentage increase to overall product yield this will potentially contribute.
CONCLUSION

Today, numerous technologies and techniques exist in beneficiating fine and coarse iron ore to a saleable product. These technologies and techniques can treat various feed envelope ranges (depending on the application) and also exploit specific material characteristics (e.g. density, magnetic susceptibility, etc.) in upgrading low value streams into profitable shipments. In today’s economically-orientated, volume-driven and quality-demanding world the focus has shifted to delivering iron ore material of satisfactory grade that is sagaciously mined and processed. This paper was aimed at presenting where the main processing trends are currently heading and where today’s technologies and techniques can also aid mining companies, design houses and vendors alike in enhancing their respective places as part of the iron ore value chain. Efforts and new approaches are going into bolstering product stockpiles and minimising waste footprints by building fit-for-purpose, phased-approached plants with the latest technology on offer.

Processes are constantly evaluated, optimised and improved with equipment aimed at satisfying this insatiable demand for maximum product generation with minimum related effluent footprint. The growing awareness of the environmental cost of landfill sites is spurring the development of profitably operating secondary recovery plants. Not only do such plants recover valuable products, but they also reduce the volume of the sites (and hence reduce dumping costs) and enable operators to comply with ever more stringent and costly regulations that are being placed upon them. Likewise, rather than simply starting new landfills as existing ones become full, consideration is now being given to “mining” old fill sites to recover values and to reduce volumes. Rehabilitation of the old land fill sites becomes more manageable and economical due to the shrinking of associated footprint when the material is treated to recover valued product. In the end it can be said that advances in fine and coarse beneficiation for iron ores are alive and well, so watch this space!

REFERENCES


