Ore Sorting in Mining

Association of Mining Analysts

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Content

- Introduction to Sorting
  - Application to Mining
  - Benefits and Limitations
- Principles & Technology
  - Sensors
- Testwork and Optimisation
- Economics
- What an Analyst should look at
Introduction to Sensor Based Sorting (SBS)
What is Sorting?

- Ore sorting is a mineral concentration process where **individual** ore particles are separated from the unwanted material based on some physical (or chemical) property.

- Ore Sorting can be used for:
  - Pre-Concentration / Waste Rejection
  - Ore-type diversion
  - Concentration to product

- Sensor Based Sorting is the automation of this process.
Hand Picking Ore in Agricola’s 1556 “De Re Metallica”

Source: Tomra
Hand sorting ore at Sullivan Mine circa. 1915
Source: Wills’ Mineral Processing Technology
Long History

Hand sorting ore at a mine in Turkey 2012

Source: Tomra
Diamond sorting – early days

Namibian diamond rush - circa. 1908
Hand “sorting” diamonds in the Sperrgebiet
Diamond sorting - today

Tomra large diamond recovery (LDR) machine using XRT sensors at Karowe Mine, Botswana.
Diamond sorting - today

1,111 carat diamond recovered by a Tomra large diamond recovery (LDR) machine using XRT sensors at Karowe.
History of Sorting in Mining

- **1940’s Radiometric Sorters**
- **1950’s Photometric Sorter**
  - Mary Kathleen U mine, Australia
- **1970’s Photometric Sorter**
  - GFSA Doornfontein Gold Mine (RTZ Ore Sorters)
  - Looked at difference in colour between lighter “reef” and darker “waste”
  - First to use laser technology
  - First high tonnage sorters
Why the slow uptake?

- Historically poor throughput rates
  - Computer processing power

- Misconception of robustness of this technology in mining environment

- Aversion to new technology
  - Unlike the oil industry, mining has been slow to adopt new technologies
  - Mining companies and the financiers promote “tried and trusted, traditional technologies”
## Sorting is widespread

### Mining
- Applicable for:
  - Precious metals
  - Base metals · Diamonds
  - Coal · Ferrous metals
  - Copper · Platinum · Slag
  - Industrial minerals · Gold
  - Tailings · Gemstones

### Recycling
- Applicable for:
  - E-scrap · CRT Glass · Wood
  - Single Stream · Paper
  - Packaging · Wire · C&D waste
  - Car shredder · Plastics
  - Organic · MSW · Metals
  - RDF monitoring

### Food
- Applicable for:
  - Dried fruit · Fresh cut · Fruit
  - Nuts · Seeds · Processed potato
  - Whole potatoes · Seafood
  - Meat/Process Analytics
  - Vegetables · Whole products
  - Peeling solutions

### Specialty Products
- Applicable for:
  - Raw Materials
  - Virgin plastics · Synthetic rubber
  - Virgin wood chips · Pharmaceuticals
  - Tobacco
  - Treshing stems · Oriental leaf
  - Primary lamina · Primary stems
  - Cigar · Recon · OTP · Additives

### Common development of core components
Mining Applications

INDUSTRIAL MINERALS
COLOR · XRT · NIR
Calcite, quartz, feldspar, magnesite, talc, dolomite, limestone, rock salt, phosphates, potash

GEMSTONES
COLOR · XRT · NIR
Diamonds, emeralds, rubies, sapphires, tanzanite

FERROUS METALS
XRT · EM · NIR
Iron, manganese, chromite

NON-FERROUS METALS
XRT · COLOR · EM · NIR
Copper, zinc, gold, nickel, tungsten, silver, platinum group metals

FUEL
COLOR · XRT · NIR
Coal, oil shale

SLAG
XRT · EM
Stainless steel slag, carbon steel slag, ferro silica slag, ferro chrome slag, non ferrous slag
Wet Mineral/Ore Processing

ROM

Comminution (multiple stage)

Wet Separation

- Concentrate
- Waste
And Waste is here

Syncrude Tailings Dam - Mildred Lake
Avoidable costs

- Every single tonne in that tailings pond has had costs for:
  - Crushing
  - Screening
  - Milling
  - Process water
  - Flotation reagents: frothers, collectors, modifiers
  - Pumping and pipes
  - Water treatment: filters, thickeners, flocculants
  - Ponds’ erection, dams, and lining
  - Pond monitoring
  - Use of land; local and environmental permits
  - Etc.
An alternative approach

ROM

Commination
Primary/Secondary

Dry sensor sorting

Milling + Wet Separation

Waste Coarse

Concentrate

Waste
Value throughout the Mining Cycle

1. Increase mining rates, resources & LOM
   & improve scheduling

2. Decrease mining costs

3. MINE SITE SORTING
   → Decrease mining costs

4. Reduce haulage costs

5. Separate ore types

6. Increase grade, production

7. Reduce energy & consumable consumption

8. Reclaim old waste dumps

9. Reduce water consumption

10. Reduce tailings

11. Int. ore stockpiles

Clean waste
Limitations of Ore Sorting

- Sorting only effective within certain particle size ranges:
  - Too fine, and the throughput decreases
    - Throughput decreases with particle size
    - +10mm is typical lower economic limit
  - Too coarse, and dilution increases
    - Upper size determined by ore characteristics and sensor
      - e.g. 40 - 50mm is average penetration depth of XRT
      - Generally less than 100mm
- Every deposit is unique; not all ores amenable to sorting
  - Style of mineralisation, mineralogy and liberation
What can be achieved?

- Variations in LIBERATION make physical separation possible – e.g. mining dilution, ore type, grade
- A distinct difference in the physical property must be DETECTABLE – contrast, sensor resolution
Principles and Technology of Sensor Based Sorting
Stages of sorting

- **Feed Preparation**
  - Crushing
  - Screening – uniform particle sizes

- **Presentation of feed**
  - Chute & Belt types
  - Clean / Wet / Dry?

- **Sensing & Processing**
  - Particle Identification & Location
  - Particle examination
  - Classification according to machine settings

- **Separation**
  - Air jets vs mechanical
Material Presentation

Particles presented as a MONOLAYER

➢ Chute Feed
  ➢ Surface detection
  ➢ Freefall material
  ➢ Multiple Face Sensors

➢ Belt Feed
  ➢ Internal detection
  ➢ Stable particles
  ➢ Single Sensor Position
Separation

- **High pressure air jets**
  - Air jets can eject large rocks up to 15kg
  - Up to 10% “Overshoot” – particle collisions etc.

- **Mechanical sorters used by RADOS**
<table>
<thead>
<tr>
<th>Sensor Technology</th>
<th>Surface detection</th>
<th>Subsurface detection</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gamma radiation</td>
<td></td>
<td>Yes</td>
<td>Not really applicable on Industrial Minerals</td>
</tr>
<tr>
<td>X-Ray transmission</td>
<td></td>
<td>Yes</td>
<td>Very successful</td>
</tr>
<tr>
<td>Color camera</td>
<td>Yes</td>
<td>Very limited</td>
<td>Very sensitive to surface coating (dust, clay)</td>
</tr>
<tr>
<td>Laser Scattering</td>
<td>Yes</td>
<td>Limited</td>
<td>Using the near surface minerals</td>
</tr>
<tr>
<td>Near Infrared</td>
<td>Yes</td>
<td>Limited</td>
<td>Using the near surface minerals</td>
</tr>
<tr>
<td>Electro-magnetic</td>
<td></td>
<td>Yes</td>
<td>Based on conductivity Not really applicable on IM</td>
</tr>
</tbody>
</table>

All technologies with full or limited sub-surface detection capabilities could be used without washing water.
## Sensors available for sorting

<table>
<thead>
<tr>
<th>Sensor Type</th>
<th>Material Property Detected</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ELECTROMAGNETIC SENSOR (EM)</strong></td>
<td>Material property detected: electro-magnetic properties like conductivity and permeability</td>
</tr>
<tr>
<td><strong>X-RAY TRANSMISSION (XRT)</strong></td>
<td>Material property detected: specific atomic density irrespective of size, moisture or pollution level</td>
</tr>
<tr>
<td><strong>COLOR CAMERA (COLOR)</strong></td>
<td>Material property detected: color properties in the color are as red, green and blue</td>
</tr>
<tr>
<td><strong>RADIOMETRIC</strong></td>
<td>Material property detected: natural gamma radiation</td>
</tr>
<tr>
<td><strong>IR CAMERA (IR); TRANSMISSION (IRT)</strong></td>
<td>Material property detected: heat conductivity and heat dissipation</td>
</tr>
<tr>
<td><strong>X-RAY FLUORESCENCE (XRF)</strong></td>
<td>Material Property detected: elemental composition</td>
</tr>
<tr>
<td><strong>VISIBLE LIGHT SPECTROMETRY (VIS)</strong></td>
<td>Material property detected: visible spectrum for transparent and opaque materials</td>
</tr>
<tr>
<td><strong>NEAR-INFRARED SPECTROMETRY (NIR)</strong></td>
<td>Material property detected: specific and unique spectral properties of reflected light in the near-infrared spectrum</td>
</tr>
</tbody>
</table>
| **LASER REFLECTION/SCATTERING/FLUORESCENCE** | Material property detected:  
  + Monochromatic reflection / absorption  
  + Scattering of laser light Fluo or bio-luminescence, Super K |
Optical Sensing – Colour/VisibleLight

- Most popular sorting technology (industry & industrial minerals)
- Detects surface colour differences – clean/wet
- Each particle is photographed and the image processed and classified according to the calibrated colours
- Requires stable and high quality illumination

Input fraction (Talc)

Output fractions:

Accept

Reject
Optical Sensing - Wet vs Dry?
Near Infrared (NIR) - principle

**Principle**

Certain NIR frequencies excite sample molecules to oscillate – these energy levels are predominantly absorbed. Other energy levels of the light are diffusely reflected. This light is directed to the detector unit and analyzed.

**Result**

Spectrum of the reflection intensity against the wavelengths.
NIR-sorting of magnesite

Unfortunately it is difficult to demonstrate invisible effect in photos, ...

Magnesite – high Si containing particles from low Si pieces

Magnesite – low Si

... but the grades are clearly visible for the scanner
A laser is permanently scanning the material

Sorting is based upon the ‘penetration’ of laser light, which depends on the product structure.

A ‘glow’ or ‘scattering’-effect is triggered...

We only see the scatter, not the laser point any more.
With color one can see no difference between both rocks, whereas using Laser the sorter gets a great signal from the scattering effect inside the Quartz. And the quartz is an indicator for gold....
LASER – Quartz vein hosted Au

➢ Host Tonalite

➢ Quartz vein

Material generally needs to be washed
Electromagnetic Sensor (EM)

- Feed rates up to up 300Tph
- Material size down to 5mm
- More faster and accurate sensors
EM - Base Metals, Sudbury

- EM ore pre-concentration before further processes (e.g. milling, flotation, hydrometallurgy, etc.)
- The challenge: Remove low grade ore (<0.5% Ni) and waste from feed material

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sorting Task</td>
<td>Remove all particles &lt;0.5% Ni</td>
</tr>
<tr>
<td>Feed rate</td>
<td>approx. 60 t/h</td>
</tr>
<tr>
<td>Size range</td>
<td>25..50mm</td>
</tr>
<tr>
<td>Feed grade</td>
<td>1.4-1.6%</td>
</tr>
<tr>
<td>Sorter concentrate</td>
<td>Product 2.0-2.7% Ni</td>
</tr>
<tr>
<td></td>
<td>Waste 0.1-0.2% Ni</td>
</tr>
<tr>
<td>Reject rate</td>
<td>Up to 40%</td>
</tr>
</tbody>
</table>

ROM Secondary EM Sorter
X-Ray Transmission
What is the challenge?

XRT-technology measures the level of x-ray energy after the rays have passed through an object. This level of attenuation is directly dependent on atomic density **and** thickness of the object.

XRT works to a particle thickness of \(\sim 40\)mm (35mm iron ore, 80mm coal)

This means: Two pieces of different materials can create the same projected picture. So use the Dual Energy technology (DE-XRT).
An image transformation of the density images of the two bands then makes it possible to classify each pixel according to atomic density.

Classification proceeds relative to a reference density, to which the system has been calibrated.
XRT – Nickel ore

Massive Sulphides

Medium Grade

Granite
XRT – Diamonds

Raw XRT Image

Classified XRT Image

Valve Control Image

Detail

Detail

Detail
Commercial XRT Sorter

2 x 1.2 m XRT Sorters
Mittersill Scheelite Mine (WBH)
- Opened in 1976 with a head grade of 0.7% WO$_3$
- Mining up to 500,000 t/y
- Head grade is now 0.2% WO$_3$
- Processing plant requires 0.3% WO$_3$
- Limited capacity of tailings pond

2 Parallel XRT sorters to pre-sort scheelite
- 70 tph; 16-30mm & 30-60mm
- Grade of feed to the processing plant: 0.38% WO$_3$
- 50% of sorted material goes straight to waste
- Over 100,000 tpa no longer needs to be processed and disposed of in the tailings pond
  - Extended the mine life
- XRT waste rock is sold as aggregate for road construction
Commercial XRT Sorter

2.4 m XRT Sorter
Phosphate – Saudi Arabia

- **Waad Al Shamal Phosphate Project**
  - ROM: 13.5 million tonnes per annum
  - 70% of ROM will be sorted
  - Nine 2.4m wide XRT sorters
  - Currently in construction phase: 2017 start-up?

- **Benefits include:**
  - Downsizing the downstream process
  - Smaller plant footprint
  - Reduced consumption of energy, water and chemicals per ton of final product

- **Throughput of sorters is no longer an issue**
Testwork and Optimisation
Application to a project
Testwork Programme for Sorting

Testwork is Relatively Cheap

- Sample Preparation
  - Sampling (representative?)
  - Crushing
  - Screening
    - Material washing?
- Sorting
  - Machine calibration
  - Geologist input
- Assaying
  - Mass Balance Calculations
Crushing & Screening

- Objective is to maximise the material which goes through the sorter

- Crushing generates fines which bypass the sorters
  - Upgrade / downgrade of material?

- Minimise fines (-10mm)
  - Poor crushing and/or screening
  - Avoid oversize

- Screening
  - Consistent across tests
  - Represent screening in a production scenario
    - Single crush
### Example of fines generation

<table>
<thead>
<tr>
<th>Process Description</th>
<th>2013 Sample</th>
<th>2014 Sample</th>
<th>2015 Sample 1</th>
<th>2015 Sample 2</th>
<th>2015 Sample 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt; Crush &amp; Screen Lab1 (-8mm)</td>
<td>9.4%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt; Crush &amp; Screen Lab1 (-10mm)</td>
<td></td>
<td>12.4%</td>
<td>13.9%</td>
<td>8.9%</td>
<td>11.3%</td>
</tr>
<tr>
<td>2&lt;sup&gt;nd&lt;/sup&gt; Crush &amp; Screen Lab2 (-10mm)</td>
<td></td>
<td></td>
<td>5.9%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Re-Screen Tomra (-8mm)</td>
<td></td>
<td></td>
<td>12.5%</td>
<td>9.5%</td>
<td>8.6%</td>
</tr>
<tr>
<td>Slimes Lab1</td>
<td></td>
<td></td>
<td>4.7%</td>
<td>1.8%</td>
<td>2.2%</td>
</tr>
<tr>
<td>Total Fines %</td>
<td>9.4%</td>
<td>18.3%</td>
<td>31.1%</td>
<td>20.2%</td>
<td>22.1%</td>
</tr>
</tbody>
</table>

Proportion of Fines generated with each crushing and/or screening
Poorest screening requires more handling
Screening

- Min:Max of range should be <3
- Typically 2 size ranges
  - e.g.
    - -10mm = Fines
    - +10-20mm
    - +20-40mm
- Liberation analysis?
  - QEMSCAN

Sizes based on narrowest particle dimension passing through screen
Geologists input is important to determine ore types and to calibrate the sorter and selection thresholds.
Optimising the process

What are we trying to do?

- Determine how the efficiency of sorting (recovery: mass pull) varies with
  - different feed types (ore type, grade etc.)
  - machine settings (thresholds)

- Quantify the sorting efficiency in such a way that this information can be applied to a block model
  - Geometallurgy

- Improve confidence
Studies looked at different sensors
- XRT and Radiometric most effective
- Sorting will lead to 50% rejection to waste
Bradshaw Au deposit, Timmins

Gowest Gold - 2015 PFS

- 2 XRT Sorters: 10-25mm, 25-75mm
- 53% mass pull for 98% Au recovery (incl. fines)
- Ore upgraded from 4.8 g/t Au to as high as 9g/t

High Grade Samples

Low Grade Samples
Economic Considerations
Containerised Installation

Gold

Magnesite

Polymetallic ore

Iron Ore
Underground installation?

- **Industrial Minerals**
  - Rock Salt
  - Underground colour sorting to remove impurities in Germany, Morocco and Canada
  - Historically in a fluorspar mine

- **Requires considerable space**
  - Conveyors, removal of waste etc

- **Not practical in most metal mines**
Capital Costs

- Very rough ballpark figures:
  - Each 1.2m sorter is ~ € 0.5 million
  - Annual Maintenance costs of 10%

- Number of machines depends on configuration and throughput rates
  - Throughputs depend on material density and particle sizes

Rule of Thumb:

10-20mm particles of 2.7 g/cm³ density 15 tph/sensor m
Running Costs

- **XRT Energy Consumption:**
  - 10 – 26 KW per sorter
  - Variation due to width (1.2m or 2.4m) and power of different x-ray tubes and motors

- **Compressed Air for Ejection:**
  - Depends on feed/hit rate and particle size
  - For 1.2m XRT, processing 60 tph of 30-50mm with a hit rate of 25-30% will need 40-50KW compressor power
Belvedere Resources Kopsa AuCu Deposit

- Constrained by pre-existing Ni mill infrastructure
- 20 km transport from mine to mill
- PEA looked at 6 scenarios with and without sorting
  - Based on the same block model
- XRT Sorting:
  - 65% mass rejection
  - 90% Au recovery
  - 75% Cu recovery

Savings throughout the mine cycle
## Comparative project economics

<table>
<thead>
<tr>
<th>Scenario</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production Rate (Mtpa)</td>
<td>0.5</td>
<td>0.75</td>
<td>1.0</td>
<td>1.0</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Sorting</td>
<td></td>
<td></td>
<td></td>
<td>Sorting</td>
<td></td>
<td>Sorting</td>
</tr>
<tr>
<td>LOM (years)</td>
<td>19</td>
<td>13</td>
<td>10</td>
<td>10</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Tonnes to Hitura Plant (Mt)</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>3.2</td>
<td>9</td>
<td>3.2</td>
</tr>
<tr>
<td>Hitura plant head grade (Cu %)</td>
<td>0.15%</td>
<td>0.15%</td>
<td>0.15%</td>
<td>0.32%</td>
<td>0.15%</td>
<td>0.32%</td>
</tr>
<tr>
<td>Hitura plant head grade (Au g/t)</td>
<td>0.91</td>
<td>0.91</td>
<td>0.91</td>
<td>2.34</td>
<td>0.91</td>
<td>2.34</td>
</tr>
<tr>
<td>Total Op Costs /t ROM (USD /t)</td>
<td>30.1</td>
<td>27.1</td>
<td>27.9</td>
<td>19.1</td>
<td>27</td>
<td>18.2</td>
</tr>
<tr>
<td>Total Op Costs (incl contingency) (M USD)</td>
<td>273</td>
<td>245</td>
<td>253</td>
<td>173</td>
<td>244</td>
<td>165</td>
</tr>
<tr>
<td>Total Cap Costs (incl contingency) (M USD)</td>
<td>54</td>
<td>55</td>
<td>69</td>
<td>49</td>
<td>70</td>
<td>48</td>
</tr>
<tr>
<td>Undiscounted cashflow (M USD)</td>
<td>-6.6</td>
<td>19.4</td>
<td>-1.4</td>
<td>58.2</td>
<td>5.6</td>
<td>65.5</td>
</tr>
<tr>
<td>Post-tax NPV @8% (M USD)</td>
<td>-11.5</td>
<td>1.2</td>
<td>-11.5</td>
<td>21.8</td>
<td>-8</td>
<td>26.4</td>
</tr>
<tr>
<td>Post-tax IRR (%)</td>
<td>-</td>
<td>10%</td>
<td>-5%</td>
<td>31%</td>
<td>-1%</td>
<td>36%</td>
</tr>
</tbody>
</table>
Questions to ask?

- Extent of studies
  - Quantification of sorting efficiency

- Is the sample representative?
  - Different ore types? (Liberation; disseminated ore)
  - Different grades?

- Crushing and Screening?
  - Have fines been suitably accounted for?

- Economics
  - Throughput rates?
  - Costs
  - Realistic expectations?
Conclusion

- **Proven technology**
  - Diamonds, Industrial Minerals

- **Multiple benefits**
  - Project economics
  - More complete exploitation of a deposit
  - Environmental

- **Not just for new projects**
  - Cost savings
  - Extend resources, lower grade ores become accessible
  - Extending mine life

- **Not a “silver bullet”**
  - All deposits are unique, not all are amenable to sorting