Magnetic Conditioning of Flotation Feed to Increase Recovery of Fine Value Minerals at Boliden’s Garpenberg Concentrator

Hamid-Reza Manouchehri (Ph.D.), Sandvik Mining, Sweden

Hassna Aitahmed-Ali & Stellan Sundberg, Boliden Mineral, Sweden
Background- Flotation Process

As a physico-chemical process it is defined by different parameters

- Flotation comprises of three different sub-processes:
  Collision, Attachment, detachment (stability)
Background - Flotation Process

✓ In practices ≥10% of values are lost (either fine or coarse)
✓ Reasons? Low Stability (coarse) & Low Collision Efficiency (fine)

<table>
<thead>
<tr>
<th>Processes</th>
<th>Efficiency vs Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>✓ Collision</td>
<td>✓ Direct</td>
</tr>
<tr>
<td>✓ Attachment</td>
<td>✓ Inverse</td>
</tr>
<tr>
<td>✓ Stable pulp transport</td>
<td>✓ Inverse</td>
</tr>
<tr>
<td>✓ Transportation across froth zone</td>
<td>✓ Inverse</td>
</tr>
</tbody>
</table>
Flotation of Fine Particles

✓ Low recovery for fines may be due to lower hydrophobicity and reduced bubble-particle contacts

✓ Increasing recovery of fines in plant practice (strategy):
  • Correct circuit design
  • Increasing collision $E_c$ (higher power)
  • Smaller bubbles generation
  • Larger bubbles generation to provide sufficient levitation force
  • Increased surface hydrophobicity
  • Flocculation /Agglomeration of particles (e.g., Magnetic Agglomeration using Profloat)
  • Surface cleaning (HIC, Stirred media milling)
  • Increasing contact angle by chemicals (reagents/extender)
Flotation of Fines (Flocculation)

✓ Shear/Hydrophobic Flocculation:
Surfactant can coat particles to favor interactions and stable aggregates are formed because of strong hydrophobic energies that withstand the disruptive turbulence energies at high rates.

✓ Floc-Flotation:
Aggregation of fine particles can be performed by selective polymer flocculation or by the addition of kerosene with the collector to the pulp prior to vigorous agitation. Stable aggregates are formed because of strong hydrophobic energies (well documented studies on non-sulfide minerals).

✓ Magnetic Flocculation:
It is caused by magnetic attraction between ferromagnetic or weakly magnetic particles in an external magnetic field. Magnetic particles can become magnet in an external magnetic field and aggregate to form magnetic flocs in turbulent flow.
Magnetic Agglomeration/Flocculation

✓ Magnetic Mineral’s Characteristics:
  • ferromagnetic  • paramagnetic  • diamagnetic

Two other classes are considered: antiferromagnetic & ferrimagnetic which are critical to the temperature (Tc, Currie Temperature)

✓ Aggregation of fine particles in media due to magnetic attraction between particles

- Good aggregation of fine paramagnetic particles can occur and the aggregation is enhanced if the minerals are made hydrophobic
- Sulfides minerals have natural hydrophobicity to some degree, however, their hydrophobicity can be improved by reagent addition, consequently, there may be the possibility to enhance the flotation recovery of sulfide minerals by magnetic conditioning of the pulp.
- Magnetic aggregation can be performed either prior to flotation or during the flotation.
Magnetic Agglomeration/Flocculation

The magnetic attraction force is defined by:
- magnetic force applied,
- magnetic susceptibility
- distance between the particles

Magnetic attraction $V_M$, for paramagnetic particles is defined by:

$$V_M = \frac{32 \pi^2 a^6 \chi^2 B_0^2}{9 \mu_0 r^3}$$

The Stability of the agglomerated magnetic particles is defined by interplay among the repulsive and attractive forces (DLVO theory, van der Waal’s, electrostatic, magnetic forces):

$$V_T = V_A + V_R + V_M$$

Variations of threshold of flocculating magnetic field field with particle diameter of some minerals
Magnetic Agglomeration/Flocculation

- Selective aggregation of the fine paramagnetic particles can be achieved by applying a high intensity magnetic field within the pulp
- Magnetic aggregation is dependent on the magnetic induction, particle size and the magnetic susceptibility of the mineral
- Paramagnetic minerals, e.g., sulfides, at P<20 μm can be aggregated at magnetic inductions of $10^{-2}$-$10^{-1}$T, implementing permanent rare earth magnets
- Variations in Fe content in sulfide minerals attribute to the magnetic susceptibility
- Only fine paramagnetic particles are affected from a primarily diamagnetic matrix to improve grade/recovery curve
The magnetic conditioning device (ProFlote)

- The well-known relationship between the flotation recovery of sulfide minerals and particle size plus possibility to aggregate fine paramagnetic minerals were the main wheels behind emerging of magnetic conditioning device “ProFlote” (US Patent 7429331 in 2001).

- ProFlote, consists of strong neodymium magnets arrayed within a tubular stainless steel assembly. A strong magnetic field of about 0.5 T is in contact with the surrounding slurry. The magnets are at frequent and regular intervals automatically removed from the slurry to clean the magnets of ferromagnetic material in the slurry that blind the magnets.

General Configuration of the ProFlote and its plant’s installation
Magnetic Conditioning Device (Proflote)

The magnetic conditioning device (ProFlote)

- ProFlote is a pre-flotation conditioning technology that substantially improves selective sulfide mineral flotation (selectively magnetizes and aggregates the paramagnetic minerals including: chalcopyrite, bornite, chalcocite, marmatite, pentlandite, freibergite, etc.,)

- The size of device is generally 200mm diameter and 3000mm long, however, flexibility exists based on needs

- The number of devices employed are defined by the feed rate, cell dimensions, amount of values in fine particles, etc.,

- First step is based on statistical analysis of “ON” and “OFF” in plant practice
Improve Sulfide Minerals Flotation

That improves flotation kinetics and recovery

<table>
<thead>
<tr>
<th>Plant and kind of ore</th>
<th>Location of Proflote – Size</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Golden Grove – high iron oxide chalcopyrite ore and a pyritic galena/sphalerite/precious metals (Engelhardt, Ellis and Lumsden, 2005).</td>
<td>Cleaner scavenger circuit 80% &lt; 38 µm</td>
<td>3.84% increase in zinc recovery 1.65% increase in zinc grade 13% reduction of zinc in tail 3.90% increase in copper recovery 39% reduction of copper in tail</td>
</tr>
<tr>
<td>Cannington – galena/sphalerite ore containing Ag, low pyrite with iron and silicate gangues (Holloway, Clarke and Lumsden, 2008)</td>
<td>Lead split float circuit 80% &lt; 20 µm</td>
<td>4.0% increase in lead recovery 1.3% increase in lead grade 3.5% increase in silver recovery 18% reduce in lead in tail 16% reduction in silver in tail</td>
</tr>
<tr>
<td>Northparkes Mine – copper-gold porphyry chalcopyrite and bornite ore (Rivett, Wood and Lumsden, 2007).</td>
<td>Rougher feed conditioner 80% &lt; 100 µm</td>
<td>For P&lt; 20 µm: 2.08% increase in copper recovery; 14% reduction in copper in tail; 3.5% increase in gold recovery For + 20 –38 µm fraction: 0.98% increase in copper recovery; 23% reduction in copper in tail</td>
</tr>
<tr>
<td>Jaguar Mine - iron sulfide complex chalcopyrite/sphalerite ore with Ag (Wilding and Lumsden, 2011).</td>
<td>Rougher feed conditioner of copper and zinc circuit 80% &lt; 45 µm</td>
<td>Copper circuit: 10% reduction in Cu in tail, 7% reduction in Zn recovery to Cu conc; 1.8% increase in Zn recovery to Zn conc and 10% reduction in Zn in tail Zinc circuit: further 9% reduction in Zn in tail</td>
</tr>
</tbody>
</table>
A complex Zn-Pb-Cu sulfide is treated at Garpenberg plant (1.5 Mt/y, Zn 5.6%, Cu 0.06%, Ag > 100 ppm, Au 0.027 ppm).
Mineralization sphalerite, galena, and chalcopyrite with quartz, dolomite, talc, mica, amphibole and serpentine as gangue.
AG and pebble milling to grind the ore to p<160 μm for flotation and liberation size between 75 and 100 μm.
Traditional way of Zn-Pb-Cu flotation, Cu-Pb flotation and Zn flotation.
Garpenberg Flotation Scheme

- Classical Cu-Zn-Pb complex sulfide flotation
  - Pb-Cu flotation: Dextrine, ZnSO4, KAX, frother alkaline pH around 10
  - Zn flotation: Dextrine, CuSO4, IBX, frother
  - Cu-Pb separation: Dextrine, Chromate, frother,
Implementation of ProFlote at Garpenberg Plant

- The idea for installing ProFlote to recover fine value particles was initiated in 2011 (H.R. Manouchehri) and devices were installed after a short survey done in mid-2012.

- The idea was to improve recovery and grade for Cu-Pb circuit as well as Zn flotation, however, one interesting target would be to increase Ag recovery.

- A number of ProFlote devices were installed in Zinc and Cu-Pb separation circuits

- At first step four “ProFlote”s were installed at Zn-flotation circuit (first cell@40 m³)

- Later on those “ProFlote”s were moved to the Cu-Pb flotation circuit.

- Two smaller ProFlotes were installed in Cu-Pb separation circuit as well.

- After the first three months of testing, the devices were permanently installed in plant.
Implementation of ProFlote at Garpenberg Plant

- First series of tests were conducted by installation of ProFlote in Zn rougher flotation and Cu-Pb separation stage
- To evaluate the performance, samples were taken (P> 45 and P<45 µm) for analysis, however, the effect on grade and recovery is mainly related to the finer fraction
- Detailed analysis of the first series of “ON” and “OFF” tests, at >95% confident rate, revealed an improvement in the <45µm Cu-Pb separation with a relative 10% increase in Cu grade and a relative 28% reduction in Pb grade in the Cu-con that resulted in a 25% decrease in Pb recovery to the Cu con.
- At Zn circuit, however, an improvement in Pb grade (26%) and recovery (13%) were observed at lowering the Zn to the tail by 12% (>90% confidence).
- Ag recovery and grade in Zn-con improved dramatically by 14% and 13% respectively
- A good recovery results for Ag and Pb in the zinc rougher indicated that the magnetic conditioning would be perform better in the Cu/Pb rougher circuit
Implementation of ProFlote at Garpenberg Plant

- Second series of tests were performed by installing “ProFlote” in the Cu/Pb rougher,
- Ag recovery was improved by 13%, with a 10% increase in its grade.
- Deportment of Zn to the final tail reduced by 17% and its recovery in plant increased by 1.2%.
Implementation of ProFlote at Garpenberg Plant – Summary

✓ The summary of the statistical analysis indicated (confidence level greater than 95%):

• For 2012 and first quarter of 2013:
  
  **Cu-Pb circuit:** 1% Cu-con grade increased by 1%,
  0.47% reduction in Zn grade in Cu-Pb con
  0.37% Zn reduction in Pb-con,

  **Zn circuit:** 12 ppm increasing in Ag grade and 0.2% increase of Pb grade in Zn-con.,
  0.06% reduction in Zn grade to the final tail (90% level of confidence).

• For the second and third quarters of 2013:
  
  **Cu-Pb circuit:** 1.0 % increase in Cu-con grade,
  0.3% reduction in both Zn and Pb recovery in Cu-con.
  1.2% and 0.5% , Au and Ag recovery in that concentrate respectively
  0.47% reduction in Zn grade in Cu-Pb con
  0.37% Zn reduction in Pb-con,

  **Zn circuit:**  1.2% increase in Zn recovery.,
  0.9%, 0.8% increase in Ag, and Pb in Zn-Con.
Implementation of ProFlote at Garpenberg Plant

✓ Increasing in Zn and Cu recovery can be easily understood by considering the ore mineralogy, however, one must think about why both Ag and Pb recoveries are improved in Zn-con independently of whether magnetic aggregation occurs in the Cu or Zn circuit.

✓ Possibly, fine Ag/Pb bearing minerals may be partially locked/enclosed within sphalerite particles, or there are Pb and Ag associated with sphalerite crystals, or there are agglomerated Ag/Pb composite particles that cannot be floated until activated by copper sulfate.

✓ Detailed mineralogical analysis must be conducted on different fractions of feed, concentrates and tails.

✓ Mineralogical analysis is going on (QEM-Scan) for better understanding the results.
Conclusions

✓ Magnetic conditioning technique in Garpenberg flotation plant demonstrated a success by increasing the recoveries and/or grades for value minerals.

✓ In particular, great results in recovering Zn and Ag (total increasing of 1100-1500 t/y in Zn production and about 1500 kg/y in sealable Ag production)

✓ Cu grade within increased by 1% where Zn recovery decreased in Cu-con.

✓ The device was shown to be effective in agglomerating fine paramagnetic particles and improving their recoveries.

✓ The device has a small footprint, can be easily installed and maintained,

✓ Small amount of air is needed

✓ No operator practice (in-line between pump and float)

✓ Magnetic agglomeration is simple, selective, effective on fines, cost effective
Thank You