Fine grinding, a refresher

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Purpose

• Metallurgists use models as tools, and
• each tool is suited to a particular task.
• Fine grinding requires different tools to “regular” grinding.
Bond work index

- Commonly used model that describes conventional grinding.
- Based on fixed exponent of -0.5.
- Empirically fit to data collected in the 1930’s and 1940’s.
Bond work index

- Did not fit all data and often has issues at upper and lower size boundaries.
- Fudges, kludges and bodges are applied to “finer” grinding, Eg. below 75 µm.
The bigger picture

• Bond’s model is one of a larger family of power-based models.

• Other examples:
  – Von Rittinger’s model
    \[ E = a \times X^{-1} \]
  – Kick’s model
    \[ E \propto \frac{X_1}{X_0} \]

• Overall model

  \[ E = a \times X^{-b} \]

  where:
  – \( E \) is specific energy consumption, kWh/t
  – \( X \) is particle 80% passing size, \( \mu m \)
  – \( a \) and \( b \) are fitted parameters.
The following may be disturbing to some viewers.

User discretion is advised.
The bigger picture

- Many power-based models are solutions to a single equation:
  \[
  \frac{dE}{dx} = K \times X^{-c}
  \]
  where:
  - \( K \) and \( c \) are ore-specific fitted constants
- One integrated form:
  \[
  E = a \times \left( X_1^{-b} - X_0^{-b} \right)
  \]
Hukki’s Conjecture

- R. Hukki did experiments measuring specific energy consumption across a range of sizes.
Hukki’s Conjecture

- The exponent changes with particle size.
- A fixed exponent is suitable for limited size ranges.
Fine grinding

- The definition of “fine grinding” is somewhat material-specific. Propose the definition be based on “where Bond’s model no longer applies”.

- Generally translates to sizes below 100 µm, becomes more acute below 75 µm.
Option 1: Use a variable exponent

- Jar mill test from Merriam et al, CMP 2015

\[
f(x) = 8,109.29 x^{-1.96}
\]

\[
R^2 = 1.00
\]

<table>
<thead>
<tr>
<th>x, µm</th>
<th>E, kWh/t</th>
</tr>
</thead>
<tbody>
<tr>
<td>110</td>
<td>0</td>
</tr>
<tr>
<td>53</td>
<td>3.38</td>
</tr>
<tr>
<td>38</td>
<td>6.75</td>
</tr>
<tr>
<td>33</td>
<td>8.44</td>
</tr>
</tbody>
</table>
Option 2: use exponent -1

- Von Rittinger’s model generally works better in 50 µm to 100 µm size range.

Fitting data from Aureus Mining (2012) Bond ball mill tests on gold ore
Option 3: Use material-specific exponents

<table>
<thead>
<tr>
<th>Material</th>
<th>Exponent</th>
<th>Equation</th>
<th>Size range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gold ore (hydrothermal, greenstone, silicate hosted)</td>
<td>-0.9</td>
<td>( E = C \times -0.9 )</td>
<td>500 → 40 µm</td>
</tr>
<tr>
<td>Lead-zinc ore (massive sulphide)</td>
<td>-1.0</td>
<td>( E = C \times -1.0 )</td>
<td>65 → 45 µm</td>
</tr>
<tr>
<td>Lead-zinc ore (massive sulphide)</td>
<td>-1.4</td>
<td>( E = C \times -1.4 )</td>
<td>45 → 5 µm</td>
</tr>
<tr>
<td>Porphyry ore (silica, feldspars, minor sulphides)</td>
<td>-0.5</td>
<td>( E = C \times -0.5 )</td>
<td>235 → 78 µm</td>
</tr>
<tr>
<td>Copper rougher concentrate (chalcopyrite and pyrite)</td>
<td>-1.5</td>
<td>( E = C \times -1.5 )</td>
<td>110 → 33 µm</td>
</tr>
<tr>
<td>Pyrite concentrate</td>
<td>-2.0</td>
<td>( E = C \times -2.0 )</td>
<td>40 → 8 µm</td>
</tr>
<tr>
<td>Base metal matte (copper, nickel)</td>
<td>-1.5</td>
<td>( E = C \times -1.5 )</td>
<td>300 → 60 µm</td>
</tr>
<tr>
<td>Iron ore (hematite, magnetite)</td>
<td>-0.7</td>
<td>( E = C \times -0.7 )</td>
<td>160 → 75 µm</td>
</tr>
<tr>
<td>Iron ore (hematite, magnetite)</td>
<td>-1.8</td>
<td>( E = C \times -1.8 )</td>
<td>75 → 15 µm</td>
</tr>
<tr>
<td>Zinc concentrate (Gao et al, 2007)</td>
<td>-1.2</td>
<td>( E = C \times -1.2 )</td>
<td>20 → 5 µm</td>
</tr>
</tbody>
</table>
Comments

• Assumes that specific energy consumption is material-specific and size-specific. Any “efficient” equipment should give similar results.
  – Equipment vendors may have different opinions.

• Fitting to plant data will give an equipment-specific model. Other classes of equipment may be more efficient.
  – Grinding media size, for example, affects fine grinding efficiency.
Conclusions

• Stop using Bond models for fine grinding.
  - Use specific energy consumption & size in NI43-101 reports.

• Use an appropriate model for fine grinding.
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