Mud2Metal
A holistic flow sheet for the Bauxite Residue valorization
Efthymios BALOMENOS, Dimitrios PANIAS, Yiannis PONTIKES
Mud2Metal Scope

- The Mud2Metal consortium is focused on solving the Bauxite Residue (BR) disposal, through a holistic metallurgical solution for metals and minerals recovery from BR.

- AoG leads this effort as one of Europe’s largest Alumina refinery, producing more than 700,000 tpa of BR.

- Core RTD partners include NTUA, RWTH-Aachen, KU-Leuven and MEAB -Germany.

- Mud2Metal is the result of a long history of RTD Effort on behalf of all partners.
Since 1999 AoG is actively participating in RTD projects for BR treatment.

AoG BR used in:

- Cement Industry (iron source in clinker)
- Brick/Tile Industry (substitution of clay)
- Geopolymer bricks
- Soil Remediation/ Vegetation cover
- Road Base Construction
- Landfill barrier / cover
- Backfilling of Abandoned Bauxite Mines
AoG Brief History in BR Innovation

In 2006 AoG was the first Western European Alumina Refinery plant to apply filter-press technology for dry disposal of Bauxite Residue. Today all AoG’s BR is disposed as filter cake.

2010 - 2014 AoG Coordinates the FP7 ENEXAL Project, demonstrating the complete conversion of BR to pig-iron and mineral wool products.

2013 - 2017 AoG is partner in the FP7 EURARE Project, researching technologies for REE extraction from BR.

Since 2015 AoG supervises 2 PhD studies under the recently approved Marie Curie project on “European Training Network for Zero-Waste Valorisation of Bauxite Residue (Red Mud)”
AoG BR filter cake (ferroalumina)

Utilize alumino-silicates as raw materials for building products (cement, insulation material, ...)

Utilize as alternative REE resource

Minor elements utilized in steel production

However till this day no single one utilization has proven economically viable or capable of valorizing 100% of the produced BR
AoG BR filter cake (ferroalumina)

The solution must:
• Be zero-waste (consume 100% of BR)
• operate as a stand-alone process
• be economically viable
• be flexible enough to follow various sectors’ market fluctuations

To fully valorize the 700,000 tpa with an economically viable process we need:
• Production of bulk products like pig iron and cement
• Production of niche products like REEs and mineral wool to enhance the economy of the process
Mud2Metal – Pig Iron
From 700,000 t BR can be produced 210,000 t pig iron

- Pig Iron can be produced through carbothermic reductive smelting of BR in Electric Arc Furnace (ENEXAL Project)
- Bulk product, practically limit-less market
- Current selling price app 300 EUR/t
- The BR pig iron would also concentrate all Ni, Cr, V present in the BR. Elements highly valuable for steel production

<table>
<thead>
<tr>
<th>Element (%)</th>
<th>Fe</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>Ni</th>
<th>Cr</th>
<th>V</th>
<th>Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td>ENEXAL BR Pig iron</td>
<td>92.30</td>
<td>4.25</td>
<td>0.09</td>
<td>1.89</td>
<td>0.22</td>
<td>0.05</td>
<td>0.21</td>
<td>0.57</td>
<td>0.41</td>
<td>-</td>
</tr>
<tr>
<td>Average Steel scrap</td>
<td>98.56</td>
<td>0.09</td>
<td>0.06</td>
<td>0.01</td>
<td>0.02</td>
<td>0.06</td>
<td>0.12</td>
<td>0.11</td>
<td>0.01</td>
<td>0.37</td>
</tr>
<tr>
<td>Grey cast iron alloy</td>
<td>92.78</td>
<td>3.40</td>
<td>0.5</td>
<td>1.80</td>
<td>0.20</td>
<td>0.07</td>
<td>-</td>
<td>0.35</td>
<td>0.15</td>
<td>-</td>
</tr>
</tbody>
</table>
Mud2Metal – Slag Products

From 700,000 t BR can be produced 300,000 t of slag

- Slag is produced along with the Pig-Iron production process and can be utilized in the cement or insulation industry
- Slag can be valorized as low-value products in bulk applications or as high added value products in niche application – exploiting the high alumina content of the slag

<table>
<thead>
<tr>
<th>%wt</th>
<th>Al₂O₃</th>
<th>CaO</th>
<th>MgO</th>
<th>SiO₂</th>
<th>TiO₂</th>
<th>FeO</th>
<th>Na₂O</th>
</tr>
</thead>
<tbody>
<tr>
<td>ENEXAL BR Slag (400 kg/t of BR)</td>
<td>37.0</td>
<td>29.0</td>
<td>0.7</td>
<td>25.0</td>
<td>8.0</td>
<td>1.0</td>
<td>-</td>
</tr>
<tr>
<td>Typical Blast Furnace Slag</td>
<td>7-16</td>
<td>32-45</td>
<td>5-15</td>
<td>32-42</td>
<td>-</td>
<td>0.1-1.5</td>
<td>-</td>
</tr>
<tr>
<td>Calcium Aluminate Cement</td>
<td>36-42</td>
<td>36-42</td>
<td>0.1</td>
<td>3-8</td>
<td>&lt;2</td>
<td>12-20</td>
<td>0.1</td>
</tr>
<tr>
<td>Typical slag wool products</td>
<td>5-16</td>
<td>20-43</td>
<td>4-14</td>
<td>38-52</td>
<td>0.3-1</td>
<td>0-5</td>
<td>0-1</td>
</tr>
<tr>
<td>Refractory ceramic fibers</td>
<td>35-51</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>47-54</td>
<td>0-20</td>
<td>0-1</td>
<td>&lt;1</td>
</tr>
</tbody>
</table>
Mud2Metal – Slag Cement Products
From 700,000 t BR can be produced 300,000 t of slag

- Slag can be used as raw material or even substitute of Ordinary Portland Cement (OPC)
  - Bulk product - practically limit-less market
  - Current Market Price for Slag Cement: 20 EUR/t

- Slag could also be used as raw material for Aluminate Cements (HAC, CAC) are used in technical applications where resistance from corrosion or fire is essential.
  - Specialized product with a Market of 300,000 - 400,000 tpa in Europe and America
  - Price 300 – 600 EUR/t (depending on alumina content)
Mud2Metal – Slag Insulation Products
From 700,000 t BR can be produced 300,000 t of slag

Mineral Wool products

- Specialized product, market limited by transporting costs (high volume-low density) to: 60,000 – 120,000 tpa

- Market prices for final mineral wool product: 500-1000 EUR/t, depending on quality, properties and fiber final processing.

- In-situ production of the fiber products, utilizes the latent heat of the produced slag, saving up to 70% of processing energy.
Mud2Metal – Slag Building Products
From 700,000 t BR can be produced 300,000 t of slag

Geopolymer building products

- Geopolymers can be engineered from practically any alumino-silicate raw material [NTUA, KUL]
- Advantage of the Alumina industry is that their formation requires the use of a soda solution
- New products can be built like: tiles or lightweight insulation or composite materials
- Potential market value: 200 EUR/t
Mud2Metal – REE products

Rare Earth Oxides (REO)

- AoG’s BR contains 1.4 kg/t REO
- Europe imports 8000 tpa of REO / REE metals; AoG’s disposes app 1000 tpa of REO in the BR
- Market price: 3 – 60 EUR/kg (depends on the oxide); for a mixed REO concentrate: 7 EUR/kg
Mud2Metal - Scandium

Scandium, Al-Sc alloy

- New developing (niche) market with a global size of 50 tpa
- Sc applications include high-tech sectors like SOFC and 3D printing
- When alloyed with Al it produces the strongest Al-alloy known
- Price for Al-Sc (2%) master alloy: 220 EUR/kg
Strength evolution in extruded AlMgSc alloys (0 < Sc < 1.0 wt%)
(=> 0.1 wt% Sc = ca. 45 MPa strength increase)

Strength gain (MPa)

Alloy content of Sc (usable for precipitation hardening)

=> 315 MPa
The Mud2Metal Flowsheet

- Bauxite Ore
  - Alumina Refinery
    - Alumina
      - Alumina Smelter
        - Al

- Bauxite Residue
  - Selective Leaching/Separation
    - REE oxides
      - Sc Metal production
        - Al-Sc Alloy

- EAF Carbothermic Smelting
  - Fe (Cr,V,Ni)

- Slag Processing
  - Mineral Fibers
  - Aluminate Cement
    - Geopolymerization
      - Geopolymers

Aluminium Industry

Mud2Metal
Are we there yet?
The ENEXAL Bauxite Residue Treatment Process – AoG’s 1st Pilot Plant [2012-2014]

- 2012: 1 MVA-EAF and Melt fiberizing system installed in AoG Pilot Plant
- During a two year long experimental campaigns treated more than 25 t of BR
- More than 5 t of Pig Iron produced and tested in secondary steel production
- High Quality mineral wool product produced from the slag
Panagiotis Davris, et al.: Use Of Ionic Liquids for Rare Earth Element Extraction from Bauxite Residue. Case of EmimHSO4 and HbetTf2N

REE selective Extraction with ILs

LEACHING with HBET/water

filtration

filtrate

Stripping with acid

Bauxite residue

Leaching residue

PLS contains 60-80% BR's REE, 30% of Al and 4% of Fe, almost 100% Ca and Na

<table>
<thead>
<tr>
<th>Component</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO2</td>
<td>6.54%</td>
</tr>
<tr>
<td>Al2O3</td>
<td>12.27%</td>
</tr>
<tr>
<td>Fe2O3</td>
<td>56.11%</td>
</tr>
<tr>
<td>CaO</td>
<td>0.06%</td>
</tr>
<tr>
<td>TiO2</td>
<td>7.51%</td>
</tr>
<tr>
<td>Cr2O3</td>
<td>0.28%</td>
</tr>
<tr>
<td>NiO</td>
<td>0.11%</td>
</tr>
<tr>
<td>ZrO2</td>
<td>1.37%</td>
</tr>
<tr>
<td>Other</td>
<td>7.92%</td>
</tr>
<tr>
<td>LOI</td>
<td>7.82%</td>
</tr>
</tbody>
</table>
Furthermore…

- Sc selective leaching and separation from BR was pioneered by Prof. Ochsenkühn-Petropulu in NTUA in 1994. A pilot plant for Sc extraction is available in NTUA (99% pure Sc solution produced)

- UPatras and NTUA have both done extensive research in cement production and aluminate cement production

- Geopolymer technology is being developed for the last decade in NTUA and KUL

But…

- Sc Metal production remains an expensive multi-stage technology (separation, purification, ScF$_3$ formation and Ca-thermic reduction)
Can it be economically viable?
700,000 t BR

986 t REE
- 411 t CeO₂
- 139 t La₂O₃
- 136 t Sc₂O₃
- 99 t Nd₂O₃
- 95 t Y₂O₃

4,444 t Al-Sc master alloy

209,318 t Iron (Ni,Cr,V)

300,000 t BR Slag

Slag
- 60,000 t Mineral Wool
- 50,000 t Aluminate Cement
- 80,000 t Geopolymer products
- 110,000 t Slag Cement

50,000 t Aluminate Cement

986 t REE

300,000 t BR Slag

700,000 t BR

ALUMINIUM OF GREECE
### Economics of the flowsheet

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Iron product (209,000 t per annum)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Iron Product</td>
<td>209,000</td>
<td>300 -1000</td>
<td>210</td>
</tr>
<tr>
<td><strong>Slag Products (300,000 t per annum)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BR Mineral Wool</td>
<td>60,000</td>
<td>600-800</td>
<td></td>
</tr>
<tr>
<td>BR Aluminate Cements</td>
<td>50,000</td>
<td>300-600</td>
<td></td>
</tr>
<tr>
<td>BR Geopolymers</td>
<td>80,000</td>
<td>100-200</td>
<td></td>
</tr>
<tr>
<td>BR Slag Cement / raw material for industry</td>
<td>110,000</td>
<td>0-20</td>
<td></td>
</tr>
<tr>
<td><strong>REE products (1038 t per annum)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \text{Sc}_2\text{O}_3 \text{ 99%} )</td>
<td>136</td>
<td>500-1000</td>
<td>140</td>
</tr>
<tr>
<td>Mixed REO concentrate</td>
<td>902</td>
<td>6-8</td>
<td></td>
</tr>
</tbody>
</table>

*OPEX is estimated based on the ENEXAL pilot results and the Ochsenkuhn-Petropulu Sc-Removal pilot plant*
Economics of the flowsheet

We are here

Revenues with the low price products

Need to get here

Revenues with the high price products

Sc, REE

Slag

Fe

Sc, REE

Slag

Fe

OPEX
The way forward

RTD is needed at a level of industrially enhancing the possible products

- From pig-iron to grey cast iron
- From slag cement to aluminate cement
- From loose fibers to mineral wool products
- From Geopolymer pastes to final products
- From $Sc_2O_3$ to Al-Sc alloy

**Cooperation with industrial partners is necessary**
AoG’s Mud2Metal Ambition

In the next 5 years to take the next step in BR treatment and produce the **first fully functioning** industrial pilot unit for the complete valorization of BR

- 30,000 tpa BR treatment capacity
- 100% BR utilization
- Zero -Waste processing
- Economically profitable process through a diverse product range
- Introduce industrial innovations in REE extraction and building materials production
- Launch join-ventures with iron, cement, mineral wool, REE and other industries
Thank you for your attention