Corrosion Resistance of Al-Fe-alloy-coated Steel, Refractory Metals and Ceramics in Lead-Bismuth at 700°C

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Motivation

High boiling points of lead alloys can provide high temperature reactor with thermal efficiency higher than 40%.

Candidate materials compatible with lead alloys

- **Structural materials**: 400-550 ºC
  - High Cr F-M steels (with Si and Al addition)
- **Cladding materials**: 650-700 ºC
  - High Cr F-M steels with Si and Al additions
  - Al-Fe-Surface coated steels
  - Refractory metals
  - Ceramics
## Results of previous corrosion tests

Flowing fluid: Pb-Bi eutectic (LBE)
Temperature: 550°C
Velocity: 1 or 2 m/s
Exposure time: 1,000 or 2,000 hrs
Oxygen concentration: 10^{-8}-10^{-6} (wt%)  

<table>
<thead>
<tr>
<th>Steels</th>
<th>Materials</th>
<th>Compatibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Austenitic steels</td>
<td>SS316, SS316FR</td>
<td>poor</td>
</tr>
<tr>
<td>12Cr steels</td>
<td>HCM12A, etc.</td>
<td>good</td>
</tr>
<tr>
<td>10-18Cr steels with Si and Al addition</td>
<td>SUH3, NTK04L, Recloy10, SUS430</td>
<td>excellent</td>
</tr>
<tr>
<td>Al-alloyed surface (GESA)</td>
<td>ODS</td>
<td>locally good</td>
</tr>
<tr>
<td>Refractory metals</td>
<td>W, Mo</td>
<td>excellent</td>
</tr>
<tr>
<td>Ceramics</td>
<td>SiC, Si₃N₄</td>
<td>excellent</td>
</tr>
</tbody>
</table>
Purpose

To investigate the compatibility of materials in stirred LBE at 700 °C

- Steels: High Cr steels, Al-Fe-coated ones
- Ceramics: SiC, Ti$_3$SiC$_2$, SiC/SiC composites
- Refractory metals: W, Mo, Nb
Test apparatus

- Ar + H₂
- Ar
- Moisture
- Steam Generator
- Injection Nozzle
- Exhaust Nozzle
- Electrometer
- Digital Controller
- Specimens
- Atmosphere

Ar + H₂ gas enters and passes through valves V1, V2, V3, V4, V5, V6, V7, V8, and V10 before reaching the test apparatus. The gas then passes through the moisture generator, the steam generator, and the injection nozzle before entering the exhaust nozzle. The test apparatus includes an electrometer and a digital controller.
Corrosion test section

- Specimens
- Thermocouple Alumina Crucible
- Oxygen Sensor
- Mo Wire
- Injection Nozzle
- Ceramic
- LBE
- 340 mm
- 100 mm
- 72 mm
- Specimens
### Experimental conditions

<table>
<thead>
<tr>
<th>Run</th>
<th>No. 1</th>
<th>No. 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials</td>
<td>STBA26, SiC/SiC composites</td>
<td>NTK04L, SUS316FR Recloy10, SUS430, Al-Fe-coated steel, W, Mo, Nb, SiC, Ti$_3$SiC$_2$</td>
</tr>
<tr>
<td>Oxygen concentration (wt%)</td>
<td>$\sim 6.8 \times 10^{-7}$</td>
<td>$\sim 5 \times 10^{-6}$</td>
</tr>
<tr>
<td>Injection Gas</td>
<td>Ar</td>
<td>Ar+H$_2$ (3%) and Ar</td>
</tr>
<tr>
<td>Type of Sensor</td>
<td></td>
<td>Y$_2$O$_3$-ZrO$_2$</td>
</tr>
<tr>
<td>Temperature of LBE (°C)</td>
<td></td>
<td>700</td>
</tr>
<tr>
<td>Immersion time (hr)</td>
<td></td>
<td>1,000</td>
</tr>
</tbody>
</table>
Unbalanced Magnetron Sputtering (UBMS)

Al-Fe coating
(thickness: 21.45µm)
Unbalanced Magnetron Sputtering (UBMS)
Oxygen concentration

\[
\Delta G^\circ, \Delta G_{ox}, (1/2)RT \ln P_{O_2}
\]

Temperature \( ^\circ C \)

\[
\text{Oxygen potentials of oxides} \quad \Delta G^\circ
\]

\[
\text{Oxygen potential in Pb-Bi} \quad \Delta G_{ox}
\]

\[
\text{Oxygen potential in injected gas (1/2)RT \ln P}_{O_2}
\]

\[
5 \times 10^{-6} \text{ wt}\% \\
6.8 \times 10^{-7} \text{ wt}\%
\]
High Cr Steels (NTK04L, STBA26, SUS316FR)

$CO_2 = 5 \times 10^{-6}$ wt.% (NTK04L, SUS316FR)

$CO_2 = 6.8 \times 10^{-7}$ wt.% (STBA26) 700ºC
High Cr Steels (Recloy10 17.7Cr-1Si-0.9Al)

\[ CO_2 = 5 \times 10^{-6} \text{ wt\%}, \ 700^\circ \text{C} \]
High Cr Steels (SUS430 18Cr-0.75Si)

$C_{O_2} = 5 \times 10^{-6}$ wt\%, 700°C
Al-Fe-coated (STBA26)

$C_{O_2} = 6.8 \times 10^{-7}$ wt.%, 700ºC
1000 hours, $C_{O_2} = 5 \times 10^{-6}$ wt.% (SiC, Ti$_3$SiC$_2$)

$C_{O_2} = 6.8 \times 10^{-7}$ wt.% (SiC/SiC composite), 700°C
Weight Change of Ceramics

- SiC
- Ti3SiC2
- SiC/SiC Composite

Weight loss (g/m²)

Specimens
Result - Refractory Metals

$C_{O_2} = 5 \times 10^{-6} \text{ wt.\%}, 700^\circ C$
Weight Change of Refractory Metals

![Graph showing weight loss (g/m²) for different specimens: W, Mo, Nb.Nb specimen shows a significant weight loss compared to W and Mo.]
Conclusions

1. **Al-Fe-coated steel, W, Mo, SiC and Ti$_3$SiC$_2$** exhibited good corrosion-resistance in LBE at 700 ºC.

2. **Nb** exhibited poor corrosion-resistance in LBE at 700 ºC.

3. **SiC/SiC composite** showed that LBE penetrated into the matrix due to high porosity of the material, and a thin crack layer appeared in LBE at 700 ºC.