Microchannel Heat Exchangers Based on Alloy 230 - Exposure Characteristics and Mechanical Behavior

FWP 1022406 - Advanced Alloy Development
Period of performance: 10/1/2016 - 9/30/2017

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Project Goals and Objectives

• Accelerating commercialization of supercritical carbon dioxide power cycle technology by addressing materials and manufacturing challenges for components of sCO₂ power systems.
  • Joining of similar and dissimilar power plant alloys
  • Performance of joints in sCO₂ power cycle environments

• Milestones
  • Demonstrate mechanical and environmental performance of joints in supercritical CO₂ - 09/30/2017

• Deliverables
  • Technical report (either presentation or publication) on the high temperature corrosion of the joined power plant materials. - 09/30/2017
  • Technical report (either presentation or publication) on the cross-joint strength of typical power plant materials. - 09/30/2017
• Supercritical CO₂ power cycles and compact heat exchangers
• Materials issues in manufacturing compact heat exchangers
  • Diffusion bonding (DB)
  • Transient liquid phase bonding (TLPB)
• Mechanical strength of bonded structures
• High-temperature corrosion of bonds in sCO₂
Supercritical CO₂ Power Cycles

Indirect sCO₂ Cycle

Direct sCO₂ Cycle

<table>
<thead>
<tr>
<th>Cycle/Component</th>
<th>Inlet</th>
<th></th>
<th></th>
<th>Outlet</th>
<th></th>
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<tbody>
<tr>
<td></td>
<td>T (C)</td>
<td>P (MPa)</td>
<td></td>
<td>T (C)</td>
<td>P (MPa)</td>
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<tr>
<td>Indirect</td>
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<td></td>
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<tr>
<td>Heater</td>
<td>450-535</td>
<td>1-10</td>
<td></td>
<td>650-750</td>
<td>1-10</td>
<td></td>
</tr>
<tr>
<td>Turbine</td>
<td>650-750</td>
<td>20-30</td>
<td></td>
<td>550-650</td>
<td>8-10</td>
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</tr>
<tr>
<td>HX</td>
<td>550-650</td>
<td>8-10</td>
<td></td>
<td>100-200</td>
<td>8-10</td>
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</tr>
<tr>
<td>Direct</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combustor</td>
<td>750</td>
<td>20-30</td>
<td></td>
<td>1150</td>
<td>20-30</td>
<td></td>
</tr>
<tr>
<td>Turbine</td>
<td>1150</td>
<td>20-30</td>
<td></td>
<td>800</td>
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<tr>
<td>HX</td>
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<td>3-8</td>
<td></td>
<td>100</td>
<td>3-8</td>
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</tr>
</tbody>
</table>

Essentially pure CO₂

CO₂ with combustion products including O₂, H₂O and SO₂
Compact Heat Exchangers for sCO₂ Cycles

- Higher efficiency
  - Due to much shorter heat diffusion lengths in fluid
- Smaller size
  - Use of less materials (expensive superalloys)
  - Takes less space
- Modular design
  - Expandable to large power plants
Heat Exchangers

Microchannel heat exchangers

- Higher heat transfer efficiency due to shorter heat diffusion lengths
- Smaller size
- Modular Design

- Pattern microscale flow paths
- Join these using laser welding, diffusion bonding or brazing

- Dimensional Tolerances
  - Pressure & Temperature Drop
- Uniform microstructure
  - Environmental Resistance

Diffusion bonding, brazing, and transient-liquid-phase (TLP) bonding are the most robust approaches for sCO₂ cycles

Schematic of diffusion bonding process

- Solid state process
- Applied high pressure at high temperature
- Void closure due to diffusion of constituent atoms and creep processes by application of high pressure

Transient-Liquid-Phase Bonding

Ni-P plating acts as a low-melting interlayer

- Both solid state and liquid state reactions
- Less pressure than diffusion bonding
- Lower melting point interlayer
- Isothermal melting and solidification of interlayer
Output of Bonding - stacks

• Downselect between H230 & H282
• H230 – NiCrW solid solution strengthened alloy
• H282 – Gamma prime strengthened alloy
• H230 was selected and challenges with H282 will be discussed later

Cold rolled and 1232 °C solution annealed - 550 µm H230 shims
Stacked onto a fixture
Pressed at 1150°C, 12.7MPa in vacu

Tensile Samples

Stacks
Diffusion Bonding of Alloy H230

Microstructure

Etched microstructure to observe grain growth through the bond line

Grain growth

Mechanical Behavior

Ductile fracture along the precipitate bands.
TLP Bonding of Alloy H230

Grain growth across the bond

No nanoscale phase near the bondline

- Cr important for oxidation resistance - Slight reduction in Cr near the bondline
- P should be as low as possible to avoid formation of brittle phases - P is ~0.2 wt. % near the bondline

M. Kapoor, Mat. & Met. Trans. A, 2017
Yield strength of TLP stacks is ~86% of bulk H230

Tensile samples from H230 stacks

Ductile fracture through the ISZ

Plastic strain is constrained in the ISZ
High temperature mechanical properties

Low cycle fatigue properties @ 760°C

Creep properties

Low cycle fatigue properties @ 760°C

Bulk H230 760°C

Cycles to Failure

Total Strain Range (%)
Challenges in bonding of H282

Ni-12P coating on the metal for TLP bonding

Coating does not adhere to the metal

Bondline after TLP bonding

EDS maps in the vicinity of the bondline

Intermetallic formation

Fracture Surface

Challenges with TLP bonding of H282 – Surface oxides & Intermetallic Formation
Shrinkage Pores in TLP Bonding

Pores in the vicinity of the bondline with a lamellar structure.

Scheil calculation with 0.20 wt. % P

Liquid + FCC

Liquid + FCC + M3P

Responsible for lamellar microstructure
High-Temperature Oxidation of Bonded Regions in CO₂

1 bar CO₂ Exposures
- Gas: 1 bar CO₂ (99.999% purity)
- O₂ level in furnace tube: <12 ppm
- Gas flow rate: 0.032 kg/h
- Temperature: 700°C
- Duration: 4000 h in 500 h increments
- 24 h purging with CO₂ before heating

250 bar CO₂ Exposure
- Gas: CO₂ (99.999% purity)
- Flow rate: 2 ml/min
- Temperature: 720°C
- Duration: 1500 h in 500 h incr.
- Argon purging before heating

Characterization
Mass Change
XRD
SEM
Oxidation in sCO$_2$ (720°C - 250 bar)

H282 continues to have mass gain up to 1500 hrs BUT H230 mass gain tapers off after 500 hrs
Atmospheric CO\(_2\) Exposure

Fastest oxidation rate within first 500 hrs, then slower, but steady continued oxidation

- **H282**
  - Surface is predominantly Cr\(_2\)O\(_3\), with some M\(_3\)O\(_4\) phase appearing at longer exposure times

- **H230**
  - Surface is primarily Cr\(_2\)O\(_3\), with a smaller portion of M\(_3\)O\(_4\) phase

**Glancing angle XRD**
Bonded alloys exposed to 700 °C aCO₂

500 h exposure time

1500 h exposure time

- Thin, protective Cr-rich oxide layers are formed for H230 and H282 during exposure to 700 °C aCO₂.
- Internal oxidation of Al leads to a sub-surface layer depleted of γ’ phase in H282.
- No difference in oxidation resistance is observed near/far from the bond layer for either alloy.
Bonded alloys exposed to 720 °C sCO₂

500 h exposure time

Similar results as H230 and H282 bonded samples exposed to 700 °C aCO₂:

- Thin Cr-rich oxide layers.
- Internal oxidation of Al leads to a subsurface layer depleted of γ' phase in H282.
- No difference in oxidation resistance observed near/far from the bond layer.

One difference is that sCO₂ exposures show a 2-layer oxide structure containing some Mn (H230) or Ti (H282) in addition to Cr. This is the subject of ongoing investigation.
Performance of welded alloys in sCO₂

• Similar and dissimilar metal welds (1 inch thick plates) were done with gas tungsten arc welding (GTAW) and post weld heat treated at Edison Welding Institute.
  • P22 – P22,
  • P91 – P91,
  • 347H – 347H,
  • Alloy 625 – Alloy 625,
  • Alloy 263 – Alloy 263,
  • P22 – P91,
  • P91 – 347H,
  • P22 – Alloy 263,
  • Alloy 625 – Alloy 263,
  • 347H – Alloy 263

• Changes in microstructure (Heat affected zone – HAZ) due to welding were characterized using optical microscopy and hardness testing

• sCO₂ exposures of weld samples will be performed
  • Corrosion performance
  • Mechanical performance
Summary

1) Uniform bond with grain growth across the bondline

2) Ni increase, Cr dip through the bond

3) TLP-bonded H230 with ~ 86% strength of bulk @ 760°

4) Ductile fracture through the bond, plastic strain constrained in the bond region

5) Similar oxidation behavior between the bond region and base metal