Additively Manufactured Graded Composite Transition Joints (AM-GCTJ) for Dissimilar Metal Weldments in Advanced Ultra-Supercritical Power Plant

Xingbo Liu\textsuperscript{1}, Kostas Sierros\textsuperscript{1}, Zhili Feng\textsuperscript{2}, Yanli Wang\textsuperscript{2}, David Novotnak\textsuperscript{3}, Ron Alman\textsuperscript{3}, Haiyang Qian\textsuperscript{4}, Ray Chamberland\textsuperscript{4}

\textsuperscript{1}West Virginia University; \textsuperscript{2}Oak Ridge National Laboratory
\textsuperscript{3}Carpenter Additive; \textsuperscript{4}GE Steam Power.

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DMWs in A-USC and HRSG

AUSC power plant - boiler and turbine schematic

Potential Material Selections

Main Steam Piping
345 bar/625-735°C
HR6W/740H

SHO Header
345 bar/625-735°C
HR6W/740H

SH/RH Tubes
345 bar/625-735°C, 74 bar/633-763 °C
SS/Sanicro 25/HR6W/740H/H282

Membrane wall
365 bar/500-560°C
T23/T24/T92/T93

Evaporator
Eco

ST Inlet conditions: 330 bar/620 to 730°C/630 to 760°C

RHO Header
74 bar/633-763°C
HR6W/740H

HRH piping
74 bar/673-763°C
HR6W/740H

IP ST Inlet
70 bar/670-760°C
H282/MarBN/A617(F)/A625(C)

HP ST Inlet
330 bar/620-730°C
H282/MarBN/A617(F)/A625(C)

740H, H282, HR6W & A617/A625 for boiler outlet headers, piping and ST inlet are the material enablers

DMW:
1. Grade 91 – Austenitic Stainless Steel
2. Ni based alloy – Austenitic Stainless Steel

GE Steam: A-USC Mock Header
Mismatch of coefficient of thermal expansion and thermal cycling:

DMW with sharp material transition

Higher cycling requirements in power industry:

- Steam Boilers: A sample required number of cycles for a new unit
  
<table>
<thead>
<tr>
<th></th>
<th>Total # of cycles of 25 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold Start</td>
<td>455</td>
</tr>
<tr>
<td>Warm Start</td>
<td>910</td>
</tr>
<tr>
<td>Hot Start</td>
<td>4550</td>
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</tbody>
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- HRSGs: Typical required number of cycles for a cyclic operating CCPP
  
<table>
<thead>
<tr>
<th></th>
<th>Total # of cycles of 25 years</th>
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</thead>
<tbody>
<tr>
<td>Cold Start</td>
<td>250</td>
</tr>
<tr>
<td>Warm Start</td>
<td>1250</td>
</tr>
<tr>
<td>Hot Start</td>
<td>4250</td>
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Mismatch of coefficient of thermal expansion between different materials lead to high strain range along the interface during thermal transients.

Increasing demand in industry for flexible operation of steam boilers and more cycling capability of HRSGs.
Failures in DMWs at the fusion boundary between Grade 91 and nickel based filler metal, often accompanied with considerable damages in the HAZ of Grade 91

HT exposure during PWHT or service causes carbon diffusion from the ferritic matrix toward the austenitic matrix. Leads to the formation of a carbon-depleted soft zone on the ferritic side and nucleation/growth of carbides on the ASS side that have very high hardness.

Under imposed residual, external, and thermal stresses caused by the CTE mismatch between different alloys of the DMW, creep and/or creep fatigue cracks can occur along the fusion boundary and HAZ.
“Conventional” melting based AM

Grade 91 0.08C-9Cr-1Mo-0.4Ni

0.08C-14Cr-4Ni-0.5Mo: microstructure?

SS304 0.08C-18Cr-8Ni

“Conventional” AM (wire or powder) approach melts alloys A&B completely together

- A critical issue is the continuous transition in composition creates complex and often undesired microstructure

From: DuPont, Babu, Feng, 2018
Advantages of AM-GCTJ

• Solid-state Process, composites material” transition with constituents of known chemistry (such as P91, SS304, A182) mixed in controlled proportion
  • Solved the critical drawbacks of undesired/unpredictable phases/microstructure in conventional AM approach to fabricate the transition joint
• 100% smooth transitions
• Welding happens at A-A, and B-B, no DMWs
• Minimize scale-up issues expected to manufacture large quantity of joints

PROJECT OBJECTIVES – PHASE I

(1) To develop and demonstrate at the lab-scale the additively manufactured graded composite transition joints (AM-GCTJ) for dissimilar metal weldments (DMW) in next generation advanced ultra-supercritical (A-USC) coal-fired power plants, that can significantly improve the microstructural stability, creep and thermal-mechanical fatigue resistance, as compared with their conventional counterparts;

(2) To prepare for Phase II of the project, in which we will manufacture and test the components with AM-GCTJ, to advance the technology readiness level to TRL-7, and manufacturing readiness level to MRL 6-7, for targeted commercial applications identified by GE Steam Power, the primary industry partner of the project team.
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Fabricated 2 types of welds using either SS309 or A182 weld wire
Temperature - 650 °C  
Time – 30 days  
Coal Ash - 10% Na$_2$SO$_4$, 10% K$_2$SO$_4$, 10% Fe$_2$O$_3$, 35% Al$_2$O$_3$, and 35% SiO$_2$  
Gas - 1 vol. % SO$_2$, 4 vol. % O$_2$, 15 vol. % CO$_2$ & 80 vol. % N$_2$
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Gas - 1 vol. % SO$_2$, 4 vol. % O$_2$, 15 vol. % CO$_2$ & 80 vol. % N$_2$
• Designed AM-GCTJ to significantly reduce the strain accumulation at critical locations during thermal cyclic loading
• It will also significantly improve the creep failure life – predicted failure will be shifted to Grade 91 base metal
ICWE Prediction of Creep Strain Accumulation and Rupture Life at 650 °C and 90 MPa

Predicted life of conventional DMW: 230 hrs, failure at the weld interface in the G91 HAZ

The predicted failure is in G91 base metal. Predicted rupture life is 1815 hours
Actual Creep Test – DMW vs Transition Joint (650 °C and 90 MPa)

Failed at 214 hrs in the G91 HAZ near the interface

Minimal strain localization on the transition joint at 200 hrs. Failed after 1259 hrs near the G91 base metal. Over 5.8x improvement of creep life
DIC Measurement of Creep Strain Evolution and Localization

Convention al DMW

AM-GCTJ
Grade 91-304H Transition Joint (650°C-90MPa)

T = 479 hrs

Total lifetime: 1259 hrs

<table>
<thead>
<tr>
<th>650°C, 90MPa</th>
<th>Conventional DM</th>
<th>AM-GCTJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model Prediction</td>
<td>230 hrs, at G91 interface</td>
<td>1815 hrs, in G91 base metal (near interface)</td>
</tr>
<tr>
<td>Actual Test</td>
<td>214 hrs, at G91 interface</td>
<td>1259 hrs, near G91/Transition Joint interface</td>
</tr>
</tbody>
</table>
Model Captured Essential Features of Strain Distributions in Thermal Cyclic Loading (25-650°C, 2-2-2 h)

Conventional DMW

Model prediction

DIC measurement

AM-GCTJ

Model prediction

DIC measurement
Experimental Measurement of Strain Evolution during Thermal Cyclic Test (On-going)

• Initial observations from in-situ DIC measurement:
  – Considerable reduction of thermal cyclic strain range with AM-GCTJ

AM-GCTJ: averaged over the transition region
Conventional DMW: averaged over P91/SS304 interface region
Pipe: Conventional DMW vs AM-GCTJ

- Conventional weld

E, Max. Principal (Avg: 75%)

-7.407e-02
+6.500e-02
+5.958e-02
+5.417e-02
+4.875e-02
+4.333e-02
+3.792e-02
+3.250e-02
+2.708e-02
+2.167e-02
+1.625e-02
+1.083e-02
+5.417e-03
+0.000e+00

- Transition joint

E, Max. Principal (Avg: 75%)

-7.000e-02
+6.417e-02
+5.833e-02
+5.250e-02
+4.667e-02
+4.083e-02
+3.500e-02
+2.917e-02
+2.333e-02
+1.750e-02
+1.167e-02
+5.833e-03
+0.000e+00

Results after 40 thermal cycles
We designed and fabricated a new class of AM-GCTJ

- Avoid unknown & often undesired complex composition in the conventional AM-GTJ
- Shows similar corrosion performance in coal ash as conventional DMW
- Reduce the maximum strain & strain range, and (can) improve thermal mechanical fatigue life of DMW during cyclic operation of thermal-electric power plants
- Significantly improve creep properties, as compared with convention DMW

AM-GCTJ has broad applications in various energy systems, AUSC, Gas, CSP, NE, etc.
Phase II Plan

- Further optimize design and manufacturing
- Move up both TRL & MRL
- Detailed TEA
- Start code case
- Be ready for commercial applications
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