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DOE Advanced Methods of Manufacturing Workshop
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Innovative Manufacturing Process for Nuclear Power Plant Components via PM-HIP

Objective: Conduct design, manufacturing, and validation studies to assess PM-HIP as a method to produce both large, near-net shaped components for nuclear applications across 3 families of alloys:

1. low alloy steels
2. austenitic stainless steels
3. nickel-based alloys
Four Years Ago
at Start of DOE Project…

- No Experience in Power Industry with PM-HIP

- Good industry experience in Aerospace, Aircraft, and Off-Shore Oil & Gas:
  - However, Power Industry had/has a lot to learn….

- Began work on 316L SS and Grade 91 (toward Code Acceptance)
Since 2012….

- Four ASME Code Cases—316L SS, Grade 91, Duplex SS
- Currently working to recognize A988 (austenitics), A989 (ferritics), & B834 (nickel-base) into ASME Section II.
- Developed Detailed EPRI Roadmaps for PM-HIP
- Developed New Co-free Hardfacing Alloy—NitroMaxx
- Began research/Code acceptance to recognize A508
- Crack growth and SCC testing to support NRC recognition of 316L SS
Since 2012….

- Research at NSUF (ATR) on radiation embrittlement for multiple PM-HIP alloys—2016
- Valve and hardfacing project with EDF and Velan--2016
- ORNL/EPRI project on “Can Fabrication”
- Initiated development of ATLAS Consortium
- Continue to strive to meet Goals established by AMM Roadmap targeting Heavy Section Manufacturing
Powder Metallurgy Methods for Large Nuclear & Fossil Components

- Project Objectives
- Why Consider Powder Metallurgy for Large or Complex Nuclear Components?
- Review 7 Project Tasks & Descriptions
  - 4 major components
- Defining Success
- The Bigger Picture…
Why Consider PM-HIP for Large ALWR, SMR, or Gen IV Components?

Powder Metallurgy and Hot Isostatic Processing

– Near-net shaped (NNS) production of complex and/or large components (minimizes both machining and material volume required)
– Excellent INSPECTION characteristics
– Eliminates casting quality issues & rework
– Precise chemistry control
– Alternate supply route
– Hard-facing applications
Today's Powder Metallurgy & Hot Isostatic Pressing (HIP)

1. Gas Atomized Metal Powders

2. Mold of Component in Can

3. Hot Isostatic Pressing Apply High Pressure (>15,000psi), Temperature (>2000F)

4. Final Component
The Key Difference……..

Why is Gas Atomization Important?

- No milled powders used today
- Eliminates oxides in powders & porosity in final product
- Improved packing density

(courtesy of Carpenter Technology)
Comparison of Additive Manufacturing (AM) and Powder Metallurgy-Hot Isostatic Pressing (HIP)

Additive Manufacturing (or 3-D Printing)
- Complex or small parts: <100 lbs
- Working envelope of ~40x40x40cm (16x16x16inch)
- Just-in-time manufacturing
- Replacement of obsolete parts
- Repeatability
- Availability schedule
- Material property enhancements
- Gradient materials (corrosion, strength, cost)

Powder Metallurgy-HIP
- Near-net shaped complex or large components (internals and valves/pumps)
- Parts up to ~60 inches (150cm) in diameter
- Improved inspection
- Alternate supply route
- Eliminates casting quality issues/repairs
- Hardfacing applications
DOE Project Tasks

1. Modeling of NNS Component Alloy & Mold/Can Design
2. Test Coupon Development, Demonstration, & Screening for Surfacing Applications
3. Low Alloy Steel PM/HIP Component Development
4. Nickel-based Alloy PM/HIP Component Development
5. Austenitic Stainless Steel PM/HIP Development
6. Mechanical & Metallographic Characterization
7. Corrosion Testing of Test Coupons
Task 5--Austenitic Stainless Steel PM/HIP Development

Lead Organization: GE-Hitachi

Steam Separator Inlet Swirler (Austenitic Stainless Steel)

- Manufacture of a complex geometry to demonstrate PM/HIP for 316L SS
- SMR, ALWR, GEN IV applications
- Produce a NNS Inlet Swirl via PM/HIP
  - Evaluate dimensionally, metallurgically, and mechanically
  - Corrosion assessment is Task 7

GEH → Validation of 316L PM capabilities
BWR or ALWR Steam Separator Inlet Swirl
Inlet Swirler Design & Manufacture
--Modeling
Inlet Swirler Design & Manufacture
--Fit up
Inlet Swirler Can Design & Manufacture
Inlet Swirler Manufacture
Inlet Swirl Block—Mechanical Properties

- **Tensile Properties @ RT**
  - UTS = 88.2 ksi (608 MPa)
  - YS = 49.8 ksi (343 MPa)
  - Elongation = 50.3%
  - ROA = 73.3%

- **Toughness** (Charpy Impact)
  - 173 ft-lbs (235 J) avg across 3 directions

- **Hardness**
  - 87.0 RHB

- **Porosity** – 99.9%
- **Density** – 7.959 g/cm³
- **Grain Size** – ASTM 7.0

<table>
<thead>
<tr>
<th>Material</th>
<th>C</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Si</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>Cu</th>
<th>O</th>
<th>Fe</th>
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<tbody>
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<td>1.5 max</td>
<td>0.040 max</td>
<td>0.040 max</td>
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<td>9-13.0</td>
<td>2-3.0</td>
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<td>Bal</td>
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<td>Block--Inlet Swirl</td>
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<td>1.73</td>
<td>0.023</td>
<td>0.007</td>
<td>0.49</td>
<td>17.67</td>
<td>12.34</td>
<td>2.49</td>
<td>0.04</td>
<td>0.02</td>
<td>Bal</td>
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</table>

Meets GEH 316L wrought/cast requirements
Fatigue Data—316L SS

Measured 316LSS LCF data compared with ASME and NUREG-5704 data.

NUREG-5704: Effects of LWR Coolant Environments on Fatigue Design
Curves of Austenitic Stainless Steels
Corrosion Testing
--SCC Crack Growth Rates

- Tested as-received, 20% cold worked, and HAZ conditions
- Under BWR and PWR Conditions

- Results: PM-HIP coupons produced similar Crack Growth Rates to Wrought 316L SS

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Specimen</th>
<th>K, MPa·m</th>
<th>High ECP *</th>
<th>Low ECP *</th>
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<td>Wrought 316L</td>
<td>---</td>
<td>~40</td>
<td>(»3 x 10^-9)</td>
<td>(»2 x 10^-9)</td>
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<tr>
<td>PM 316L</td>
<td>C720</td>
<td>~49</td>
<td>~9 x 10^-8</td>
<td>~3 x 10^-9</td>
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<tr>
<td>PM 316L</td>
<td>C725</td>
<td>~32</td>
<td>~7 x 10^-8</td>
<td>~2 x 10^-9</td>
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<td>Wrought 316L</td>
<td>C126</td>
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<td>~2 x 10^-7</td>
<td>~2 x 10^-8</td>
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<tr>
<td>PM 316L</td>
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<td>~3 x 10^-7</td>
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<tr>
<td>PM 316L</td>
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<tr>
<td>Wrought 348</td>
<td>C111</td>
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<td>~2.5 x 10^-7</td>
<td>~5 x 10^-9</td>
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<tr>
<td>PM 316L</td>
<td>C724</td>
<td>28</td>
<td>~5 x 10^-8</td>
<td>~2 x 10^-9</td>
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<tr>
<td>Wrought 600</td>
<td>---</td>
<td>---</td>
<td>(»3 x 10^-8)</td>
<td>(»2 x 10^-9)</td>
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<td>~33</td>
<td>~1.3 x 10^-7</td>
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Task 4--Nickel-based Alloy (600M) PM/HIP Component Development

Lead Organization: GE-Hitachi

Chimney Head Bolt (Ni-based Alloy)

- Using PM/HIP, manufacture NNS bolt from Alloy 600M.
- Normally forged, then welded.
- Perform dimensional, microstructural, and mechanical characterization
Chimney Head Bolt

Note: Mild steel can is still attached.

Huge savings in machining and materials costs
Chimney Head Test Block—Mechanical Properties

- **Tensile Properties @ RT**
  - UTS = 102.5 ksi (706 MPa)
  - YS = 46.2 ksi (318 MPa)
  - Elongation = 45.7%
  - ROA = 68.2%

- **Toughness** (Charpy Impact)
  - 144 ft-lbs (195 J) ave, 3 directions

- **Hardness**
  - 84.3 (HRB) ave

Porosity – 99.7%
Density – 8.469 g/cm³
Grain Size – ASTM 8.5

<table>
<thead>
<tr>
<th>Material</th>
<th>C</th>
<th>Mn</th>
<th>S</th>
<th>Si</th>
<th>Cr</th>
<th>Ni</th>
<th>Cu</th>
<th>Fe</th>
<th>Cb</th>
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<tr>
<td>600-ASTM A351</td>
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<td>1.00 max</td>
<td>0.015 max</td>
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<td>14.0-17.0</td>
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<td>1.00 max</td>
<td>0.015 max</td>
<td>0.50 max</td>
<td>14.0-17.0</td>
<td>72 min</td>
<td>0.50 max</td>
<td>6.0-10.0</td>
<td><strong>1.0-3.0</strong></td>
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<tr>
<td>Block – C Head Bolt</td>
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<td>&lt;0.01</td>
<td>0.001</td>
<td>0.05</td>
<td>15.96</td>
<td>Bal</td>
<td>0.02</td>
<td>8.73</td>
<td>1.31</td>
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Task 3--Low Alloy Steel PM/HIP Component Development

Lead Organization: EPRI

Reactor Pressure Vessel Steels (Low Alloy Steel)

- Demonstrate feasibility of PM/HIP to produce low alloy steel RPV sections (8 x 8 x 24” coupons) – SA508 Class 1, Grade 3 steels
- Perform mechanical & microstructural characterization
- Manufacture a NNS RPV nozzle
- Manufacture a large RPV section
Task 3. Status -- Nozzle

- Manufactured three 8” x 8” x 24” test blocks with different CE’s
- Performed tensile, hardness, Charpy, microstructural characterization

<table>
<thead>
<tr>
<th>Table 1. Low Alloy Steel &quot;Actual&quot; Chemistries and Calculated Hardnability Values.</th>
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<tbody>
<tr>
<td></td>
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<tr>
<td>A 508 Cl 3 Min</td>
</tr>
<tr>
<td>A 508 Cl 3 Max</td>
</tr>
<tr>
<td>Carpenter 160114</td>
</tr>
<tr>
<td>Carpenter 160115</td>
</tr>
<tr>
<td>Carpenter 160116</td>
</tr>
</tbody>
</table>

*C$_{eq}$ = C + Mn/6 + Si/24 + Ni/40 + Cr/5 + Mo/4
Task 3. Status – Test Block Properties

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Tempering Time (h)</th>
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<tbody>
<tr>
<td>1175 °F</td>
<td>4 10 20</td>
</tr>
<tr>
<td>1200</td>
<td>4 10 20</td>
</tr>
<tr>
<td>1225</td>
<td>4 10 20</td>
</tr>
</tbody>
</table>

- Low – CE = 0.55 → 160116
- Med – CE = 0.62 → 160114
- High – CE = 0.69 → 160115

<table>
<thead>
<tr>
<th>Heat</th>
<th>O</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>160114</td>
<td>0.024</td>
<td>0.022</td>
</tr>
<tr>
<td>160115</td>
<td>0.022</td>
<td>0.018</td>
</tr>
<tr>
<td>160116</td>
<td>0.018</td>
<td>0.020</td>
</tr>
</tbody>
</table>

Grade: SA508
Task 3. Status – Test Block Properties

- UTS ranged from 85-110 ksi (586-758 MPa)
- YS ranged 67-92 ksi (462-634 MPa)

UTS spec = 85-105 ksi
YS spec = >50 ksi
Task 3. Status – Test Block Properties

- Elongation: 22-30%
- ROA 67-77%

Spec Elongation = 18% min
Spec ROA = 38% min
Charpy Impact Data for the Low Hardenability Test Block

Solution Annealed at 2050F/10hrs, quenched, normalized 1650F and tempered at 1200F/10 hrs
A 508, Class 1, Grade 3 Nozzle

- Manufactured a NNS 16” BWR Feedwater Nozzle
  - 3700 lbs
  - 36 inches vessel diameter x 16 inches pipe diameter
A 508, Class 1, Grade 3 Ring Section
Defining Success….

Success in this project was defined as:

1. Manufacture of 4 large components from low alloy steel, stainless steel, and a Ni-based alloy (3 different alloy families)
   - Nozzle, curved RPV section, steam separator inlet swirl, chimney held bolt.
   - Establish design criteria, shrinkage & NNS quality
2. Generate excellent mechanical properties, along with good product chemistry & uniform grain size
3. Application of wear resistant surfacing material to a substrate alloy
4. Corrosion performance comparable to forgings
Summary

PM-HIP for Structural & Pressure Retaining Applications:

– Large, complex, near-net-shape components
– Alternate supply route for long-lead time components
– Improves inspectability
– Eliminates rework or repair in castings
– Hardfacing applications
The Team....

- Lou Lherbier & Dave Novotnak (Carpenter Powder Products)
- Myles Connor, James Robinson, Ron Horn (GE-Hitachi)
- Steve Lawler and Ian Armson (Rolls-Royce)
- Will Kyffin (N-AMRC)
- Dave Sandusky (X-Gen)
- Ben Sutton, Dan Purdy, Alex Summe (EPRI)
Together…Shaping the Future of Electricity