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DOE Advanced Methods of Manufacturing Workshop
September 29, 2015
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
Three 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….

- Three ASME Code Cases—316L SS and Grade 91
- Developed Detailed EPRI Roadmaps for PM-HIP
- Developed New Co-free Hardfacing Alloy--NitroMaxx
- Initiated R&D aimed at Eliminating DMWs—Phase 2
- Began research/Code acceptance to recognize several other alloys:
  - 304L, 625, 690, 718, and SA508
  - ASTM and ASME
  - Aimed at SMRs and ALWRs
- 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—starts in 2016
- Valve and hardfacing project with EDF and Velan (2016)
- ORNL/EPRI project on “Can Fabrication”
- 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 Intricate Nuclear Components?
- Optimize an Alloy for Nuclear Performance
- Review 7 Project Tasks & Descriptions
  - Highlight 2 Components Manufactured
- Defining Success
- EPRI Roadmap on PM-HIP
- The Bigger Picture...
Why Consider Powder Metallurgy-HIP To Produce Pressure Components?

- Industry leadership in the manufacture of large NPP components (Gen III & SMRs)
  - eg., RPVs, SG, valves, pumps, turbine rotors
- Transformational technology
  - Moves from forging and rolled & welded technologies to powder met/HIP
- Enables manufacture of large, complex “Near-Net Shape” components
- Excellent Inspection characteristics
- Eliminates casting quality issues
- Alternate supply route for long-lead time components

P/M-HIP Valve
Optimize An Alloy for Nuclear Performance

**Valve/Pump Housing/Flange**
- Tensile/Yield Strength
- Adequate Ductility & Toughness
- Weldability (optional)
- Corrosion Performance

**RPV Internals**
- Tensile/Yield Strength
- High Ductility & Toughness
- Weldability
- Corrosion Performance
- Fatigue Resistance
- Radiation Resistance
- Good Inspection Characteristics

- Near-Net Shape Capabilities
- Alternate Supply Route for Long-Lead Time Components
Powder Metallurgy-Hot Isostatic Processing

<table>
<thead>
<tr>
<th>Powder Making</th>
<th>HIP Capsule Fabrication</th>
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<tbody>
<tr>
<td>Atomisation</td>
<td>Cut and Shape Sheet Metal</td>
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<tr>
<td></td>
<td>Weld</td>
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<tr>
<td>Sieve</td>
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<tr>
<td>Blend</td>
<td>Leak Test</td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Capsule Fill</td>
</tr>
<tr>
<td></td>
<td>Bake Out</td>
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<td>Seal</td>
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<td>HIP</td>
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</tbody>
</table>

(courtesy of Carpenter Technology)

Courtesy of Steve Mashl, Z-Met Corporation
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 and ALWR 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 Swirl
-- 3D Geometry

Vane Insert—one of 8 that fit into the swirler
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

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<table>
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<tr>
<th></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>
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<td>0.040</td>
<td>0.040</td>
<td>1.5 max</td>
<td>17-21.0</td>
<td>9-13.0</td>
<td>2-3.0</td>
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<td>NA</td>
<td>Bal</td>
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<td>0.006</td>
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<td>17.60</td>
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<tr>
<td>Block--Inlet Swirl</td>
<td>0.014</td>
<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**
Sensitization Susceptibility (ASTM A262) -- Acceptable

100x

Direction 1

Direction 2

Direction 3

500x
Density, Porosity, Inclusions, Grain Size

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

<table>
<thead>
<tr>
<th>Laboratory Number</th>
<th>Type A</th>
<th>Type B</th>
<th>Type C</th>
<th>Type D</th>
<th>Series</th>
<th>Direction</th>
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<tr>
<td>15757-MET1</td>
<td>0</td>
<td>0.5</td>
<td>0</td>
<td>2.0</td>
<td>Thin</td>
<td>X</td>
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<tr>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.0</td>
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<td>2.5</td>
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<td>0</td>
<td>0</td>
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<td>0.5</td>
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<td>0</td>
<td>0</td>
<td>1.0</td>
<td>Heavy</td>
<td></td>
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Samples were taken at the longitudinal direction and examined at 100x magnification. Method(s): ASTM E45-13

Grain structure and inclusion content exceed GEH SS CRB wrought 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 (Preliminary Results)

### Preliminary Table of SCC Growth Rates of Wrought and Powder Metallurgy 316L and 600M

288C Water with 20 ppb Sulfate as H₂SO₄ — ~30 MPa√m

<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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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>As-Received</td>
<td></td>
</tr>
<tr>
<td>Wrought 316L</td>
<td>---</td>
<td>~40</td>
<td>(≈3 x 10⁻⁸)</td>
<td>(≈2 x 10⁻⁹)</td>
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<tr>
<td>PM 316L</td>
<td>C720</td>
<td>~40</td>
<td>~1 x 10⁻⁷</td>
<td>~2 x 10⁻⁹s</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>20% Cold Work</td>
<td></td>
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<tr>
<td>Wrought 316L</td>
<td>C126</td>
<td>~30</td>
<td>~2 x 10⁻⁷</td>
<td>~2 x 10⁻⁸</td>
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<tr>
<td>PM 316L</td>
<td>C719</td>
<td>~30</td>
<td>~2 x 10⁻⁷</td>
<td>~1 x 10⁻⁸</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>As-Received</td>
<td></td>
</tr>
<tr>
<td>Wrought 600</td>
<td>---</td>
<td>~35</td>
<td>(≈2 x 10⁻⁸)</td>
<td>(≈1 x 10⁻⁹)</td>
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<tr>
<td>PM 600M</td>
<td>C735</td>
<td>35</td>
<td>5 x 10⁻⁸</td>
<td>2 x 10⁻⁹</td>
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<tr>
<td></td>
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<td></td>
<td>20% Cold Work</td>
<td></td>
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<tr>
<td>Wrought 600</td>
<td>C129</td>
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<td>2 x 10⁻⁷</td>
<td>3 x 10⁻⁸</td>
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<tr>
<td>PM 600M</td>
<td>C734</td>
<td>30</td>
<td>1 x 10⁻⁷</td>
<td>1 x 10⁻⁸</td>
</tr>
</tbody>
</table>

*High ECP is 2 ppm O₂, which is ~150 – 200 mV. Low ECP is 63 ppb H₂ which is ~-510 mV.*
Inlet Swirler Design & Manufacture
--Modeling
Inlet Swirler Design & Manufacture
--Fit up
Inlet Swirler Can Design & Manufacture
Inlet Swirler Manufacture
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.
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

<table>
<thead>
<tr>
<th></th>
<th>C</th>
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<th>S</th>
<th>Si</th>
<th>Cr</th>
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<td>14.0-17.0</td>
<td>72min</td>
<td>0.50 max</td>
<td>6.0-10.0</td>
<td>N/A</td>
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<td><strong>600M-N-580-1</strong></td>
<td>0.05 max</td>
<td>1.00 max</td>
<td>0.015 max</td>
<td>0.50 max</td>
<td>14.0-17.0</td>
<td>72min</td>
<td>0.50 max</td>
<td>6.0-10.0</td>
<td>1.0-3.0</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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Density, Porosity, Inclusions, Grain Size

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

<table>
<thead>
<tr>
<th>Lab Number</th>
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<th>Type C</th>
<th>Type D</th>
<th>Series</th>
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<td>0.5</td>
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<tr>
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<td>0</td>
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<td>Heavy</td>
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<tr>
<td>5977-MET2</td>
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<td>0.5</td>
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<td>5977-MET3</td>
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<td>0</td>
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<td>0</td>
<td>Heavy</td>
<td></td>
</tr>
</tbody>
</table>

Samples were taken at the longitudinal direction and examined at 100x magnification
Method(s): ASTM E45-13
Defining Success…. 

Success in this project is 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
Technology Gaps/Applications Covered by PM-HIP Roadmap (1)

- Recognize ASTM A988 & A989 in ASME Code
- Nickel-based Alloy Specification Additions (ASTM and ASME)
- Recognize Alloys—304L, 625, 690, 718 & Property Data
- Recognize SA508 (RPV steels) in ASME Code
- Components for SMR and ALWR Applications
- Crack Growth and SCC Characterization (SS and Ni-based)
- Irradiation Embrittlement Assessment for Internals
Technology Gaps/Applications Covered by PM-HIP Roadmap (2)

- Hard-facing Materials Development
- Eliminate Dissimilar Metal Welds
- Advanced Valve Manufacturing
- Innovative Manufacturing for Nuclear
- Silicon Carbide Alloys
- Recognize Alloys via Regulatory Guides (NRC)
- Corrosion Resistant Coatings
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
Supporting DOE AMM Roadmap toward Heavy Section Manufacturing

**Highest Priority Items**

1. Develop technical position paper that allows welds in vessels outside the beltline region.
2. Develop/Demonstrate Powder metallurgy – HIP of Plate (Ring Sections)
3. Develop/Demonstrate Nozzle Manufacturing Capabilities
4. Install/Commission large diameter HIP Unit – 3.1 meters
5. Manufacture vessel internals via nickel-based alloys
The Team....

- Lou Lherbier & Dave Novotnak (Carpenter Technology)
- 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