Low-Cost HIP Fabrication of Advanced Power Cycle Components and PM/Wrought Inconel 740H Weld Development

DOE-NETL 2020 FE R&D Virtual Project Review Meeting - High Performance Materials Alloy Manufacturing Panel

Phase 1 Project (10/01/2019 ~ 3/31/2021)
Contract # DE-FE0031818
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Background & Motivation

High capital costs offset efficiency gains using $\gamma'$ strengthened Ni-based superalloys in AUSC and sCO$_2$ components

- Limited supply chain of large components using cast or wrought IN740H or HA282
- Extensive machining of complex features
- Technical difficulties in sand casting thick walls or complex shapes

Alternative manufacturing modality for cost reduction: Powder Metallurgy (PM) Near-Net-Shape (NNS) Hot Isostatic Pressing (HIP)

- Reduced 2~3X input material than wrought
- Minimum machining
- Reduce welds & weld repair
- Chemical & structural homogeneity
- Ultrasound inspectability

(prior SUNSHOT project: HA282 sand casting trial for turbine case)

Project Description and Objectives

Objectives of Phase 1
- Demonstrate NNS HIP feasibility by a prototype pipe elbow using IN740H powder
- Develop PM/wrought IN740H welding procedure and evaluate microstructure, properties
- Deliver a manufacturing and capital cost analysis of IN740H NNS HIP components for AUSC power plants

Technical Approach to Address Challenges/Risks
- Dimension control by accurate design of HIP tooling via modeling non-uniform shrinkage
- HIP cycle and powder size distribution studies to show a clear path for microstructure/property improvement
- PM/wrought IN740H cross weld microstructure/property evaluations

Anticipated Benefits & Impacts Aligned with FE Strategic Goals
- 50% cost reduction in manufacturing large components ($115/kW, $13/kW reduction in CAPEX for sCO2, AUSC power cycles)
- US manufacturing supply chain for NNS HIP
## Project Milestones Status

<table>
<thead>
<tr>
<th>Milestone Number</th>
<th>Task/Subtask</th>
<th>Milestone Title &amp; Description</th>
<th>Planned Completion Date</th>
<th>Actual Completion Date</th>
<th>Verification Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>M-1</td>
<td>1</td>
<td>Project Management Plan (PMP)</td>
<td>10/31/2019</td>
<td>10/10/2019</td>
<td>Revised PMP submitted to NETL project manager</td>
</tr>
<tr>
<td>M-2</td>
<td>1</td>
<td>Project Kick-off Meeting</td>
<td>12/31/2019</td>
<td>11/21/2019</td>
<td>Presentation from the meeting submitted to NETL project manager</td>
</tr>
<tr>
<td>M-3</td>
<td>1</td>
<td>Workforce Readiness Plan</td>
<td>12/31/2019</td>
<td>12/09/2019</td>
<td>Workforce Readiness Plan submitted to NETL project manager</td>
</tr>
<tr>
<td>M-4</td>
<td>2</td>
<td>IN740H powder and HIP property measurements up to 1150°C completed</td>
<td>3/31/2020</td>
<td>5/22/2020</td>
<td>Properties of IN740H powder and HIP for model input will be summarized in quarterly report</td>
</tr>
<tr>
<td>M-5</td>
<td>2</td>
<td>Effect of HIP cycle and powder cut on density, PPB evaluated</td>
<td>12/31/2020</td>
<td></td>
<td>Data will be provided in quarterly report to show the interrelationship among various parameters, and suggest improved powder and HIP cycle</td>
</tr>
<tr>
<td>M-6</td>
<td>3</td>
<td>HIP tooling designed</td>
<td>8/31/2020</td>
<td>5/30/2020</td>
<td>Images of the designed HIP tooling in CAD will be provided by Synertech</td>
</tr>
<tr>
<td>M-7</td>
<td>3</td>
<td>Desired dimension, surface condition, microstructure of prototype elbow achieved</td>
<td>12/31/2020</td>
<td></td>
<td>The resulting dimension, surface condition of the prototype elbow will be compared with the targets. The microstructure will be characterized</td>
</tr>
<tr>
<td>M-8</td>
<td>5</td>
<td>500 hr creep properties evaluated</td>
<td>2/28/2021</td>
<td></td>
<td>Results of 500 hr creep properties will be summarized in quarterly report by EPRI</td>
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### Argon Gas Atomized IN740H Powder

**Composition (in weight percent, wt. %)**

| Alloy, wt.% | Ni | Cr | Co | Al | Ti | Nb | C | Mo | Si | Fe | Mn | Cu | P | S | B | O | N |
|-------------|----|----|----|----|----|----|---|----|----|----|----|----|---|--|--|--|--|--|
| IN740H, norm | bal. | 24.5 | 20 | 1.35 | 1.35 | 1.5 | 0.03 | 0.1 | 0.15 |    |    |    |    |   |   |   |   |
| Min (IN740) | bal. | 23.5 | 15 | 0.2 | 0.5 | 0.5 | 0.005 |    |    |    |    |    |    |   |   |   |   |
| Max (IN740) | bal. | 25.5 | 22 | 2 | 2.5 | 2.5 | 0.08 | 2 | 1 | 3 | 1 | 0.5 | 0.03 | 0.03 | 0.006 | 0.006 |
| 2019 IN740H powder | bal. | 24.6 | 20.2 | 1.34 | 1.34 | 1.5 | 0.039 | 0.06 | 0.15 | 0.2 | 0.2 | 0.01 | 0.004 | 0.0009 | 0.001 | 0.0062 | 0.0059 |
| 2020 IN740H powder | bal. | 24.5 | 20.2 | 1.31 | 1.33 | 1.4 | 0.039 | 0.06 | 0.14 | 0.2 | 0.2 | 0.02 | 0.004 | 0.0006 | 0.001 | 0.0095 | 0.0067 |

- Successful argon gas atomization trials at Wyman-Gordon Princeton R&D
- Powder composition within specification (reasonable oxygen, nitrogen)
- Good repeatability in powder size distribution and tap density (~67%)

[220lbs IN740H powder delivered for pipe elbow]

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2019 IN740H powder

2020 IN740H powder
M-4: Properties of IN740H Consolidated Powder for HIP Model

Completed IN740H powder property measurements for HIP model input
1. Compressive stress-strain properties for IN740H powder HIPed to 70~100% density
2. Specific heat, density, coefficient of thermal expansion and thermal conductivity

Model powder shrinkage during HIP: plasticity, creep, diffusion

Green’s Plasticity Criterion

\[
\frac{T^2}{f_1} + \frac{\sigma_0^2}{f_2} = \tau_s^2
\]

- $\sigma_0$ - average stress
- $T$ – stress intensity factor
- $\tau_s$ – yield strength
- $f_1$ – function of average stress, density
- $f_2$ – function of sheer stress, density
Effect of HIP, HT conditions and PSD on PPB network and grain size distribution

- Designed 16 pre-soak conditions before HIP cycle to coarsen PPB particles with less grain boundary pinning
- Prepared 5 powder size distributions (fine, coarse, bimodal)
M-6: Pipe Elbow HIP Tooling Design

- HIP densification and shrinkage modeled with the goal of achieving net shape at interior surface
- HIP tooling for pipe elbow designed, manufacturing & assembly procedure defined
- In progress of fabricating HIP tooling
PM/Wrought IN740H Weld Development

- Preliminary weldability evaluated by autogenous Gas Tungsten Arc Welding on HIP IN740H
- Argon induced porosity observed in the weld metal, but acceptable per ASME
- In preparation of HIP IN740H plate for PM/wrought plate weld development
M-8: Preliminary Creep Evaluation

A clear technical path to improve creep
1. Pre-soak before HIP
2. Powder size distribution
3. HIP temperature
4. Solution treatment
5. Alternative powder production for cleanliness
6. Minor alloy composition modification

- Goal is to evaluate creep properties with different HIP conditions/microstructure and compare with wrought IN740H
- Literature review on wrought IN740H shows a trend between grain size and creep life
Preparing Projects for Next Steps: Market Benefits/Assessment

**Market Gap**

Pipe fittings are currently very costly as they are machined out of forged blocks of material:

- Excessive waste of material and machining time.
- IN740H is not an easily sand castable alloy but can be made into powder for NNS HIP.

**Market Benefit**

- Program proposal: 15 pipe features at $300k machined verses $150k NNS HIP plus TSV: $13/kW.
- Updating market study benefit increasing to $35 to 70/kW (Over $20MM per plant):
  - Standard steam plant ~130 major pipe fittings
  - Reduced piping AUSC design: >80 major fittings
  - Actual IN740H forging for 2,000lb tee is 2x estimate
Preparing Projects for Next Steps: Technology-to-Market Path

**Technology Integration**

- Based on value story, code case finalized backed by industry (GE Power, EPRI and other OEMs)
- Post code case: hardware incorporated in future A-USC designs; supply chain established.

**Remaining Technology Challenges**

- Improved creep rupture life – trade-off with pipe wall thickness which equates to cost
- ASME B31.1 & BPVC code case/approval (i.e., creep, weld optimization)
- First application plant identified (first piece qualifications)

**Current Industry Collaborators Span from End-user to Material Supplier**

- PCC: Special Metals, Wyman-Gordon (IN740H material supplier), *project partner*
- Synertech PM (NNS HIP), *project partner*
- GE Power Steam Power Systems (plant developer), *consultant*
- EPRI (Power plant consortium), *project partner*
- Future collaborators: sub-tier suppliers
Concluding Remarks

• Applicability of NNS HIP manufacturing to Fossil Energy
  - Cost saving for manufacturing large, complex components in Ni-based alloys for AUSC, sCO2 power cycles
    (Forging $/lb ↑ with component size, HIP $/lb ↓ with component size)

• Alignment to Fossil Energy strategic goals
  - Affordability of AUSC, sCO2 power cycles
  - US manufacturing competitiveness

• Project’s next steps
  - To complete Phase 1 tasks and de-risk for Phase 2
  - To prepare Phase 2 proposal building on successful proof-of-concept elbow
    o Detailed cost/performance trade-off with IN740H PM HIP material properties
    o Valve body development with complex shapes and sizes (5 tons, 5 feet)
    o Market evaluation of smaller pipe fitting components as well as boiler, turbine components