Benefits of Tailoring
Hot Isostatic Pressure/Powdered Metal (HIP/PM) and Additive Manufacturing (AM) To Fabricate Advanced Energy System Components

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in collaboration with:

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U.S. Department of Energy
National Energy Technology Laboratory
Demonstrate how tailoring HIP/PM, coupled with advances in AM (also known as 3D printing or 3DP) has specific, measurable benefits for fabricating advanced energy (AE) system components.

Goals:

- Validate that AM, in combination with HIP, offers a viable method of producing A-282 components
- Provide key information about cost, manufacturing challenges/opportunities and lead-times when compared to other methods including traditional HIP/PM and casting.
Relevance to Fossil Energy

For expensive, high nickel alloy components, EIO activities have shown advantages of HIP/PM over other methods such as casting and forging.

- Savings up to 40% in raw material costs (vs. casting)
- Eliminates difficulties resulting from reactivity of these materials in the molten state
- Facilitates manufacture of large size requirements associated with FE/AE
- Net shape & porosity free parts require less post processing including machining & weld repair

Work in AM suggests further advantages…
Potential Significance of the Results of The Work

- Many new advanced alloys for Fossil Energy will require new manufacturing methods
- Supplier Availability will determine the rate for adopting Clean Coal technologies
- Castings, Forgings, and Extrusions are THE “pinch points”
- Current Supply Base is Mostly Off-Shore
- Saturated with Long Lead Times

Creates opportunity for evolving US industrial base
Three new methods of manufacturing advanced alloys are under evaluation:

1. Directly built AM parts;
2. AM cans for HIP/PM; and
3. AM cans produced in the final part material.

Project is utilizing

- Binderjet technology (fastest metal 3DP technique, coupled with an alloy specific sintering profile to produce a sufficiently dense part for final HIP
- Haynes 282, a high nickel material capable of withstanding the severe operating environments required in AE systems
Project Approach

Project utilizes a Westinghouse gate valve

- Modified to ¼ scale
- 3” x 4” x 2”
- ~ 2.7 lbs -
- wall thickness range ¼” – ¾”

Valve selected for the complexity of its shape & crosscutting applications to other AE systems, including nuclear
Primary Tasks

1.0 – Project Management & Planning
2.0 – Atomization of A-282
3.0 – Material Characterization & Sintering Methodology (MC/SM) for A-282
4.0 – Produce 2 Valve Components via AM Cans & HIP/PM Manufacturing
5.0 – Produce 1 Valve via AM/3DP and HIP
6.0 – Post Processing Analysis
7.0 – Outreach & Technology Dissemination
Task 1.0 – Project Mgmt & Planning

Team Leader:
Energy Industries of Ohio

in collaboration with

Carpenter

ExOne

Bodycote
Energy Industries of Ohio

- Non Profit 501(c) 3 Corp
- Facilitate Technology Development for Ohio’s Base load Generation
- Implement Efficiency Projects for Energy Intensive User Industries
  - 9 Industries use 30% of all energy
  - Ohio is first for 3 & in the top five for others
- Foster Collaborations & Teams
  - Federal, State, University, National Laboratories & Private Industry
  - Exploit Synergies between supply and demand sectors
Our Workforce and Skills Challenge

MW Capacity Additions

NUCLEAR

COAL

CTL

A Two Decade Gap for Coal; Three Decades for Nuclear

Lost opportunity to transfer a generation of valuable experience

Source: EIA AEO’07 reference case and Annual Energy Review 2006

2/18/2008
EIO’s Role in US Manufacturing

- Traditional manufacturing +
  - EIO is working with heavy manufacturers (castings, forgings, fabrications etc) to enhance their traditional manufacturing processes
  - Automation, energy efficiency and innovations help to offset higher labor charges domestically.

- Advanced Manufacturing
  - EIO is working on R&D projects involving both new materials and new methods of manufacturing

RESULTS: Not only are we re-shoring for US opportunities, we are also getting foreign companies approaching us with export opportunities
Technical Background/Project Motivation

National Compact Stellarator Program

- EIO charged with prototyping and providing large, high strength Nuclear Castings
- Staff experienced for working with Nuclear supplier industry, Nat’l Labs and Producers
Technical Background/Project Motivation

EIO is Prime Contractor for $50M Advanced-UltraSuperCritical Materials Program

- Pulverized Coal CCS technology
- Efficiency  Emissions
- Consortium of All U.S. Boiler and Turbine Manufacturers and EPRI
- Goal: 5000psig, 1300°F main steam and above for net plant efficiency >45%
- New Materials (nickel-based alloys) and designs
- Supply Base is key to commercialization
A-USC Consortium Members

U.S. DEPARTMENT OF ENERGY

Energy Industries Of Ohio

EPRI

ELECTRIC POWER RESEARCH INSTITUTE

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

NETL

GE

imagination at work

B&W

ALSTOM

RILEY Power
A Babcock Power Inc. Company

FOSTER WHEELER

SIEMENS

Phase 1 only
A progressive increase in steam conditions has been taking place worldwide.

**US A-USC Goal**

- 5400/1350/1400
- 5400/1300/1325/1325

**R&D ongoing** Europe, Japan, U.S.

(Ni-based Materials)

**Current Market introduction by Japan and Europe (Steel R&D)**

**Current Market introduction US**

**3600/1050/1085**

**4000/1085/1100**

**4000/1100/1130**

**4000/1165/1200**

**Mature technology**

- 2400/1005/1005
- 3480 psi / 1005°F / 1050°F

**Cost Effective Materials Have Been Critical to Achieving Increased Efficiency**

Original Illustration: Courtesy of ALSTOM Power
Materials Selection for A-USC Alloys
(Boiler Superheater/Reheater Tubing Strength)

Today’s SC & USC Technology Limited by Steel Alloys

A-USC Technology Requires Nickel-Based Alloys
UltraSuperCritical (USC) Materials Project – Potential Show-Stoppers

Product Form and Size Limitations

The U.S. domestic boiler and turbine manufacturers are working to confirm the materials technology and component fabrication feasibility for advanced USC plant components.

The production capabilities of raw material suppliers and foundries must also be assessed for:

- Large, heavy wall pipe
- Castings
- Forgings

The ultimate plant unit size and other design aspects will be influenced by the size and product form limitations of domestic and worldwide suppliers (i.e. foundries, forges, etc.) capable of working with these new, high-strength materials.
Both Programs involved locating suppliers

- Found Castings, Forgings, and Extrusions are **THE** “pinch points”

- Found Supplier Base is limited, saturated and foreign

- Found Supplier Base for Coal/Nuclear Overlaps

- Found Supplier Availability will impact the rate for introducing both Clean Coal and Nuclear Systems

Opportunity for Supply Chain Development
Ohio/TechBelt Opportunity for an Advanced Energy (AE) Supplier Program

- These needs are traditional TechBelt products
- EIO has direct relationships with these industries and their affiliated organizations FIA, OCMA, OSC, etc.
- Knowledge that their current markets are declining
- Knowledge that they are looking for new markets
- Knowledge that they are capable of transition into AE markets
  - But....They don’t know of Advanced Energy opportunities
  - And....Power Gen potential customers don’t know of them

EIO could connect the dots!
EIO Approach in Ohio & TechBelt

EIO employed a different (bottoms-up) model
1. Develop the specific “needs envelope” (sizes, alloys, etc.) of target “pinch point” items
   * Worked with key customers from fossil and nuclear
2. Use Industry organizations to ID candidate suppliers
3. Conduct on-site visits to assess interest & ability
4. Facilitate customer interaction and teaming opportunities
5. “Champion” needs for transitional assistance
6. Pursue technology development & demonstration
Program Outcomes

- A Catalogue listing Ohio Suppliers that can meet the AE Power Gen Industry needs – Project was expanded to include Pittsburgh Region
- Promoting the Catalogue to OEM’s & Customers
- Cultivation of HUBS around pinch points & market/export opportunities
- Advanced Research, Prototype Development & Industry Expansion
Technical Background/Project Motivation

Under the Ohio Program, EIO conducted Research & Technology Development Using A-282

- Produced World’s largest Step Casting followed by an AE Valve using A-282

- Working with Carpenter & Bodycote - Duplicated A-282 Step Component using HIP/PM
Additive Manufacturing is a logical progression in seeking new methods for producing FE/AE components.

Dialogue and collaboration with our colleagues at Carpenter, ExOne and Bodycote focused on finding ways to make AM and HIP/PM more competitive.

Potential advantages, including reduced costs and leadtimes, of combining AM with HIP/PM resulted in this project proposal.

Carpenter, ExOne and Bodycote are all highly respected companies in their fields, with facilities in the TechBelt.
Atomization of A-282 PEP – Carpenter Powder Products

Manufactures a broad range of gas atomized loose metal powders and consolidated powder forms

Manufacturing: PA, RI and Sweden

R&D: Reading, PA
PEP – Carpenter Powder Products

Leader in Gas Atomization Technology

Bridgeville, PA
- Air Induction
- VIM (2)
- Ar and N

Torshalla, Sweden
- Air Induction (2)
- N

Woonsocket, RI
- Protected atm.
- Ar and N

Stainless steels, nickel/cobalt base, fine powders, tool steels
Capacity – 20,000 Tons
PEP – Carpenter Powder Products

Greenfield Powder Facility – Athens, Alabama

Features

• 3000 lb. dual VIM furnace

• Two tower design

• Clean rooms

• Argon recycling

• In-line PSD determination

• Satellite control

Capacity – 2100 Tons
Superalloys

- Gas Turbine Components
- High Temp. Capability

HIP Near Net Shapes

- Isotropic Properties
- Material Utilization
- Fewer Welds
- Less Machining

Additive Manufacturing

- Complex Shapes
- BTF Ratio
- Imbed inner channels

Metal Injection Molding

- Complex Shapes
- High Volume Capability

Metal Powder Solutions

Surface enhancement and Joining

- Corrosion Resistance
- Component Repair
PEP – Carpenter Powder Products

Additive Manufacturing Initiative

- Parts Fabricators
- Equipment Mfg.
- Distributors

 Customers

Materials

Specifications

Processes

- Austenitic SS
- Maraging SS
- 718
- 625
- CCM

- PSD
- Chemistry
- Flow
- Shape
- Density

- AM process
- Powder re-use
- HIP
- Heat Treatment
- Finishing
PEP – Carpenter Powder Products

Program Task 2: Powder Manufacturing

Melting → Screening → Particle Size Determination → Blending → Chemical Analysis

- Melting
- Screening
- Particle Size Determination
- Blending
- Chemical Analysis
A Global Supplier of Industrial Additive Manufacturing Equipment

• 50-year history of developing and implementing nontraditional manufacturing processes.

• Invested >$80 million in the development and implementation of three-dimensional printing (3DP) since the early 1990s.

• Offers both the services and the equipment for applying 3DP technology for molds / cores used for sand castings and direct metal parts.

• ExOne Production Service Centers are located throughout the United States, Germany and Japan.

• ExOne systems are able to print in a variety of industrial materials with the largest available build sizes.
ExOne Technologies

Sand Casting Molds and Cores - Without a Pattern

Micro Holes and Features with Advanced Laser Machining

Industry Class Additive Manufacturing Equipment

Functional and Accurate 3D Printed Metal Parts

ExOne Technologies
Direct Metal Technology

1. Spreading new layer of metal powder
2. Powder Printing
3. Print-Bonded Particles
4. Particles agglomerated in one droplet (Voxel)
5. Parts Stilted for Infiltration
6. Sintered Particles
Direct Metal Technology

1. Spread layer of metal powder
2. Selective dispensing of binder using inkjet printing technology
3. Binder drying
4. Repeat step 1 to 3
5. Extraction and cleanup of green part
6. Binder burnout and densification
ExOne Materials Applications Laboratory

- Materials Analysis
- Mechanical Testing
- Metallography & Microscopy
- Hardness
- Density
- Coefficient of Thermal Expansion
3DP is Basic Powder Metallurgy

Product Forms

- Bonded
- Partially Sintered
- Infiltrated
- Highly Sintered

Powder metallurgy is the process of blending fine powdered materials, pressing them into a desired shape or form (compacting {printing}), and then heating the compressed material in a controlled atmosphere to bond the material (sintering). The powder metallurgy process generally consists of four basic steps: powder manufacture, powder blending, compacting...
### 3DP Binder Jetting Parts – Rapid Production

<table>
<thead>
<tr>
<th>System</th>
<th>Speed</th>
<th>Build Rate</th>
<th>Layer Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>M-Print</td>
<td>75 seconds per layer</td>
<td>2052 cm³/hr</td>
<td>Variable with minimum of 0.15 mm (0.006 in)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(125 in³/hr)</td>
<td></td>
</tr>
<tr>
<td>M-Flex</td>
<td>30 seconds per layer</td>
<td>1200 cm³/hr</td>
<td>Variable with minimum of 0.1 mm (0.004 in)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(73 in³/hr)</td>
<td></td>
</tr>
</tbody>
</table>
**Build Volume:**
15.5 x 9.5 x 9.5 in.
394 x 241 x 241 mm

**Layer Thickness:**
100 or 180 microns

**Accuracy:**
+/- 0.5%

System includes de-powdering station and curing oven
Direct Metal Technology – M-Print

Build Volume:
29.5 x 15 x 15.75 in.
750 x 380 x 400 mm

Layer Thickness:
100 or 180 microns

Accuracy:
+/- 0.5%
Bodycote operates a global HIP business with the largest equipment network in the world.

Bodycote has over 50 HIP vessels of varying sizes in multiple locations and is able to accommodate large volumes of small products as economically as large individual components.

Bodycote provides two major HIP routes for customers:

- HIP Services, providing porosity removal through HIP densification.
- HIP Product Fabrication, for the manufacture of components through powder metallurgy and diffusion bonding.
Hot Isostatic Pressure (HIP) combines high temperatures (up to 2,000°C) with isostatically applied gas pressures (up to 45,000 psi) – comparable to the Mariana Trench 11,000m deep in the Pacific Ocean.
Hot Isostatic Pressing (HIP) combines very high temperature and pressure to eliminate porosity in castings, and consolidate encapsulated powders to give fully dense materials.

Dissimilar materials can be bonded together to manufacture unique, value-added components.
Progress on Primary Tasks

1.0 – Project Management & Planning

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Task 2 - Atomization of 282

- For the HIP process – powder screened to roughly ~ 250 microns
- For the AM process – powder screened to max size 22 microns

SEM photomicrographs of the AM powder are shown in Figures 1 & 2.
Task 3 – Material Characterization & Sintering Profile

- Binder Saturation Tests were performed to establish the optimal amount of binder to be dispensed on the bed during printing
  - Too little saturation can result in flaking of the sample & poor adhesion from layer to layer
  - Too much saturation can lead to swelled samples

FINDING: Determined 80% saturation yielded best results

- Binder is subsequently removed via “burnout” in furnace
Testing of the A282 was conducted in a high vacuum furnace producing a vacuum below $3.0 \times 10^{-5}$.

Three pump downs and backfills with inert gas (96% nitrogen & 4% hydrogen) were done before each run to ensure any moisture was removed from the chamber.

Burnout Temperature $600^\circ$ C (to remove binder).

Variables in the test runs included:
- Furnace Temperature (min $1290^\circ$ C to max $1325^\circ$ C)
- Max Temperature Hold Time (1 hour – 1.5 hour)
- Ramp-up and Ramp-down Rates (5$^\circ$ C/min to 1$^\circ$ C/min. The ramp rate down from $1315^\circ$ C to $800^\circ$ C was also changed from 5$^\circ$ C/min to 1$^\circ$ C/min)
- Number of samples in a run (ranged from 1 – 3)
- Size of sample

FINDING: Achieved 95.35% density before machining, with no distortion or cracks!
For this Run 3 the maximum temperature was increased another 10°C to 1310°C and held for one hour. The details of the profile used for this test are shown in the table at right.

Result: Sample was 95.35% dense with no distortion before machining. The sample is shown at right after machining had been done.
Task 3 – Material Characterization & Sintering Profile

- Following Successful Test Runs HIP Can Test Samples were printed in “green state” by ExOne in 2 sizes: 1” x 1” x .125” and 1” x 1” x .150”
- Crisp edges remained intact during handling

Top View

Side View
Task 3 – Material Characterization & Sintering Profile

- AM Valve Test Samples were printed in “green state” by ExOne in 2 sizes: 1” x 1” x 1” and 1” x 1” x 1.5”
- Crisp edges remained intact during handling

Top View

Side View
Task 3 – Material Characterization & Sintering Profile

- Test coupons will be used to determine the final furnace profile to achieve the highest density possible.
- Coupons will be used to determine final scaling factor to account for shrinkage.
- HIP will be applied to Test Coupons to achieve max density (seeking full density).
Task 4 – Produce 2 Valve Components via AM Cans & HIP/PM Manufacturing

Current Progress: Design Cans & Produce CAD Drawings

- Major design challenge: modify the can design to accommodate the fill tube
- ExOne will build a .875” OD X .375” ID X .25” tall socket or collet over the .375” hole in the valve.
- Bodycote will use this feature to socket weld the tube to the valve.
- To test this approach, Bodycote successfully welded a 0.375” OD x 0.083” wall tube to a sample block of Haynes 282 provided by EIO and had zero issues. Helium leak check was performed and passed.
Task 4 – Produce 2 Valve Components via AM Cans & HIP/PM Manufacturing

Current Progress: Design Cans & Produce CAD Drawings
Task 5 – Produce 1 Valve Component via AM/3DP & HIP

Current Progress: First 3DP Valve Produced

The support cylinders on the flange shown in the bottom view image (blue arrows highlight two of them) were added in an attempt to allow the part to shrink uniformly and minimize distortion during sintering.
Summary: Progress To Date
(4/27/15)

1.0 – Project Management & Planning

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6.0 – Post Processing Analysis

7.0 – Outreach & Technology Dissemination
Tailoring HIP/PM with advances in AM provides specific, measurable benefits for fabricating advanced energy (AE) system components.

Three new methods of manufacturing advanced alloys under evaluation include:

1. Directly built AM parts;
2. AM cans for HIP/PM; and
3. AM cans produced in the final part material.

Potential advantages include lower manufacturing costs, ability to produce more complex designs, improved production efficiency & readily transferrable technology.
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