혁신형 SMR 적용을 위한 첨단 제조공정기술 현황

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CONTENTS

Key Design Features of SMR

❖ Integral Design

- SMR incorporates all of the components of the NSSS into a single vessel.
- Increased heat capacity and thermal inertia of the system.
- A robust inherent safety case and simpler systems, operation and maintenance

❖ Inherent safety

- Increased efficiency of passive safety systems for normal/off-normal conditions.
- More simplified design, operation and maintenance thanks to a higher reliance on passive cooling systems

❖ Lower core inventories

- On site: less shielding required; radiation exposure doses reduced
- Off-site: reduced probability of accidents; reduced need for EPZs

❖ Improved modularization & manufacturability

- Smaller size of SMR designs enables the adoption of more ambitious modularization schemes and new manufacturing techniques.

❖ Enhanced flexibility

- Enhanced load following modes, lower siting constraints and better deployment capabilities

NSSS: nuclear steam supply system
EPZ: emergency planning zone

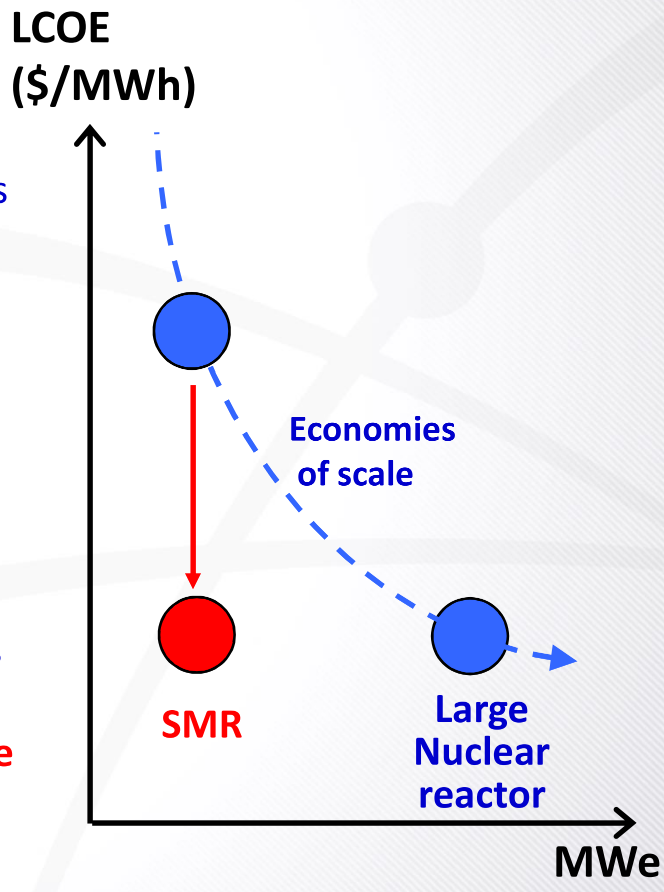
Key Economic Drivers for SMR

❖ Economies of Scale

- Lower levelized cost of electricity (LCOE*) for larger reactor

❖ Counterbalancing by Series Production

- **Design simplification**
  - ✓ Removal of the active cooling safety and auxiliary systems
  - ✓ Simplification of plant and use of COTS components
- **Standardization**
  - ✓ Promotion of learning; mobilization of the supply chain
  - ✓ Use of COTS components
- **Modularization & factory fab**
  - ✓ Factory-built, transported, and assembled on-site
  - ✓ Enhanced labor productivity and quality control by pre-assembly of modules at factory
  - ✓ Reductions of lead-time (40%) and cost (20%), the effects becoming greater with decreasing the size of reactors
  - ✓ **Advanced, cheaper manufacturing techniques applicable to fabrication/assembly of modules in factory**
- **A higher degree of harmonization : Code & Standards, licensing, and legal framework**



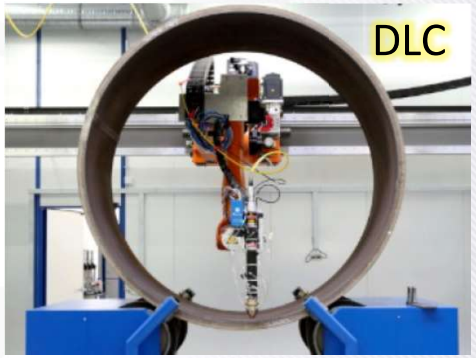
*LCOE: a measure of the average net present **cost** of electricity generation for a generating plant over its lifetime
** COTS: commercial off-the-shelf

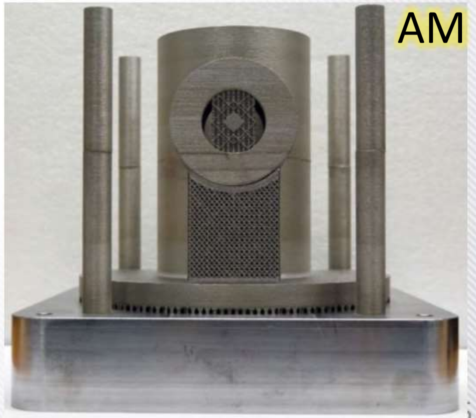
Advanced Manufacturing Technologies (NRC)

- Techniques and material processing methods that have not been:
  - Traditionally used in the U.S. nuclear industry
  - Formally standardized/codified by the nuclear industry

- Key AMTs based on industry interest:
  - Laser Powder Bed Fusion(L-PBF)
  - Direct Energy Deposition(DED)
  - Electron Beam Welding
  - Powder Metallurgy, Hot Isostatic Pressing(PM-HIP)
  - Cold Spray

- Participants
  - Vendors, utilities, EPRI, NEI, DOD, DOE (incl. labs), NIST, NASA, regulators (other U.S. government,international)





Size-Based AMT Classification

L-PBF	DED	PM-HIP
		
		
Laser Powder Bed Fusion Additive Manufacturing: <75 lbs (35 kg)	**Direct Energy Deposition Additive Manufacturing:** <500 lbs (225 kg)	**Powder Metallurgy-HIP:** 100-10,000 lbs (45-4500 kg)

Components and AMT Processes (EPRI Roadmap)

Primary Pressure Boundary

Reactor Type	Component	AMM Process	Material
AP1000	Vessel Shell (Six ring segments)	PM/HIP	LAS
AP1000	Pressurizer Shell (Four ring segments)	PM/HIP	LAS
US EPR	Pressurizer Shell (Four ring segments)	PM/HIP	LAS
US APWR	Pressurizer Shell (Four ring segments)	PM/HIP	LAS
BWR	CRD Stub Tubes	PM/HIP	CC N-580
PWR	CRDM Housings	PM/HIP	A690
ABWR	Reactor Internal Pump Case	PM/HIP	LAS
AP1000	Recirculation Pump Case (top section)	PM/HIP	SS
BWR/PWR	Medium Size Valve Bodies and Bonnets	PM/HIP	SS
BWR/PWR	Reactor Vessel Nozzles	PM/HIP	LAS
BWR/PWR	Small Valves & Fittings	PM/HIP or DED	SS
BWR/PWR	Very Small Valves and Fittings	Powder Bed AM	SS

Reactor Internals

Reactor Type	Component	AMM Process	Material
AP1000	Core Barrel (Six ring segments)	PM/HIP	SS
Advanced PWRs	Core Barrel Nozzles	PM/HIP	SS
AP1000	Upper Guide Tube Components	PM/HIP	SS
AP1000	Control Rod Guide Cards	Powder Bed AM	SS
AP1000	Core Barrel Support Lugs	PM/HIP	A690
BWR/PWR	Dome Cooling Spray Nozzles	PM/HIP or DED	SS
EPR	Heavy Reflector Positioning Keys	PM/HIP	SS
ABWR/ESBWR	Control Rod Guide Tube Base Plate	PM/HIP	XM-19
ABWR/ESBWR	Steam Separator Swirlers	PM/HIP	SS
ABWR	Shroud Head Bolt Tees	PM/HIP	CC N-580
BWR	Fuel Spacers	Powder Bed AM	X-750
BWR	Fuel Tie Plates	Powder Bed AM	SS
BWR/PWR	Fuel Debris Filters	Powder Bed AM	SS
BWR/PWR	Control Rod Drive Components	PM/HIP, DED, or Powder Bed AM	SS or Co-Free Alloys

Powder Metallurgy based HIP

❖ SMR project led by EPRI, NuScale Power & Nuclear AMRC (UK)

- Tech.: PM-HIP, electron beam (EB) welding, diode laser cladding, additive manufacturing (AM) and advanced machining methods
- Components: RPV, SG, Pressurizer…
- Goals:
  - ✓ Acceleration of the deployment of SMRs
  - ✓ Reducing the production time of SMRs to < 12 months
  - ✓ Eliminating 40% of the costs of a SMR vessel

❖ PM-HIP in SMR

- Components: upper and lower reactor heads, steam plenum, and steam plenum access covers (those used in NuScale)
  → RPV at 2/3 scale in progress
- Many of components are being produced in half sections and then assembled with EB welding (due to limited size of HIP vessels).

SMR vessel head (44% scale); A508/Gr. 3/Class 1 low-alloy steel powder (1,650 kg). 27 penetrations

Production of Near-Net-Shaped Parts with PM-HIP

Powder Making

- Induction melting of raw alloy products
- Optimization of the size distribution of powders
- Blending to develop specific packing density

Powder atomization → Sieve → Blend

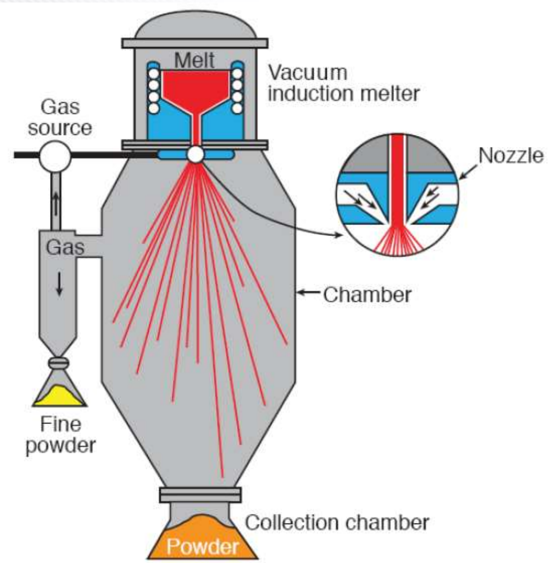
Capsule Fab

Shaping sheet metal → Weld → Leak test

- Modeling capsule tooling to allow for shrinkage and movement of capsule

Blend + Leak test → Capsule fill → Bake out → Seal → HIP & De-canning

- Capsule fill: Vibration of capsule for even dispersion of powder
- Bake out: Degassing to remove trapped gases



1.6 m dia HIP unit

Key Benefits of PM-HIP

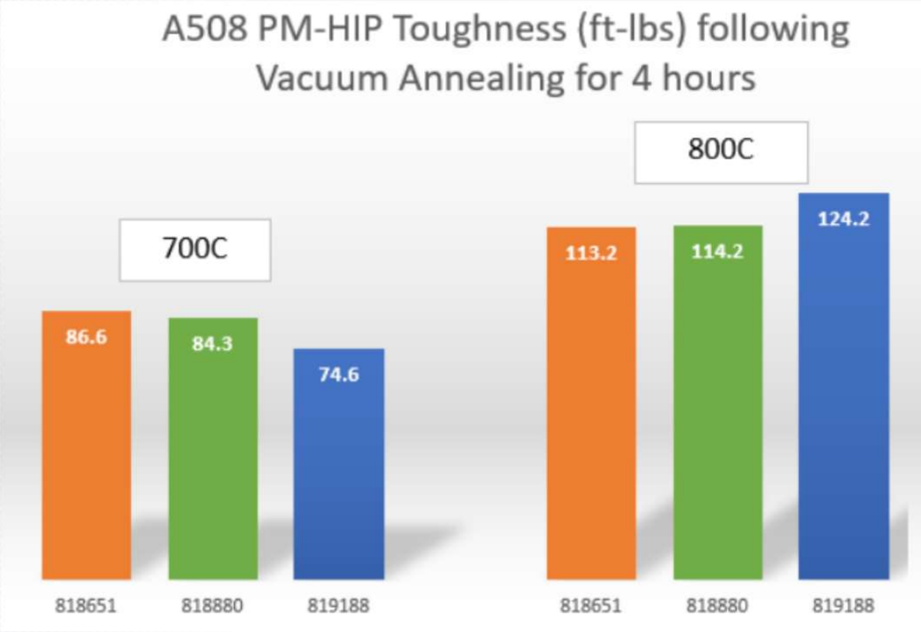
What impact can PM-HIP have in the production of the parts and components in small modular & advanced reactors over the next few decades?

The manufacture of large, structural and pressure-retaining components produced with PM-HIP:

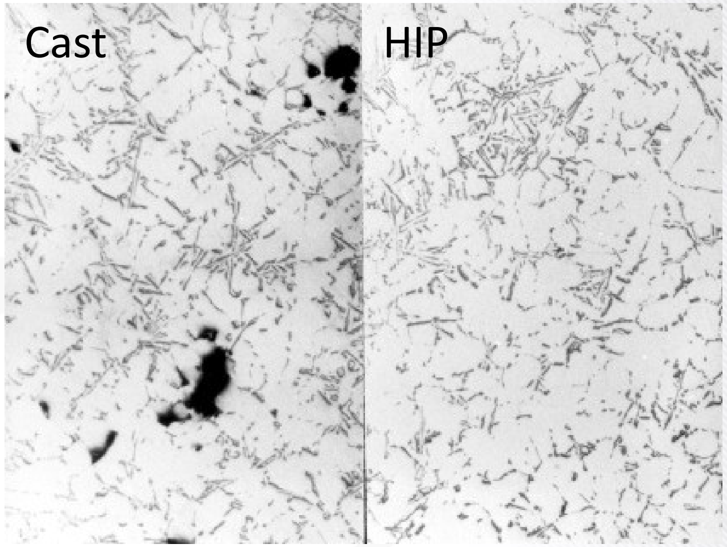
- A cost-effective alternative to current processes such as casting, forging, drawing and extrusion
- Near-net-shaped feature enables reduced machining and material volume required.
- Homogeneous microstructure promotes superior inspection characteristics and minimize mechanical anisotropy.
- Elimination of certain welds
- Shortened delivery time
- Ideal for multiple penetration applications

(EPRI QIB, 2020)

Properties of PM-HIPed Materials



Microstructure (HIPed vs Cast)



Ultrasonic inspectability

Table III Inspectability of UDIMET Alloy 720

Form	Billet Dia. (mm)	ASTM G.S.	Noise Level FBH*
P/M Extruded	150-300	14	6% @ #1
P/M SS-HIP/Cog	300	10	25% @ #1
P/M HIP	165	10	15% @ #1
P/M SS-HIP	300	3	50% @ #1
Cast/Wrought	165	11	100% @ #2

* # 1 =1/64 = 0.40 mm

Tensile properties (HIPed vs Cast)

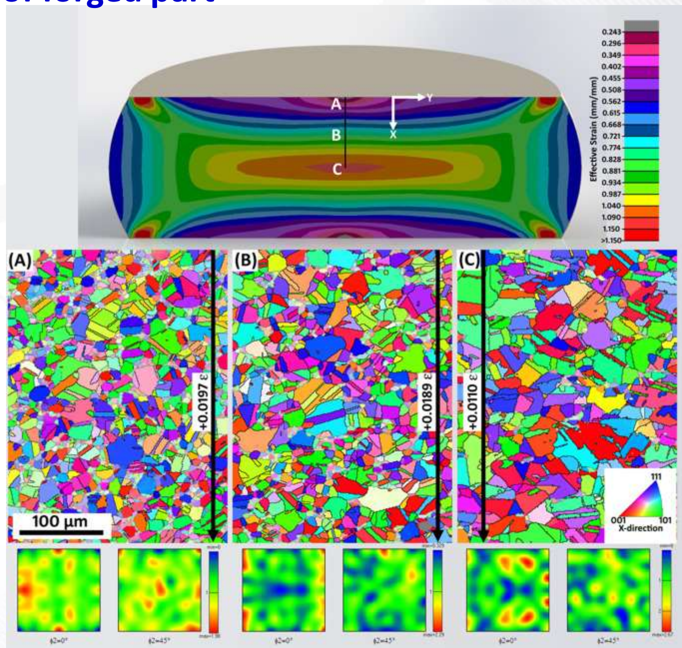
	Tensile strength (MPa)		*0.2% Proof strength* (MPa)		*Elongation* (%)	
Alloy	*As cast*	*HIPed*	*As cast*	*HIPed*	*As cast*	*HIPed*
A356	193	248	138	172	5.4	6.7
A357	200	255	179	207	2.6	5.8
A201	386	441	365	421	1.4	11.2
450 steel	993	1,069	903	1,000	19.4	20.7

Source: ASM (1988).

HIP: Improved Inspection Characteristics

- Key attribute of PM-HIP is the ability to produce near-net-shaped components that are readily inspectable.
  - PM-HIP component exhibits a very homogeneous microstructure
  - The homogeneous microstructure renders the component highly inspectable across any direction wherein ultrasonic sound can be directed through the part.
  - Uniformity in the microstructure also minimize the mechanical anisotropy that is usually exhibited by the parts produced by conventional processes.

Inhomogeneous microstructure and texture of forged part



Code & Standards Issues for PM-HIP

- ❖ PM-HIP technologies are recognized by ASME Boiler & Pressure Vessel Code via Code Case, and directly within ASME standards.
  - 316L stainless steel (CC N-834)
  - Grade 91 steel (CC-2770)
  - Duplex stainless steel (CC-2840)
- ❖ BPVC-II: Materials – Mandatory Appendix 5
  - "Guidelines on the approval of new materials under the ASME BPVC" recognizes PM-HIP products in a similar manner to other product forms.
- ❖ Austenitic SS produced by PM-HIP are similar in cost with forged product forms.
  - Machining cost can be reduced as produced in near-net-shaped form
  - Delivery time can be lowered to 4-6 months (cf., 2-5 years for forging processes)

Elimination of Welds via Heat Treatment

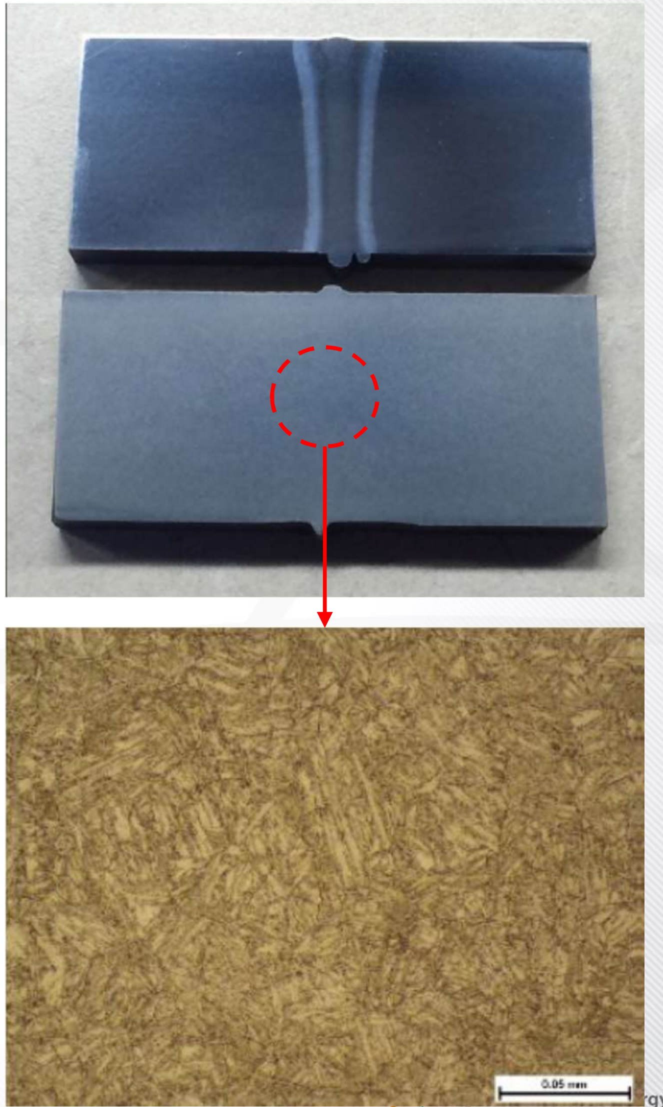
❖ Elimination of the weld
- Chamber EB weld of sub-assemblies
- Solution HT, Quench, Normalizing & Tempering (SQNT)

❖ Resulting microstructure
- Same as base metal
- Fracture toughness comparable to BM

❖ Inspection
- Fab inspection prior to & following initial SQNT
- No weld is visible after HT
- Fracture toughness comparable to BM
- Potentially no weld inspection required at 10 year intervals

Assembly of four quarter sections of upper head may be viable with EB welding & SQNT.

WCLs of EBW prior to and following HT



ATLAS (Advanced Tech for Large-Scale)

❖ Scale-up of HIP Unit

- The production of PM-HIP based large nuclear components require a much larger HIP capability than presently exists today.
- EPRI with industry has brought ATLAS HIP unit to enable production of large components ($55M project).
- HIP vessel spec. of ATLAS
  - ✓ Load capacity: 113 tons
  - ✓ Diameter: 3.55 m
  - ✓ Height: 2 m

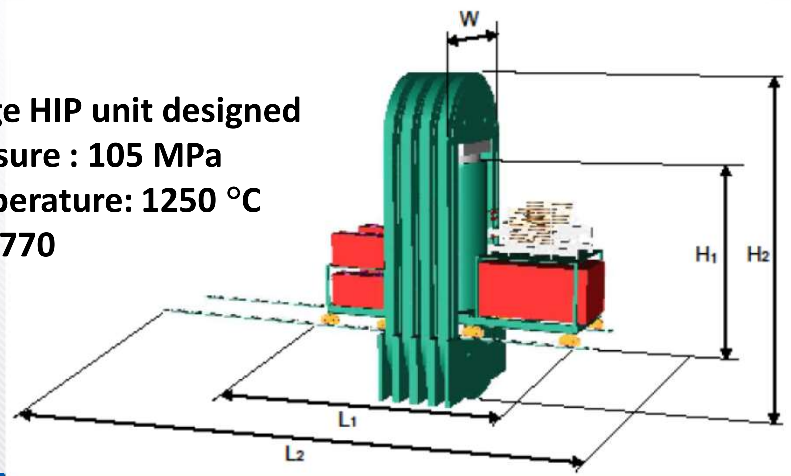
World's largest HIP unit GIGA HIP in Japan

- Max pressure : 118 MPa
- Max temperature: 1350 °C

Company	Vessel Size [mm] (dia x length)
Kinzaku Giken (JP)	2,050 x 4,200
Bodycote (SWD)	1,789 x 3276
Bodycote (UK)	1,235 x 2,470
Bodycote (US)	1,163 x 2,520
ATI (US)	1,285 x 2,898
Alcoa Howmet (US)	1,487 x 2,016
DAT (KOR)	580 x 1,000
KOHIPS (KOR)	550 x 1,300

QUINTUS large HIP unit designed

- Max pressure : 105 MPa
- Max temperature: 1250 °C
- 3,520 x 6,770

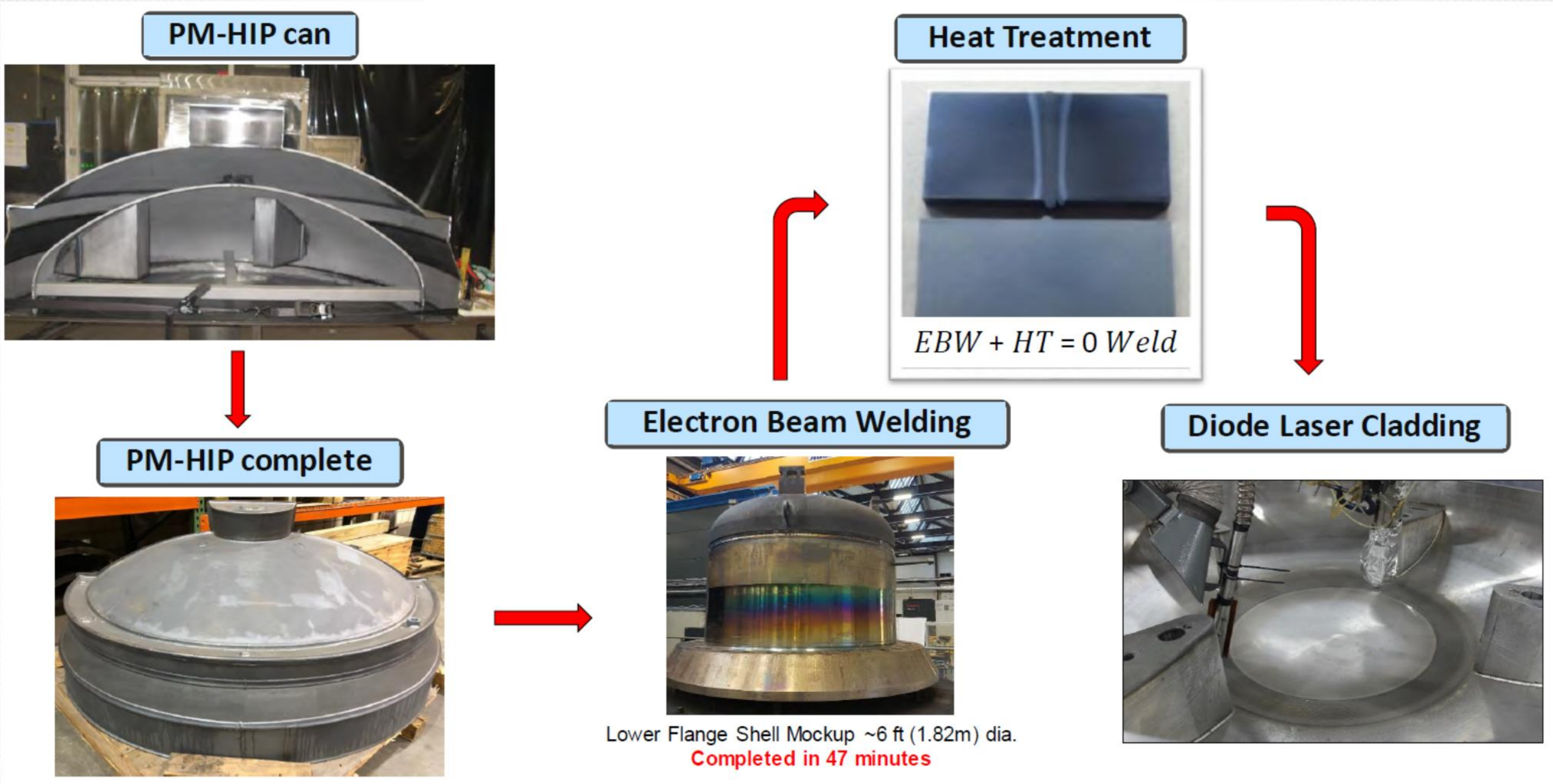


Key Technologies to Acquire for Realization of PM-HIP

In order of importance:

1. **Modeling, Design, Fabrication & Dimensioning of Capsule**
    - Key technologies required to produce near-net-shaped parts or components
    - Collaboration with industries is mandatory for fabrication and dimensioning
2. **Powder making & Optimization of Size Distribution Powder**
    - Production of powders with a chemical composition within specification
    - Optimization of size distribution of powder for good consolidation quality
3. **Neutron Irradiation Tests & Property Qualification**
    - Property qualification of neutron-irradiated HIPed and welded materials is mandatory for acceptance of PM-HIP in ASME or other Codes and licensing.
4. **Optimization of PM-HIP Processing Variables**
    - Optimization of temperature, time and pressure for HIP and correlation with the resultant microstructure and properties of PM-HIP products
5. **Development of Method to Eliminate the Weld**
    - Heat treatments to eliminate of the weld are core technology for the improvement of manufacturing economy and in-service inspection characteristics.

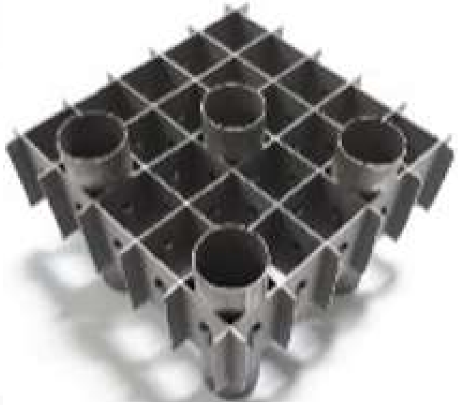
Manufacturing Components with PM-HIP/EBW/HT/DLC

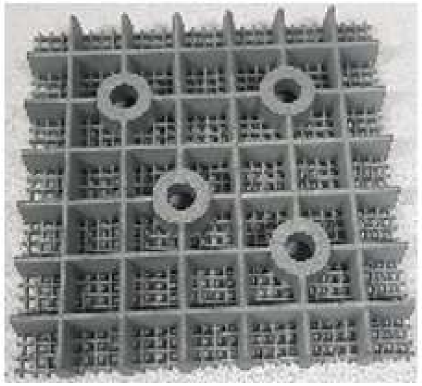


- HIP of sub-sections of component
- Joining of the sub-sections by EB welding
- Elimination of weld by advanced heat treatment

Motivation for Additive Manufacturing

- Complex geometries
  – Example: novel fuel assembly debris filters
- Reduce cost to build complex geometries
  – Example: valve bodies
- Simplify inventory management
  – Just-in-time manufacture of low-volume spares from digital library
- Increase reliability with integrated assembly
  – Example: thimble plug assembly
- Simplify supply chain
  – Reduce number of active qualified vendors
- Manufacture in-kind replacements for obsolete parts
  – Example: fire protection pump impellers
- Othermotivations
  – Functionally graded materials





Additive Manufacturing ASME Code Case Activities

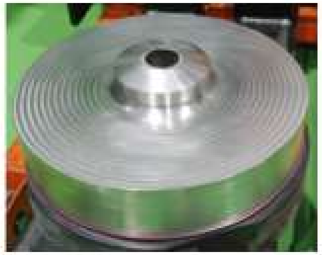
- **Valve for ASME Code Case**
  : 3 inch Cl.1, 2500lbs, Globe Valve

- **ASME Code Case Material & Additive Manufacturing (3D Printing)**
  : 316L (UNS S31603)
  : WA DED (Directed Energy Deposition)
  : Laser DED

- **ASME Code Case Items**
  : Valve Body & Bonnet

3D Printing Items

Additively Manufacturing by Laser DED

full scale Prototype			
			
Flange	Cage	Bonnet	Body
  	Welding procedure specification of Body and Flanges		Body with Inlet and Outlet Channels and assembled with Flanges

Code Case for DED

※ **Same Additive Manufacturing Code** : ASTM F3187 DED requirements

Heat Energy : Arc or Laser

※ **Same Welding Code** : ASME Section IX

Process : Based on GMAW or Laser Welding

※ **Same Material Code** : ASME Section II SA-182

※ **Same Material** : 316L (UNS S31603)

Type : Wire or Powder

※ **Same ASME Section III NB Requirements**

※ **Same ASTM Testing & Evaluation Standards**

Code Case Contents

Wire Arc and Laser Directed Energy Deposition

Case N-xxx

ASTM F3187-16 UNS S31603, Subsection NB, Class 1 Components, Section III, Division 1

Inquiry: May ASTM F3187-16 (Wire Arc and Laser Directed Energy Deposition) UNS S31603 be used for Section III, Division 1, Subsection NB, Class 1 Components construction?

Reply: It is the opinion of the Committee that, ASTM F3187-16 UNS S31603 may be used for Section III, Division 1, Subsection NB, Class 1 Components in construction provided the following additional requirements are met:

(a) For purposes of additive manufacturing and performance qualification, this material shall be considered P-No. 8.

(b) The design stress intensity values and the maximum allowable stress values, fatigue design curves, tensile strength and yield strength values, thermal expansion and other properties shall be the same as for SA-182 UNS S31603.

(c) In Wire Arc Directed Energy Deposition, the maximum allowable filler metal wire diameter shall be 0.047 in. (1.2mm) or less and filler metal wires shall be stored in a dry environment with 18~25℃ atmosphere in accordance with NB-2440.

(d) In Laser Directed Energy Deposition, the maximum allowable powder particle size shall be 0.02 in. (0.5 mm) or less. Following atomization, powders shall be stored in a dry environment.

(e) Test coupons over 8 in. (200 mm) length by thickness thicker than the thickest section of that item shall be printed depending on number and size of test specimens. Or an 8 inch (200 mm) or longer protrusion (extension) can be added to one end of each item that equals or exceeds the thickest section of that item. The protrusion can be removed and coupons are made from the protrusion. Coupons or protrusion shall be printed with optimized printing parameters. These coupons shall be used for chemical composition analysis, microstructural and inclusion examination, delta-ferrite, intergranular corrosion tests, guided bend tests, CVN tests, hardness tests, tensile tests, and fatigue tests as required below.

(1) Chemical composition analysis, microstructural and inclusion examination, delta-ferrite, and inter-granular corrosion measurement shall be performed at the midsection of coupons or coupons removed from the protrusion and in accordance with following requirements.

ⓐ Chemical composition analysis shall be performed in accordance with ASTM E353 or ASTM E1086.

ⓑ Microstructural examination through micro-etching shall be performed in accordance with ASTM E407.

ⓒ Inclusion analysis shall be performed in accordance with ASTM E45.

ⓓ Delta-ferrite content and number are critical for hot cracking susceptibility and shall be performed in accordance with NB-2433. The content may also be measured using ferrite scope instrument.

ⓔ Inter-granular corrosion tests shall be performed in accordance with ASTM A262 Practice E.

(2) Mechanical property tests, including tension tests at room temperature and temperatures up to 525℃, hardness tests, guided U-bend tests, and CVN impact tests at room temperature, and fatigue tests at room temperature and 300℃, shall be performed at the midsection of coupons or coupons removed from the protrusion and in accordance with following requirements.

ⓐ Tensile tests at room temperature and temperatures from 100℃ up to 525℃ shall be performed in accordance with ASTM E8, and ASTM F2971. The results shall be evaluated in accordance with SA-182 UNS S31603 requirements of ASME Section II Part D.

ⓑ CVN impact tests shall be performed in accordance with ASTM E23.

ⓒ Hardness tests shall be performed in accordance with ASTM E18.

ⓓ Guided U-bend tests shall be performed in accordance with ASTM E190.

ⓔ Fatigue tests shall be performed in accordance with ASTM E606.

(3) Nondestructive examination shall be in accordance with NB-2540. The ultrasonic examination shall cover 100% of its volume using both straight and angle beam methods. Items that are produced in the form of tubular products shall be examined in accordance with NB-2550.

(f) The material shall not be used for components where the neutron irradiation fluence levels will exceed 1×10^{17} n/cm^2 (E > 1 Mev) within the design life of the component.

(g) All other requirements of NB-2000 for austenitic materials shall apply.

(h) This Case number shall be marked on the material and listed on the Certified Material Test Report and on the Component Data Report.

THANK YOU