AMM Advanced Methods for Manufacturing

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HIP Cladding and Joining to Manufacture Large Dissimilar Metal Structures for Modular and GEN IV Reactors

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Background

Powder metallurgy-hot isostatic pressing (PM-HIP) has been implemented into ASME code case and is currently being evaluated to fabricate RPV elements for SMRs and GEN IV reactors.

Reactor Ring Section

Lower Reactor Head

Steam Plenum Access Port

- ❑ Net or near net shape manufacturing for large nuclear structures
- ❑ Good mechanical properties often comparable or exceeding those of forged and cast materials
- ❑ Support "factory fabrication"
- ❑ Reduced manufacturing cost and time
- ❑ Improved inspectability and reliability

Limitation: the current PM-HIP technology is mainly limited to fabrication of single material components

Common dissimilar structures in RPV

1) RPV cladding for corrosion resistance
2) Dissimilar metal welding (DSW)

RPV Cladding

Metallic cladding is critical in terms of providing surface protection against corrosion and wear damage for SMRs and GEN IV reactor components.

Current Technology
(separate steps to create large dissimilar metal
res)

Component Fabrication

HIP Capsule Removal

Surface Cladding

On Complex Geometry

Technical Issues

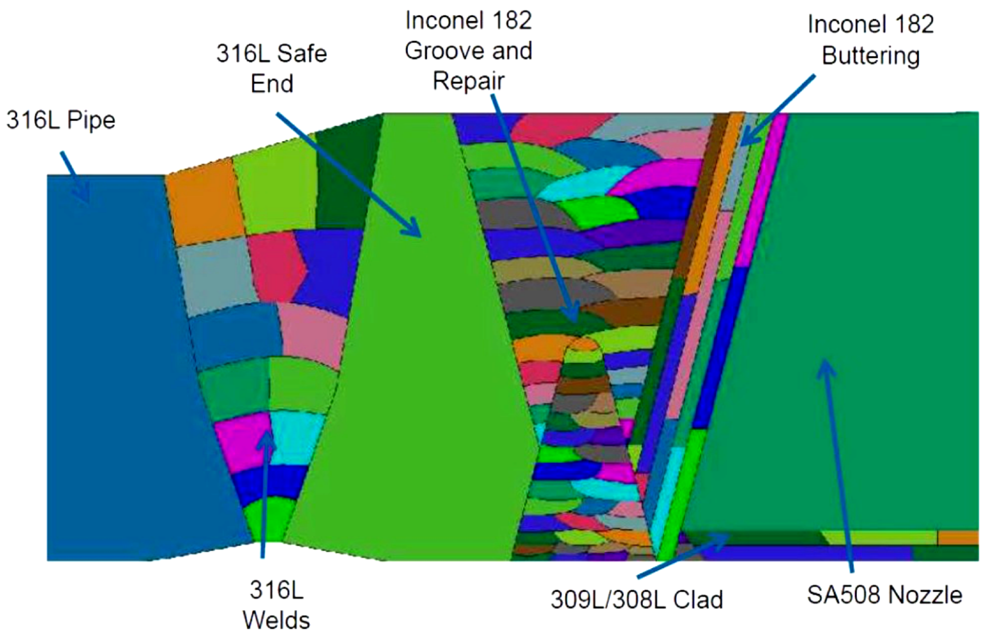
- ❑ Multiple steps involved with increased cost and time;
- ❑ Weld thickness limitation;
- ❑ Quality issue;
- ❑ Clad complex geometry;
- ❑ Additional machining

Proposed Approach
PM-HIP +
Bimetallic HIP

- ❑ Net or near net-shape dissimilar structure
- ❑ Eliminate HIP capsule removal
- ❑ HIP surface cladding
- ❑ High quality than arc welding

Dissimilar Metal Welding

Dissimilar metal welding is common in reactor structures.



Technical Issues

- ❑ Welding issues, causing DMW damage, premature failure
- ❑ Poor inspectability
- ❑ Microstructural inhomogeneity
- ❑ Susceptible to environmental attacks and long-term material degradation, such as stress corrosion cracking
- ❑ Cost and time due to field operation

Alternative: Utilizing powder based HIP joining to eliminate the need for dissimilar metal welding

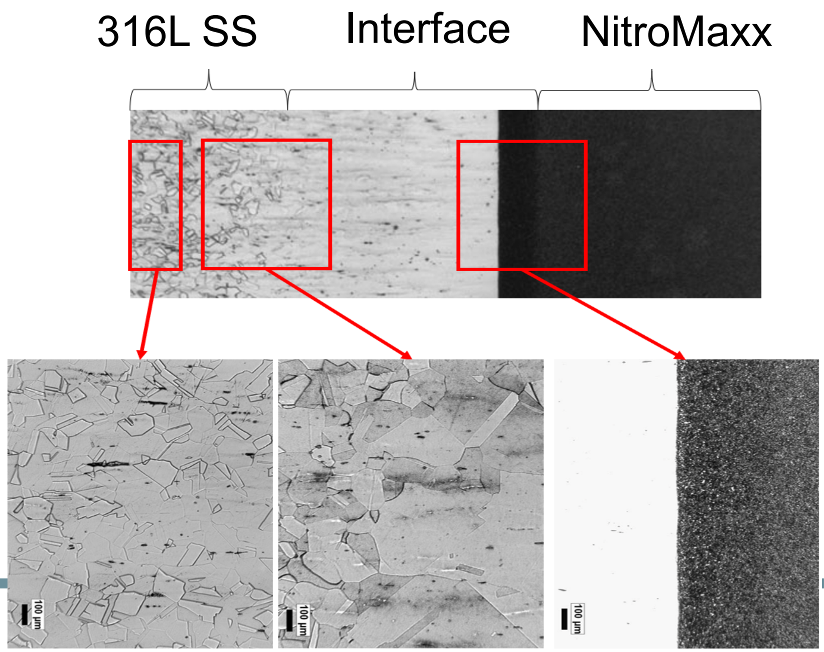
Major Technical Challenge 1

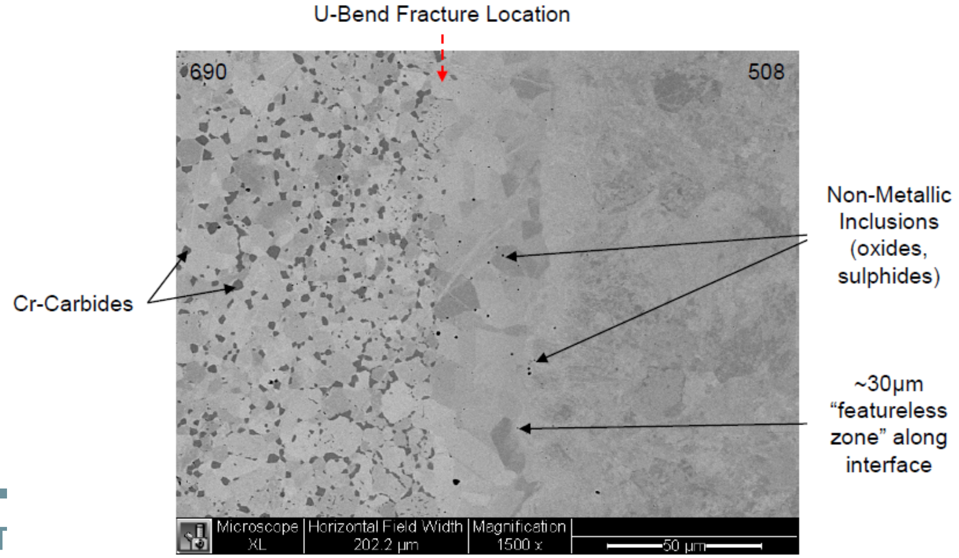
Short-term and long-term metallurgical stability across the interface

Post HIP RPV Heat Treatment
- Solution annealing
- Normalization
- Tempering
- Post-weld heat treatment

- ❑ Processing defects
- ❑ Grain inhomogeneity
- ❑ Carbon and nitrogen redistribution
- ❑ Elemental segregation
- ❑ Precipitation (oxides, carbides, etc.)
- ❑ GB sensitization

- ❑ Reduced strength/toughness
- ❑ Enhanced corrosion susceptibility



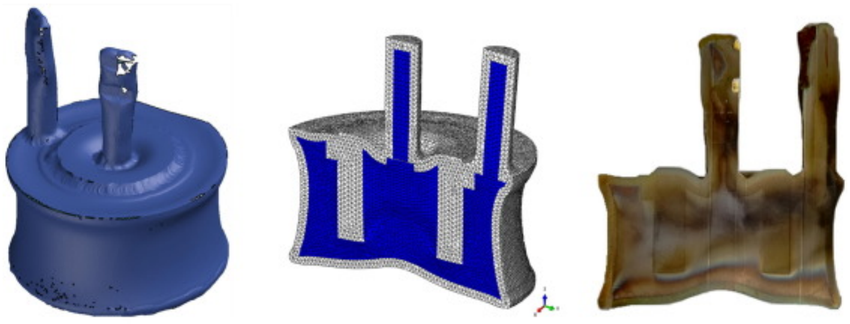


Major Technical Challenge 2

Predicting geometric distortion and shrinkage for large structures

For large structural components, the geometry distortion or size shrinkage is expected and can reach up to 35% of the volumetric value.

Efficient process simulation and HIP capsule design are essential to enable near net shapes without multiple experimental iterations.



A.Abena, M.Aristizabal, K.Essa, Advanced Powder Technology, 30 (11), p. 2451 (2019)

Knowledge Gaps

Dissimilar Metal Cladding and Joining:

Very few studies have been conducted to understand dissimilar metal structures made by advanced manufacturing, including PM-HIP

Design and Process Strategies for HIP Cladding and Joining:

- ❑ Candidate design and configuration
- ❑ Materials
- ❑ Transitional joint and compositionally graded joint
- ❑ Heat treatment

Accurate Model Prediction to Support Large Structure Manufacturing

- ❑ Finite element model for geometric distortion/shrinkage
- ❑ Plasticity enhanced diffusion model for process simulation

Material Properties

Long term performance of such joint at reactor temperatures is unknown

Component-level Demonstration

Lack of business practice and experience at the component level

Project Objectives

Develop and commercially demonstrate the cost/time reduction and quality improvement by implementing powder-based hot isostatic pressing (HIP) cladding and joining strategy (powder-to-solid or powder-to-powder) for manufacturing large-size and thick-section dissimilar metal pressure retaining components of SMRs and GEN IV reactors

Design and Optimization

- ❑ Coupon-level design, fabrication, and optimization
- ❑ Metallurgical and mechanical evaluations
- ❑ Thermal-aging and environmental effects
- ❑ Quality control

HIP Modeling

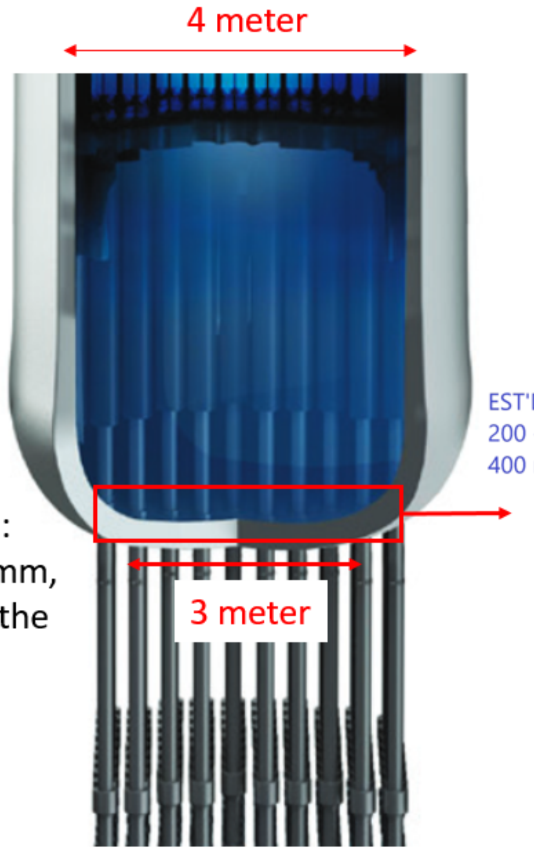
- ❑ Modeling of non-uniform shrinkage for accurate HIP tool design
- ❑ Powder based diffusion bonding model

Component Demonstration

- ❑ Subscale sized component fabrication
  - ▪ RPV cladding for SMR
  - ▪ Dissimilar metal joining for advanced reactor
- ❑ Destructive and non-destructive component testing
  - ▪ Material property
  - ▪ Inspection

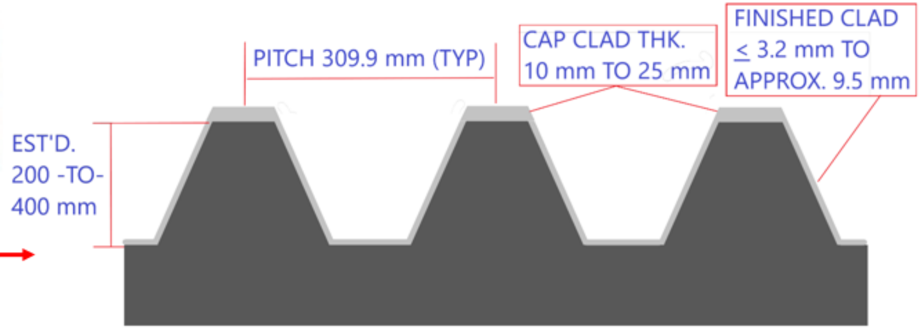
Targeted Reactor Applications

Case 1 – Cladded bottom section of RPV in GE's BWRX-300 SMR



Wall Thickness: 263mm – 463mm, depending on the location

Complex cone geometry for Bottom Mounted Instrumentation nozzle



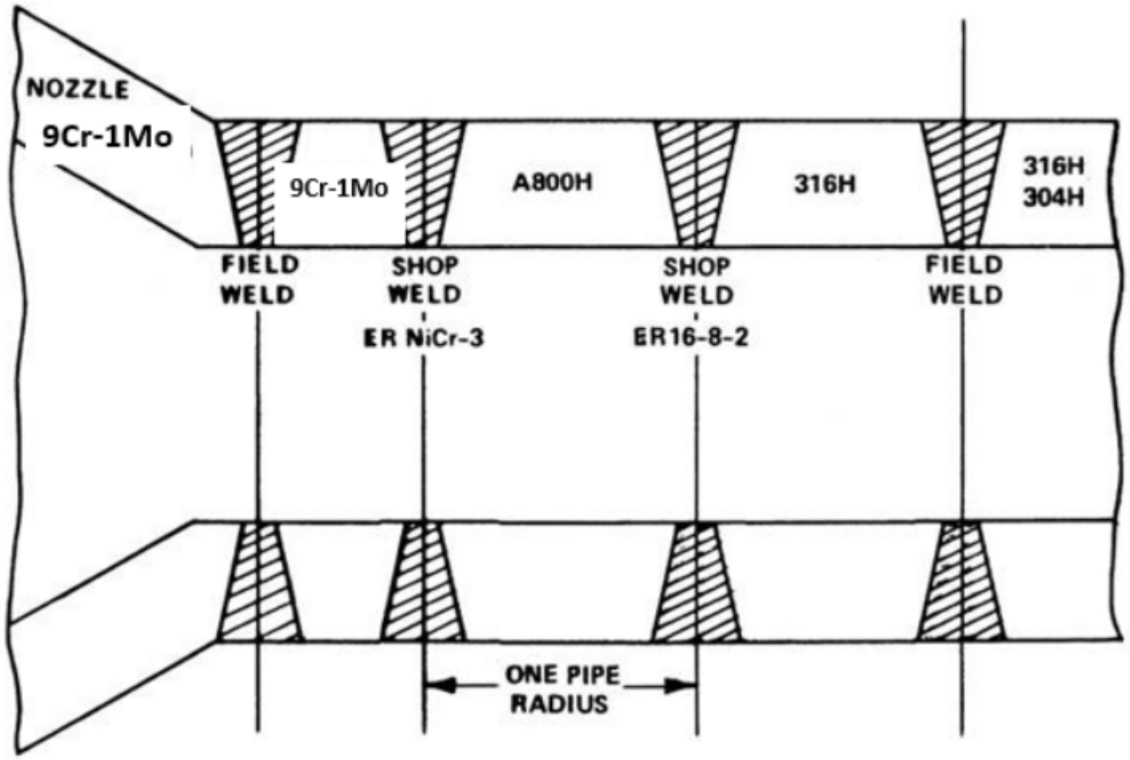
BASE MATERIAL SA-508 GR. 3 CONDITION 2

Forged flat plate with truncated-cone buildups, orthogonal 4X4 array with 300-series stainless steel for corrosion resistant overlay cladding.

A508 Solid	Powder	316L Solid

Targeted Reactor Applications

Case 2 – DMW in intermediate heat transfer system piping for GE PRISM sodium advanced reactor



This dissimilar metal structure represents the high complexity of transition joint for high temperature applications:

<u>Total 7 material transitions through this joint</u>

P91 Solid	Ni Powder	316H Solid

Program Task Overview and Schedule

Program Activities	AU	EPRI	Synertech	Nuclear AMRC	UW	GE-R	GEH	Westinghouse	1st Year				2nd Year				3rd Year			
									Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Task 1: Design Review and Material Selection							X	X												
Task 2: HIP Process Development and Optimization			X	X																
Task 3: Material Evaluation and Characterization	X	X				X														
Task 4: HIP FEM Model Optimization			X																	
Task 5: Powder Based Diffusion Model					X															
Task 6: Component Demonstration			X	X			X	X												
Task 7: Destructive and non-destructive component evaluation		X																		
Task 8: Powder Oxidation on Part Quality	X																			
Task 9: Long-term thermal-aging and Environmental Assessment	X					X														
Project management	X	X																		
Annual Report																				

Task 1: HIP Coupon Fabrication and Process

HIP cycle designs: (1) HIP pressure, (2) temperature, and (3) dwell time.

HIP joint configuration:
(1) Direct joint: metal A/powder B configuration;
(2) Transition joint: metal A/powder C/metal B configuration;
(3) Graded joint: metal A/graded powder region (A+B)/metal B.

Geometric study on small parts:
(1) geometric distortion; (2) size shrinkage.

Post HIP heat treatment study per OEM spec.

Task 2: Metallurgical and Mechanical Evaluations (short-term and long-term)

Objectives:
- Guide the down-selection of the joint configurations
- Support model development in terms of geometric change and element diffusion
- Develop material property data package
- Evaluate post-HIP heat treatment effects
- Long-term thermal and environmental effects

Metallurgical Aspects
- Diffusion and element redistribution
- Grain structure
- Precipitation
- Microstructural evolution

Mechanical Aspects
- Hardness
- Toughness
- Tensile properties at different temperatures
- Fatigue
- Creep

Environmental Aspects
- Sensitization
- Corrosion

Manufacturing Aspects
- HIP defects
- Geometric distortion and shrinkage

Task 3: HIP Finite Element Model for Non-uniform Shrinkage

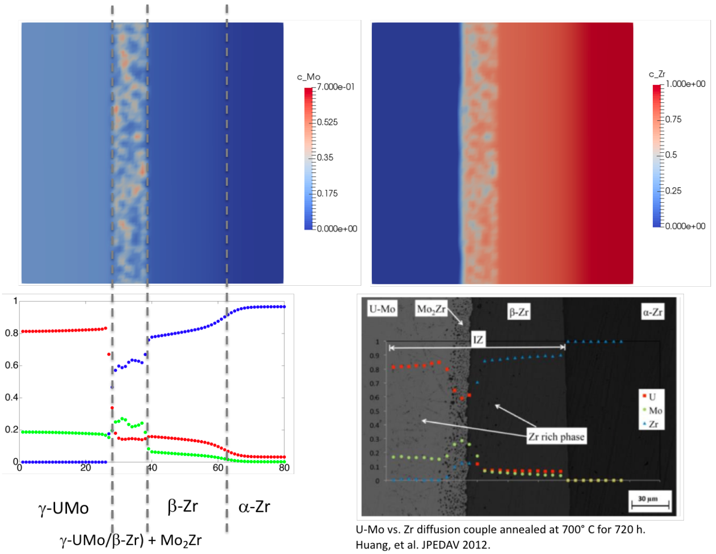
Code is currently available in Synertech for designing HIP tooling and predict geometric change. However, additional work needs to be done to support the accurate prediction for large nuclear structures.

- ❑ The existing FEM codes will be expanded to predict the multi-material behavior during the joint plastic flow of compressible and non-compressible media.

- ❑ Update the model with the yield criterion as a function of the temperature and density inside the large capsule.

- ❑ High temperature property data through high-temperature compression test

Task 4: Powder-based diffusion bonding model



U-Mo vs. Zr diffusion couple annealed at 700° C for 720 h.
Huang, et al. JPEDAV 2012.

- Create surrogate model alloys for the two components to be bonded, for instance, FeNiCr for stainless steels and FeCr for F/M steels;
- Implement temperature-dependent materials models for the free energies (chemical potentials) and the diffusion coefficients;
- Create a plasticity model for the model alloys using temperature-dependent modulus, strength, and hardening coefficients;
- Develop and implement a model that describes the dependence of diffusion coefficients on temperature, stress, and plastic strain (dislocation density).

Task 5: Component demonstration and evaluation

Two sub-scale size demonstration:

(1) Stainless steel cladding for RPV bottom along with BMI nozzles

- Eliminate the need for capsule removal and cladding
- Thicker cladding
- Simultaneously manufacture RPV, BMI nozzles, and cladding

(2) DMW in intermediate heat transfer system piping for GE PRISM

- Reduce the complexity of the transition joint
- Improve the joint quality
- Integrate to RPV manufacturing

Goals:

- ❑ Cost and time assessment at the component level
- ❑ Validate the fidelity of HIP FEM prediction model
- ❑ Confirm metallurgical and mechanical properties from the actual component
- ❑ Non-destructive inspection

Possible Areas/Industries/Programs (and Readiness) for Adoption

The project develops alternative cladding and joining technologies to address the industry's near-term needs to fabricate multi-material reactor structures. If demonstrated successfully, the technology is well positioned to be adopted by industry

- HIP cladding for thick-section RPV structures
- Dissimilar metal joining for RPV components or reactor internals
- HIP modeling tools

Contact Information and Questions

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