Advanced Manufacturing with Advanced Materials for Nuclear Applications

ROBERT OELRICH
Fuels and Materials Performance, National Security Directorate, PNNL
NRC Public Workshop on Advanced Manufacturing - December 7-10, 2020

IR# PNNL-SA-158421
Additive Manufacturing: Components are now being introduced into commercial LWRs

- PWR thimble plug assembly installed at Exelon’s Byron Unit 1 in Spring 2020
- BWR channel fasteners to be installed at Brown’s Ferry in Spring 2021

Advanced Manufacturing: Accident Tolerant Fuel (ATF) coated cladding also being introduced in PWRs and BWRs

- GNF Armor-coated Zirconium at Plant Hatch
- Framatome EATF Chromium-coated M5® into Vogtle 2
- Westinghouse EnCore® Chromium-coated rods in Byron 2
Advanced Materials with Advanced Manufacturing

The combination of Additive Manufacturing flexibility with advanced materials can result in innovation that was previously unachievable.

Additive Manufacturing
- Complex Geometry
- Improved Heat Transfer
- Debris Filtering
- Anisotropic Mechanical Properties

Advanced Materials
- Thermal Performance
- Strength and Ductility
- Corrosion Resistance
- Wear Resistance

Game-Changing Innovation

Industry Benefits:
- Higher Safety Margins
- More Favorable Economics
- Enhanced Accident Survivability
- Enabling of Advanced Reactor Concepts
Advanced Materials with Advanced Manufacturing

► **Advanced Manufacturing**
  - Complex geometries not possible with traditional manufacturing
  - Material and weight savings
  - Materials: SS 316L, Inconel 718, Zirconium, Titanium & Aluminum alloys

► **Advanced Materials**
  - Improved thermal and mechanical properties
  - Enhanced radiation, wear and corrosion resistance
  - Materials: new alloys, carbides, nitrides, MAX phase, ceramics, ODS steels

► **Advanced Manufacturing with Advanced Materials**
  - Functionally Graded Materials (FGM)
  - Applications of some new non-traditional reactor materials
  - New components for advanced reactors (unrestricted by existing environments and configurations)
Advanced Manufacturing (AM) can be useful for direct component replacement, and/or to implement evolutionary improvements in performance or weight.

- However, costs may not justify AM for high volume parts or for long qualification processes.

- Strongest opportunities may be for totally new concepts for future advanced reactor components which may not be constrained by pre-existing requirements: enveloping geometry, thermal and other environmental conditions, licensing bases, etc…

Diagram:

- **Advanced**
  - Enhanced Material Performance
    - SiC Fuel Cladding
    - Carbides, Nitrides, MAX Phase Coatings
  - Advanced Reactor Components
    - Gen IV+ Fuel & Rx components
    - Nano-materials
    - Functionally Graded Materials (FGM)
- **Materials**
  - Cr Coated Cladding
  - Carbides, Nitrides, MAX Phase Coatings
  - Functionally Graded Materials (FGM)
- **Existing Reactor Components**
  - BWR Channel Fasteners
  - PWR Thimble Plug Assembly
  - Debris Filter Components
- **Complex Geometries**
  - Fuel Assembly Spacer Grids
  - Nano-materials
Additive Manufacturing introduces new variables that must be controlled throughout the development and qualification cycle.

Parameters
- Energy, speed of deposition
- Thermal conditions, temperature gradients, solidification velocities, localized annealing rates
- Powder characteristics
- Alloys, impurities

Material Properties
- Isotropic/Anisotropic performance
- Strength, Ductility
- Production Rates
- Surface Finish
- Microstructure
- Composition Homogeneity
There are at least three separate opportunities to introduce Advanced Manufacturing into the development and qualification process…

1. Enhance Conceptual Design
2. Enable rapid prototyping
3. Help to optimize production (e.g. minimize weight, optimize costs and energy)
The many forms of Advanced Manufacturing introduces new flexibility into the development and qualification process. Also, AM technology continues to evolve at a fast pace.

- Technology can outpace the qualification and licensing process.
- Traditional certification and qualification processes need to be improved.

To retain the most flexibility from AM, consider qualifying material and irradiation performance as much as possible based on material characterization - specific AM technology can/will evolve.
Advanced Manufacturing in the Development Process

- Evolving AM technology can disrupt material performance, jeopardizing the qualification process.
- Define and control basic material characteristics early in the process.
- Also inform regulators in advance of new technology as early as possible.

![Diagram showing the development process](attachment:image.png)
The third “AM”, Advanced Modelling, supports Additive Manufacturing and Advanced Materials
- Additive Manufacturing can enable rapid prototyping in the testing phase
- However, it also introduces additional variables into the prototyping/testing process
- So, empirical modelling and qualification can be much more challenging

Advanced modelling can be utilized to better predict and control the governing AM parameters influencing the product performance

Finally, with so much more computer-based modelling earlier in the development cycle, Cyber Security becomes even that much more critical to protect Intellectual Property.
Case Study – Accident Tolerant Fuels

- ATF coated cladding development represent a similar qualification and licensing challenge as other AM development programs
  - Material properties are heavily dependent upon new but controllable process parameters, such as temperature, speed, carrier gas, energy of deposition, impurities
- Critical to understand and control desired microstructure characteristics, not just process parameters
  - Qualification and licensing based on fundamental material properties, not simply deposition process parameters
  - Key modelling and material characterization must be brought forward in the process
IL TROVATORE:

- An international collaboration with strong academic input & industrial support
- Beneficiaries: 28 from Europe, 1 from the US, and 1 from Japan
- External Expert Advisory Committees:
  - Scientific Advisory Committee
  - End Users Group (Oelrich member)
  - Standardization Advisory Committee (ASTM/C28, CEN/TC 430, ISO/TC 85)
Goal: Help to address the global societal & industrial need for improved nuclear energy safety by optimizing and validating select ATF cladding material concepts in an industrially relevant environment (i.e., under neutron irradiation in PWR-like water in the BR2 research reactor)

Candidate ATF Cladding Material Concepts:
- SiC/SiC composite clads, different concepts
- Coated clads (e.g., Cr-coated zircaloys); innovative coating materials: MAX phases, doped oxides
- GESA surface-modified clads
- ODS-FeCrAl alloy clads
Goal: Help to address the global societal & industrial need for improved nuclear energy safety by optimizing and validating select ATF cladding material concepts in an industrially relevant environment (i.e., under neutron irradiation in PWR-like water in the BR2 research reactor)

<table>
<thead>
<tr>
<th>SiC/SiC Composite Clads</th>
<th>Coated &amp; Surface-Modified Clads</th>
<th>ODS-FeCrAl Clads</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="SiC/SiC Composite Clads" /></td>
<td><img src="image2" alt="Coated &amp; Surface-Modified Clads" /></td>
<td><img src="image3" alt="ODS-FeCrAl Clads" /></td>
</tr>
<tr>
<td>1 µm</td>
<td>2 nm</td>
<td>300 nm</td>
</tr>
<tr>
<td>GESA Clad Surface Modification</td>
<td>FeCrAl-coated DIN 1.4970 SS</td>
<td></td>
</tr>
</tbody>
</table>
The accelerated development of nuclear materials entails:

- Interconnectivity of *application-driven material design, material production and material performance assessment* in application-relevant conditions

- Development of *reliable high-throughput material screening tools*, e.g., use of *ion/proton irradiation* to assess radiation tolerance; *select modelling approaches* (atomic scale, FE, etc.) to predict in-service material behavior
Material Design: Basic Considerations

- **Phase Purity**: $(\text{Nb}_{0.85}\text{Zr}_{0.15})\text{AlC}_3$
  - Minimize cracking by differential swelling
  - GB: $0.5 \mu m$

- **Texture**: $\text{Cr}_2\text{AlC}$
  - Minimize cracking by anisotropic swelling

- **Grain Size**: $\text{Ti}_3\text{SiC}_2$
  - $(3.4 \text{ dpa, } 735^\circ\text{C})$
  - Maximize radiation defect annihilation
  - Denuded zone $0.5 \mu m$
In conclusion...

- Ensure the value proposition (business case) up front: safety and economics
  - Balance potential benefits against realistic risks of new materials and processes
  - Introducing AM to existing parts without advanced materials may not justify costs of development and qualification
- Seek successful collaboration approaches between industry, DOE, national labs, and NRC
- Leverage prior qualification of first-of-a-kind AM processes, materials, and modelling
  - Apply lessons learned from ATF coated cladding development and qualification
  - Coated cladding workshop at PNNL
- Plan well in advance for a successful qualification process
  - NRC AMT Application Guidance
  - Apply advanced predictive technology, including atomic and meso-scale modeling and in-situ testing
  - Meet with regulators early in cycle to share new technologies and qualification bases as early as possible
Thank you for your attention…