Present status of surface-modified Zr alloy claddings in KAERI

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Objective
- Enhanced performances during accidents than current Zr cladding
- Increased/Maintained performances under normal condition

Approach
- Surface modification (1)
- Metal-ceramic hybrid (2)

Considered issues
- Oxidation/corrosion resistance
- Mechanical strength
- Thermal conductivity
- Thermal expansion coefficient
- Phase stability
- Adhesion to the matrix
- Neutron economy
- Irradiation susceptibility
- Tube fabricability
- Unknowns...

Mid-term
- Surface Modified Zr Cladding
- Zr alloys
- Surface modification

Long-term
- Metal-Ceramic Hybrid Cladding
- Zr alloys
- Ceramic composite
- Surface coating
Surface Modification Technology

**Objective**
- √ Surface coating
  - Increase of oxidation/corrosion resistance in both accident and normal condition
- √ Partial ODS-Zr
  - Increase of strength at high-temperature without severe decrease of ductility under normal condition

**Approach**
- √ Surface coating (~50 micron)
  - Coating technology development
    → Cold spray + Laser beam scanning
    → Arc ion plating + Laser beam scanning
    → 3D laser coating
  - Coating material development
    → Cr, Cr-alloy, FeCrAl/Cr...
- √ Partial ODS-Zr (~100 micron)
  - ODS technology development
    → Laser beam scanning with oxide powder
Irradiation Test Plan

- **Halden reactor test: Cooperation with “THOR Energy”**
  - Two ATF rods with instrumentation
  - **Rod 1:** Metallic microcell pellet(\(\text{UO}_2+5\text{vol}\%\text{ Cr}\)) + Coated(Cr-based alloy) Zr cladding
  - **Rod 2:** Ceramic microcell pellet(\(\text{UO}_2+0.6\text{wt}\%\text{Si-Ti-O}\)) + Coated(FeCrAl/Cr) Zr cladding
  - Irradiation period: 2015.09 ~ 2017.05
  - Estimated burn-up: 25 GWd/MTU

- **Halden reactor test: Halden Reactor Project (HRP)**
  - ATF Claddings and ATF Pellets were proposed as candidates for test
  - **Surface modified Zr claddings (ODS + coating)** are proposed
  - Irradiation period: 2016 ~
Coating Material Development for ATFC

- **Objective of new coating material development**
  - More increased oxidation resistance than Cr metal in accident condition
  - More increased corrosion resistance than Zr alloy in normal condition

- **Approach**
  - Model alloy design based on physical/mechanical property, neutron economy, corrosion characteristics, manufacturing process of alloying and coating...
  - Performance evaluation of model alloy
Performance Evaluation of Test Samples

- Corrosion test of coating materials
  - Test conditions: PWR simulated-loop, 360°C, 18.9MPa

![Graph showing weight gain over time for different samples](image)
Sample Fabrication for Irradiation Test

Test sample design

Coating
Zircaloy-4

Outer Diameter: 9.6~9.75 mm
Inner Diameter: 8.36 mm
Length: 405~435 mm
Zry-4: OD 9.5 mm, ID 8.36 mm, WT 0.57 mm

Test sample fabrication

3D laser coating
Arc ion plating

Coating A  FeCrAl/Cr coated Zry-4 cladding
Coating B  Cr-alloy coated Zry-4 cladding
Performance Evaluation of Test Samples

- Oxidation test of coated cladding tubes
  - Test conditions: 1200°C for 2000s, steam
    no internal pressure

<table>
<thead>
<tr>
<th>Coated cladding</th>
<th>Ref. cladding</th>
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<tbody>
<tr>
<td>Zry-4 cladding</td>
<td>ZrNbSnFe cladding</td>
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</table>

Oxidation resistance of coated cladding is superior to that of Ref. cladding.
Performance Evaluation of Test Samples

- 4-point bend test after oxidation test
  - Test conditions: 0.15mm/min

Bending strength of coated cladding is superior to that of Ref. cladding
Performance Evaluation of Test Samples

- LOCA-simulation test
  - Test conditions: 1200°C for 300s, steam hoop stress of 61 ± 2MPa

Ballooning and rupture behaviors are shown in both claddings.
Performance Evaluation of Test Samples

- 4-point bend test after oxidation test
  - Test conditions: 0.15mm/min

Bending strength of coated cladding is superior to that of Ref. cladding
Performance Evaluation of Test Samples

- **Microstructural observation**
  - Test conditions: 1200°C for 300s, steam hoop stress of 61 ± 2MPa

Coated cladding

Ref. cladding

Oxidation resistance of coated cladding is superior to that of Ref. cladding at outer surface.
Performance Evaluation of Test Samples

- Corrosion test of coated cladding tubes
  - Test conditions: static autoclave, 360°C, pure water, 18.9MPa

Coating A: FeCrAl/Cr  
Coating B: Cr-based alloy

From the static autoclave test result, the flaking and other damages were not observed in the tested samples, although the period of corrosion test was not fully enough.
**ODS Technology Development for ATFC**

- **Objective of partial ODS-Zr development**
  - more increased mechanical strength than Zr-alloy at high-temperature
  - reduce of severe ballooning/rupture deformation during accident

- **Approach**
  - consideration of strength mechanism of Zr-alloy at high-temperature
  - consideration of performance, easy application, and efficiency

  - **Laser Beam Scanning with Y$_2$O$_3$ Powder**

![Laser treatment image](image-url)

![Graph showing engineering stress vs. engineering strain](graph-url)

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**Laser Beam Scanning with Y$_2$O$_3$ Powder**

- **Y$_2$O$_3$ dispersed layer**

Test temperature: 500°C

![Graph showing engineering stress vs. engineering strain](graph-url)
Performance Evaluation of Test Samples

- Observation of oxide particles with increasing temperatures

HVEM

RT

350°C

700°C

1000°C
Summary

- For the research reactor test, the two types of coated samples were fabricated.
  - New Cr based alloys are developed and coated on the Zry-4 cladding.
  - Oxidation resistance of coated cladding is superior to that of Ref. cladding.
  - Adhesion property of coated claddings is very reasonable during the accident conditions and normal operating corrosion.

- Stability of oxide particles is identified to accomplish the surface-modified concept (partial ODS + coating).
  - The $Y_2O_3$ particles are maintained without a reaction to Zr matrix up to 1000°C.
감사합니다.
Thank you for your attention.