Cold Spray Mitigation & Repair for Nuclear Applications

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VRC Metal Systems

- Cold Spray Equipment Manufacturer and Commercialization Partner, specializing in process development for Repair, Additive Manufacturing, Coating, and Joining applications.
- Veteran Owned Small Business Established in 2012 focused primarily on DoD applications.
- Headquartered in Rapid City, South Dakota. 3 US locations.
- 63 Full Time Staff
Problem – *Seawater Corrosion*

- Corrosion of structural steels in military and industrial applications is a widespread problem
  - Cost to the US Navy:
    - 20-25% of total maintenance costs Corrosion mitigation and remediation –
    - Estimates as high as $4B Annually
  - Cost to Nuclear Energy:
    - Corrosion-related causes of partial LWR outages - $5M/year
    - Corrosion-related causes of zero power LWR outages - $665M/year
    - Contribution of corrosion to LWR operation and maintenance (O&M) - $2B/year

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Stainless Steel Materials for Seawater Service

• Common Austenitic Grades
  • 304 & 316 most common industrial wrought steels
  • CF series most commonly used cast stainless steel
  • Cast Austenitic grades can contain up to 40% Ferrite, although higher levels of Ni and C stabilize Austenite in highly alloyed steels

• Even the most corrosion resistant grades are susceptible to
  • Stress Corrosion Cracking
  • Crevice Corrosion

• Solution: Cold Spray Corrosion Mitigation

<table>
<thead>
<tr>
<th>Wrought</th>
<th>Cast</th>
</tr>
</thead>
<tbody>
<tr>
<td>304L</td>
<td>CF3</td>
</tr>
<tr>
<td>304</td>
<td>CF8</td>
</tr>
<tr>
<td>304H</td>
<td>CF10</td>
</tr>
<tr>
<td>316</td>
<td>CF8M</td>
</tr>
<tr>
<td>AL-6XN</td>
<td>CN3MN</td>
</tr>
<tr>
<td>Alloy 20</td>
<td>CN7M</td>
</tr>
</tbody>
</table>
Solution – Cold Spray Corrosion Mitigation

• Applied at Low Temperatures
  • Coatings can be applied as low as 400 °C

• Dense and Highly Adherent
  • Less than 1% porosity and greater than 10ksi adhesion typical

• Can be applied with Nitrogen for cost sensitive applications
  • Pure Metals (e.g. CP-Ni), Alloys (e.g. 316L) and Metal Matrix Composites (e.g. Ni / CrC) can be sprayed with high Deposition Efficiency.

• Cold Spray contains crack retarding compressive residual stresses
  • Resists stress corrosion cracking

• Corrosion Control Coatings typically non-structural, allowing quicker implementation.

Solution – Cold Spray Corrosion Mitigation

• Typical Cold Spray coatings exhibit porosity less than 1%.
• Dependent on material and processing parameters
• Polished cross section – No particles can be seen
• Etched cross section shows particle boundaries
• Significant flattening observed

Cold Sprayed Nickel
Case Study – Cold Spray CISCC Mitigation

• Long term on-site is now being considered.
  • Large Existing Fleet Made from welded 304SS - Known for susceptibility to SCC
  • Chlorine-assisted SCC threshold in austenitic stainless steel as low as 80-100 MPa
  • 304 stainless steel girth welds are likely sites for initiation and propagation of SCC

• Dry Canisters not readily maintainable
  • Difficult to inspect and repair
  • Potential for CISCC environment to form, especially near seawater
  • Canister removal and replacement or repair costly

• Cold Spray Corrosion Resistant Coatings with Compressive Residual Stresses Offer an Ideal Solution to CISCC Mitigation.

Case Study – Cold Spray CISCC Mitigation

- ASTM G36 Boiling MgCl testing
  - Very effective cracking of 304 and 316 Stainless
  - Boiling point of 140 °C assures cracking efficacy.
    - MgCl Concentration Increased to achieve 140 °C
  - Samples welded to create tensile residual stresses.
  - Uncoated and Cold Spray Coated Samples tested
  - Samples exposed for 24 hours
  - Extensive and deep CISCC on Uncoated 304L
  - No cracking observed on Coated 304L
- The Challenge -

Can the Cold Spray solution be applied in a difficult-to-access application?

YES!

• Cold Spray Mitigation coatings have been demonstrated in laboratory mock-up canisters and in field conditions.
• Coatings can be applied within Overpack from a modified inspection crawler.
• Demonstrations have been performed in laboratory and field environments for vertical canisters using upper vent access.
  • Mockup demonstrations include straight-vent & stepped vent access and direct overpack placement designs.
  • Field demonstrations have been performed on an ISFISI.
Case Study – Cold Spray CISCC Mitigation
Case Study – Cold Spray CISCC Mitigation

- Cold Spray CISCC Mitigation has been successfully deployed on an active ISFSI within a commercial vertical canister system.
  - Developed with and approved by customer.
  - Independently analyzed and verified.
  - Commercial Grade Dedication Process
  - Deployed within a heated test canister
  - Integrated into Long-Term Inspection and Mitigation Plan

<table>
<thead>
<tr>
<th></th>
<th>Stability</th>
<th>Inspect-ability</th>
<th>Adhesion</th>
<th>Porosity</th>
<th>Tensile Strength</th>
<th>Thickness Capability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tech. Obj.</td>
<td>Y</td>
<td>Y</td>
<td>&gt; 10 ksi</td>
<td>&lt; 2 %</td>
<td>&gt; 36 ksi</td>
<td>&gt; 0.100 in.</td>
</tr>
<tr>
<td>Result</td>
<td>Y</td>
<td>Y</td>
<td>&gt; 11.2 ksi</td>
<td>0.6 %</td>
<td>40.6 ksi</td>
<td>0.103 in.</td>
</tr>
</tbody>
</table>
Crevice corrosion plagues even the most seawater corrosion resistant materials

- Especially prevalent in quiescent or slow-moving seawater & brackish water.

Cold Spray offers the ability to apply extremely crevice corrosion resistant materials to isolate structural materials.

Example Seawater Handling Check Valve

- CN3MN – Cast SS, High Mo
- Crevice Corrosion on flange faces
- Casting Defects can lead to pitting and Leakage.
For this application, Focus on Nitrogen-sprayed coatings on AL-6XN

- High Nickel Materials with hard phase blend
- Titanium-based coatings and hard phase blends

Commercially Pure Titanium (CP-Ti) best performer in ASTM G192 re-passivation crevice corrosion tests.

<table>
<thead>
<tr>
<th>A59/CRC on AL-6XN</th>
<th>C276/CRC on AL-6XN</th>
<th>CP-Ti on AL-6XN</th>
<th>CP-Ti/TiC on AL-6XN</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05% Porosity</td>
<td>0.75% Porosity</td>
<td>1.00% Porosity</td>
<td>~1.00% Porosity</td>
</tr>
<tr>
<td>+10 ksi Glue</td>
<td>+10 ksi Glue</td>
<td>4.61 ksi Adhesion</td>
<td>+10 ksi Glue</td>
</tr>
</tbody>
</table>
Case Study – Seawater Crevice Corrosion Mitigation

• Long-Term Seawater Exposure Crevice Corrosion Testing
  • Candidate Materials Tested on AL-6XN Substrates with Crevice Formers
  • Long-Term Exposure to Chesapeake Bay water, silt, and organic matter.
  • 10 May 2019 – 36 cold sprayed sampled + 9 controls installed
  • 10 Sept. 2019 – Half of the sample set pulled for inspection
  • 3 Feb. 2020 – Remainder of sample set pulled for inspection

• No Crevice or Galvanic Corrosion observed in CP-Ti materials
Case Study – Seawater Crevice Corrosion Mitigation

• Application of Ti-based coating for crevice corrosion resistance
  • Excellent adhesion to AL-6XN, low porosity, equivalent or higher hardness, no crevice corrosion

• Qualification Plan developed with and approved by customer
  • Adhesion, Porosity, Hardness, Deposition Efficiency
  • Additional testing for impact resistance, thermal cycling, and salt fog galvanic to ensure no cracking, spallation, or corrosion will occur in the application.

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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&gt; 10 ksi</td>
<td>&lt; 1 %</td>
<td>None</td>
<td>&gt; 50%</td>
<td>No Cracking</td>
<td>No Spallation</td>
<td>No Corrosion</td>
</tr>
<tr>
<td>Result</td>
<td>&gt; 11.3 ksi</td>
<td>0.73 %</td>
<td>188 HV</td>
<td>62%</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
</tr>
</tbody>
</table>

*Porosity of Metal Matrix between Carbide Hard Phases
Case Study – Seawater Crevice Corrosion Mitigation

- Cold Spray Ti-based coating applied to the flange and internal surfaces.
- Coating application performed at VRC Spray Operations Facility, Box Elder, SD.
Case Study – Seawater Crevice Corrosion Mitigation

• Cold Spray Application Process
  1. Apply targeted cold spray non-structural fill to crevice sites and blended defects.
  2. Apply uniform cold spray coating robotically.
  3. Post-Machine, as necessary.
  4. Repeat for all component sections.

• Applicable to various seawater handling components.

• Process travelers and quality control processes developed and maintained.

• Witness Coupons collected and tested.
  • Results within Acceptance Criteria
Conclusions

• High Pressure Cold Spray can be used to generate coatings of extremely corrosion resistant materials at low temperatures.

• Compressive residual stresses present in the coating help prevent stress corrosion cracking.

• Cold Sprayed coatings can be applied in critical applications to protect sensitive materials in corrosive environments, key points:
  • Material Selection is Critical!
  • Process Parameter development, process control, and in-process monitoring are important to achieve desired coating performance and quality assurance.

• Select applications that make sense for cold spray
  • High Value, Temperature Sensitive Components for Critical Applications
  • Applications where In-Situ restoration / mitigation is necessary

• Potential Future Applications
  • High Capacity, High Level Waste Tanks
  • In-Situ Dimensional Restoration of Steam Erosion in Secondary Systems
Thank You!

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