Cold Spray Technology for Repair of Magnesium Rotorcraft Components

*ESTCP Proposal 06-E-PP3-031*

**Team:**
- ARL
- Bruce Sartwell - Naval Research Laboratory
- Yogi Kestler – NADEP Cherry Point
- Tim Eden – ARL-PSU
- Robert Guillemette SIK
**Title:** Cold Spray Technology for Repair of Magnesium Rotorcraft Components

**Performing Organization:** Naval Research Laboratory, 4555 Overlook Ave., SW, Washington, DC, 20375

**Meeting Information:**

**Distribution/Availability Statement:**
Approved for public release; distribution unlimited

**Abstract:**
Not provided in the document.
Cold Spray Technology for Repair of Magnesium Rotorcraft Components

Program Objectives:

- To reclaim ZE 41A magnesium alloy components on Army and Navy helicopters that have been removed from service due to severe corrosion and/or wear.

- ARL will provide a repair/rebuild cold spray procedure for scrapped parts and assist in the transition and implementation of this technology, initially, at NADEF, Cherry Point, NC.
Cold Spray Technology for Repair of Magnesium Rotorcraft Components

Meeting Objective: to lay the foundation for a JTP that can be executed by the ESTCP team such that at the completion of the program NADEP, Cherry Point has a fully functional cold spray system that is reclaiming magnesium rotorcraft components.

• Overview of Cold Spray Technology
  • Leveraged Programs (unprecedented head start)
  • Discuss ARL Capabilities and Advantages of Cold Spray

• Present Test Results to Date
  • Coating Integrity and Microstructural Analysis
  • Adhesion, Hardness and Corrosion Tests
  • Coating Material Selection and Powder Development
  • Cold Spray Process Development and Hardware Modifications
  • Cold Spray Demonstration on ZE 41A Mg Housings
## ARL Cold Spray Research Team

<table>
<thead>
<tr>
<th>Name</th>
<th>Position</th>
<th>Phone Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phillip Leyman</td>
<td>Process Engineer</td>
<td>(410) 306-0818</td>
</tr>
<tr>
<td>Dr. Dennis Helfritch</td>
<td>Process Engineer</td>
<td>(410) 306-1928</td>
</tr>
<tr>
<td>Dr. Matthew Trexler</td>
<td>Materials Engineer</td>
<td>(410) 306-0808</td>
</tr>
<tr>
<td>Michael Lister</td>
<td>Materials Engineer</td>
<td>(410) 306-1592</td>
</tr>
<tr>
<td>Scott Grendahl</td>
<td>Materials Engineer</td>
<td>(410) 306-0819</td>
</tr>
<tr>
<td>Dr. William DeRosset</td>
<td>Modeling/Simulation</td>
<td>(410) 306-0816</td>
</tr>
<tr>
<td>Marc Pepi</td>
<td>Mechanical Engineer</td>
<td>(410) 306-0848</td>
</tr>
<tr>
<td>Victor Champagne</td>
<td>Team Lead/Materials</td>
<td>(410) 306-0822</td>
</tr>
</tbody>
</table>
ARL Leveraged Formal Programs

• to develop aluminum cold spray coatings for aluminum, magnesium and/or steel substrates have been established with the following:

1. Defense Science & Technology Organization (DSTO)
2. Joint Strike Fighter (JSF)
3. National Center for Manufacturing Sciences (NCMS)
4. Lockheed Martin
5. Penn State Applied Research Laboratory
6. Lawrence Livermore National Labs (LLNL)
7. South Dakota School of Mines (SDSM)
Cold Spray: a process by which particulates are deposited by means of ballistic impingement upon a suitable substrate at super sonic velocities to form a coating or a free-standing structure.

- Main Gas Stagnation Pressure 100-500 psi
- Gas Temperature 0-1300°F
- Main Gas Flow Rate 30-100 CFM
- Powder Feed Rate 10 to 30 pounds/hour
- Particle Velocity 300-1500 m/sec.
- Particle Size 1-100um diameter
Cold Spray Advantages

Super Plastic Particle Agglomerate Mixing (SPAM) bond
- plastic deformation may disrupt thin oxide surface films to permit bonding similar to explosive welding

Compressive residual stresses
- particles “peen” surface
- plasma and wire-arc thermal spray coatings tend to be in tension

High density
- low porosity: < 0.5%
- low oxide content <0.3%

Thick coatings
- free-form fabrication

Low Temperature Application
- thermally sensitive substrates
- low stresses due to CTE mismatch
Cold Spray vs. Thermal Spray

Cold Spray is performed at lower temperatures at high particle velocities.
Cross section of the impact site between a copper particle and a stainless steel substrate.

The melting of particles that occurs during most thermal spray processes can result in oxidation of both the coating and substrate materials. The resulting oxides decrease the adhesive and cohesive strengths of the coating. The cold spray process avoids such reactions.
Mechanical Mixing at Interface

EDS X-ray Mapping showing mechanical mixing between coating material and substrate

- Copper
- Aluminum
Particle Velocity Distribution
Measured by DPV 2000

20 micron copper particles
25 mm downstream
400 psi, 400 C N₂ gas
Cold Spray Coating of Nickel On 6061-T6 Al

Cold Spray Ni has a hardness of HRC 41 and a resistivity of 6.84 uohm/cm

Nickel Coating

100% Dense
316L SS Deposited by the Stationary System Using He

316L SS Cold Spray Coating

Aluminum Substrate
Stationary Cold Spray System at ARL

Robot-Controlled, High Pressure, He and N Gas

Main Gas Stagnation Pressure 100-500 psi  Gas Temperature 0-1300°F  Main Gas Flow Rate 30-100 CFM
Powder Feed Rate 10 to 30 pounds/hour  Particle Velocity 300-1500 m/sec.
Portable Cold Spray Systems at ARL

- Hand-Held Heater-Nozzle
- Shop Compressed Air
- Particle Velocity 300-500 m/s
EMI Shielding for HMMWV Shelter by Cold Spray

ARL Produces First Prototype Using Cold Spray Technology for the Terminal High Altitude Area Defense (THAAD) Project Office.

- HMMWV shelters require EMI shielding to prevent entrance/escape of electronic signals.
- The joints in al-composite walls must be sealed with a non-porous, conducting metal.
- The composite structure requires low-temperature application of sealer.

Conductive material needed to fill seams

Aluminum

Composite
Applying EMI Shielding on the HMMWV Shelter

Copper and Tin Deposited Onto The Doorframe with the Portable Cold Spray System

Aluminum/Zinc Applied to Interior Seams

Cross Section of Cold Spray Coating
Cold Spray vs. Thermal Spray

Flame Spray Sn & Steel Coating, 12.2% Porosity

Cold Spray Sn Coating, 0% Porosity

Cold Spray Al Coating, 0.83% Porosity
1. Corrosion protection of ferrous materials
   - Painted structures – viz. ALV – access cover (USMC)
   - Hardened steel landing structures (Boeing)
   - Iron brake components (Delphi)

2. Corrosion protection and restoration of magnesium
   - Repair ZE41 & AZ91-D Magnesium (U.S. Army Research Lab, NADEP–Cherry Point, Ford)

3. Corrosion protection and restoration of aluminum
   - Repair of Alclad (Boeing commercial, Air logistics, Cherry Point)

4. Aluminum brazements (Delphi)

5. Cold-spray consolidation by Ultrasonics (Solidica)

* Commercial Technologies for Maintenance Activities
** National Center for Manufacturing Sciences
Cold Spray Coating of CP-Al On ZE 41A-Mg

Cold Spray CP-Al Coating

~100% Dense

Coating / Substrate Interface

ZE 41A-Mg
CP- Al Cold Spray Coating
Applied to ZE 41AMg

Cold Spray Al Coating 0.015 inch

8,500 psi adhesion

Interface is free of voids and oxides
### CP- Aluminum Cold Spray Coating Adhesion to Magnesium

<table>
<thead>
<tr>
<th>Program</th>
<th>Conditions</th>
<th>Adhesion (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARL-DSTO</td>
<td>N₂, 380 psi, 250°C</td>
<td>2743</td>
</tr>
<tr>
<td>ARL-DSTO</td>
<td>He, 380 psi, 20°C</td>
<td>&gt;6527</td>
</tr>
<tr>
<td>ARL-NCMS</td>
<td>He, 380 psi, 20°C</td>
<td>&gt;8505</td>
</tr>
</tbody>
</table>

**New Data Generated FY07 for ESTCP**

<table>
<thead>
<tr>
<th>Program</th>
<th>Conditions</th>
<th>Adhesion (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARL-ESTTCP</td>
<td>N₂, 380 psi, 400°C</td>
<td>&gt;10,350</td>
</tr>
</tbody>
</table>
Repair of Alclad Aircraft Skin by Cold Spray using CP Aluminum

Machined slot

Template shielded before spray

Cold Spray CP Al

0.035 inch thick cold spray repair
Example of Damage Repair

Machined Pit
Machined Groove
ZE 41A Magnesium Plate
CP-Aluminum Cold Spray Coating
Machined Flush
The hardness of a cold-sprayed material is significantly higher than that of a conventional wrought material.

The hardening is a result of the plastic deformation that occurs during particle impact and the refined microstructure of the material.
Cold Sprayed vs. Wrought Materials: Hardness

<table>
<thead>
<tr>
<th>Material</th>
<th>Brinell Hardness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wrought (annealed)</td>
<td>60</td>
</tr>
<tr>
<td>Wrought (fully worked)</td>
<td>230</td>
</tr>
<tr>
<td>Cold Sprayed</td>
<td>390</td>
</tr>
</tbody>
</table>

Pure Nickel: 41 HRC
Cold Sprayed vs. Wrought Materials: Hardness

316 L Stainless Steel

Brinell Hardness

- Wrought (annealed)
- Wrought (fully worked)
- Cold Sprayed

43 HRC

Cold Sprayed
Cold Sprayed vs. Wrought Materials: Hardness

Pure Aluminum

Brinell Hardness

<table>
<thead>
<tr>
<th>Condition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wrought (annealed)</td>
<td>20</td>
</tr>
<tr>
<td>Wrought (fully worked)</td>
<td>40</td>
</tr>
<tr>
<td>Cold Sprayed</td>
<td>60</td>
</tr>
</tbody>
</table>
Aluminum Powder Morphology

-325 mesh 5056 Al Flake

-325 mesh Pure Al Spherical

5056 Aluminum

<table>
<thead>
<tr>
<th></th>
<th>Wrought (annealed)</th>
<th>Wrought (fully worked)</th>
<th>Cold Sprayed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Pure Aluminum

<table>
<thead>
<tr>
<th></th>
<th>Wrought (annealed)</th>
<th>Wrought (fully worked)</th>
<th>Cold Sprayed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Coating quality is critically dependent on the feed powder composition, morphology, oxygen content, and mechanical properties.
The oxygen content of the cold spray coating is largely determined by the oxygen content of the original powder, not the process.

Oxygen content measured by Inert Gas Fusion
ASTM E 1019-03

- 325 Mesh Cp-Al Powder

0.34 % Oxygen

Cold Spray CP-Al Coating

0.25 % Oxygen
Portable ARL Cold Spray System

Regulator —> High pressure feeder —> Flow control valve —> Nozzle

Braided flex hose

Helium cylinder

Helium Tank

Powder Feeder

Spray Nozzle
# ARL Portable System Parameters for Applying CP-Al to ZE41A - Mg

<table>
<thead>
<tr>
<th>Operating Parameter</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helium Pressure</td>
<td>400 – 500 psi</td>
</tr>
<tr>
<td>Helium Temperature</td>
<td>20 Degree C</td>
</tr>
<tr>
<td>Helium Flow</td>
<td>20 SCFM</td>
</tr>
<tr>
<td>Powder Flow</td>
<td>1 – 5 gram/minute</td>
</tr>
<tr>
<td>Particle Mean Diameter</td>
<td>20 micron</td>
</tr>
<tr>
<td>Particle Exit Velocity</td>
<td>1000 meter/second</td>
</tr>
<tr>
<td>Helium Cylinder Life</td>
<td>9 minutes</td>
</tr>
</tbody>
</table>
CP-Al Deposited by the ARL Portable Cold Spray System
CP-Al Deposited by the ARL Portable Cold Spray System
5056 Al Deposited by the Stationary System Using He

5056 Al Cold Spray Coating

Interface

Aluminum Substrate

X100 100μm
5056 Al Deposited by the Stationary System Using He

Cold Spray 5056 Coating

Coating / Substrate Interface

X330  50μm
This is before process optimization!
**Applying CP-Al by Cold Spray over Magnesium**

**ARL Achievements (FY07 Results Highlighted in Red)**

**Corrosion Resistance:**
- >5,000, >7,000 hrs salt fog resistance-ASTM B117 (Al, 4340 steel substrates)
- >619, >1,000hrs (ZE 41A magnesium substrate)

**Hardness:**
- 57 Brinell Hardness

**Yield Strength:**
- 22ksi comparable to ZE41A-T6 and AZ91E-T6 magnesium

**Density:**
- >99% with oxide content of 0.25%

**Adhesion:**
- > 8,500 psi, >10,350 psi

**Cold Spray Process Summary:**
- can be applied in production or in the field at room temperature
ARL Technical Hurdle

**Technical Approach**

* nozzle design
* system modifications (heater, powder feed)
* powder morphology and condition

: to achieve similar results with the use of nitrogen as the carrier gas

: this hurdle has been overcome in FY07 with the use of a plastic nozzle!
Future Developments

Specification Development:
Like to explore using Mantech program at ARL-PSU to create commercial specification for cold spray

Cold Spray Book:
Published through the UK