Cold Spray Aluminum for Magnesium Gearbox Repair

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US Army Research Laboratory
Weapons & Materials Research Directorate

SERDP/ESTCP Surface Finishing Workshop
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**Report Documentation Page**

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**Standard Form 298 (Rev. 8-98)**
Prescribed by ANSI Std Z39-18
ESTCP Program Goal

*ESTCP Proposal 06-E-PP3-031*

- To reclaim 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 NADEP, Cherry Point, NC.
Problems With Current Surface Treatment Methods

- Exposure to hexavalent chrome is hazardous to workers’ health. OSHA limits on chromium exposure are becoming increasingly stringent.
- Even with chromated surface treatments, Mg components suffer severe degradation in service.
- Most corrosion occurs at mating pads, supports, and mounting lugs where dissimilar metal is in contact with Mg; damage is most likely to occur in those locations as well.

H-60 Main Transmission Housing showing areas most susceptible to corrosion

Corrosion on H-53 Tail Gearbox Housing
Program Objectives

- Develop the densest, thinnest, most corrosion resistant Aluminum-based Cold Spray coating with the greatest adhesive bond strength to Magnesium.

- Determine effects of feedstock material and process parameters on coating thickness, microstructure, adhesion, and corrosion performance for the Cold Spray coatings on Magnesium substrates.
Joint Test Protocol (JTP) has been developed

U.S. DEPARTMENT OF DEFENSE
Environmental Security Technology Certification Program (ESTCP)

JOINT TEST PROTOCOL

Supersonic Particle Deposition Technology for Repair of Magnesium Aircraft Components

Date: October 2, 2006

Prepared By:
Hard Chrome Alternatives Team (HCAT)
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 Center at the
US Army Research Laboratory (ARL)
Aberdeen Proving Ground, MD 21005-5069

ARL Cold Spray Research Team

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Carl Paxton  Process Technician  (410) 306-2026
Marc Pepi  Mechanical Engineer  (410) 306-0848
Overview of Cold Spray Technology

**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.

**Cold Spray System Configuration**

- **Gas Control Module**
- **Electric Heater**
- **Powder Feeder**
- **Supersonic Nozzle**
- **Deposit**
- **Particle Stream**
- **Substrate**

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

Robot-Controlled, High Pressure, He and N Gas
Cold Spray Advantages

Mechanical mixing bond at substrate interface
- 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.
Particle/Substrate Interaction

*from H. Assadi, www.modares.ac.ir/eng/ha10003/CGS.htm
Advantages of Low Temperature Process

Thermal Spray

Cold Spray

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.
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**
Mechanical Mixing at Interface

EDS X-ray Mapping showing mechanical mixing between coating material and substrate.
Particle Velocity Distribution
Measured by DPV 2000

20 micron copper particles
25 mm downstream
400 psi, 400 °C N₂ gas
Cold Spray Coating of CP-Al On ZE 41A-Mg
(Helium Carrier Gas)

- ~100% Dense
- Cold Spray CP-Al Coating
- 8,500 psi adhesion
- Coating / Substrate Interface

ZE 41A-Mg Substrate
ARL Technical Hurdle

No Porosity & 8,500 psi bond strength using Helium

Achieve similar results with the use of nitrogen as the carrier gas

Technical Approach

- Nozzle – Material & Design
- Powder Size, Morphology
- Process Parameters
Cold Spray Coating of CP-Al on ZE41A-Mag (Nitrogen at 380 psi, 250 C)

This is before process optimization!
Aluminum Powder Morphology

- 325 mesh 5056 Al Flake

CP Al Spherical

### 5056 Aluminum

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<th>Condition</th>
<th>Brinell Hardness</th>
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<tr>
<td>Wrought (annealed)</td>
<td></td>
</tr>
<tr>
<td>Wrought (fully worked)</td>
<td>100</td>
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<tr>
<td>Cold Sprayed</td>
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### Pure Aluminum

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<th>Brinell Hardness</th>
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<td>Wrought (annealed)</td>
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<tr>
<td>Wrought (fully worked)</td>
<td>60</td>
</tr>
<tr>
<td>Cold Sprayed</td>
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Localized Plastic Deformation

Complete Work Hardening
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.
Gasdynamic equations are used to calculate gas velocity and temperature within the nozzle and downstream of the nozzle exit.

The resulting particle velocities and temperatures are then calculated by gas-particle drag and heat transfer.

The log normal particle size distribution is integrated from the smallest diameter to the largest diameter for those particles with velocities greater than the critical velocity, to determine DE.
Particle Velocity & Deposition Efficiency

The graph shows the relationship between particle diameter (microns) and velocity (m/s) for different batches (DE). The y-axis represents velocity, and the x-axis represents particle diameter. Each batch has a distinct line indicating its deposition efficiency percentage.

- Batch 1: 1%
- Batch 2: 97%
- Batch 3: 27%
- Batch 4: 88%
- Batch 5: 94%

The critical velocity (V critical) is also indicated on the graph.
## Nozzle Designs

<table>
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<th>Material</th>
<th>Length (mm)</th>
<th>Process Conditions</th>
<th>Particle Velocity</th>
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<td>Tungsten Carbide</td>
<td>115</td>
<td>He, 380psi, RT</td>
<td>1020</td>
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<tr>
<td>Tungsten Carbide</td>
<td>115</td>
<td>N2, 380psi, 250°C</td>
<td>590</td>
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<tr>
<td>WC/Thermoplastic</td>
<td>115</td>
<td>N2, 380psi, 300°C</td>
<td>605</td>
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<td>Thermoplastic</td>
<td>125</td>
<td>N2, 380psi, 400°C</td>
<td>690</td>
</tr>
<tr>
<td>Thermoplastic</td>
<td>153</td>
<td>N2, 380psi, 400°C</td>
<td>710</td>
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Thermoplastic Cold Spray Nozzles

125mm

153mm

Tungsten Carbide Section

Thermoplastic Section

Two-Piece

Thermoplastic Nozzles
Cold Spray Coating of CP-Al On ZE 41A-Mg
(Nitrogen Gas @ 400°C)

10,350 psi adhesion (ASTM C-633)
Bond Bar Adhesion Set-up

Bond Strength Measurements on ZE41A Magnesium and 7075 Aluminum Alloy
Bond Bar Adhesion Testing Setup
## Results for CP- Aluminum Cold Spray Coatings on 6061 Aluminum Bond Bars

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<th>Nozzle Powder</th>
<th>Adhesion (psi)</th>
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<tr>
<td>N2, 380psi, 250C</td>
<td>Metal 15-45 um</td>
<td>2743</td>
</tr>
<tr>
<td>He, 380psi, 20C</td>
<td>Metal 15-45 um</td>
<td>1657-3302</td>
</tr>
<tr>
<td>N2, 380psi, 300C</td>
<td>Metal/Plastic 7-28 um</td>
<td>2387-4476 (cohesive)</td>
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<tr>
<td>N2, 380psi, 400C</td>
<td>Plastic (125mm) 7-28 um</td>
<td>5787-7247 (cohesive)</td>
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### Results for CP- Aluminum Cold Spray Coatings on Magnesium

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<th>Corrosion Results</th>
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<td>N2, 380psi, 250°C</td>
<td>Metal 15-45 um</td>
<td>2743</td>
<td>8 hrs</td>
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<tr>
<td>He, 380psi, 20°C</td>
<td>Metal 15-45 um</td>
<td>&gt;8,505 (glue failure)</td>
<td>&gt;500 hrs*</td>
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<tr>
<td>N2, 380psi, 300°C</td>
<td>Metal/Plastic 7-28 um</td>
<td>4764-5985</td>
<td>1000 hrs</td>
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<tr>
<td>N2, 380psi, 400°C</td>
<td>Plastic 7-28 um</td>
<td>&gt;10,350 (glue failure)</td>
<td>&gt;2,400 hrs*</td>
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* Failure of Edge Maskant
Salt Spray (Fog) Corrosion Test
(ASTM B-117)

- Specimens at 15-30\(^0\) angle from vertical
- 5 +/- 1\% (by weight) NaCl Solution (pH 6.5-7.2)
- Spray Nozzle Baffled at 10-25psi
- Chamber Temperature at 35 + 1.1 – 1.7 \(^{0}\)C
- Continuously sprayed in closed chamber

Note: No Direct Relation between B117 & Outdoor Exposure
Aluminum coated ZE41A Magnesium (8 Hours in Salt Spray)

Cold Spray Aluminum deposited using N\textsubscript{2} Gas at 250 °C
Aluminum coated ZE41A Magnesium (336 Hours in Salt Spray)

Cold Spray Aluminum deposited using Helium Gas at 20 °C
Cold Spray Aluminum coated ZE41A Magnesium Coupons

- Bare Coupon
- Coated (.5mm)
- Coated (1mm)
Aluminum Cold Spray Coated Magnesium Coupons After Salt Spray Exposure

2400 Hours Exposure (.5mm)  2400 Hours Exposure (1mm)

Cold Spray Aluminum deposited using N₂ Gas @ 400 °C
RCB Cold Spray Set-Up

ZE41A Magnesium & 7075 Aluminum Alloy RR Moore Fatigue Specimens
Fatigue Results – AA7075-T651

Source – Australian Defence Science & Technology Organisation
Fatigue Results – ZE41A-T5

Source – Australian Defence Science & Technology Organisation
Mg Housing Coated with CP-Al

Flat surface of Mg housing covered with CP-AL Cold Spray
Al12Si & 5356 Al Deposited on ZE41A Using Helium

Adhesion Results - > 8,000 psi (Glue Failure)
# Summary

Achieved High Density, Low Porosity Cold Spray Aluminum Coating

Bond Strength Exceeds 10,000 psi.

Corrosion Resistance exceeds 2500 hours B117 Salt Fog Spray

No Reduction in Fatigue Strength on Magnesium

Slight fatigue credit on 7075 Aluminum Alloy

Future Work – Investigate Aluminum Alloys & High Purity Aluminum