Cold Spray for Repair of Magnesium Gearboxes

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# Cold Spray for Repair of Magnesium Gearboxes

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## Abstract
ASETSDefense 2011: Sustainable Surface Engineering for Aerospace and Defense Workshop, February 7 - 10, 2011, New Orleans, LA. Sponsored by SERDP/ESTCP.
Technical Objectives

Demonstrate and qualify cold spray aluminum alloy coatings which provide surface protection and a repair/rebuild methodology for Mg alloy components on Army and Navy helicopters and advanced fixed-wing aircraft such as the Joint Strike Fighter

1. Cost-effective
2. ESOH-acceptable technology
Unique solid-state deposition process which utilizes high velocity particles impinging upon a substrate to build up material.

**Technical Approach**

**Cold Spray Process**

- Feed stock typically ranges from 1 to 50 µm
- Particle ductility is crucial
- Gas temperature range from R.T. to 800°C
- No melting of particles
- Negligible oxidation
- No decomposition or phase changes of deposited particles or substrate
COLD SPRAY EQUIPMENT at FRC EAST

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**Technical Approach**

**Joint Test Protocol**

### Mechanical Tests
- Adhesion Tensile Bond Test (ASTM C633)
- XRD Residual Stress
- R.R. Moore RB Fatigue
  - surface finished 125 \( R_A \)
- Fretting Fatigue – UTRC
- Impact - ASTM D5420
- Hardness
- Porosity
- Triple Lug Shear

### Corrosion Tests
- Un-scribed ASTM B117
- Scribed ASTM B117
- GM9540 Scribed
- Galvanic Corrosion (G71)
- Crevice Corrosion (G78)
- Beach Corrosion
- G85 Annex 4-SO\(_2\)

*Stack Up: RockHard, 23377, and 85285*

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*UTRC Fretting Fatigue Specimen*
*The oxygen content of the cold spray coating is largely determined by the oxygen content of the original powder, not the process.*
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Modeled deposition efficiencies appear to be close to experimental values while the calculated velocities are well above the critical velocities for Al (~500 m/s)
Microstructures of 6061 Cold Spray Optical Microscopy

Increasing Gas Pressure

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### Technical Progress

#### ZE41A-T5 Substrate Temperature Recorded at 163.4°C (326.1°F)

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Condition</th>
<th>Aging Temp (°F)</th>
<th>Time (Hrs)</th>
<th>Solutionizing Temp (°F)</th>
<th>Aging after Solutionizing Temp (°F)</th>
<th>Time (Hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AZ91C</td>
<td>-T5</td>
<td>335</td>
<td>16</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>AZ91C</td>
<td>-T6</td>
<td>---</td>
<td>---</td>
<td>775</td>
<td>335</td>
<td>16</td>
</tr>
<tr>
<td>AZ92A</td>
<td>-T5</td>
<td>500</td>
<td>---</td>
<td>---</td>
<td>420</td>
<td>5-6</td>
</tr>
<tr>
<td>AZ92A</td>
<td>-T6</td>
<td>---</td>
<td>---</td>
<td>765</td>
<td>425</td>
<td>5</td>
</tr>
<tr>
<td>ZE41A</td>
<td>-T5</td>
<td>625</td>
<td>2</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>

T5 means artificially aged
T6 means solution heat treated and artificially aged


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Technical Progress

Wrought versus Cold Spray 6061

Key

T4, T451- Solution heat-treated and naturally aged to a substantially stable condition. Temper -T451 applies to products stress-relieved by stretching.²

T6, T651- Solution heat-treated and then artificially aged, Temper -T651 applies to products stress-relieved by stretching.²

In Process Anneal- 640°F for 10 to 12 Hours

<table>
<thead>
<tr>
<th>6061 Condition</th>
<th>Source</th>
<th>UTS, ksi</th>
<th>YS, ksi</th>
<th>%EL</th>
</tr>
</thead>
<tbody>
<tr>
<td>annealed</td>
<td>¹</td>
<td>18</td>
<td>8</td>
<td>25</td>
</tr>
<tr>
<td>T4, T451</td>
<td>²</td>
<td>30</td>
<td>16</td>
<td>18</td>
</tr>
<tr>
<td>T6, T651</td>
<td>²</td>
<td>42</td>
<td>35</td>
<td>10</td>
</tr>
<tr>
<td>cold sprayed (CS)</td>
<td>³</td>
<td>49.3</td>
<td>42.5</td>
<td>3</td>
</tr>
<tr>
<td>CS- In process anneal</td>
<td>³</td>
<td>29.0</td>
<td>24.0</td>
<td>17</td>
</tr>
</tbody>
</table>

¹Matweb
²Alcoa.com
³Microtensile Test by Aaron Nardi at UTRC of ARL Cold Spray Block
Vickers Hardness of CP Al (Valimet H-12) Sprayed with 20 bar He versus Gun Temperature

- Model
- Cold Sprayed
- Work Hardened
Triple Lug Shear Test
Test Description: Thick coating is deposited and machined into three lugs (3/16” x 1”) and then tested in compression.

7 out of 12 6061 on ZE41A-T5 samples failed within the Mg.
## Technical Progress

### Bond Bar Adhesion (ASTM C633)

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Coating System</th>
<th>Average Thickness (in)</th>
<th>Average Max Tensile Stress (PSI)</th>
<th>Stddev. Tensile Stress (PSI)</th>
<th>95% Confidence Tensile Stress (PSI)</th>
<th>Observed Failure Mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZE41A-T5</td>
<td>6061 He</td>
<td>0.0134</td>
<td>11052</td>
<td>808</td>
<td>560</td>
<td>100% Glue</td>
</tr>
<tr>
<td></td>
<td>CP-Al He</td>
<td>0.0197</td>
<td>12069</td>
<td>597</td>
<td>370</td>
<td>100% Coating Adhesion</td>
</tr>
<tr>
<td></td>
<td>CP-Al N₂</td>
<td>0.0228</td>
<td>10400</td>
<td>846</td>
<td>677</td>
<td>100% Coating Adhesion</td>
</tr>
</tbody>
</table>

**Observed for Public Release; Distribution Unlimited**
Fretting Fatigue Setup at UTRC

Fretting rig pressure = 848 psi
Projected area fretting stress = 5 ksi (34 Mpa)
Fretting pin load = 167 lb
Fretting slip amplitude = ±0.001 inches (±25 microns)
Range of max axial test loads = 443 – 2955 lbs
Range of max axial test stress = 3 – 20 ksi
Range of lives = 32,000 – 10 million (runout)
Phasing = in phase with fret slip increasing at max axial
Pin Type = 0.206 diameter 4340 steel with cadmium plating

ARL Fretting Fatigue Test Matrix

<table>
<thead>
<tr>
<th>Specimen Base Material</th>
<th>Counterface Pin Material</th>
<th>Coating</th>
<th># of Specimens Tested</th>
<th>Specimens Remaining</th>
</tr>
</thead>
<tbody>
<tr>
<td>AZ91C-T6</td>
<td>4130, 30-35 HRC, Cadmium plated</td>
<td>None</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6061 using Helium</td>
<td>9</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CP-Al using Nitrogen</td>
<td>11</td>
<td>0</td>
</tr>
<tr>
<td>ZE41A-T5</td>
<td></td>
<td>None</td>
<td>11</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6061 using Helium</td>
<td>9</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CP-Al using Nitrogen</td>
<td>9</td>
<td>0</td>
</tr>
</tbody>
</table>

Slide Courtesy of Aaron Nardi, United Technologies Research Center

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Cold Spray Repair Fretting Fatigue

Slide Courtesy of Aaron Nardi, United Technologies Research Center
AZ91C-T6 and ZE41A-T5 with no coating applied exhibited a 10 million cycle life of approximately 6.2 ksi.

Both Magnesium alloys with cold sprayed 6061 applied by helium exhibited a 10 million cycle life of approximately 5.3 ksi.

ZE41A-T5 with cold sprayed CP Aluminum applied using helium exhibited a 10 million cycle life of approximately 4.9 ksi.

AZ91C-T6 magnesium with cold sprayed CP aluminum using nitrogen exhibited a 10 million cycle life of approximately 3.3 ksi.

Fretting failures on baseline materials matched the expected fracture pattern:
- The cracking from top edge of fretting scar
- Coating cracks propagated without changing direction at the interface suggesting a good bond and higher modulus.

*Slide Courtesy of Aaron Nardi, United Technologies Research Center*
ESTCP RR Moore Data: 6061 and CP-Al N$_2$ on AZ91C-T6

- AZ91C-T6 Baseline
- CP Al N2 HCAT Approach: Substrate Diameter Only
- CP-Al N2 Two Modulus Approach
- 6061 HCAT Approach: Substrate Diameter Only
- 6061 Two Modulus Approach

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ESTCP RR Moore Data: 6061 and CP-Al N₂ Sprayed with N₂ on EV31-T6

- EV31-T6 Baseline
- CP-Al N₂ HCAT Approach: Substrate Diameter Only
- CP-Al N₂ Two Modulus Approach
- 6061 HCAT Method: Substrate Diameter Only
- 6061 Two Modulus Approach

Maximum Stress, $S$ (ksi)
Fatigue Life, $N$ (cycles)
XRD Residual Stress Versus Depth for 6061 Cold Spray on ZE41A-T5

Compressive Residual Stress (ksi)

- X-Direction
- Y-Direction
Un-scribed ASTM B117
- CP-Al went well (7000 hours at Army and 1000 hours at PSU)
- 6061 went 7000 hours at Army and will be retested at PSU due to thin spots

Scribed ASTM B117
- 1000 hours through top coat but 24 hours through to substrate. On par with HVOF Al-12Si

GM9540 Scribed- Sprayed

Galvanic Corrosion (G71)

Crevice Corrosion (G78)- No Crevice mechanism

Beach Corrosion- Undergoing testing

*vs uncoated ZE41
-Cd plated steel specimens are currently being fabricated for comparison
Sump Qualification

Substrates: ZE41A & AZ91C Magnesium
Coating Material: CP-Aluminum and/or 6061 Al

Total Replacement Cost Savings estimated to be $935,000.00/ year

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Cold Spray Coating Parameters Optimized at ARL

All Specimens from the JTP have been sprayed by ARL

Testing is nearing completion for all Mechanical and Corrosion Specimens - All Partners (UTRC, Westmoreland, PSU, FRCEast, NAVAIR, ARL)

- Unscribed B117- 7000 hours
- Fretting Fatigue- Acceptable for He coatings
- RR Moore- CP-Al N2 for non-structural, 6061 potential for structural repair

Cold spray system at FRCEast is operational and ready for limited production