Supersonic Particle Deposition for Repair and Corrosion Protection of Mg Gearboxes

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After

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Demonstrate and qualify SPD aluminum alloy coatings as a cost-effective, ESOH-acceptable technology to 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.
Cold spray, involves the introduction of a heated high-pressure gas such as He or N₂ together with 1 to 50 µm diameter particles of a metal, ceramic and/or polymer into a gun fitted with a De Laval rocket nozzle designed such that the particles exit at supersonic velocities ranging from 400 to 1500 meters-per-second and consolidate upon impacting a suitable surface to form a coating or free-standing structure.

- Gas temperature range from R.T. to 800°C
- No melting of particles
- Negligible oxidation
- No decomposition or phase changes of deposited particles
SPD Depot overhaul
CH-53 gearboxes

- SPD has little or no impact on repair cost
- Most of cost is setup – actual process cost is small (same as glue shims)
- Payback of capital and implementation cost is 15 yrs with CH-53 only
  - Depends on performance – reduced repair or condemnation
  - Faster payback over all FRC workload

CH-53 Foot repair - total cost
- Run powder: 3%
- Run electricity: 0%
- Run gas: 1%
- Run labor: 2%
- Setup/maintenance labor: 94%

SPD cost $418
(same as shim)

CH-53 only $\pm 2\sigma$

15 year NPV
- $0$
- $(1,000,000)$
- $(2,000,000)$
- $(3,000,000)$
- $(4,000,000)$
- $(5,000,000)$
- $(6,000,000)$
- $(7,000,000)$

Condemnation rate as % of current
- 0%
- 20%
- 40%
- 60%
- 80%
- 100%
**UH-60 sump flange repair**

<table>
<thead>
<tr>
<th></th>
<th>SPD</th>
<th>HVOF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Setup/maintenance labor</td>
<td>$392.50</td>
<td>$392.50</td>
</tr>
<tr>
<td>Run labor</td>
<td>$3.74</td>
<td>$2.64</td>
</tr>
<tr>
<td>Run powder</td>
<td>$9.71</td>
<td>$11.38</td>
</tr>
<tr>
<td>Run gas</td>
<td>$4.29</td>
<td>$6.49</td>
</tr>
<tr>
<td>Run electricity</td>
<td>$0.04</td>
<td>$0.00</td>
</tr>
<tr>
<td><strong>Total cost</strong></td>
<td><strong>$410.28</strong></td>
<td><strong>$413.01</strong></td>
</tr>
<tr>
<td><strong>Run cost</strong></td>
<td><strong>$17.78</strong></td>
<td><strong>$20.51</strong></td>
</tr>
</tbody>
</table>

*No cost impact (both processes vendor-supplied)*
Problem is that HVOF does not really work
- Therefore SPD saves condemnation
- 85 gearboxes/year
  - $11k ea to replace
  - $1k ea to repair
- Cost analysis includes equipment installation and adoption cost
- Larger cost savings with more expensive gearbox housings

<table>
<thead>
<tr>
<th></th>
<th>-2 sigma</th>
<th>Value</th>
<th>+2 sigma</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 yr NPV</td>
<td>$8,682,158</td>
<td>$9,229,033</td>
<td>$9,775,908</td>
</tr>
<tr>
<td>IRR</td>
<td>145%</td>
<td>111%</td>
<td>91%</td>
</tr>
<tr>
<td>ROI</td>
<td>82%</td>
<td>111%</td>
<td>140%</td>
</tr>
<tr>
<td>Payback period</td>
<td>1.2</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>
Sump Cost Recovery

UH-60 Sump Assembly Main Module-Main Gearbox Repair

Substrates:
ZE41A & AZ91C Magnesium

Coating Material:
CP-Aluminum and/or 6061 Al

Part Numbers:
70351-48141-041
70351-08141-047

• Cost of new component $11,000.00 DLA (Defense Logistics Agency)
• 85 sumps need repair per year based on a Sikorsky study over the last 3 years
• Total Replacement Cost Savings estimated to be $935,000.00/year
### Substrate Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Heat Treat (tens. strength)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>AZ91C-T6</td>
<td>34 ksi</td>
<td>Legacy systems</td>
</tr>
<tr>
<td>ZE41A-T5</td>
<td>29 ksi</td>
<td>Legacy systems</td>
</tr>
<tr>
<td>EV31-T6</td>
<td>36 ksi</td>
<td>New CH-53, AAAV</td>
</tr>
</tbody>
</table>

### Candidate Coating Materials

- **Commercially Pure Al:**
  - Hardness similar to ZE41A (60 to 70 VHN), Good general corrosion resistance. Candidate for non-structural coatings.

- **High Purity Al:**
  - Best Galvanic compatibility with Mg alloys but at a cost of lower hardness (50 VHN).

- **6061 aluminum alloy:**
  - 90 to 110 VHN, good general corrosion resistance, future candidate for more structural or load bearing coatings.
Galvanic Corrosion

Galvanic Corrosion - Al-Mg Couple

Cathode slightly larger than anode
Full JTP Qualification Plan

1. 6061 Aluminum Alloy (He carrier gas)
2. HP-Al Bond Coat/CP-Al (N₂ carrier gas)

Mechanical Tests
- Adhesion Tensile Bond Test (ASTM C633)
- Almen Strips
- Flat Tensile Specimens
- R.R. Moore RB Fatigue
  - surface finished 125RA
- Fretting Fatigue – UTRC
- Impact - ASTM D5420
- Hardness
- Porosity
- ROSAN Insert Test
- 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-SO₂

UTRC Fretting Fatigue Specimen
Substrates: ZE41A & AZ91C Magnesium Alloys

Coating Material:
1.1. 6061 Aluminum Alloy (He carrier gas)
2. HP-Al Bond Coat/CP-Al (N₂ carrier gas)

- Porosity < 1%
- Almen Strips
- Adhesion Tensile Bond Strength Test
- Unscribed ASTM B117 Salt Spray Test
- Scribed ASTM B117 Salt Spray Test
- G85 SO₂
- Beach Corrosion
- Hardness –(Pre/Post 385F-6hrs)
- Machining Evaluation Coupons (1/2 coated) & ½” diameter rods (2” of 6” length)
Timeline

- Over 550 Coated Samples (JTP and Sump Qualification)
  - 6061 samples were started on July 25 and anticipated to be completed by September 1
  - HP-Al bond coat/CP-Al sprayed with N\textsubscript{2} should be completed by September 25

- Testing is being coordinated with Penn State, Pax River, Cherry Point, Westmoreland, L&M Machine Shop, TEC, and UTRC. December 2009 for most data!

- Demonstration at Cherry Point by the end of 2009

- Qualification of ASB and Demonstration at their site by the end of 2009

- Possibility that DSTO, Rosebank, and the Australian Navy might sign off on the process by the end of 2009
- 47 kW system installed 6/2008 at APG (30 kW on floor and 17 kW on gun)
- Only high pressure/high temperature C.S. system currently on the market
  - Temperatures up to 800°C (1472°F)
  - Pressures up to 40 bar (580 PSI)

- 17 kW system installation at NADEP-CP
  - Larger heat to be installed in late 2009

- Ktech System at ARL:
  - Temperature limited to 500°C
  - Pressures up to 35 bar (500 PSI)
  - 25 kW heater on floor
  - Heated powder gas feed
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)
Valimet 6061 Cold Spray on 6061
Substrate: Optical Microscopy

50X

Before Etching

Coating

Substrate

Artifact

10-20 Seconds Kroll’s Etch
Valimet 6061 Cold Spray on 6061 Substrate: Optical Microscopy

Before Etching

10-20 Seconds Kroll’s Etch

Coating

Substrate

200X
- Improved D.E. from 34% to over 60% as compared to the K-Tech
- Adhesion values similar to K-Tech (10 KSI for CP-Al)
- Coating Densities >98.5%
  - Theoretical Density for CP-Al with N₂
  >99.3% for 6061AA with He

CP-Al Cold Spray Coatings entered Salt Fog on 3/4/09 (~1/2 yr.)

6061 Cold Spray Coatings entered Salt Fog on 3/9/09 (~1/2 yr.)
CP-Al Hardness

Vickers Hardness of CP Al (Valimet H-12) Sprayed with 20 bar He versus Gun Temperature

Impact Velocity, m/s

Vickers Hardness

- model
- cold sprayed
- work hardened

Gun Temperature (°C)

Vickers Hardness (500g)
Bond Bar Adhesion (ASTM C633)

6061 Results:
All Samples failed within the adhesive and not at the coating/substrate interface

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Average (ksi)</th>
<th>Stdev (ksi)</th>
<th>95% Confidence (ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZE41A-T5</td>
<td>11.1</td>
<td>0.8</td>
<td>10.5, 11.6</td>
</tr>
<tr>
<td>AZ91C-T6</td>
<td>10.8</td>
<td>1.1</td>
<td>9.9, 11.6</td>
</tr>
<tr>
<td>EV31-T6</td>
<td>11.2</td>
<td>0.7</td>
<td>10.8, 11.7</td>
</tr>
</tbody>
</table>

CP-Al Preliminary ESTCP Data and DSTO Data show 10 ksi+
AZ91C-T6 and EV31-T6 failed with a relatively clean break at coating the interface.

7 out of 12 ZE41A-T5 samples failed within the Mg.
Fatigue from DSTO Project

Fatigue Results – ZE41A-T5

Source – Australian Defense Science & Technology Organization
**Fatigue Results – AA7075-T651**

- **Uncoated**
- **Grit-Blasted**
- **Coated**

Source – Australian Defense Science & Technology Organization
Overview of 2008/Early 2009
Technical Progress: DSTO

**Interior section of Intermediate Gearbox (IGB)**

**Exterior corroded area on one of the as-received IGB pads**
Overview of 2008/Early 2009 Technical Progress: DSTO

Interior section of IGB pads coated with CP-aluminum

Pre-Cold Spray

CP Al Cold Spray
Repair Site:
Rubber O-ring insert
Blending of Corroded Sites on Flange

Cold Spray Repair of Inside Diameter of Flange
Repair Site:

Filter Bowl Mount

Cavities collect water
Cold Spray offers a cost effective and environmentally friendly method for repair and corrosion protection of Mg Components

- **Hardness**
  - ZE41A Magnesium alloy = 68 Vickers
  - Cold Spray CP-Al = 63 Vickers
  - 6061 = 105 Vickers

- **Bond Strength**
  - >6061 has >10,000 psi on ZE41, AZ91, and EV31 (CGT)
  - >6061 surpassed 15,000 PSI for Triple Lug Shear
  - >CP-Al/HP-Al has >=10,000 psi on ZE41 and AZ91 (K-Tech and CGT)

- **RCB Fatigue Strength**
  - Minimal effect on both 7075-T6 and ZE41A Magnesium Alloy

- **Salt Fog Corrosion**
  - >4000 hrs on CGT (on going) and 6000+ hrs for K-Tech