Cold Spray Technology for DOD Applications

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Multiscale modeling of the quantum mechanical, molecular dynamics, and mesoscale levels is used in the Multifunctional Materials Branch to study phenomena such as reactions of organic molecules on solid surfaces, water diffusion in sulfonated copolymers, and morphology of the styrene-isobutylstyrene (SIS) copolymer.
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*Standard Form 298 (Rev. 8-98)  
Prescribed by ANSI Std Z39-18*
Unique solid-state materials consolidation process which utilizes high velocity particles impinging upon a substrate to build up coatings and/or free-standing structures without the use of combustion fuels.

- Stationary Robot Controlled Systems for precision and or high volume
- Portable Hand-held Systems for field repair and mobility

- Feed stock typically ranges from 1 to 50 µm diameter
- Gas temperature ranges from R.T. to 1,000°C and pressures from 300 - 725psi
- No melting of particles
- Negligible oxidation
- No decomposition or phase changes of deposited particles or substrate
Color changes denote temperature gradients. Higher temperatures are at splat boundaries.

*from H. Assadi, www.modares.ac.ir/eng/ha10003/CGS.htm
Mechanical Mixing at Interface

copper

aluminum
Cold Spray vs. Thermal Spray

- **Particle Velocity (10^3 ft/sec)**
  - Cold Spray
  - Wire Arc
  - Plasma Arc
  - High Velocity Oxygen Fuel, D-Gun
- **Gas Temperature (10^3 °F)**
  - Powder Flame
  - Wire Arc
  - Cold Spray

- **(10^3 °C)**
  - 16.8
  - 8.3
  - 2.7
Schematic of the Cold Spray Process

- **Acoustic Room** (10'L x 10'W x 8'H)
- **Spray Gun** (Nozzle and Prechamber)
- **Gas Heater Power Supply**
- **Silencer**
- **Cyclone**
- **Dust Collector** (6'L x 3.5'W x 12'H)
- **Compressed Nitrogen/Helium**
- **Process Controller**
- **Gas Control Module**
- **Powder Feeder**
- **Fume Hood**
- **Workpiece Heater**
- **Turntable**
- **Robot Arm**
- **Thermocouple**
- **Nozzle**
- **Prechamber**
- **SS Tubing to Pressure Transducer**
- **Gas Heater**
- **Power Cables**
- **Main Gas Line**
- **Powder Feed Line**

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Cold Spray System Components

- Powder Feeder
- Fume Hood
- Heater

Robotically Controlled Spray Gun

Spray Nozzle
Advantages of Cold Spray

• Low Temperature Process
  • Particles “peen” the surface and develop compressive stresses (beneficial for fatigue)
  • Bonding mechanism similar to explosive cladding (mechanical mixing & metallurgical bond)
  • Conducive for thermally sensitive substrates (i.e. magnesium, composites)

• Strength/Hardness
  • High strength/hardness (often greater than comparable wrought materials)

• Density
  • 100% consolidation possible with many materials, equal to theoretical
  • Little to no porosity or inherent defects (i.e. oxides), good electrical/thermal conductivity

• Wide Selection of Commercially Available Powders/Materials
  • Metals, oxides, hydrides, polymers, nanostructured materials

• Versatility
  • Graded structures and coatings (lengthwise and/or through thickness)
  • Complex geometries
  • Free-form fabrication of parts

• Ease of Production
  • Fully automated/robotically controlled turnkey system
  • No harmful fuels or extraordinary safety equipment
  • Minimal material waste-high deposit efficiency (i.e. 80W-20Cu 94%, 6061 Al 100%)
  • Deposition rates reported up to 40 kg/hr and higher (CP Titanium)
Cold Sprayed vs. Wrought Materials Hardness Comparison

- Pure Aluminum:
  - Wrought (annealed): 20
  - Wrought (fully worked): 40
  - Cold Sprayed: 63 HV

- Pure Nickel:
  - Wrought (annealed): 10
  - Wrought (fully worked): 25
  - Cold Sprayed: 41 HRC
Overview of Accomplishments

- Cold Spray Coating Parameters Optimized at ARL for CP-Al & 6061Al
- FRC-East cold spray system is installed, set up and processing parts
- All training sessions and quality control sample production completed at FRC-East.
- DEMVAL successfully completed at FRE-East, June 2011

2008 Defense Standardization Program Achievement Award


Sikorsky is proceeding with the sump repair for the H-60 platform

- Approval obtained for Overhaul Repair Instruction (ORI) SS8491 (2011)

Cold Spray has been approved through MAB, AED and PO-UH-60 for UH-60 Sump Repair

Transition Plan:

FLEET READINESS CENTER EAST

DOD VERTICAL LIFT CENTER OF EXCELLENCE
Cold Spray Shim Replacement for Mounting Feet on H-53 Main Gearbox
Examples of Corrosion Damage on Fielded Parts and Subsequent to Cold Spray Repair

UH-60 Main Rotor Transmission

Before

After

Cross-section of a Cold Spray Repair

Cold Spray HP-Aluminum Fill

Coating Interface

Magnesium Substrate
Development and Implementation of Commercially Pure (CP) Aluminum and 6061 Aluminum Alloy Cold Spray Coatings for the Repair of Magnesium Helicopter Gearbox Components

Before

After

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Candidate Parts
- Pump Housing
- Fan Case
- Exhaust Case
- Augmenter Duct Support
- Fan Ducts
- Bleed Valve
- Intermediate

Materials
- Ti6Al-4V
- Inconel
- Waspalloy
- Aluminum

Problems
- Cavitation
- Wear
- Corrosion
Cold Spray Applications Development at ARL

- Corrosion Damage Repair and Dimensional Restoration
- High Conductive and Wear Resistant Coatings
- Production of Exotic Materials Not Capable By Conventional Ingot Metallurgy
- Erosion Resistant Coatings
- Near Net Fabrication of Components
- Aerospace Specialty Coatings
- Conformable Antennas
- Selective Galvanization
- Aircraft Skin Repair
- Heat Sinks and Power Modules
- Cladding
Fielded SH-60 Seahawk with Cold Spray Mg Repair Operating Since August, 2009 - Australian Navy
ARL/JSF/DSTO Collaboration

Fielded B-1 Bomber with Cold Spray Ti Repair Operating Since September 2009 - Tinker AFB
ARL/Tinker AFB/HF Webster Collaboration

Three Fielded Blackhawk Medvac Units with Cold Spray Al Repair Operating Since August, 2009
ARL/AMCOM/Ft. Hood Collaboration

Two Expeditionary Fighting Vehicles with Cold Spray Mg Repair Fielded and Operating Since September, 2008

- Power Transfer Module - PTM
  - 10 Magnesium Castings
- Transmission
  - 13 Magnesium Castings
From Prototype to Production
OSD Mantech Program FY12-FY14

Integrate laboratory, coupon and prototype data to make the technology successful for production

Integrate CAD/CAM to Produce Complex Geometries, Minimize Machining and Eliminate Material Waste

Production Engineering: Couple with Cold Spray Production Facility at Mid-America, Webster, MA

Engineering Data: Performance Validation
Data In Hand
ESTCP/JSF/ARL/NRL

Real-Time Process Mapping

In-flight particle temperature, velocity, and particle size measurement

Robotic Control for Precision and Repeatability
Cold spray is a proven technology

Has demonstrated potential as a means of producing near-net shape complex components.

Upgrade conventional CS systems for near-net fabrication.

New powders and processes are required.

Future goals
Integrate CAD/CAM to produce complex geometries, minimize machining and eliminate material waste

Using CAD/CAM reproduce a shaped charge line (above) eliminating dimensional machining

Demonstrate production of a 6061 Al part

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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
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

UTRC Fretting Fatigue Specimen
Microstructures of 6061 Cold Spray Optical Microscopy

Increasing Gas Pressure
### Technical Progress

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

<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></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>420</td>
<td>5-6</td>
</tr>
<tr>
<td>AZ92A</td>
<td>T5</td>
<td>500</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</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>

## Technical Progress

### Wrought versus Cold Spray 6061

<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>

**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

\(^1\)Matweb  
\(^2\)Alcoa.com  
\(^3\)Microtensile Test by Aaron Nardi at UTRC of ARL Cold Spray Block
Triple Lug Shear Test
Technical Progress

ESTCP Triple Lug Data

- Baseline Material
- 6061 He Cold Spray Coating
- CP-Al He Cold Spray Coating
- CP-Al N2 Cold Spray Coating

Shear Adhesion (ksi)

<table>
<thead>
<tr>
<th>Substrate</th>
<th>AZ91C-T6</th>
<th>ZE41A-T5</th>
<th>EV31-T6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Azimuth</td>
<td>18 ± 2</td>
<td>16 ± 2</td>
<td>18 ± 2</td>
</tr>
<tr>
<td>ZE41A-T5</td>
<td>14 ± 2</td>
<td>15 ± 2</td>
<td>17 ± 2</td>
</tr>
<tr>
<td>EV31-T6</td>
<td>13 ± 2</td>
<td>16 ± 2</td>
<td>18 ± 2</td>
</tr>
</tbody>
</table>

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### 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>Stdev. Tensile Stress (PSI)</th>
<th>95% Confidence Tensile (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>

**failure mechanisms**

- 100% Glue
- 100% Coating Adhesion
XRD Residual Stress Versus Depth for 6061 Cold Spray on ZE41A-T5

Compressive Residual Stress (ksi)

- X-Direction
- Y-Direction
Technical Progress

- 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

Sump Assembly Main Module-Main Gearbox Repair

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

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

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- ARL Cold Spray Team
- Oak Ridge Institute for Science and Education

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