Advanced Cold Spray Development for Aerospace Aluminum Alloys

presented by: Gehn Ferguson

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Enhancing the Performance of Materials and Components
• Initial State of Cold Spray of Al Alloys
• CS Aluminum Alloy Development Process
  – Research Consortium and Modeling Efforts
  – Powder Characterization
  – Process Parameter Optimization
• Applications Development
• Repairs Qualification and Testing
• Current State of Cold Spray Aluminum Alloys
Cold Spray Coating Prior to Optimization
MATERIALS BY DESIGN APPROACH

Modeling & Simulation
Powder Synthesis
Intelligent Processing & Controls
Alloy Development/Optimization
Characterization/Materials Database
Hardware/Software Improvement
Nondestructive Inspection/Controls
Materials Properties Prediction
Applications Transition

ARL 5056 Alloy Development

From ½ % 3% 6% 15%

IMPROVE DUCTILITY

State-of-the-art
Research Team-75 researchers from academia and industry

Effect of temperature and particle cooling

Powder Characterization

Effect of encapsulation on deformation

NEU

PSU

UDM & MIT

NEU

UTRC

Materials ductility explained by particle impact model*

WPI

Cold spray process

Cold Spray Deposit

Models will be calibrated & compared

Continuum + Kinetic model

Predicted dislocation density map

Suddenly particle impact test

Material ductility explained by particle impact model*

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Holistic Approach to Cold Spray AM
Integrated Computational Materials Engineering (ICME)

Output from Powder Production & Powder Pre-Processing models are used as input to the Particle Impact Model.

- Powder Production
- Powder Processing
- Process Parameters
- Particle Impact
- Bulk Material
- Prediction of Properties

predictive models to replace the Edisonian experimental approach.
Ballistic Impact of Particles

Luke Bassett-WPI

75° impact

jet

Aaron Nardi-UTRC
Technical Results - Cold Spray Model

**Single Particle Subroutine Implementation**

### Bilinear Johnson-Cook (NEU)

- **V = 175 m/s**
- **V = 286 m/s**
- **V = 416 m/s**
- **V = 530 m/s**
- **V = 663 m/s**
- **V = 699 m/s**

### Experimental Results (UMASS)

- **V = 175 m/sec**
- **V = 286 m/sec**
- **V = 416 m/sec**
- **V = 530 m/sec**
- **V = 663 m/sec**
- **V = 699 m/sec**

### Initial PTW Results (PSU)

- **V = 175 m/sec**
- **V = 286 m/sec**
- **V = 416 m/sec**
- **V = 530 m/sec**
- **V = 663 m/sec**
- **V = 699 m/sec**

**A. Alizadeh & S. Muftu, Northeastern University**

2 sets of Johnson-Cook parameters required to create a 2 region curve fit that is strain-rate dependent

**W. Xie, J.-H. Lee, UMass**

20 um diameter 6061 Al particle impact results

**J. Schreiber, T. Eden, I. Smid – Penn State**

No parameter changes are required during analysis for PTW model.
\[ \lambda = \lambda_0 \left( \frac{12}{\rho C_p} \left( \frac{T_d - T_f}{k_0} \right) \frac{k_0}{a^2} \right)^n \]
Images of cross sectional view of 6061 powders produced through different methods resulting in significantly varied ductility due to the presence of internal defects.
Importance of Powder for the CS Process

- 325 mesh 5056 Al Flake

Aluminum Powder Morphology

- 325 mesh Pure Al Spherical
Purity of Cold Sprayed Aluminum

Oxygen content measured by Inert Gas Fusion

ASTM E 1019-03

9-40 um HP-Al Powder

Cold Spray HP-Al Coating

0.88 % Oxygen

0.58 % Oxygen

*The oxygen content of the cold spray coating is largely determined by the oxygen content of the original powder, not the process.
**Powder**: 6061 Valimet Batch-07-8070S

**Substrate Dimensions**: 1/2 x 5 x 5
**Substrate Prep**: 60 Grit @ 40 PSI
**Substrate Cleaning**: Alcohol + Air

**Nozzle**: Plastic-PBI
**Prechamber**: Short Stainless Steel
**Wheel**: 120 hole

**Gas Type**: He
**Gas Mode**: Pressure
**Gas Pressure**: 20 bar
**Heater**: 400C Gun, 350C Pre
**Powder Feeder**: 1.3 RPM, N2 gas, 3.0 m3/hr flow
**Vibrator**: 1 bar
**Stand off**: 1 1/8 inch
**Raster Speed**: 1000 mm/sec
**Step**: -0.5
Full JTP Qualification Plan

### Mechanical Tests
- Microstructure (Porosity, Interface, etc)
- Adhesion Bond Test (ASTM C633)
- Triple Lug Shear Test
- Fretting Fatigue
- Almen Strip and XRD (residual stress)
- Flat Tensile Specimens (bulk material)
- RR Moore Rotating Beam Fatigue
- Impact Testing - ASTM D5420
- Bend Test
- Hardness
- ROSAN Insert Test
- Surface finish 125RA
- Machinability

### Corrosion Tests
- Unscribed ASTM B117
- Scribed ASTM B117
- GM9540 Scribed
- Galvanic Corrosion (G71)
- Crevice Corrosion (G78)
- Beach Corrosion
- G85 SO2
- Adhesion of Coatings
Microstructure of 6061 Al

100X

Fully dense cold spray coating

Coating

Substrate

Etched 6061 Cold Spray Coating

ZE41A magnesium

200X

Fully dense cold spray coating

Coating

Substrate

Before

After
6061 Aluminum Cold Spray Coating

6061 block-unetched-50X

6061 etched-50X
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 ESTCP Data and DSTO Data show 10 ksi+
Modifying ASTM C633

- **Glueless Adhesion Test**
  - Evaluate full adhesion strength
  - Enables elevated temp testing

- **Specimen Design**
  - Neck and cap design based on Huang and Fukanuma
  - Cold spray / substrate interface located in neck
  - 1.5” substrate bar diameter to accommodate cold spray taper

- **Fixturing Design**
  - Dual plate fixture accommodates varying cap thicknesses
  - Couples to load frame similar to ASTM C633 uniaxial loading design

Glueless Adhesion Test

Al 6061 cold spray on cast Al C355-T6 test specimens: as sprayed condition
Glueless Adhesion Test

Fixturing for uniaxial loading

Tested specimen

Failure at deposit/substrate interface
Cold Spray Al 6061 on Cast Mg ZE41A-T5 and Cast Al C355-T6 Glueless Adhesion Test Results

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Max Load (lbf)</th>
<th>UTS (ksi)</th>
<th>Failure Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mg ZE41A-T5</td>
<td>4810</td>
<td>24.5</td>
<td>Adhesion to substrate failure</td>
</tr>
<tr>
<td>Mg ZE41A-T5</td>
<td>4664</td>
<td>23.8</td>
<td>Adhesion to substrate failure</td>
</tr>
<tr>
<td>Mg ZE41A-T5</td>
<td>4710</td>
<td>24.0</td>
<td>Adhesion to substrate failure</td>
</tr>
<tr>
<td>Mg ZE41A-T5</td>
<td>4551</td>
<td>23.2</td>
<td>Adhesion to substrate failure</td>
</tr>
<tr>
<td>Mg ZE41A-T5</td>
<td>4508</td>
<td>23.0</td>
<td>Adhesion to substrate failure</td>
</tr>
<tr>
<td>Mg ZE41A-T5</td>
<td>4621</td>
<td>23.5</td>
<td>Adhesion to substrate failure</td>
</tr>
<tr>
<td>Al C355-T6</td>
<td>3583</td>
<td>18.2</td>
<td>Adhesion to substrate failure</td>
</tr>
<tr>
<td>Al C355-T6</td>
<td>4057</td>
<td>20.7</td>
<td>Adhesion to substrate failure</td>
</tr>
<tr>
<td>Al C355-T6</td>
<td>5039</td>
<td>25.7</td>
<td>Adhesion to substrate failure</td>
</tr>
<tr>
<td>Al C355-T6</td>
<td>3886</td>
<td>19.8</td>
<td>Adhesion to substrate failure</td>
</tr>
<tr>
<td>Al C355-T6</td>
<td>4727</td>
<td>24.1</td>
<td>Adhesion to substrate failure</td>
</tr>
<tr>
<td>Al C355-T6</td>
<td>5492</td>
<td>28.0</td>
<td>Adhesion to substrate failure</td>
</tr>
</tbody>
</table>
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.
Localized simulated repair using ARL CS process parameters developed for the UH-60 Sump. Typical inclusions dominate failure and is commensurate with fatigue results of base material.
Fatigue Test Results

All repair sample failures originated from inclusions typical to magnesium and removed from the repair location.
# Mechanical Properties of CS Aluminum

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Parameters</th>
<th>Specimen ID</th>
<th>HRB</th>
<th>%IACS</th>
<th>UTS MPa (ksi)</th>
<th>%El</th>
</tr>
</thead>
<tbody>
<tr>
<td>6061</td>
<td>Press. 20 bar</td>
<td>400°C</td>
<td>CS-12-275</td>
<td>31.0</td>
<td>44.03</td>
<td>239 (34.6)</td>
</tr>
<tr>
<td>6061</td>
<td>Press. 25 bar</td>
<td>450°C</td>
<td>CS-13-096</td>
<td>40.4</td>
<td>41.5</td>
<td>310 (45.0)</td>
</tr>
<tr>
<td>2024</td>
<td>Press. 25 bar</td>
<td>400°C</td>
<td>CS-14-150</td>
<td>64.6</td>
<td>30.18</td>
<td>392 (56.8)</td>
</tr>
<tr>
<td>2024</td>
<td>Press. 30 bar</td>
<td>500°C</td>
<td>CS-14-152</td>
<td>57.3</td>
<td>31.96</td>
<td>346 (50.2)</td>
</tr>
<tr>
<td>7075</td>
<td>Press. 25 bar</td>
<td>400°C</td>
<td>CS-14-128</td>
<td>65.2</td>
<td>31.08</td>
<td>387 (56.2)</td>
</tr>
<tr>
<td>7075</td>
<td>Press. 25 bar</td>
<td>400°C</td>
<td>CS-14-120</td>
<td>50.1</td>
<td>35.92</td>
<td>326 (47.3)</td>
</tr>
<tr>
<td>7075</td>
<td>Press. 30 bar</td>
<td>500°C</td>
<td>CS-14-125</td>
<td>62.7</td>
<td>31.11</td>
<td>394 (57.2)</td>
</tr>
<tr>
<td>5056</td>
<td>Press. 20 bar</td>
<td>500°C</td>
<td>CS-14-101</td>
<td>63</td>
<td>26.25</td>
<td>406 (58.9)</td>
</tr>
<tr>
<td>5056</td>
<td>Press. 30 bar</td>
<td>500°C</td>
<td>CS-14-102</td>
<td>62</td>
<td>26.64</td>
<td>400 (58.0)</td>
</tr>
</tbody>
</table>
Questions?