Overview of Cold Spray

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Particle Velocity (m/s)
- > 325
- > 350
- > 375
- > 400
- > 450
- > 475
- > 500

Gas Pressure (psig)
- 200
- 250
- 300
- 350
- 400

Gas Temperature (°C)

Air, 22 µm Copper

100 µm
A “Cold” Process Technology from Siberia

Deposition Efficiency

- Copper
- Iron
- Nickel
- Aluminum

Particle Velocity m/s

After Alkimov, et al., 1990
Sandia Cold Spray System
Spray Ductile Metals, Cermets, Polymers

Examples of Materials Successfully Deposited at Sandia

<table>
<thead>
<tr>
<th>Active Braze Alloy</th>
<th>Fe$_3$Pt</th>
<th>Polymer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>Molybdenum</td>
<td>StelCar</td>
</tr>
<tr>
<td>Aluminum Bronze</td>
<td>Monel</td>
<td>Tantalum</td>
</tr>
<tr>
<td>Copper</td>
<td>80Ni/20Cr</td>
<td>Tin</td>
</tr>
<tr>
<td>304 Stainless Steel</td>
<td>NiCrAlY</td>
<td>Titanium</td>
</tr>
<tr>
<td>420 Stainless Steel</td>
<td>NiCr-Cr$_3$C$_2$</td>
<td>WC-Co (nanophase)</td>
</tr>
</tbody>
</table>
Cold Spray vs. Air Plasma Spray

**Cold Sprayed Copper**

- Superior Density
- Less Oxide

**Plasma Sprayed Copper**
Some Exciting New Possibilities

• Avoid melting & solidification
  - Avoid thermally induced stress
  - Avoid undesirable phases
  - Avoid oxidation (deposit metals in ambient air!)
  - Preserve desired phases & chemistry
  - Preserve original grain size (nanocrystalline mat’ls)

• Low Porosity (>99% dense, as deposited)

• High thermal / electrical conductivity (>80% OFHC Cu)

• High Deposition Efficiencies (>98%)

• Recycle feedstock & process gas

• Work with highly dissimilar materials combinations
New Possibilities, cont’d.

- Highly wrought material (high hardness / strength)
- Potential for high deposition rates
- Relatively insensitive to standoff, work up close (<1 cm)
- Minimal substrate heating
- May eliminate surface prep / masking
- Good as-sprayed surface finishes
- Non-circular spray patterns
- Potential for smooth surfaces
Cold Spray Direct Fabrication

- Additively build net / near-net shapes directly from a computer
- Key technical challenge is focusing the spray stream

Do you want a Print or a Part?
- Print
- Build

~ 1 mm Focused Stream for Subsonic Flow

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Example Applications

- **Anti-corrosion** (superior density, less oxide)
- **Wear resistance** (superior hardness & density)
- **Metals on ceramics / glass**
- **High-alloy / specialty metals** (preserve composition & phases)
- **Plastic coatings without volatile organics**
- **Defect repair** (minimal masking / heating, machinable)
- **Direct fabrication**
- **Satellite structures** (high conductivity, low residual stress)
Reclaiming Parts & $$$

Unusable $150k GPS satellite part reclaimed with Cold Spray

- Low heat input
- Low stress
- Dense, machinable
- High conductivity,
State of the Art

- Technology ~ 10 years old
- Success with many metals, some cermets & polymers
- New materials / processing / manufacturing possibilities
- Considerable industrial interest
- Patented, but licenses available
- No commercial use yet
Barriers to Commercial Use

Technical Issues:

• Process fundamentals poorly understood
• Cannot predict materials / parameters
• Reduce / eliminate expensive helium
• Nozzle fouling / optimization

Build-up in nozzle
Barriers to Commercial Use

Manufacturing Issues:

- No commercial equipment / coating suppliers
- Need articulated robot compatible spray gun
- Lack of property data / field experience
- Need better fine powder feeders

Uneven deposition due to uneven powder feed
Understanding Critical Velocity

19 µm Copper powder onto Aluminum

Particle Velocity Distributions

Deposition Efficiency (%)

Mean Particle Velocity (m/s)

Normalized Counts

Particle Velocity (m/s)

Deposition Efficiency

0 % 53 % 95 %

Experiment Prediction

1 2 3

Experiment Prediction

1 2 3

1 2 3

0 20 40 60 80 100

450 500 550 600 650 700 750 800

200 400 600 800 1000 1200
Process Maps Guide Optimization

Air, 22 µm Copper

Particle Velocity (m/s)
- > 500
- > 475
- > 450
- > 425
- > 400
- > 375
- > 350
- > 325

Gas Pressure (psig)
- 200
- 250
- 300
- 350
- 400

Gas Temperature (°C)
- 0
- 100
- 200
- 300
- 400
- 500
Models Guide Nozzle Design

\[
\frac{dV_p}{dt} = \frac{D}{m}
\]

\[
\frac{dD}{dP} = C_D A_p \left( \frac{M^2}{2} - 1 \right)
\]

max @ \( M = \sqrt{2} = 1.4 \)

\( V_p = \text{particle Velocity} \)
\( D = \text{Drag force} \)
\( m = \text{particle Mass} \)
\( P = \text{Pressure} \)
\( C_D = \text{Drag coefficient} \)
\( A_p = \text{Area of particle} \)
\( M = \text{Mach number} \)

\( A*/A = \text{Choke Point/Nozzle Exit Area Ratio} \)

(Axial Position measured from choke point)
"Estimator" ver. 1.0 for Spray Parameters

### Air

<table>
<thead>
<tr>
<th>INPUTS</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas Type (0=Helium, 1=Air)</td>
<td>1</td>
</tr>
<tr>
<td>Gas Temperature (°C)</td>
<td>200</td>
</tr>
<tr>
<td>Gas Pressure (psig)</td>
<td>400</td>
</tr>
<tr>
<td>Particle size (µm)</td>
<td>22</td>
</tr>
<tr>
<td>Particle density (g/m³)</td>
<td>2</td>
</tr>
<tr>
<td>Drag coefficient</td>
<td>1</td>
</tr>
</tbody>
</table>

| NOZZLE LENGTH (mm) | 0.4     |
| Thread Diameter (mm) | 2      |
| Nozzle exit width (mm) | 1.0    |

<table>
<thead>
<tr>
<th>OUTPUTS</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimum Nozzle Particle Velocity (m/s)</td>
<td>43.7</td>
</tr>
<tr>
<td>Gas Flow Rate (SLPM)</td>
<td>792</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>EXIT CONDITIONS</th>
<th>ACTUAL NOZZLE</th>
<th>OPTIMUM NOZZLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas Velocity (m/s)</td>
<td>831</td>
<td>763</td>
</tr>
<tr>
<td>Gas Pressure (psig)</td>
<td>-1</td>
<td>0</td>
</tr>
<tr>
<td>Gas Temperature (°C)</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Mach Number</td>
<td>3.43</td>
<td>2.74</td>
</tr>
<tr>
<td>Exit-Throat Area Rate</td>
<td>0.45</td>
<td>0.50</td>
</tr>
<tr>
<td>Exit Slot Width (mm)</td>
<td>10</td>
<td>9.16</td>
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</table>

### Helium

<table>
<thead>
<tr>
<th>INPUTS</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas Type (0=Helium, 1=Air)</td>
<td>0</td>
</tr>
<tr>
<td>Gas Temperature (°C)</td>
<td>200</td>
</tr>
<tr>
<td>Gas Pressure (psig)</td>
<td>400</td>
</tr>
<tr>
<td>Particle size (µm)</td>
<td>22</td>
</tr>
<tr>
<td>Particle density (g/m³)</td>
<td>0</td>
</tr>
<tr>
<td>Drag coefficient</td>
<td>1</td>
</tr>
</tbody>
</table>

| NOZZLE LENGTH (mm) | 0.4     |
| Thread Diameter (mm) | 2      |
| Nozzle exit width (mm) | 1.0    |

<table>
<thead>
<tr>
<th>OUTPUTS</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimum Nozzle Particle Velocity (m/s)</td>
<td>782</td>
</tr>
<tr>
<td>Gas Flow Rate (SLPM)</td>
<td>2102</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>EXIT CONDITIONS</th>
<th>ACTUAL NOZZLE</th>
<th>OPTIMUM NOZZLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas Velocity (m/s)</td>
<td>2053</td>
<td>1643</td>
</tr>
<tr>
<td>Gas Pressure (psig)</td>
<td>-4.5</td>
<td>-4.5</td>
</tr>
<tr>
<td>Gas Temperature (°C)</td>
<td>215</td>
<td>215</td>
</tr>
<tr>
<td>Mach Number</td>
<td>4.13</td>
<td>1.21</td>
</tr>
<tr>
<td>Exit-Throat Area Rate</td>
<td>5.5</td>
<td>1.06</td>
</tr>
<tr>
<td>Exit Slot Width (mm)</td>
<td>10</td>
<td>2.27</td>
</tr>
</tbody>
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Sandia National Laboratories
Understanding Particle Impact

1 km Asteroid Impacting Ocean
300 Gigatons TNT Equivalent (10x Peak of All Cold War Nuke’s)

Sandia Teraflops computer running CTH code
100 million computational cells
18 hr @ 91% capacity (8,192 of 9,000 processors)
Predicted peak temp. of 1280 K is below the melting point of Cu (1357 k).
Summary

- New materials / processing / manufacturing possibilities
- Opportunity to be first to exploit market advantage
- Several pre-competitive barriers need to be solved
- Faster / cheaper / better to work together on pre-comp.
- Partners will gain access to best technology & new IP