



# **Cold Spray Aluminum for Magnesium Gearbox Repair**

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**US Army Research Laboratory**

**Weapons & Materials Research Directorate**

**SERDP/ESTCP Surface Finishing Workshop**

**February 26-28, 2008**

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# ESTCP Program Goal

*ESTCP Proposal 06-E-PP3-031*

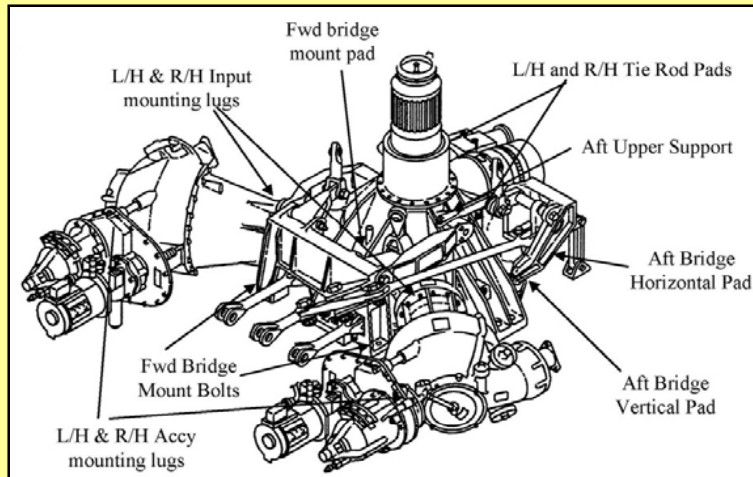
- **To reclaim Magnesium alloy components on Army and Navy helicopters that have been removed from service due to severe corrosion and/or wear.**
- **ARL will provide a repair/rebuild Cold Spray procedure for scrapped parts and assist in the transition and implementation of this technology, initially, at NADEP, Cherry Point, NC.**



## Problems With Current Surface Treatment Methods



- Exposure to hexavalent chrome is hazardous to workers' health. OSHA limits on chromium exposure are becoming increasingly stringent.
- Even with chromated surface treatments, Mg components suffer severe degradation in service
- Most corrosion occurs at mating pads, supports, and mounting lugs where dissimilar metal is in contact with Mg; damage is most likely to occur in those locations as well



**H-60 Main Transmission Housing showing areas most susceptible to corrosion**



**Corrosion on H-53 Tail Gearbox Housing**



## Program Objectives

- **Develop the densest, thinnest, most corrosion resistant Aluminum-based Cold Spray coating with the greatest adhesive bond strength to Magnesium.**
- **Determine effects of feedstock material and process parameters on coating thickness, microstructure, adhesion, and corrosion performance for the Cold Spray coatings on Magnesium substrates.**



U.S. DEPARTMENT OF DEFENSE  
Environmental Security Technology Certification Program  
(ESTCP)

## JOINT TEST PROTOCOL

*Supersonic Particle Deposition Technology for  
Repair of Magnesium Aircraft Components*

*Joint Test Protocol (JTP)  
has been developed*

Date: October 2, 2006

Prepared By:  
Hard Chrome Alternatives Team (HCAT)





# ARL Leveraged Formal Programs



***Develop aluminum cold spray coatings for aluminum, magnesium and/or steel substrates have been established with the following:***

- 1. Defense Science & Technology Organization (DSTO)**
- 2. Joint Strike Fighter (JSF)**
- 3. National Center for Manufacturing Sciences (NCMS)**
- 4. Lockheed Martin**
- 5. Penn State Applied Research Laboratory**
- 6. Lawrence Livermore National Labs (LLNL)**
- 7. South Dakota School of Mines (SDSM)**



**Cold Spray Center at the  
US Army Research Laboratory (ARL)  
Aberdeen Proving Ground, MD 21005-5069**

**ARL Cold Spray Research Team**

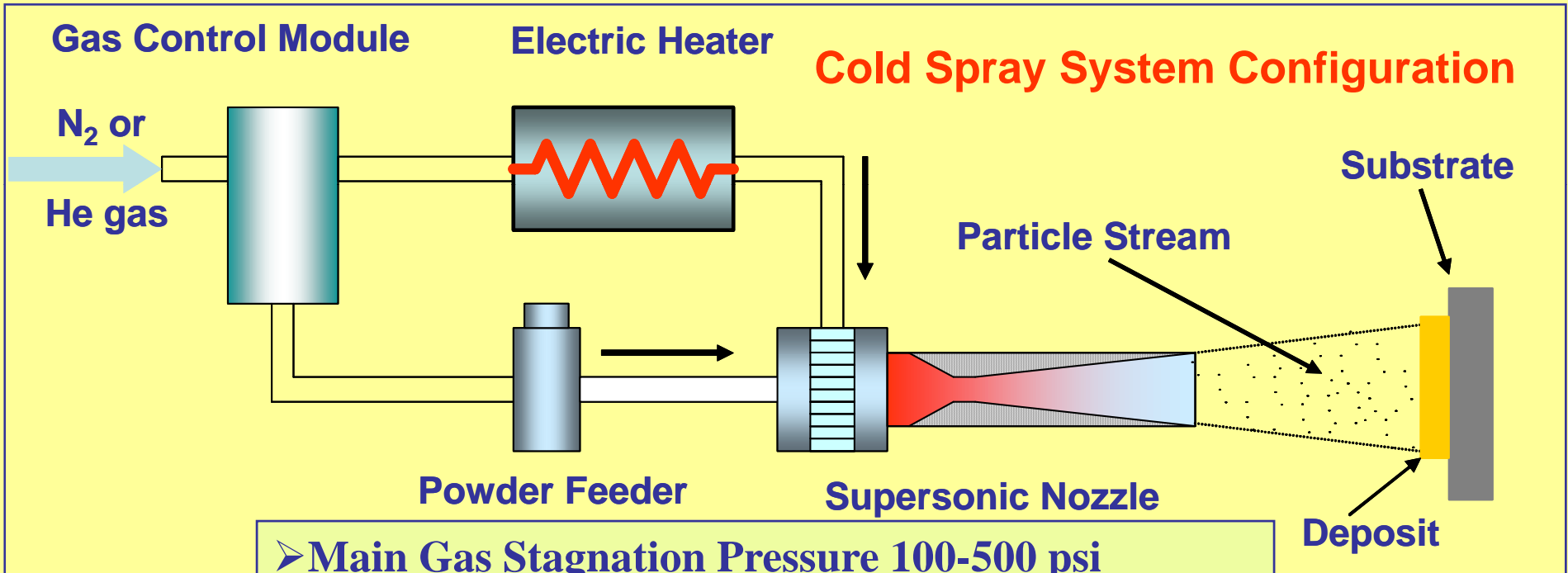
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# Overview of Cold Spray Technology



**Cold Spray:** a process by which particulates are deposited by means of ballistic impingement upon a suitable substrate at super sonic velocities to form a coating or a free-standing structure.



- Main Gas Stagnation Pressure 100-500 psi
- Gas Temperature 0-500°C
- Main Gas Flow Rate 30-100 CFM
- Powder Feed Rate 1 to 10 pounds/hour
- Particle Velocity 300-1500 m/sec.
- Particle Size 1-100um diameter



# Stationary Cold Spray System at ARL



**Robot-Controlled, High Pressure, He and N Gas**





# Cold Spray Advantages



## **Mechanical mixing bond at substrate interface**

plastic deformation may disrupt thin oxide surface films to permit bonding similar to explosive welding

## **Compressive residual stresses**

particles “peen” surface

plasma and wire-arc thermal spray coatings tend to be in tension

## **High density**

low porosity:  $< 0.5 \%$

low oxide content  $< 0.3\%$

## **Thick coatings**

free-form fabrication

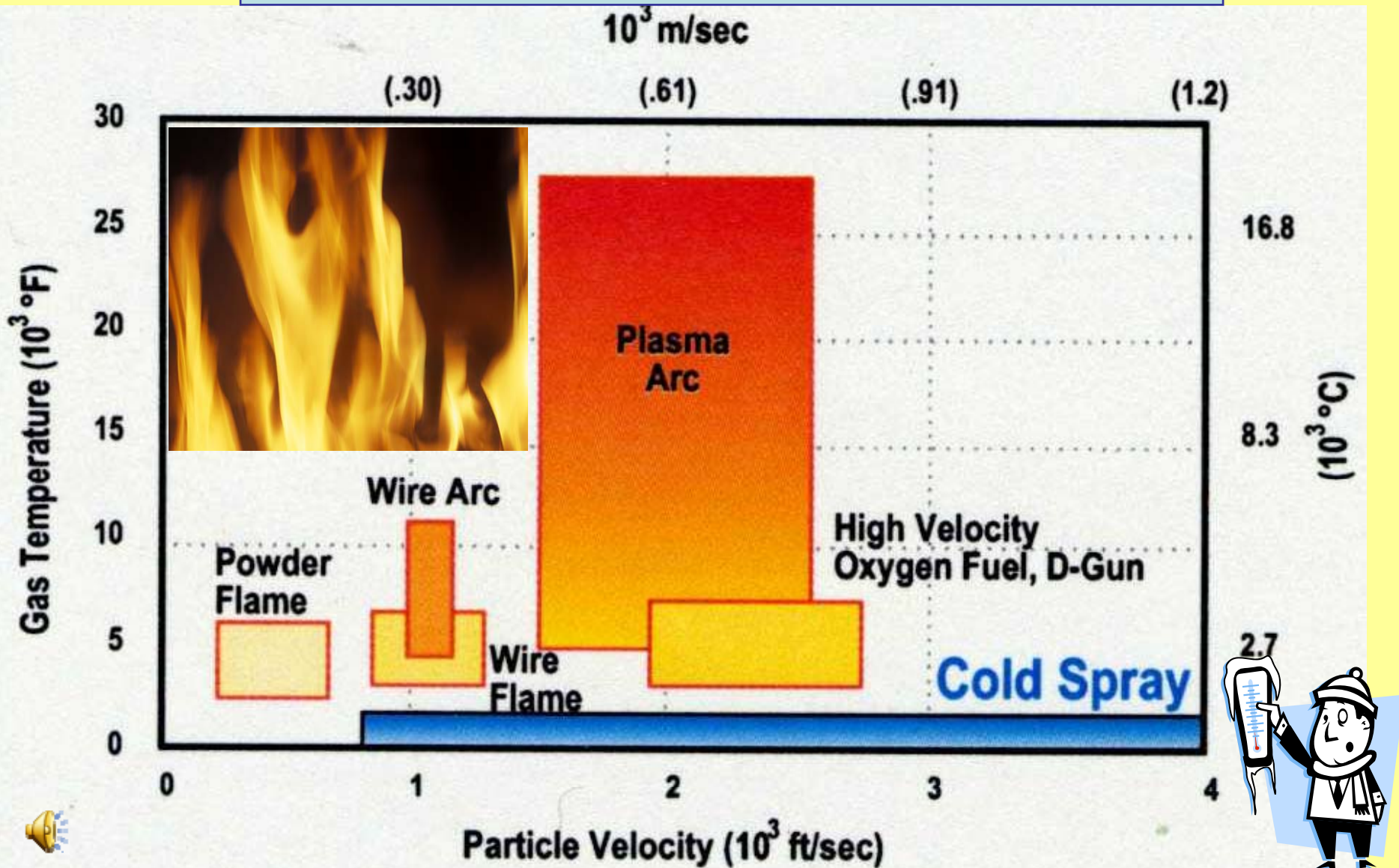
## **Low Temperature Application**

thermally sensitive substrates

low stresses due to CTE mismatch



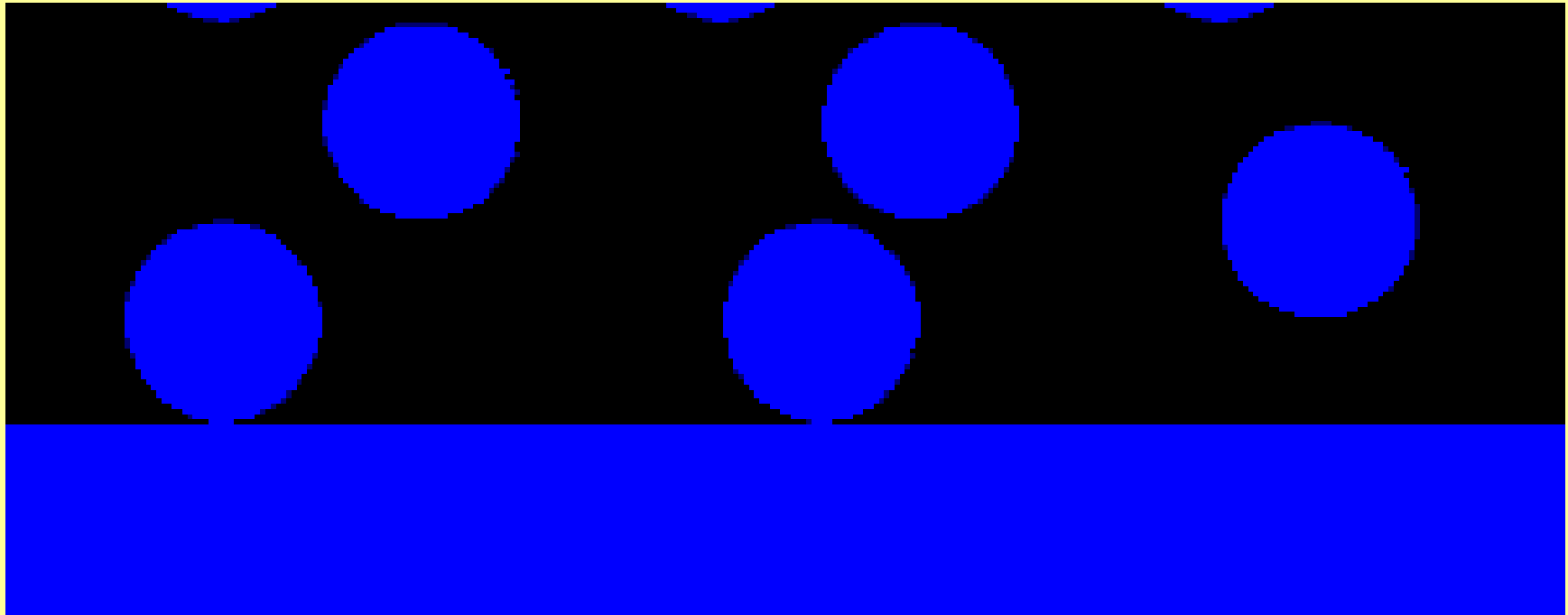
# Cold Spray vs. Thermal Spray



Cold Spray is performed at lower temperatures at high particle velocities



## Particle/Substrate Interaction\*



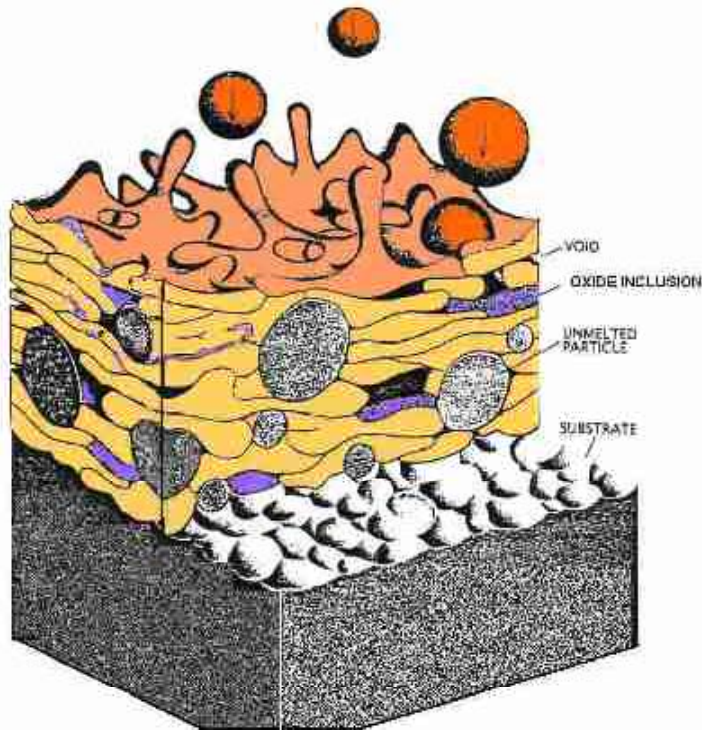
\*from H. Assadi, [www.modares.ac.ir/eng/ha10003/CGS.htm](http://www.modares.ac.ir/eng/ha10003/CGS.htm)



# Advantages of Low Temperature Process

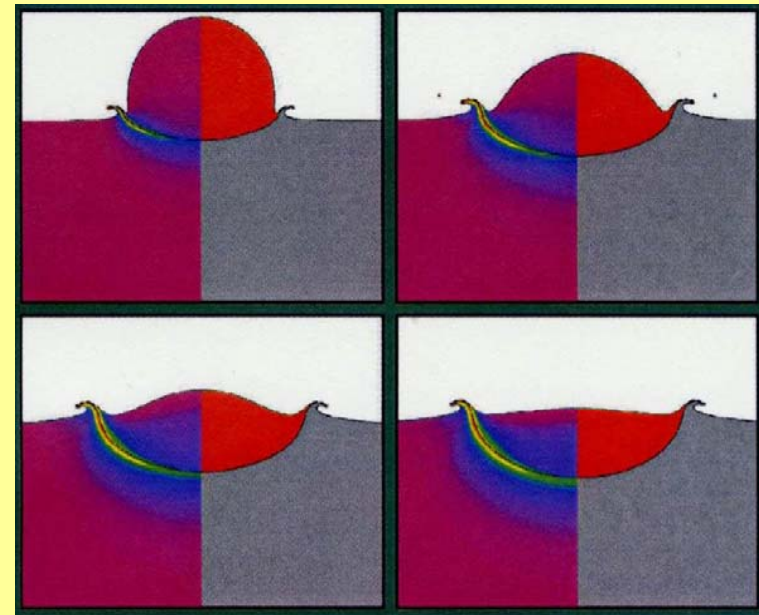


## Thermal Spray



[www.gordonengland.co.uk](http://www.gordonengland.co.uk)

## Cold Spray



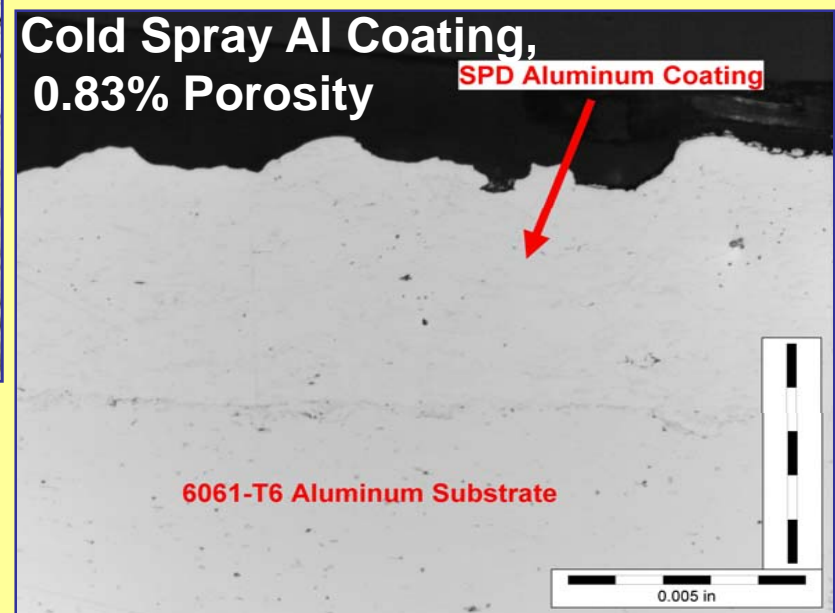
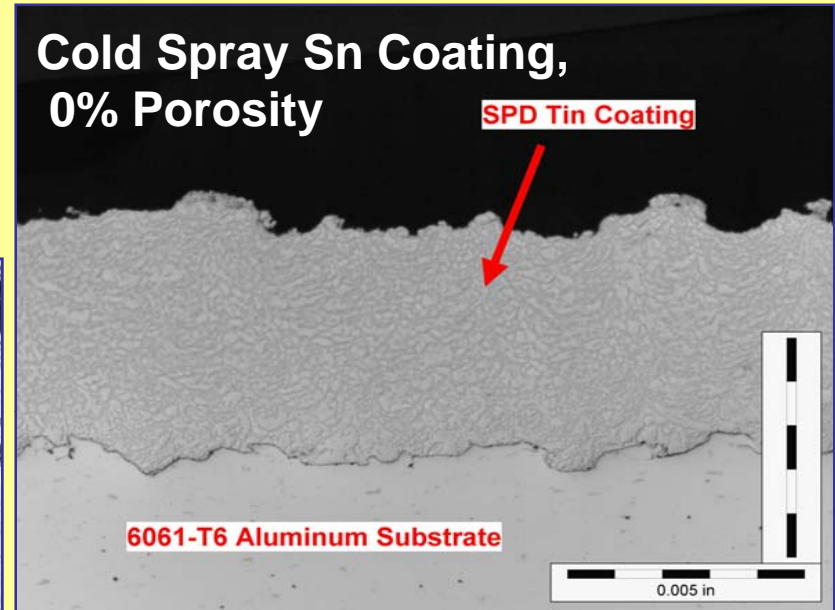
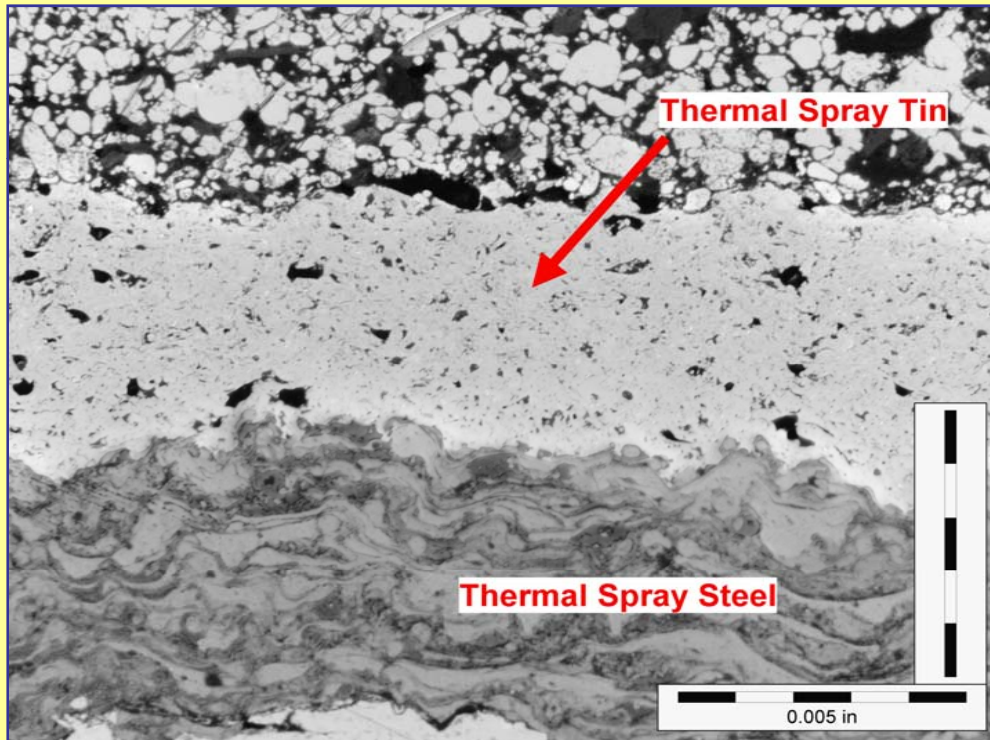
The melting of particles that occurs during most thermal spray processes can result in oxidation of both the coating and substrate materials. The resulting oxides decrease the adhesive and cohesive strengths of the coating. The cold spray process avoids such reactions.



# Cold Spray vs. Thermal Spray

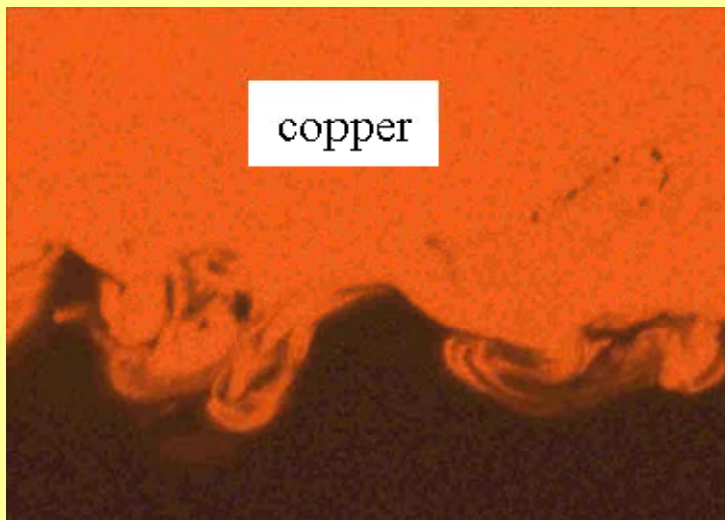
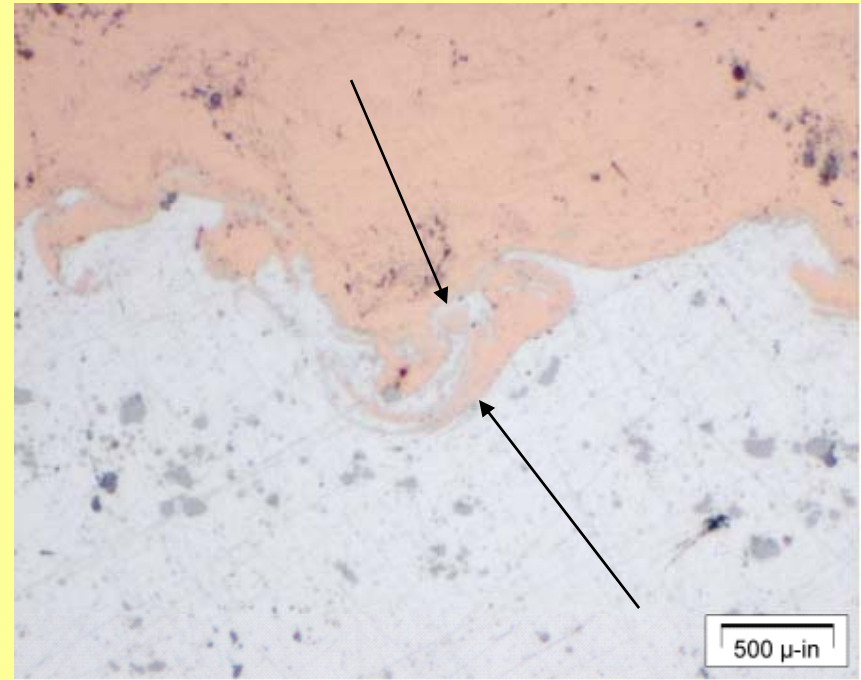
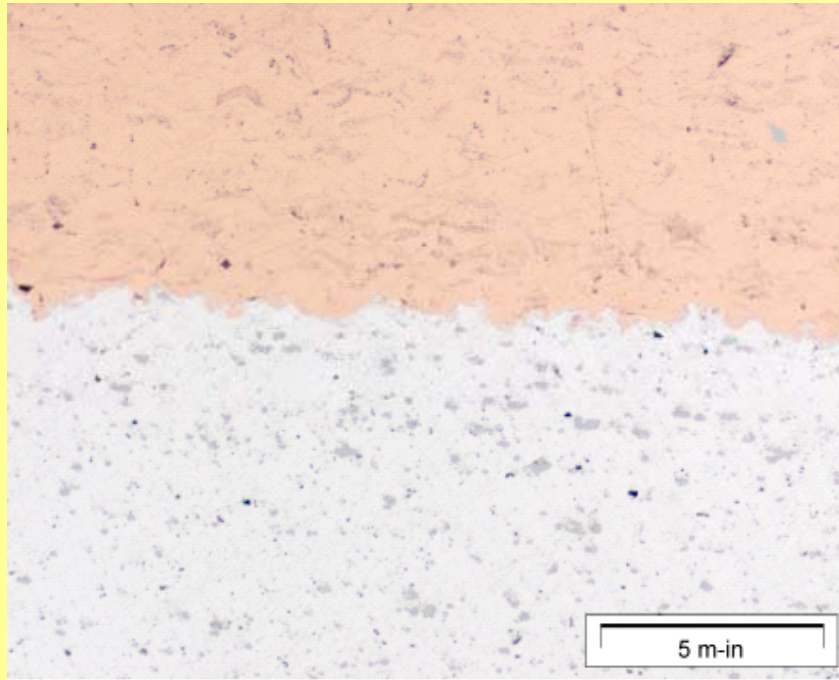


**Flame Spray Sn & Steel Coating, 12.2% Porosity**



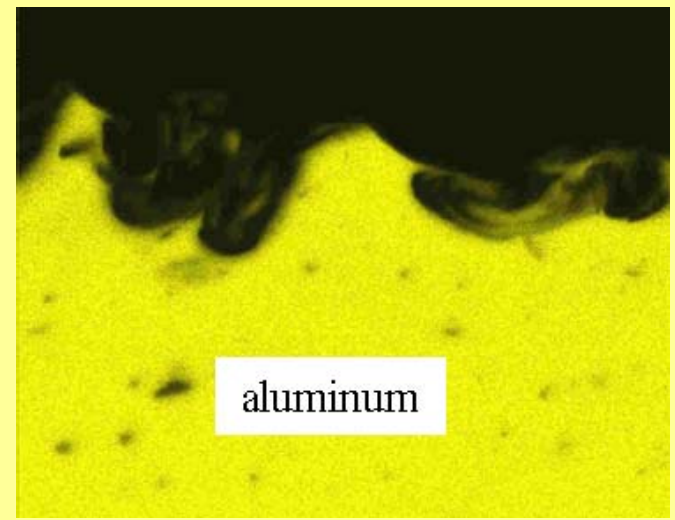


# Mechanical Mixing at Interface



copper

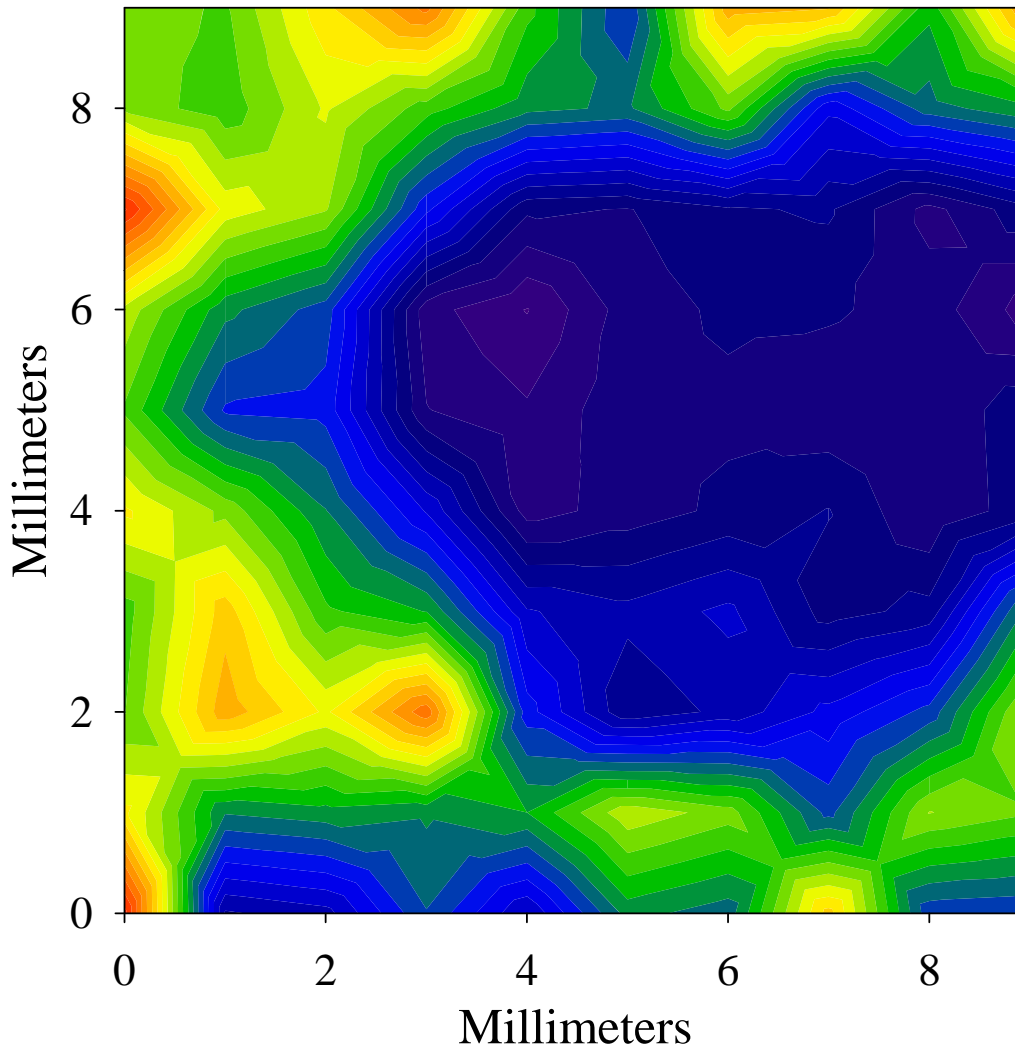
EDS X-ray Mapping showing mechanical mixing between coating material and substrate



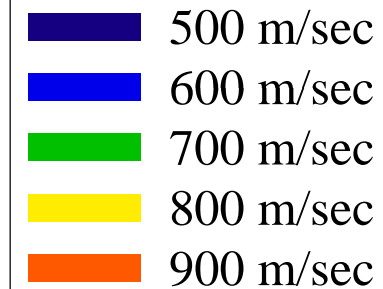
aluminum



# Particle Velocity Distribution Measured by DPV 2000



**20 micron copper particles  
25 mm downstream  
400 psi, 400 C N<sub>2</sub> gas**





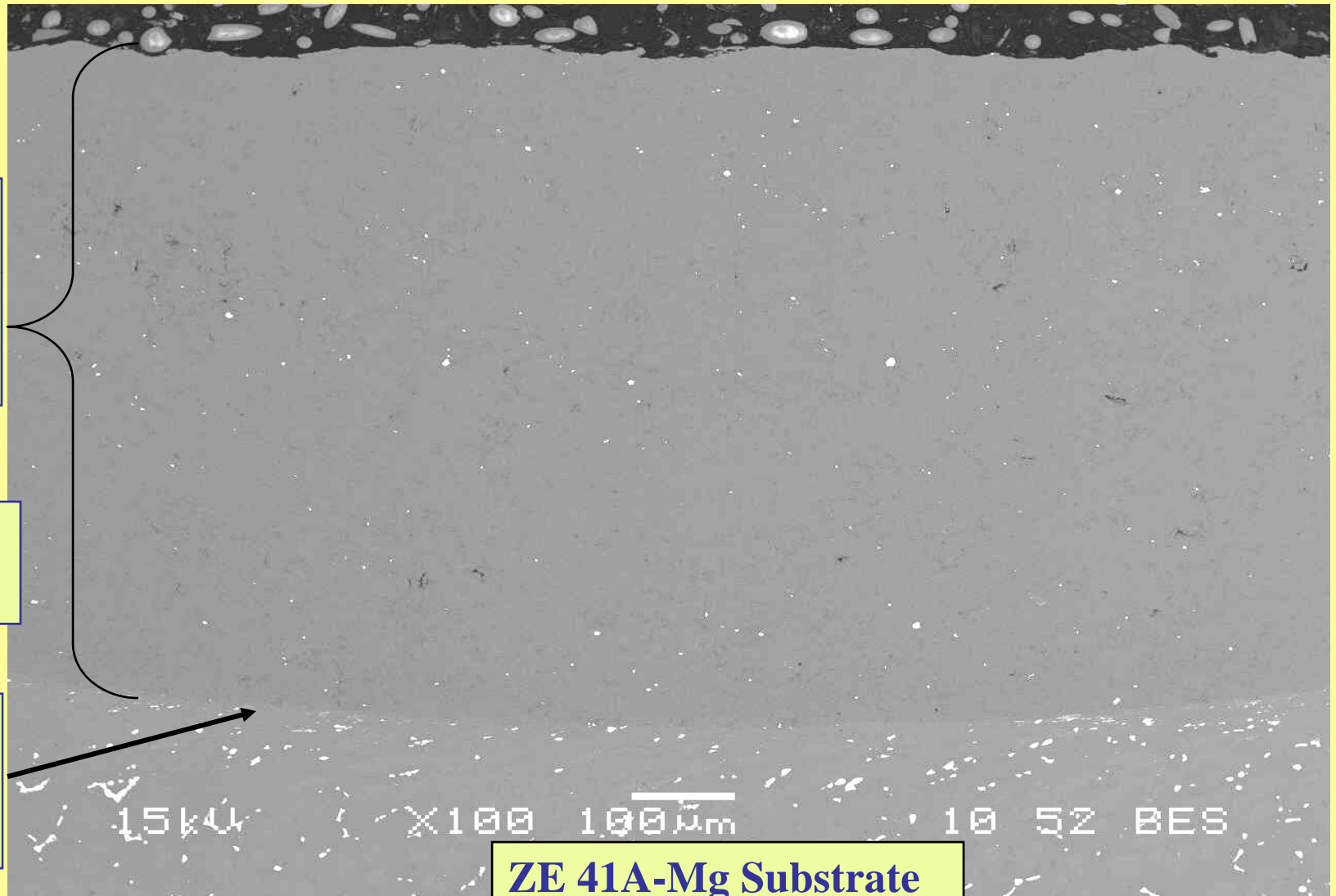
# Cold Spray Coating of CP-Al On ZE 41A-Mg (Helium Carrier Gas)

~100%  
Dense

Cold  
Spray  
CP- Al  
Coating

8,500 psi  
adhesion

Coating /  
Substrate  
Interface



ZE 41A-Mg Substrate

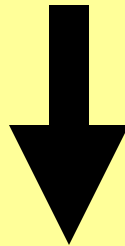


# ARL Technical Hurdle

No Porosity & 8,500 psi bond strength using Helium

**Achieve similar results with the use of nitrogen as the carrier gas**

## Technical Approach

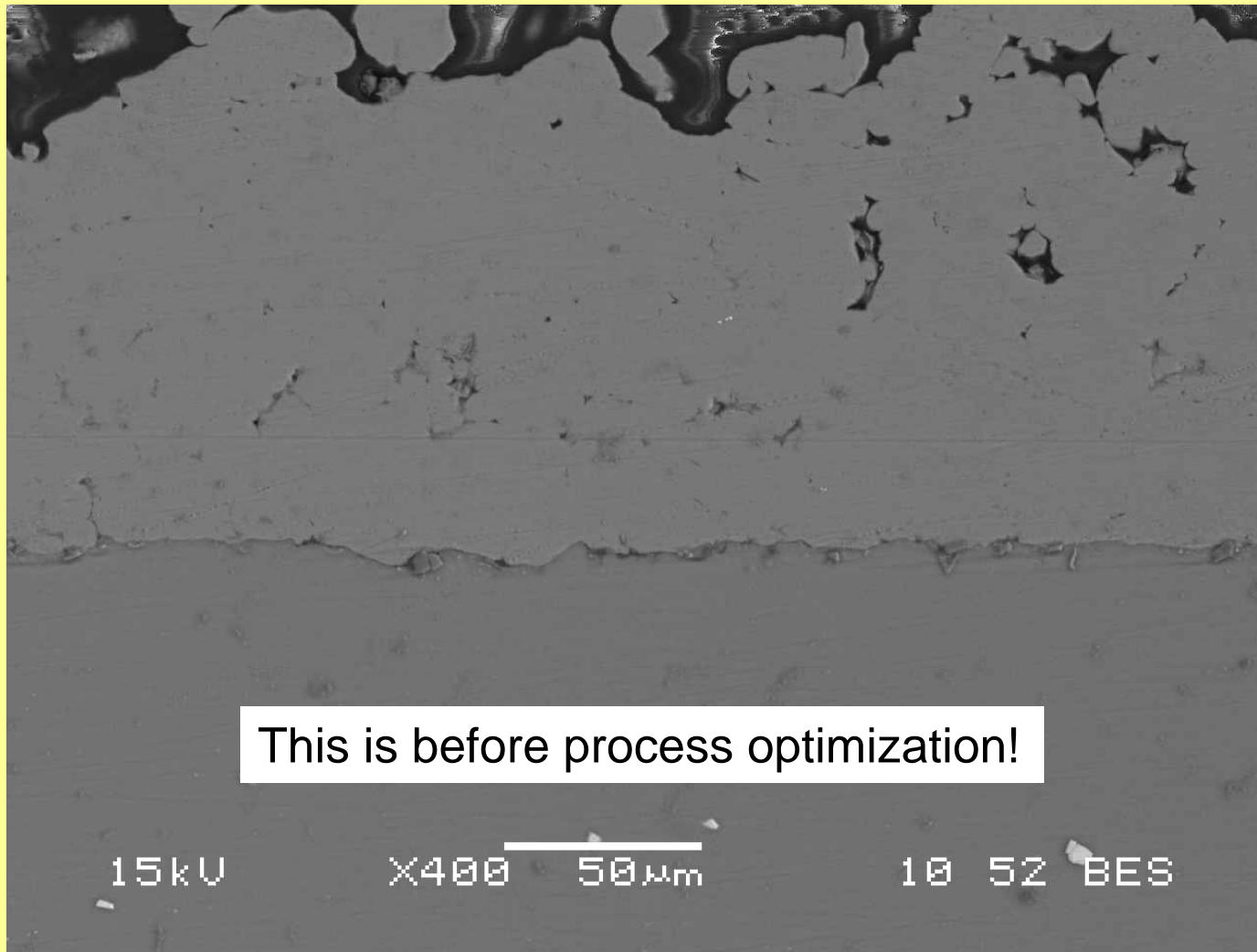


- Nozzle – Material & Design
- Powder Size, Morphology
- Process Parameters



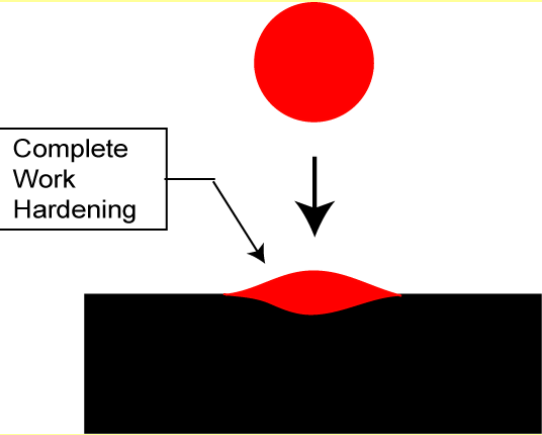
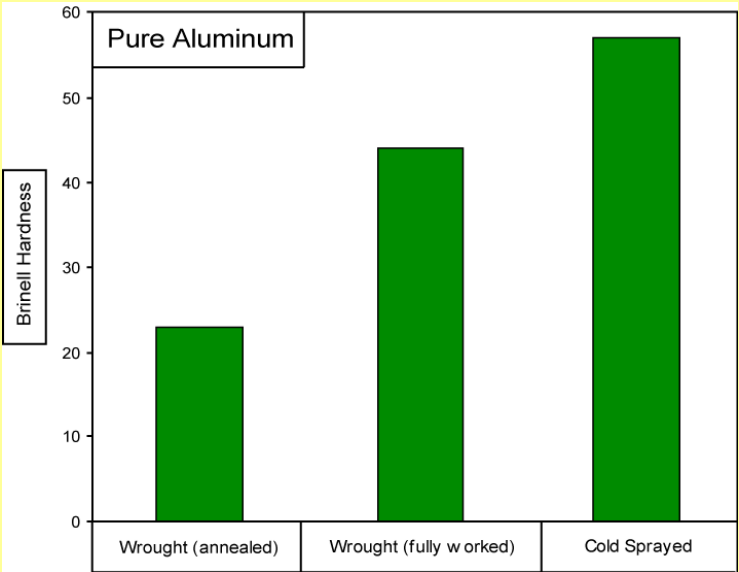
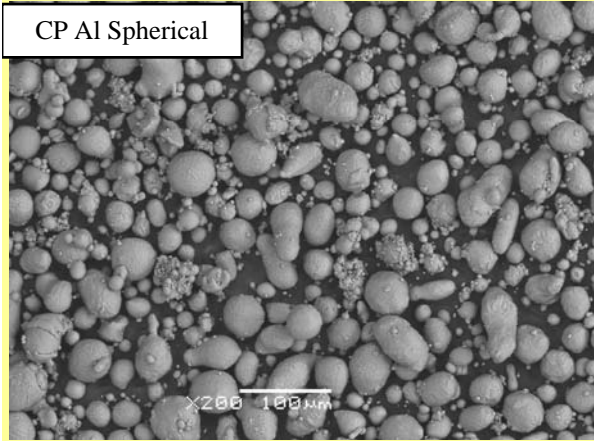
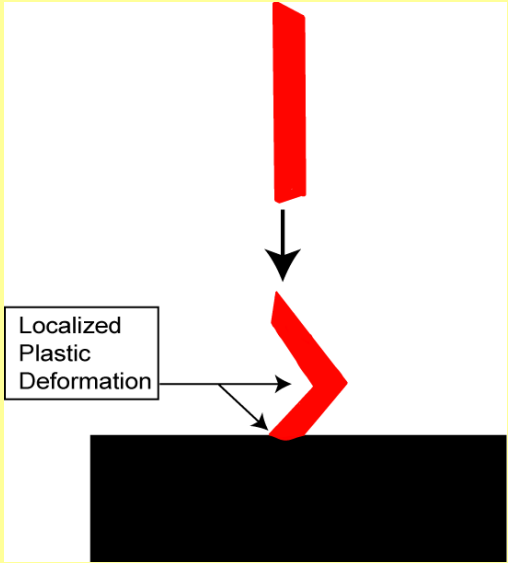
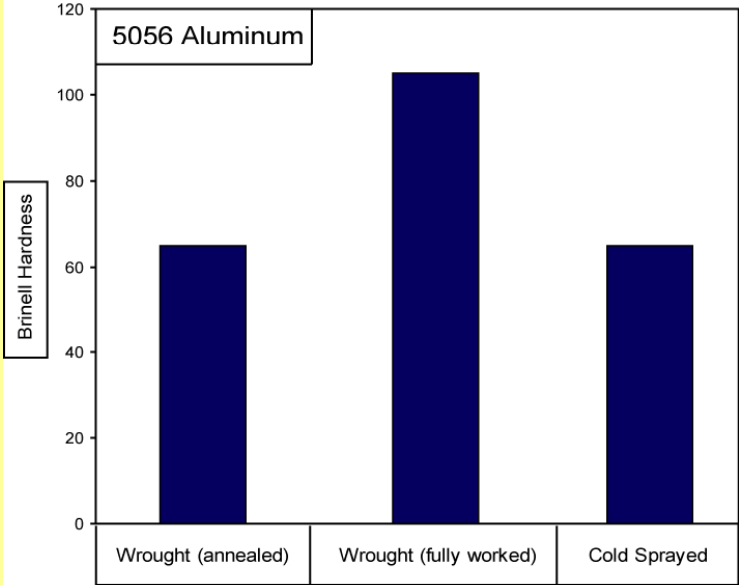
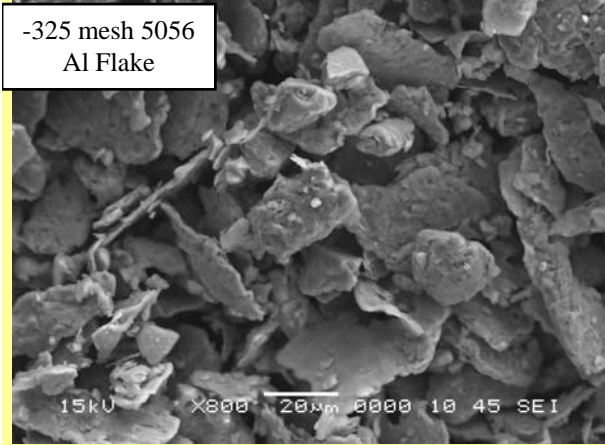


# Cold Spray Coating of CP-Al on ZE41A-Mag (Nitrogen at 380 psi, 250 C)



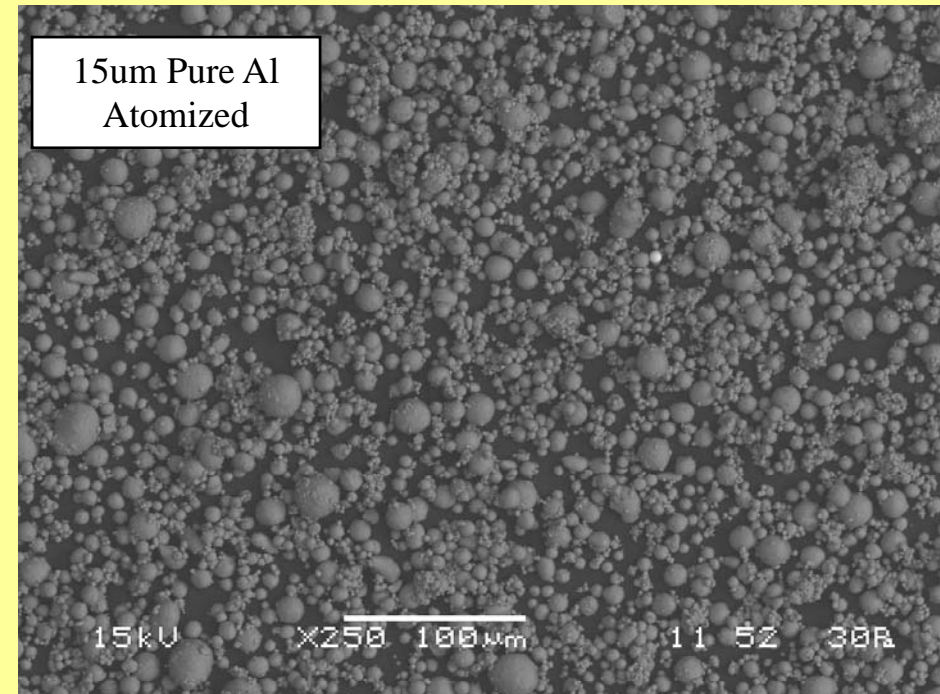


# Aluminum Powder Morphology





# Aluminum Powder Morphology



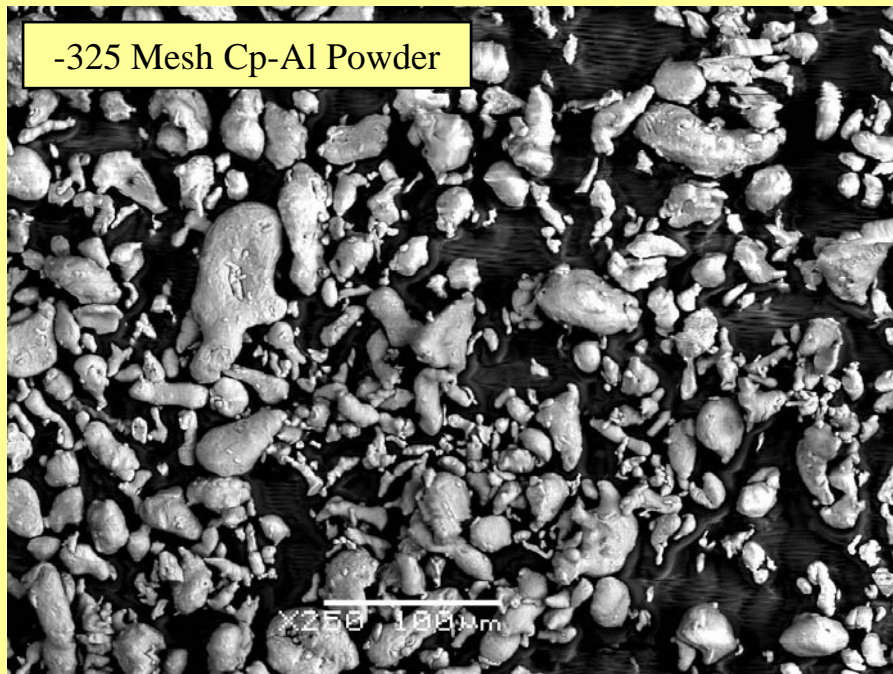
**Coating quality is critically dependent on the feed powder composition, morphology, oxygen content, and mechanical properties.**



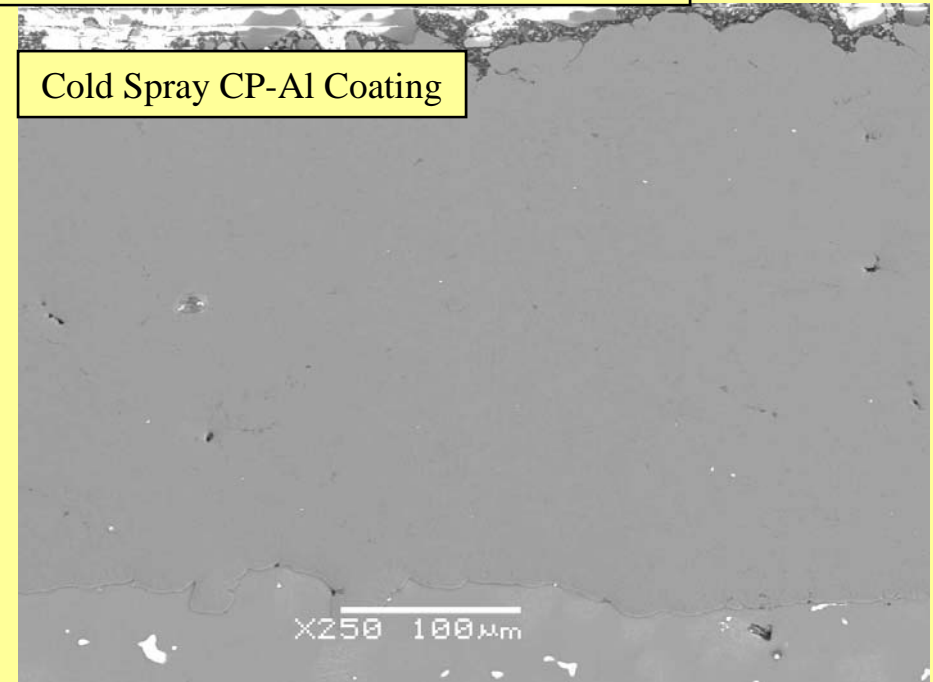
# Purity of Cold Sprayed Aluminum



Oxygen content measured by Inert Gas Fusion  
ASTM E 1019-03



**0.34 %Oxygen**



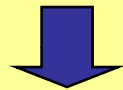
**0.25 %Oxygen**

\*The oxygen content of the cold spray coating is largely determined by the oxygen content of the original powder, not the process.

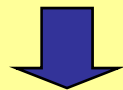


## Modeling Efforts

Gasdynamic equations are used to calculate gas velocity and temperature within the nozzle and downstream of the nozzle exit.



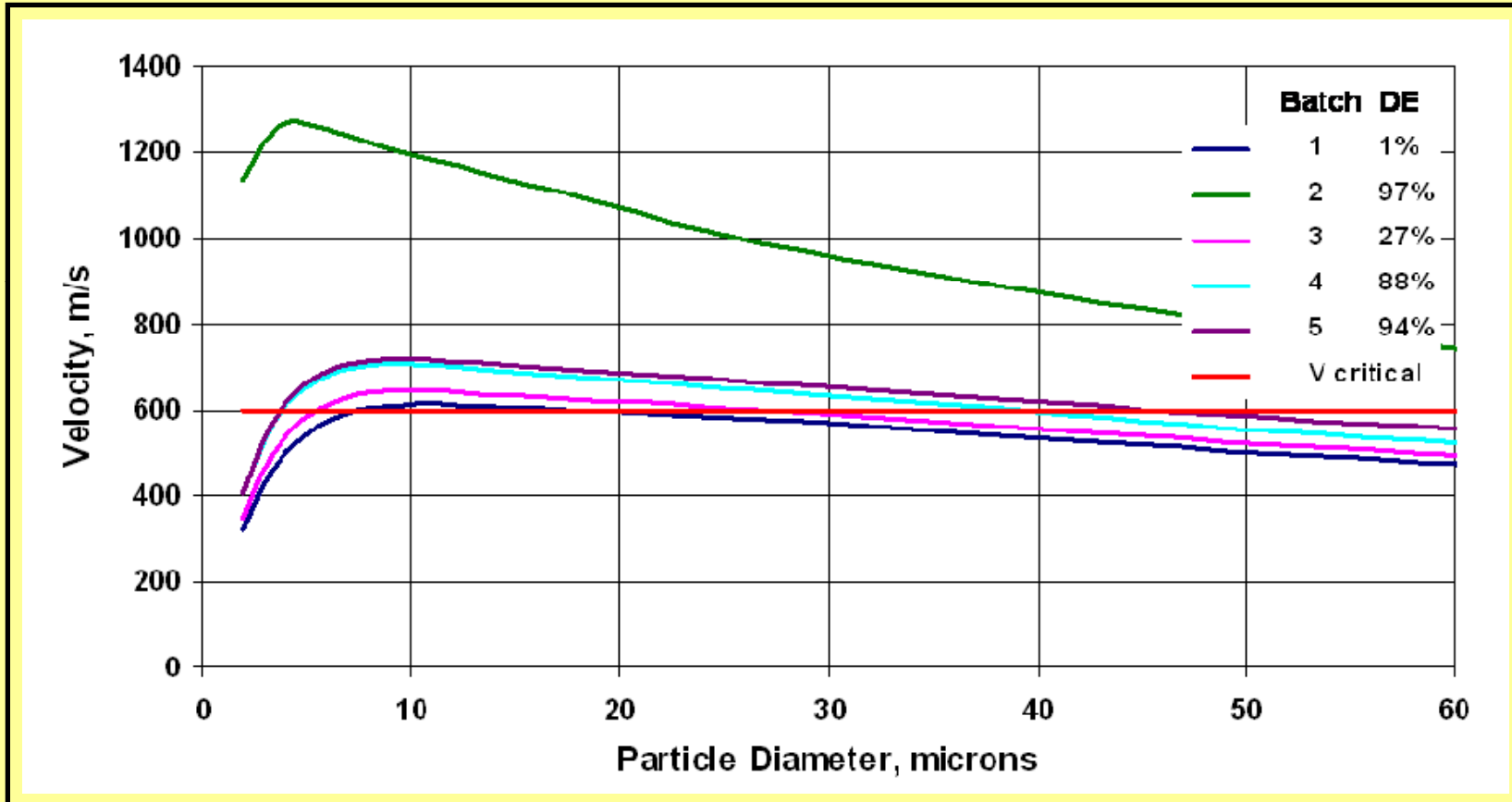
The resulting particle velocities and temperatures are then calculated by gas-particle drag and heat transfer.



The log normal particle size distribution is integrated from the smallest diameter to the largest diameter for those particles with velocities greater than the critical velocity, to determine DE.



# Particle Velocity & Deposition Efficiency





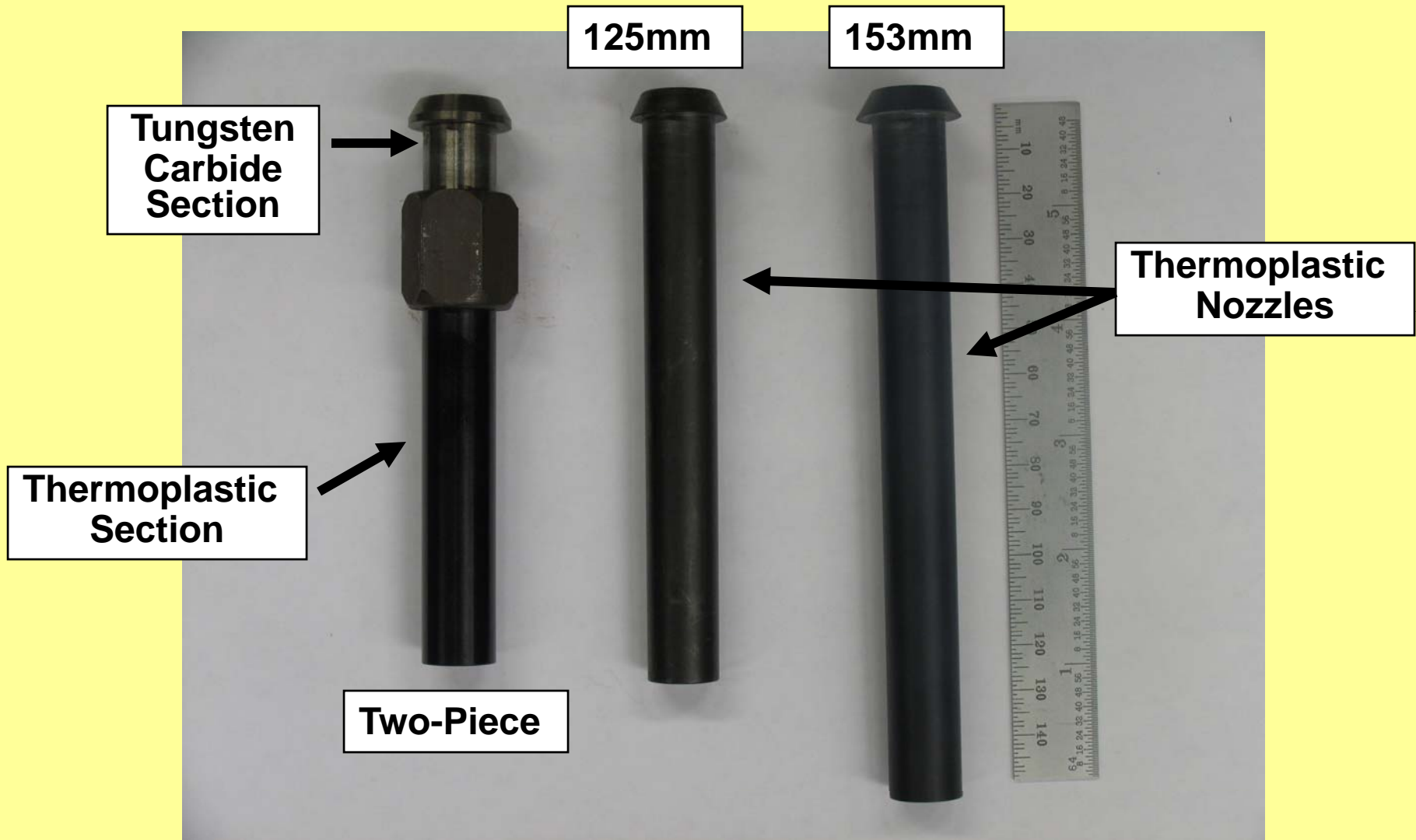
# Nozzle Designs



Material	Length (mm)	Process Conditions	Particle Velocity
Tungsten Carbide	115	He, 380psi, RT	1020
Tungsten Carbide	115	N2, 380psi, 250C	590
WC/ Thermoplastic	115	N2, 380psi, 300C	605
Thermoplastic	125	N2, 380psi, 400C	690
Thermoplastic	153	N2, 380psi, 400C	710



# Thermoplastic Cold Spray Nozzles





# Cold Spray Coating of CP-Al On ZE 41A-Mg (Nitrogen Gas @ 400°C)

Cold  
Spray  
CP- Al  
Coating

Coating /  
Substrate  
Interface



10,350 psi adhesion (ASTM C-633)



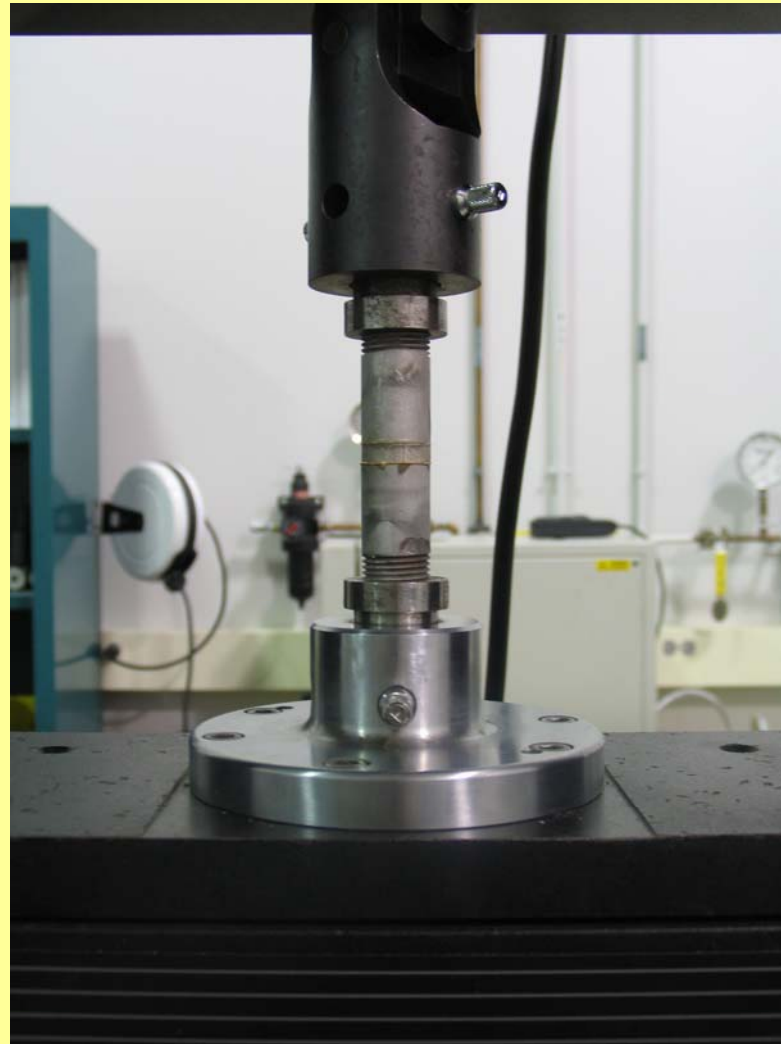
## Bond Bar Adhesion Set-up



Bond Strength Measurements on ZE41A Magnesium and 7075 Aluminum Alloy



# Bond Bar Adhesion Testing Setup





## Results for CP- Aluminum Cold Spray Coatings on 6061 Aluminum Bond Bars

<b><i>Process Conditions</i></b>	<b><i>Nozzle Powder</i></b>	<b><i>Adhesion (psi)</i></b>
<b>N<sub>2</sub>, 380psi, 250C</b>	<b>Metal 15- 45 um</b>	<b>2743</b>
<b>He, 380psi, 20C</b>	<b>Metal 15- 45 um</b>	<b>1657-3302</b>
<b>N<sub>2</sub>, 380psi, 300C</b>	<b>Metal/Plastic 7-28 um</b>	<b>2387-4476 (cohesive)</b>
<b>N<sub>2</sub>, 380psi, 400C</b>	<b>Plastic (125mm) 7-28 um</b>	<b>5787-7247 (cohesive)</b>



# Results for CP- Aluminum Cold Spray Coatings on Magnesium

<i>Process Conditions</i>	<i>Nozzle Powder</i>	<i>Adhesion (psi)</i>	<i>Corrosion Results</i>
N2, 380psi, 250C	Metal 15- 45 um	2743	8 hrs
He, 380psi, 20C	Metal 15- 45 um	>8,505 (glue failure)	>500 hrs*
N2, 380psi, 300C	Metal/Plastic 7-28 um	4764-5985	1000 hrs
N2, 380psi, 400C	Plastic 7-28 um	>10,350 (glue failure)	>2,400 hrs*

\* Failure of Edge Maskant



## Salt Spray (Fog) Corrosion Test (ASTM B-117)



- Specimens at 15-30° angle from vertical
- 5 +/- 1% (by weight) NaCl Solution (pH 6.5-7.2)
- Spray Nozzle Baffled at 10-25psi
- Chamber Temperature at 35 + 1.1 – 1.7 °C
- Continuously sprayed in closed chamber

Note: No Direct Relation between B117 & Outdoor Exposure



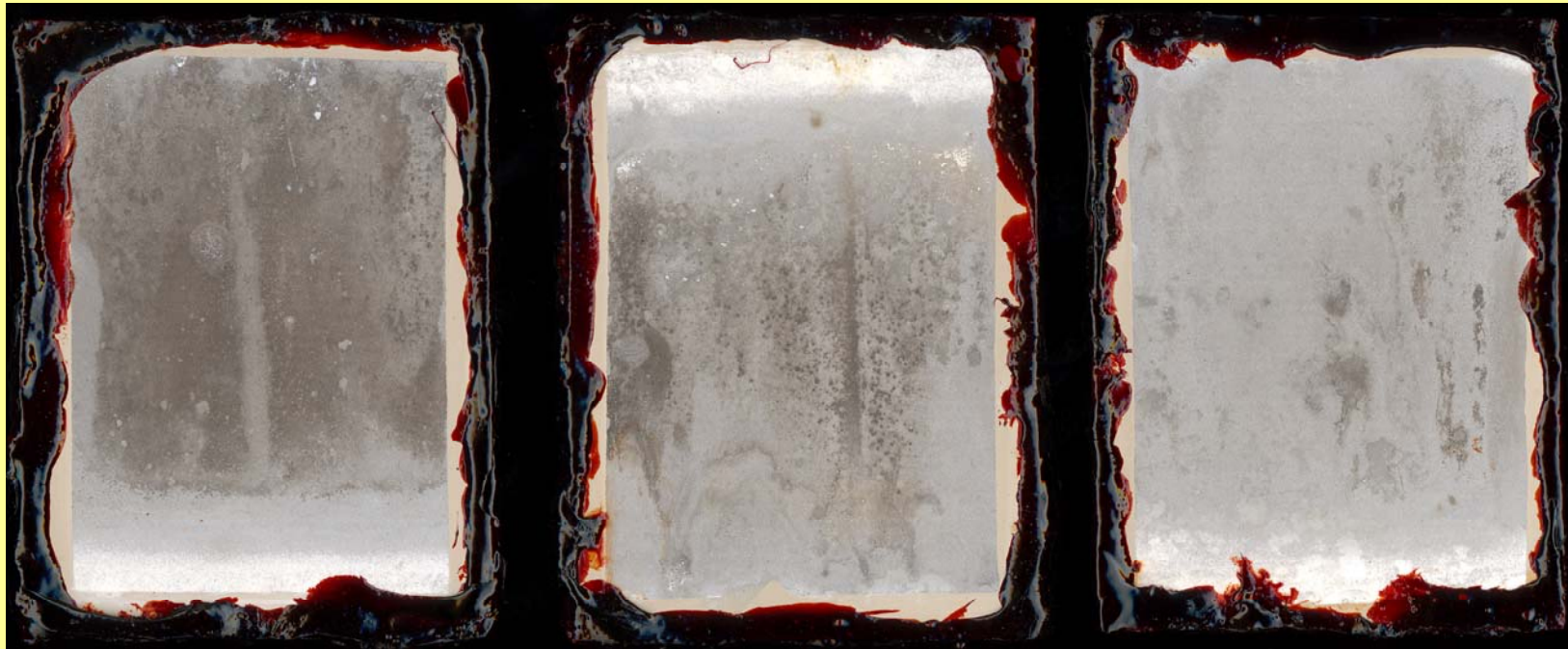
## Aluminum coated ZE41A Magnesium (8 Hours in Salt Spray)



**Cold Spray Aluminum deposited using N<sub>2</sub> Gas at 250 °C**



## Aluminum coated ZE41A Magnesium (336 Hours in Salt Spray)



**Cold Spray Aluminum deposited using Helium Gas at 20 °C**



# Cold Spray Aluminum coated ZE41A Magnesium Coupons



**Bare Coupon**



**Coated (.5mm)**



**Coated (1mm)**



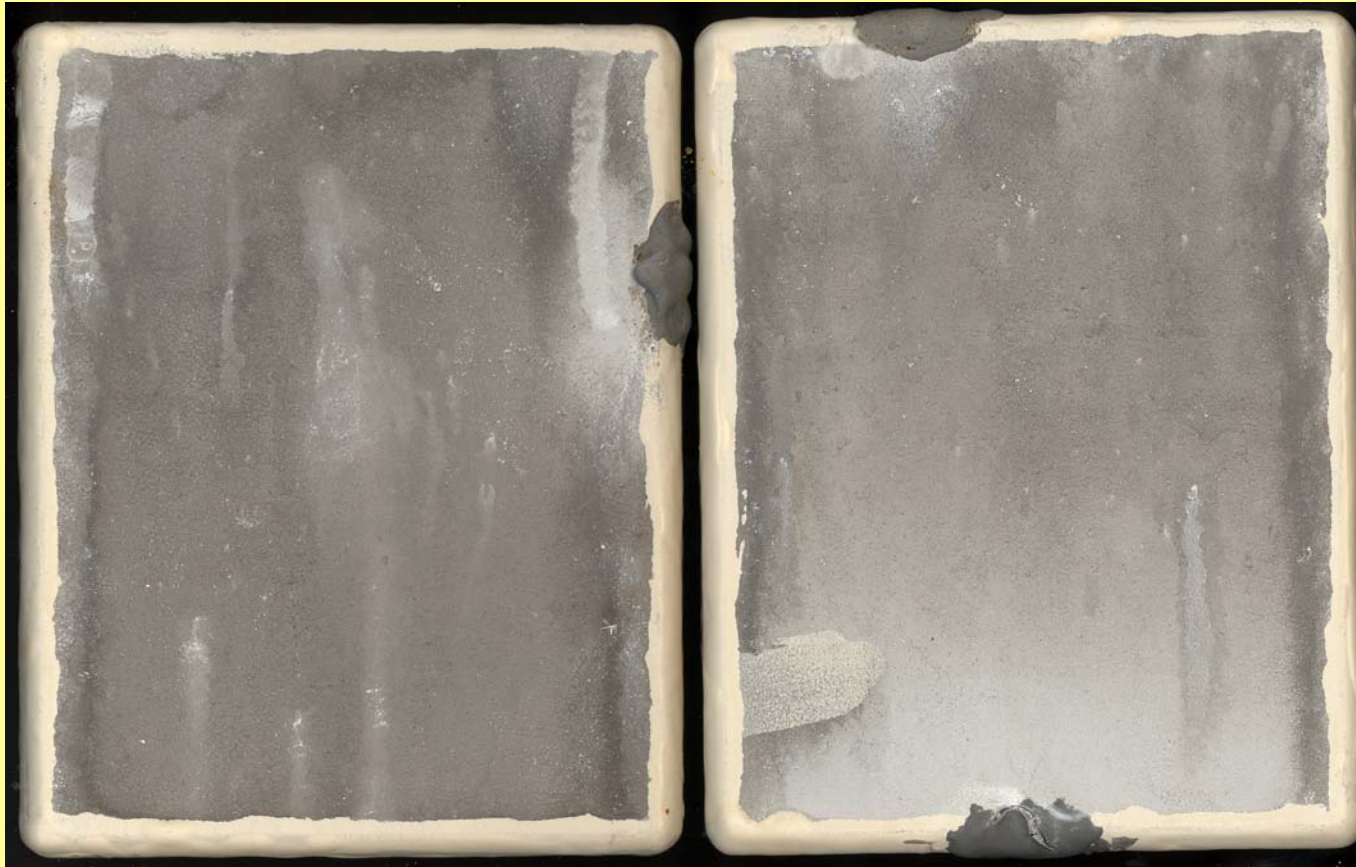


## Aluminum Cold Spray Coated Magnesium Coupons After Salt Spray Exposure



2400 Hours Exposure (.5mm)

2400 Hours Exposure (1mm)



**Cold Spray Aluminum deposited using N<sub>2</sub> Gas @ 400 °C**



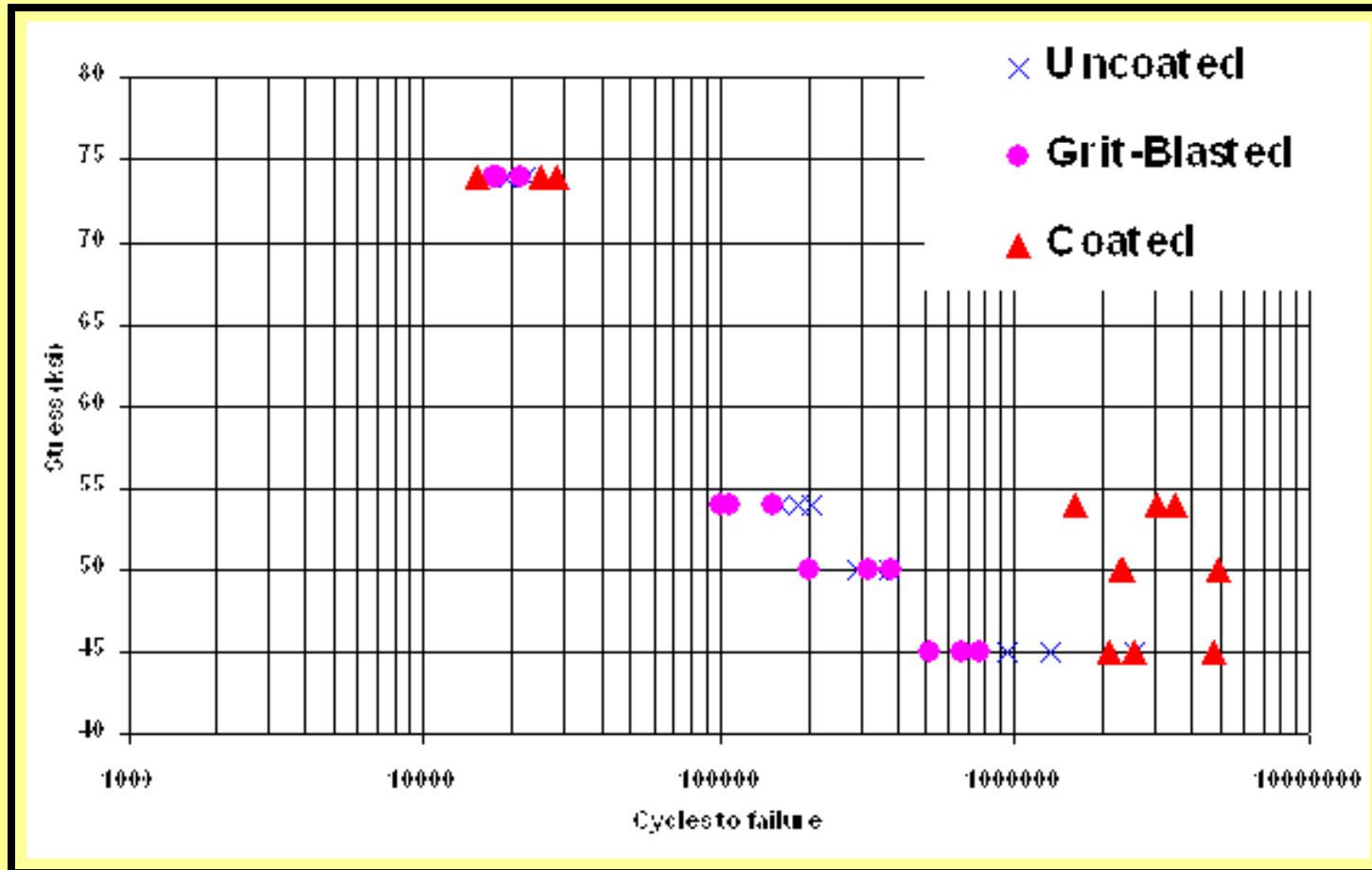
## RCB Cold Spray Set-Up



ZE41A Magnesium & 7075 Aluminum Alloy RR Moore Fatigue Specimens



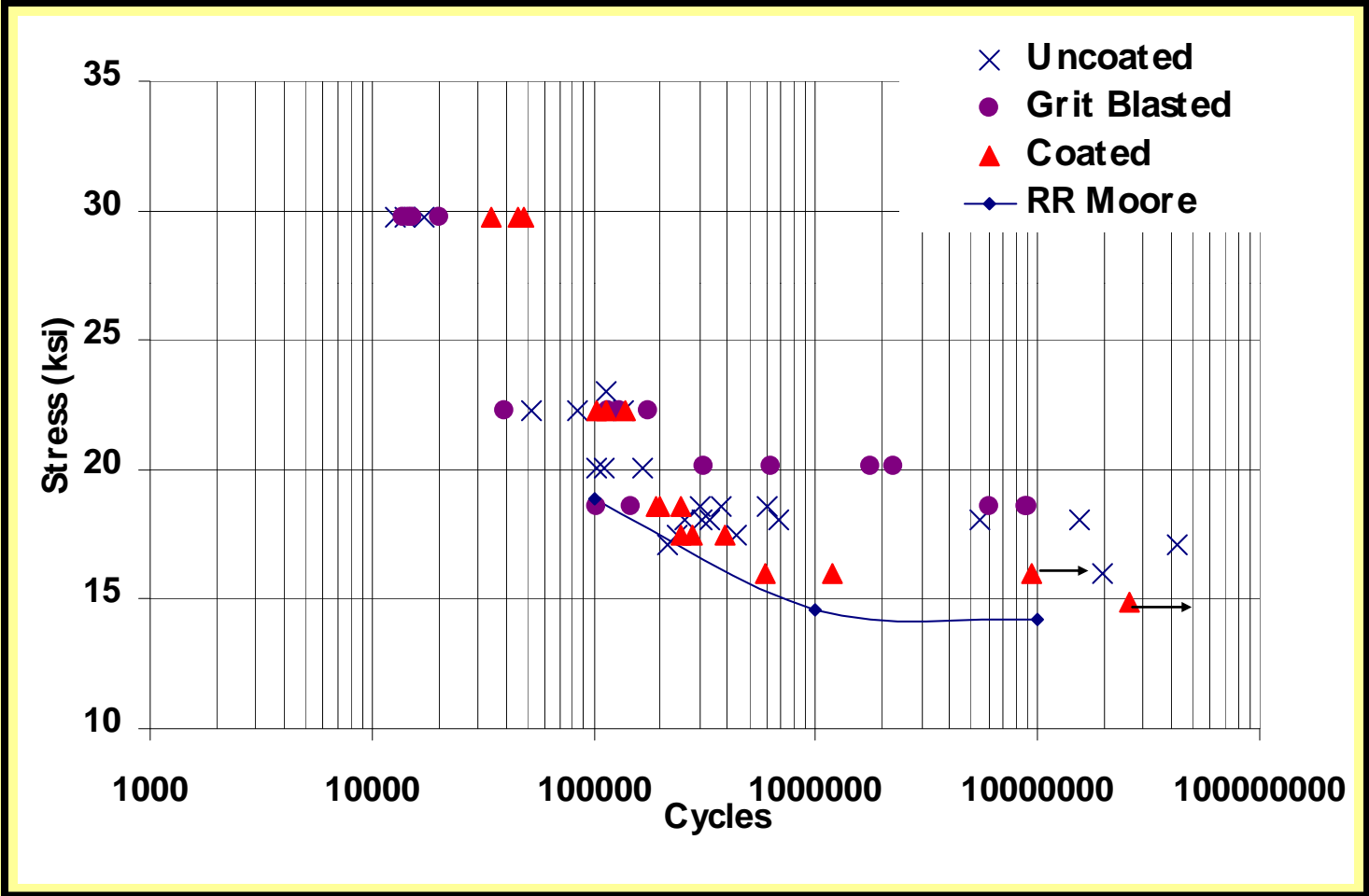
# Fatigue Results – AA7075-T651



Source – Australian Defence Science & Technology Organisation



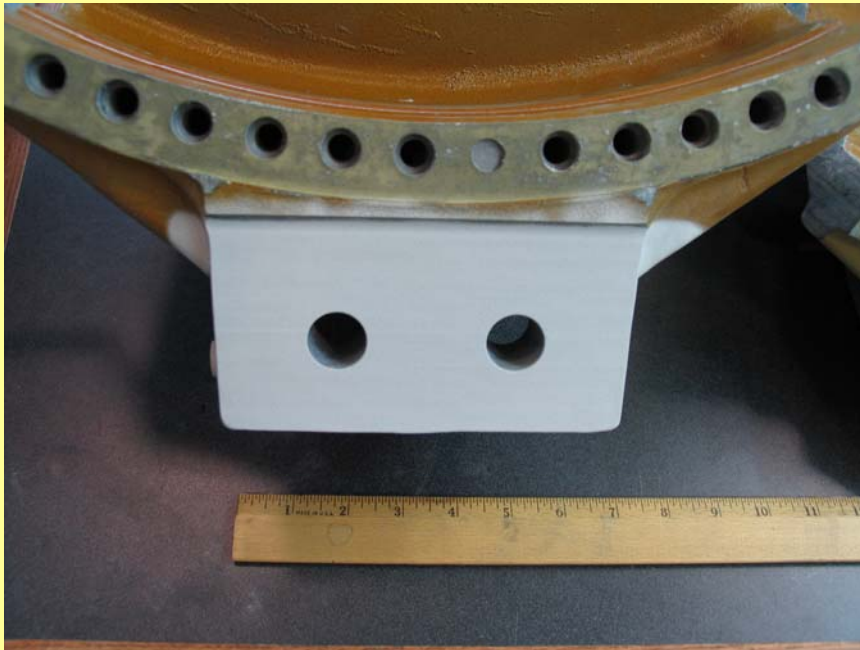
# Fatigue Results – ZE41A-T5



Source – Australian Defence Science & Technology Organisation



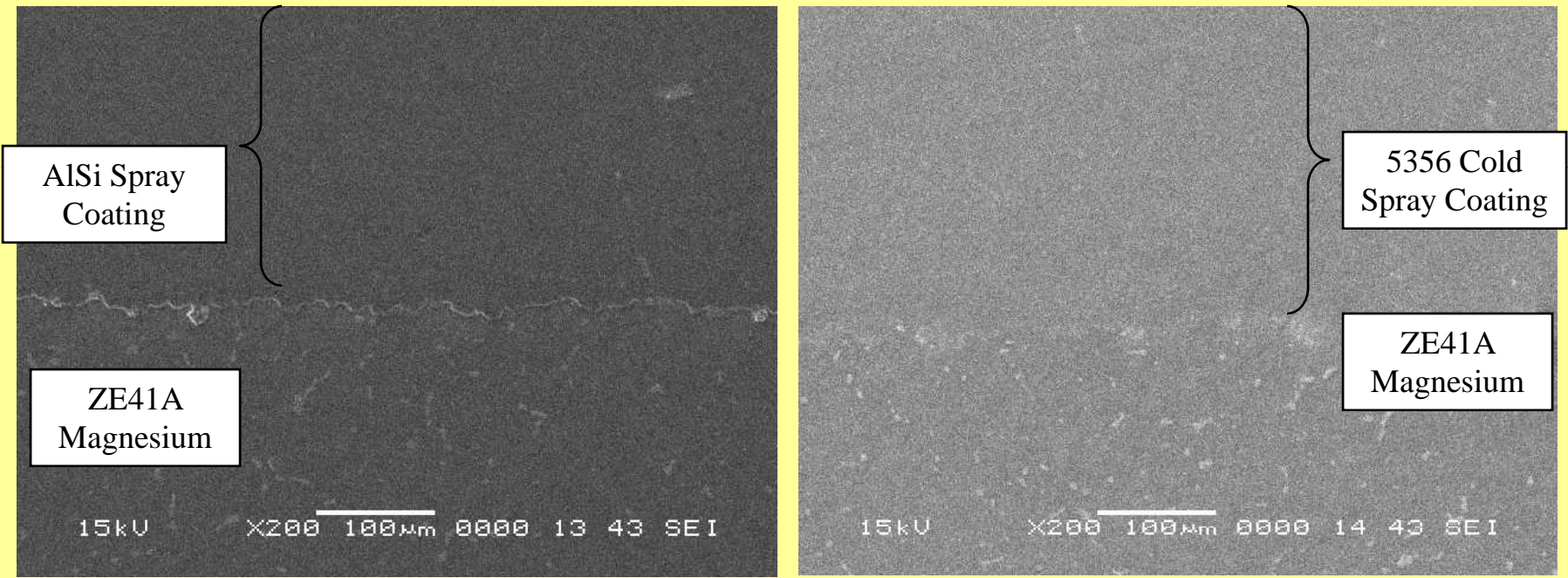
# Mg Housing Coated with CP-Al



*Flat surface of Mg housing covered with CP-AL Cold Spray*



# Al12Si & 5356 Al Deposited on ZE41A Using Helium



Adhesion Results - > 8,000 psi (Glue Failure)



# Summary

Achieved High Density, Low Porosity Cold Spray Aluminum Coating

Bond Strength Exceeds 10,000 psi.

Corrosion Resistance exceeds 2500 hours B117 Salt Fog Spray

No Reduction in Fatigue Strength on Magnesium

Slight fatigue credit on 7075 Aluminum Alloy

Future Work – Investigate Aluminum Alloys & High Purity Aluminum