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Qualification of Cold Spray for Repair of MIL-DTL-83488 Aluminum Coatings

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ASC/ENNV Project Information

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- **POP - 24 month project**
 - 7-31-2007 to 9-30-2009
 - Final Report 10-30-2009
- **Objectives**
 - Identify Portable Cold Spray Equipment
 - Develop Procedures to Repair Damaged IVD Aluminum Coatings
 - Certify Cold Spray Process to Meet Requirements in MIL-DTL-83488
 - Cold Spray Process Can Also be Used to Repair any Damaged Aluminum Coating
 - Aluminplate, Sputter Aluminum, or CVD Aluminum
- **Program Manager – Brian Tobin ASC/ENNV**

Cold Spray Equipment Selection Criteria

- **Equipment Requirements**
 - **Portable**
 - **Easy to operate**
 - **Safe to operate**
 - **Low cost to operate**
 - **Apply aluminum coatings (1 to 3 mil thick)**
 - **Cold Spray Al coating meets MIL-DTL-83488**
 - **Readily available and easy to maintain**
 - **Off the shelf technology**

Cold Spray Equipment Suppliers

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- **Dymet**
- **CGT**
- **K-Tech**
- **Delphi**
- **Inovati**
- **Centerline (Dymet)**
- **ARL**

Previous Cold Spray Studies Conducted

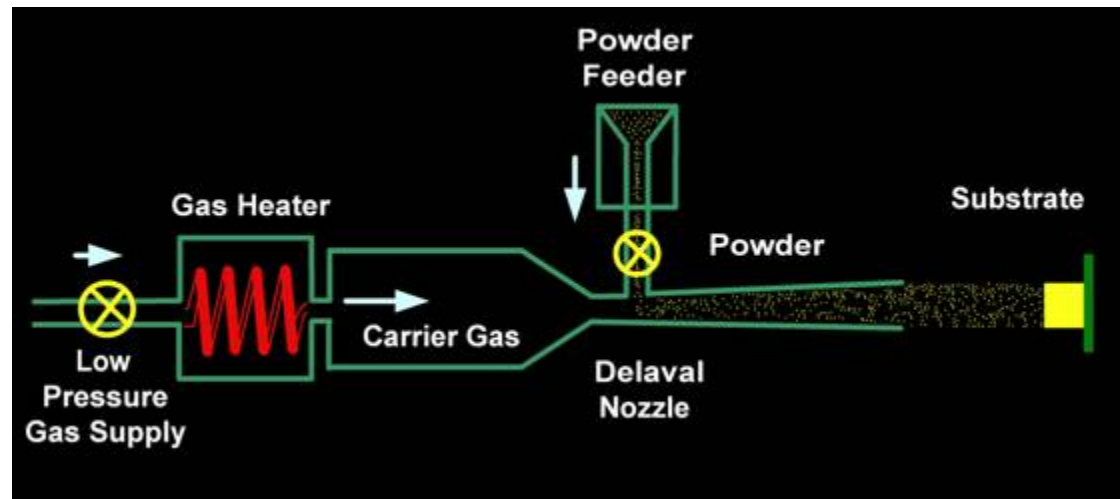
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- **Boeing – Moscow**
 - Dymet Equipment
- **CTMA/NCMS**
 - ARL, Delphi, Centerline Equipment
- **ARL**
 - ARL and Centerline Equipment
- **ASB Industries**
 - CGT Kinetics
- **Centerline**
 - SST Equipment

Portable Cold Spray Equipment Selected

- Centerline SST
 - **Low Pressure**
 - Air @ 80 to 110 psig
 - **Portable**
 - **Off the shelf**
- **Low cost**
- **Easy to operate and maintain**
- **Has potential to apply MIL-DTL-83488 Aluminum coatings**



Centerline SST Cold Spray Equipment

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Installation of SST

- **PO Placed February 2008**
- **Equipment Received May 2008**
- **Equipment Installed July 2008**
- **No Problems with Installation**
 - **Cold Spray Equipment Performed Flawlessly**
 - **Programming of Robot was Difficult**
 - **Required Learning a Programming Language**
 - **P-SEL**
 - **Centerline Provided Hands-On Training**

Aluminum Powder Selection

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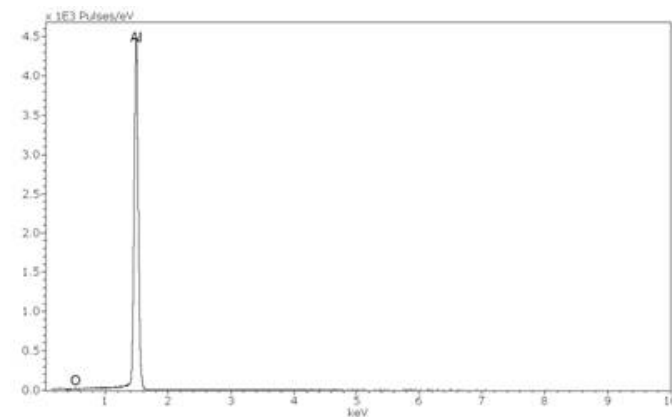
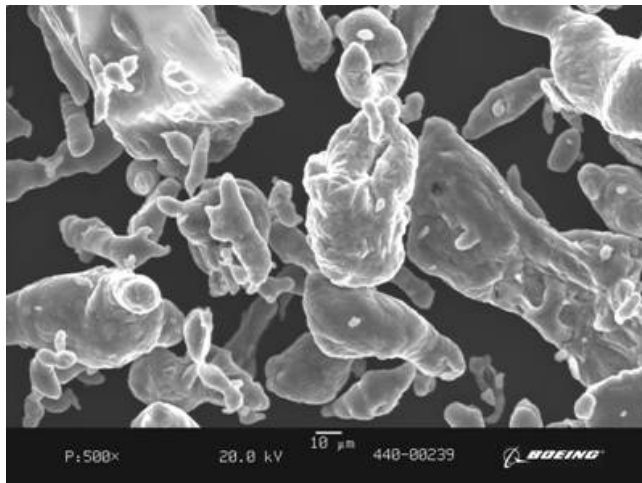
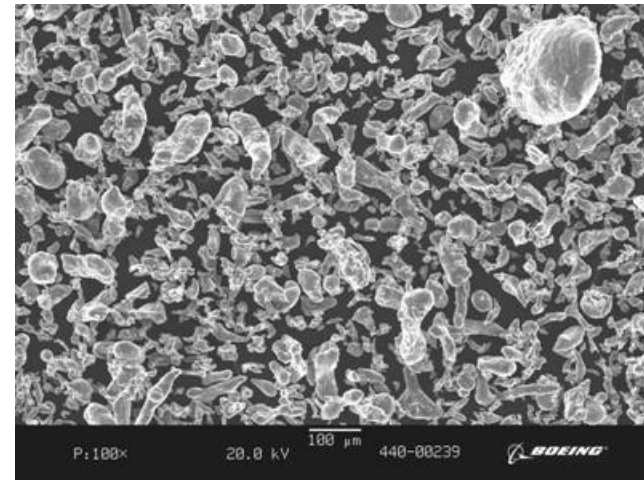
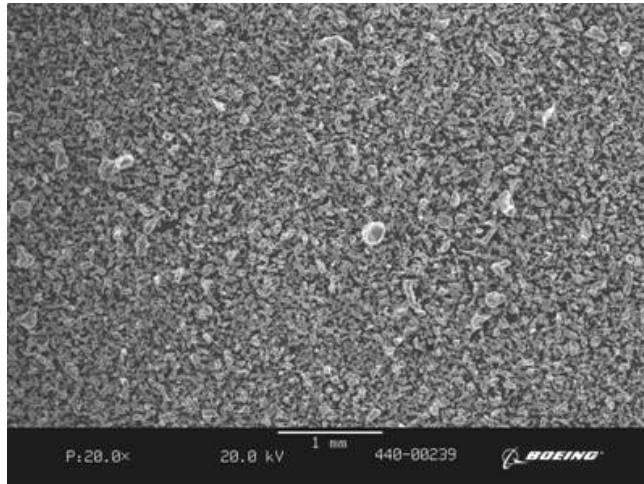
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Metal Group	Catalogue Number (Old Catalogue Reference #)	Typical Applications	Typical Substrates	Description
Aluminum	SST-A0017 (KSF-A017-1)	Corrosion Protection	Steel and Magnesium Alloys	Special size distribution blend of pure aluminum. Characterized with high deposition efficiency, fast build-up and hardness of HB: 27-29. Ideal for corrosion protection.
	SST-A0027 (KSF-A027)	Component Repair	Steel, Aluminum, Magnesium and their Alloys	General purpose aluminum-based mixture containing aluminum, zinc and alumina with fast deposit build-up speed. Good for repairing a variety of components and freeform fabrication. Good bonding strength (>4500 psi), hardness HB: 45-55 and good machinability. Can produce very thick and smooth deposition.
	SST-A0050 (KSF-A50)	Component Repair	Steel, Aluminum, Magnesium and their Alloys	Blend of aluminum and alumina. Fast deposition and smooth surface. Good for repairing a variety of components. Zinc free coating with good bonding strength (>5000 psi). Hardness (HB: 50-60)
	SST-A0053 (KSF-A053)	Mold Repair	Aluminum	Blend of aluminum, stainless steel and alumina. Builds up smooth and thick coatings. Has been used for aluminum mold repairs.
	SST-A0071	Dimension restoration	Magnesium and Aluminum Alloys	Blend of aluminum and alumina with good deposit growth rate, smooth surface, very high bonding strength (>7500 psi) on Mg and Al alloys. Good for dimension restoration of both Al and Mg alloys parts.
	SST-A0073	Bond Coating	Aluminum and its Alloys	Blend of aluminum 356 alloy, aluminum and alumina with fast buildup rate, smooth surface, very high bonding strength (>10000 psi) on aluminum and its alloys. Good for bond coat.
	SST-A5001 (KSF-A21339)	Corrosion Protection	Steel and Magnesium Alloys	Pure aluminum powder with special size distribution for cold spray process, good deposition rate, smooth surface, good bonding strength (>4000 psi), hardness HB: 25-30 and excellent machinability. Good for corrosion protection.

440-00239 (KSF-A017-1) – Blended Aluminum

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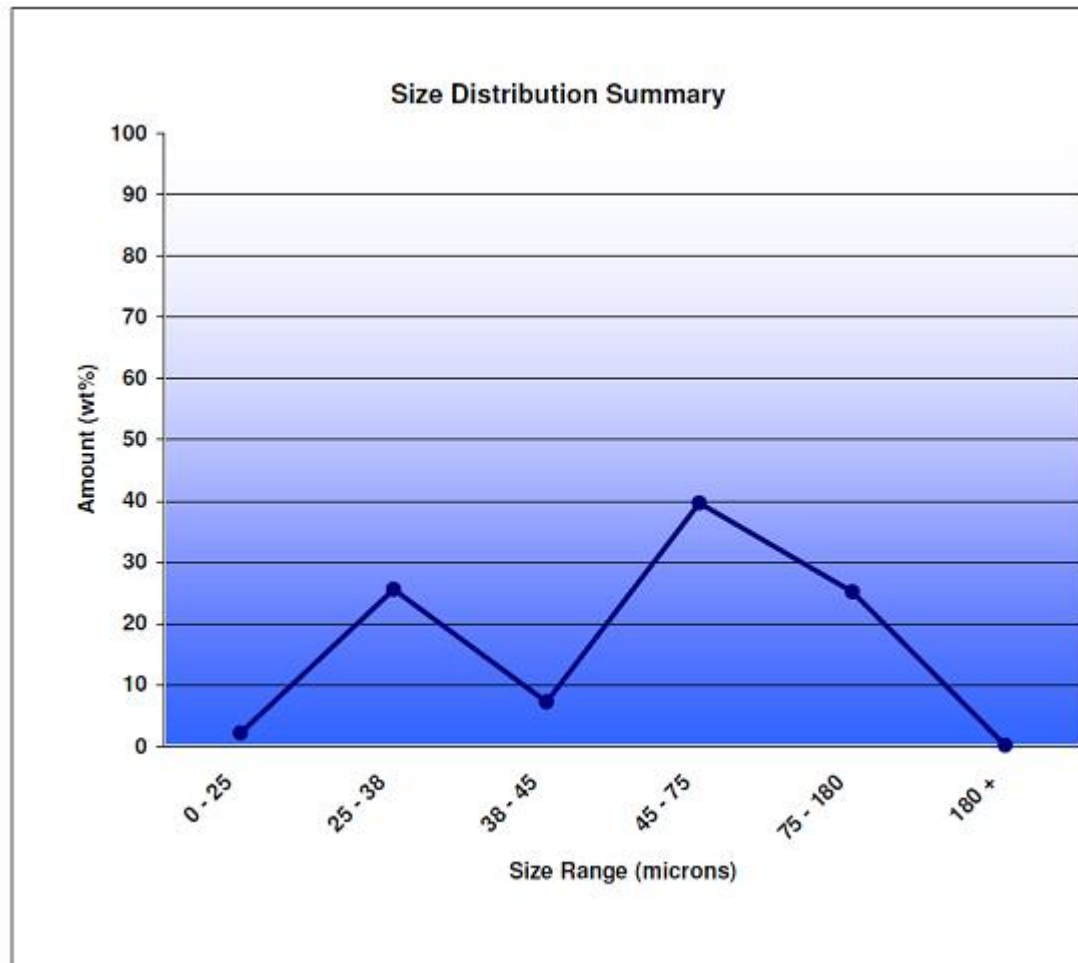
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SST-A0017 Particle Size Distribution

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Optimization Test Results

- **Optimum Gun Conditions to Apply a MIL-DTL-83488 Cold Spray Al Coating**
 - Stand-off Distance = 0.5 inch (-0.25/+0.5)
 - Speed = 100 to 150 mm/sec
 - Line Index = 1 to 2 mm
 - Air Pressure = 90 to 100 psig
 - Temperature = 250 to 300°C
 - Flow = 20% (+/- 10%)
 - SST-A0017 Blended Aluminum Powder

Optimization Test Results (Cont.)

- **Preferred Procedure for Applying MIL-DTL-83488 Cold Spray Al Coatings**
 - **Degrease with MPK or Desoclean 45**
 - **Grit Blast @ 40 to 60 psig (2 passes) with 80 grit Al Oxide (white preferred)**
 - **Apply 1 to 3 mil Al coating**
 - 90 to 100 psig – 250 to 300° C
 - Multiple Passes May Be Required
 - **Glass Bead Burnish @ 40 to 60 psig with #10 Glass Beads**
 - 100% Adhesion Test (Used for IVD Al Process)

MIL-DTL-83488D Certification Tests

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- **3.1.1 - Composition**
- **3.2.1 - Process**
- **3.2.1.1 - Cleaning**
- **3.3 - Areas of Deposit**
- **3.4 - Chromate Treatment**
- **3.5 - Thickness**
- **3.6 - Stripping of Aluminum Coating**
- **3.7 - Adhesion**
- **3.8 - Corrosion Resistance**
- **3.10 - Base Metal Integrity**

3.1.1 Composition

Requirement: Coating shall be $> 99\%$ Al

CHEMICAL ANALYSIS								
Al	Cr	Cu	Fe	Mg	Mn	Si	Ti	Zn
99.86 %	< 0.005 %	< 0.005 %	0.08 %	< 0.005 %	< 0.005 %	0.05 %	0.009 %	< 0.005 %

Tested In Accordance To: ASTM-D1976 M

Comment: Sample was tested as received.

Aluminum concentration reported was calculated by difference based on the essential elements reported above.

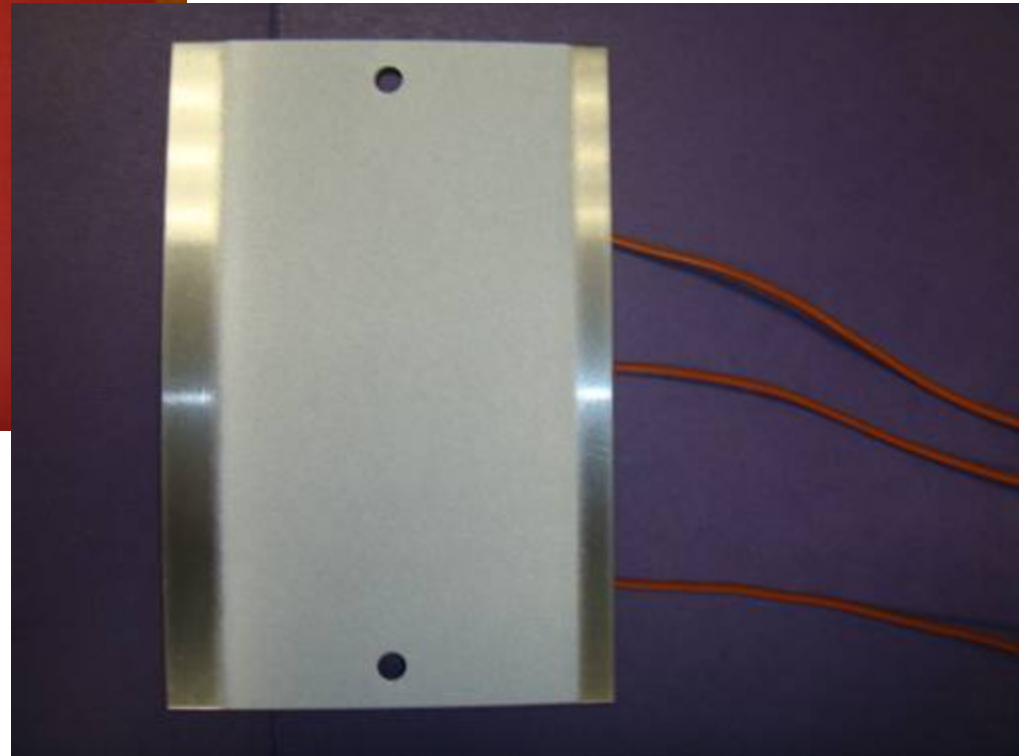
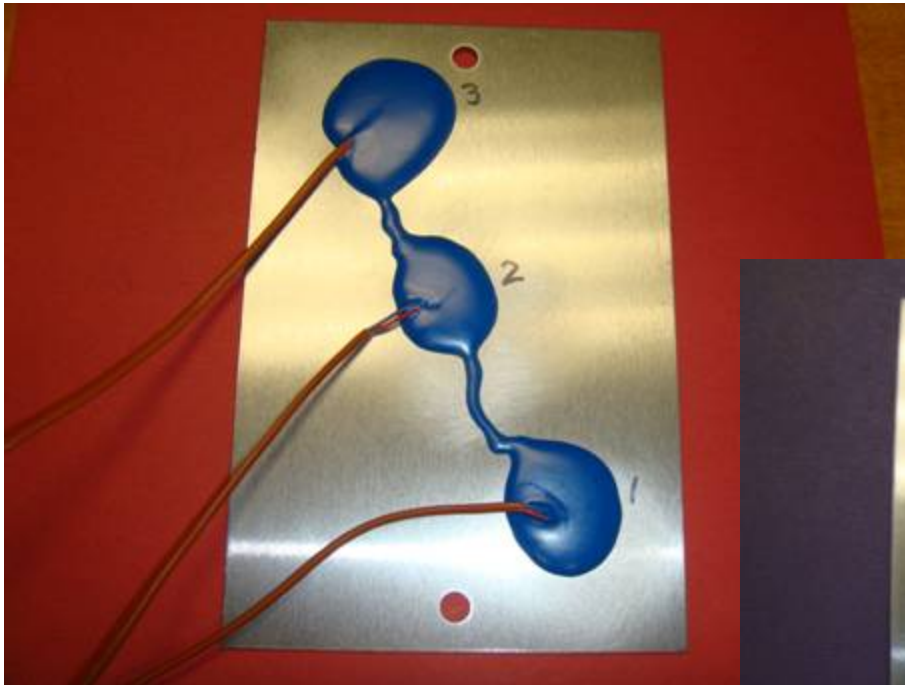
3.2.1 Process

- Requirement - Process shall not cause a temperature rise that has an adverse reaction between the coating and the substrate or adversely affect the substrate.
 - For example – If Substrate is High Strength Steel alloy, such as 300M, 4340 or 4130, the temperature shall not exceed 400° F.
- Process Test Performed:
 - Apply thermocouples to back side of 0.040 thick steel test panel.
 - Apply a 1 to 3 mils of aluminum coating using high gun temperatures (350° C) on 4x6 inch test panel.
 - Check thermocouple readout during metal spraying to insure that temperature did not exceed 400° F.

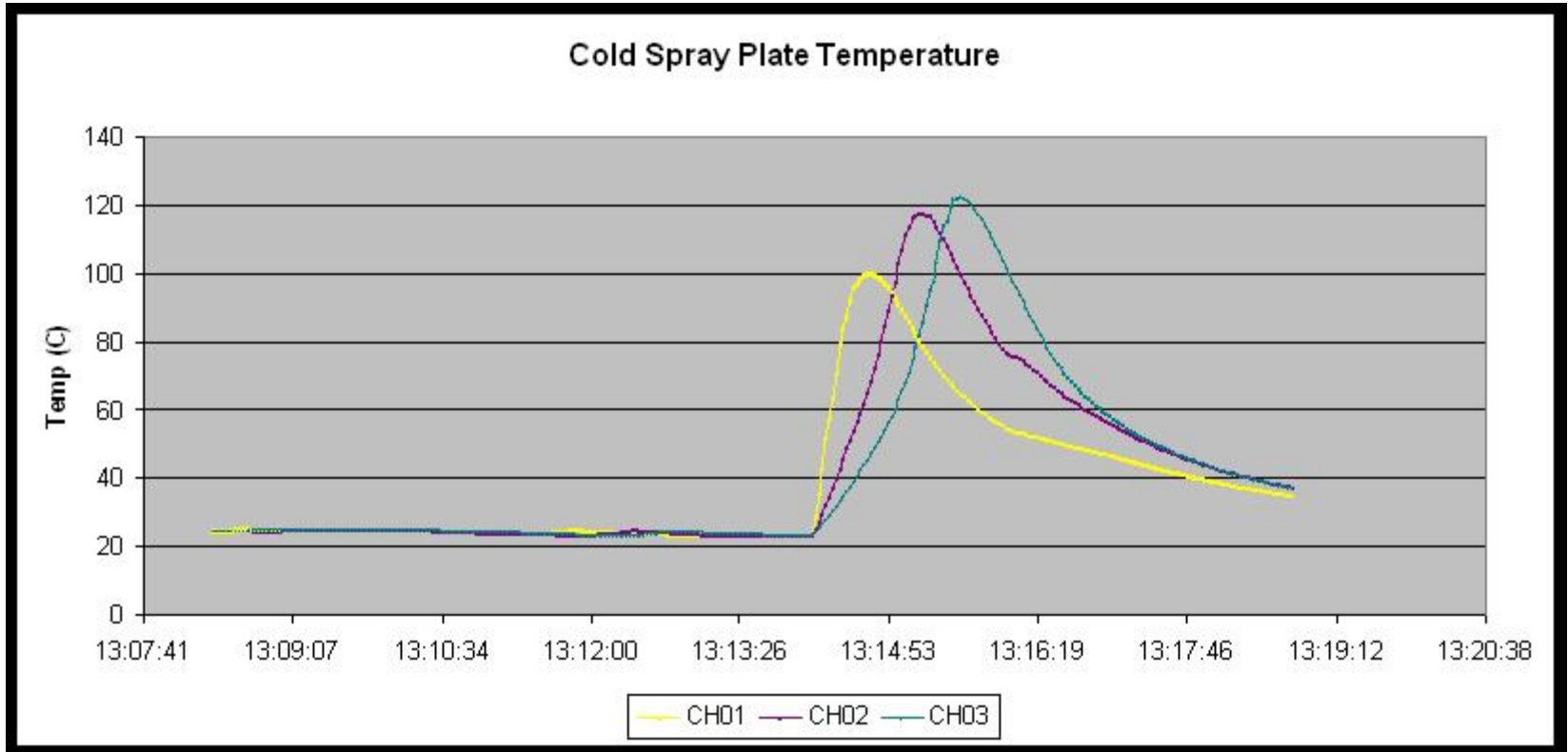
3.2.1 Process – Test Set-Up

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3.2.1 Process - Test Results (Cont.)



3.2.1.1 Cleaning

- **Requirement - Base metal shall be cleaned IAW MIL-S-5002 or equivalent prior to coating application**
- **Test Results –**
 - **MIL-S-5002 Cleaning Process Used:**
 - All test specimens were solvent cleaned and then abrasive cleaned by grit blasting with aluminum oxide grit (80 grit size).

3.3 Areas of Deposit

- **Requirement - Coating shall completely cover all visible surfaces**
- **Test Results –**
 - **All cold spray aluminum coated test specimens were visually examined for coverage and found to be acceptable**

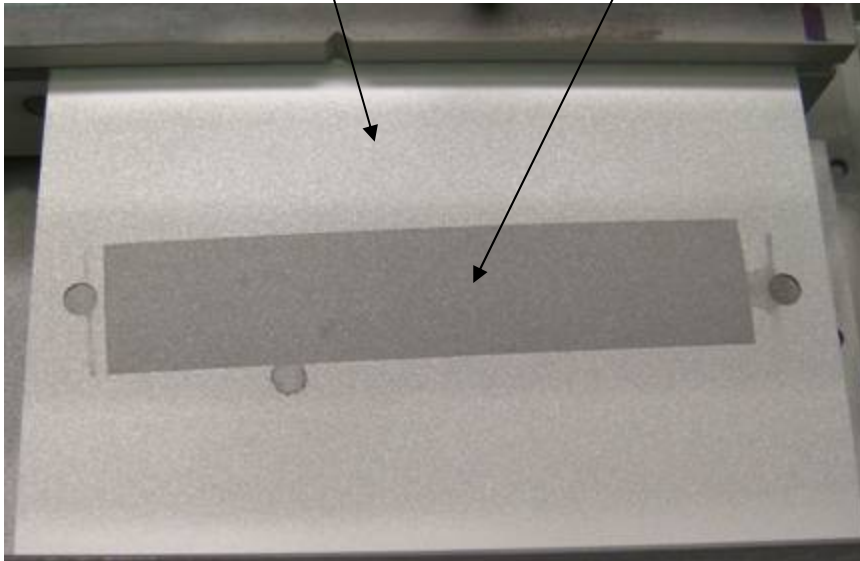
3.3 Areas of Deposit – Test Results

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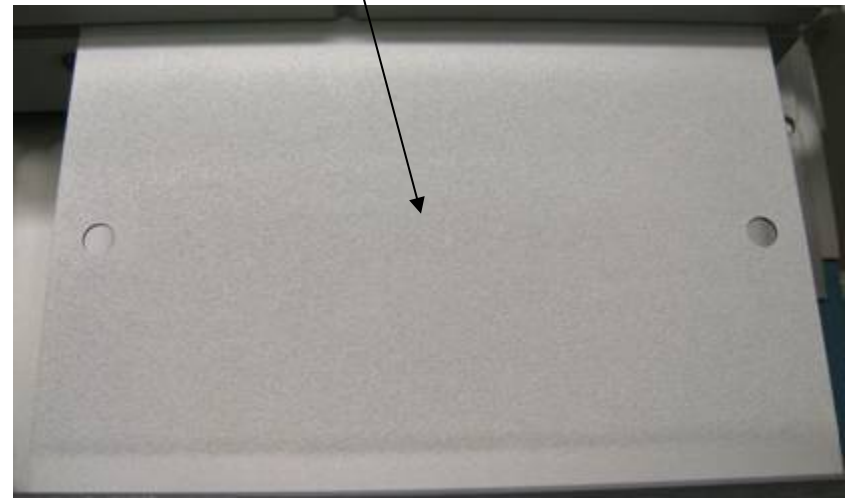
IVD Aluminum

Bare Steel



Damaged IVD Aluminum Steel Panel

Cold Spray Al Repair



Damaged IVD Aluminum Steel Panel
After Repair with Cold Spray Aluminum
Showing Uniform Aluminum Coating
Over Entire Surface

3.4 Chromate Treatment

- **Requirement - Type II specimens shall be conversion coated per MIL-DTL-5541**
- **Test Results –**
 - **Iridite 14-2 conversion coat was easily applied directly to Type II Cold Spray Aluminum test specimens.**
 - **Specimens did not require a chemical etch or deoxidize prior to conversion coating.**

3.4 Chromate Treatment – Test Results

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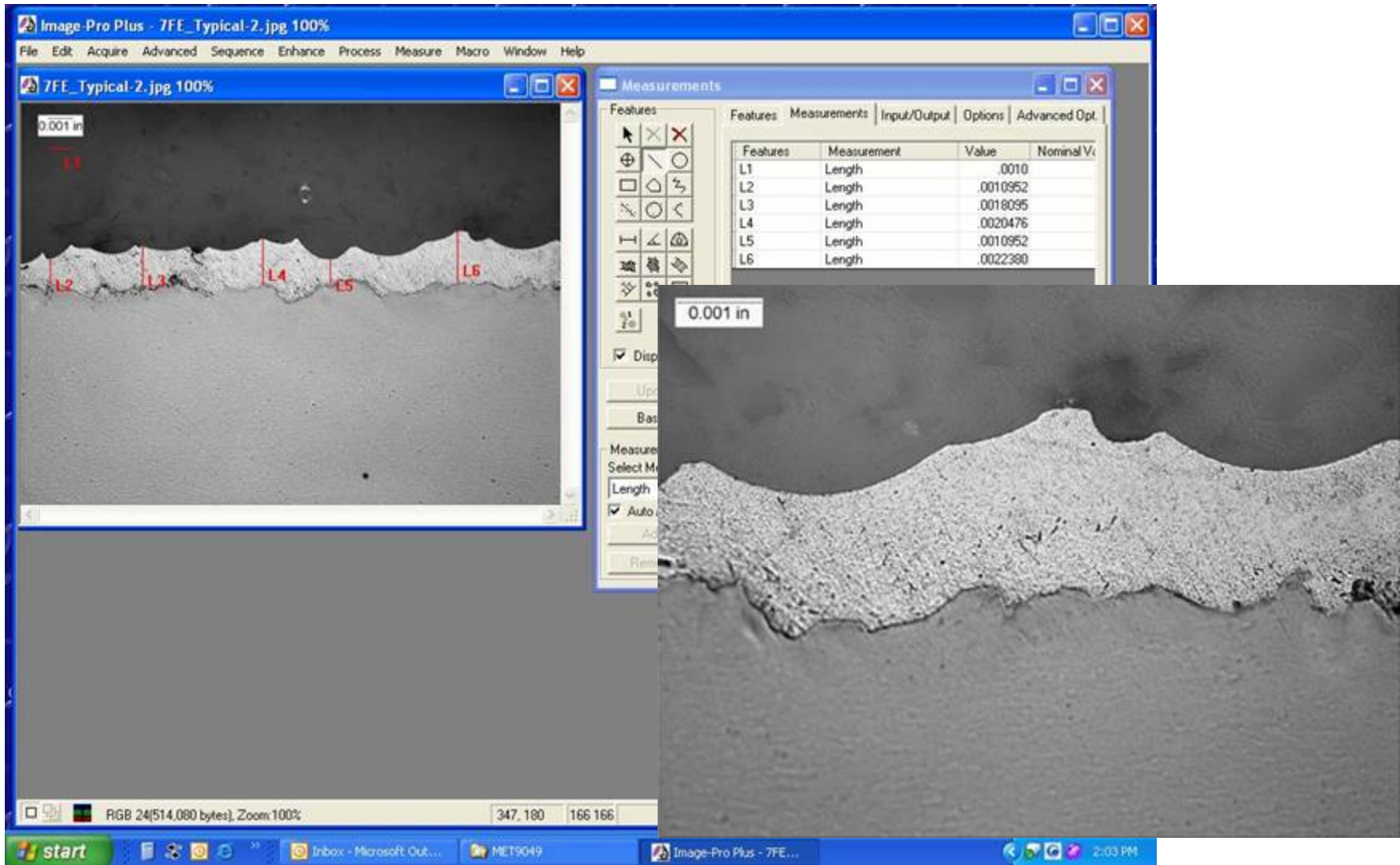


Type II Conversion Coating on Cold Spray Al

3.5 Thickness

- **Thickness Requirement for Class 1 Aluminum Coating**
 - 0.001 inch (Min) and thickness shall not exceed 0.003 inch.
 - Cold spray aluminum coating shall be free of any defects and base metal shall also be free of any irregularities.
- **Test Procedure –**
 - Measure thickness on aluminum coated steel test strips with a magnetic induction thickness gage (DeFelsko Positector).
 - Aluminum coating thickness on test specimens shall be Class 1.
 - Also measure thickness and determine workmanship (see requirement 3.9) by micro-examination of metallographic cross-sections.

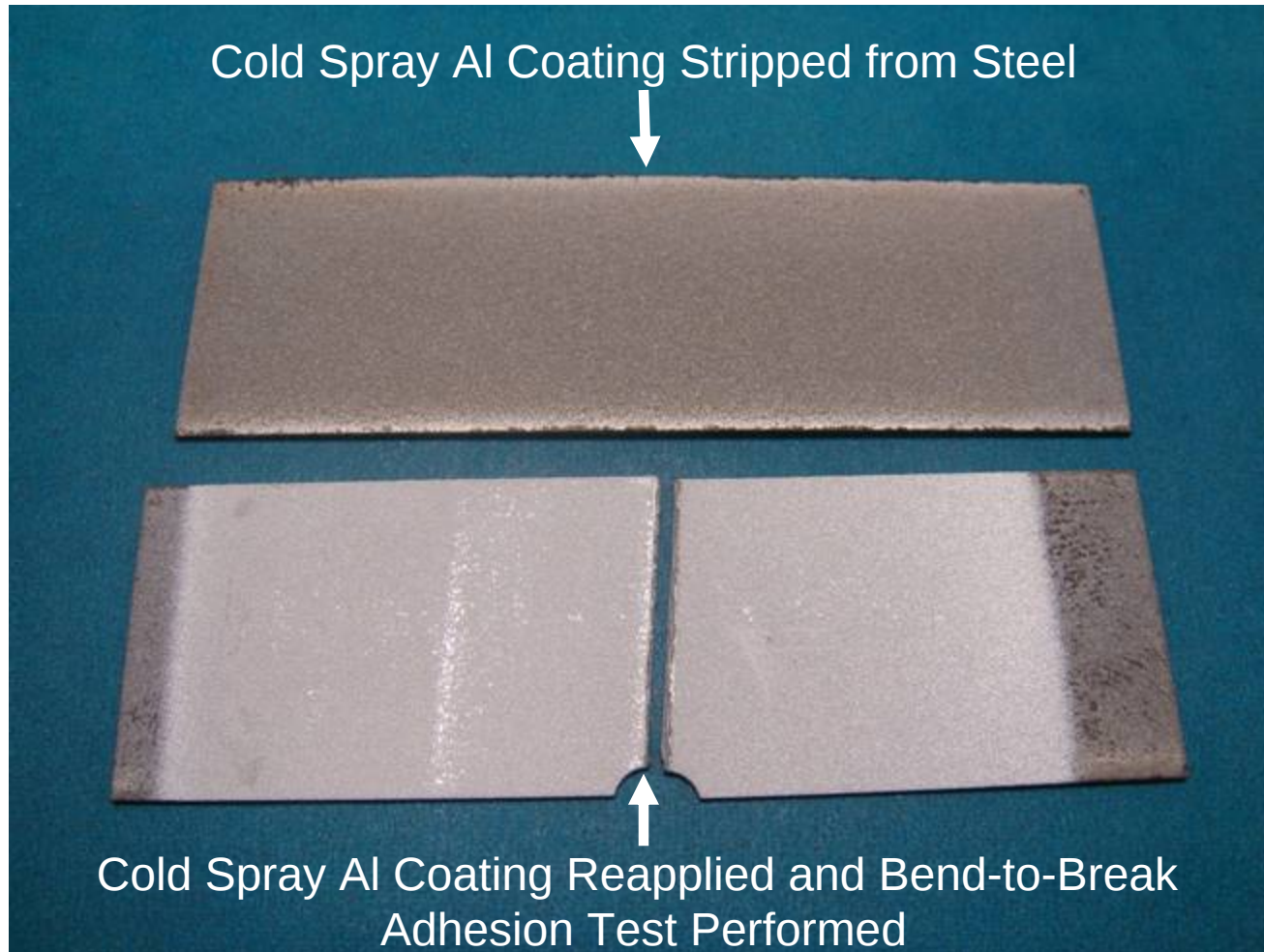
3.5 Thickness - Test Results



3.6 Stripping of Aluminum Coatings

- **Requirement - Remove cold spray aluminum coating on steel by stripping in a caustic solution, Steel parts > Rc 40 shall be hydrogen embrittlement relief baked for appropriate time and temp.**
- **Test Procedure –**
 - Strip 4 aluminum coated test strips in caustic etch to remove aluminum cold spray coating.
 - Strip in a caustic solution containing 14 to 18 ounces of sodium hydroxide per gallon of water at a temperature of 120° to 130° F.
 - Verify complete removal on two of the stripped specimens by examining surface for aluminum by SEM/EDX analysis.
 - Apply a Class 1 (1 to 3 mils) cold spray aluminum coating to the remaining two specimens and perform a glass bead burnish adhesion test on them to verify good adhesion.

3.6 Stripping – Test Results



Stripped (Top) – Recoated (Bottom)

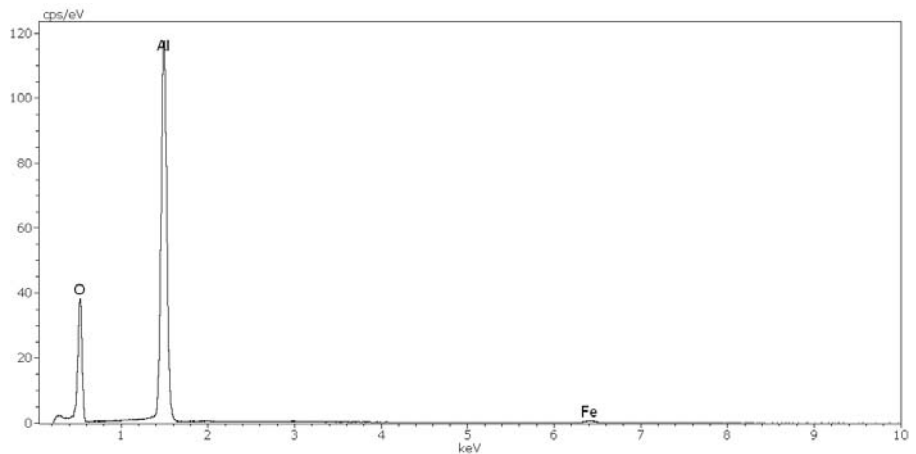
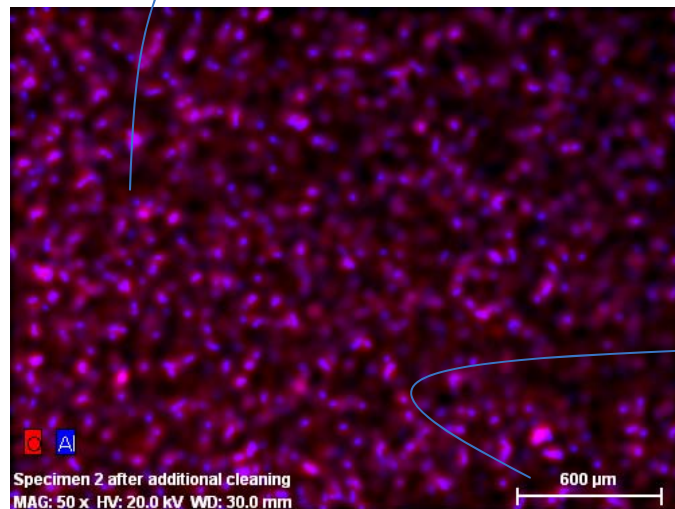
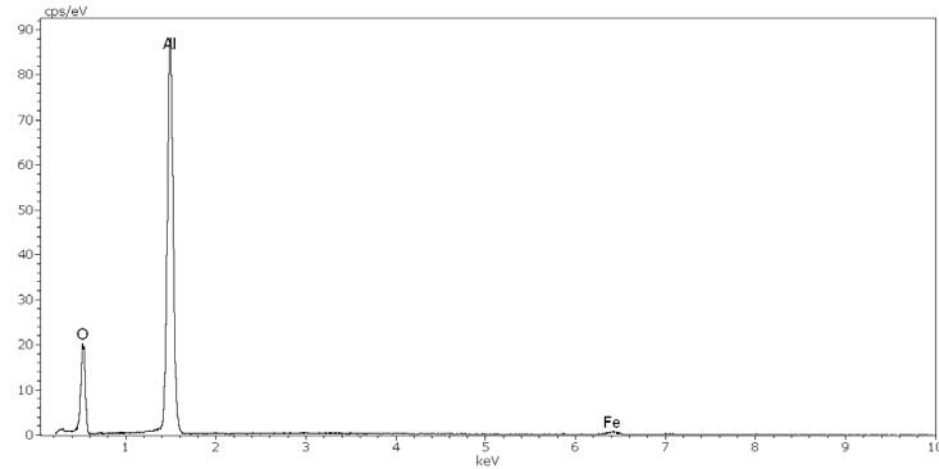
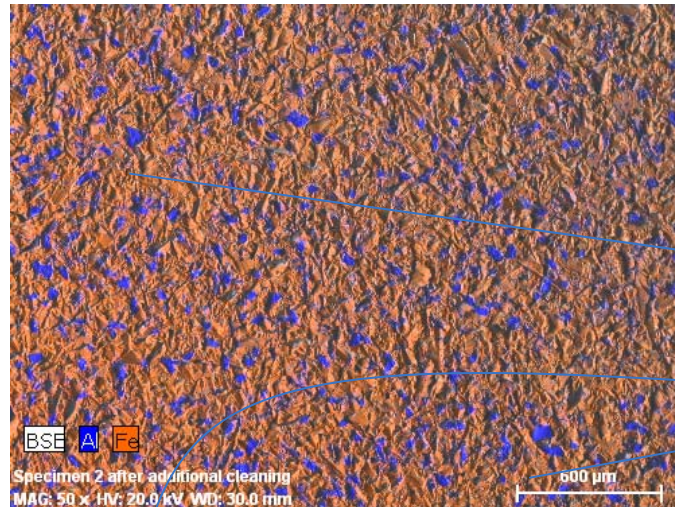
3.6 - Stripping Test Results (Cont.)

- **SEM/EDX Analyses Conducted to verify that all Cold Spray Aluminum Coating was Removed by Caustic (NaOH) Stripping Solution**

SEM/EDX Analysis for Steel Surface After Stripping Cold Spray Aluminum Coating in NaOH Solution

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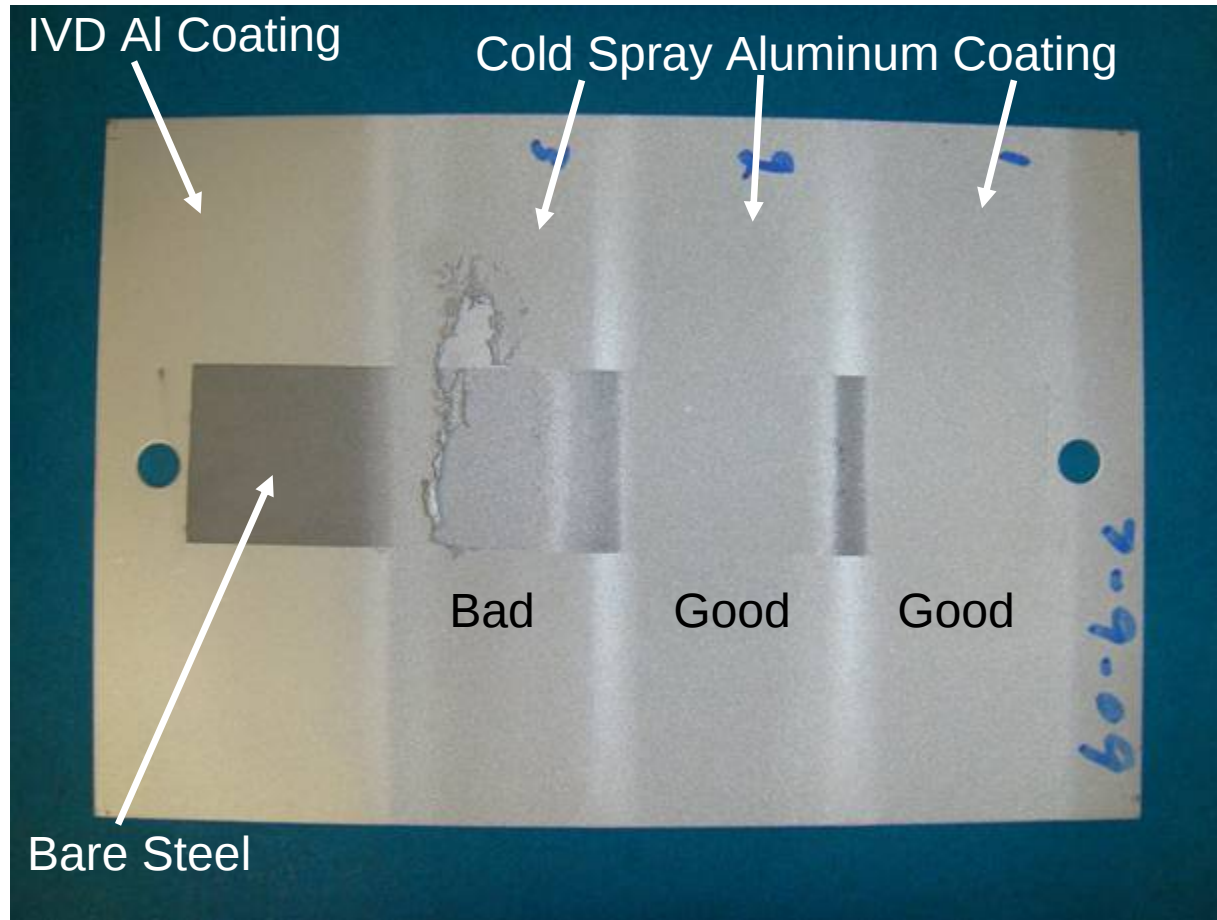


Residual Aluminum Oxide Particles Found Embedded in Steel
but No Residual Cold Spray Al Coating Found

3.7 Adhesion

- **Requirement - When tested per 4.4.2 (of MIL-DTL-83488) the adhesion of the coating shall not show separation from the base metal**
- **Test Procedure –**
 - **First perform magnetic induction thickness test on cold spray aluminum coated 1x4x.040 steel strips to verify Class 1 thickness**
 - **Next perform glass bead burnishing tests on the cold spray aluminum coated test specimens**
 - **Finally perform strip rupture tests (bend-to-break) on the cold spray aluminum coated test specimens.**

3.7 Adhesion – Glass Bead Burnish Test Results

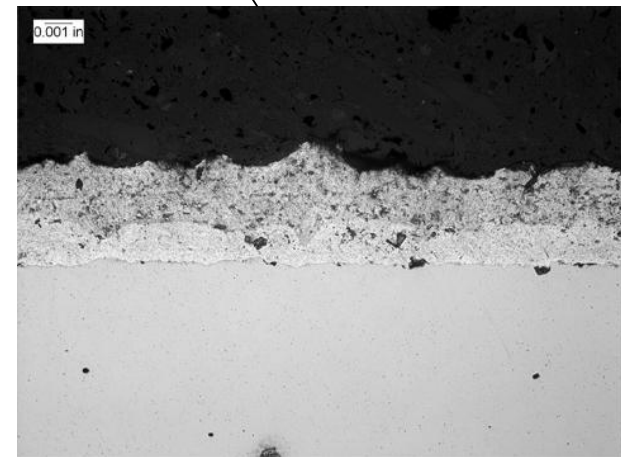
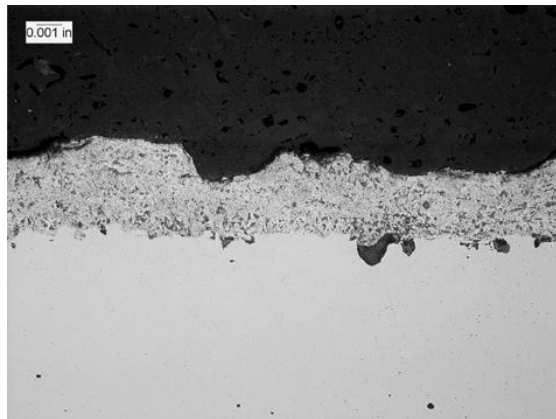
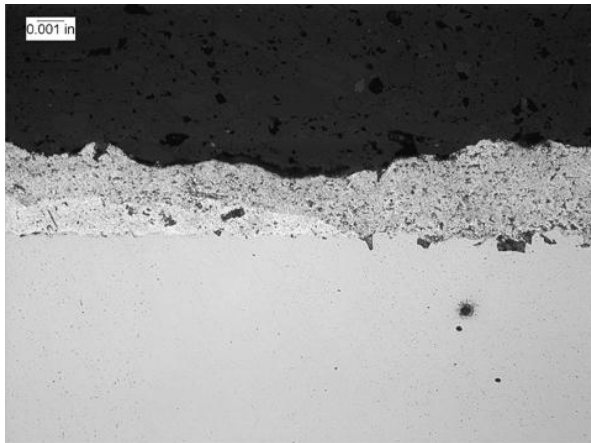
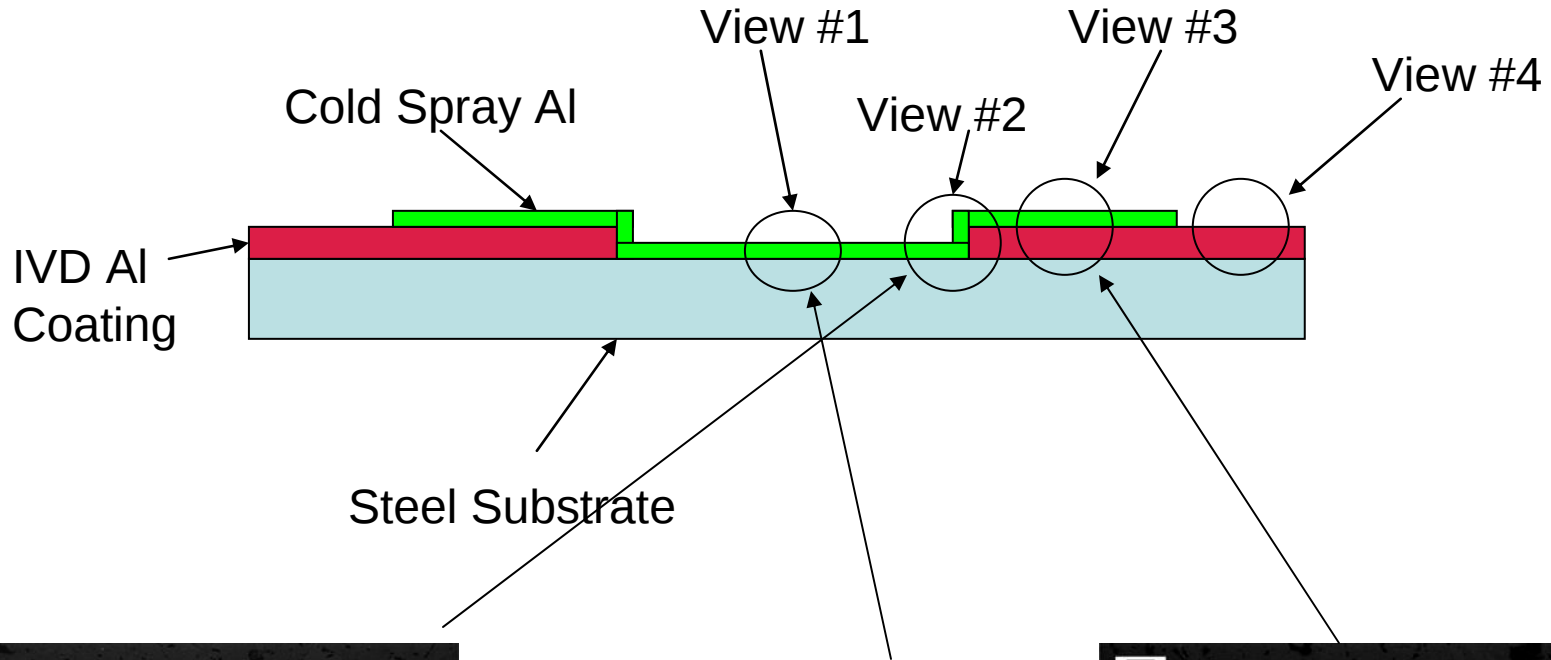


Example of Good and Bad Adhesion After Glass Bead Burnishing
At 60 psig with #10 Glass Beads

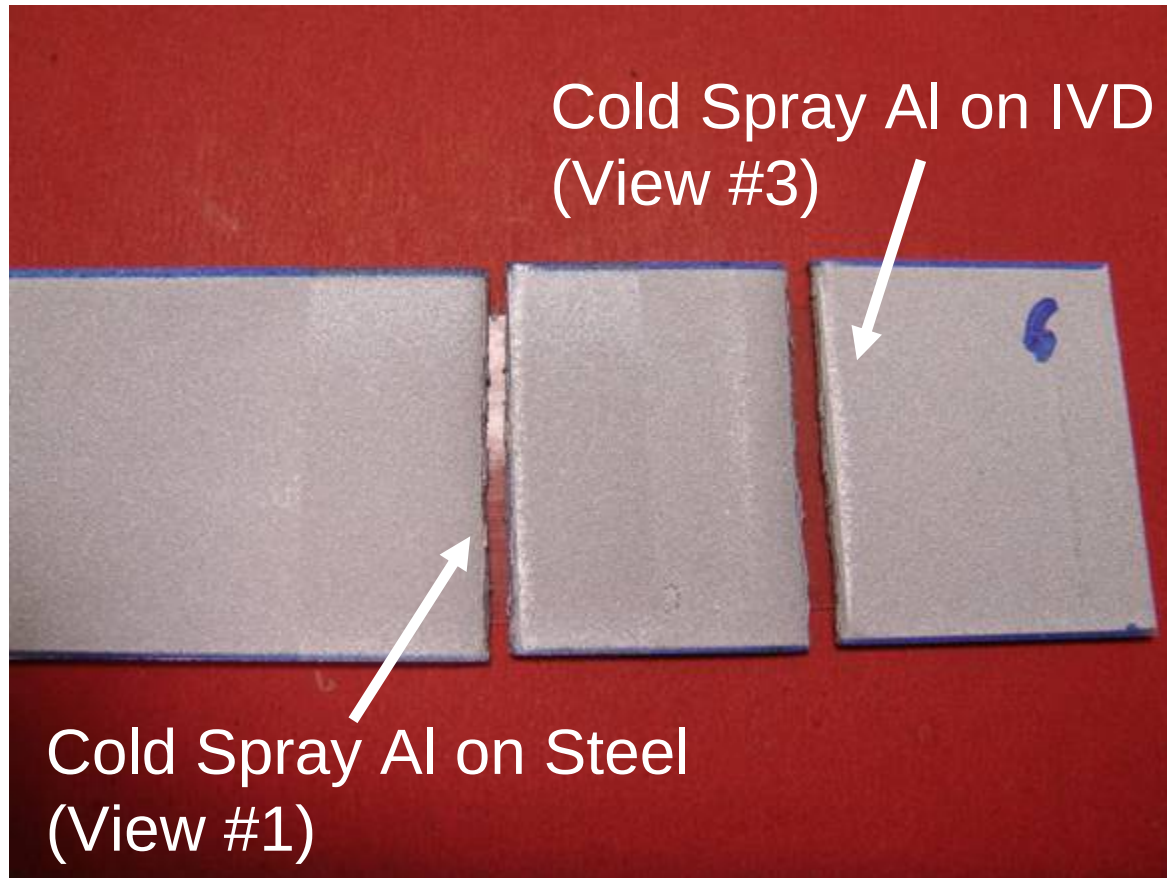
Test Specimen with Cold Spray Al on Steel / IVD

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3.7 Adhesion – Bend-to-Break Test Results



Cold Spray Al Coating Passed Bend-To-Break Adhesion Test
on Bare Steel and IVD Coated Steel

3.8 Corrosion Resistance

- **Requirement - When tested per 4.4.3 (of MIL-DTL-83488) the test samples shall show no evidence of corrosion of the base metal after testing per Table 1 (of MIL-DTL-83488).**
- **Test Procedure –**
 - Mask the uncoated edges and back side of 4x6x0.040 cold spray aluminum coated steel test specimens with masking tape
 - Subject the masked test specimens to ASTM B 117 neutral salt spray for:
 - 504 hrs. minimum for Class 1, Type I specimens
 - 672 hrs. minimum for Class 1, Type II specimens
 - Look for red rust after required exposure times and no red rust is passing

3.8 Corrosion Resistance – Test Results



1000 Hours in ASTM B 117 (Scribed Corrosion Test) –
Cold Spray Al on Steel (Left) and Cold Spray Al on Damaged IVD Al (Right) –
No Red Rust Observed on Scribed Test Panels

3.10 Base Metal Integrity

- **Requirement - For aluminum parts, after application of cold spray aluminum coating, check the Rockwell B hardness and verify that hardness did not vary by 3 points and still meets the hardness range for the aluminum alloy and temper being inspected.**
- **Test Procedure –**
 - **Apply cold spray aluminum to two 3x6 pieces of 7075-T6 aluminum**
 - **Coat one at 250° C and the other at 300° C spray gun temperatures**
 - **Check hardness and conductivity before and after cold spray application**

3.10 Base Metal Integrity – Test Results

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Specimen	Results HR _b	<i>Pre Coating</i>	(% IACS)
Plate 1	91.7 91.8 92.0 Average		32.9
Plate 2	91.7 91.8 91.9 Average		33.0
<i>After Coating</i>			
Plate 1 300°C	92.2 92.3 92.5 Average		32.8
Plate 2 250°C	Not Done.		

Health Risk Assessment

- **HRA of Cold Spray Equipment was Performed at Boeing – STL**
 - **Air Force does not want to introduce a hazardous coating process into their ALCs (Air Logistic Centers)**
 - **New Cold Spray Aluminum Coating Process Shall Not be Harmful to Workers or Environment**
 - **HRA Requirements specified in:**
 - ***AIR FORCE MANUAL 48-153 (28 MARCH 2007)***

HRA for Cold Spray Aluminum Technology

- **Parameters Used For Operation Of Cold Spray Unit**
- **Gas – Air**
- **Pressure – 90 to 100 psig**
- **Gas Temperature – 250 to 300°C**
- **Stand-off Distance ~ 0.5 inch**
- **Travel Speed ~ 100 to 150 mm/sec**
- **Line to Line Index ~ 1 to 3 mm**
- **Aluminum Powder – KSF-AL0017, Centerline**
- **Powder Flow Rate Setting – 20 to 30%**
- **Operation Mode – Manual**
- **Location of Test – Boeing Parking Lot**

Cold Spray Equipment Used for HRA

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Centerline SST Portable Cold Spray

Monitoring For Aluminum Particles During Portable Cold Spray Operation

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HRA Results for Cold Spray Equipment

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Average Total Dust: 0.25 mg/m³

Peak Total Dust: 0.51 mg/m³

Average Respirable Dust: 0.073 mg/m³

Peak Respirable Dust : 0.081 mg/m³

OSHA PEL – 15 mg/m³ for Total Dust 5 mg/m³ for Respirable Fraction

NIOSH REL – 10 mg/m³ for Total Dust 5 mg/m³ for Respirable Fraction

ACGIH TLV – 10 mg/m³ for Metal Dust

Recommended Personal Protection Equipment (PPE)

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- **Safety glasses with face shield; or safety goggles**
- **Filtering face piece respirator (i.e. dust mask) if face shield not utilized**
- **Disposable gloves (any)**
- **Disposable coveralls**

Conclusions

- **Centerline SST Cold Spray Equipment Can Be Used to Apply MIL-DTL-83488 Aluminum Coatings**
 - Providing that proper materials and processes are carried out.
- **Testing was conducted to repair damaged IVD Aluminum but Cold Spray Aluminum process could also be used to repair damaged Alumiplate, Sputter Aluminum, CVD Aluminum and Ionic Liquid Aluminum Coatings.**
- **Additional work is required to use the Cold Spray process to repair damaged Alclad Aluminum Coatings**
 - Additional requirements apply for qualifying an Alclad repair process (e.g. specular reflectance)

Questions?

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