Cold Spray Technology for DOD Applications

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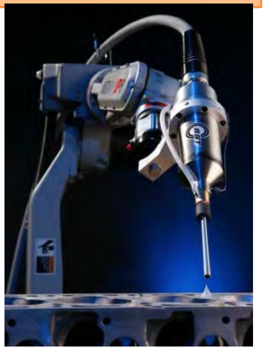
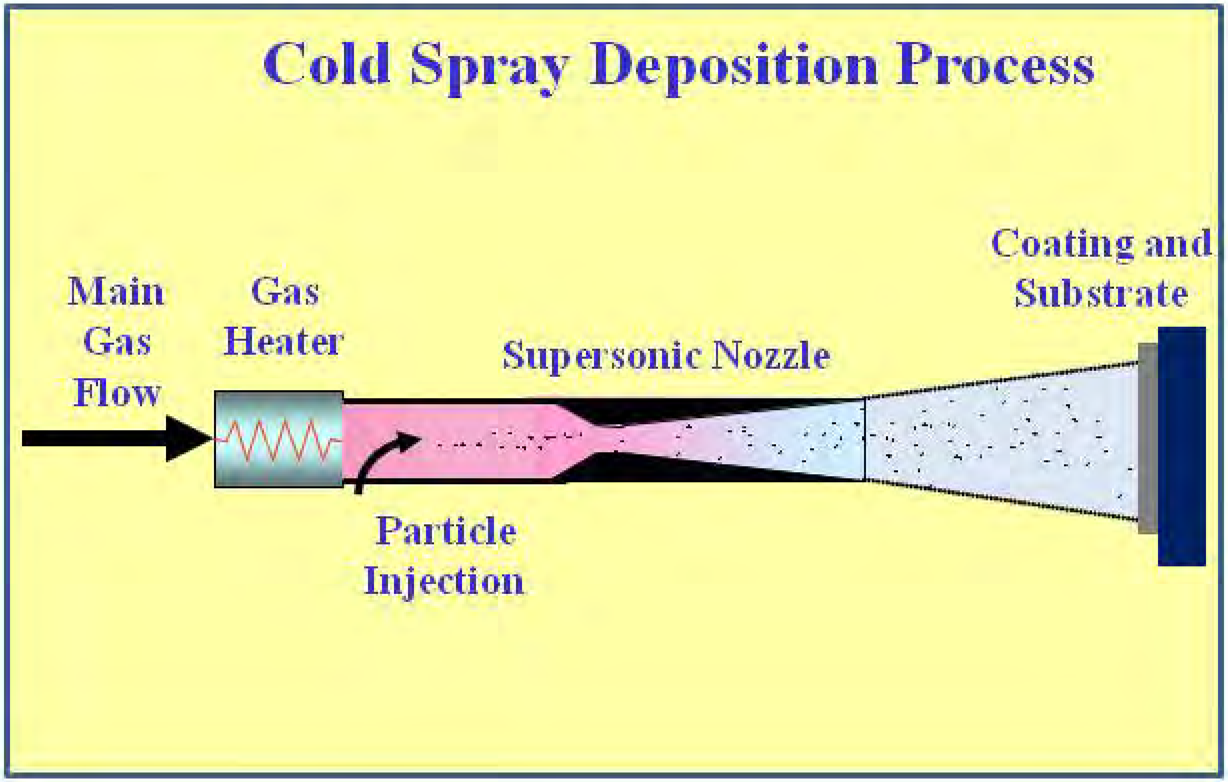
The Cold Spray Process

➢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.

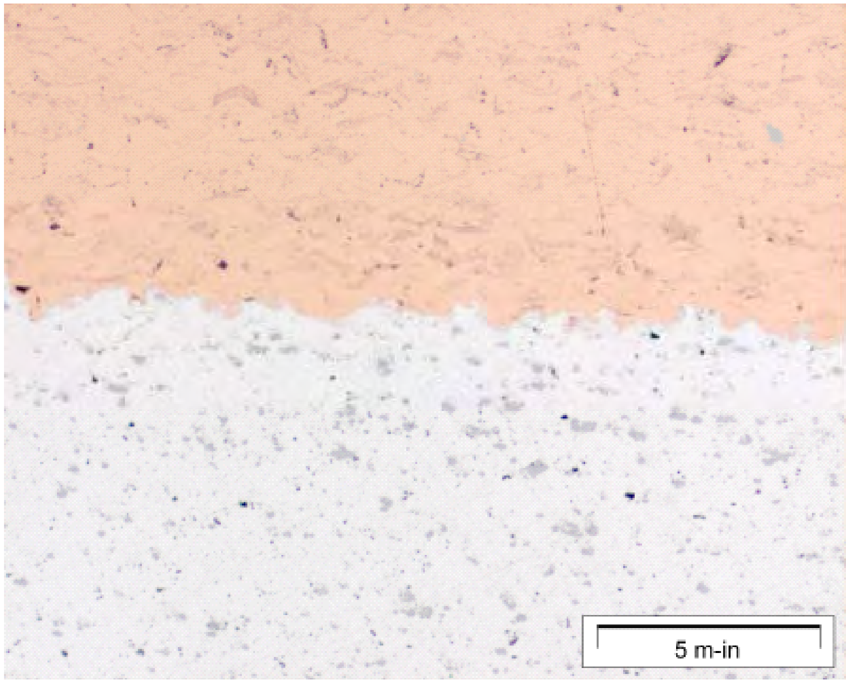
•Stationary Robot Controlled Systems for precision and or high volume
•Portable Hand-held Systems for field repair and mobility

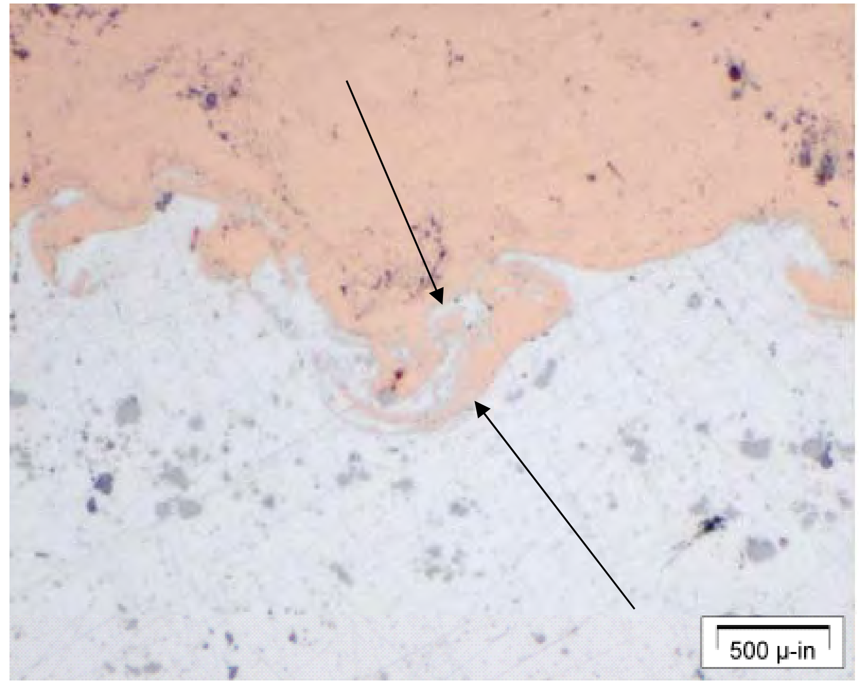


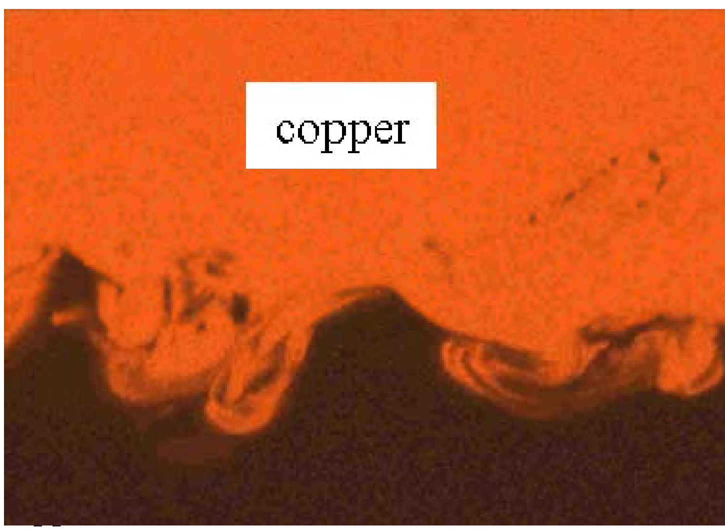


- **Feed stock typically ranges from 1 to 50 µm diameter**
- **Particle ductility is crucial**
- **Gas temperature ranges from R.T. to 1,000°C and pressures from 300 - 725psi**
- **No melting of particles**
- **Negligible oxidation**
- **No decomposition or phase changes of deposited particles or substrate**

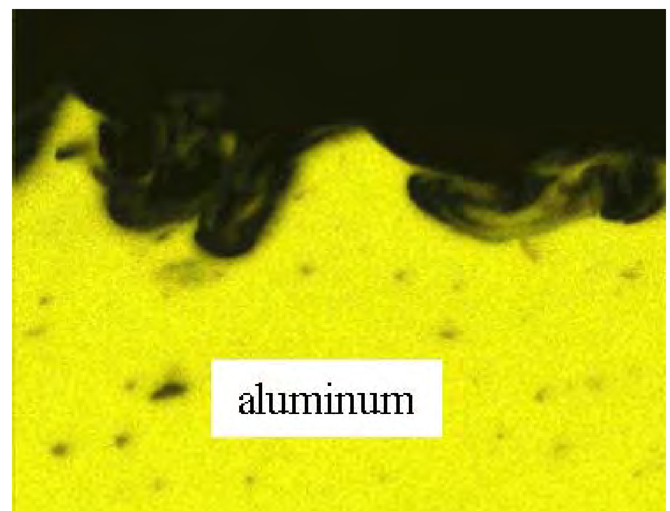
Mechanical Mixing at Interface





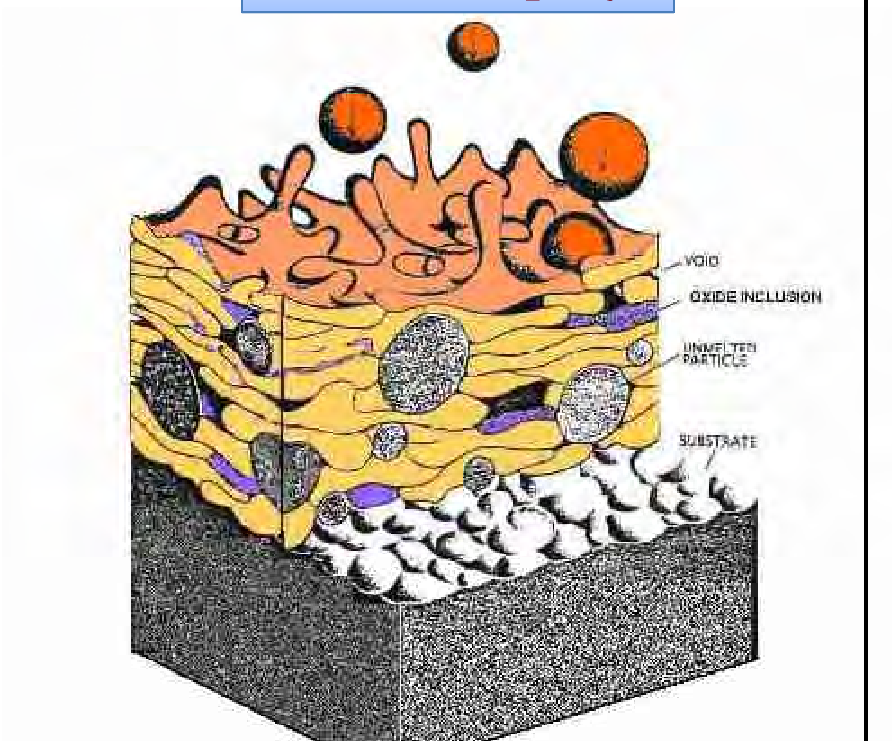


EDS X-ray Mapping showing mechanical mixing between coating material and substrate



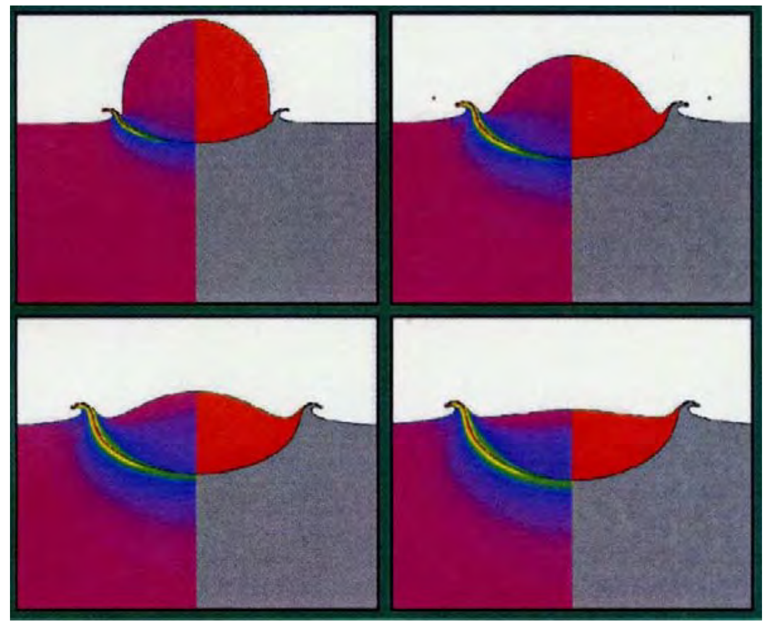
Advantages of Low Temperature

Thermal Spray



www.gordonengland.co.uk

Cold Spray

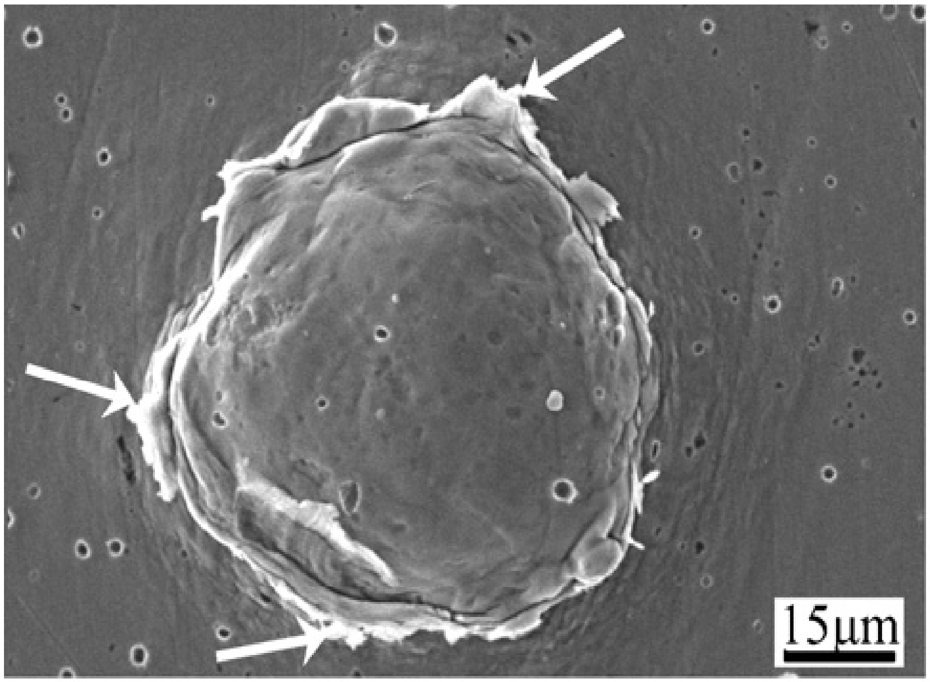


•The melting of particles that occurs during most thermal spray processes can result in oxidation of both the coating and substrate materials.

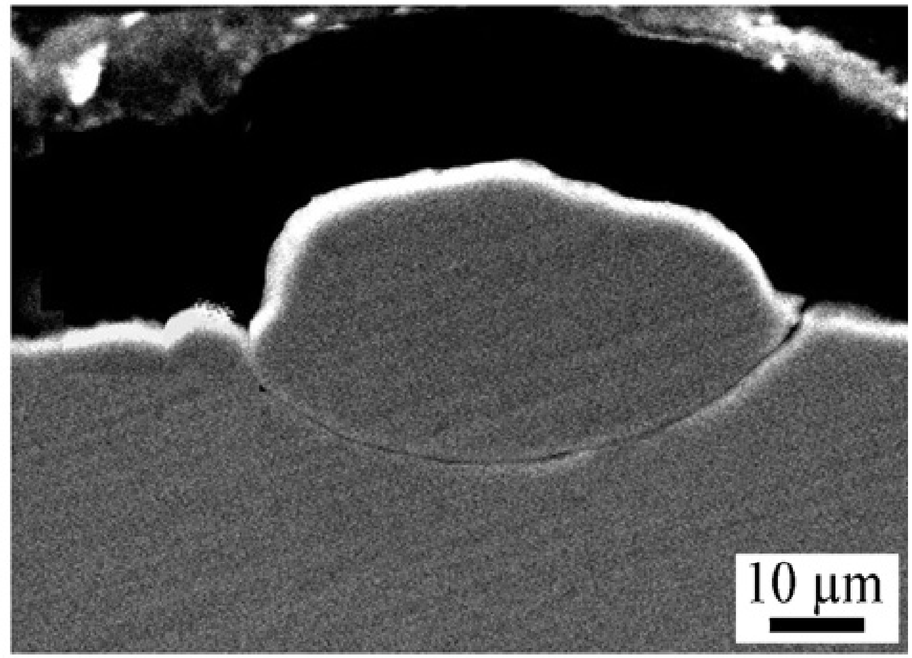
•The resulting oxides decrease the adhesive and cohesive strengths of the coating.

•The cold spray process avoids such reactions.

Particle Impact During Cold Spray



(a)



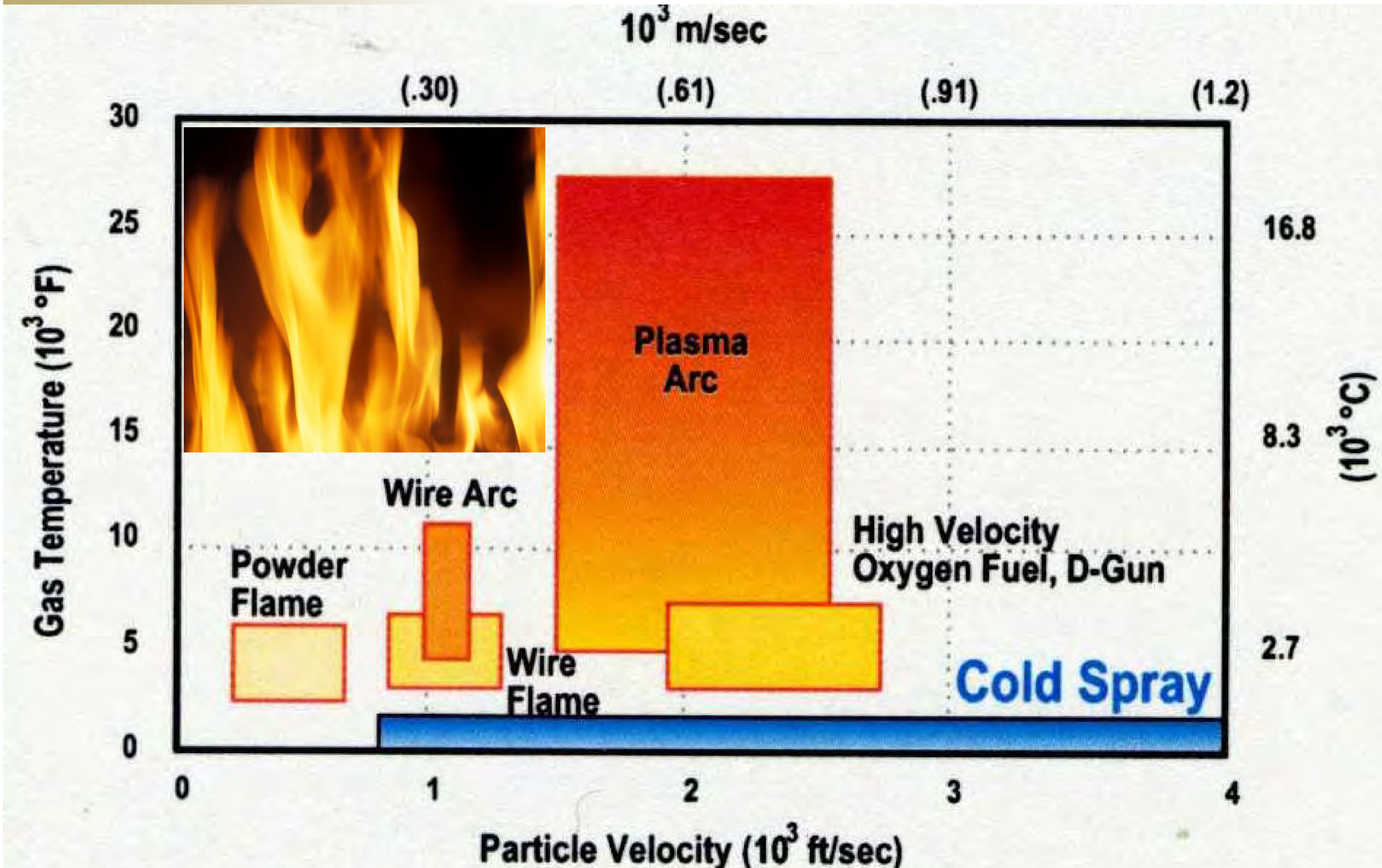
(b)

Copper Particle Cold Sprayed onto a Polished Copper Substrate

- **material jets identified by arrows**
- **Spray conditions: helium, 2 MPa, 390°C**

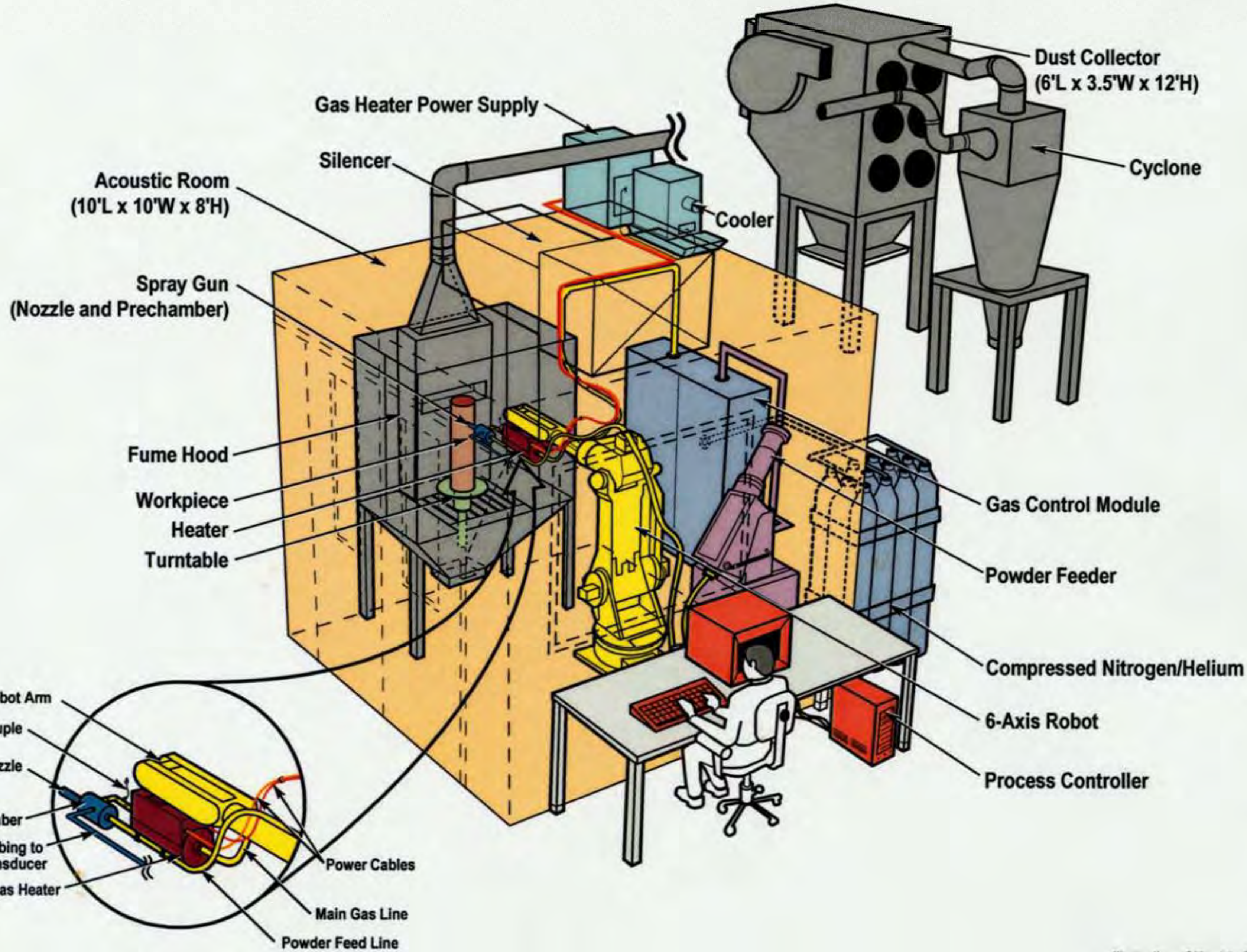
From W-Y Li, et al, "On high velocity impact of micro-sized metallic particles in cold spraying", Applied Surface Science 253 (2006) 2852–2862

Cold Spray vs. Thermal Spray



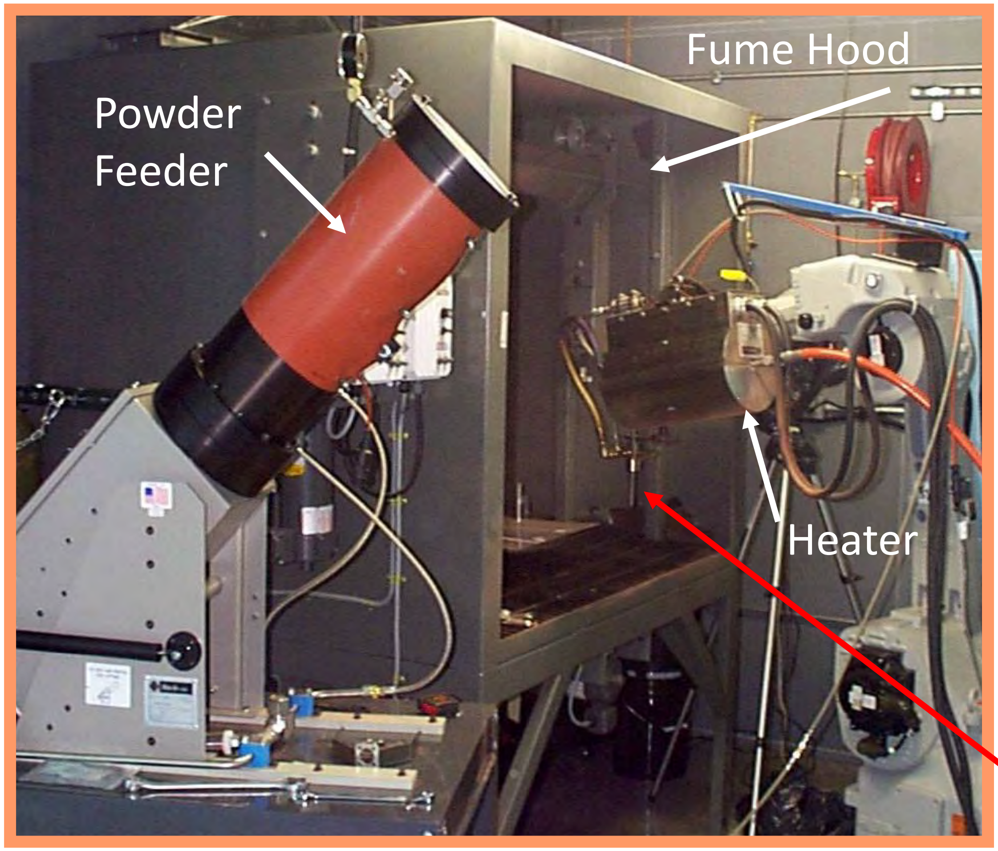
Cold Spray is performed at lower temperatures and at higher particle velocities

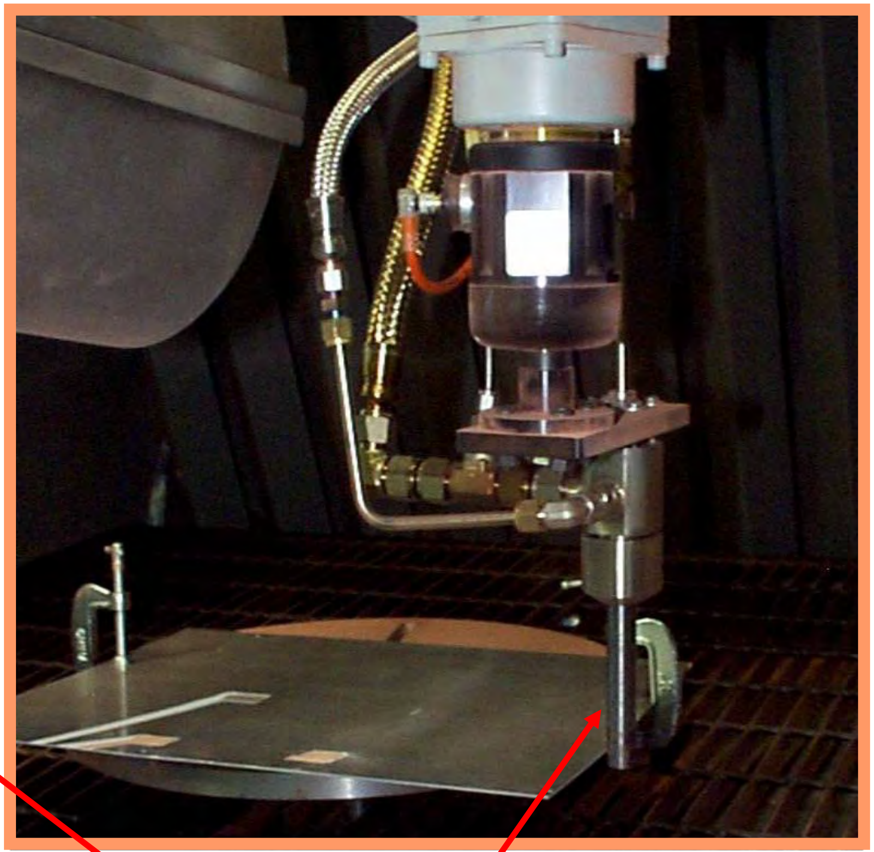
Schematic of the Cold Spray Process



Ktech Cold Spray System at ARL

Cold Spray System Components





Robotically Controlled Spray Gun

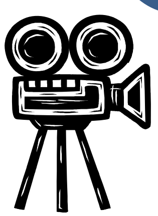
Spray Nozzle

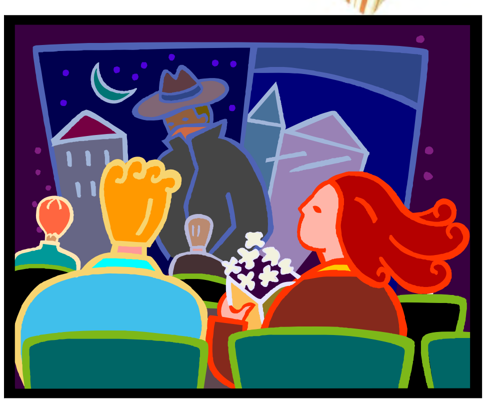
Advantages of Cold Spray

- **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)

ARL Portable Cold Spray System

Manual or Robot-Controlled, High Pressure, He and N Gas

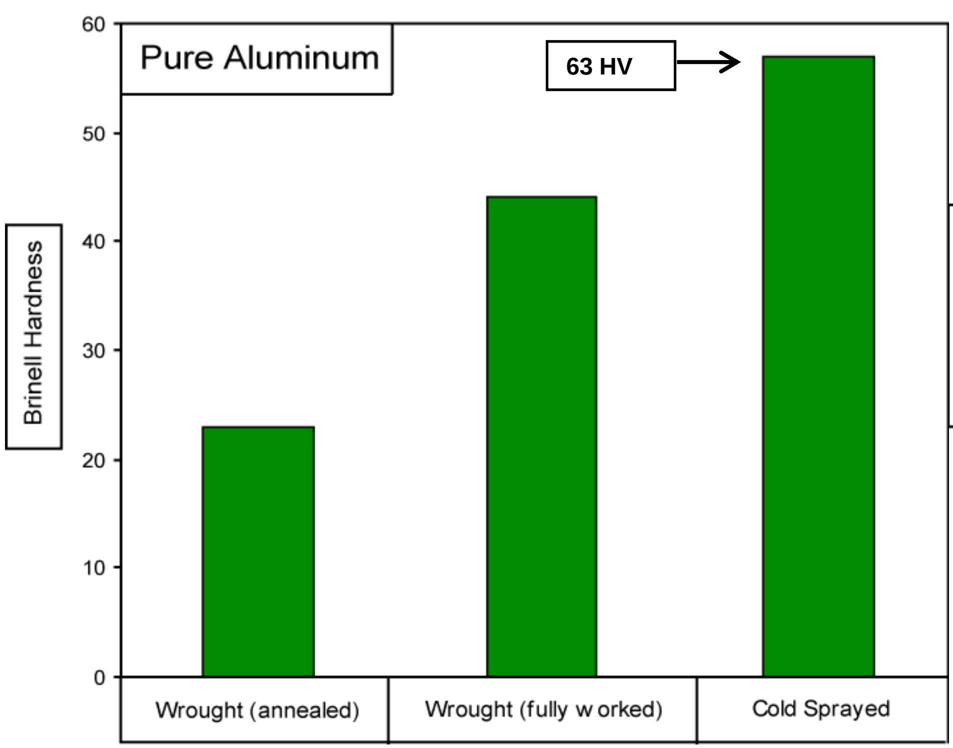


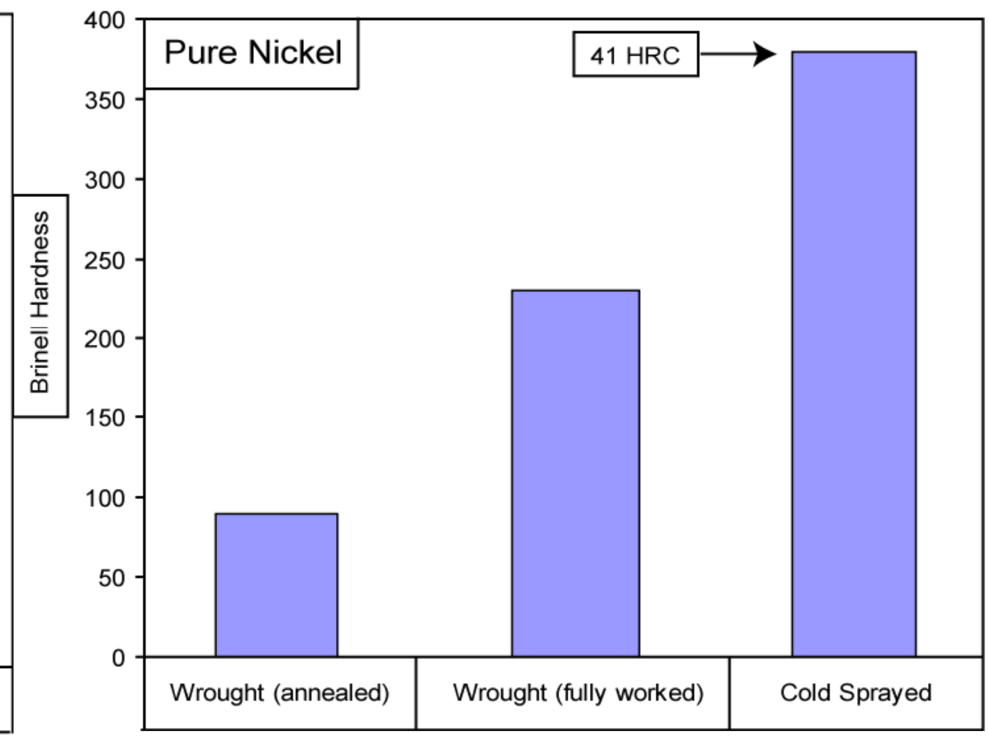


Cold Sprayed vs. Wrought Materials Hardness Comparison

- The hardness and strength of a cold-sprayed material can be significantly higher than that of conventional wrought material.

- The hardening is a result of the plastic deformation that occurs during particle impact and the refined microstructure of the material.



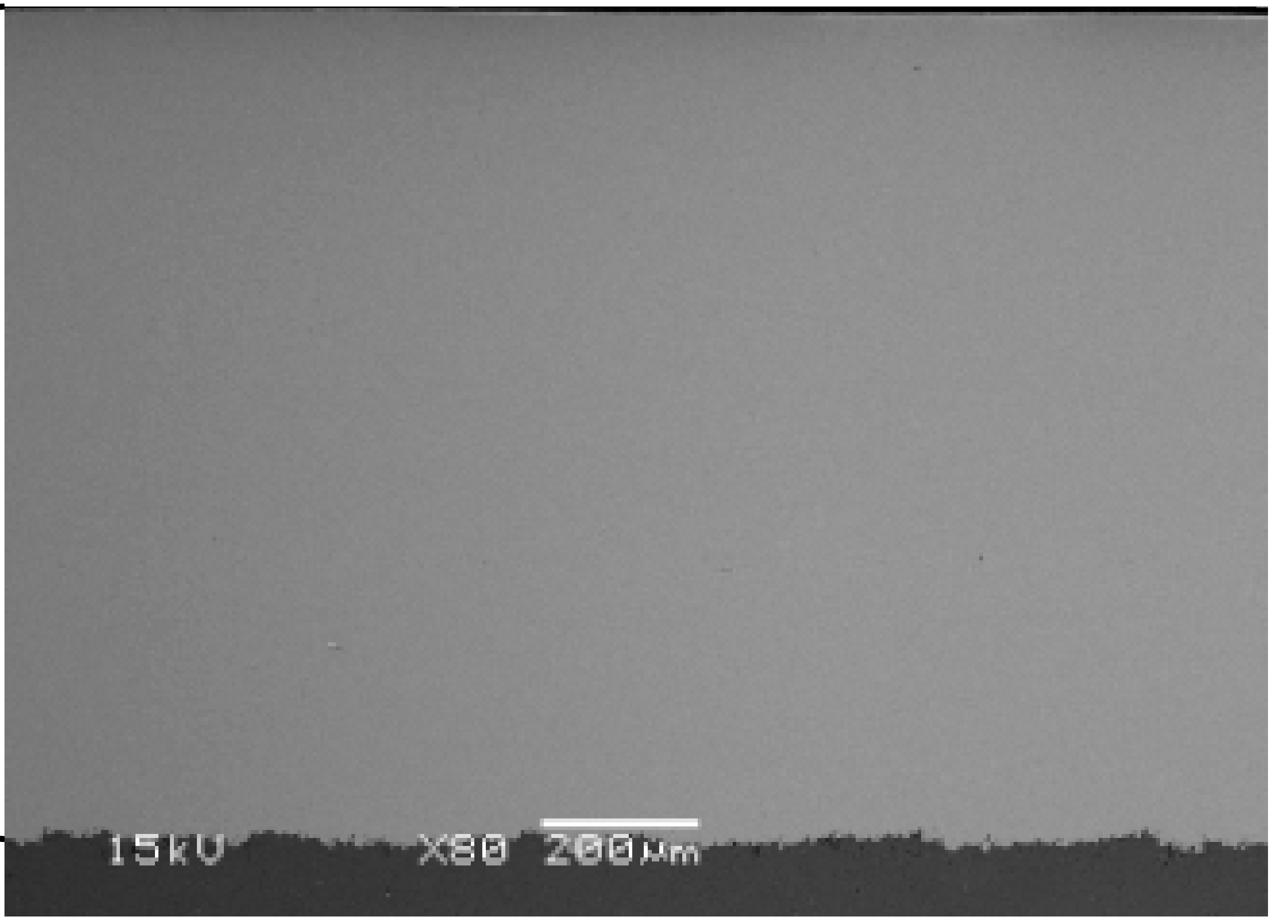


Cold Spray Coating of Nickel On 4340 Steel

Nickel

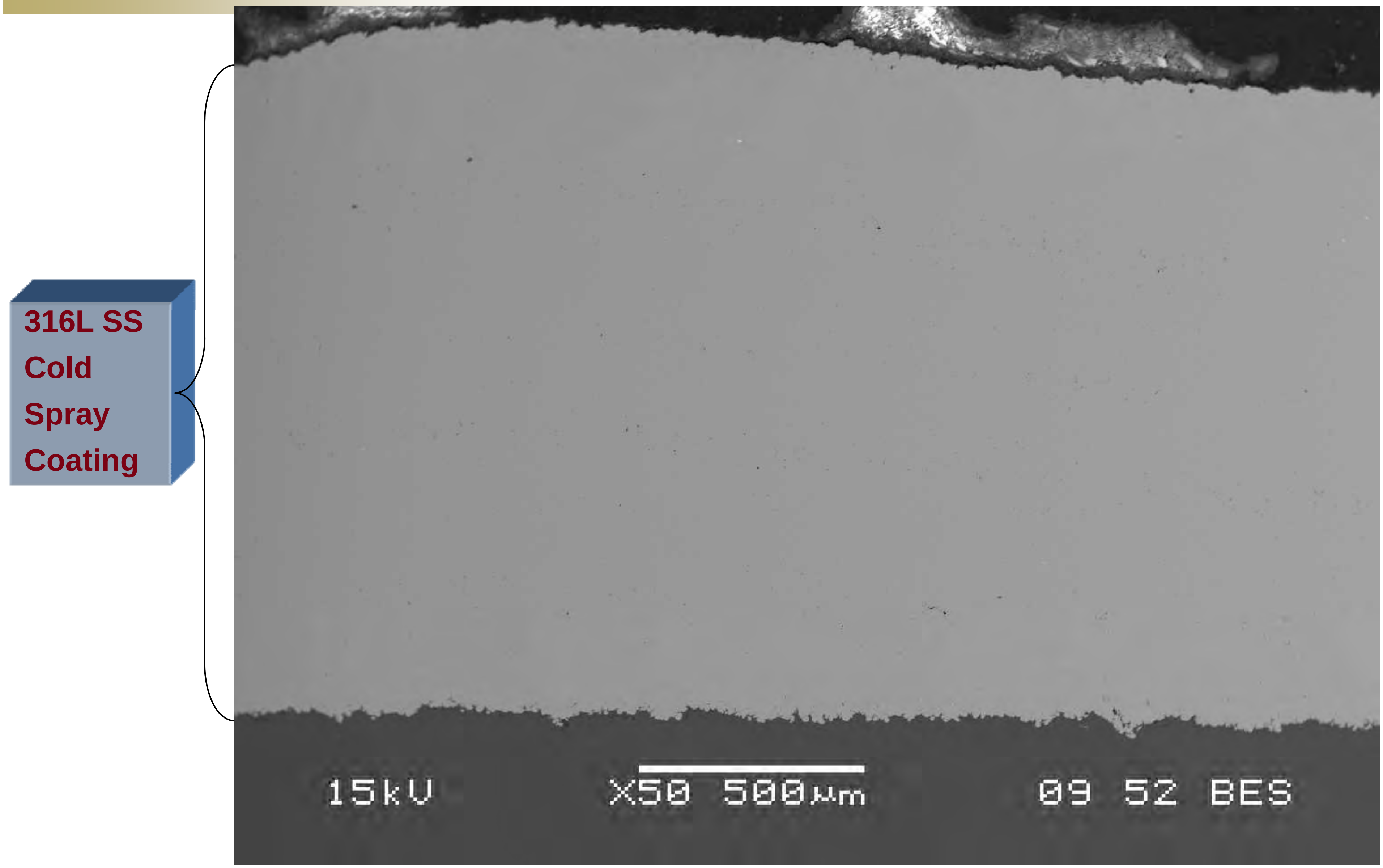
Coating

100% Dense

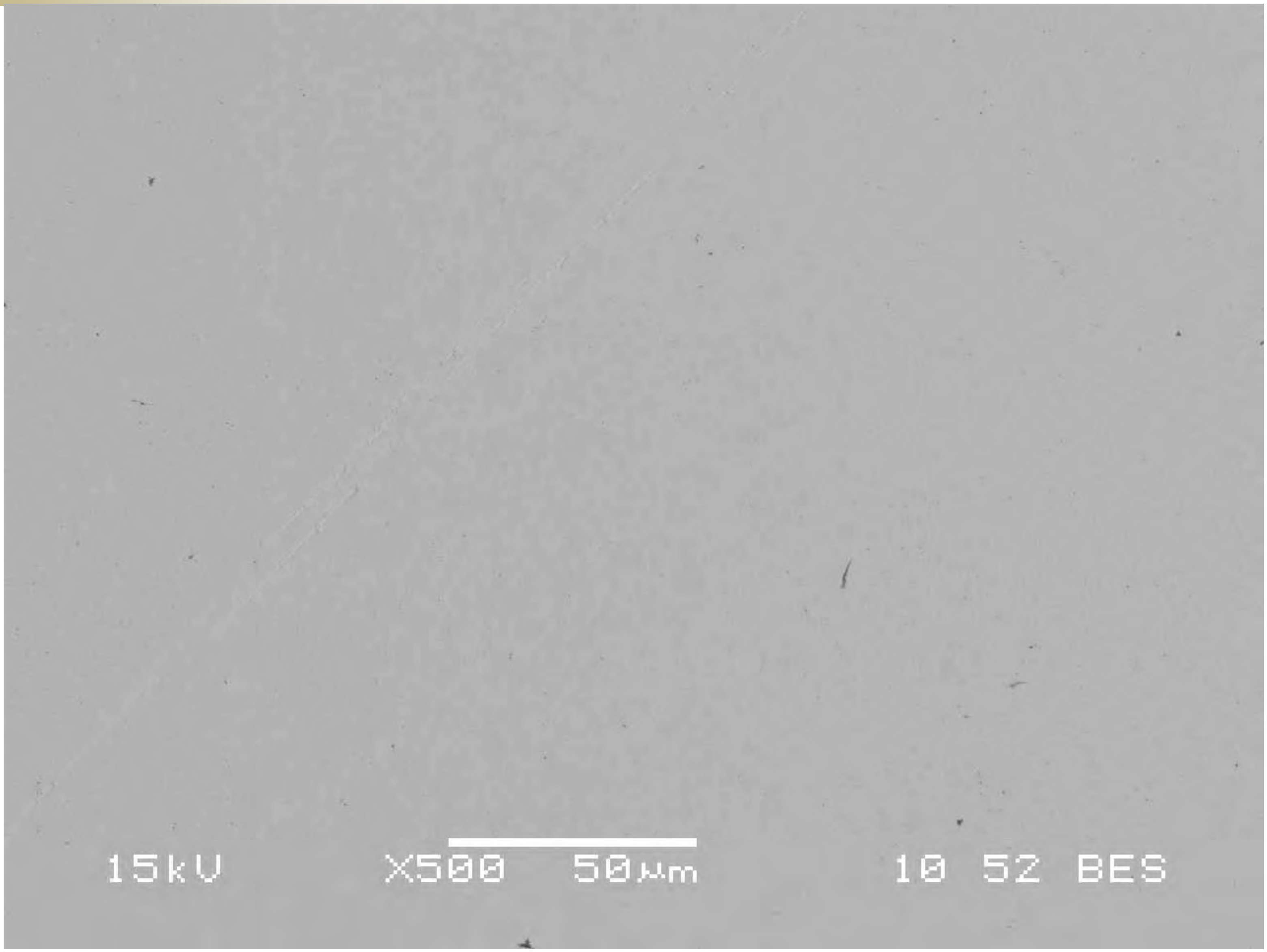


Cold Spray Ni has a hardness of HRC 41 and a resistivity of 6.84uohm/cm

316L SS Deposited by Cold Spray



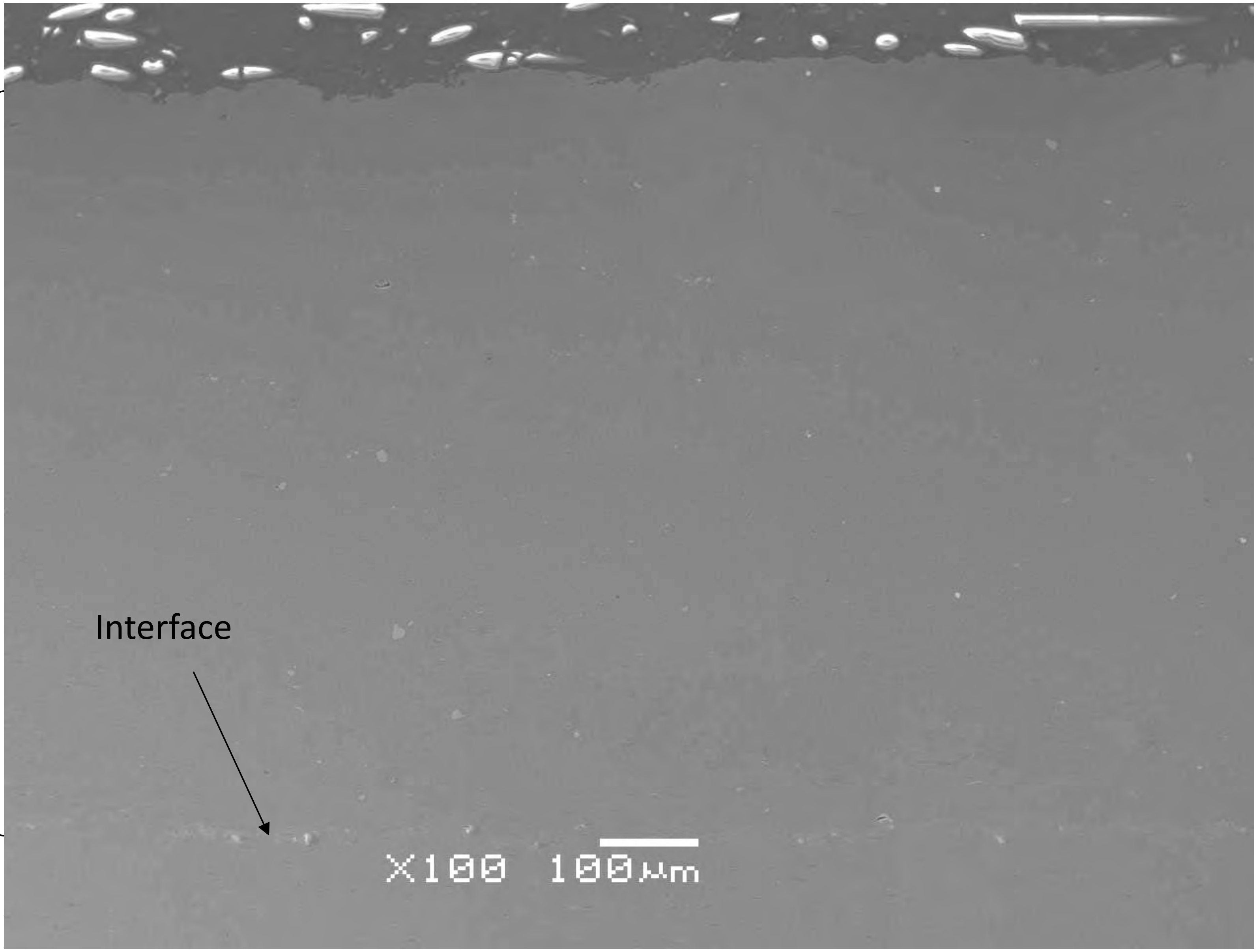
Cold Spray Tantalum



5056 Aluminum Deposited Onto 6061-T6 Al

5056 Al Cold Spray Coating

6061-T6 Aluminum Substrate



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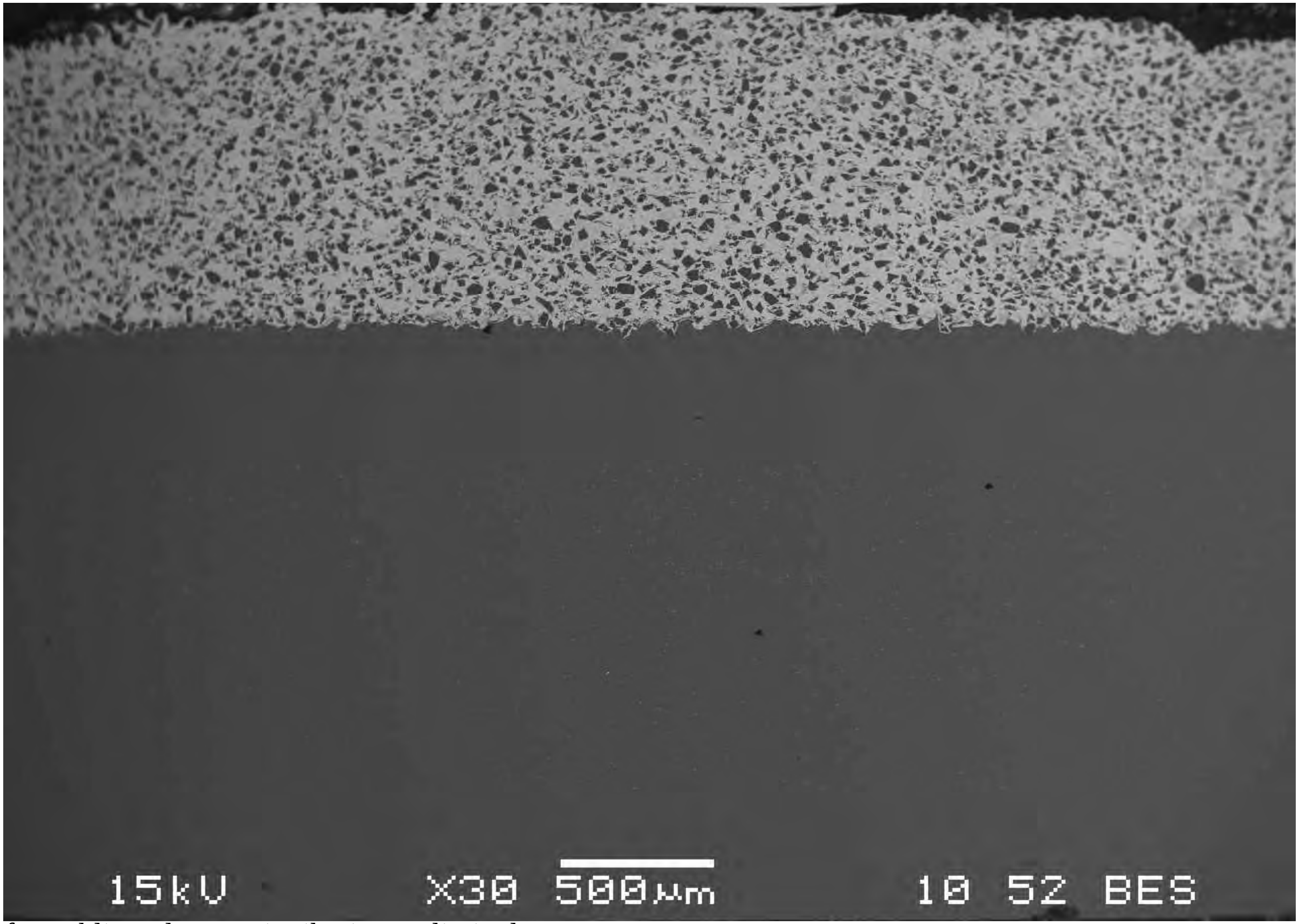
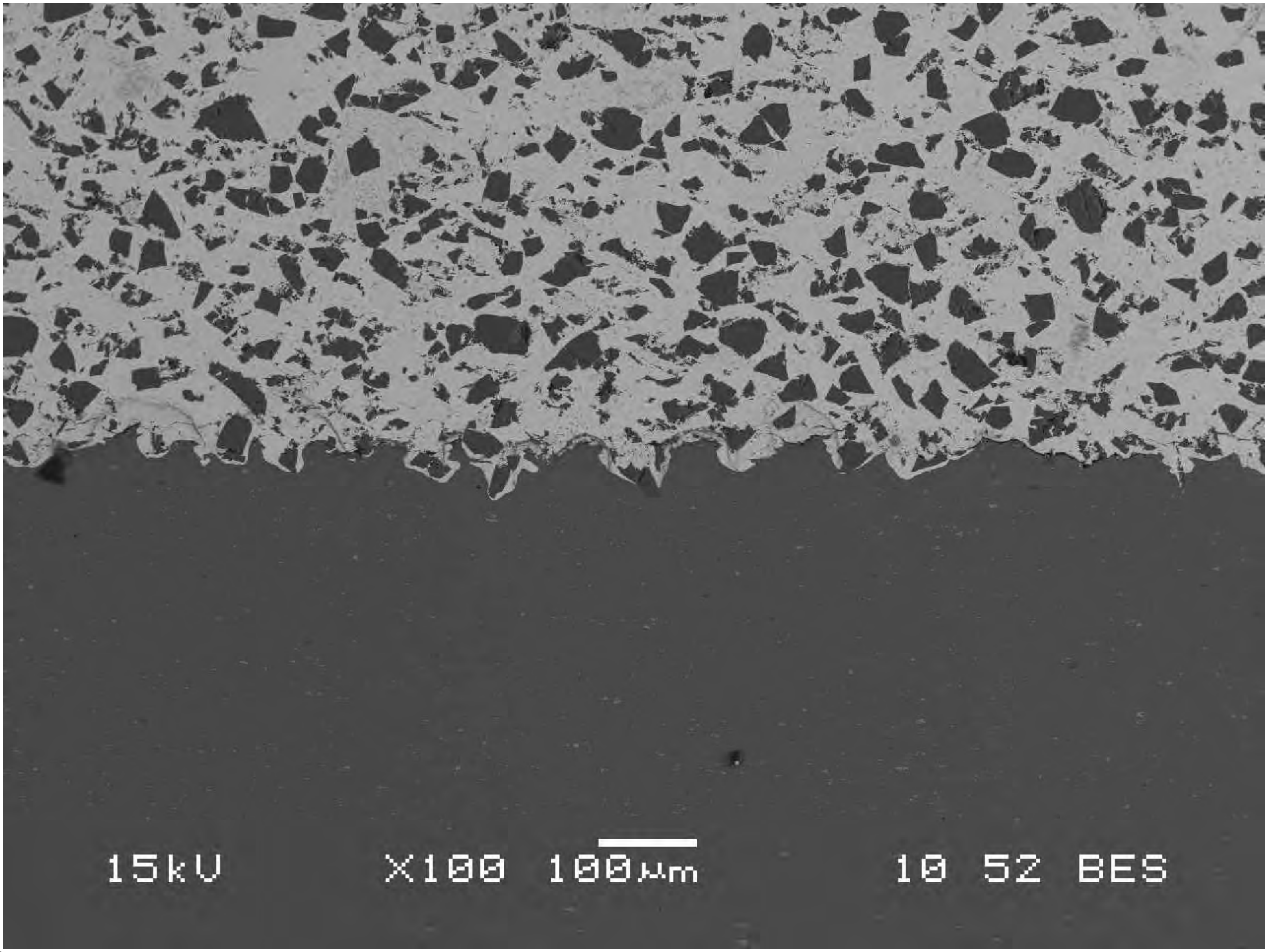
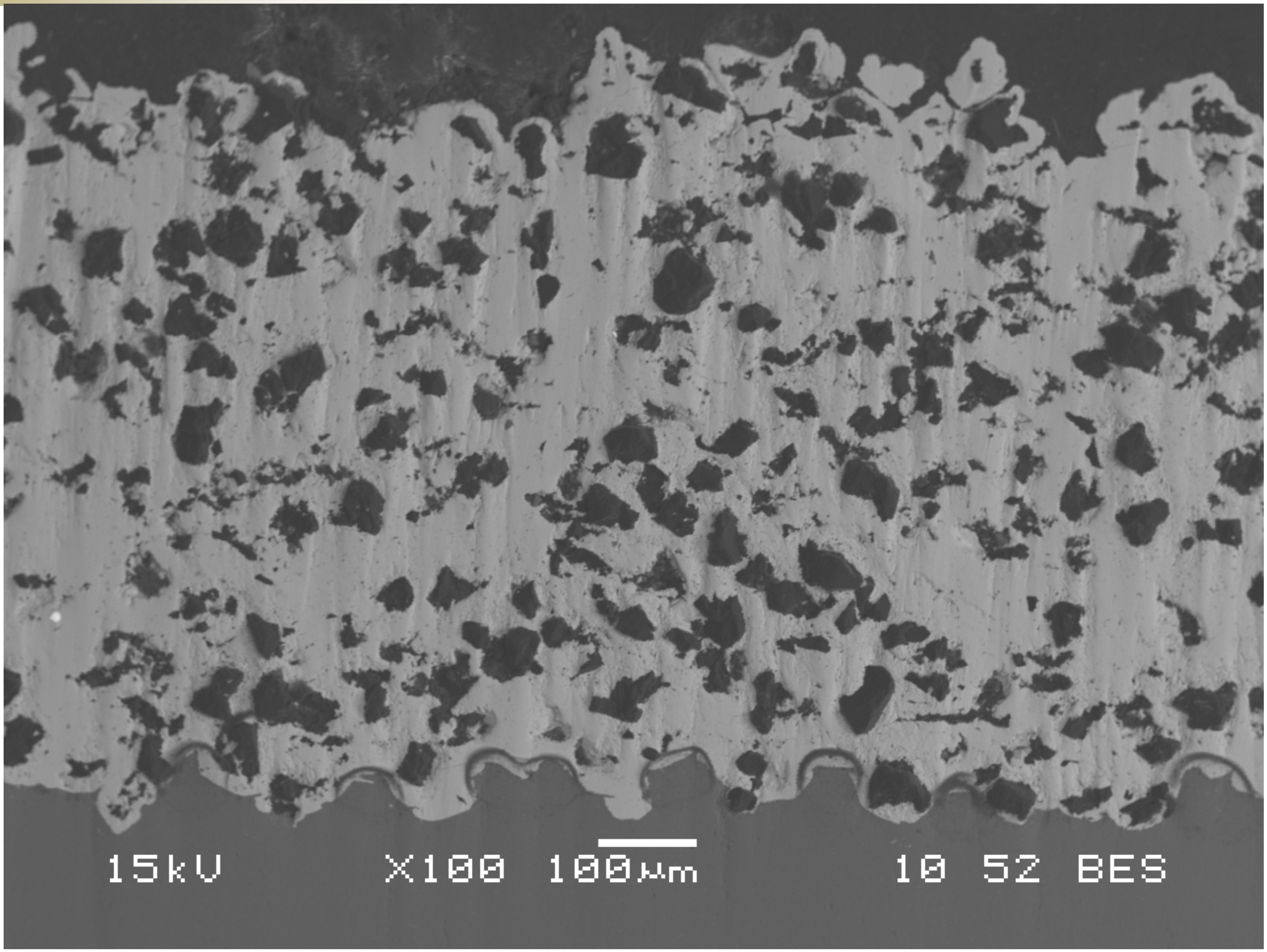
Cu-49%SiC Cold Spray Deposit



Cu-49%SiC Coating/Substrate Interface



Cu-Diamond Cold Spray Deposit



Cold Spray Nickel Consolidated by the Cold Spray Process

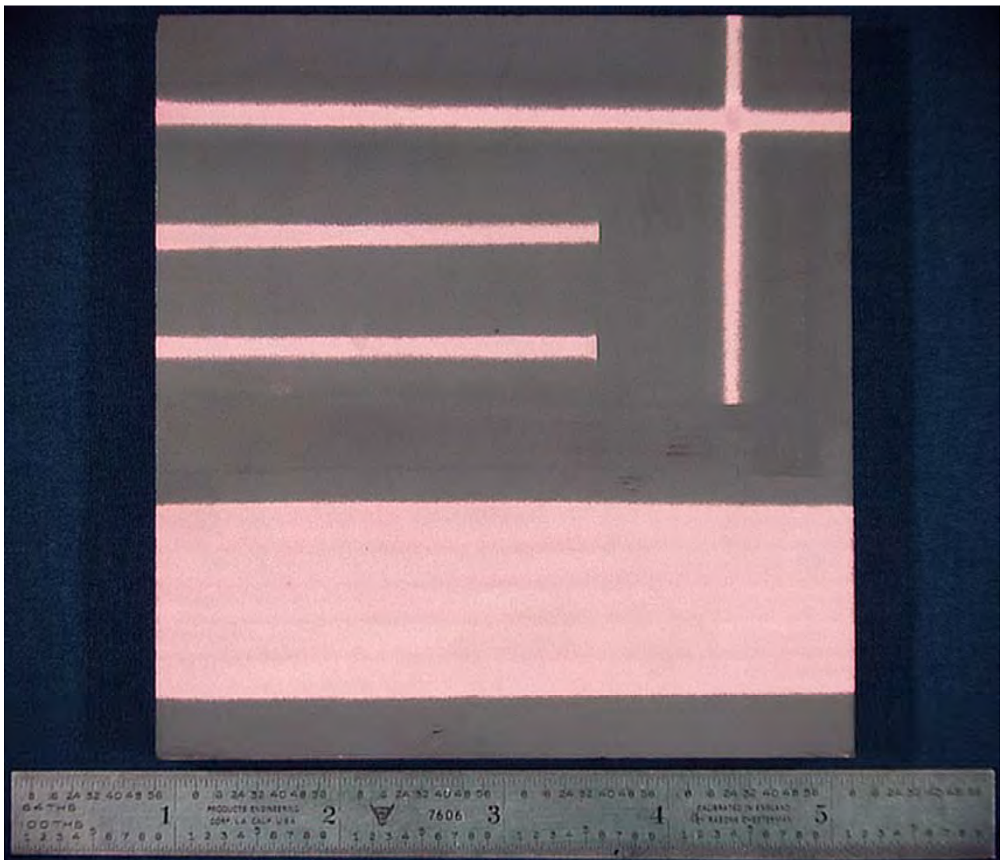
Nickel

Coating

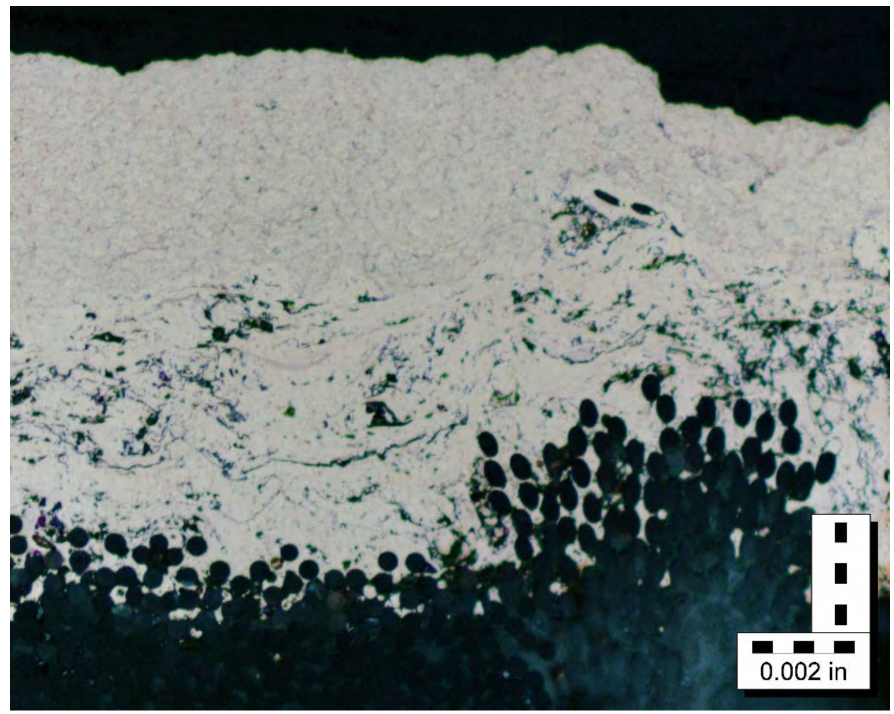
- 100% dense
- hardness of HRC 41
- compressive strength of 200ksi
- resistivity of 6.84uohm/cm

Additional Materials onto which Cold Spray May Be Applied

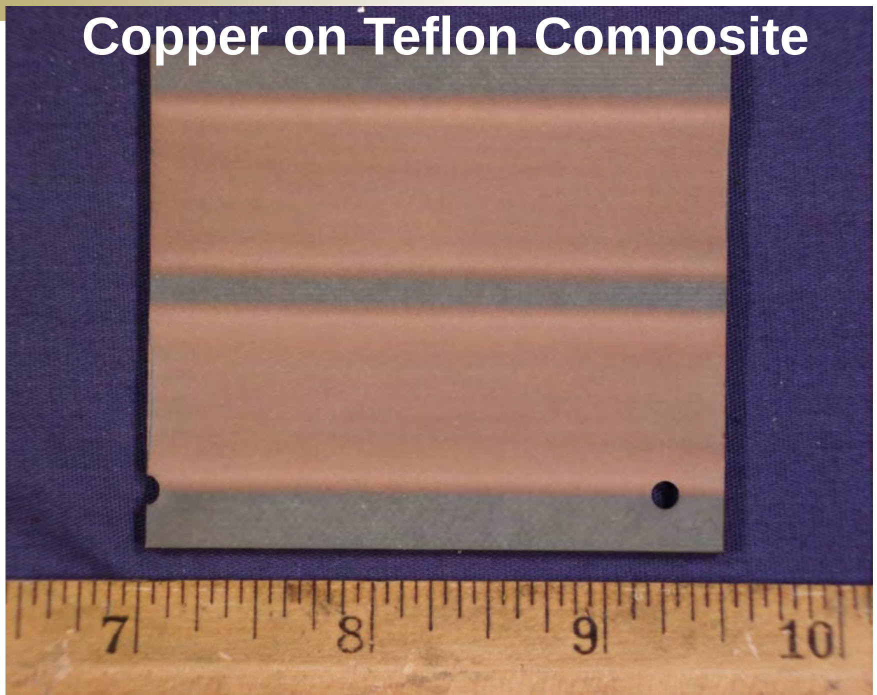
Copper on Silicon Carbide Deposited By Cold Spray

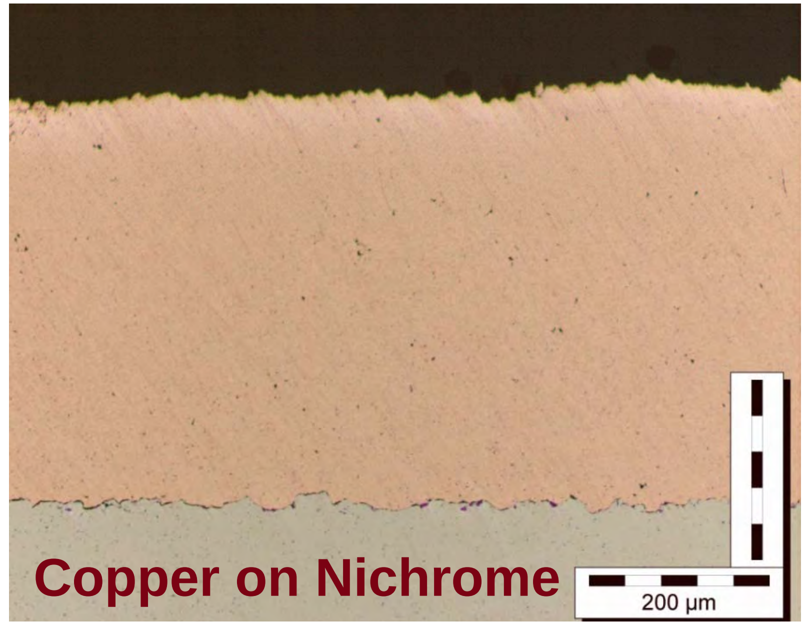


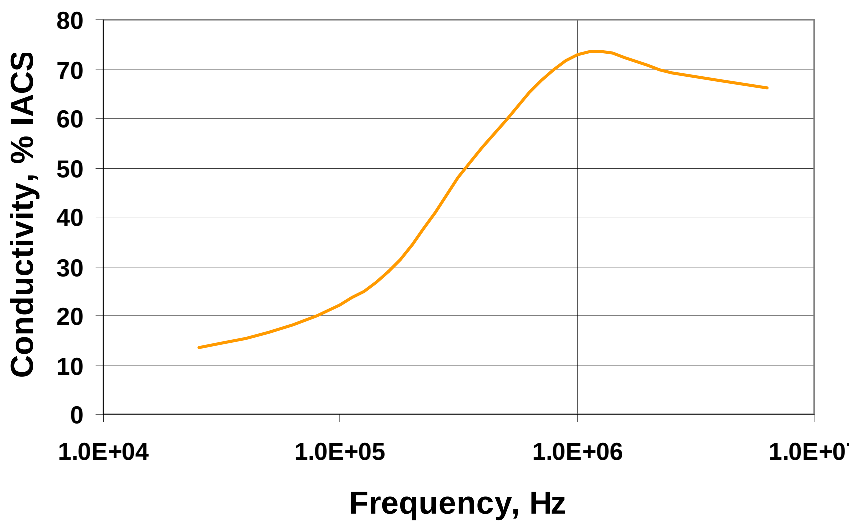
Copper on Fiber Glass Deposited By Cold Spray



Additional Materials onto which Cold Spray May Be Applied



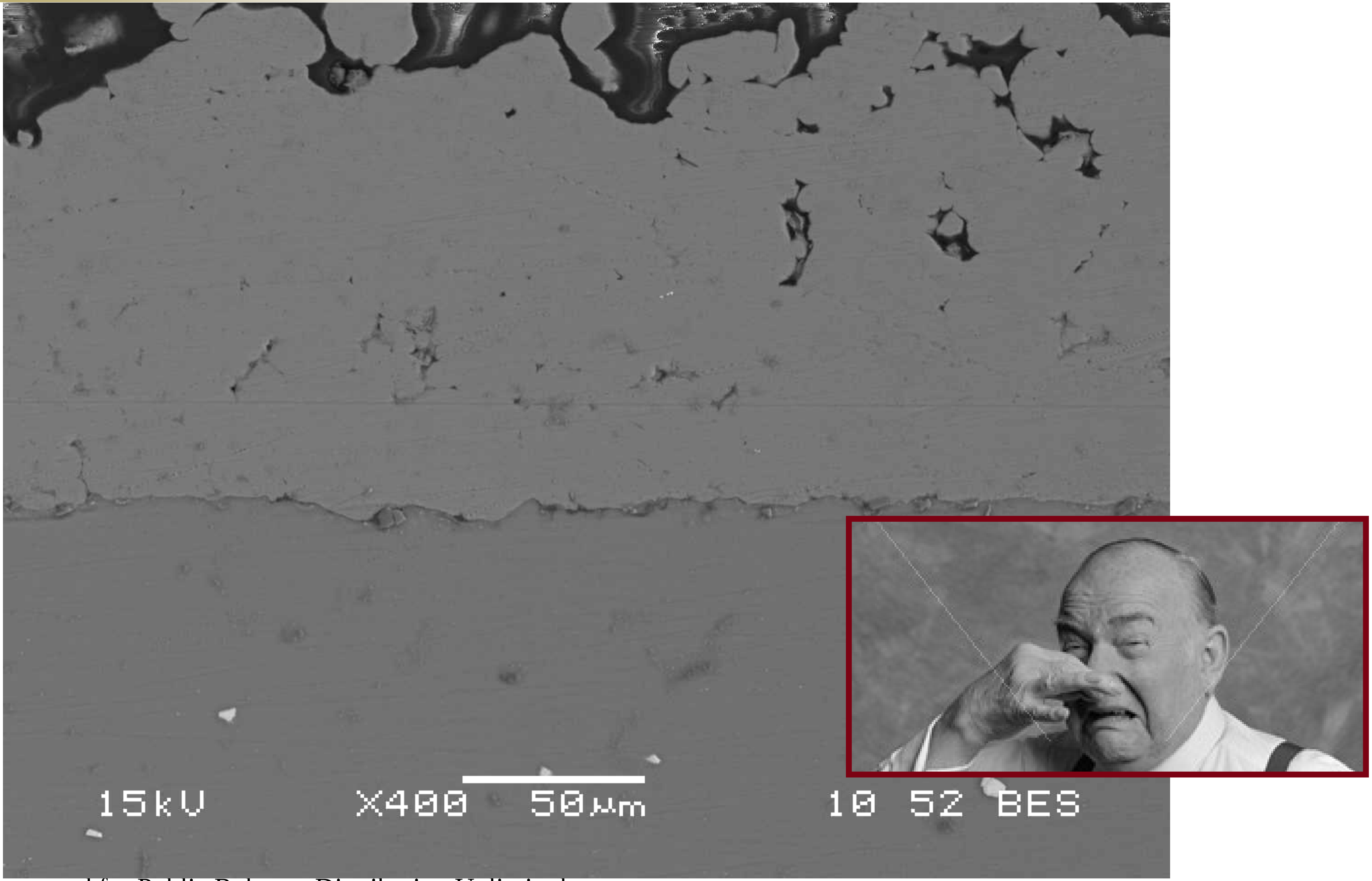




Coating Conductivity is ~ 74% IACS

Approved fo

Cold Spray Coating Prior to Optimization



COLD SPRAY APPLICATIONS DEVELOPMENT

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 Galvanizing
- Aircraft Skin Repair
- Heat Sinks and Power Modules
- Cladding

from Prototype to the Field

Fielded SH-60 Seahawk with Cold Spray Mg Repair Operating Since August, 2009-Australian Navy
ARL/JSF/DSTO Collaboration

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

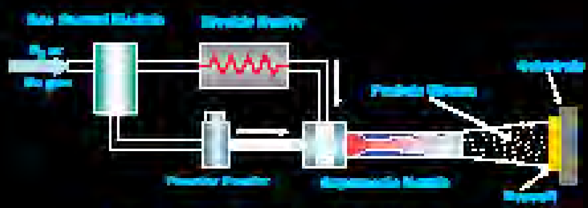
Fielded B-1 Bomber with Cold Spray Ti Repair Operating Since September 2009- Tinker AFB
ARL/Tinker AFB/HF Webster Collaboration

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

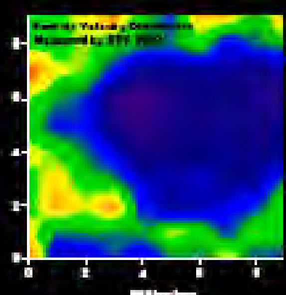
ARL Center for Cold Spray

ENHANCING THE PERFORMANCE OF MATERIALS AND COMPONENTS



Cold Spray System Configuration

Stationary Cold Spray System



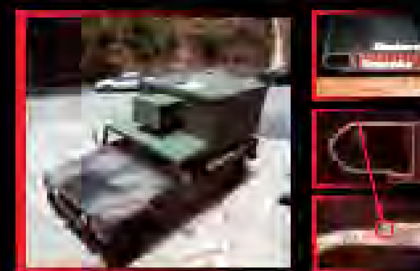
Modeling of Cold Spray Process Parameters

Advantages

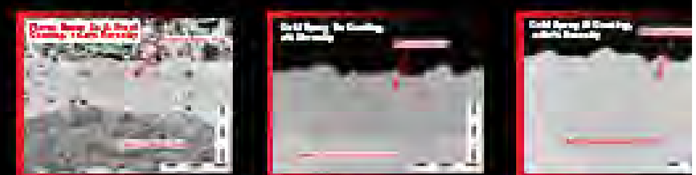
- Low Temperature Process
  - Below Melting Point of Metals
  - No Combustion Fuels, Gases
  - Results in Highly Conductive Deposits
- Solid State Bonding
  - Mechanical Mixing of Particles and Substrate
  - Similar to Explosive Bonding
  - Plastic Deformation of Particles Disrupt Oxide Films
  - Compressive Residual Stresses
- High Density Deposits
  - Form Thick Coatings at High Deposition Rates
  - Low Oxide and Porosity Content (<1%)
  - Form Free-Standing Structures

Applications

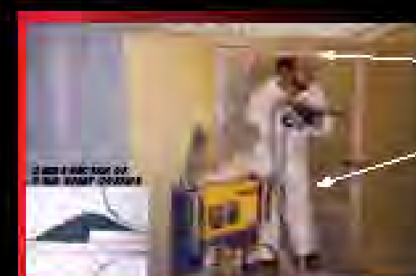
- Corrosion Resistant Coatings (Zn, Al)
- Dimensional Restoration and Repair (Ni, Stainless Steel, Titanium, Aluminum)
- Wear Resistant Coatings (CrC-NiCr, WC-Co, WCu)
- EMI Shielding
- Portable Units for Field Repair



EMI Shielding for HMMWV Shelter by Cold Spray



Comparison of Cold Spray and Thermal Spray



Applied EMI Shielding on the HMMWV Shelter

ARL Center for Cold Spray

- World Class Research and Development Facility Recognized Internationally as the most well equipped and sophisticated cold spray facility in the world
- ARL Center for Cold Spray est. 2000 (12 dedicated employees, 13 CS systems)

The direct link is: http://www.arl.army.mil/www/default.htm
The link from the homepage is: Doing Business with ARL | Center for Cold Spray

- Working with over 125 companies, as well as DOD, DOE, Foreign Countries
- Aerospace, automotive, petrochemical, medical & electronics applications
- Cold Spray Additive Manufacturing *Hot Isostatic Press (HIP)
- Integrated Diode Laser with Cold Spray (1KW Continuous)
- DPV 2000 Dual Slit Laser Particle Measuring System
- Developed the first Cold Spray Process Specification (MIL-STD-3021, titled “Materials Deposition, Cold Spray”)

Supersonic Particle Deposition Technology for Repair of Magnesium Aircraft Components

RDECOM

SERDP DOD • EPA • DOE ESTCP

ESTCP Project # 06-E-PP3-031

Environmental Security Technology Certification Program

Objective: Demonstrate and qualify Supersonic Particle Deposition (SPD) or Cold Spray aluminum alloy coatings as a cost-effective, ESOH-acceptable technology to provide surface protection and a repair/rebuild methodology for Mg alloy components on Army and Navy helicopters and advanced fixed-wing aircraft.

1. To establish an overhaul and repair facility at FRE-East, Cherry Point, NC
   - Satisfy the DEM/VAL requirement for ESTCP
2. To qualify a cold spray repair process for the UH-60 Sump
   - In support of Sikorsky Aircraft Company and FRE-East
3. To qualify a cold spray vendor for Sikorsky Aircraft Company

•***Army & Navy rotorcraft & Air Force fighters have Magnesium gearboxes & other Magnesium parts that are unserviceable and need replacement***

***20-23 parts/aircraft   *4,550 aircraft between Army & Navy   *long lead times for new parts**

- **Major sustainment problem**
  - highly susceptible to corrosion and fretting wear
  - resulting in significant unscheduled maintenance actions and high replacement costs (>800K/each)
  - Army and Navy spent $17M in one year for UH-60 Main Transmission and Tail Rotor Gearbox Housing Assemblies alone
  - Corpus Christi Army Depot (CCAD) has millions of dollars of used Mg housings waiting to be reclaimed as part of the "Storage, Analysis, Failure Evaluation and Reclamation" (SAFR) program.
- **Mission-critical flight-safety equipment**
  - Loss of transmission oil and pressure causes excessive heat/wear and ultimate seizure of gears and loss of aircraft
  - Corrosion reduces strength, lowers safety factor
- **Frequent replacement needed**
  - parts most often do not even meet service/fatigue life requirements
  - logistics and readiness issue for deployed troops
  - repaired units corrode again

→ thermal spray has poor adhesion, cannot weld or laser repair due to excessive heat input that adversely affects properties of the magnesium (Mg)

Areas where magnesium housings are used on the UH-60

Main, Intermediate and Tail Gearboxes for UH-60

- **Parts are large and expensive (up to $800K/housing)**
- **Long lead times**

- **Magnesium is susceptible to wear and corrosion**

RDECOM TECHNOLOGY TO WIN

Joint Test Protocol (JTP)

ARL

Full JTP Qualification Plan

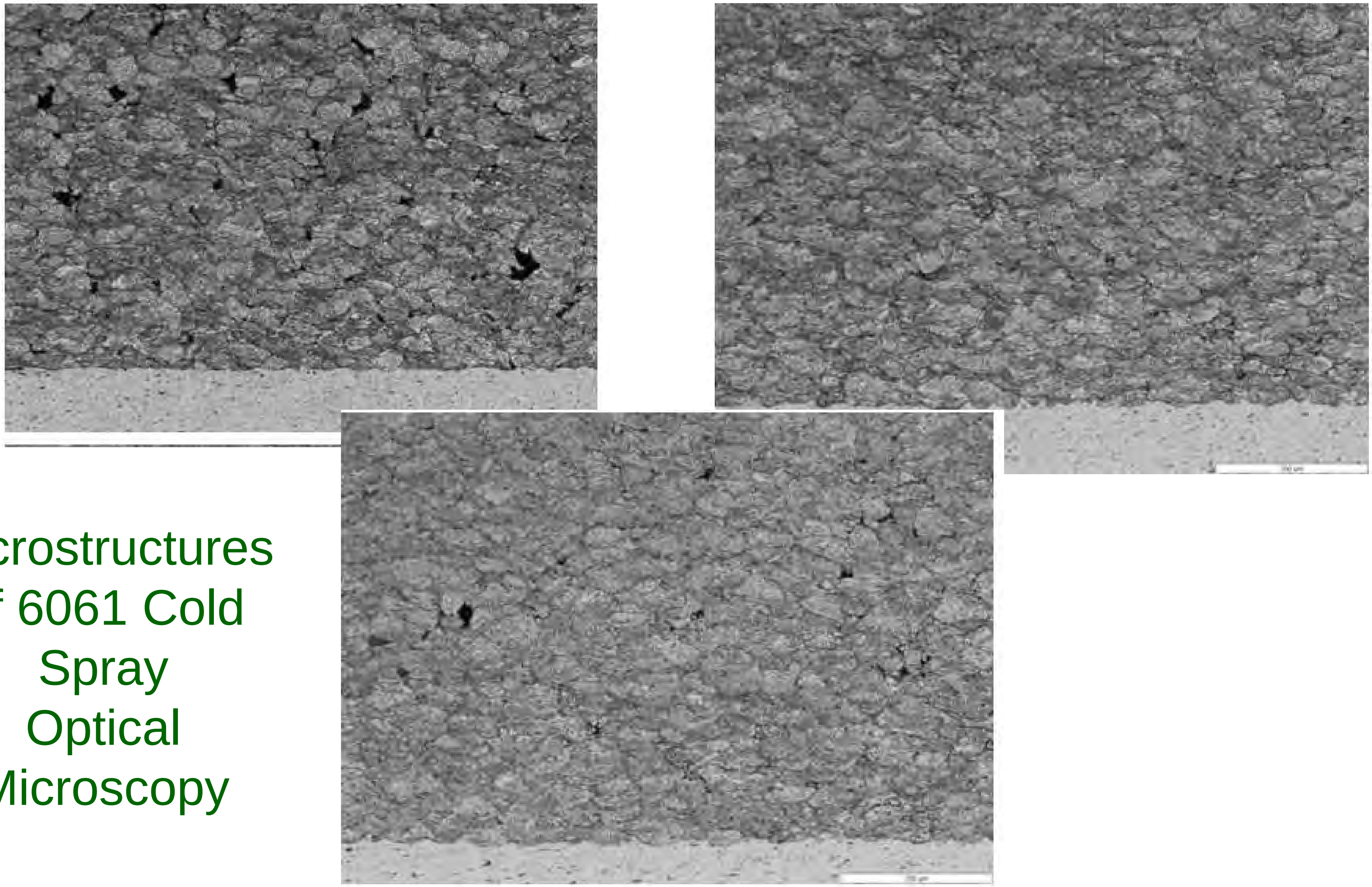
Mechanical Tests

- Adhesion Tensile Bond Test (ASTM C633)
- Almen Strips
- Flat Tensile Specimens
- RR Moore RB Fatigue
- surface finish 125RA
- Fretting Fatigue
- Impact - ASTM D5420
- Hardness
- Porosity
- ROSAN Insert Test
- Triple Lug Shear Test

Corrosion Tests

- Unscribed ASTM B117
- Scribed ASTM B117
- GM9540 Scribed
- Galvanic Corrosion (G71)
- Crevice Corrosion (G78)
- Beach Corrosion
- G85 SO2
- Adhesion of Coatings

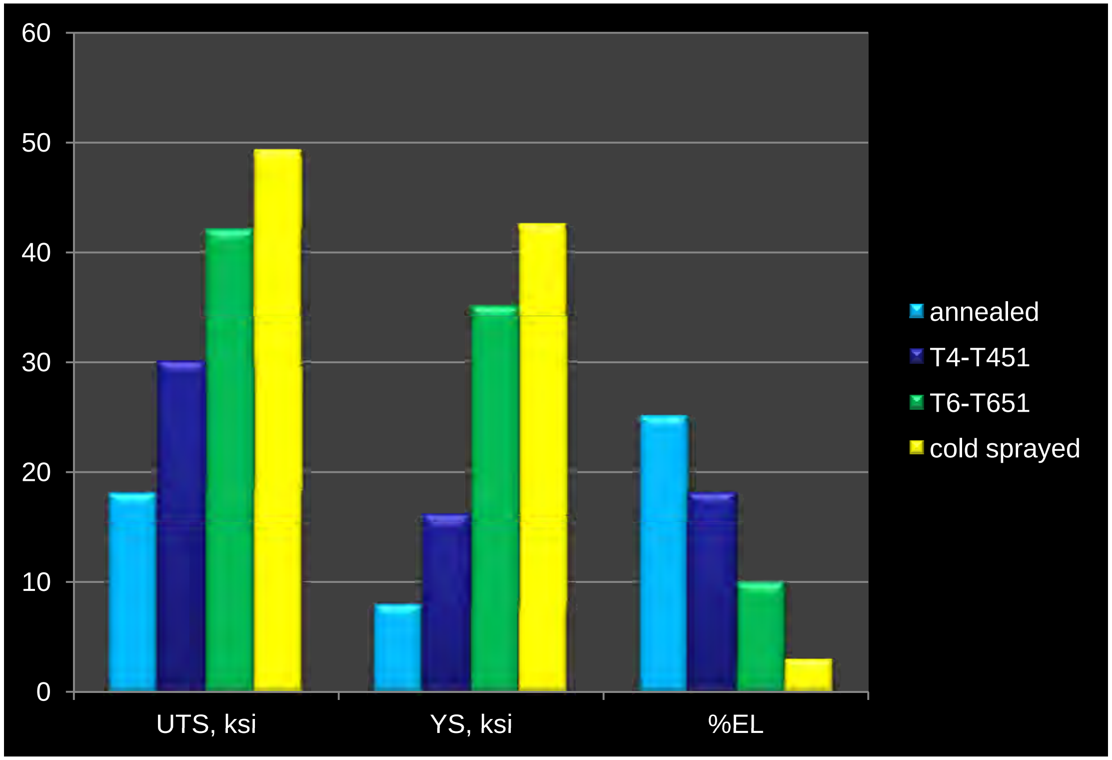
Effect of Pressure on Density



Microstructures of 6061 Cold Spray Optical Microscopy

Increasing Gas Pressure

Wrought versus Cold Spray 6061



6061 Condition	Source	UTS, ksi	YS, ksi	%EL
annealed	1	18	8	25
T4, T451	2	30	16	18
T6, T651	2	42	35	10
cold sprayed	3	49.3	42.5	3

Key

T4, T451- Solution heat-treated and naturally aged to a substantially stable condition. Temper -T451 applies to products stress-relieved by stretching. [2]

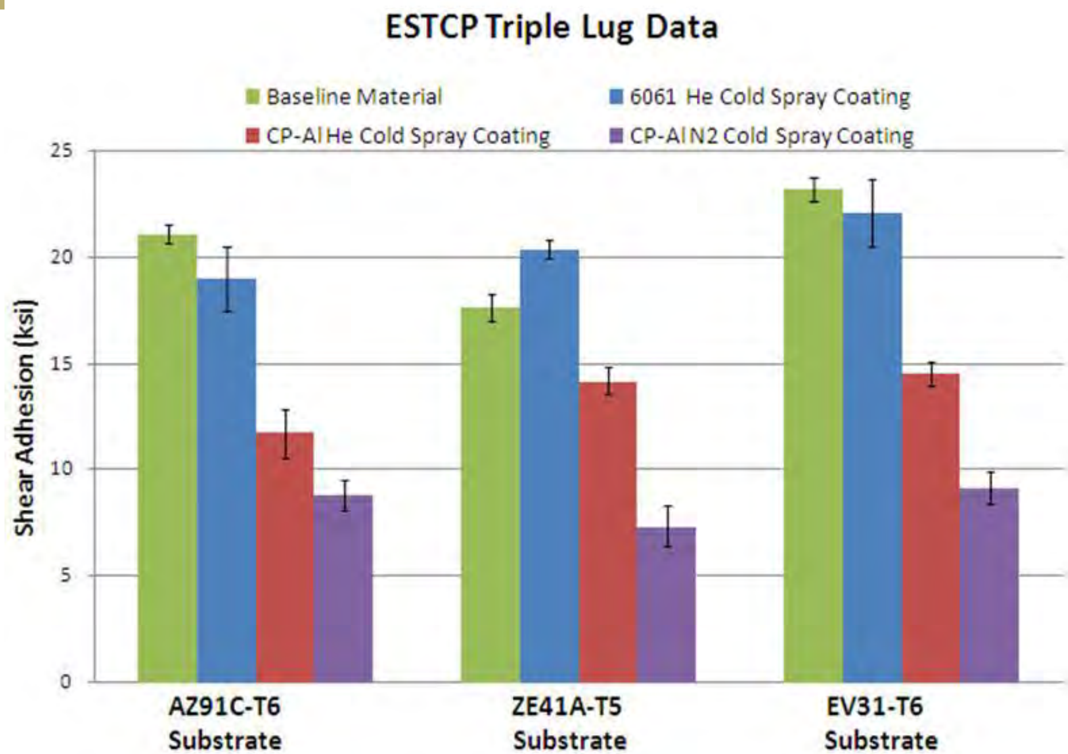
T6, T651- Solution heat-treated and then artificially aged, Temper -T651 applies to products stress-relieved by stretching.[2]

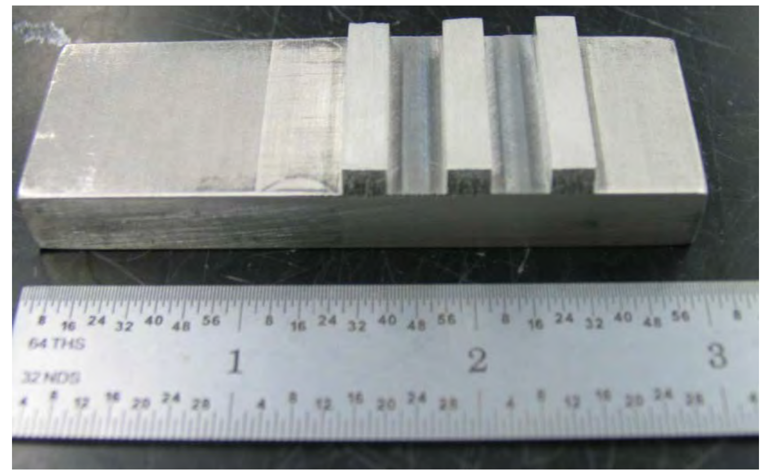
[1]Matweb

[2]Alcoa.com

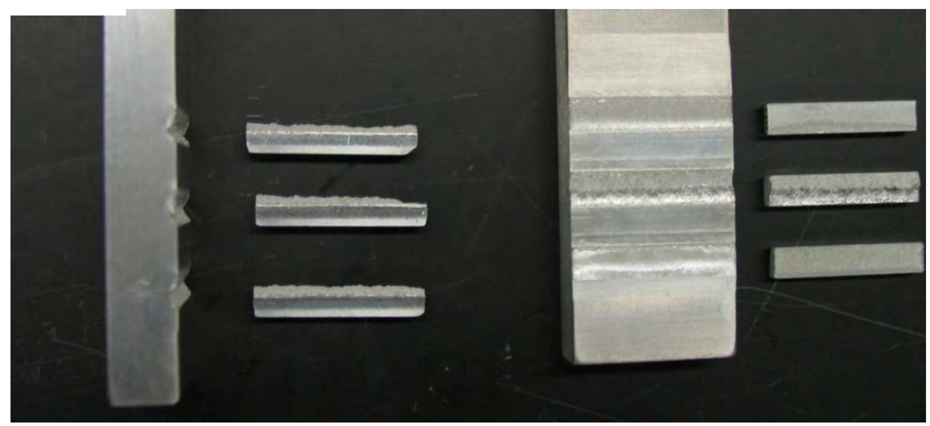
[3]Microtensile Test by Aaron Nardi at UTRC of ARL Cold Spray Block

Triple Lug Shear Test





- Test Description: Thick coating is deposited and machined into three lugs (3/16” x 1”) and then tested in compression
- 7 out of 12 6061 on ZE41A-T5 samples failed within the Mg



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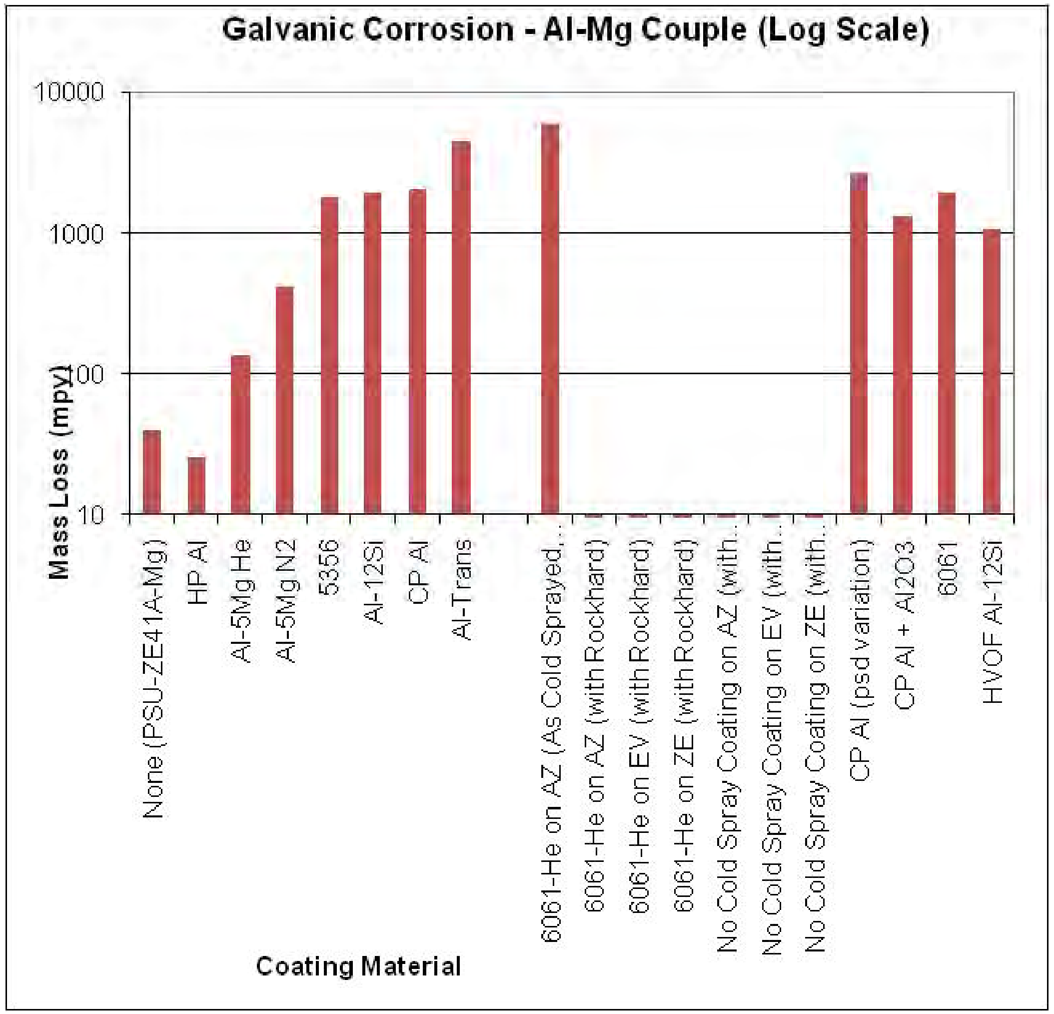
Corrosion Tests

- Un-scribed ASTM B117
  - CP-Al went 7000 hours
  - 6061 went 7000 hours
- Scribed ASTM B117
  - 1000 hours through top coat and 24 hours through to substrate. On par with HVOF Al-12Si
- GM9540 Scribed- Passed
- Galvanic Corrosion (G71)
- Crevice Corrosion (G78)- No Crevice mechanism
- Beach Corrosion- Passed



*vs uncoated ZE41

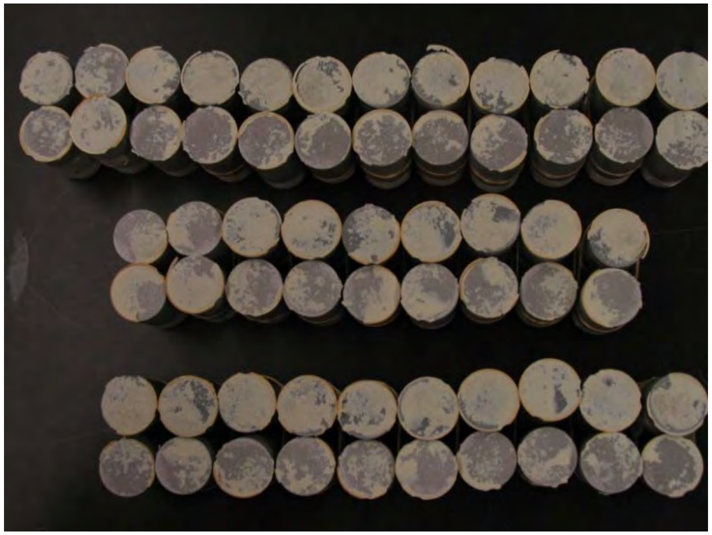
Bond Bar Adhesion (ASTM C633)

Substrate	Coating System	Averge Thickness (in)	Average Max Tensile Stress (PSI)	Stdev. Tensile Stress (PSI)	95% Confidence Tensile (PSI)	Observed Failure Mechanism
ZE41A-T5	6061 He	0.0134	11052	808	560	100% Glue
	CP-Al He	0.0197	12069	597	370	100% Coating Adhesion
	CP-Al N_2	0.0228	10400	846	677	100% Coating Adhesion

ZE41A-T5

AZ91C-T6

EV31-T6



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. (Standard Operating Procedures and Safety Standards)
- DEMVAL successfully completed at FRE-East, June 2011

2008 Defense Standardization Program Achievement Award

- **Presented to members of the Cold Spray Team for the development of a military process specification, "MIL-STD-3021, titled Materials Deposition, Cold Spray" (2008)**

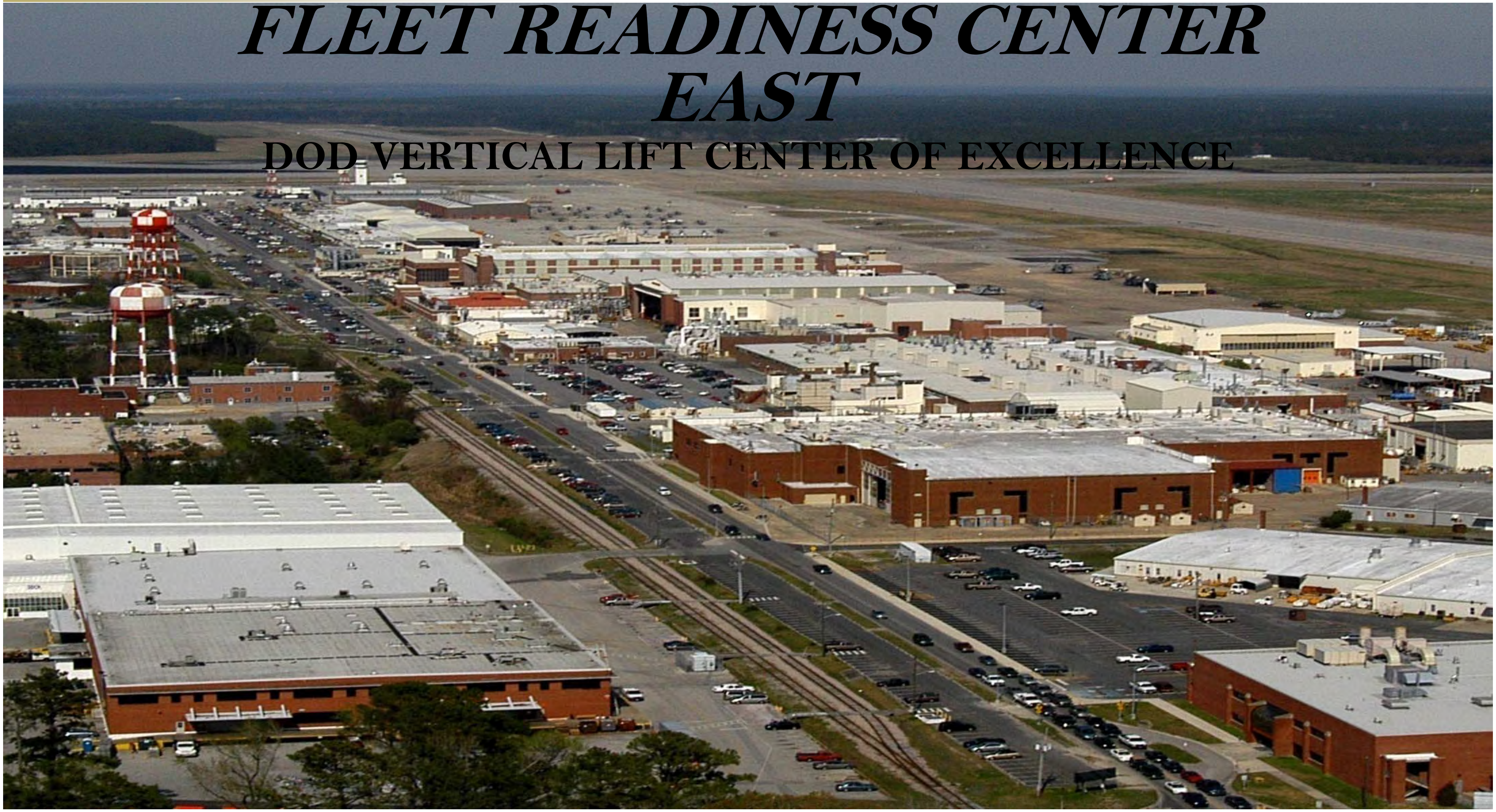
Sikorsky is proceeding with the sump repair for the H-60 platform

- **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

- **Maintenance Engineering Order (MEO)T-7631 (2012)**

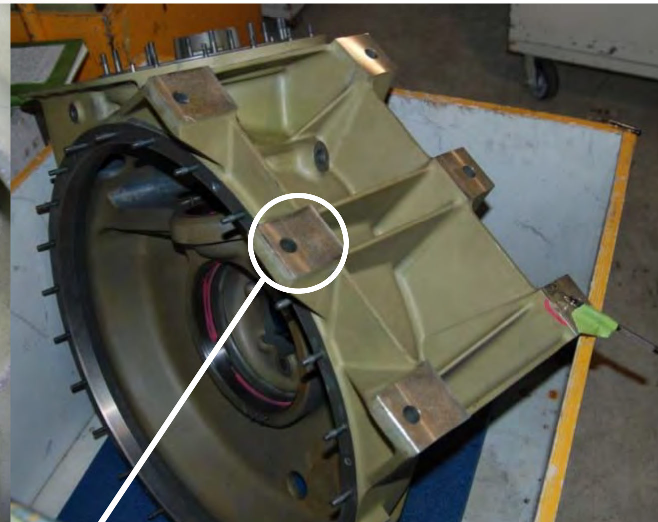
Transition Plan:

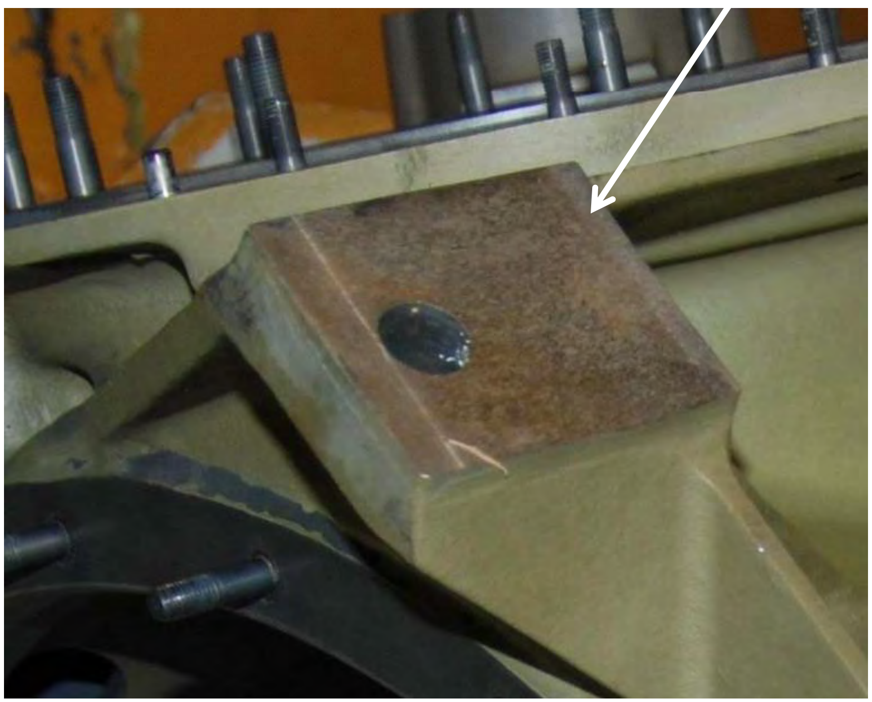


IN SERVICE SUPPORT CENTER

POC: Carl Sauer
Materials Engineer

Transition Plan at FRC- East





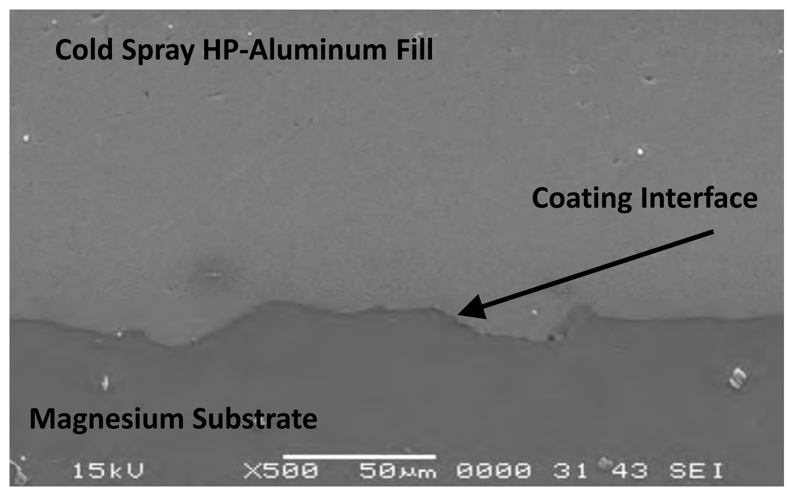
Shim Replacement

Cold Spray will replace glued shims on bottom of mounting feet.

Examples of Corrosion Damage on Fielded Parts and Subsequent to Cold Spray Repair

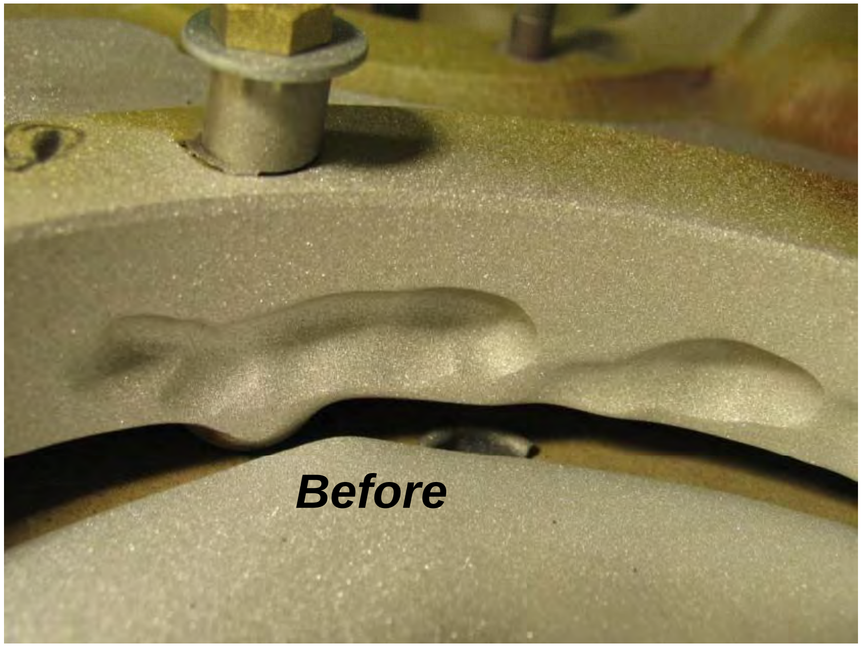
UH-60 Main Rotor Transmission

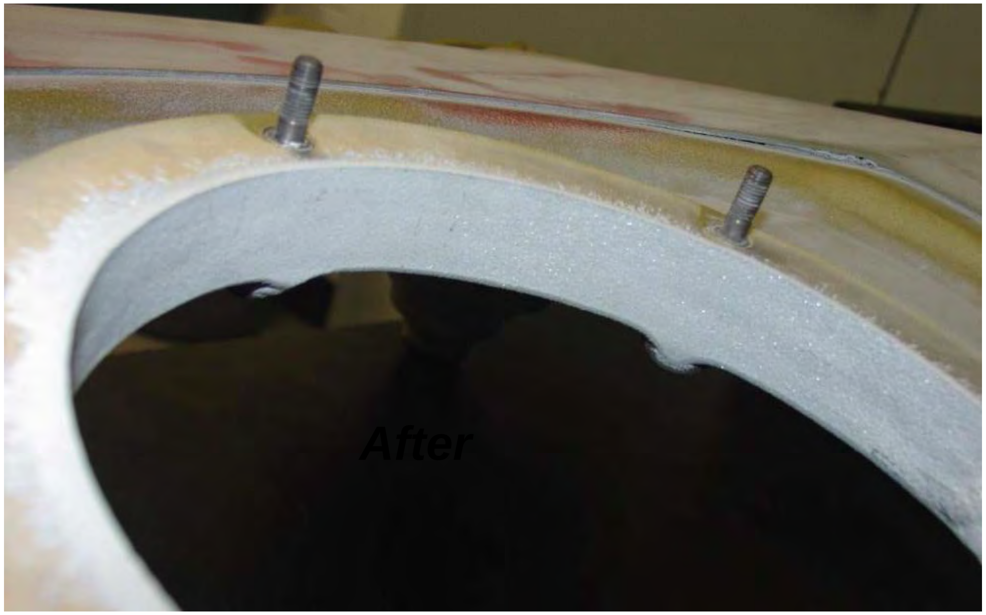
Cross-section of a Cold Spray Repair



UH-60 Magnesium Repair by Cold Spray

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





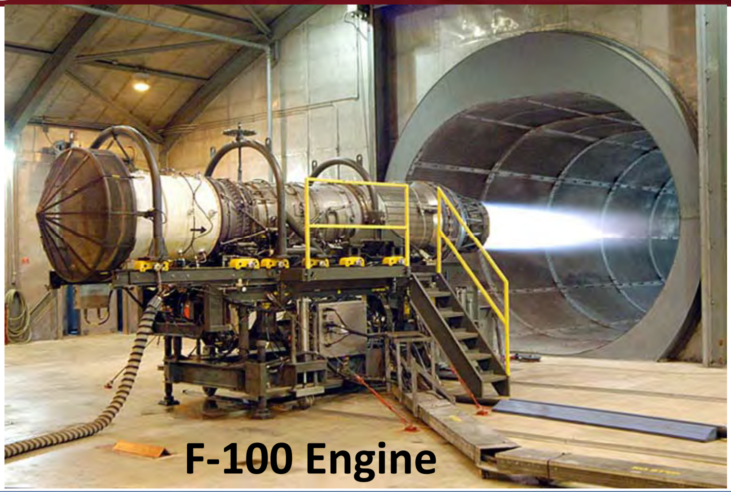
COLD SPRAY at Tinker Air Force Base
Candidate Engine Parts

Candidate Parts

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

Materials

Ti6Al-4V
Inconel
Waspalloy
Aluminum



F-100 Engine

Problems

Cavitation
Wear
Corrosion

F-15 Eagle

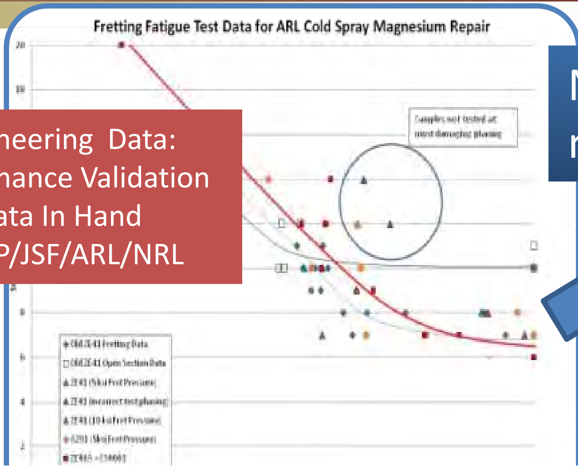
Where do we go from here?

Approved for Public Release; Distribution Unlimited

From Prototype to Production

Need to integrate laboratory, coupon and prototype data to make the technology a successful production method

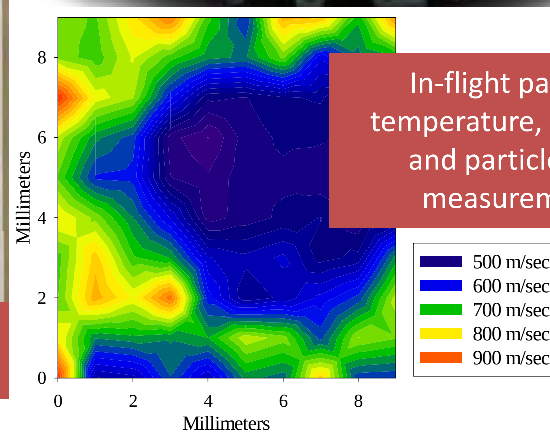
Engineering Data: Performance Validation Data In Hand ESTCP/JSF/ARL/NRL



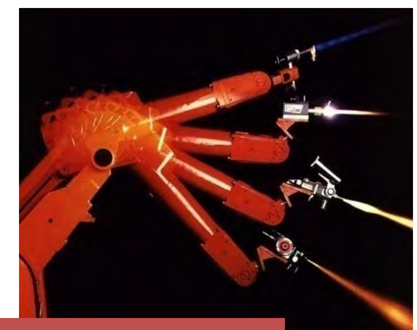
Integrate CAD/CAM to Produce Complex Geometries, Minimize Machining and Eliminate Material Waste

Real-Time Process Mapping

Production Engineering: Couple with Thermal Spray Production Facility at BASF



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

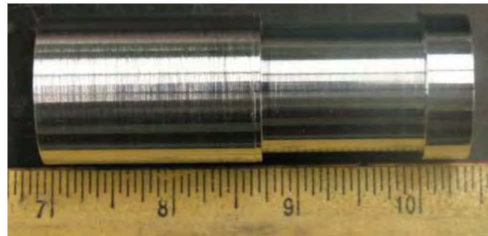


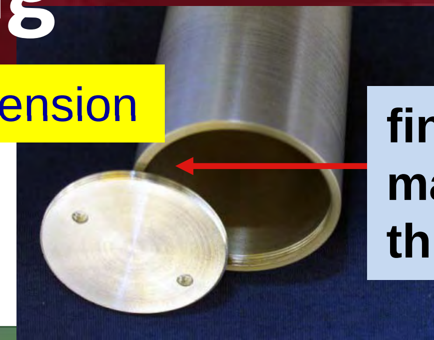
Robotic Control for Precision and Repeatability

Near Net Forming

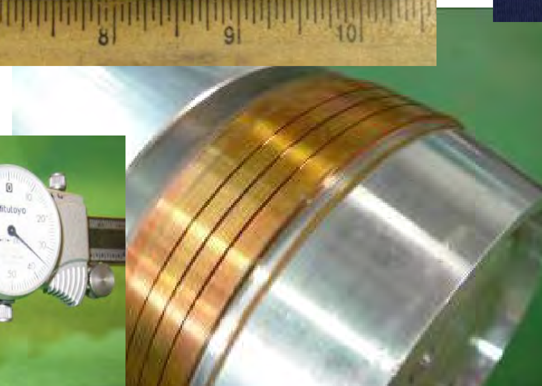
Current state of the art: parts require machining to final dimension

- 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.





fine machined threads



CAD\CAM

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