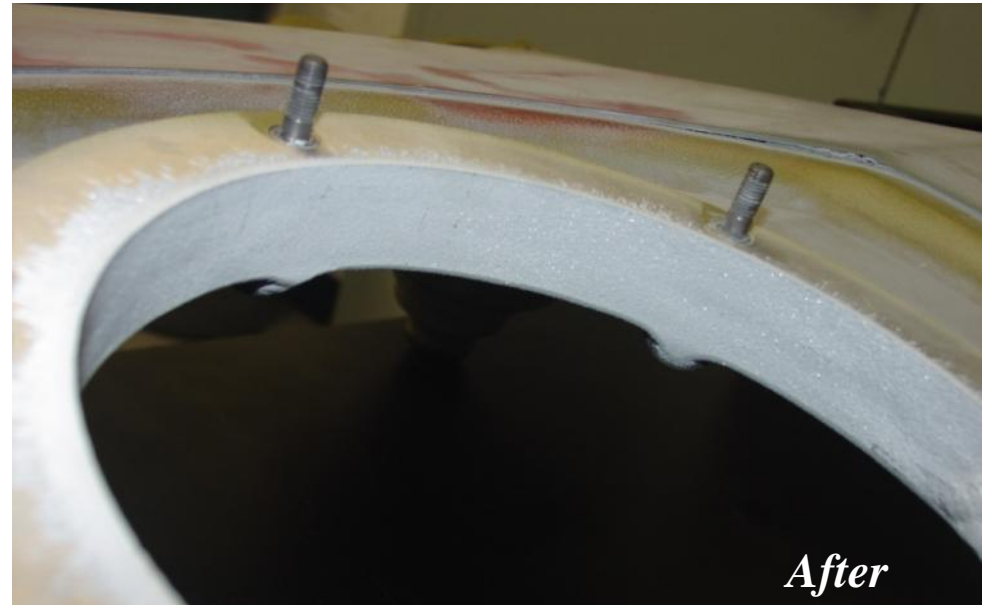
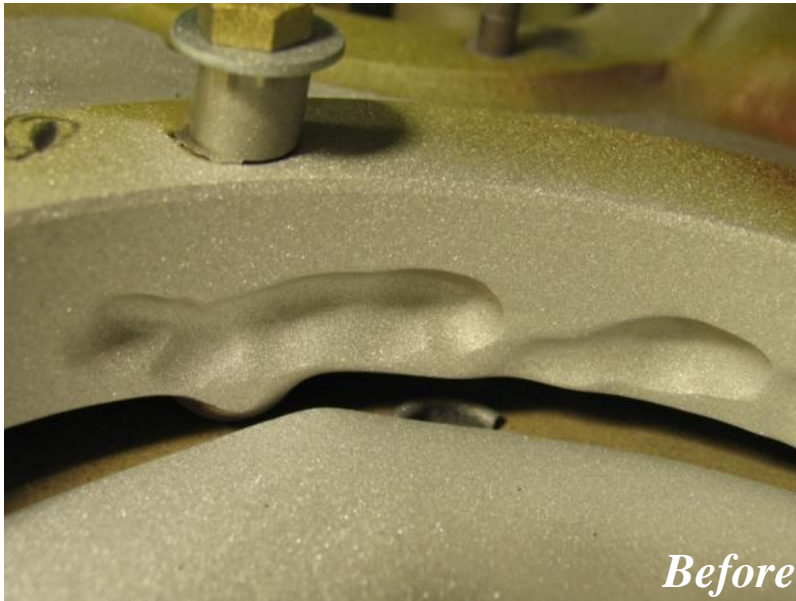


Cold Spray for Repair of Magnesium Gearboxes



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Dennis Helfritch

ARL Center for Cold Spray

8 February 2011

Report Documentation Page

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Demonstrate and qualify cold spray aluminum alloy coatings which provide surface protection and a repair/rebuild methodology for Mg alloy components on Army and Navy helicopters and advanced fixed-wing aircraft such as the Joint Strike Fighter

1. Cost-effective

2. ESOH-acceptable technology



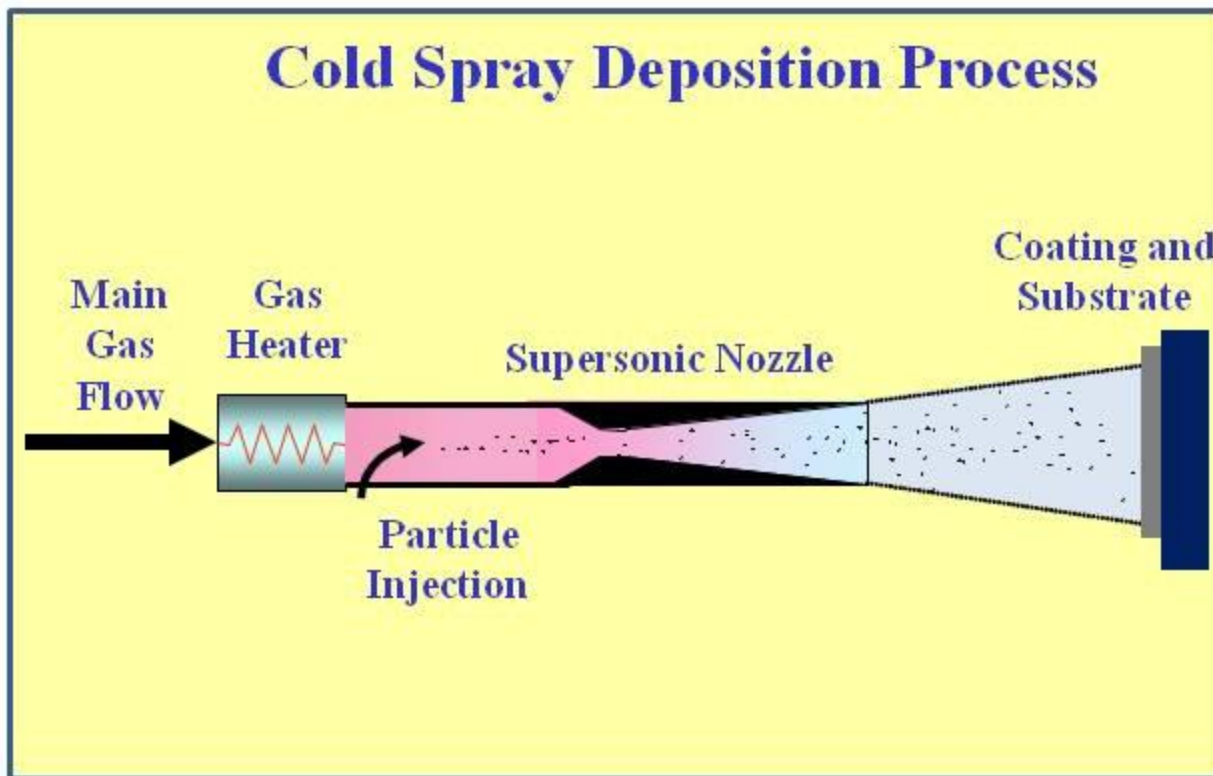
MOUNTING FEET



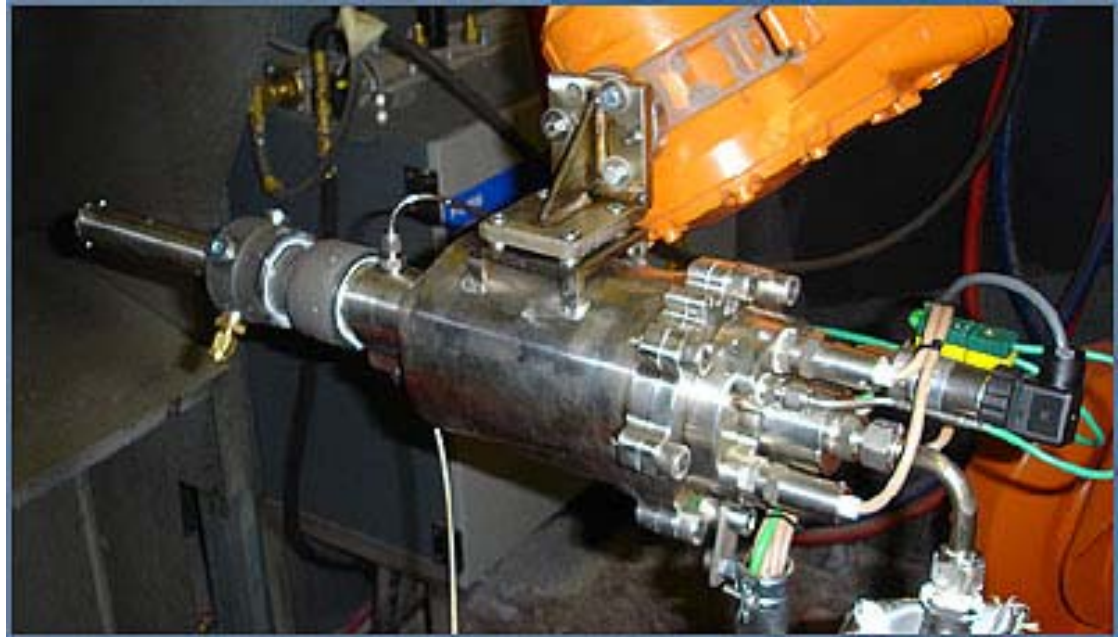
MAIN GEARBOX

Cold Spray Process

Unique solid-state deposition process which utilizes high velocity particles impinging upon a substrate to build up material



- **Feed stock typically ranges from 1 to 50 μm**
- **Particle ductility is crucial**
- **Gas temperature range from R.T. to 800°C**
- **No melting of particles**
- **Negligible oxidation**
- **No decomposition or phase changes of deposited particles or substrate**



Joint Test Protocol

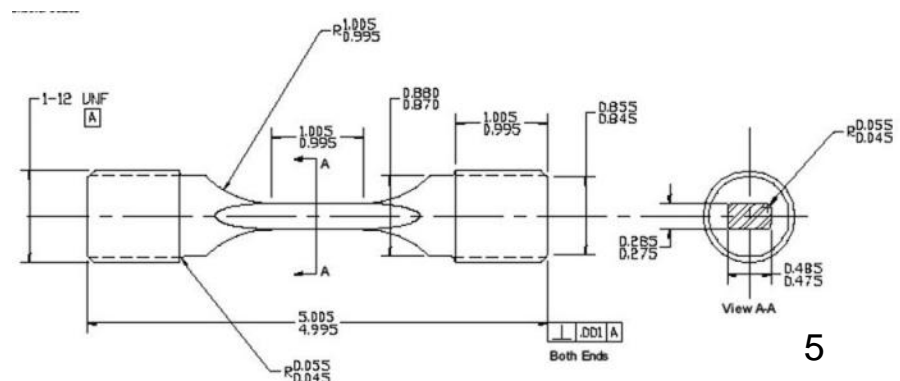
Mechanical Tests

- Adhesion Tensile Bond Test (ASTM C633)
- XRD Residual Stress
- R.R. Moore RB Fatigue
 - surface finished 125 R_A
- Fretting Fatigue – UTRC
- Impact - ASTM D5420
- Hardness
- Porosity
- Triple Lug Shear

Corrosion Tests

- *Un-scribed ASTM B117*
- *Scribed ASTM B117*
- *GM9540 Scribed*
- *Galvanic Corrosion (G71)*
- *Crevice Corrosion (G78)*
- *Beach Corrosion*
- *G85 Annex 4-SO₂*

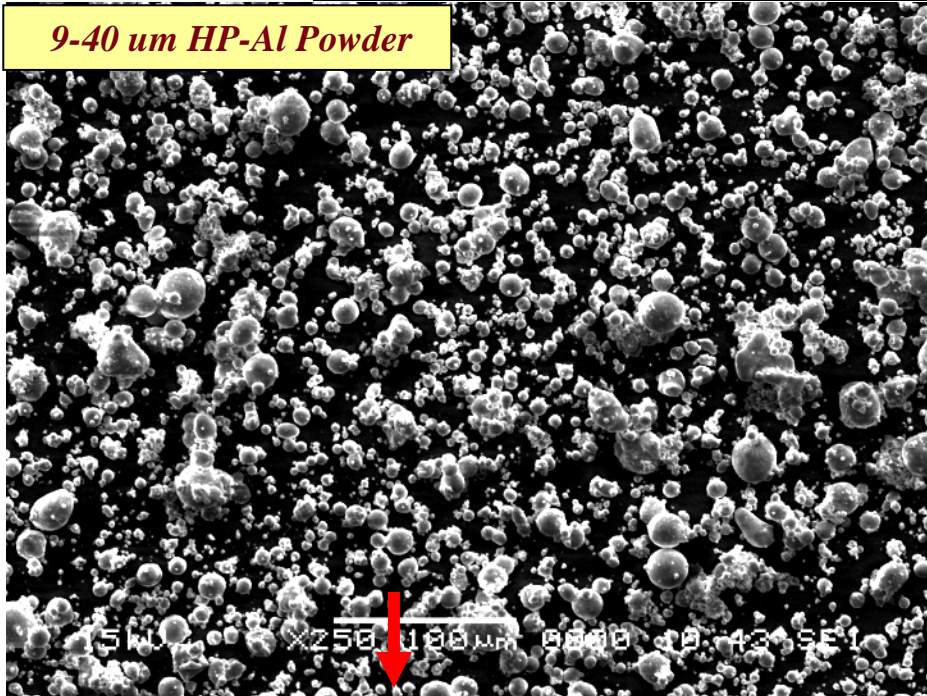
Stack Up: RockHard, 23377, and 85285



UTRC Fretting Fatigue Specimen

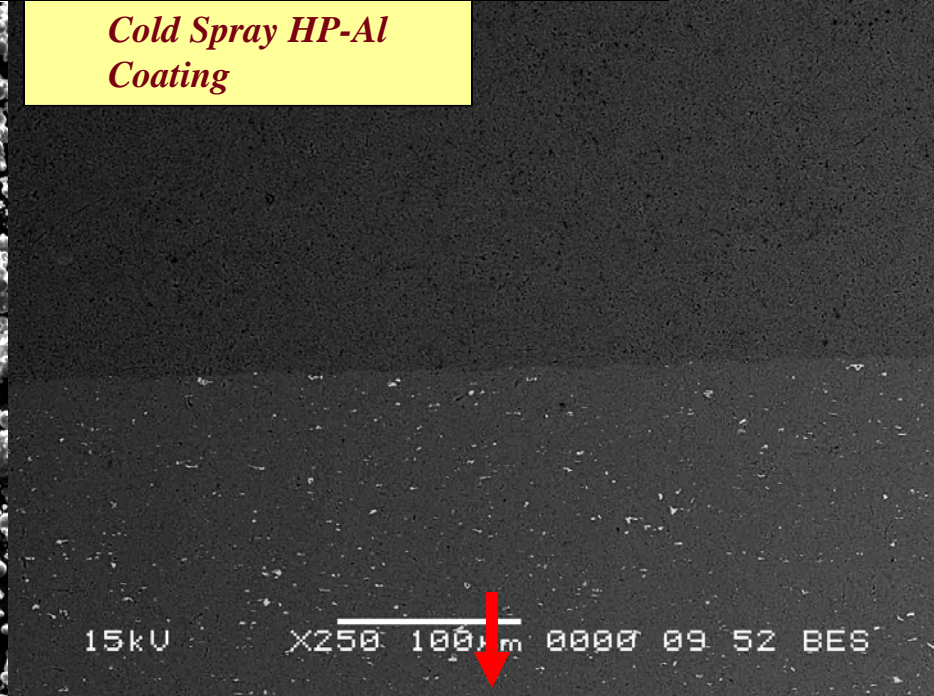
Oxygen content measured by Inert Gas Fusion ASTM E 1019-03

9-40 um HP-Al Powder



0.88 %Oxygen

Cold Spray HP-Al
Coating



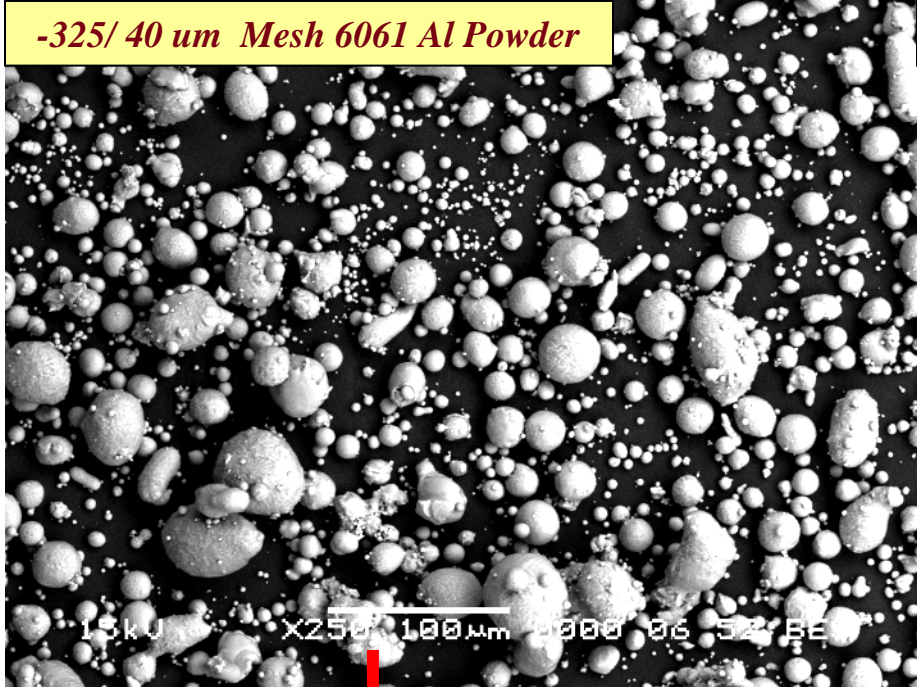
0.58 %Oxygen

CGT system

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

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

-325/ 40 um Mesh 6061 Al Powder



Cold Spray 6061 Al Coating



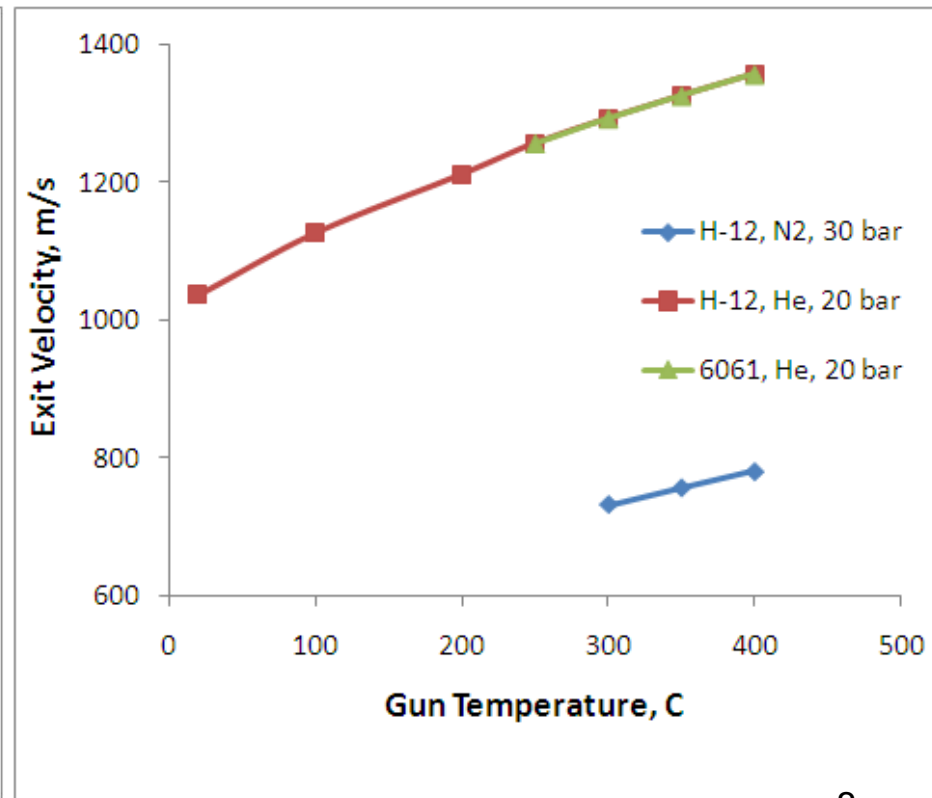
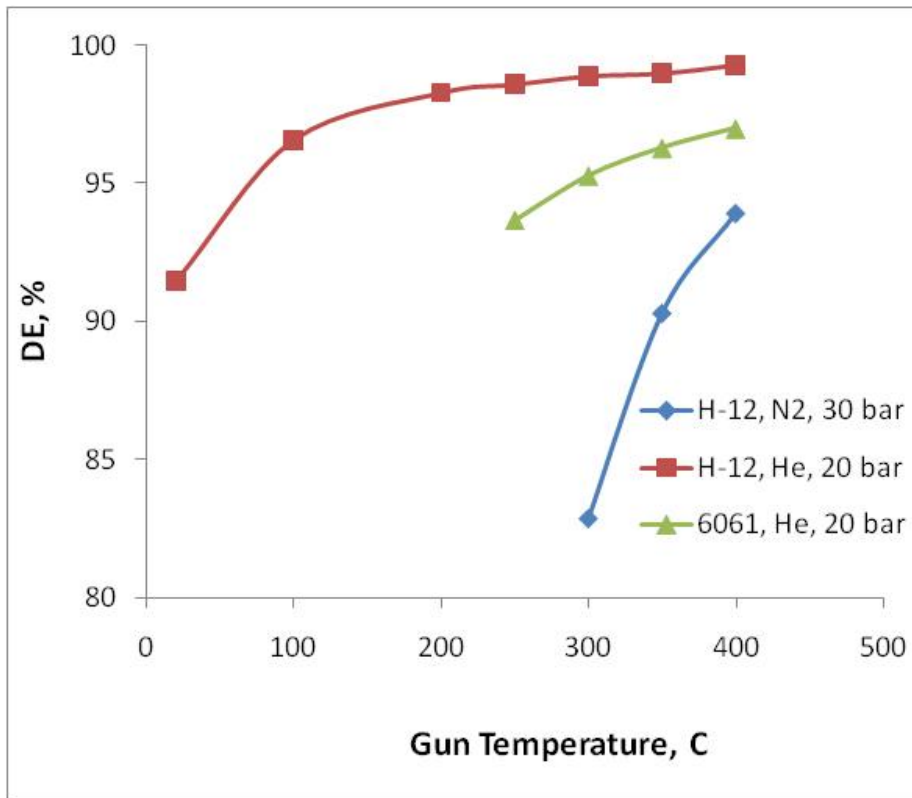
0.22 %Oxygen

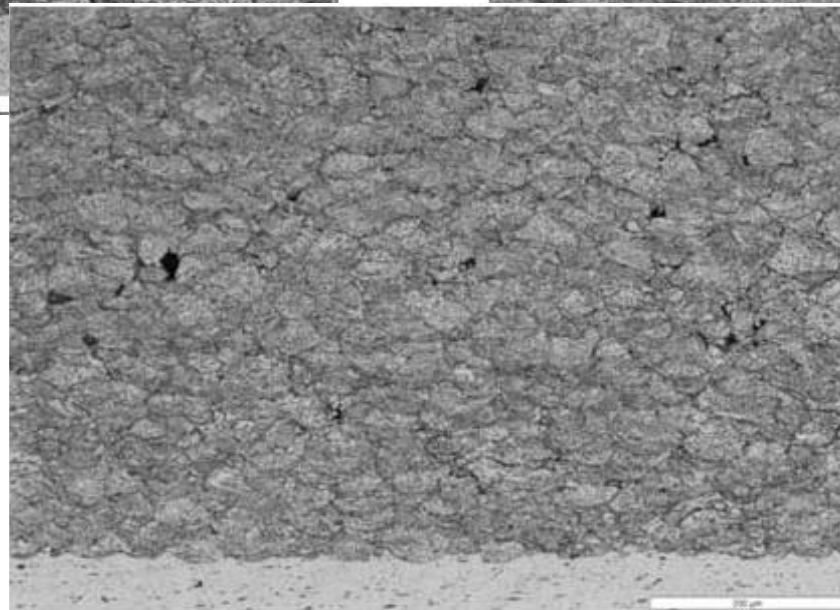
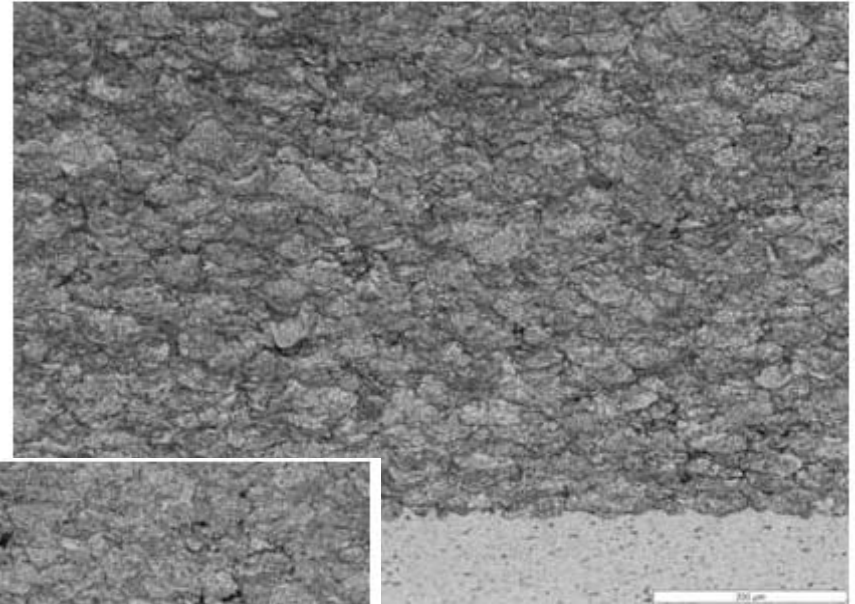
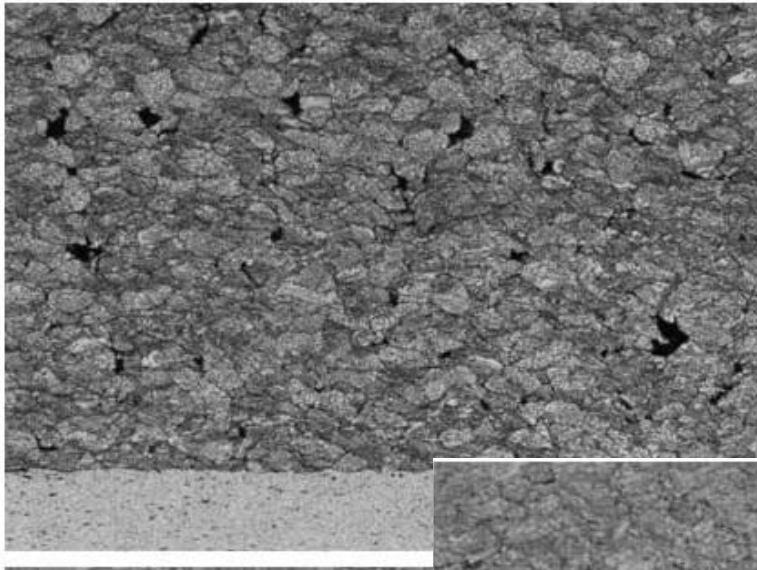
CGT system

0.207 %Oxygen

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

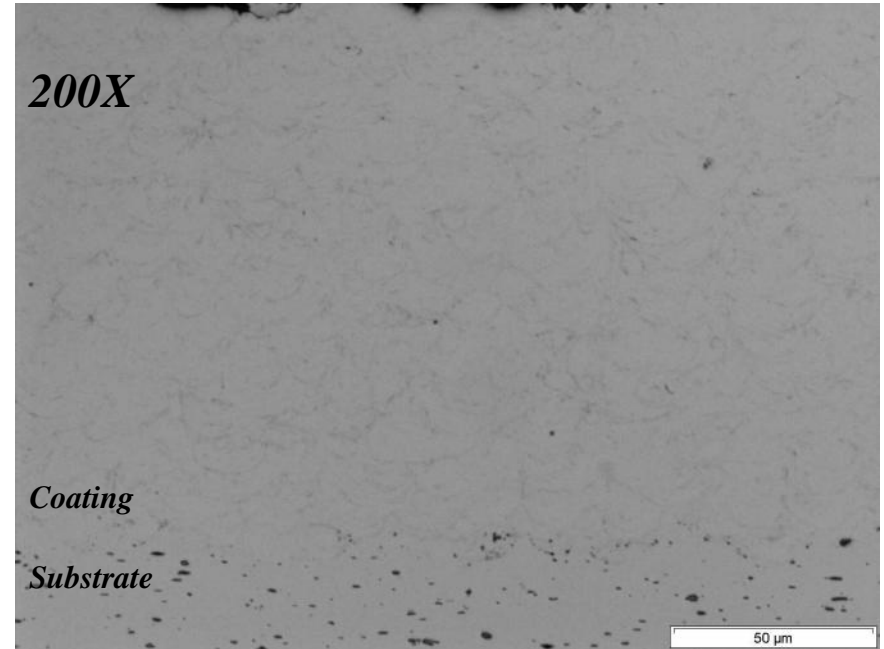
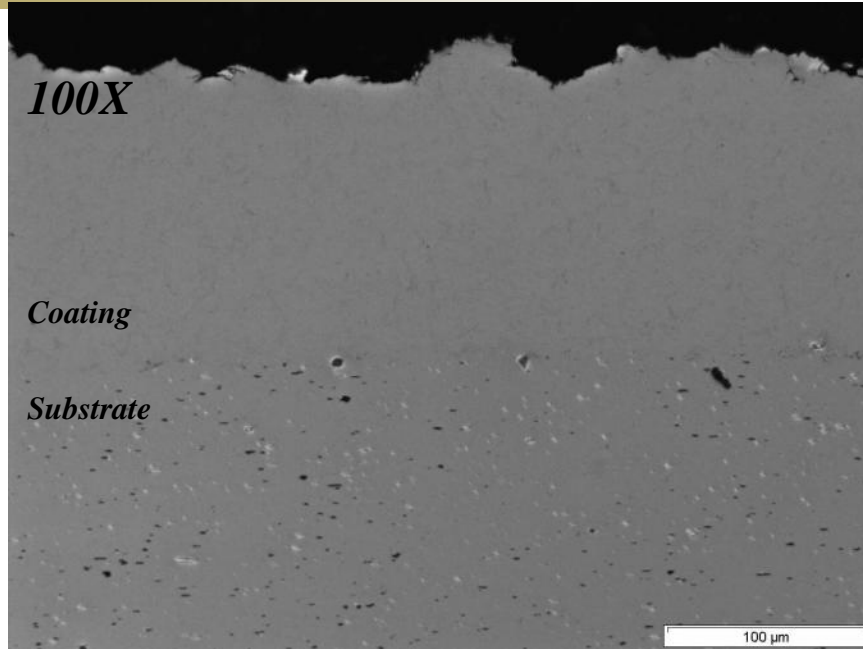
Modeled deposition efficiencies appear to be close to experimental values while the calculated velocities are well above the critical velocities for Al (~500 m/s)





*Microstructures
of 6061 Cold
Spray
Optical
Microscopy*

Increasing Gas Pressure 



| Alloy | Condition | Aging Temp (°F) | Time (Hrs) | Solutionizing Temp (°F) | Aging after Solutionizing Temp (°F) | Time (Hrs) |
|-------|-----------|-----------------|------------|-------------------------|-------------------------------------|------------|
| AZ91C | -T5 | 335 | 16 | --- | --- | --- |
| AZ91C | -T6 | --- | --- | 775 | 335 | 16 |
| | | | | | 420 | 5-6 |
| AZ92A | -T5 | 500 | --- | --- | --- | --- |
| AZ92A | -T6 | --- | --- | 765 | 425 | 5 |
| ZE41A | -T5 | 625 | 2 | --- | --- | --- |

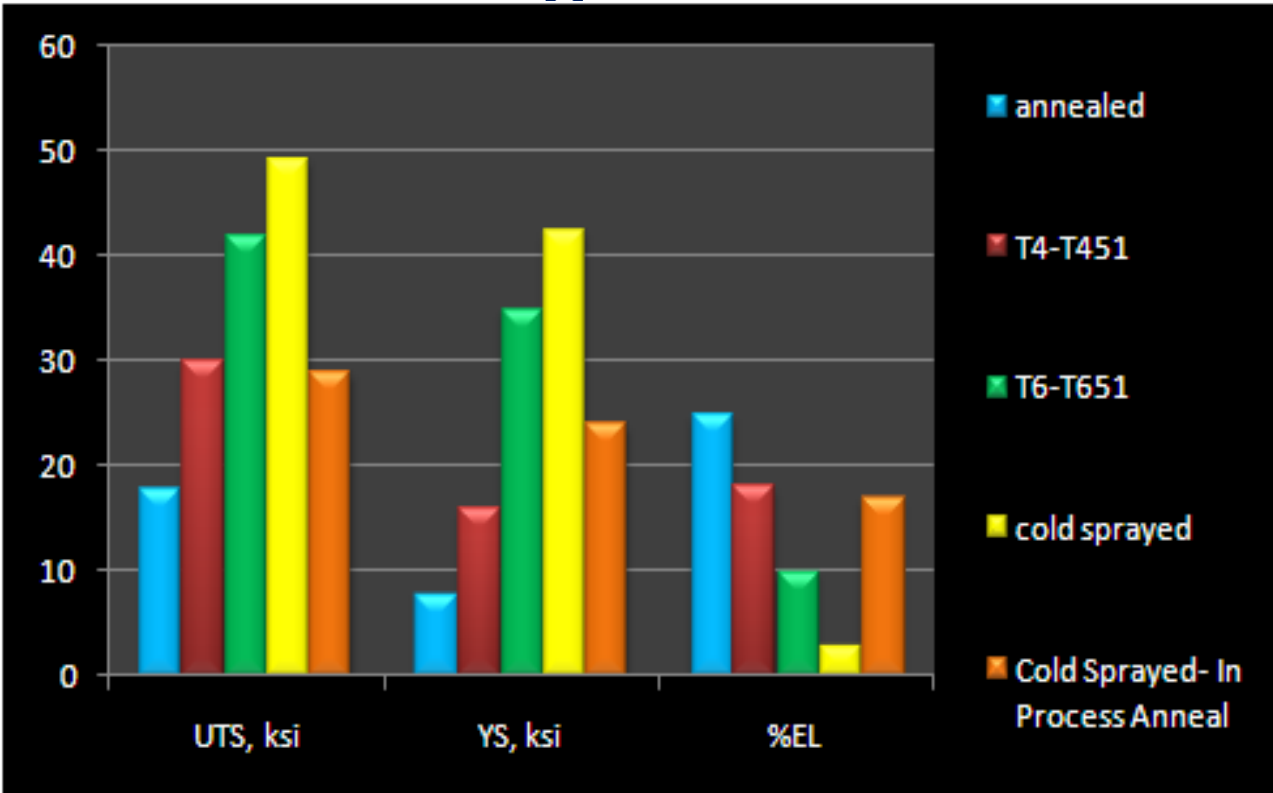
*ZE41A-T5 Substrate
Temperature
Recorded at
163.4° C (326.1° F)*

T5 means artificially aged

T6 means solution heat treated and artificially aged

M. M. Avedesian, Hugh Baker, "Magnesium and magnesium alloys", Edition: 2 - 1999, ASM International, pgs 78-79.

Wrought versus Cold Spray 6061



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

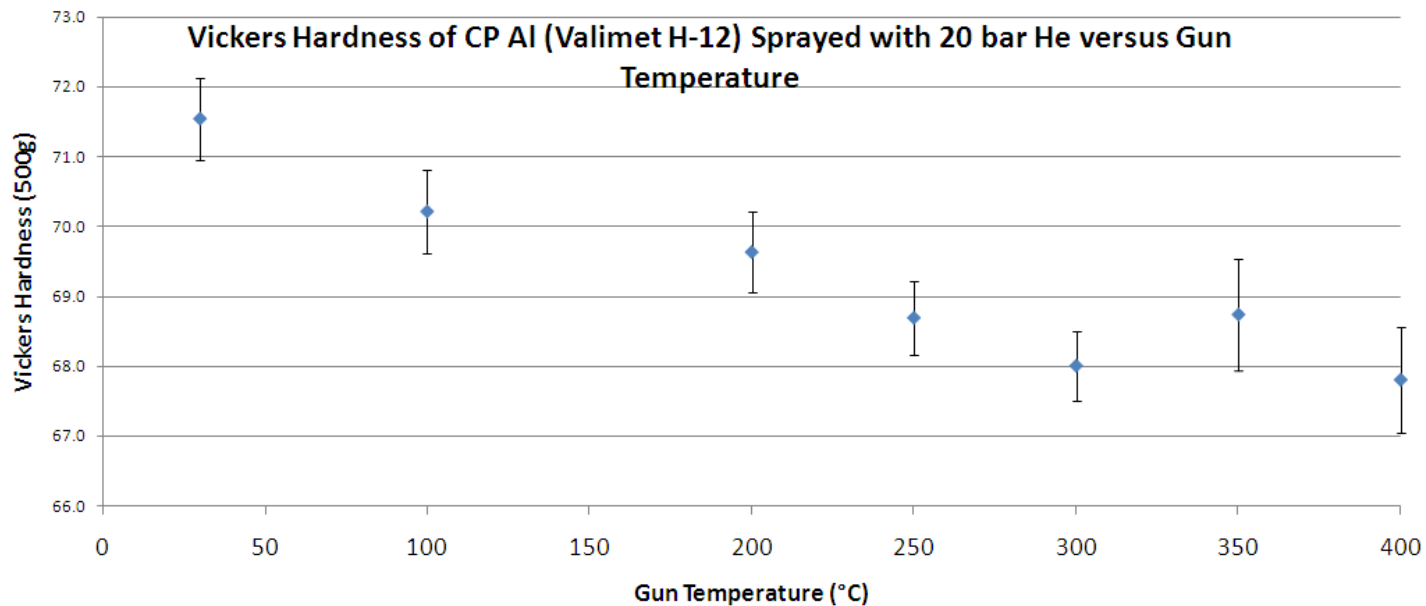
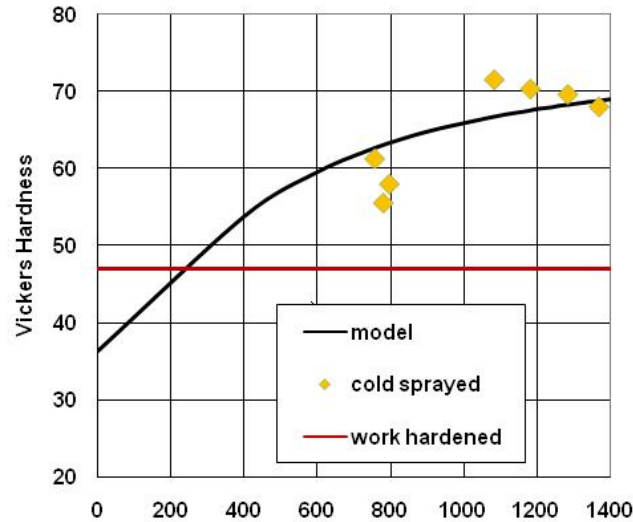
In Process Anneal- 640°F for 10 to 12 Hours

| 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 (CS) | 3 | 49.3 | 42.5 | 3 |
| CS- In process anneal | 3 | 29.0 | 24.0 | 17 |

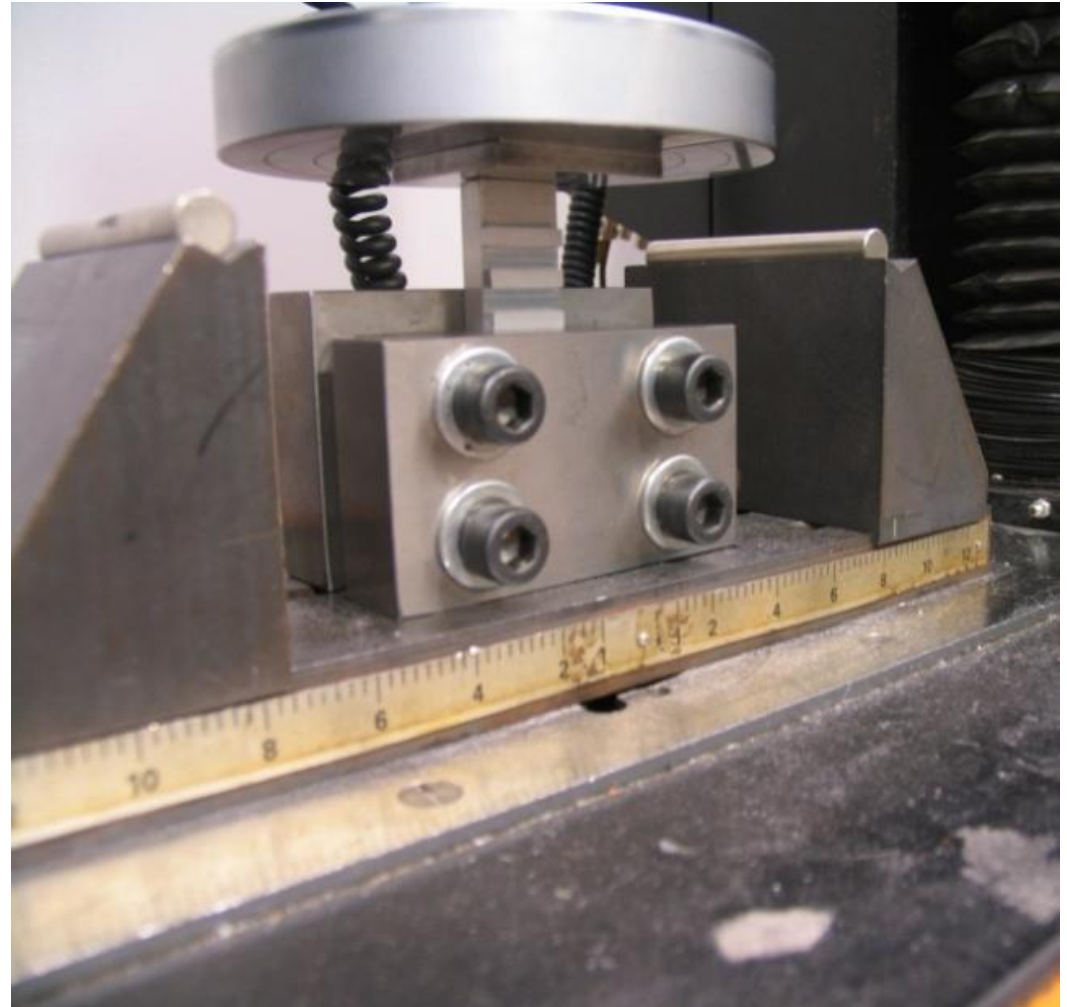
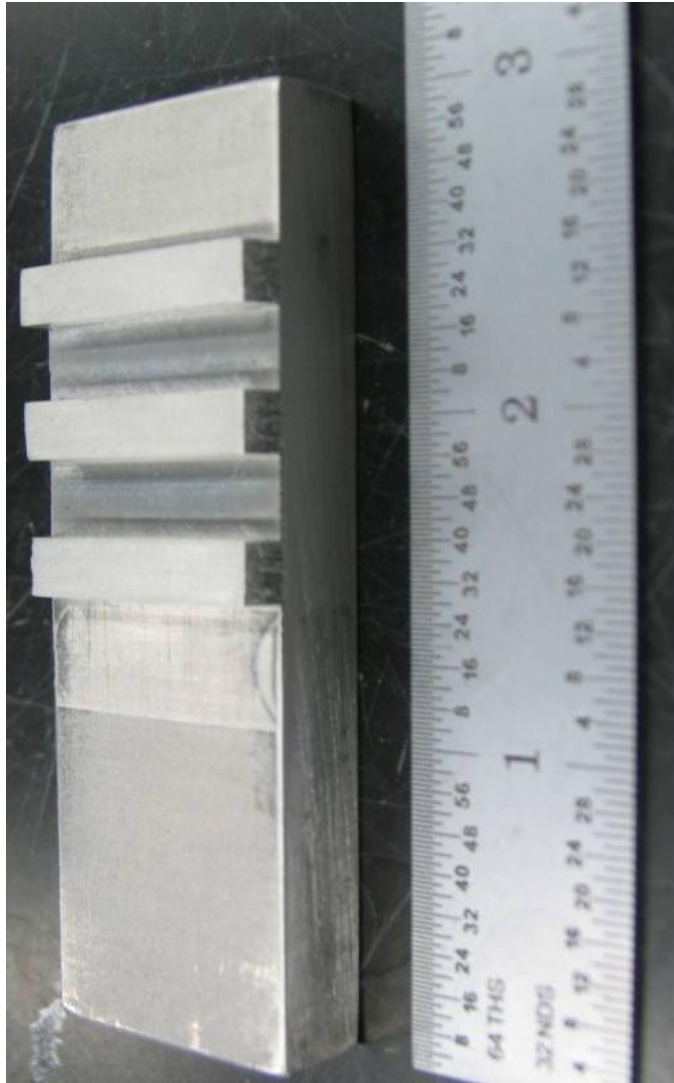
¹Matweb

²Alcoa.com

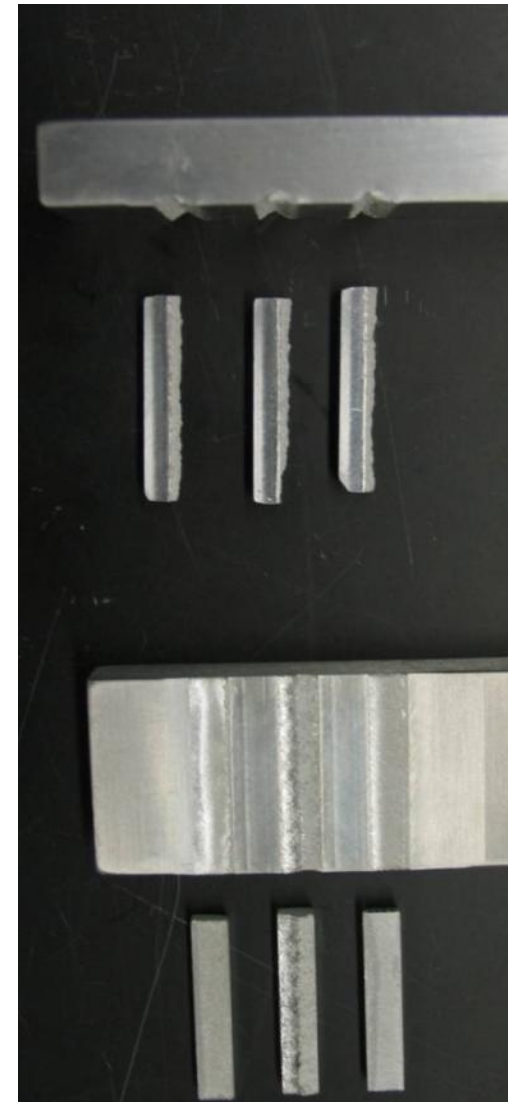
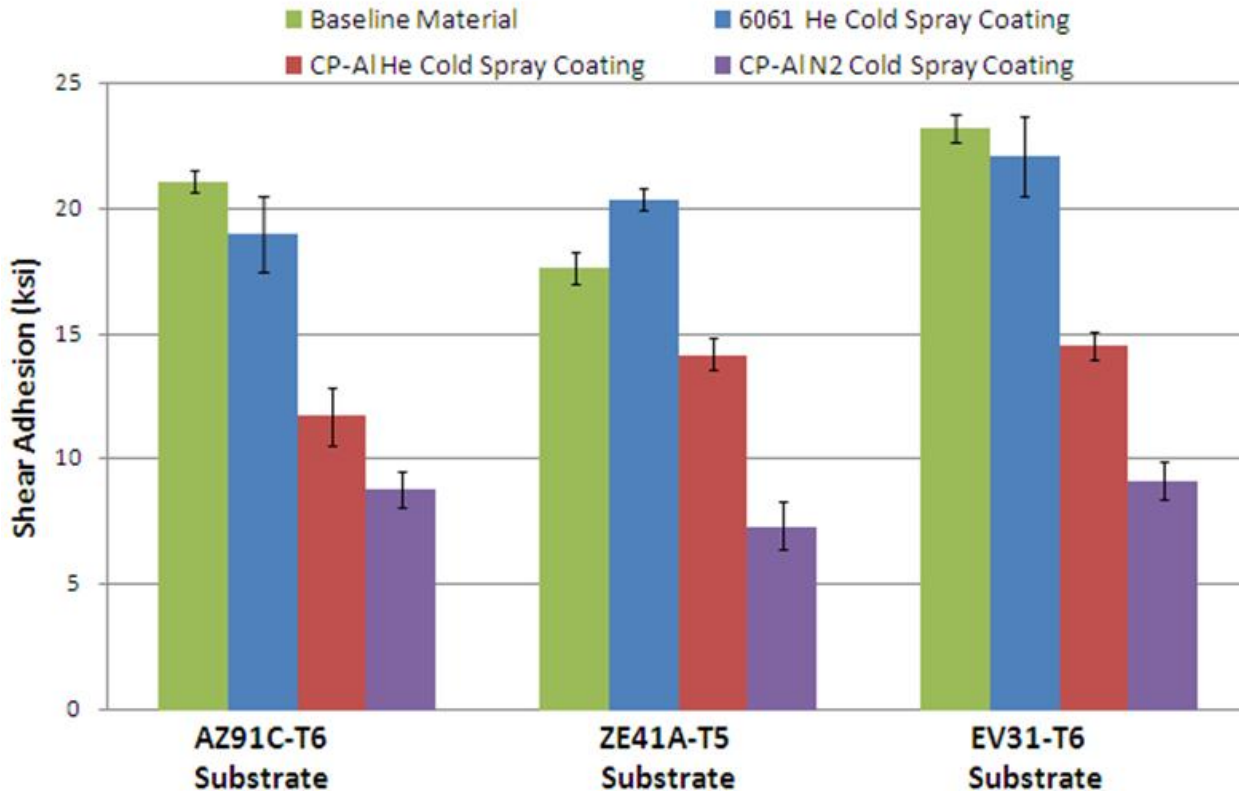
³Microtensile Test by Aaron Nardi at UTRC of ARL Cold Spray Block



Triple Lug Shear Test



ESTCP Triple Lug Data



6061/ZE41A-T6¹⁴

- 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

Bond Bar Adhesion (ASTM C633)



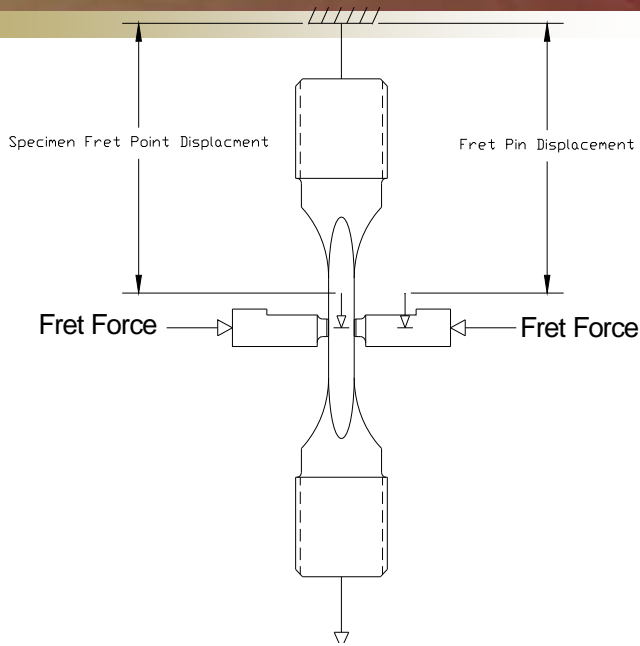
| Substrate | Coating System | Average Thickness (in) | Average Max Tensile Stress (PSI) | Stdev. Tensile Stress (PSI) | 95% Confidence Tensile (PSI) | Observed Failure Mechanism |
|-----------|----------------------|------------------------|----------------------------------|-----------------------------|------------------------------|----------------------------|
| 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



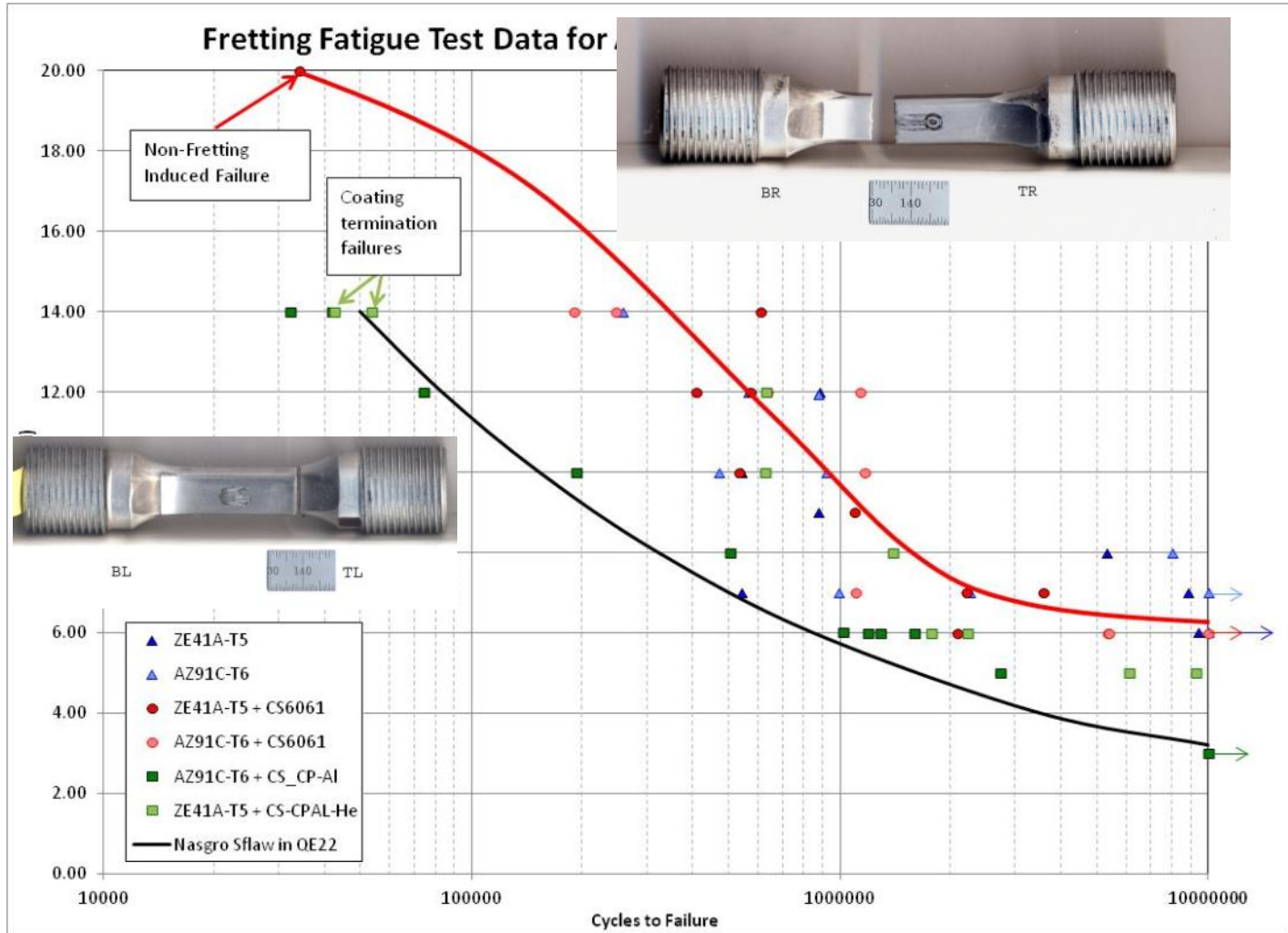


Fretting rig pressure = 848 psi
Projected area fretting stress = 5 ksi (34 Mpa)
Fretting pin load = 167 lb
Fretting slip amplitude = ± 0.001 inches (± 25 microns)
Range of max axial test loads = 443 – 2955 lbs
Range of max axial test stress = 3 – 20 ksi
Range of lives = 32,000 – 10 million (runout)
Phasing = in phase with fret slip increasing at max axial
Pin Type = 0.206 diameter 4340 steel with cadmium plating

ARL Fretting Fatigue Test Matrix

| Specimen Base Material | Counterface Pin Material | Coating | # of Specimens Tested | Specimens Remaining |
|------------------------|-------------------------------------|----------------------|-----------------------|---------------------|
| AZ91C-T6 | 4130, 30-35 HRC , Cadmium plated | None | 10 | 0 |
| | | 6061 using Helium | 9 | 0 |
| | | CP-Al using Nitrogen | 11 | 0 |
| ZE41A-T5 | | None | 11 | 0 |
| | | 6061 using Helium | 9 | 0 |
| | | CP-Al using Nitrogen | 9 | 0 |

Slide Courtesy of Aaron Nardi, United Technologies Research Center



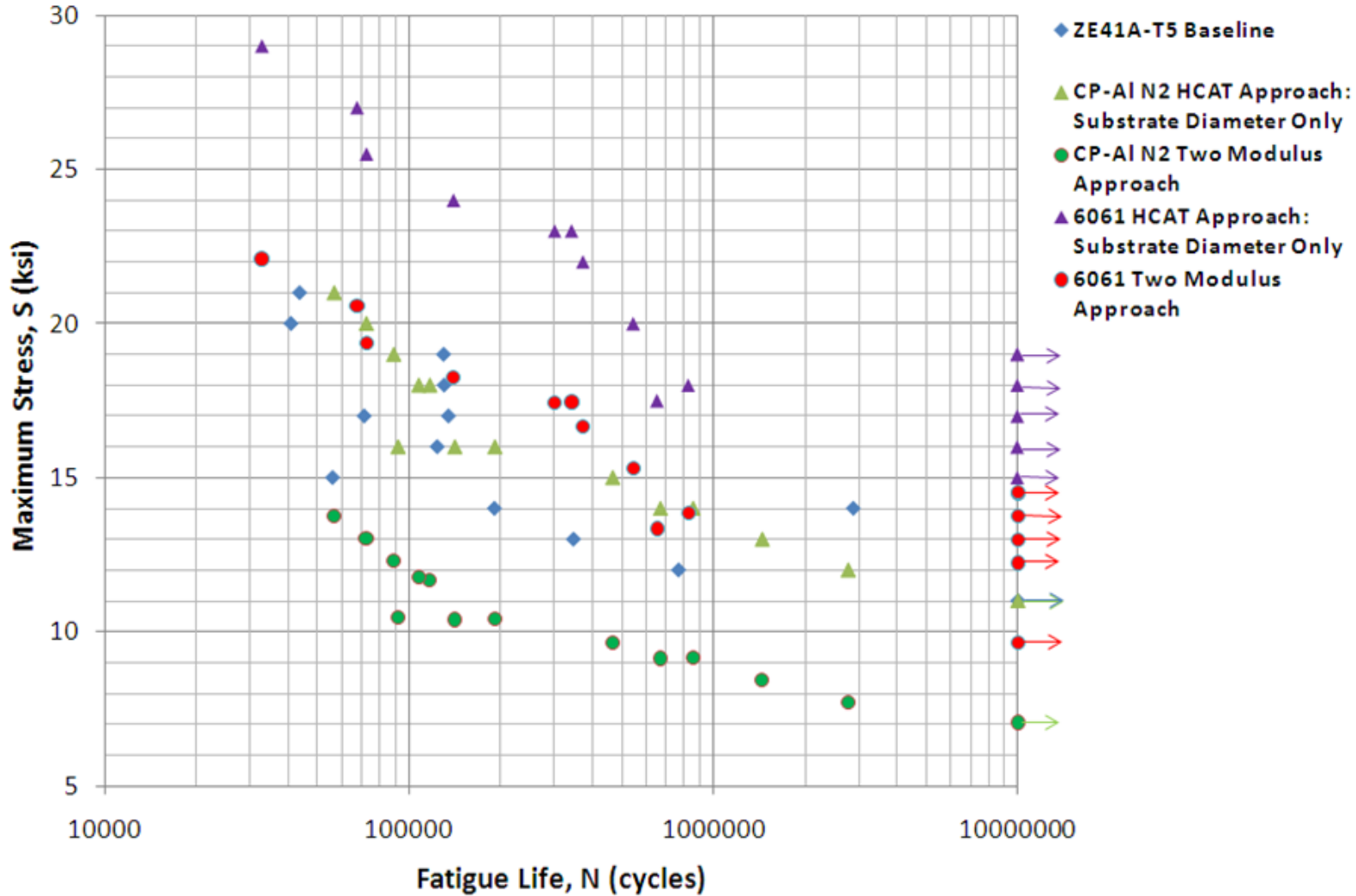
Slide Courtesy of Aaron Nardi, United Technologies Research Center

Test Results and Conclusions

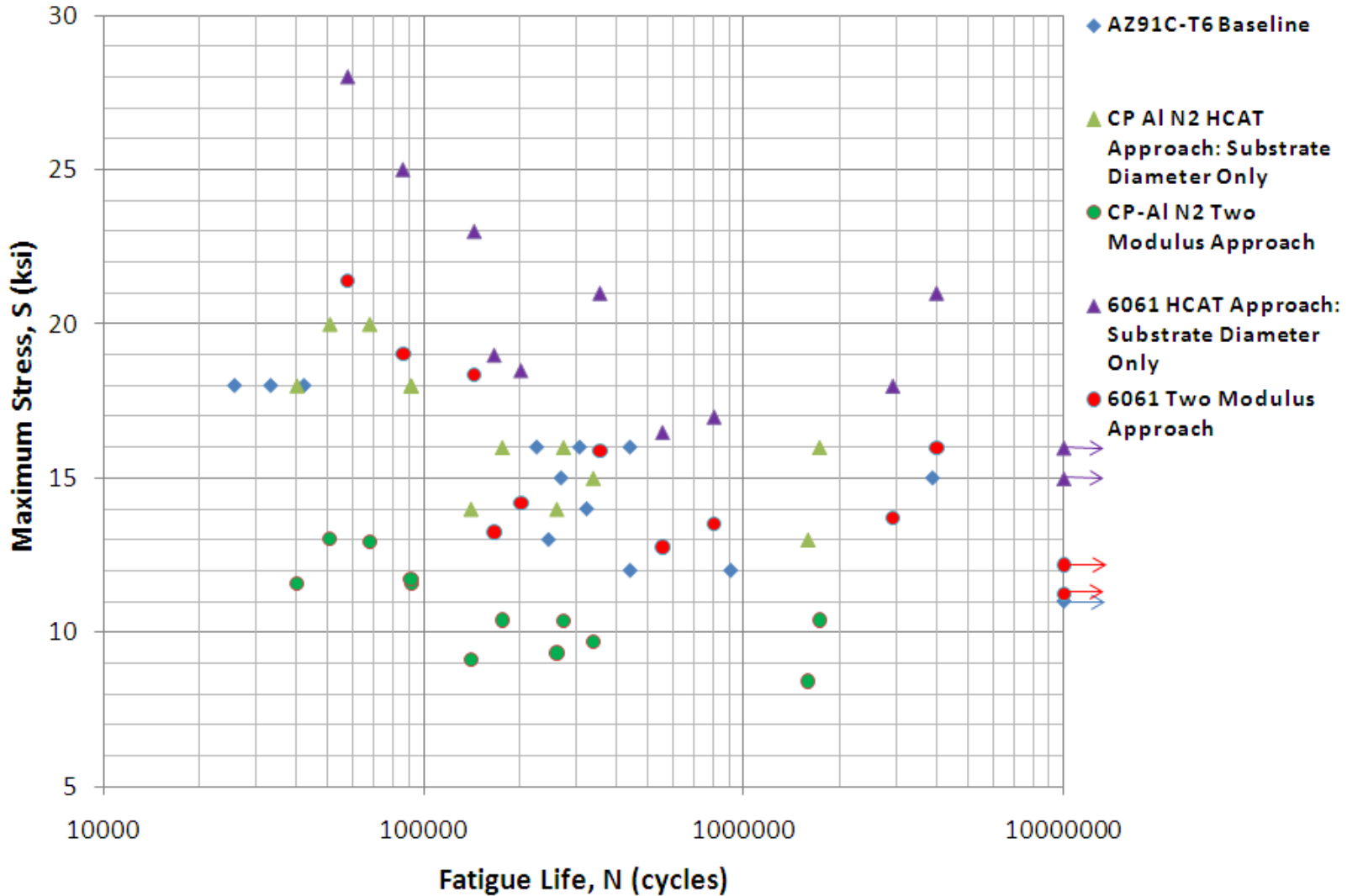
- AZ91C-T6 and ZE41A-T5 with no coating applied exhibited a 10 million cycle life of approximately 6.2 ksi
- Both Magnesium alloys with cold sprayed 6061 applied by helium exhibited a 10 million cycle life of approximately 5.3 ksi
- ZE41A-T5 with cold sprayed CP Aluminum applied using helium exhibited a 10 million cycle life of approximately 4.9 ksi
- AZ91C-T6 magnesium with cold sprayed CP aluminum using nitrogen exhibited a 10 million cycle life of approximately 3.3 ksi
- Fretting failures on baseline materials matched the expected fracture pattern
 - The cracking from top edge of fretting scar
 - Coating cracks propagated without changing direction at the interface suggesting a good bond and higher modulus

Slide Courtesy of Aaron Nardi, United Technologies Research Center

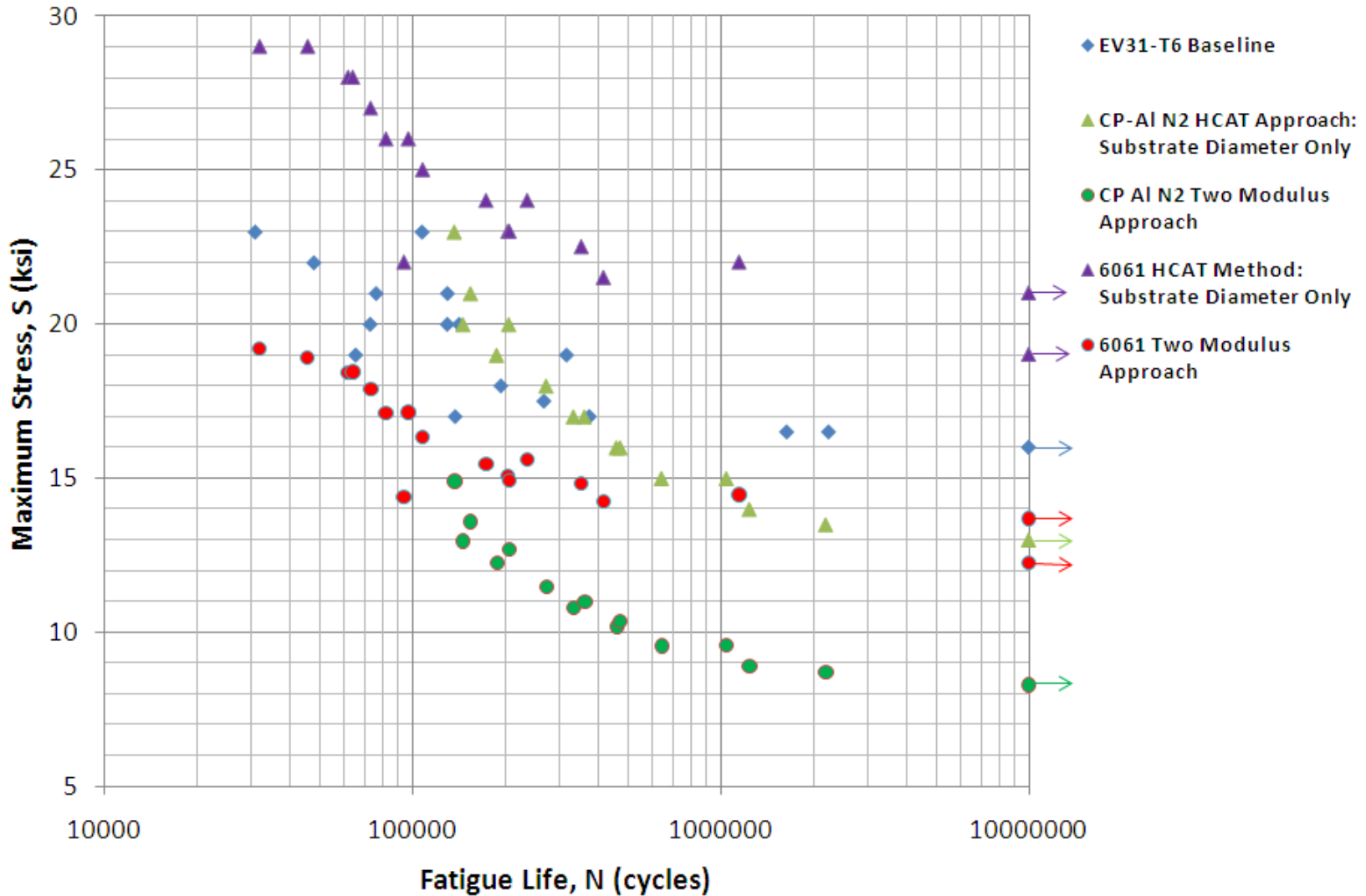
ESTCP RR Moore Data: 6061 and CP-Al N₂ on ZE41A-T5



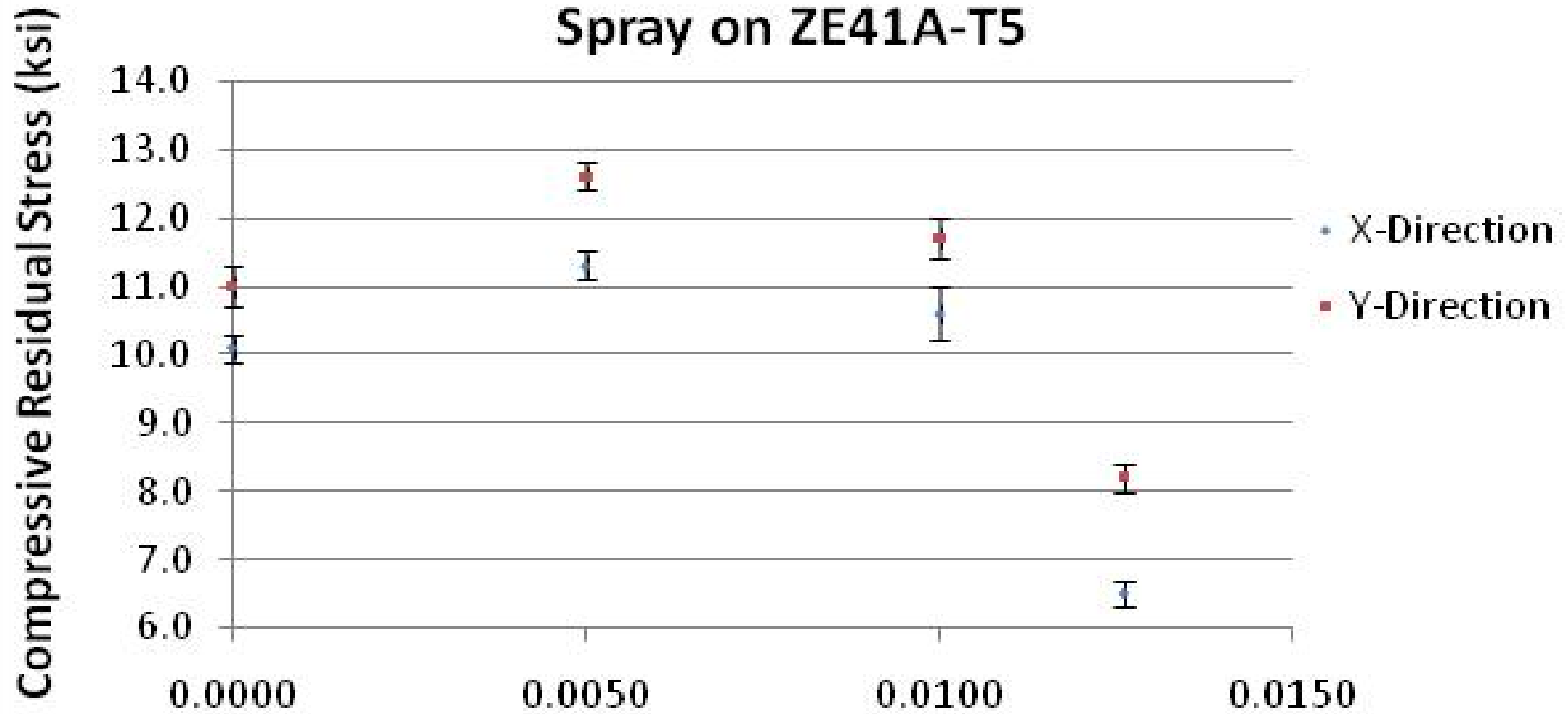
ESTCP RR Moore Data: 6061 and CP-Al N₂ on AZ91C-T6



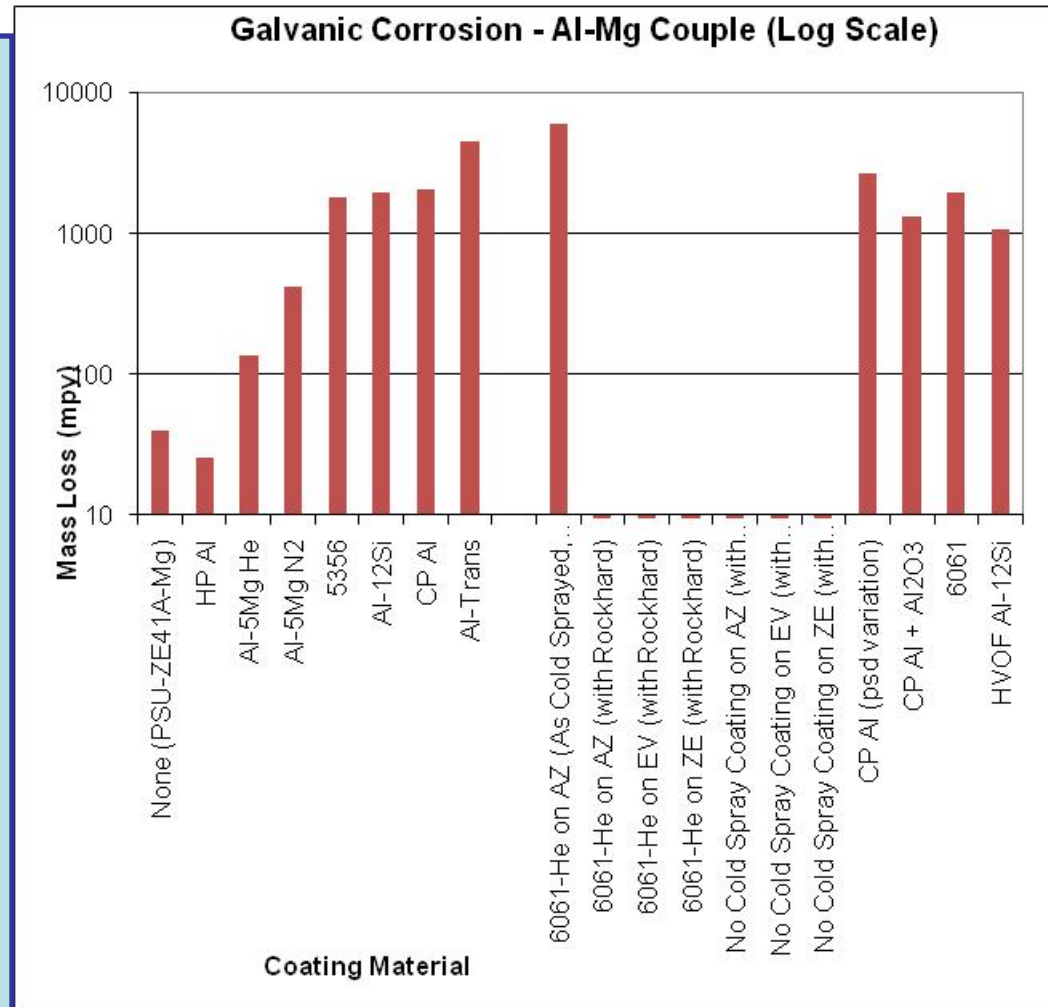
ESTCP RR Moore Data: 6061 and CP-Al N₂ Sprayed with N₂ on EV31-T6



XRD Residual Stress Versus Depth for 6061 Cold Spray on ZE41A-T5



- **Un-scribed ASTM B117**
 - **CP-Al went well (7000 hours at Army and 1000 hours at PSU)**
 - **6061 went 7000 hours at Army and will be retested at PSU due to thin spots**
- **Scribed ASTM B117**
 - **1000 hours through top coat but 24 hours through to substrate. On par with HVOF Al-12Si**
- **GM9540 Scribed- Sprayed**
- **Galvanic Corrosion (G71)**
- **Crevice Corrosion (G78)- No Crevice mechanism**
- **Beach Corrosion- Undergoing testing**



**vs uncoated ZE41*
-Cd plated steel specimens are currently being fabricated for comparison

Sump Assembly Main Module-Main Gearbox Repair



*Substrates: ZE41A
& AZ91C
Magnesium
Coating Material:
CP-Aluminum
and/or 6061 Al*

*Total Replacement Cost Savings estimated to be **\$935,000.00/ year***

Approved for Public Release; Distribution Unlimited

- Cold Spray Coating Parameters Optimized at ARL
- All Specimens from the JTP have been sprayed by ARL
- Testing is nearing completion for all Mechanical and Corrosion Specimens- All Partners (UTRC, Westmoreland, PSU, FRCEast, NAVAIR, ARL)
 - Unscribed B117- 7000 hours
 - Fretting Fatigue- Acceptable for He coatings
 - RR Moore- CP-AI N2 for non-structural, 6061 potential for structural repair
- Cold spray system at FRCEast is operational and ready for limited production