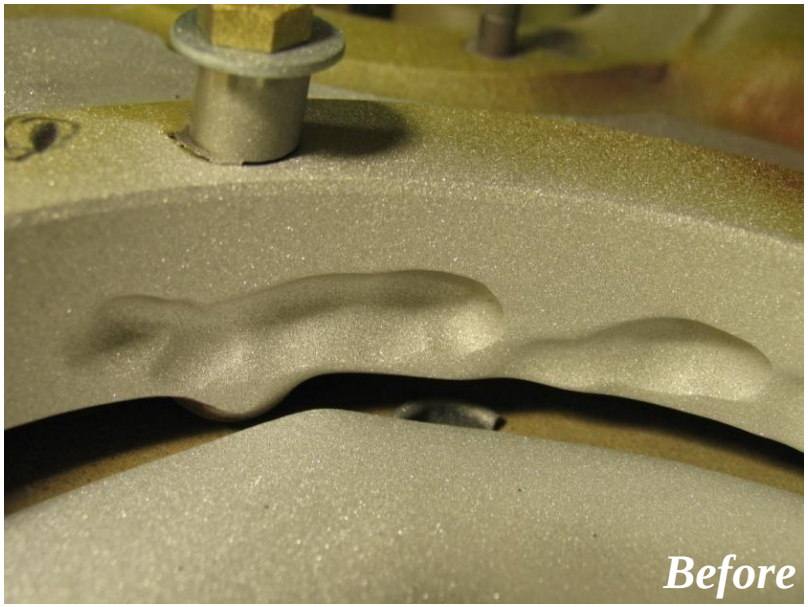
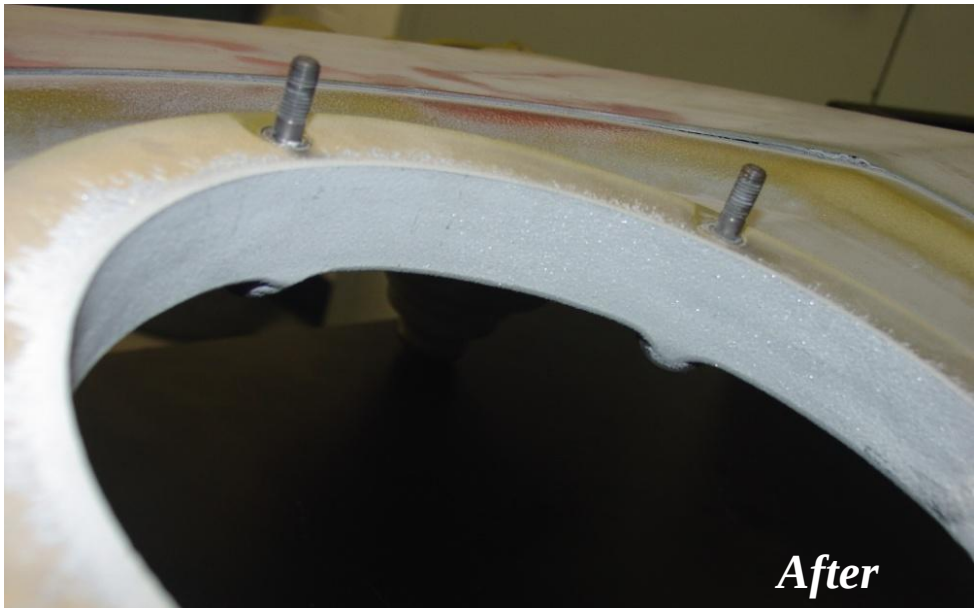
Cold Spray Repair of Magnesium





ARL Center for Cold Spray

17 May 2011

Presentation Outline

- Problem Overview
- Technical Objectives
  - High Pressure Cold Spray Systems and Coatings
  - Low Pressure Cold Spray Systems and Coatings
- Mechanical and Corrosion Test Results to Date
- Current Projects
- Cold Spray Powder Specification
- Conclusion and Open Discussion

Problem

Army & Navy rotorcraft & Air Force fighters have Mg gearboxes (several per aircraft) and other Mg parts that are unserviceable and need to be replaced.

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.

H53 Main GEARBOX
Part Numbers 65391-11602-044 /65070-35542-045
Magnesium casting
Cost New $313,800

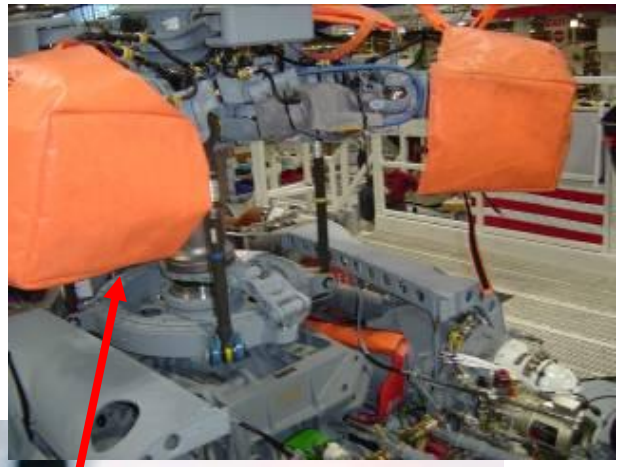
Problem

(Examples where magnesium housings are used on the UH-60)

•Magnesium is susceptible to wear and corrosion

Main, Intermediate and Tail Gearboxes for UH-60

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



"this is a critical safety and readiness issue" *(Major General Nickolas Justice, Commanding General, US Army Research, Development and Engineering Command)*

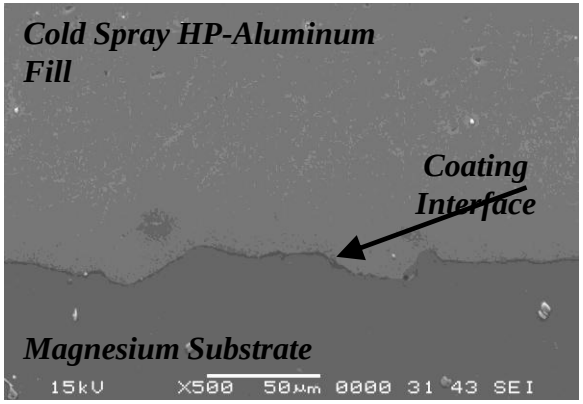
Problem

(UH-60 Magnesium Main Rotor Transmission Repair by Cold Spray)

UH-60 Main Rotor Transmission

Examples of corrosion damage from service

Microstructure of CS Repair



Technical & Warfighter Impact

UH-60 Sump Assembly Main Module-Main Gearbox Repair

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

Part Numbers:
70351-48141-041
70351-08141-047

- ***Cost of new component $11,000.00 DLA (Defense Logistics Agency)***
- ***85 sumps need repair per year based on a Sikorsky study over the last 3 years***
- ***Total Replacement Cost Savings estimated to be $935,000.00/year***
- ***This costs savings is only for one magnesium part for the UH-60***

Technical Objectives

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 LOCATION

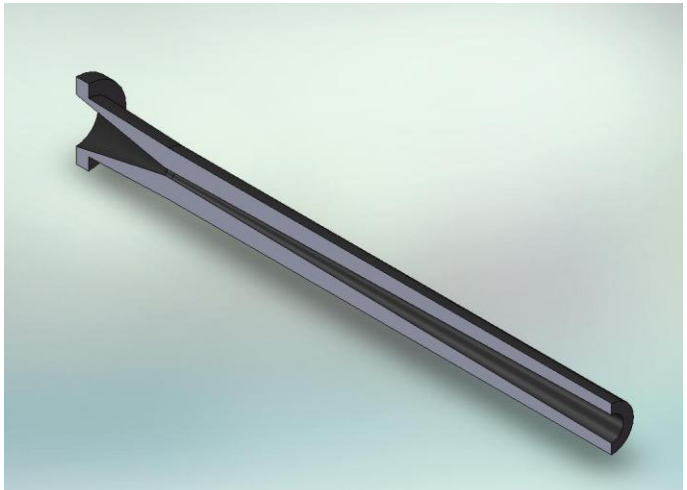
MAIN GEARBOX

High Pressure Cold Spray

CGT Kinetiks 4000 High Pressure Cold Spray System

Operating Parameter	Value
Gas Pressure	250 – 580 psi
Gas Temperature	30 - 800 °C
Gas Flow	50 - 200 SCFM
Powder Flow	10 – 50 gram/minute
Particle Exit Velocity	500 - 2000 meter/second

Coating System	Vickers Microhardness (VHN)
CP-Al N2	61
CP-Al He	68
6061 He	105
HP-Al	51
5083 Al	127
n-5083 Al	261
7075	155
ZE41A-T5	71



Polymer De Laval Cold Spray Nozzle

TECHNICAL APPROACH

Joint Test Protocol

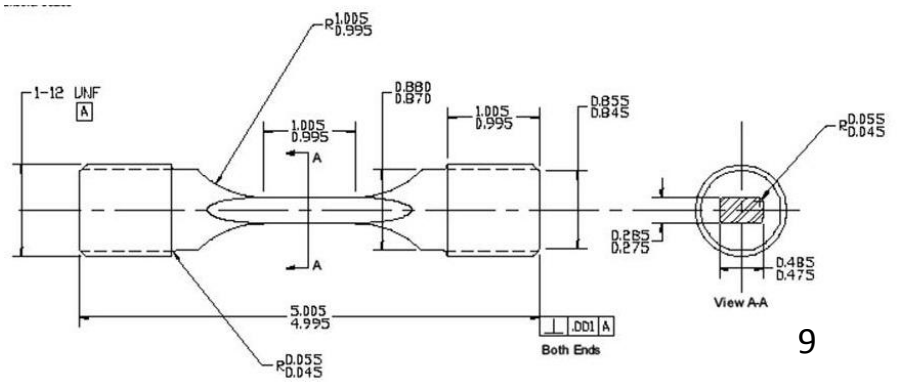
Mechanical Tests

- 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-SO_2***

Stack Up: RockHard, 23377, and 85285



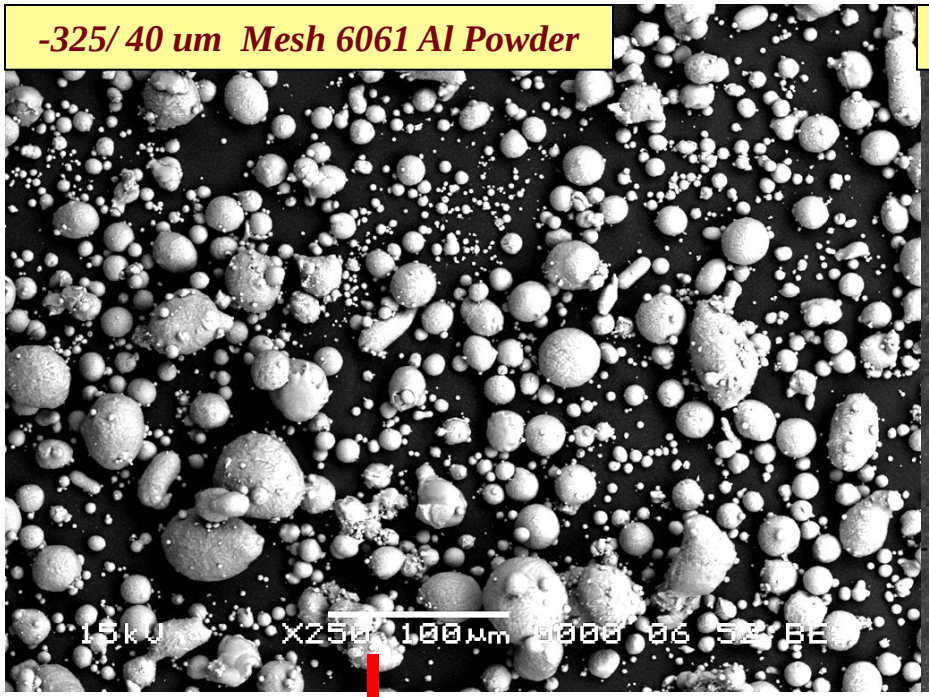
UTRC Fretting Fatigue Specimen

Powder vs. Coating

Oxygen content measured by Inert Gas Fusion

ASTM E 1019-03

-325/ 40 um Mesh 6061 Al Powder



Cold Spray 6061 Al Coating

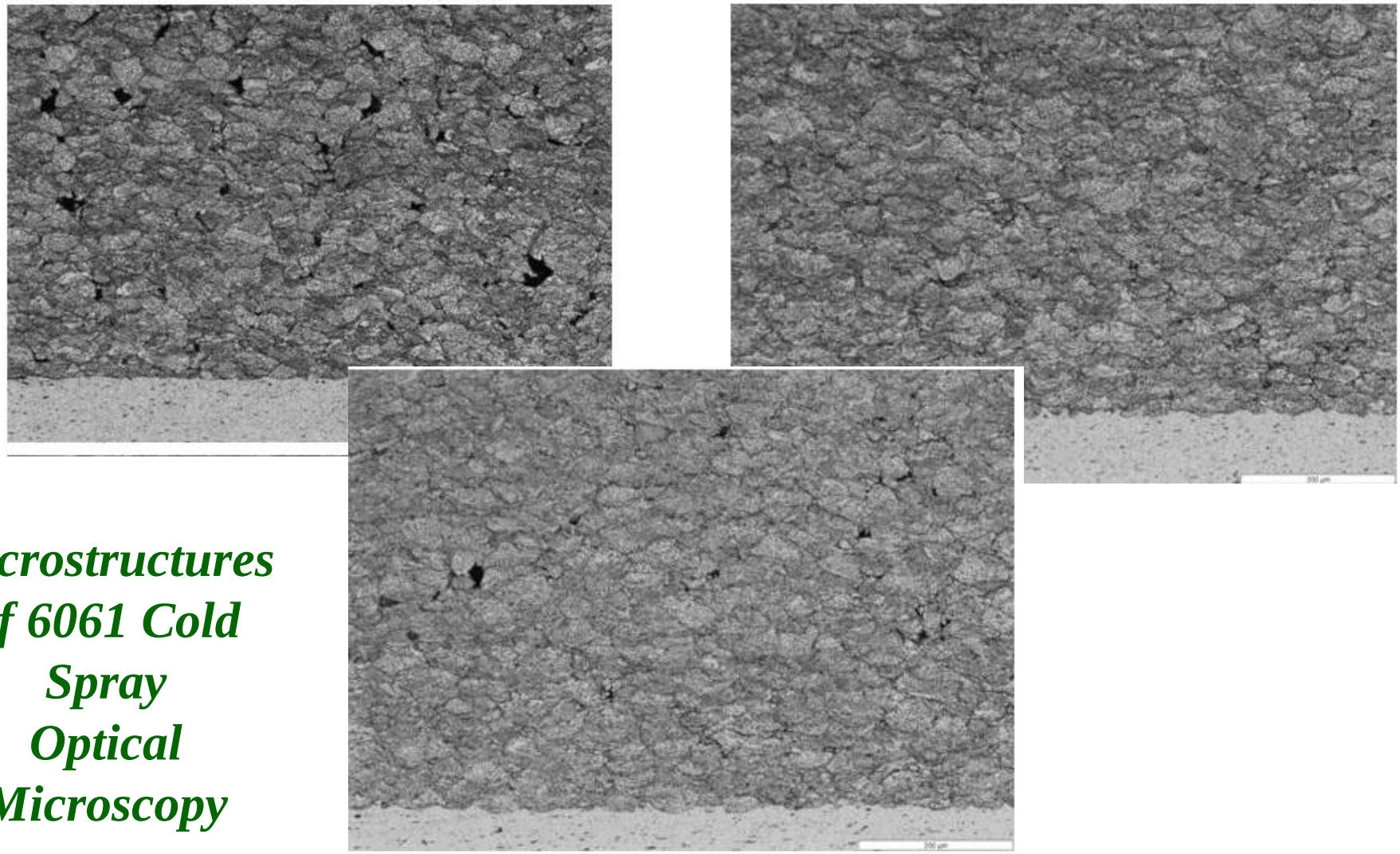
0.22 %Oxygen

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.*

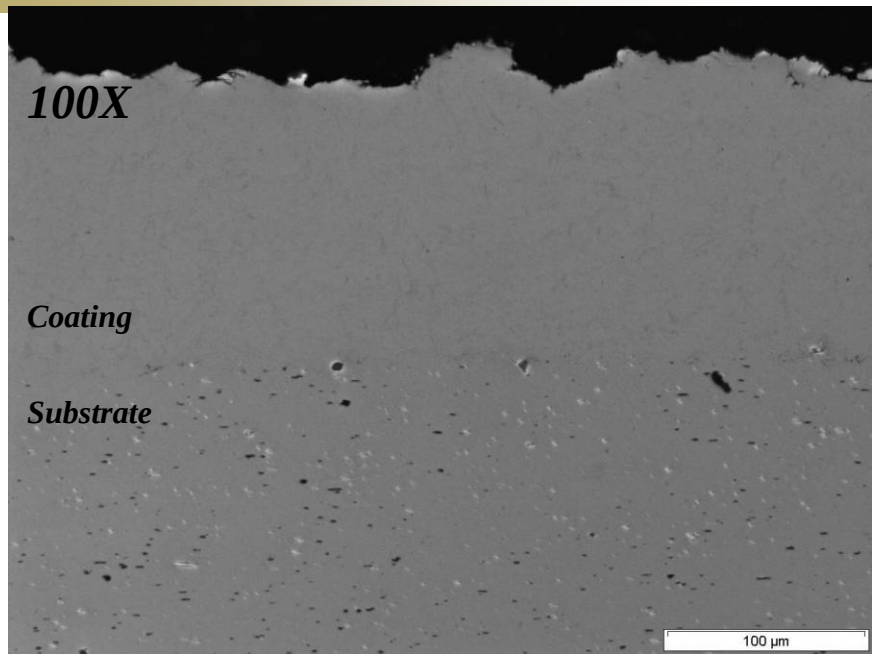
Technical Progress

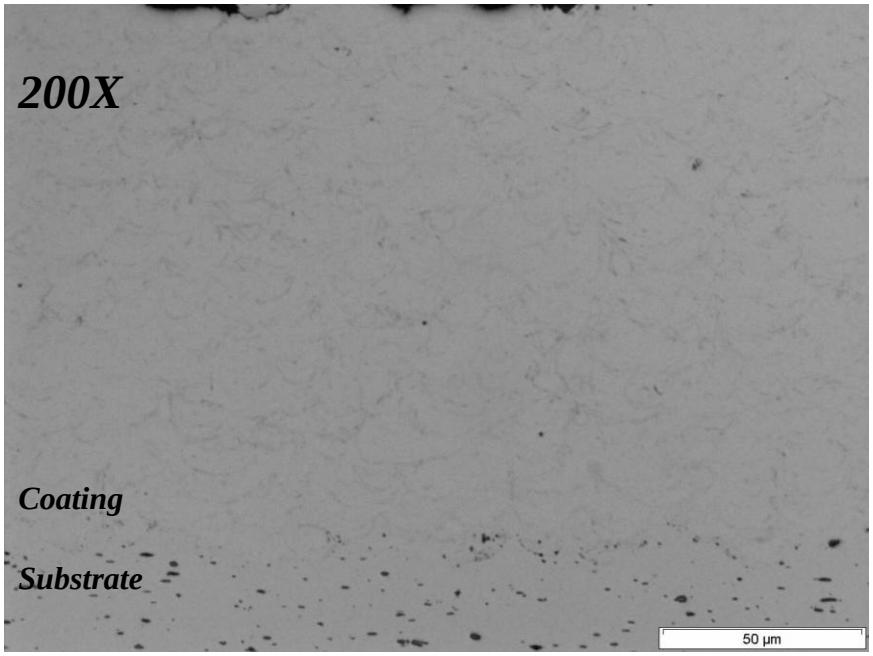


Microstructures of 6061 Cold Spray Optical Microscopy

Increasing Gas Pressure

Technical Progress





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)

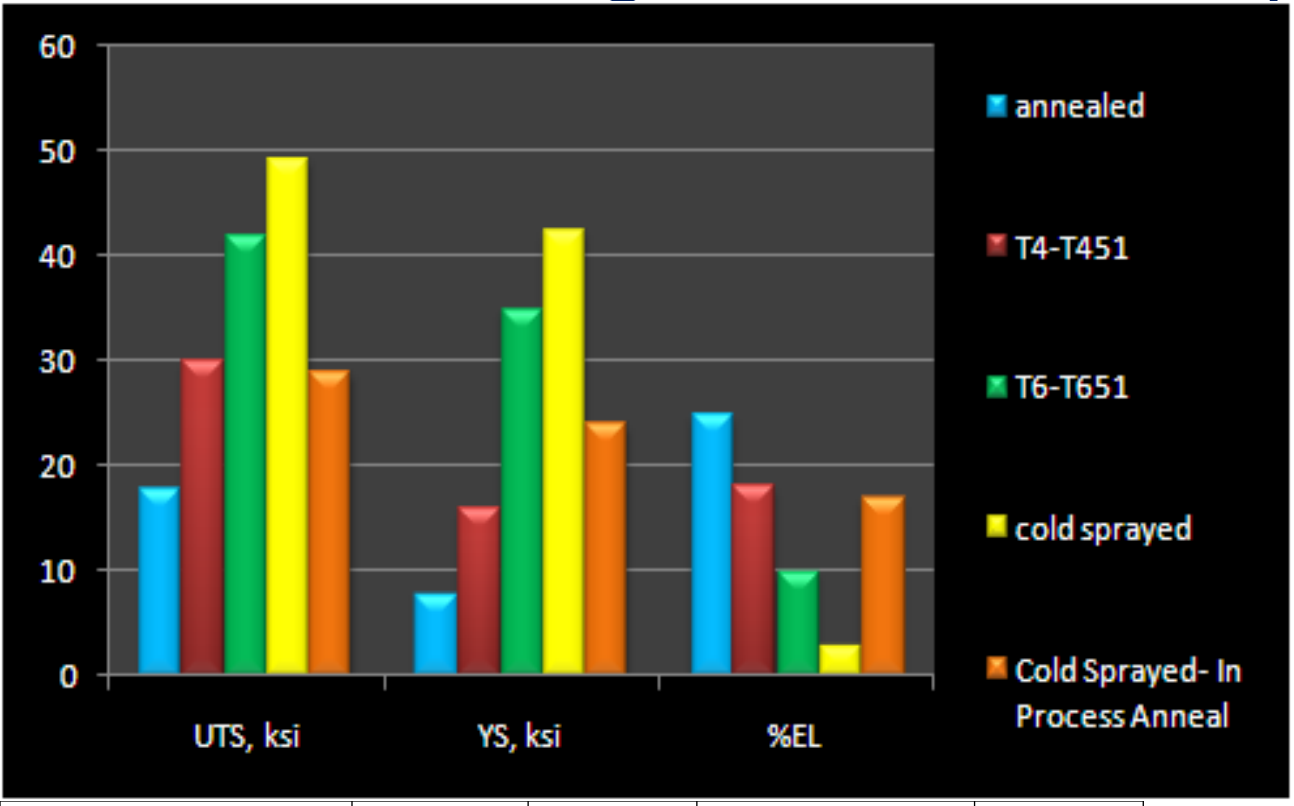
T5 means articially aged

T6 means solution heat treated and artifically aged

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

Technical Progress

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

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]

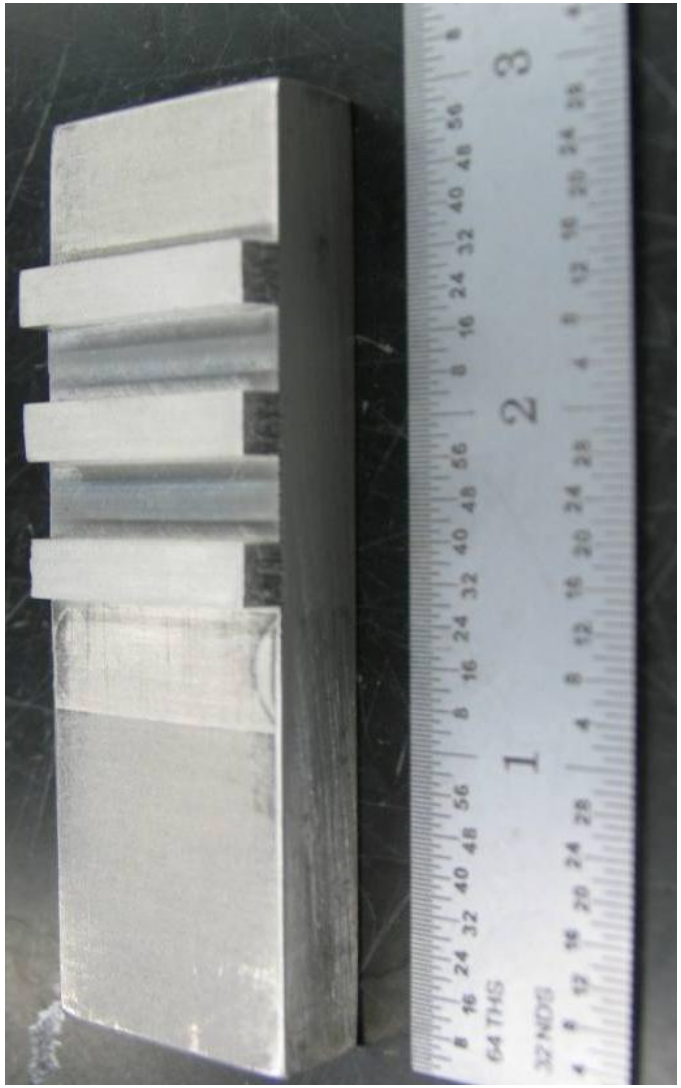
In Process Anneal- 640°F for 10 to 12 Hours

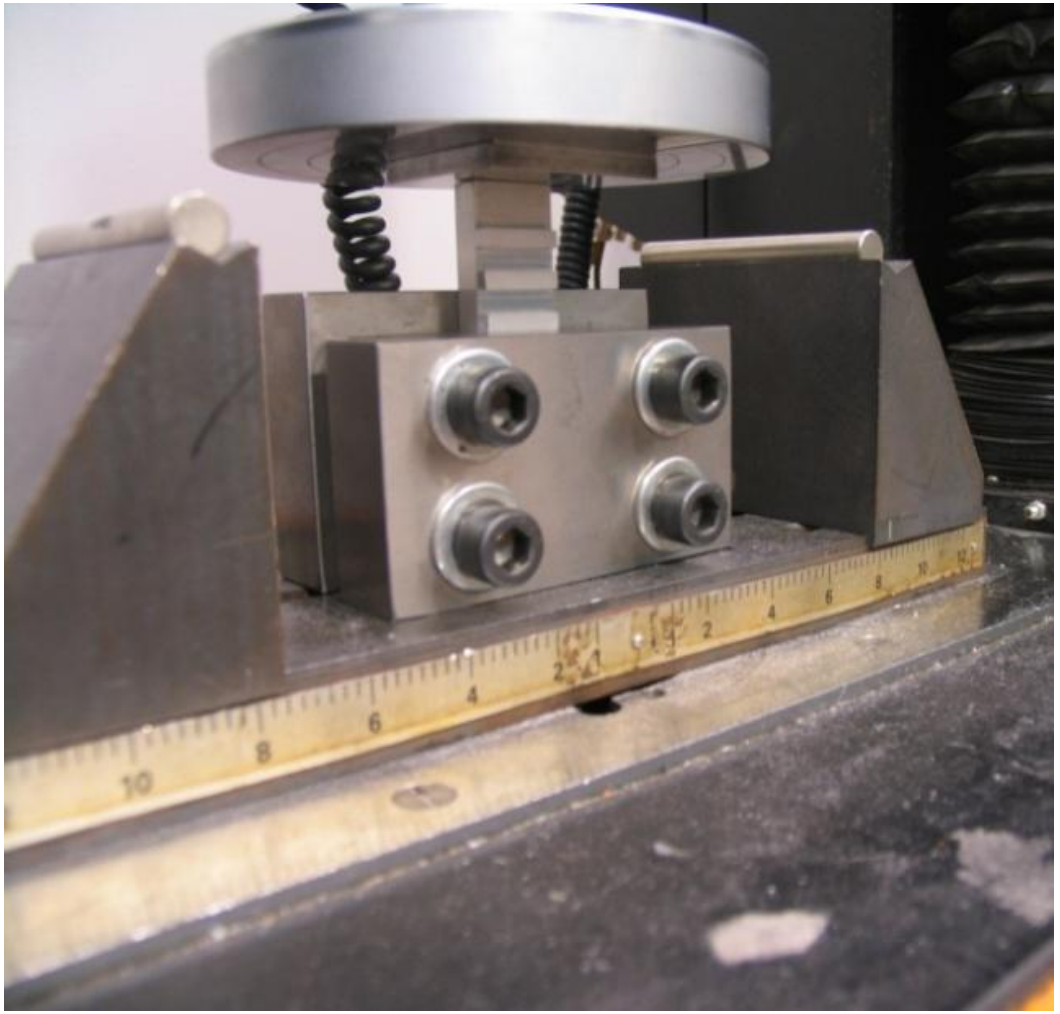
[1]Matweb

[2]Alcoa.com

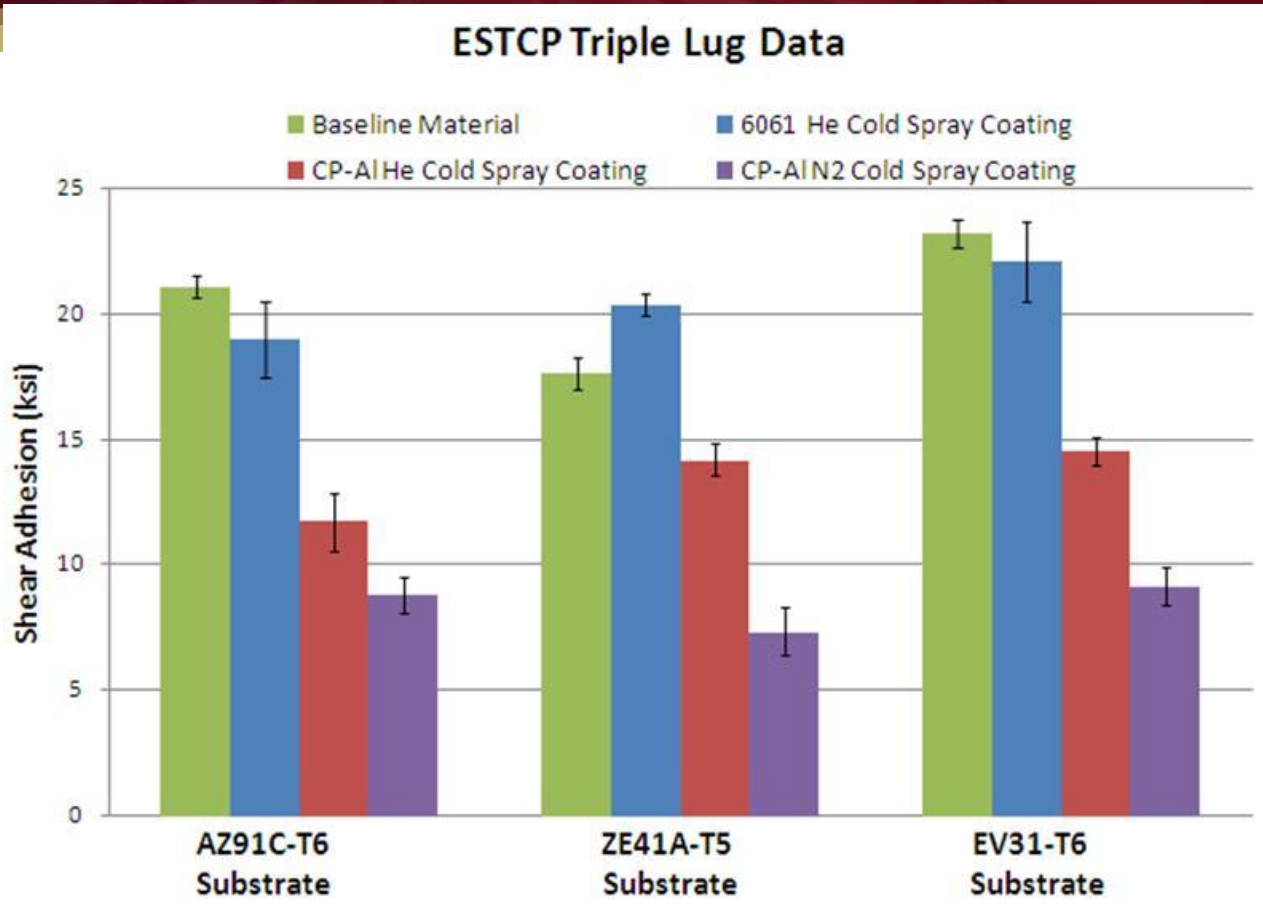
[3]**Microtensile Test by Aaron Nardi at UTRC of ARL Cold Spray Block**

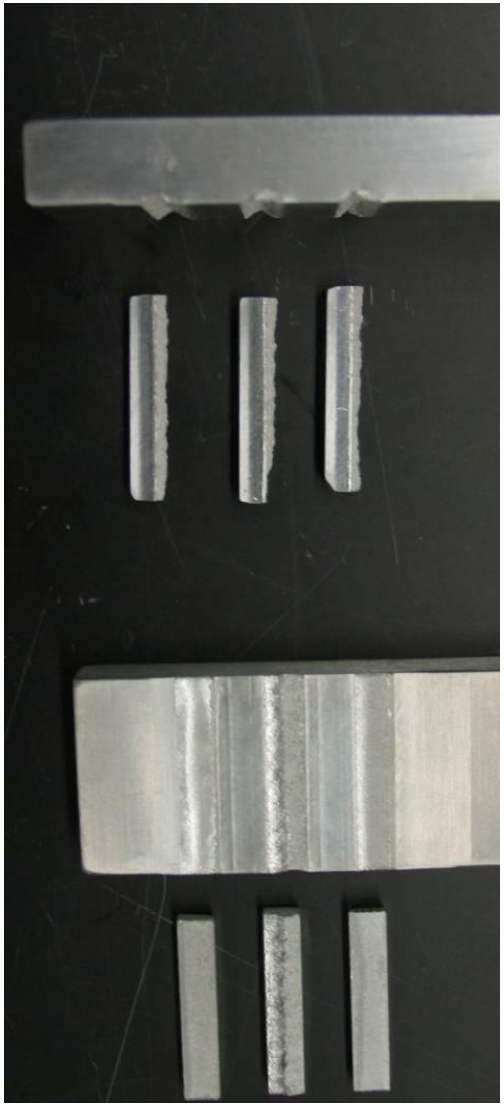
Triple Lug Shear Test





Technical Progress





6061/ZE41A-T6

- 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

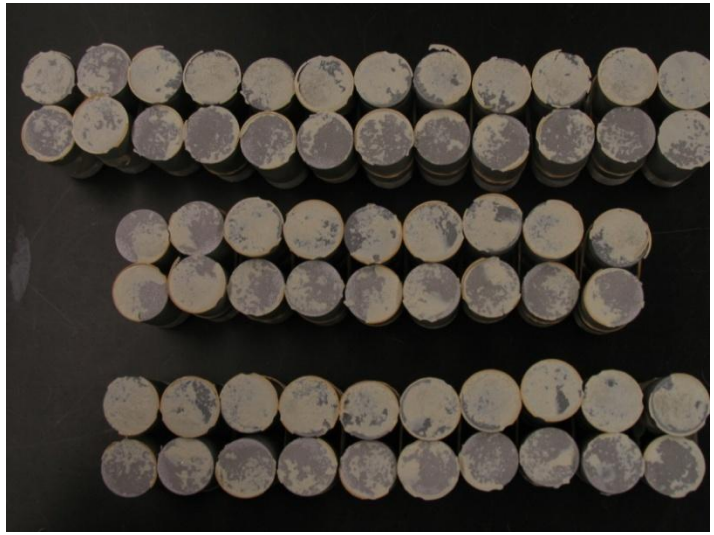
Bond Bar Adhesion (ASTM C633)

Substrate	Coating System	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

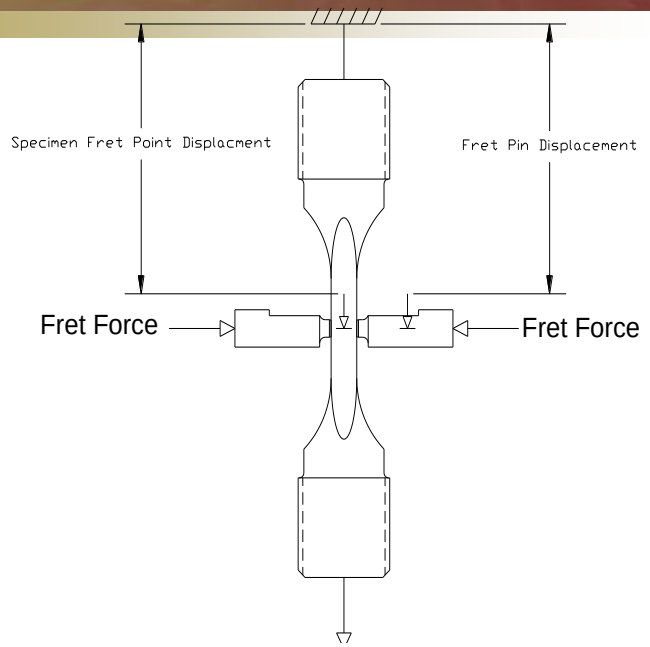
ZE41A-T5

AZ91C-T6

EV31-T6



Fretting Fatigue Setup at UTRC



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

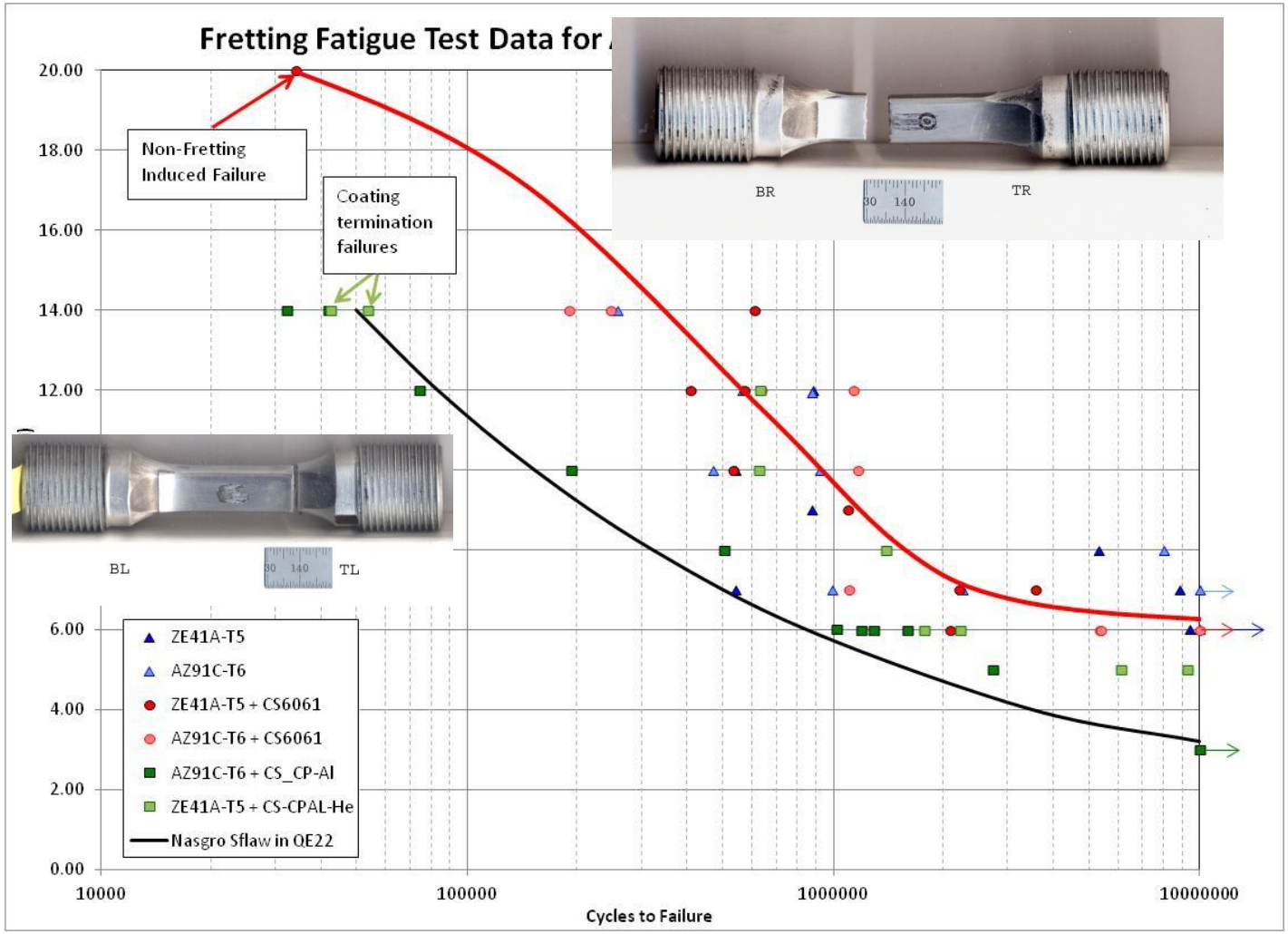
Pin Type = 0.206 diameter 4340 steel with cadmium plating

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

Cold Spray Repair Fretting Fatigue



Slide Courtesy of Aaron Nardi, United Technologies Research Center

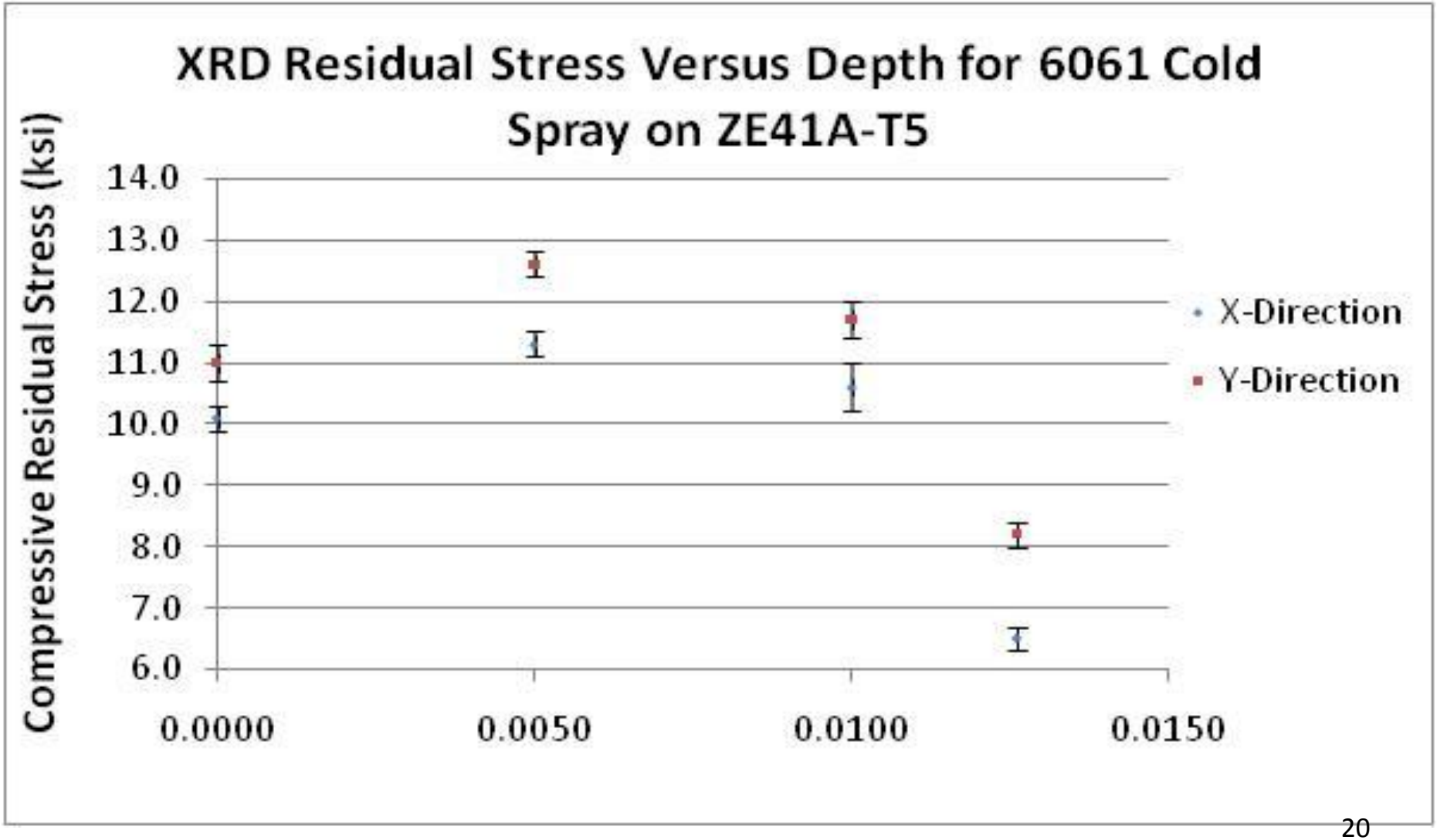
Fretting Fatigue Summary

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

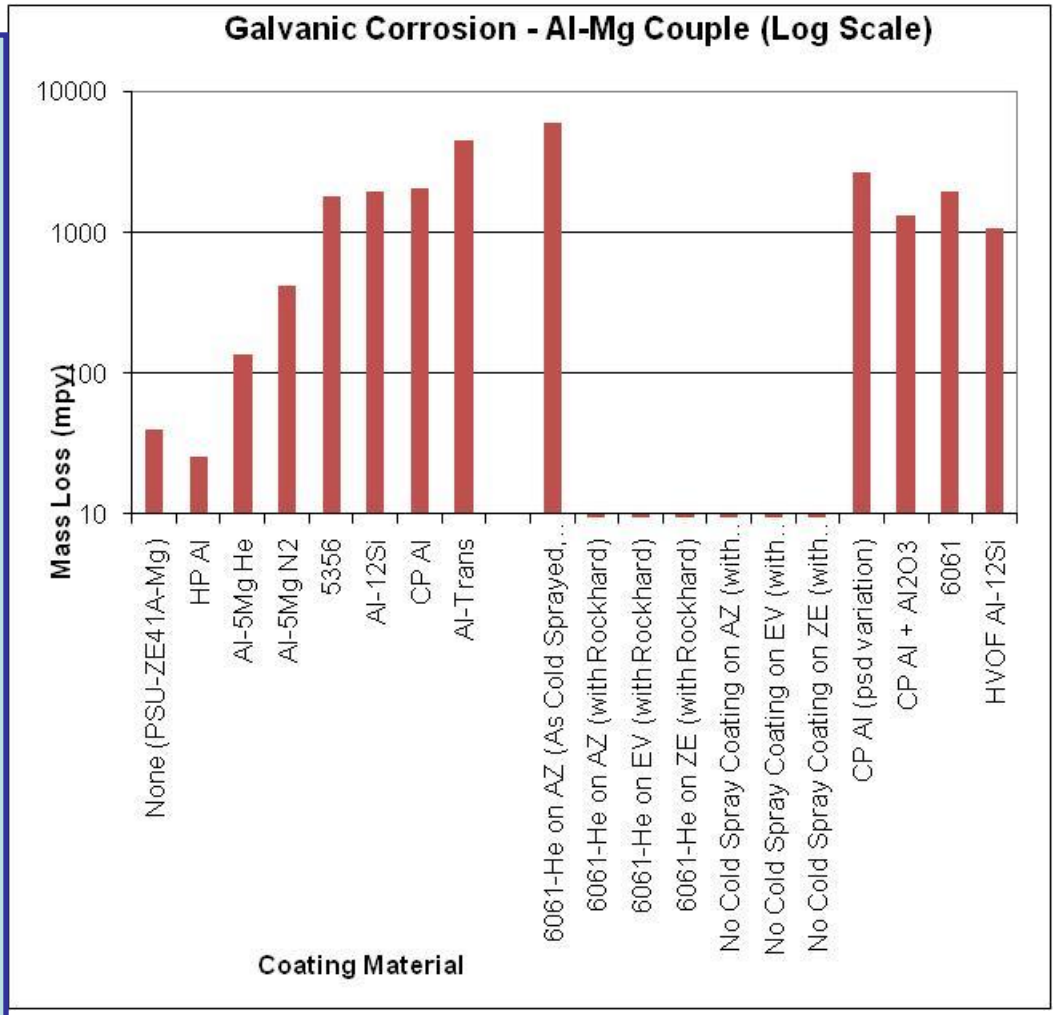
Slide Courtesy of Aaron Nardi, United Technologies Research Center

Technical Progress



Technical Progress

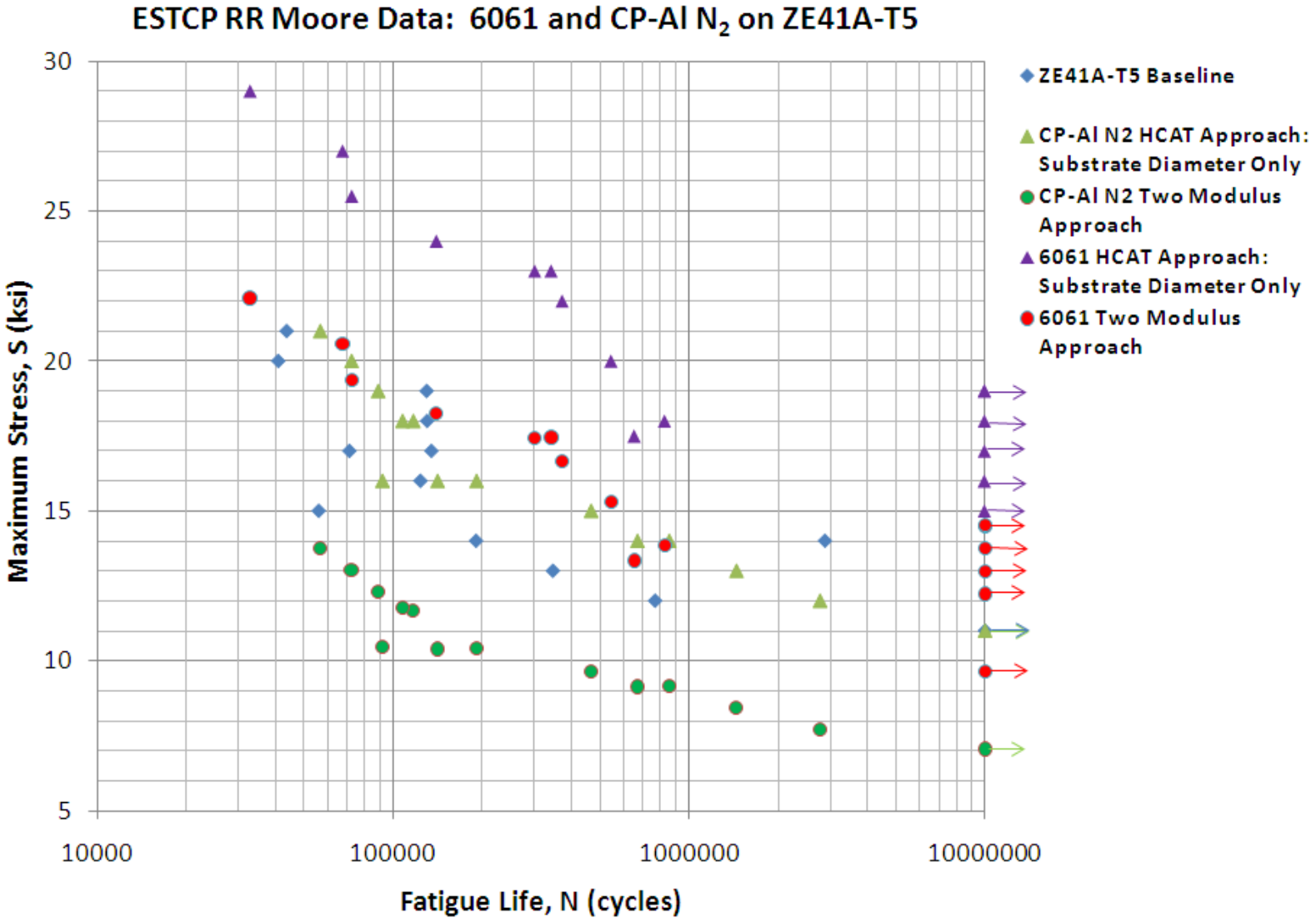
- *Un-scribed ASTM B117*
  - *CP-Al went well (7000 hours at Army and 1000 hours at PSU)*
  - *6061 went 7000 hours at Army and will be retested at PSU due to thin spots*
- *Scribed ASTM B117*
  - *1000 hours through top coat but 24 hours through to substrate. On par with HVOF Al-12Si*
- *GM9540 Scribed-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



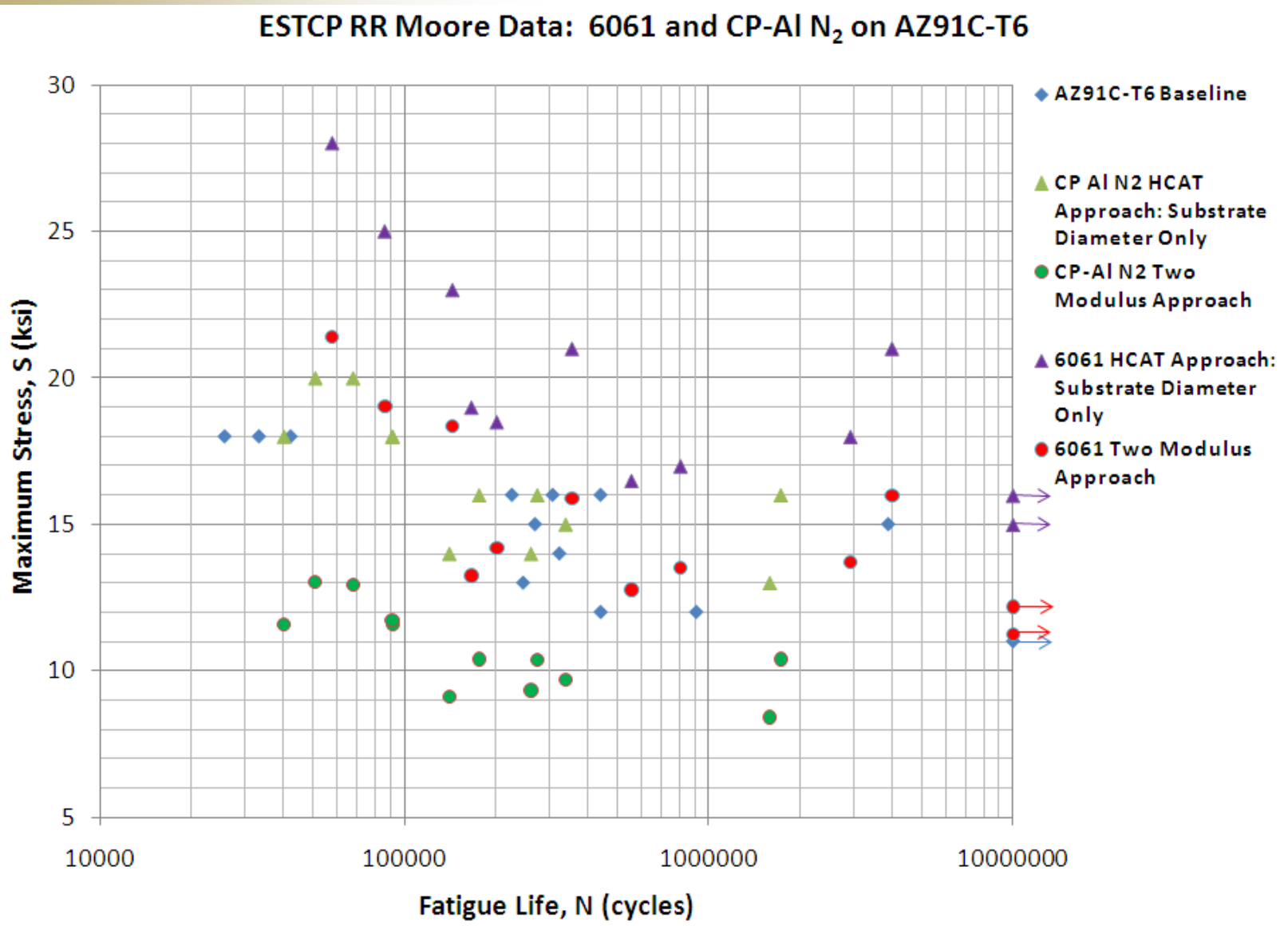
**vs uncoated ZE41*

-Cd plated steel specimens are currently being fabricated for comparison

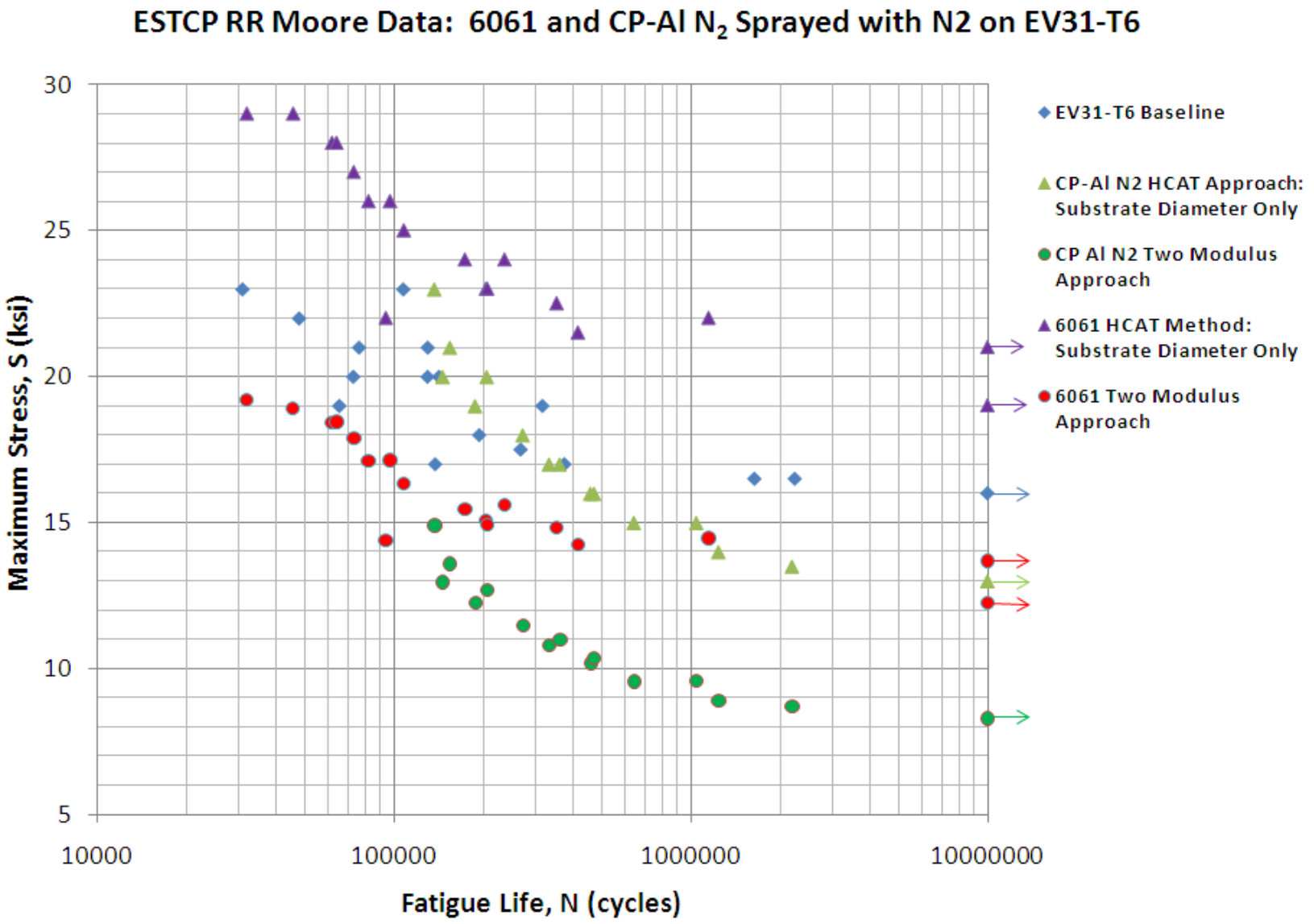
High Pressure R.R. Moore Fatigue



High Pressure R.R. Moore Fatigue

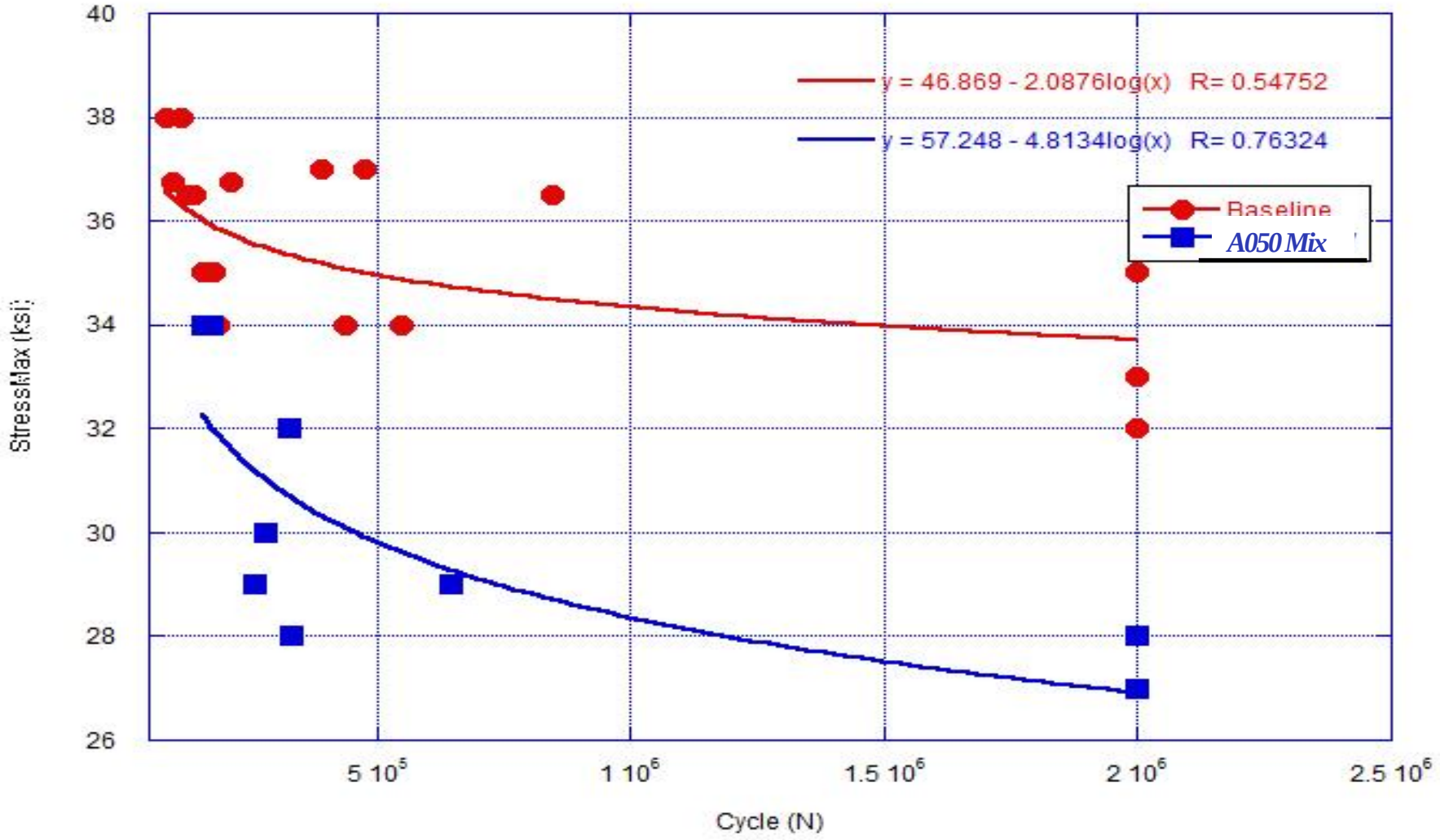


High Pressure R.R. Moore Fatigue

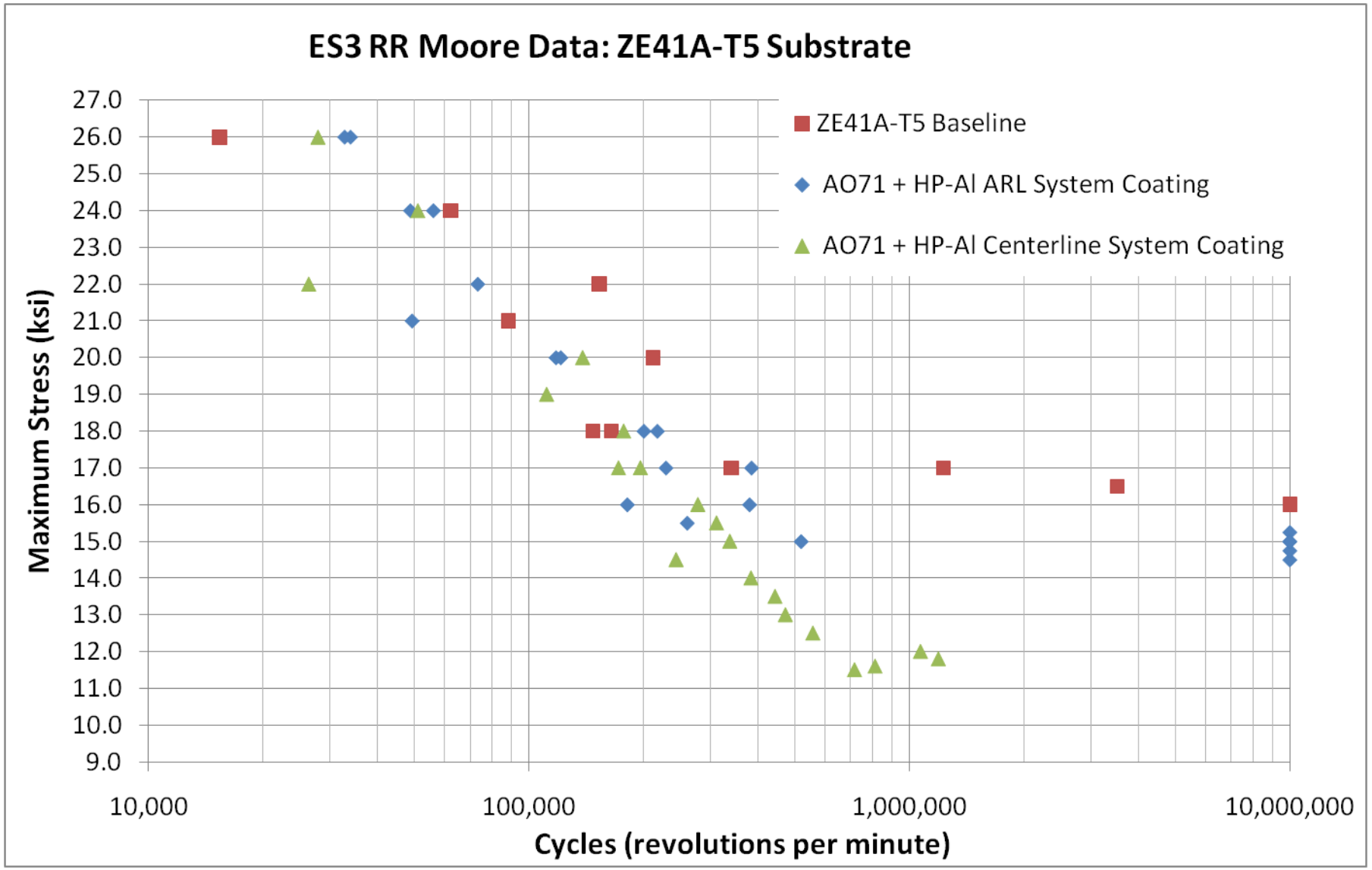


Side Discussion: Fatigue Aluminum-Alumina Mixtures on 7075 Al Alloy

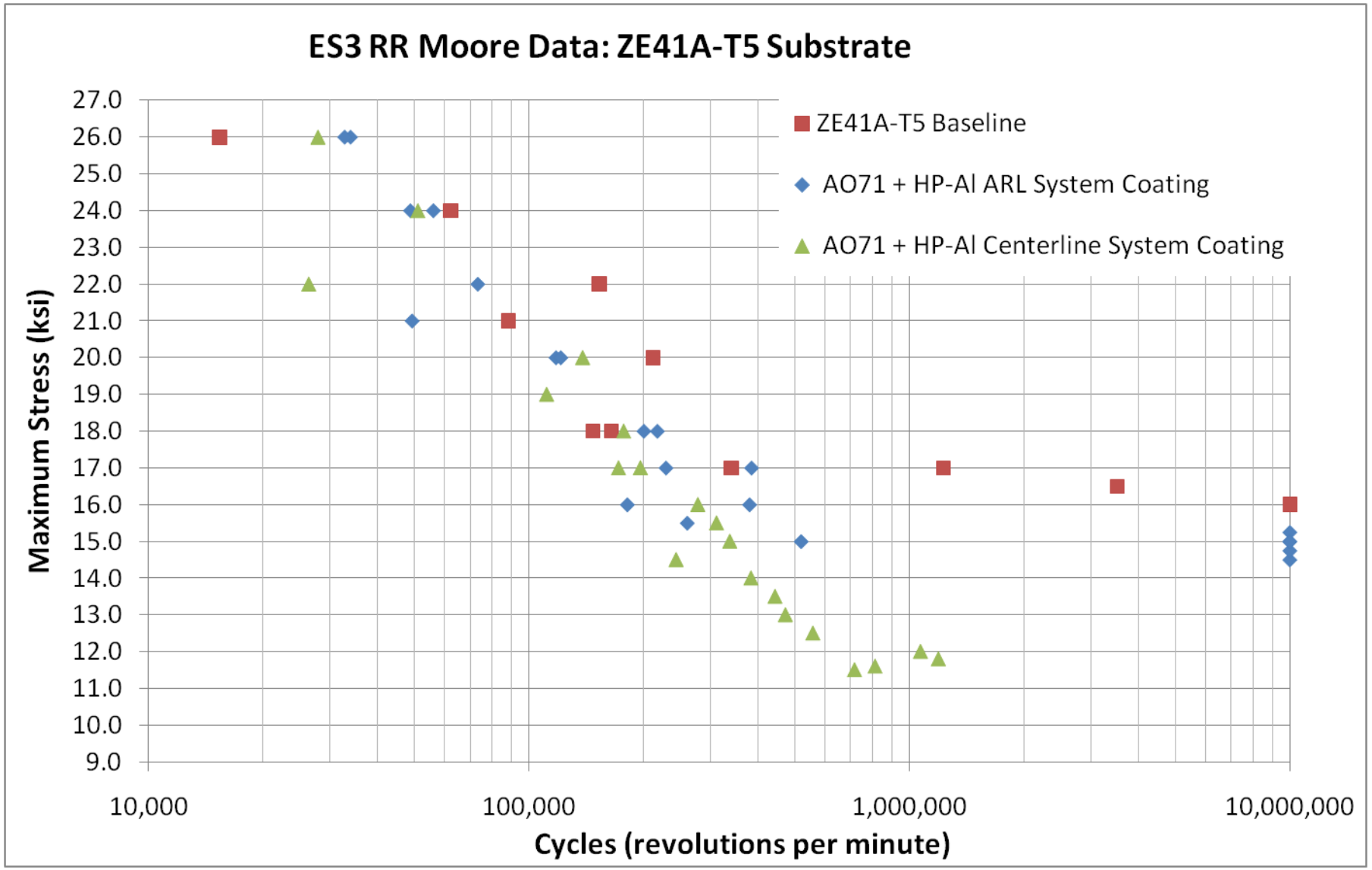
Baseline vs A050 Cold Spray Mixture Fatigue s-N Data



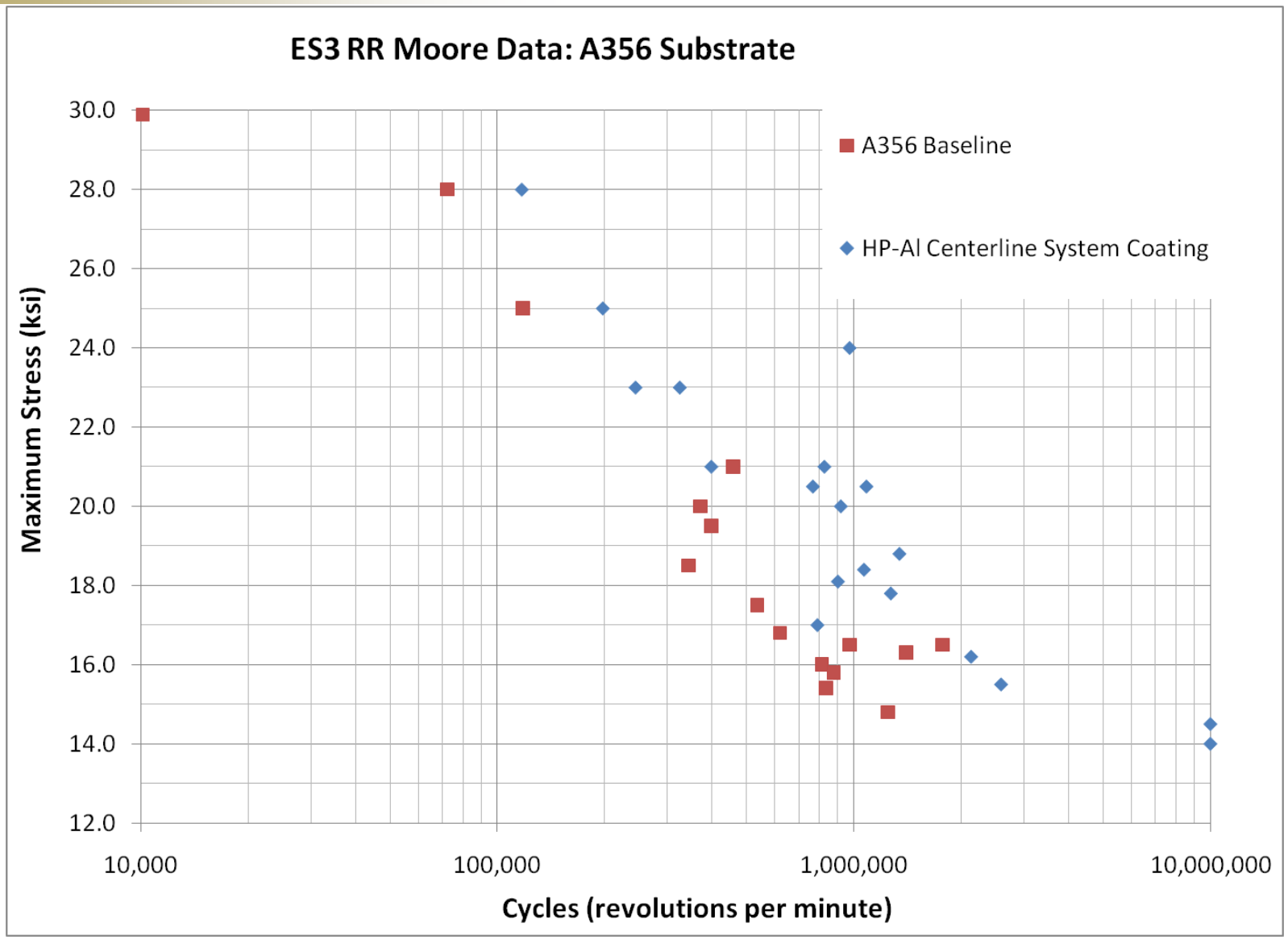
Side Discussion: Fatigue Aluminum-Alumina Mixtures on Mg Alloy



Side Discussion: Fatigue Aluminum-Alumina Mixtures on Mg Alloy



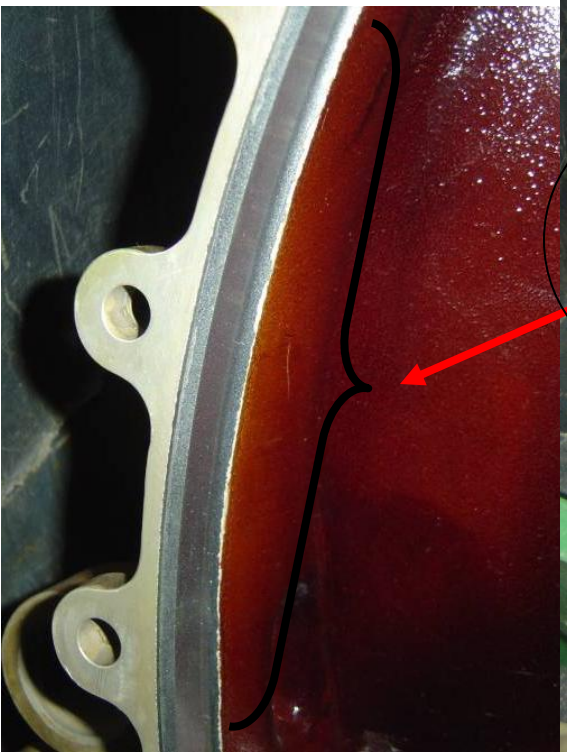
Side Discussion: Fatigue
Low Pressure HP-Al on cast Al Alloy

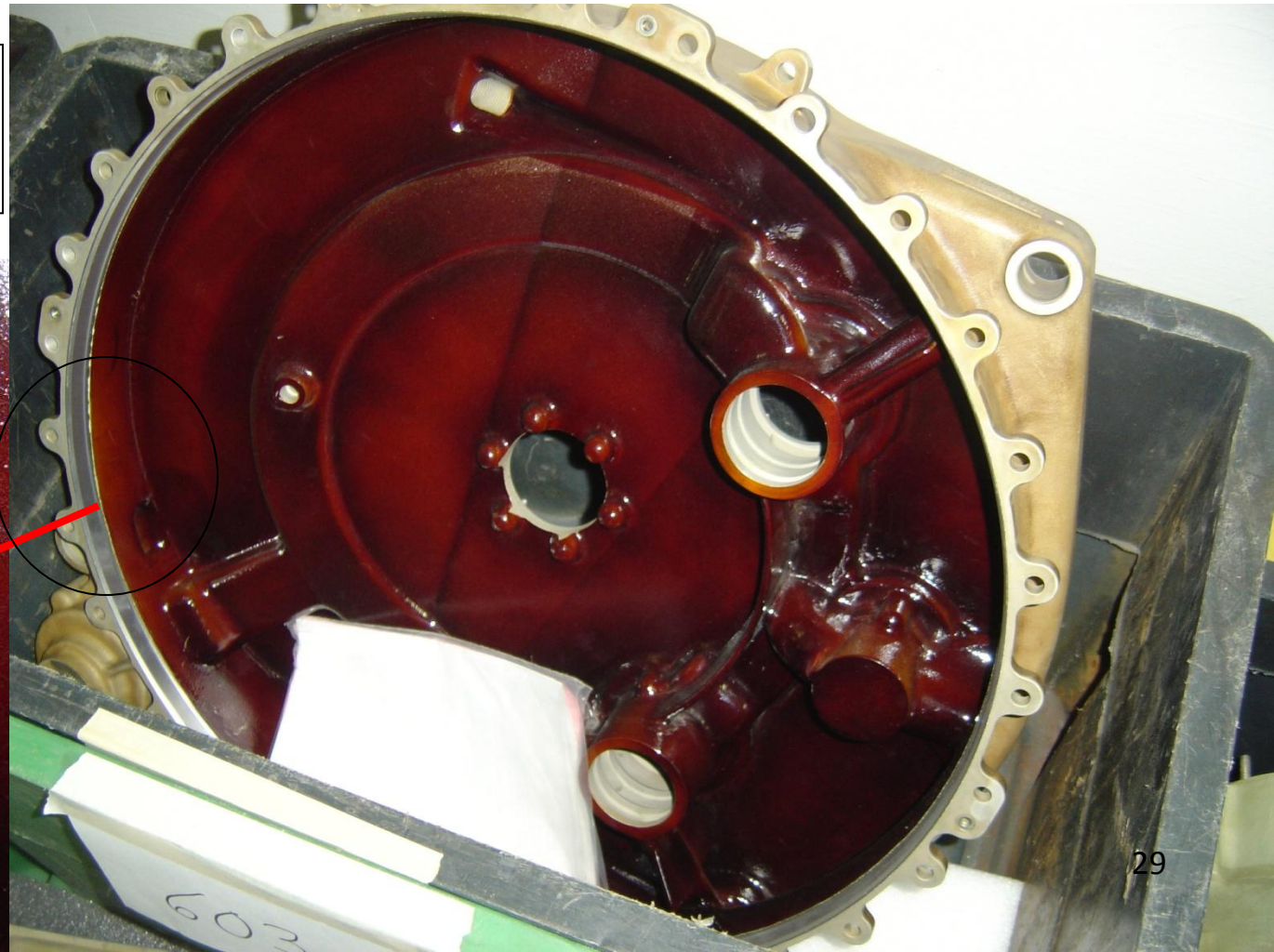


Sump Assembly Main Module -Main Gearbox Repair

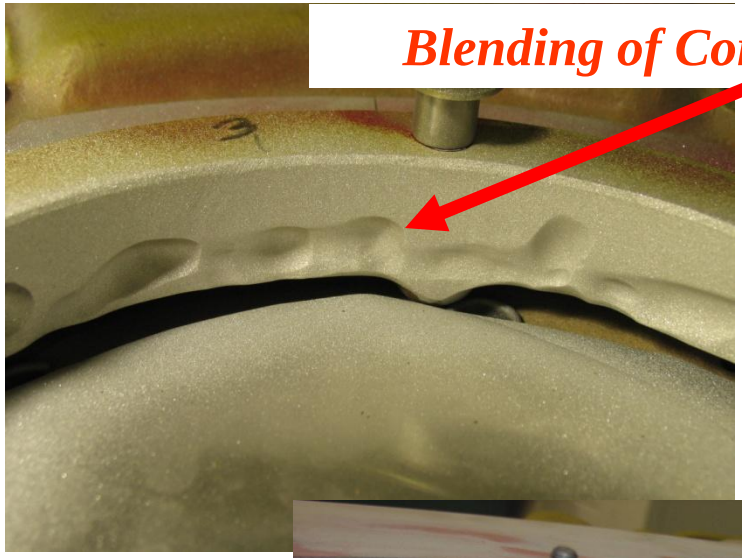
Repair Site:

Rubber O-ring insert

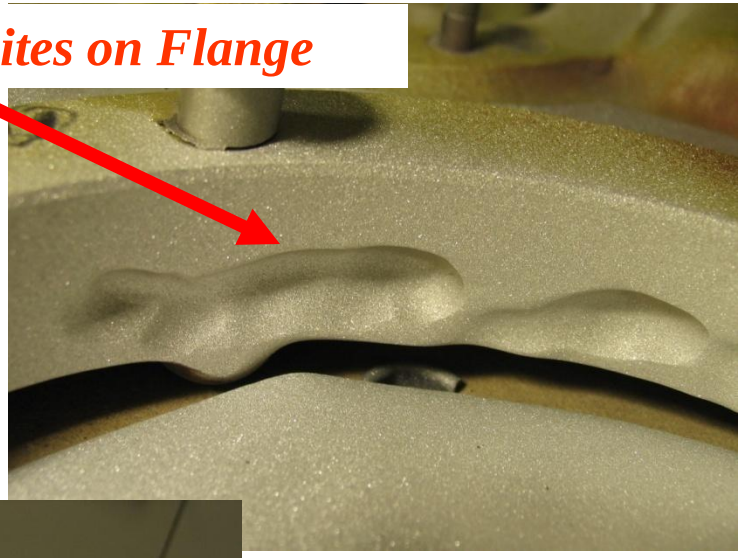


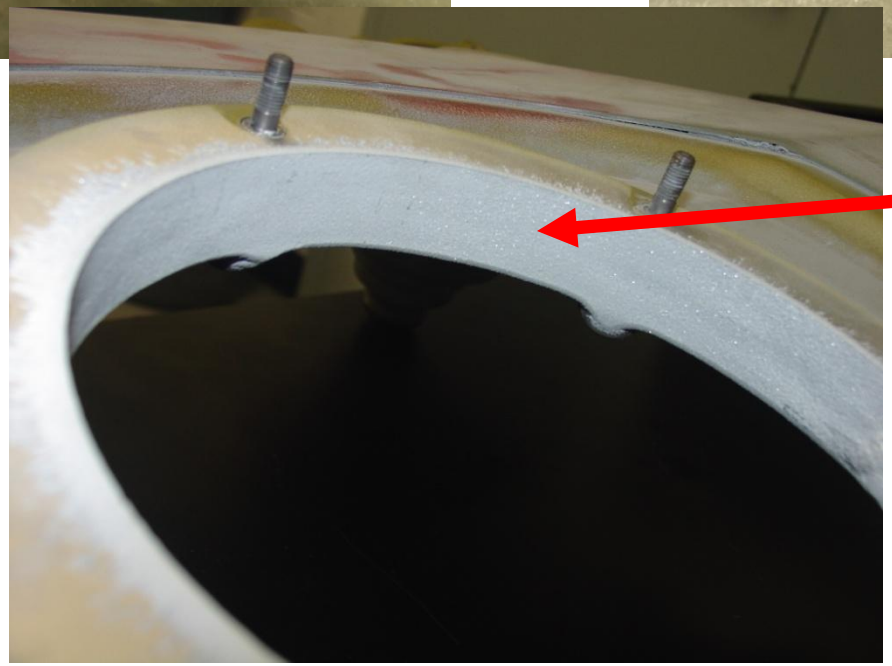


Sump Assembly Main Module -Main Gearbox Repair



Blending of Corroded Sites on Flange





Cold Spray Repair of Inside Diameter of Flange

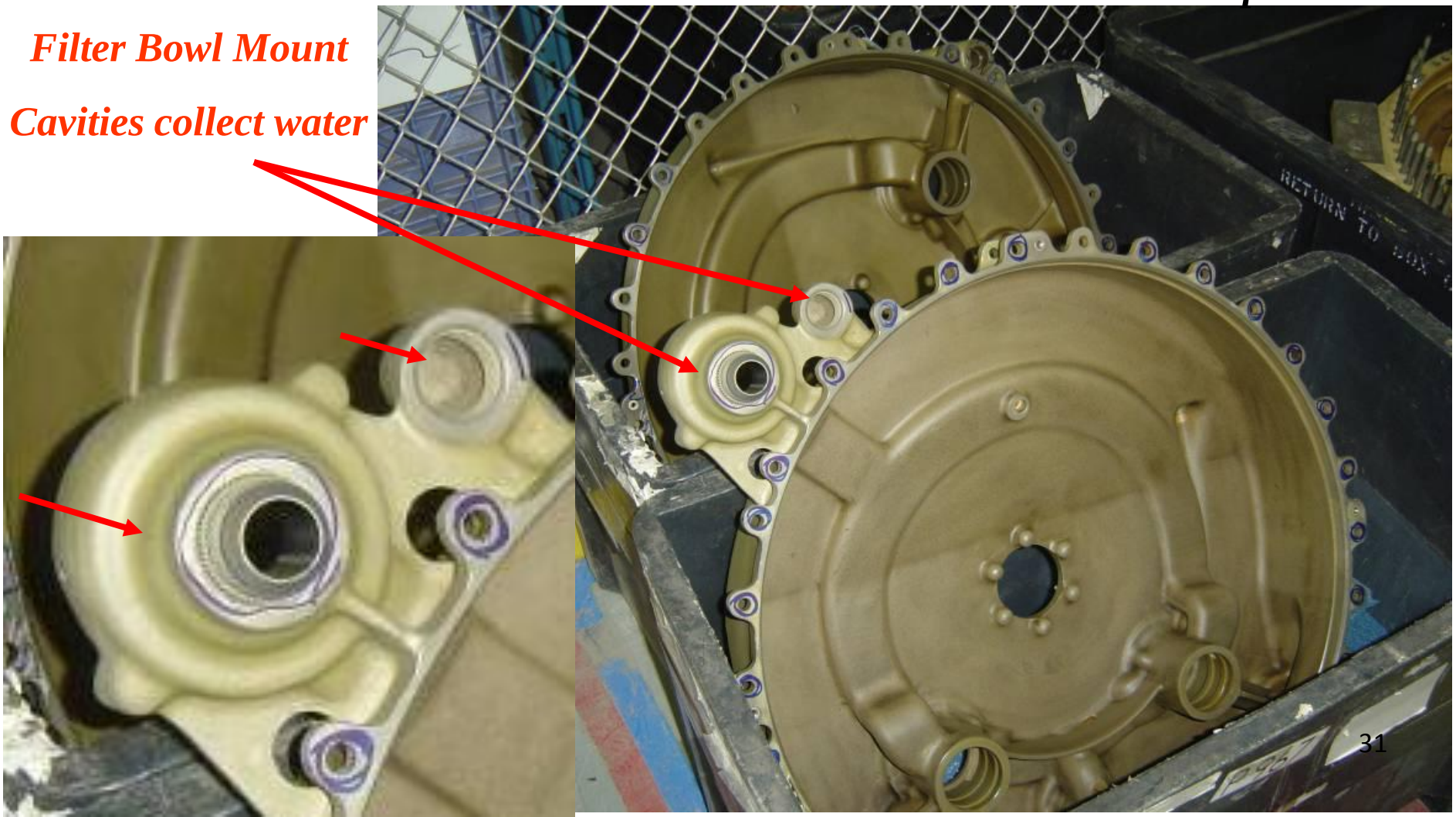
Sump Assembly Main Module -Main Gearbox Repair

Repair Site:

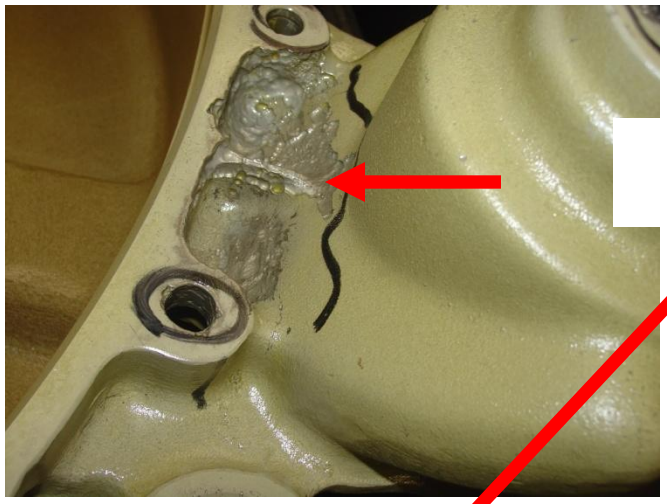
Filter Bowl Mount

Cavities collect water

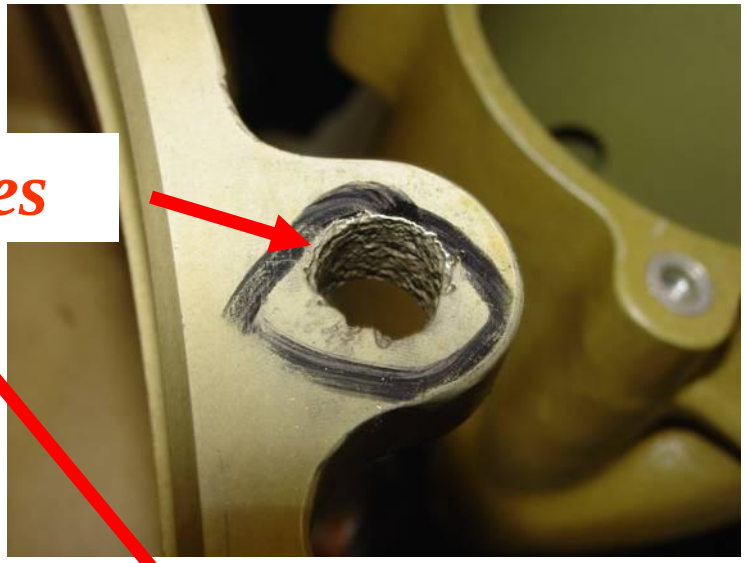
UH-60 Sump Assembly Main Module -Main Gearbox Repair

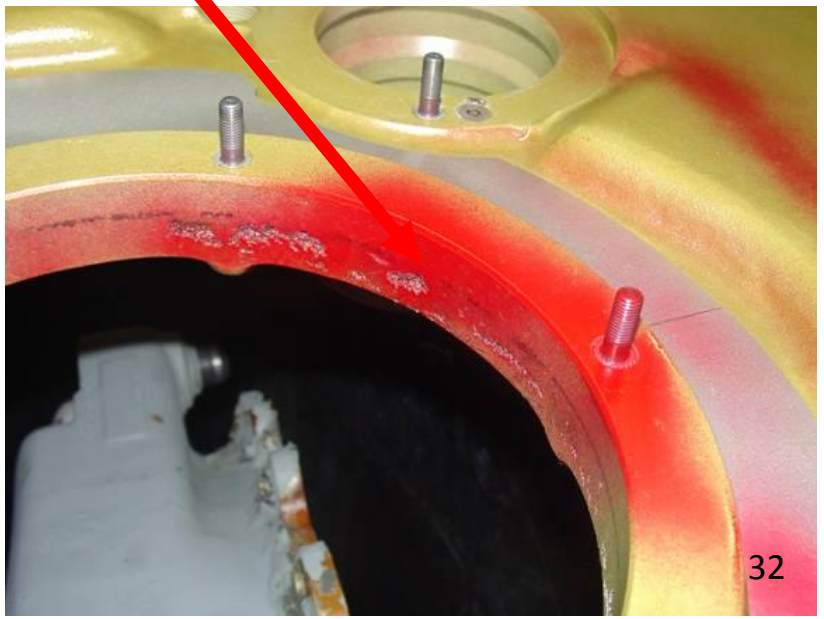


Sump Assembly Main Module -Main Gearbox Repair



Repair Sites





H-60 Intermediate Gearbox (IGB) Cold Spray Enhancement Project

Before ***After***

NAVAIR ARL

Problem

Corrosion damage on the H-60 IGB is the leading cause of component removal

- Specifically, the corrosion occurs around the mounting pads. Inside areas as well as the bottom of the feet
- FY2009: Navy removed 23 corroded IGB from Service (82% of all removals)
- Component cost is $45k
- 88 hours to remove, replace, and perform flight checks. Labor rate is $36.95 hour

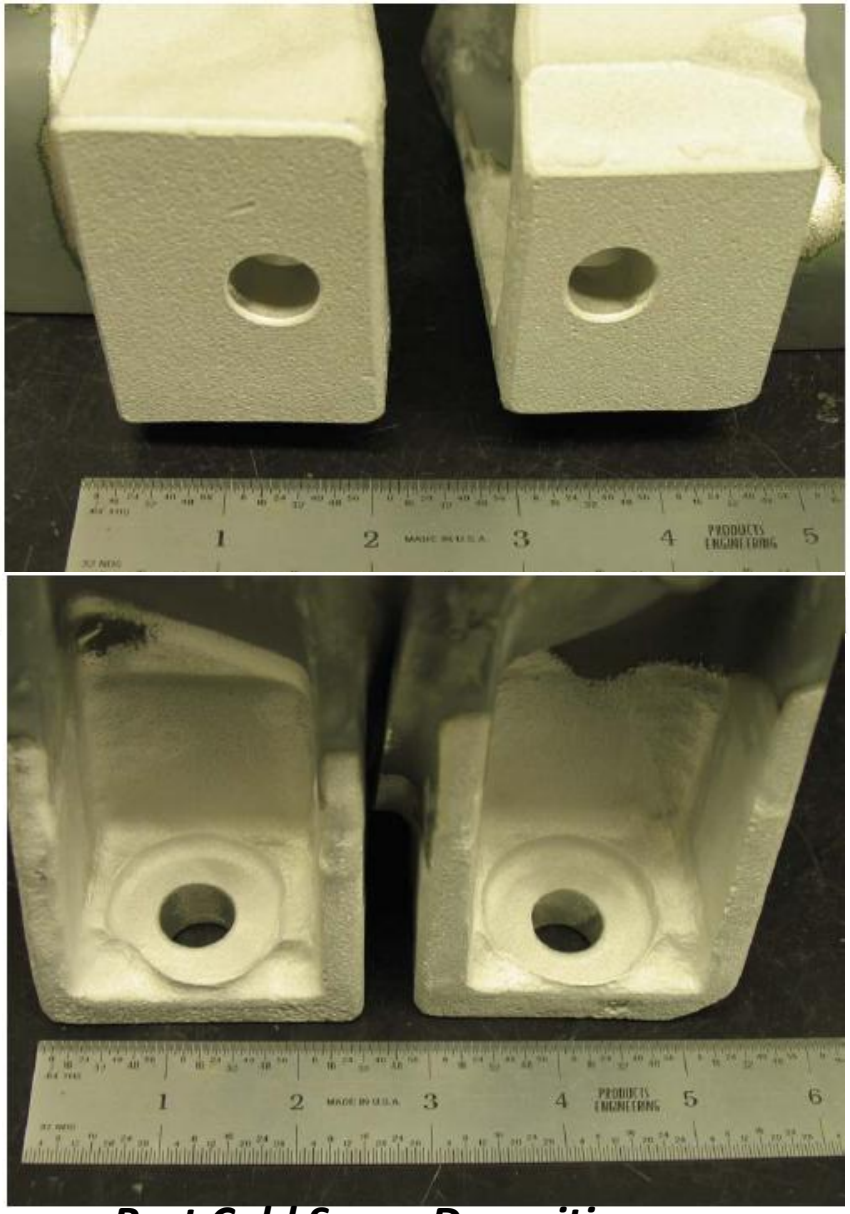
Navy spent approximately 1.1 million dollars on this issue in FY2009

Proposed Solution

Cold Spray a protective 6061 aluminum alloy coating onto the bottom of the mounting pads as well as the inside of the bolting area

- ***The cold spray will provide better resistance to crevice corrosion on the bottom of the pads***

- ***6061 aluminum alloy cold spray is harder than the ZE41A-T5 substrate and will provide better resistance to tool damage as well as better corrosion resistance on the inside of the bolting area***



Post Cold Spray Deposition

H-1 Combining Gearbox Chaffing Damage Repair

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Robert Kestler
robert.kestler@navy.mil
252-464-9888

Proposed Coating Systems

Portable Cold Spray Systems

1. ***Upgraded Centerline System- 400°C and 250 PSI***
2. ***CGT2000 Portable System- 400°C and 300 PSI***
3. ***ARL System 2.0 - 500°C and 500 PSI.***

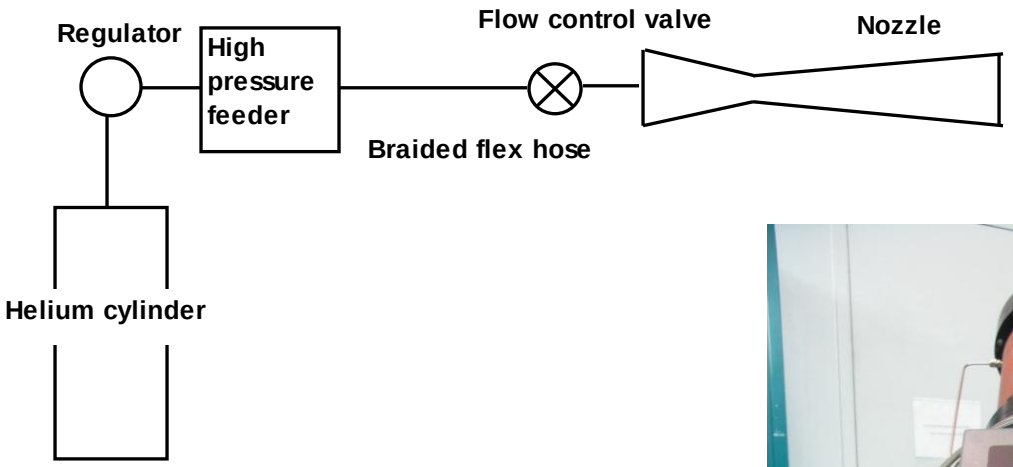
Coating Candidates- Al based coatings systems similar to compositions previously investigated by ARL for other platforms such as Sikorsky H-60

Centerline Demo at NAS North Island June 2010

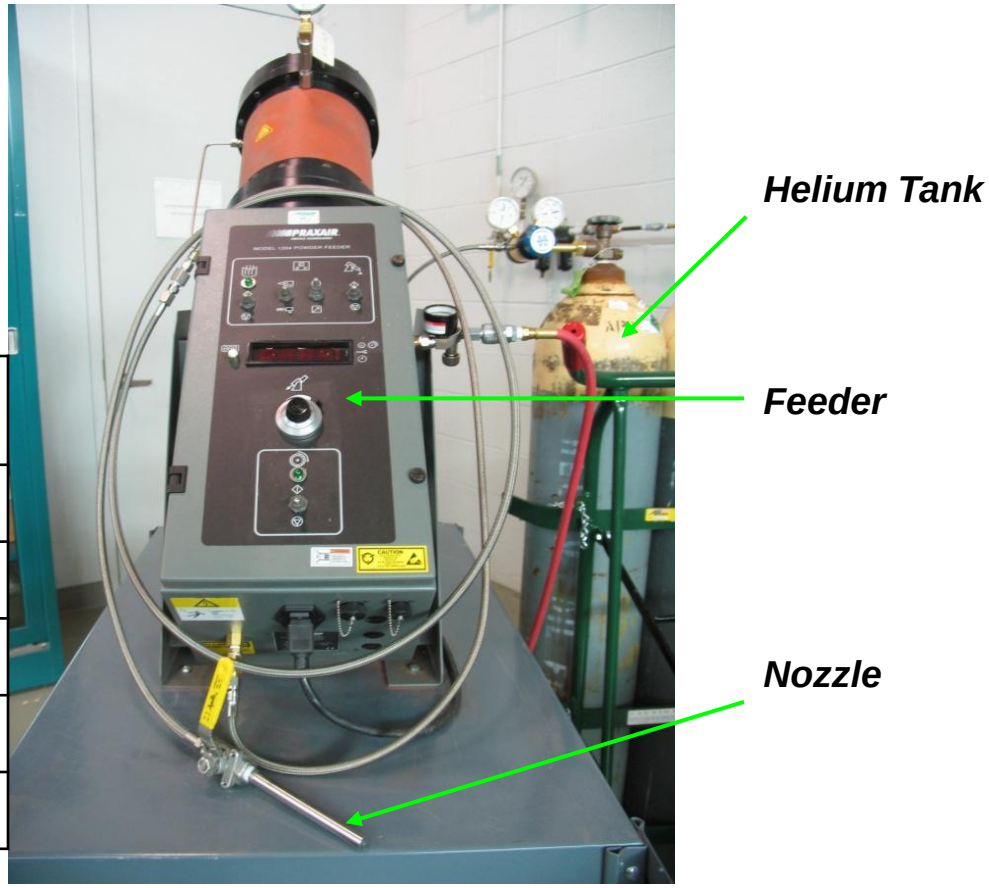
TIPS Test Matrix

Test Matrix Summary		
Test Number	**Description**	**Total Number of Specimens**
1	Tension, 1.5:1 Blend, R 0.100- ASTM B 557M-07	**42**
2	Tension, 2.5:1 Blend, R 0.100- ASTM B 557M-07	**42**
3	Tension, 1.5:1 Blend, R 0.120- ASTM B 557M-07	**42**
4	Tension, 2.5:1 Blend, R 0.120- ASTM B 557M-07	**42**
5	Tension (undamaged)- ASTM B 557M-07	**42**
6	4 point bending, 1.5:1 Blend, R 0.100- ASTM D 6272-10	**42**
7	4 point bending, 2.5:1 Blend, R 0.100- ASTM D 6272-10	**42**
8	4 point bending, 1.5:1 Blend, R 0.120- ASTM D 6272-10	**42**
9	4 point bending, 2.5:1 Blend, R 0.120- ASTM D 6272-10	**42**
10	4 point bending (undamaged) ASTM D 6272-10	**42**
11	Fatigue dog bone, 1.5:1 Blend, R 0.100- ASTM E 606-04	42
12	Fatigue dog bone, 2.5:1 Blend, R 0.100- ASTM E 606-04	42
13	Fatigue dog bone, 1.5:1 Blend, R 0.120- ASTM E 606-04	42
14	Fatigue dog bone, 2.5:1 Blend, R 0.120- ASTM E 606-04	42
15	Fatigue dog bone (undamaged) ASTM E 606-04	42
Overall Total Number of Specimens		**630**

The Portable He System

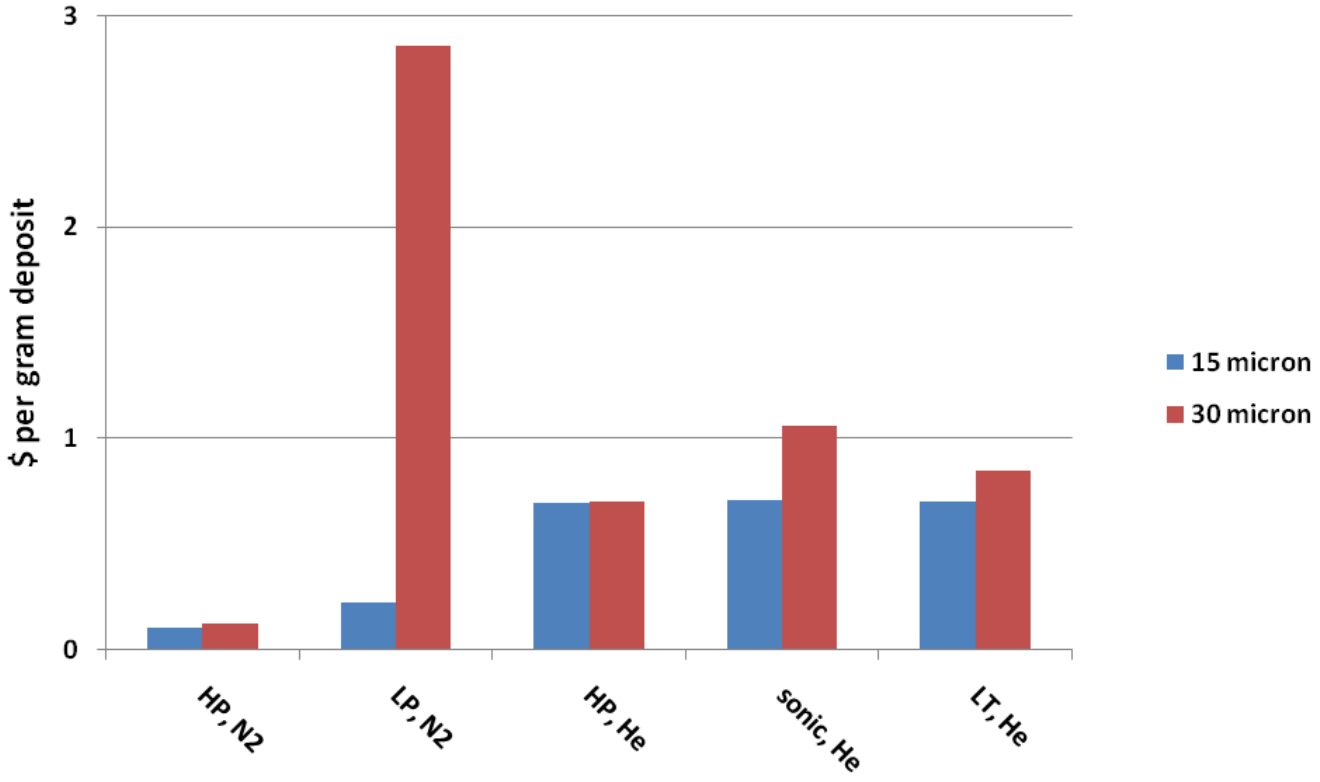


Operating Parameter	Value
Helium Pressure	400 – 500 psi
Helium Temperature	500 Degree C
Helium Flow	20 SCFM
Powder Flow	1 – 5 gram/minute
Particle Exit Velocity	1000 meter/second



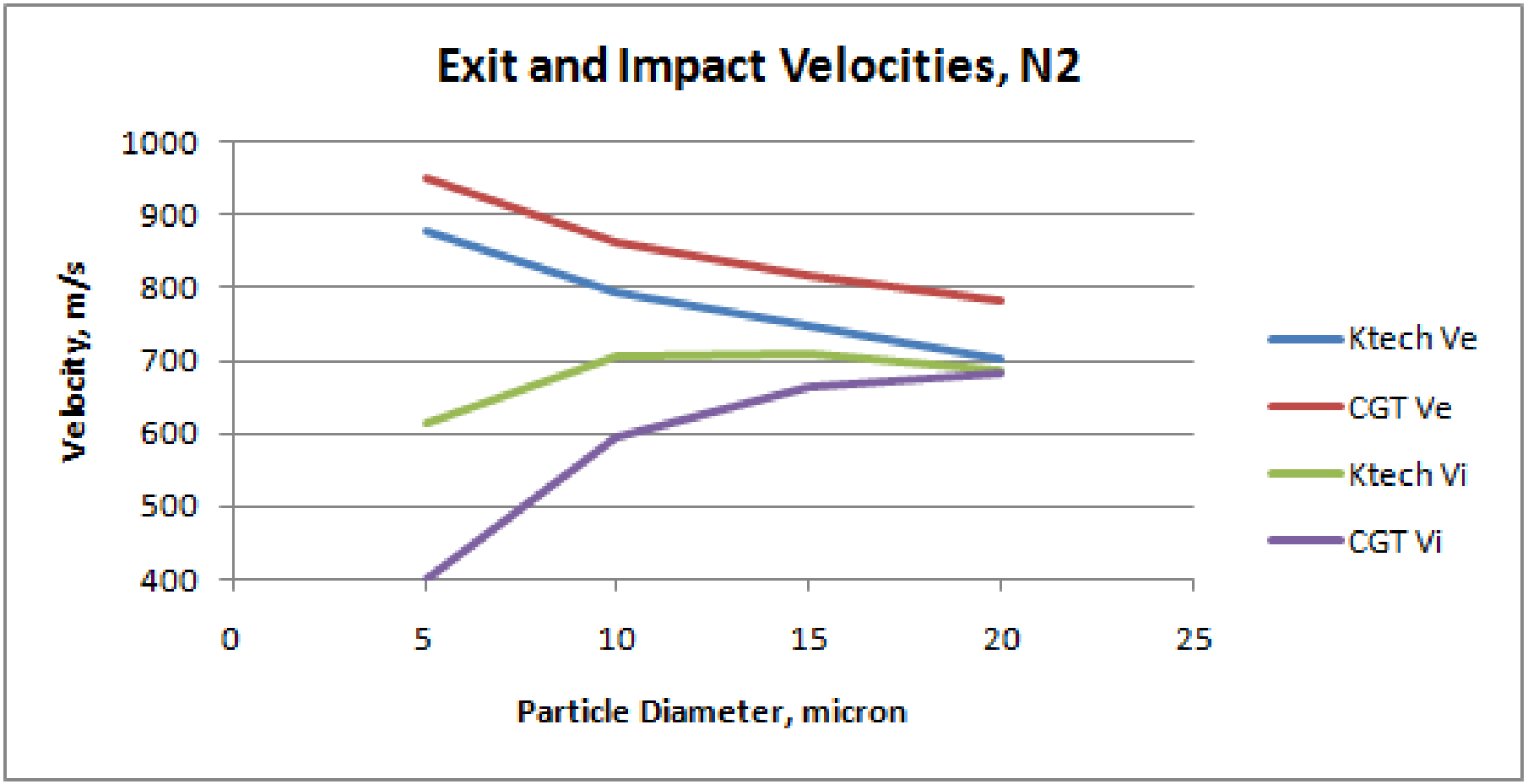
Powder Specification

- ARL is developing an Aluminum Powder Specification



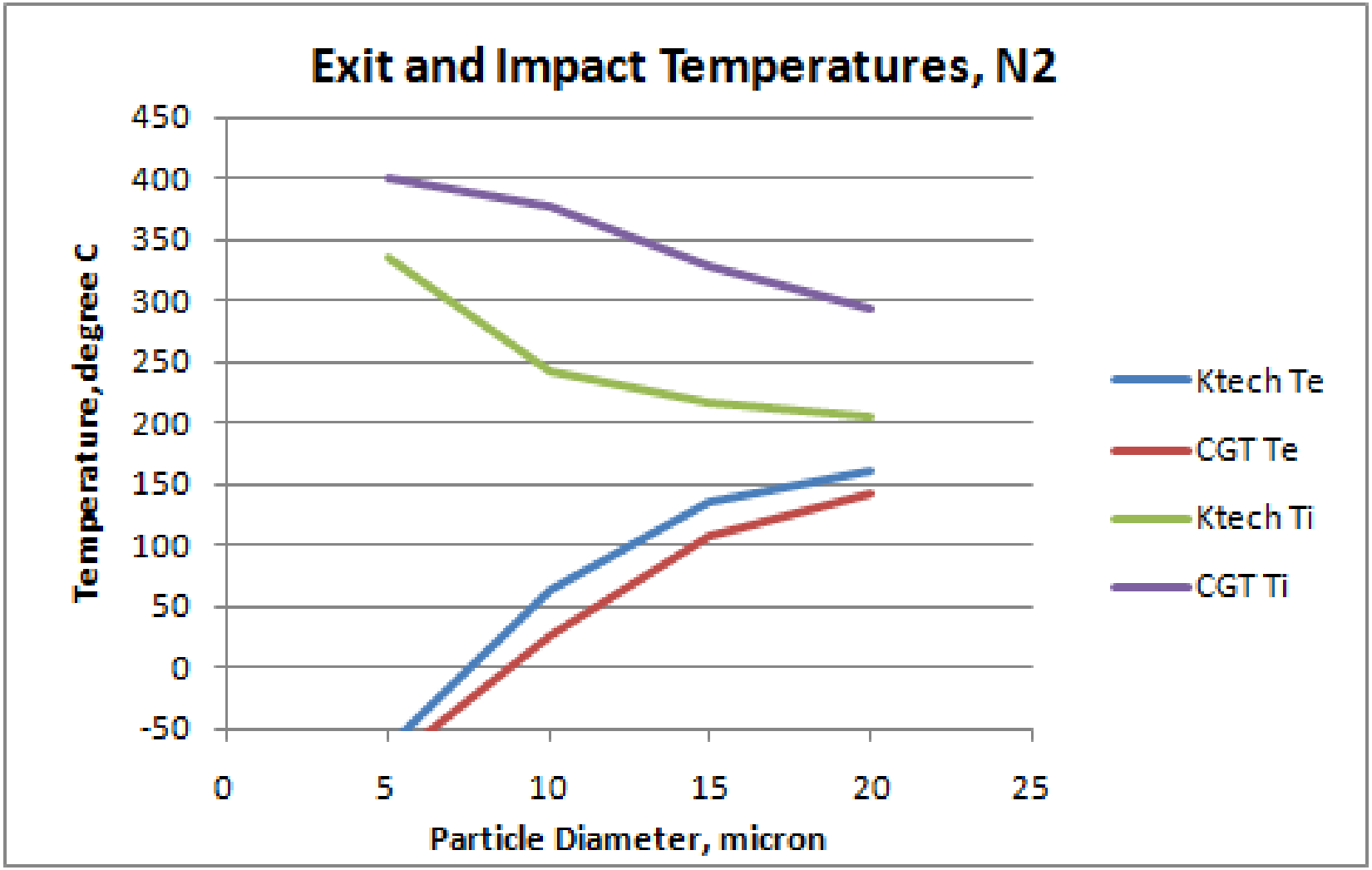
Powder Specification

- Particle Velocities vs. Particle Size



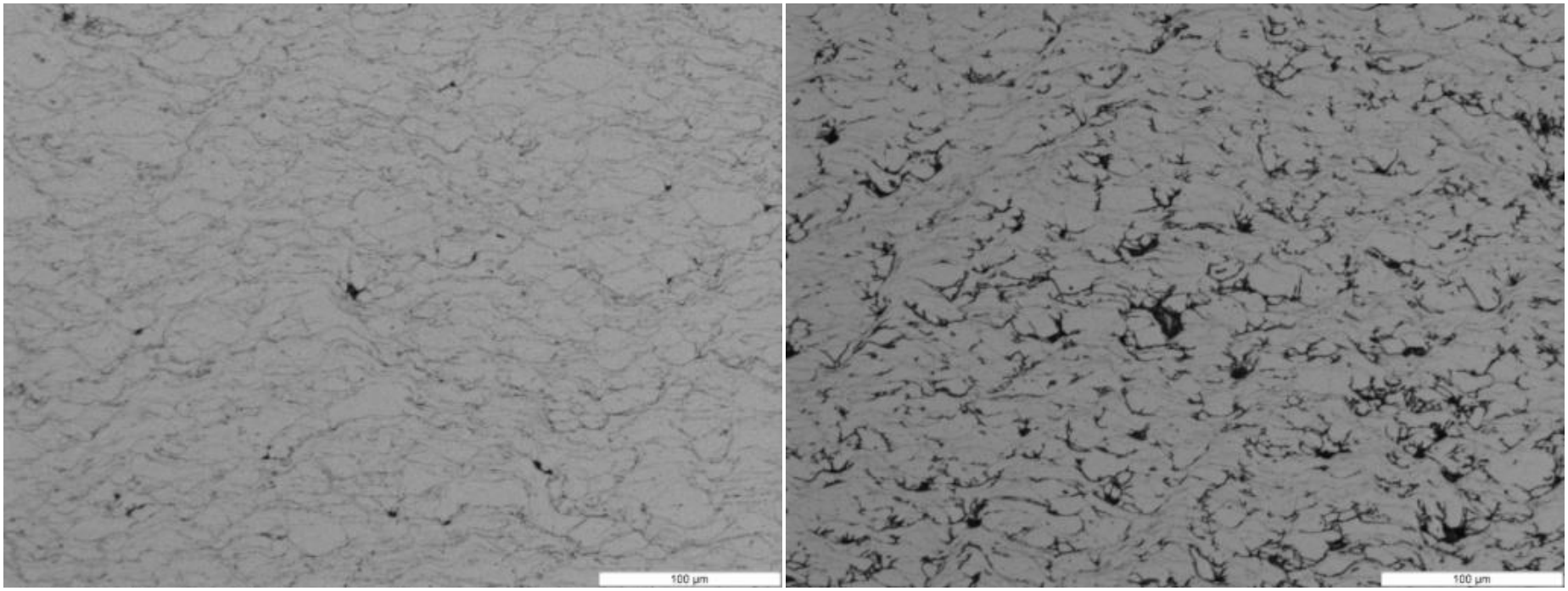
Powder Specification

- Particle Temperatures vs. Particle Size



Powder Specification

- **What role does temperature play on Al coating microstruture?**



Conclusion

- Previous projects proved non-structural cold spray repair of magnesium
  - FRC-East
  - CCAD
  - Sikorsky
- Currently Pursuing Structural Repair
  - H-60 IGB
- Qualifying Low Pressure at FRC-East
- Developing Al Powder Specification