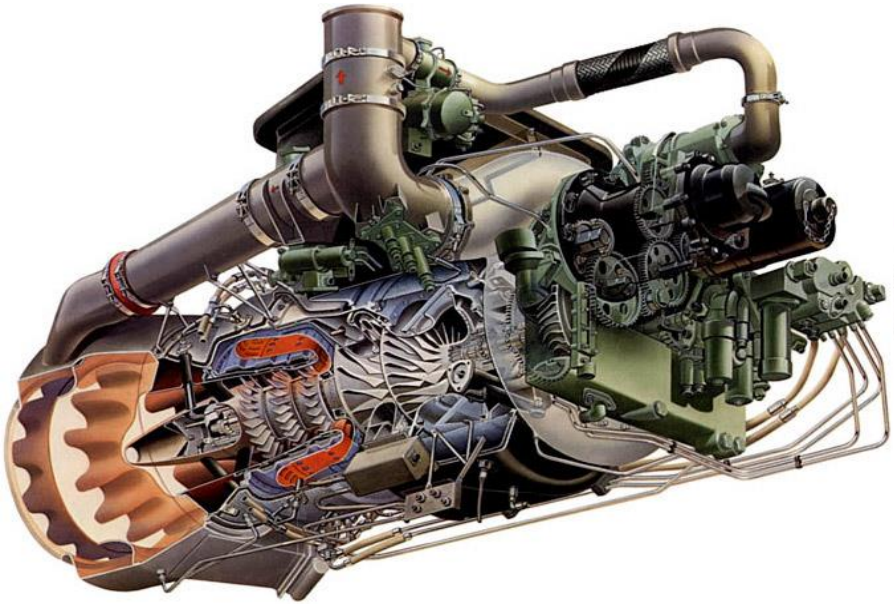
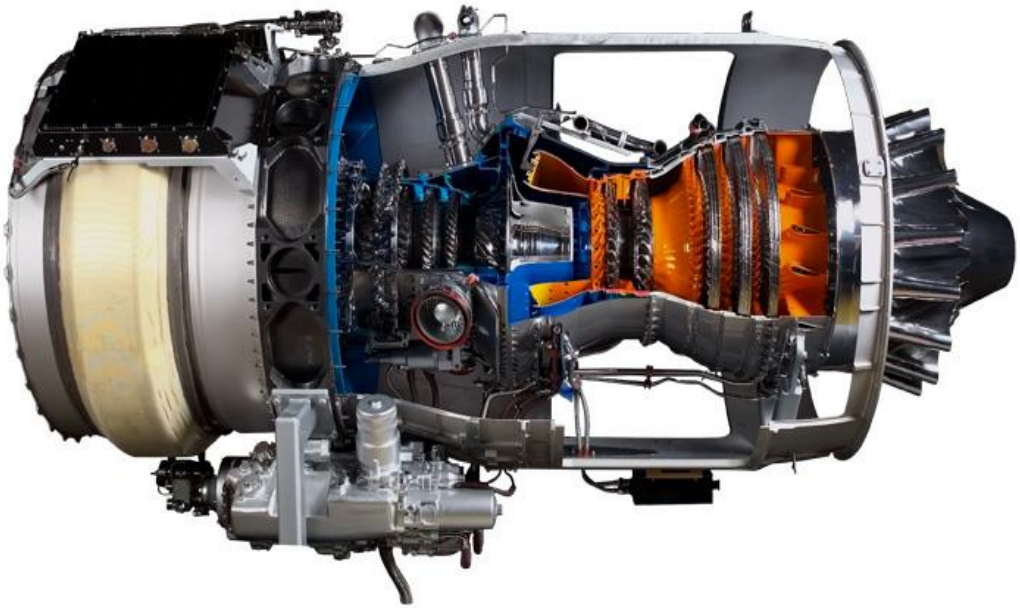




Cold Spray Repair Technology at Honeywell

Daniel Greving, Bruce Almond, Anh-Tuan Ngo, Mike Vahling, Jesus Moedano, and William Sayler

CSAT 2016

Honeywell

Agenda

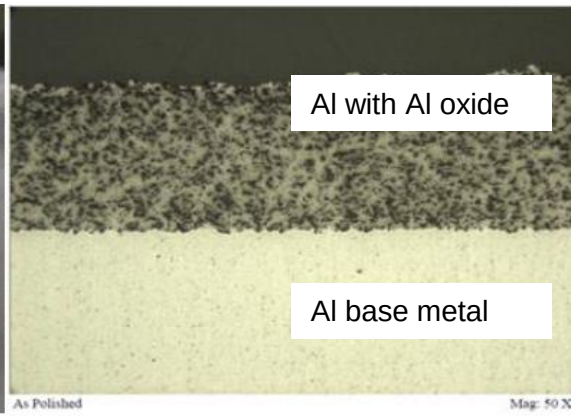
- **Introduction**
- **Background**
- **Low-Pressure Cold Spray Repairs at Honeywell**
- **Development of High-Pressure Cold Spray for Structural Repairs**
  - Process for qualifying structural repairs
  - Collaboration with Army Research Laboratory (ARL) and MOOG using Aluminum 6061 material for aluminum and magnesium components
  - Sample of preliminary results
  - Future testing
- **Summary and Conclusions**
- **Acknowledgements**

Introduction

- **Cold spray is a core repair technology for Honeywell Aerospace**
- **Currently Honeywell Repair and Overhaul (R&O) has over 160 features covered under 60+ approved part repair procedures**
- **Repairs developed using suppliers and in-house equipment**
- **All current repairs use low-pressure systems for non-structural applications**
  - Dimensional restoration
  - Fretting, pitting, corrosion repair
  - Seal surface repair
  - For APU, propulsion, fuel / oil pumps, air-cycle machines, gearboxes & other housing components
- **Developing structural repairs using high-pressure cold spray**
  - Structural is a major category repair where the load bearing capability of the material deposit is required
  - Requires FAA approval, design level material data, process control, detailed structural analysis (FEA), classical methods, and qualification

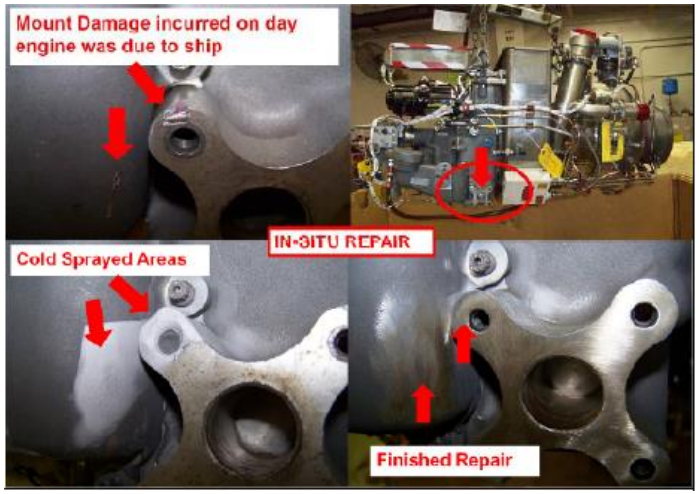
Background – Development of Cold Spray Repairs

- **Honeywell R&O first started production cold spray repair development in 2007**
- **First repairs released in 2009 using low-pressure cold spray on aluminum and magnesium gearboxes and housings**
- **Repair applications use a blend of aluminum and aluminum oxide powders**
- **Essentially all aluminum and magnesium non-structural features can be repaired with basic low-pressure systems**
  - Engine, pump, and valve components are now being repaired with cold spray



Honeywell

Background: Cold Spray Repair Applications at Honeywell



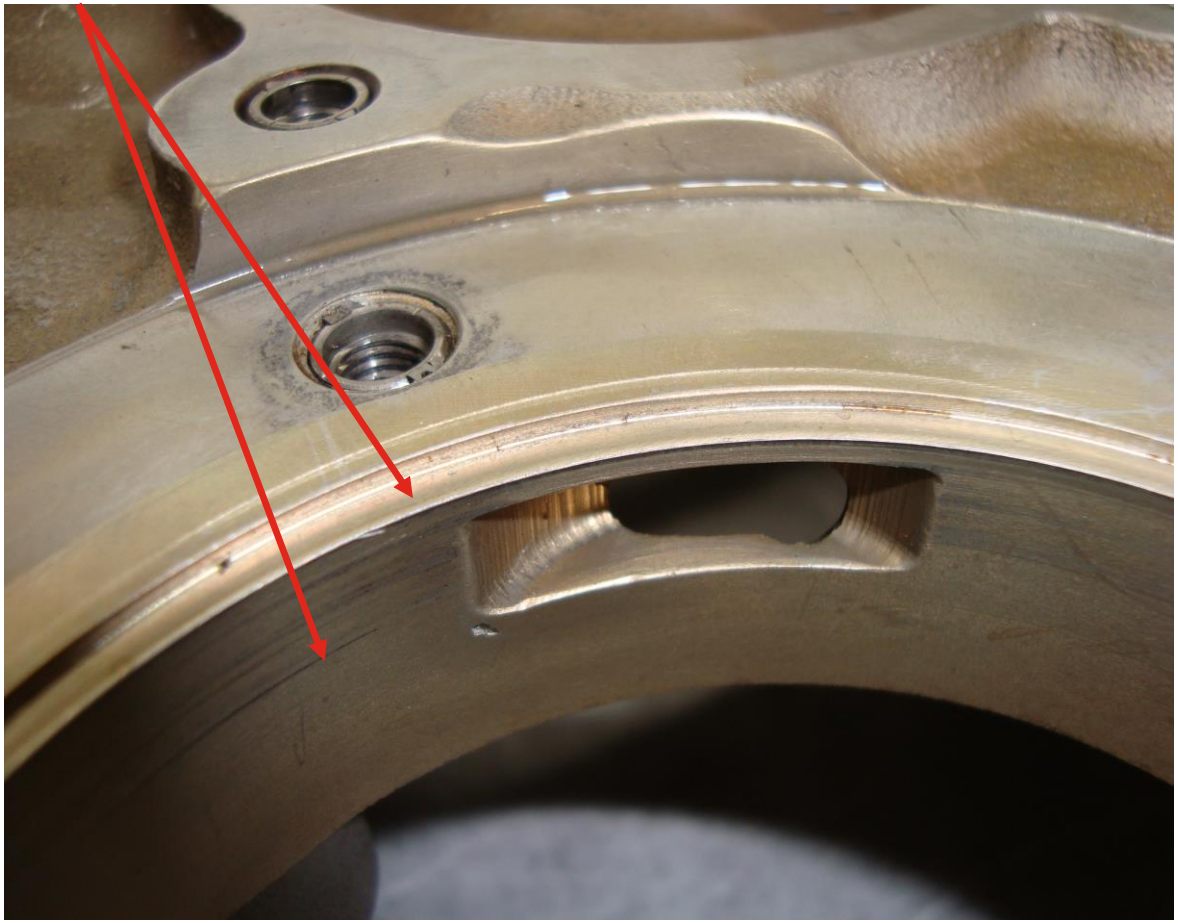
In-Situ Engine Repairs

Component Repairs

Honeywell

Background: Cold Spray Repair Applications at Honeywell

- **First parts back from service that were cold spray repaired**
- **Every bore is repaired at first shop overhaul event**



- After cold spray implementation, the bore did not require repair at next shop visit
- Tolerance for bore is .0005 inches
- Cold spray offers longer service life

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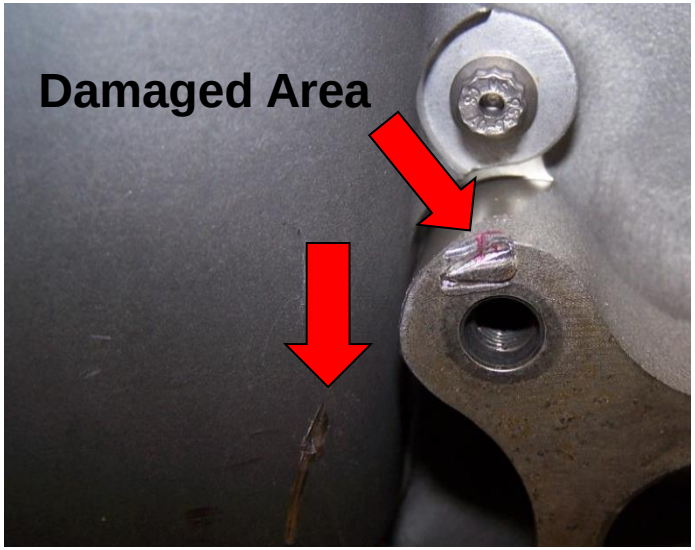
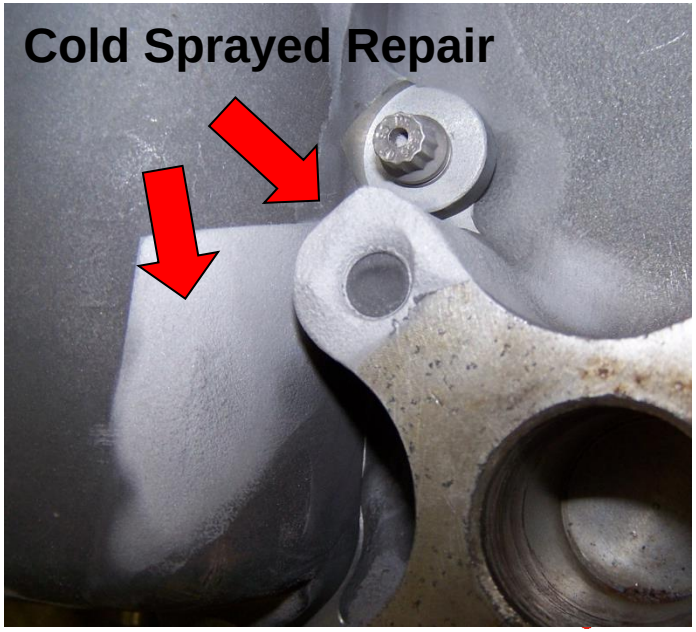
In-Situ Mount Damage Repair

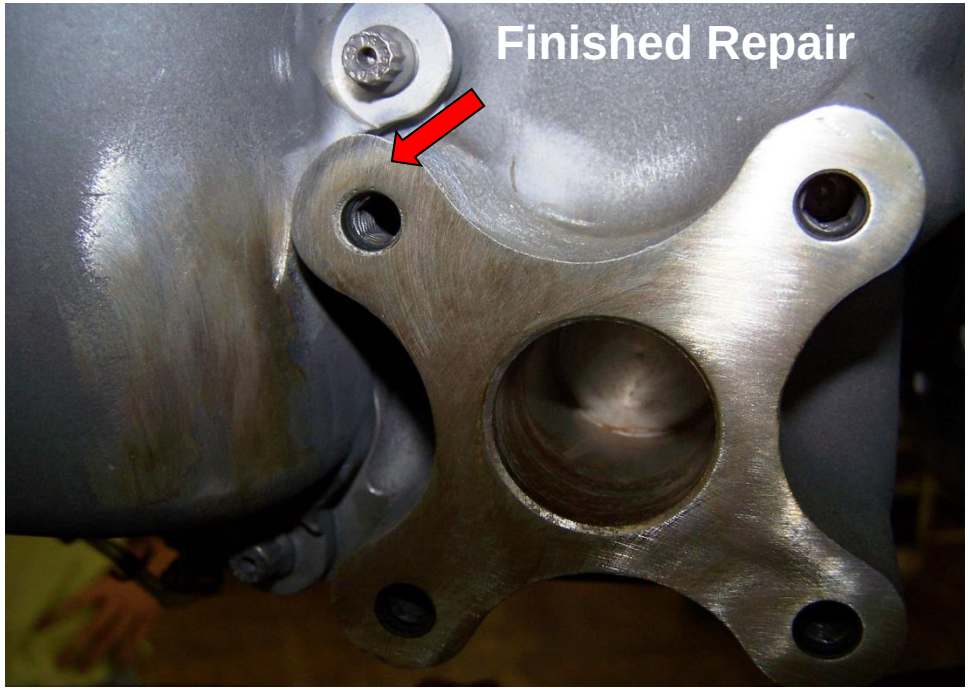
- Customer returned engine that was damaged en route after overhaul
- Engine was masked/ protected in box
- Cold Spray repair process was performed with engine still in the shipping box



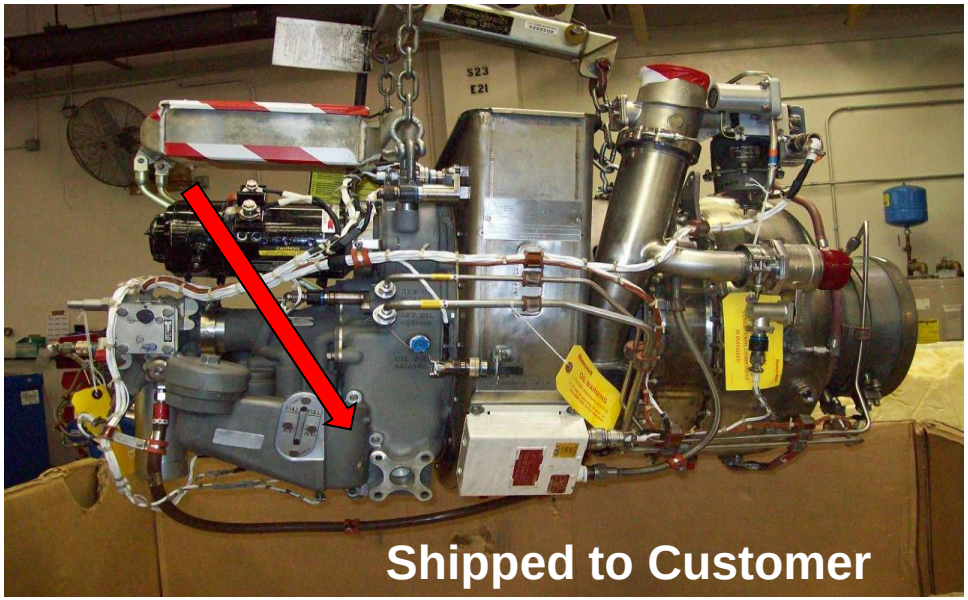
Engine in shipping box



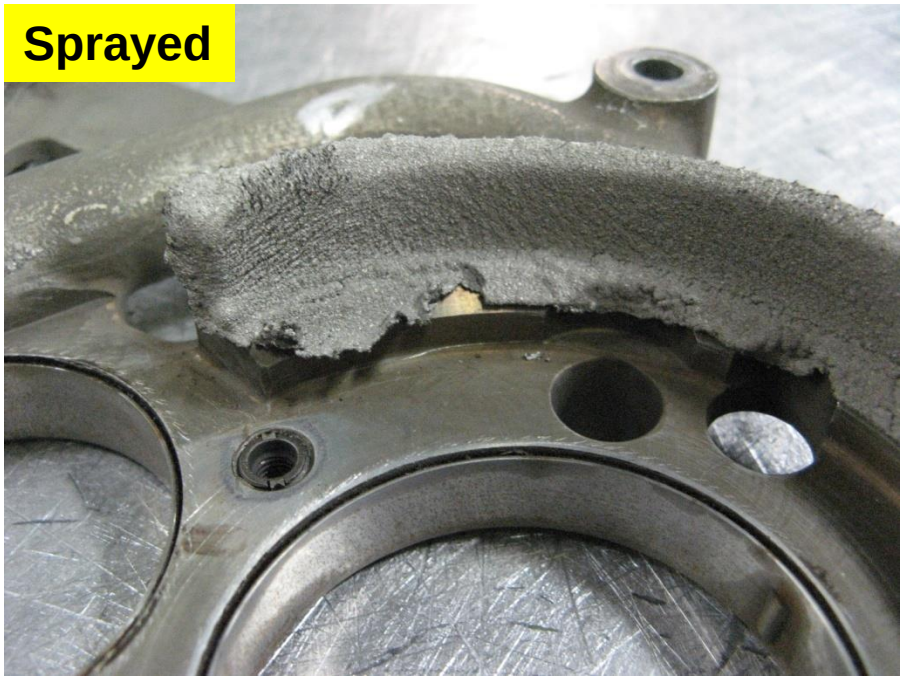
Substantial Cost and Labor Savings

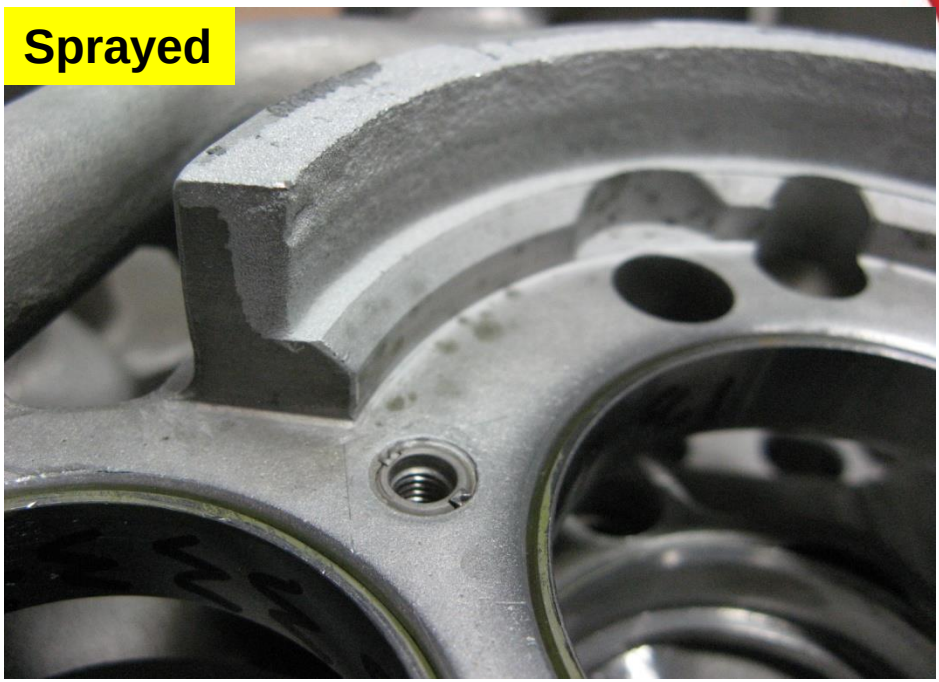


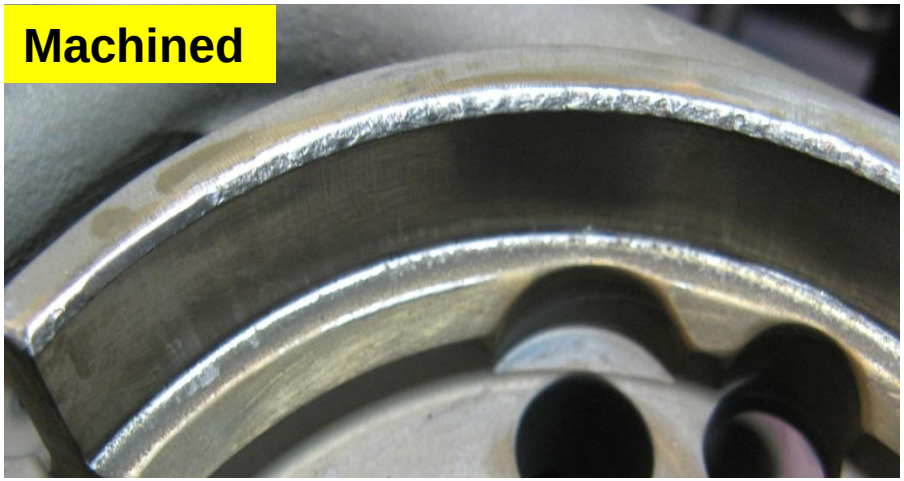
- **Total repair time from start to finish 6 hours**



Thermal spray vs Cold Spray



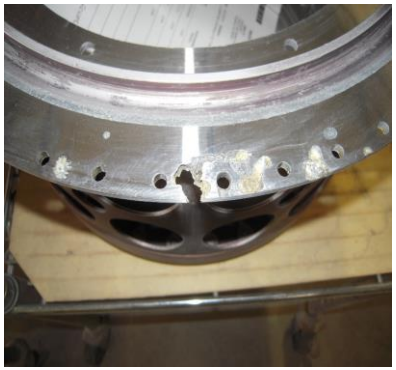


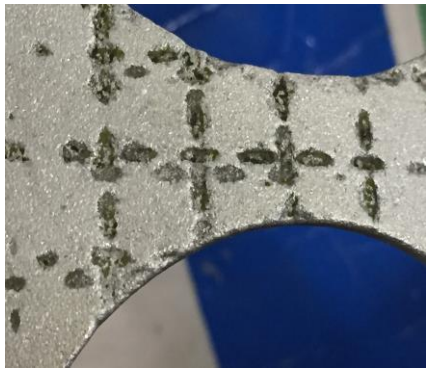


Repair Process Benefits Over Thermal Spray

Opportunities for Structural Repair

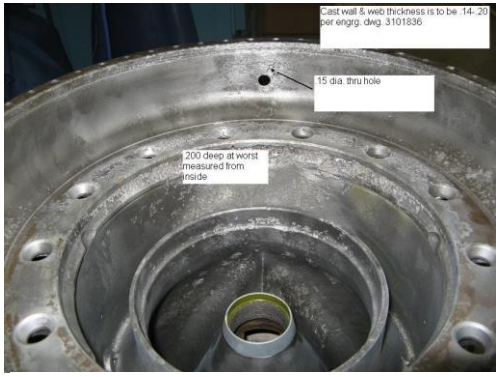
- **Repair of previously un-repairable components due to distortion associated with weld repair and parent material cutback**
  - **Structural repair where the load bearing capability of the material deposit is required**





Inlet Housings

Front Frames



Engine Housing

Seal replacement and parent bore repairs

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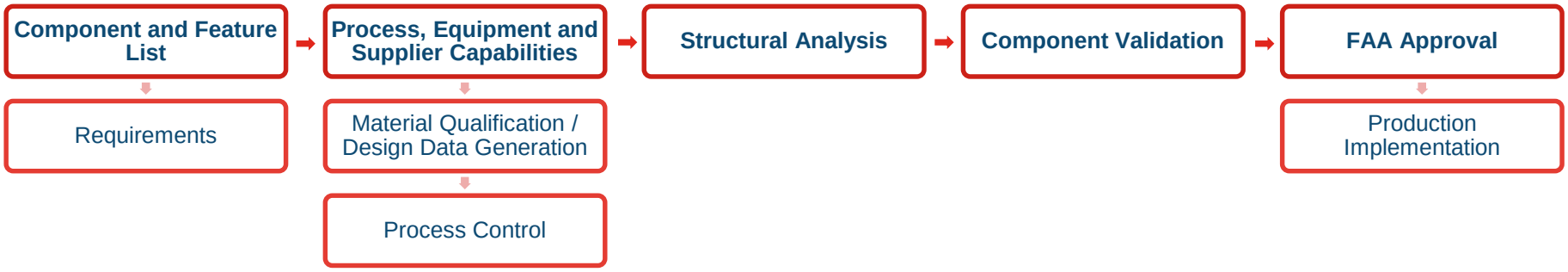
Process for Developing and Qualifying the First Structural Repairs



Initial Component Selection for Structural Cold Spray Repairs

- **Components targeted for first structural cold spray repairs**
  - Cast magnesium and aluminum gearboxes
    - Designed for stiffness, subjected to relatively low stress levels
    - Low strength cast materials
    - Not fatigue life limited
- **Locations targeted for structural cold spray**
  - Damaged threaded holes adjacent to tight tolerance bore diameters
  - Bore ID
  - Spider carrier mounting pads
  - Build up undersized casting walls (casting shifts)
  - Broken bolt ears
  - Undersized flange thickness
  - Cracks and damages at locations where welding will cause distortion and tensile and shear stress levels are below tensile and shear adhesion strength

Low Strength Materials Selected for Structural Repair

High-Pressure Cold Spray Systems Required to Meet Desired Mechanical Properties

- Requirement that the deposited material have similar or better mechanical properties to the substrate materials
  - Magnesium ZE41A-T5
  - Aluminum C355-T6

	Magnesium		Aluminum			
	ZE41A		C355		6061 Wrought + Aged	
	70°F	300°F	70°F	300°F	70°F	300°F
UTS (ksi)	29.96	23.2	41.71	37.58	45.49	37.13
Ultimate Shear (ksi)	17.97	13.92	25.02	22.54	27.29	22.27
YS (ksi)	20.26	16.46	33.61	32.66	39.56	35
Shear Yield (ksi)	12.15	9.87	20.16	19.59	23.73	21
CTE (µin/in*F)	15.1	15.1	11.91	12.6	12.44	12.19

- Aluminum 6061 powder selected due to expected properties relative to substrates

Substrate Material Properties for Powder Selection

Collaboration with ARL and MOOG

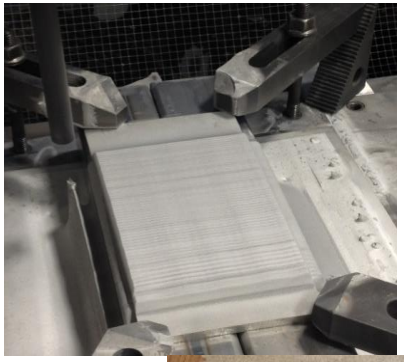
- **Honeywell started an independent collaboration with ARL to develop high-pressure cold spray for structural repairs of aluminum and magnesium gearboxes**
- **Honeywell recognized that the technical expertise and equipment required to develop the processes for a high-pressure structural repair must come from an external source**
- **ARL is the demonstrated leader in the development of high pressure cold spray processes and technology**
- **Coordinated sample preparation and production process development with MOOG**
  - Qualify repairs with a commercial third party source

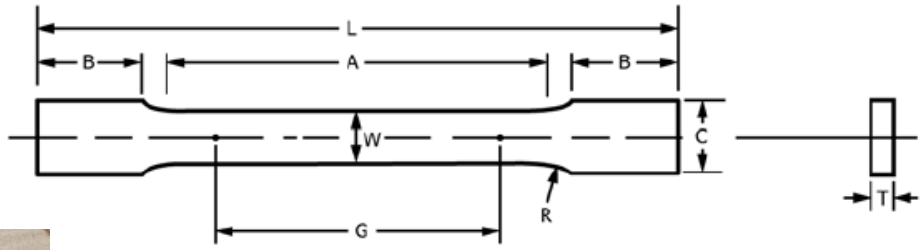
Preliminary Test Matrix

- **All spraying done with VRC Gen III system at MOOG**
- **Cold Spray Metallography and Mechanical Testing at ARL**
- **Testing on cast material substrates simulating production processes**
- **Mechanical testing includes:**
  - Bond strength, shear strength, tensile testing, threaded hole pull test
- **Same test matrix for C355-T6 Al and ZE41A-T5 Mg substrates**
  - Evaluated multiple spray angles on statistically significant quantity of samples
  - Room temp and elevated temp (300°F) testing
- **Cold spray coated specimens representative of production process**
  - Control through process spec, supplier PCC, lot sample evaluation
- **Post failure evaluation of tested specimens**
- **Final demonstration on scrap gearboxes**

Bulk Tensile Specimen

- Cold spray deposited on substrate surface
- Substrate milled away
- Tensile specimen machined to drawing
- Tested to ASTM E8 (subsize specimen)





	Subsize Specimen
	6 mm [0.250 in.] Wide
	mm [in.]
G—Gauge length (Note 1 and Note 2)	25.0 ± 0.1 [1.000 ± 0.003]
W—Width (Note 3 and Note 4)	6.0 ± 0.1 [0.250 ± 0.005]
T—Thickness (Note 5)	
R—Radius of fillet, min (Note 6)	6 [0.250]
L—Overall length, min (Note 2, Note 7, and Note 8)	100 [4]
A—Length of reduced section, min	32 [1.25]
B—Length of grip section, min (Note 9)	30 [1.25]
C—Width of grip section, approximate (Note 4 and Note 9)	10 [0.375]

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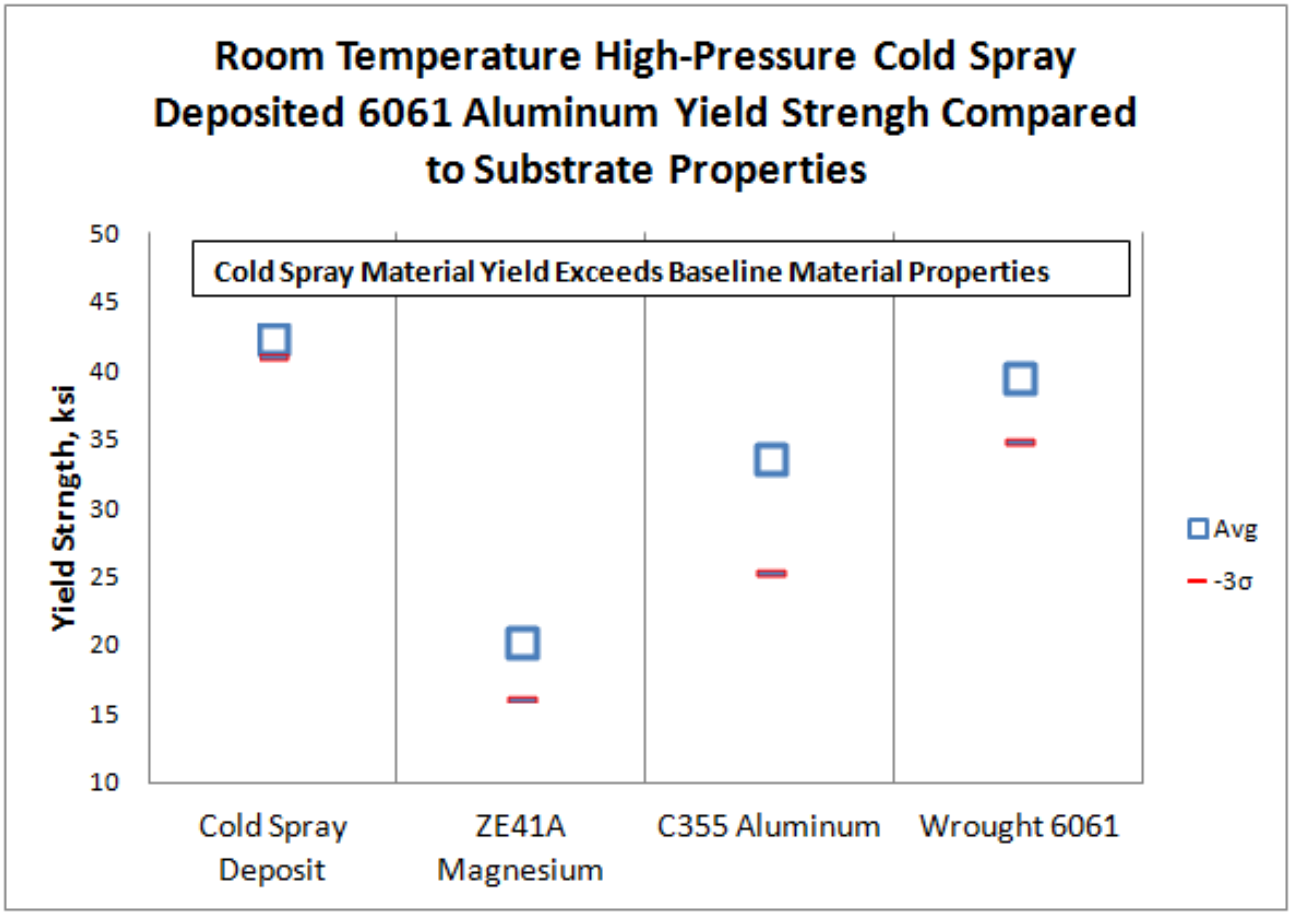
Preliminary Bulk Tensile Results

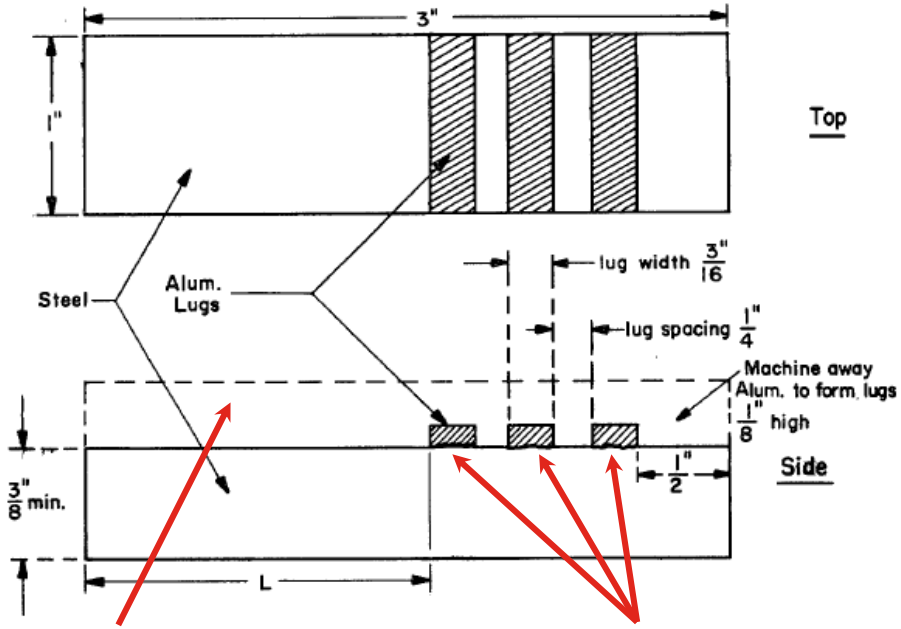


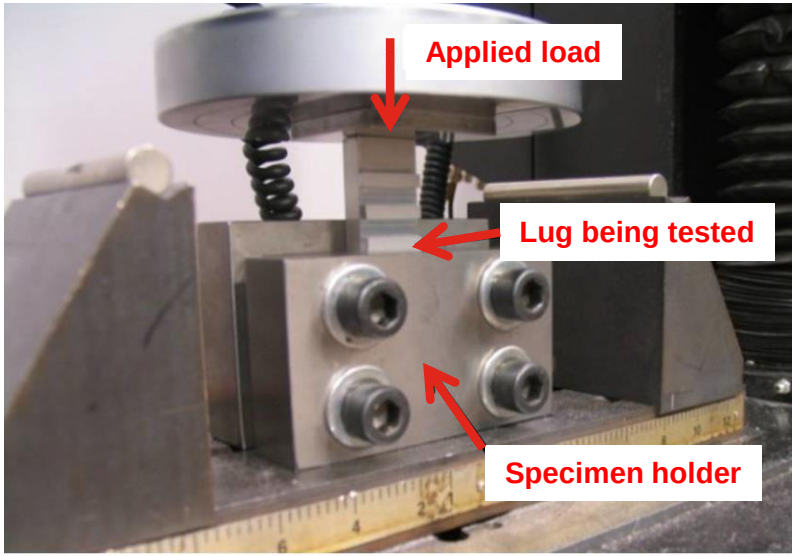
- Pooled data for aluminum and magnesium substrates
- Similar trends for ultimate and elongation values at room temperature and 300 ºF

CS Bulk Material Tensile Exceeds Substrate Properties

Triple Lug Shear Specimen

- Cold spray deposited on substrate material
- Lugs machined in cold spray coating
- Specimens tested





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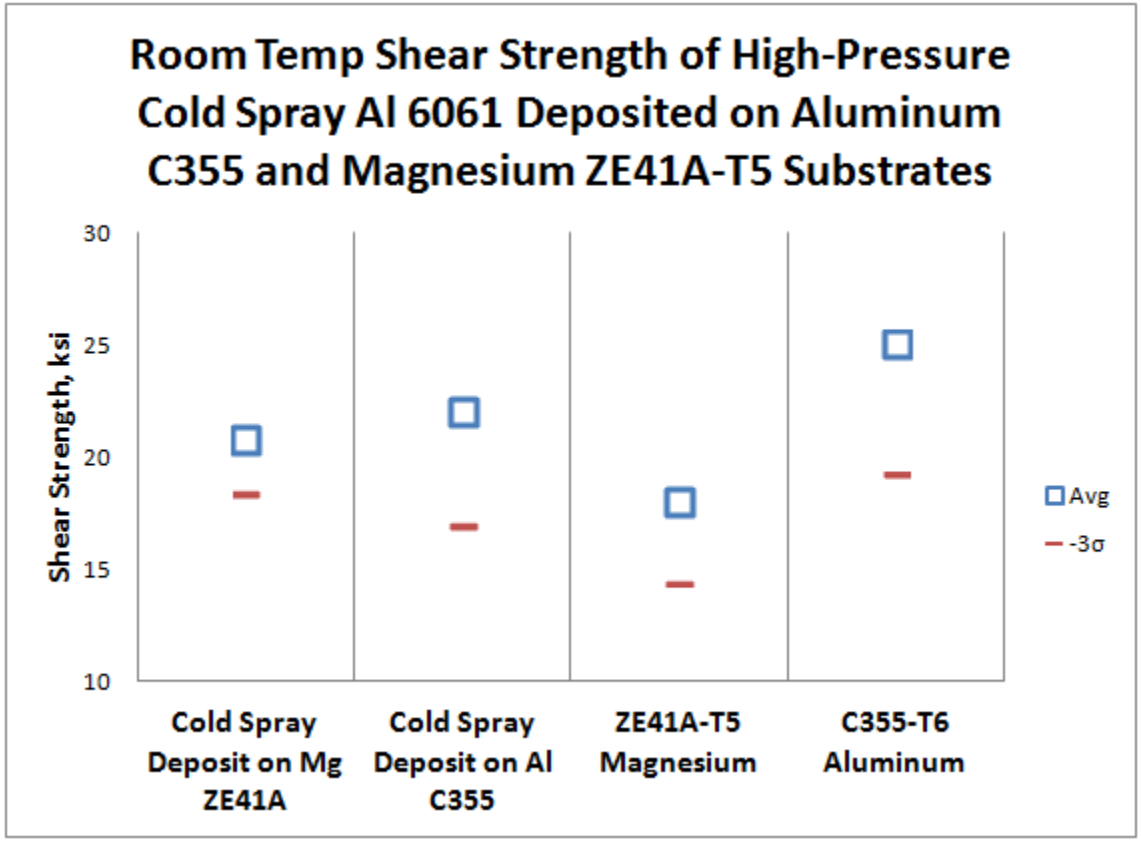
Preliminary Triple Lug Shear Strength Results



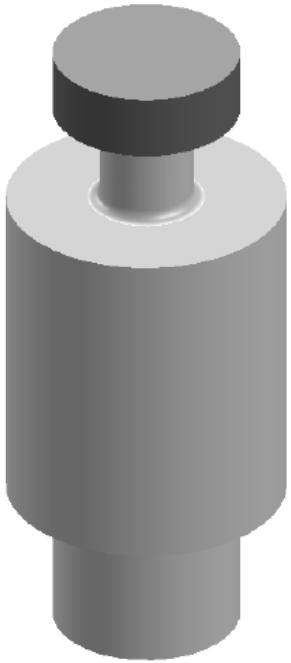
- Similar trends at 300 ºF
- Cold spray shear strength results exceed the Mg ZE41A-T5 substrate properties
- Shear strength less than Al C355-T5 substrate

Shear Strength Results Sufficient for Majority of Proposed Repairs

Glueless Bond Strength Specimen

- Cold spray applied to substrate bond bar
- Specimen machined to size
- Gauge diameter necked down to force failure in CS

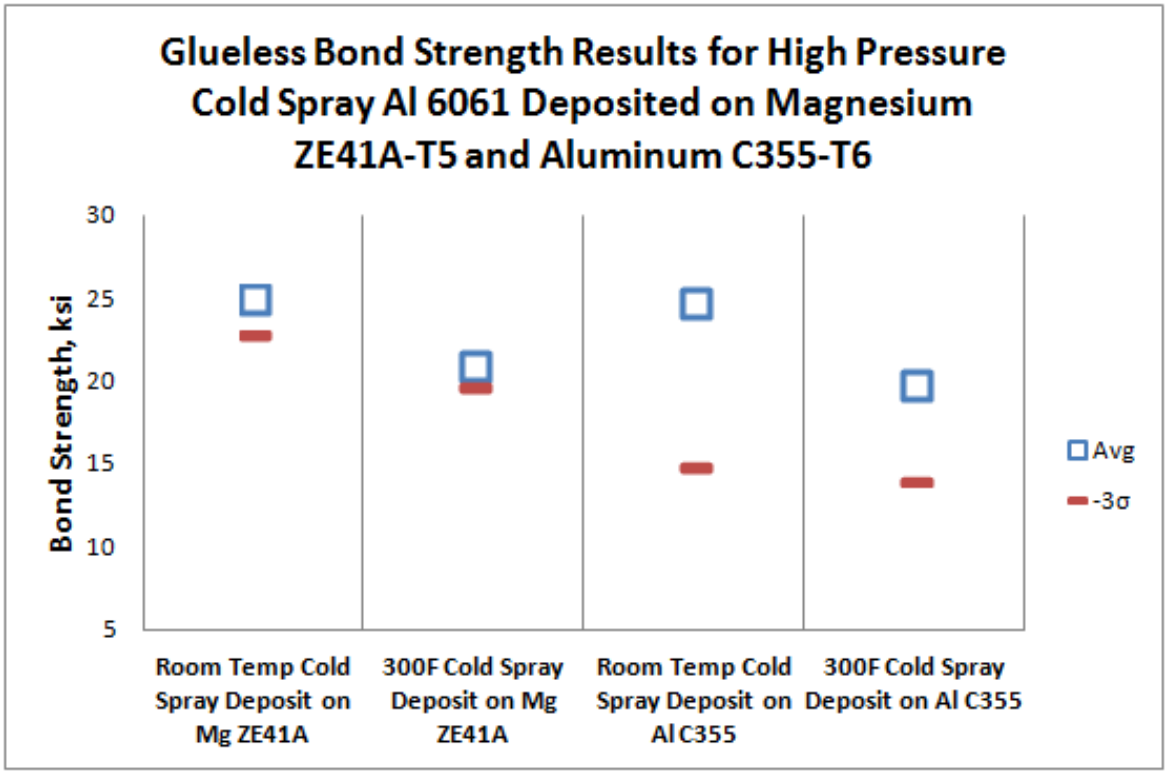
As sprayed



Machined specimen

Honeywell

Preliminary Glueless Bond Strength Results

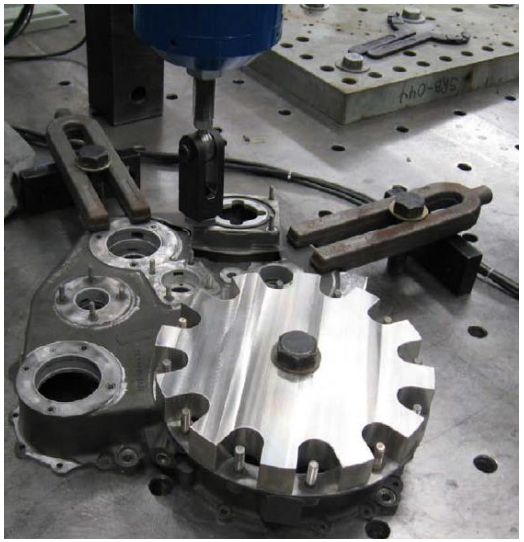


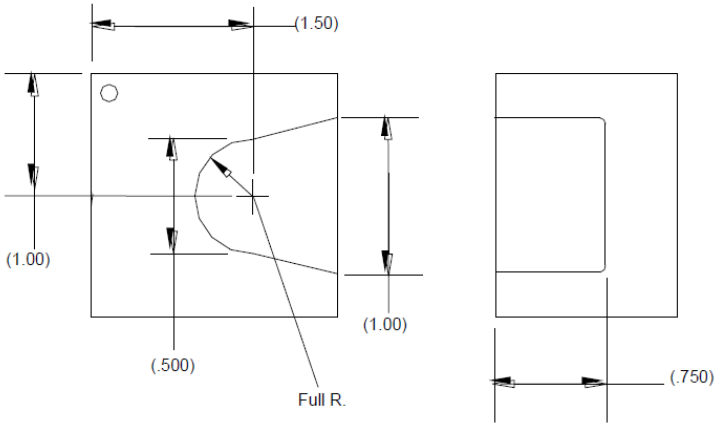
- Similar average performance relative to the two substrate materials
- Higher scatter with Al C355 substrate attributed to higher hardness of base alloy

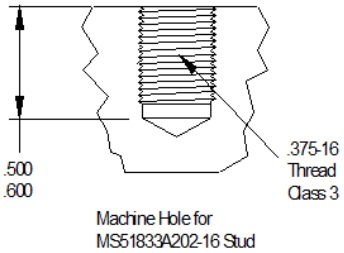
Glueless Bond Strength Results Exceed Expectations

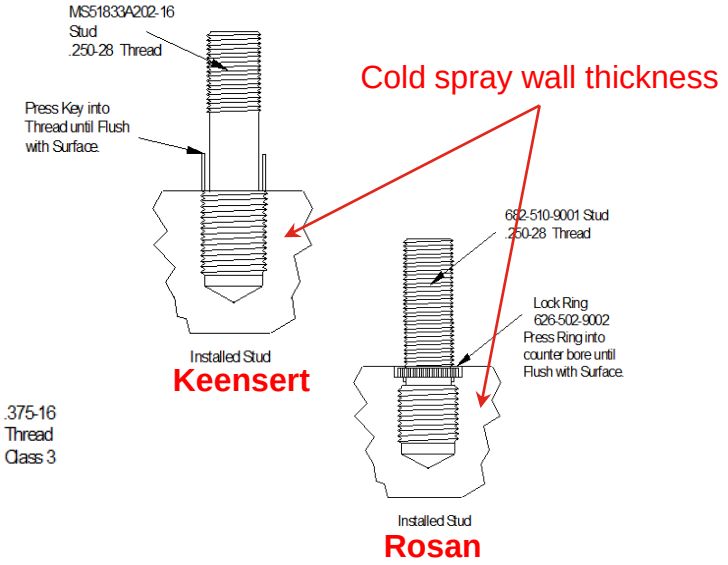
Threaded Hole Pull Test

- Replicate pull load on gearbox flange
- Slot Milled in parent material block (2” x 2” x 1.5”)
- Cold spray to fill machined slot
- Hole drilled/threaded and standard stud inserted
- Tensile load applied on MTS frame until failure
- Compared to parent material









Testing On-going

Scrapped Magnesium and Aluminum Gearboxes for Substantiation Tests

Gearbox
Al C355-T6

Gearbox
Mg ZE41A-T5

Testing On-going

Future Testing and Process Development

- **Complete current test matrix and substantiation tests**
  - Aging of deposited material (tensile/shear)
  - Evaluation of isotropic behavior (tensile)
  - Compression/physical properties
- **He-N gas mixing**
  - DOE for economical coating
  - Tensile/shear/bond strength/metallography
- **Potential of He recovery systems to improve costs**
- **Additional substrate coating development (A356.0-T6 and A357.0-T6)**
  - DOE for alternate substrates
  - Tensile/shear/bond strength/metallography
- **Explore process variation and optimization**
  - Develop production process control and specification
  - Develop processes to optimize repair requirements versus costs
- **Eventual future state is a parametric repair system allowing for optimization of structural capability to material properties and costs**

Summary and Conclusions

- Cold spray is a core repair technology for Honeywell R&O
- Low pressure non-structural repairs are being used extensively today at Honeywell
- High-pressure cold spray for structural repairs under development
  - Preliminary testing demonstrates mechanical properties exceed expectations

Acknowledgments

- Vic Champagne and Dan Kaplowitz at ARL for technical leadership, testing and support of the high-pressure development program
- Chris Howe at MOOG MA for expertise and support
- Christian Widener from South Dakota School of Mines

Questions?