Thermal Processing for Enhanced Additive Repair of Aluminum Structures by Cold Spray Deposition

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BLUF: We are developing thermal processing methods for enhanced functional and structural additive repairs by cold spray deposition for AA7075 and AA2024.

- Successfully demonstrated fastener hole repairs using as-atomized powders.
- Applying powder heat treatment methods to improve deposition and mechanical behavior
- Developing laser assisted cold spray to improve deposition and mechanical behavior
- Applying these methods to structural repairs-fastener holes
- Applying these methods to functional repairs-sills

We are very grateful for funding for this research from Mr. W. Nickerson at the ONR Sea-Based Aviation program (ONR-SBA Project N00014-18-1-2519).

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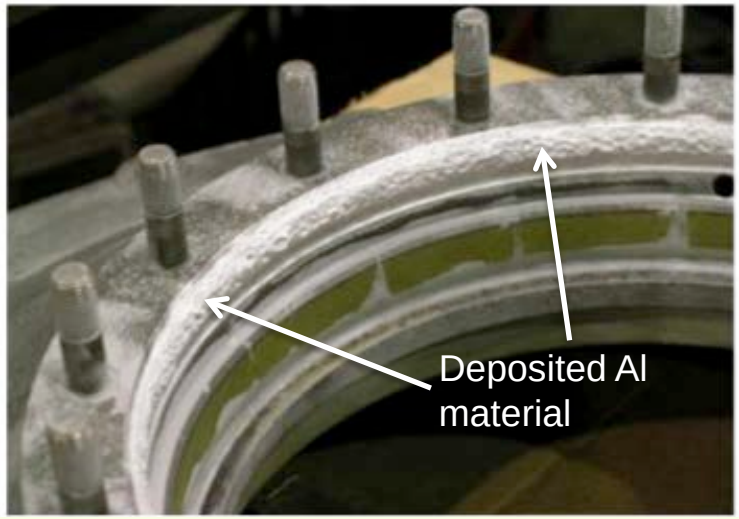
Distribution A

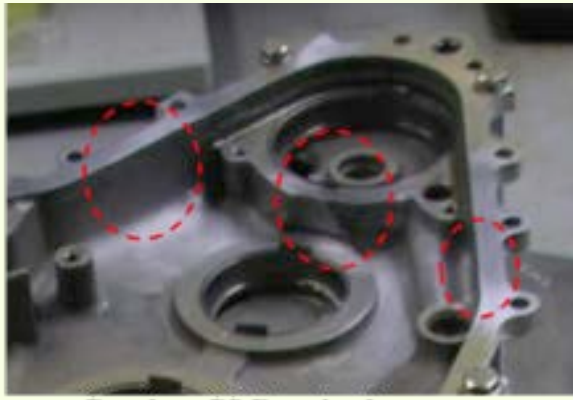
Why is this research necessary?

Cold spray deposition is being deployed for dimensional restoration (now) of DoD aircraft components



R. Jones, 2011

Gearbox Damaged



Gearbox CS Repaired

Photographs courtesy of F. Lancaster

Dimensional restoration of magnesium components with pure Al or aluminum-alumina mixtures.

Why is this research necessary?

Solid State Structural Repair (S3R).

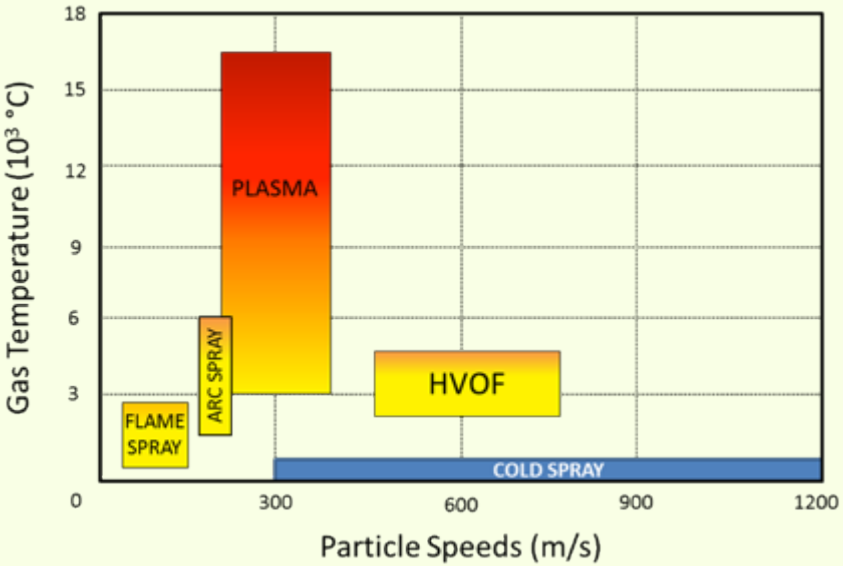
Photograph courtesy of F. Lancaster

We want to repair load-bearing, naval aircraft structures with structural aluminum alloys like AA7075, AA7050, and AA2024, etc.

Cold spray deposition is being developed for full structural repair (future) of DoD aircraft components (and functional repairs (now))

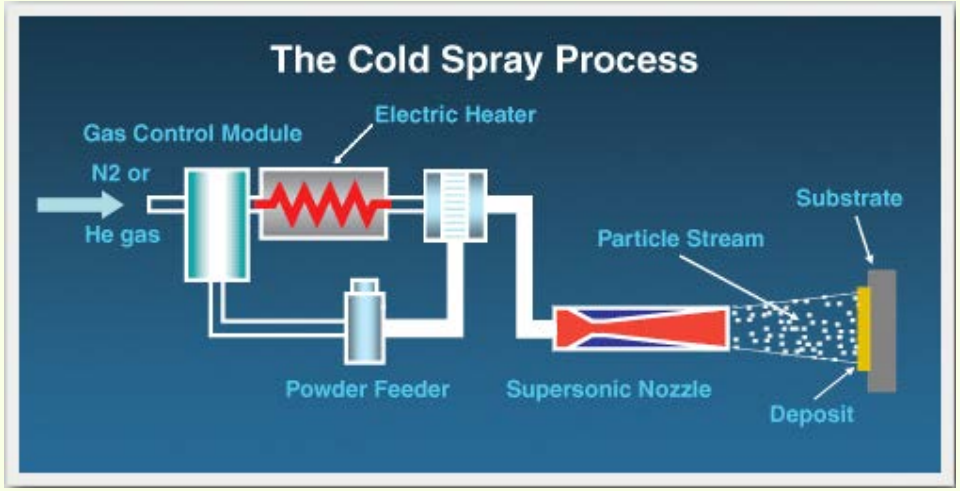
- Develop/specify the right powders
- Choose the best spray conditions
- Design the spray process for complex repair geometries
- Assess the strength and reliability of the additive repairs

Cold Gas Dynamic Spraying



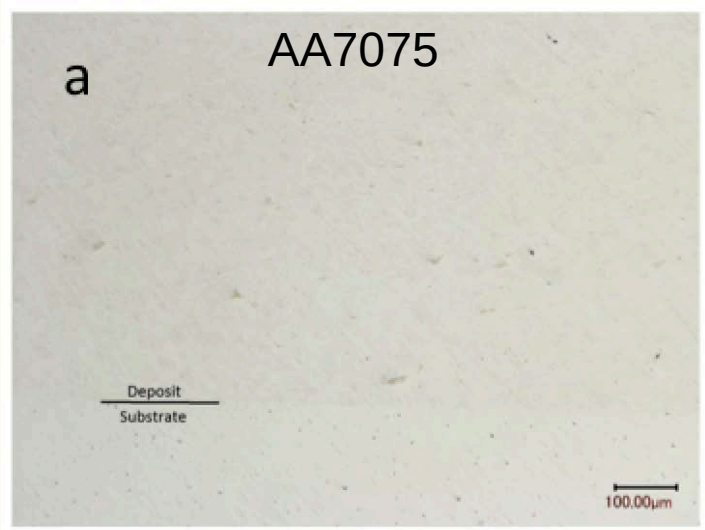
Flame temperature of different thermal spray methods and obtainable particle velocity range. (Figure from V. Champagne, 2007)

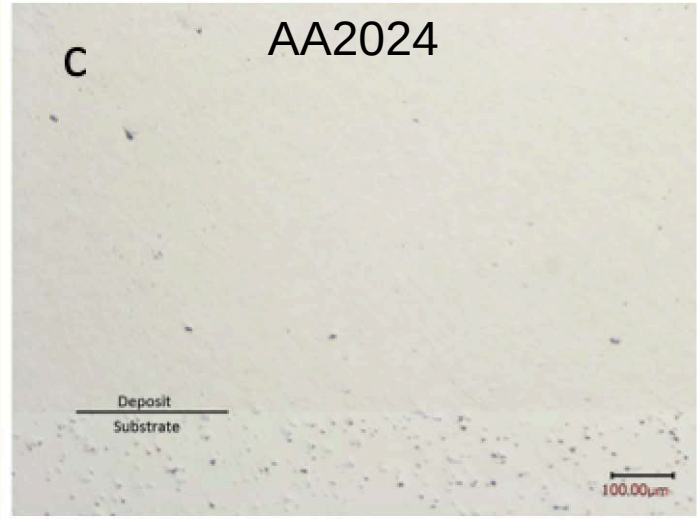
Schematic diagram of High Pressure cold spray system (VRC)

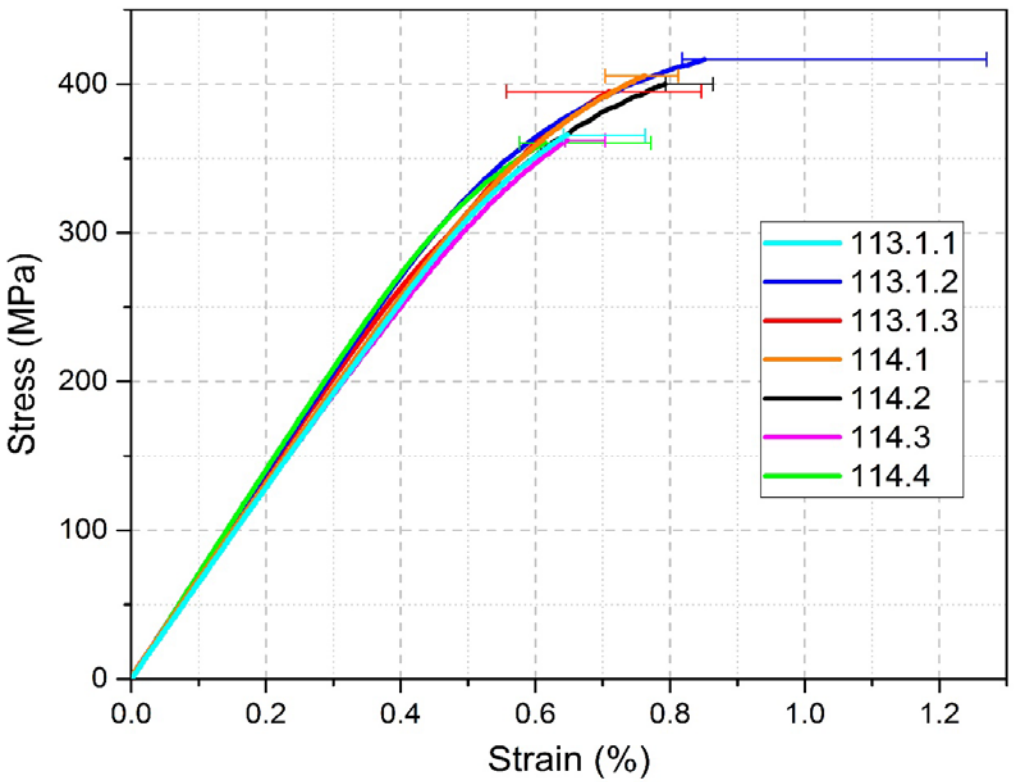


**<u>solid state</u> spray deposition achieved through supersonic velocities of the particles!

Using helium gas produces high quality deposited material.







- UTS values fairy high 370-414 MPa (54-60 ksi)
- as-sprayed ductility in these cold sprayed specimens was less than one-percent
- these results are for <u>as-atomized powder</u>.
- Ductility will very likely improve with
  - Removal of fine particles
  - Heat treatment of particles
  - *In situ* annealing

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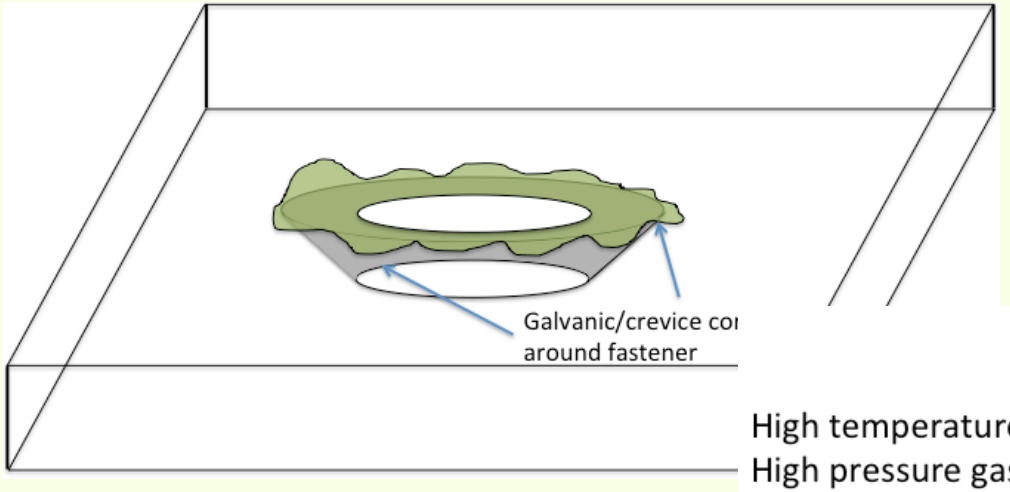
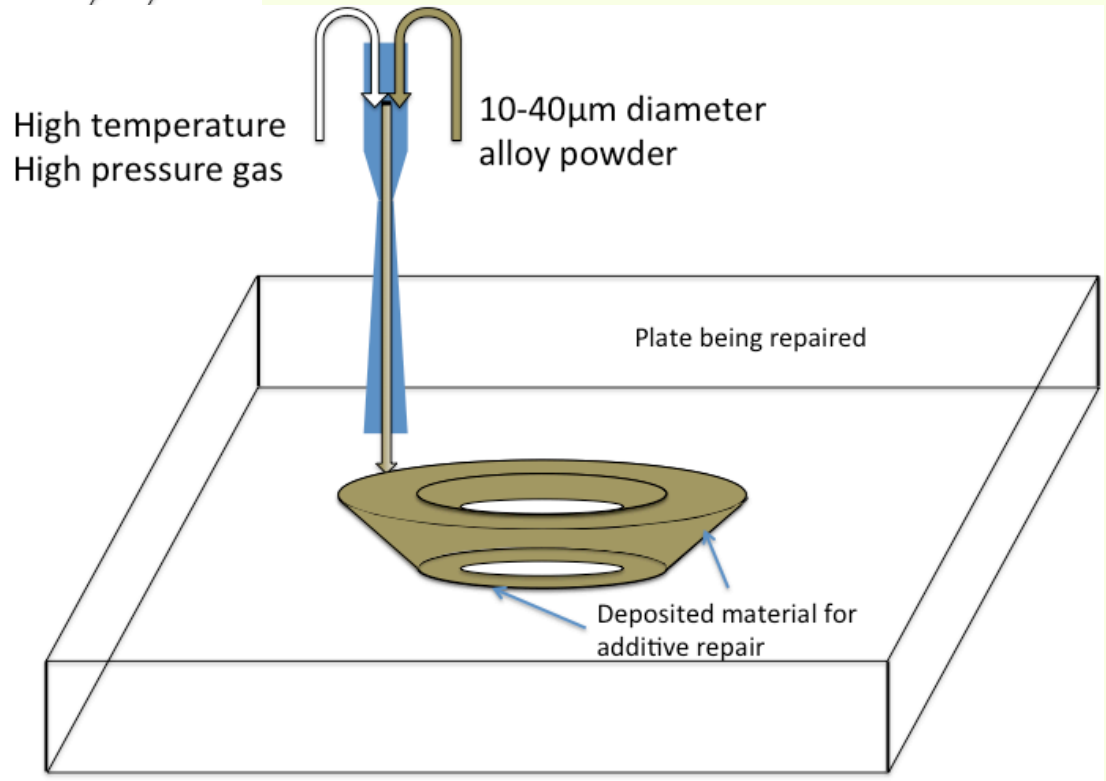
Adhesion of CS deposited AA7075 is satisfactory, but surface preparation sensitive.

- ASTM C633 adhesion test results show that CS AA7075 passes this basic adhesion test (strength > 70MPa)
- Milled surfaces appear to give a better adhesion response compared with sanded or grit-blast surfaces

Surface Condition	**Adhesion Strength MPa**	**Adhesion Strength ksi**	**Type of Failure**
Grit Blasted	74±4	10.7	adhesive
Sanded (60 grit by hand)	71±8	10.3	mixed
Rough Milled 0.05" depth of cut	72±4	10.5	epoxy
Finish Milled .005" DOC	73±4	10.5	epoxy
Angle Ground	73±3	10.6	epoxy

Additive repair of fastener hole using cold spray deposition

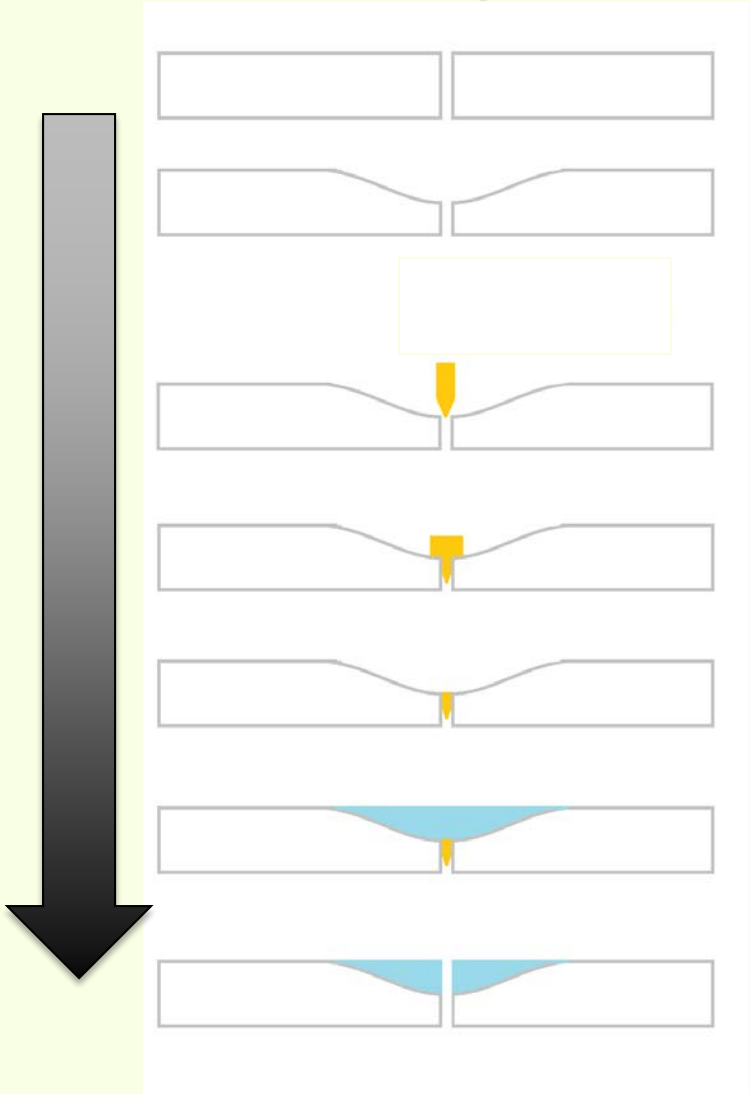




Current Process for Fastener Hole CS Repair

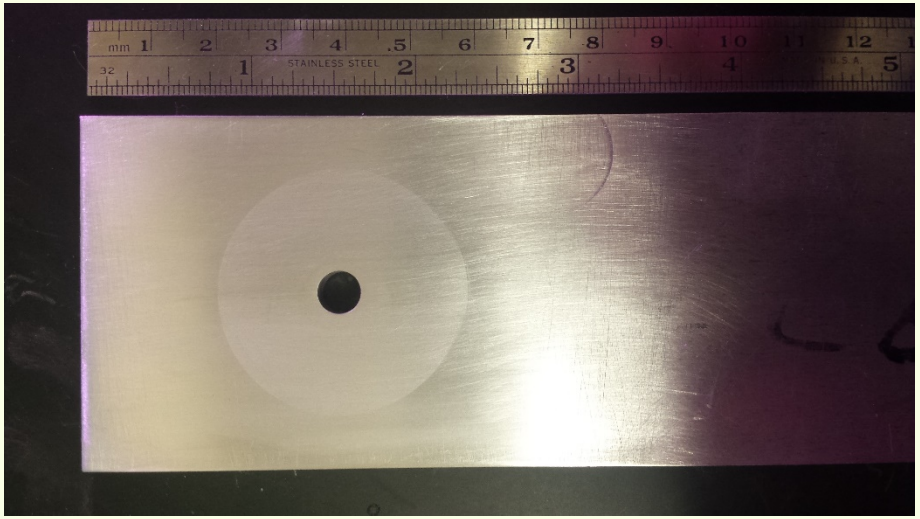
Steps for fastener hole repair process:

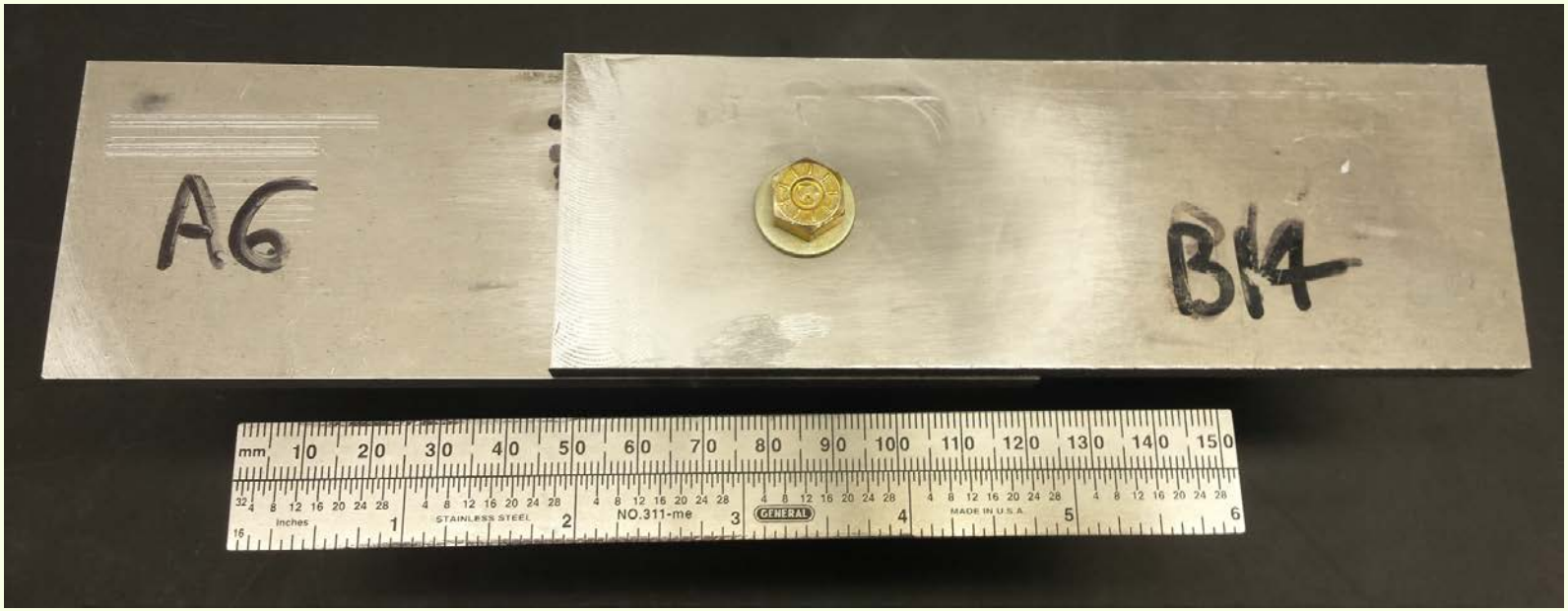
1. Hole is drilled in substrate
2. Cubic spline chamfer is for blend-out.
3. Swage peg of soft ductile material made by chamfering the end of the peg and wedging into the hole firmly.
4. Part is milled again so that the swage peg forms a continuous substrate with the chamfer
5. Part is cold sprayed
6. Hole is drilled in part from back to remove peg
7. Hole is reamed



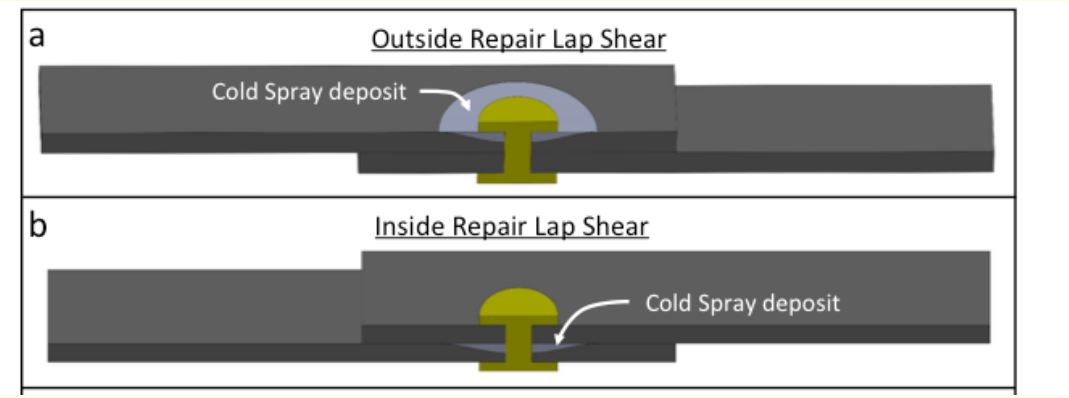
Schematic of repair process.

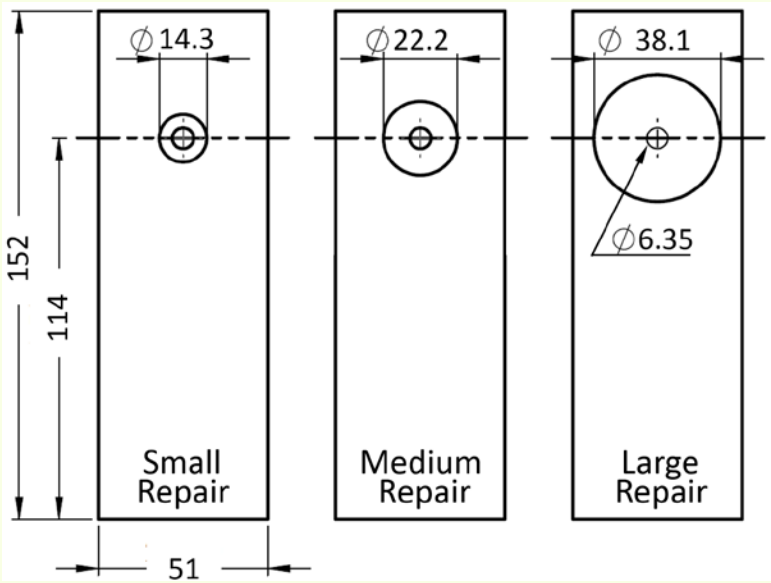
Lap Joint after Repair and Assembly





Two Types of Repair Geometries Evaluated for Fatigue



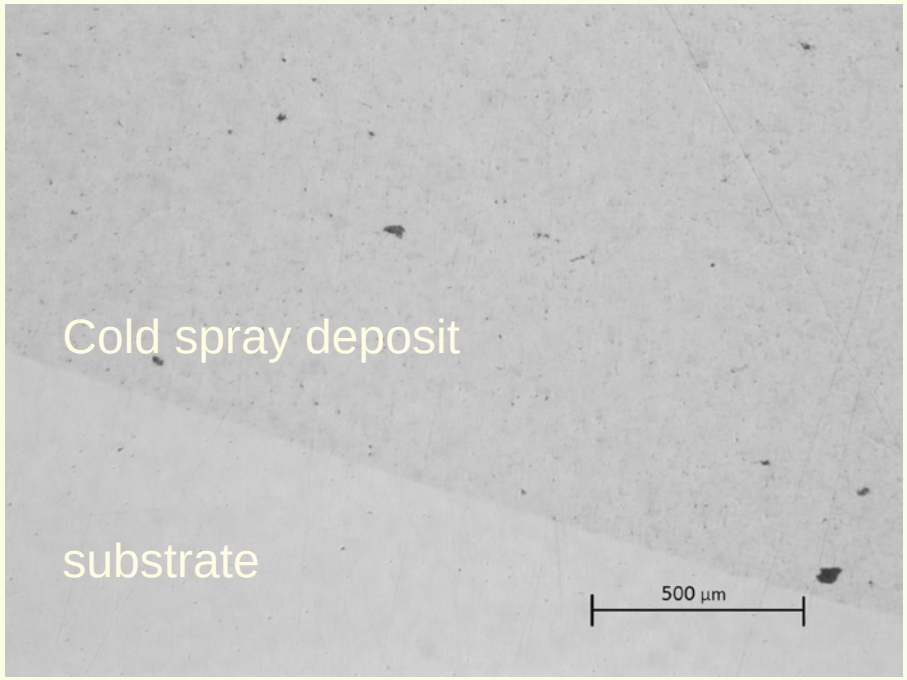


All units in millimeters

Plates are 6.35 mm (1/4”) thick in all cases

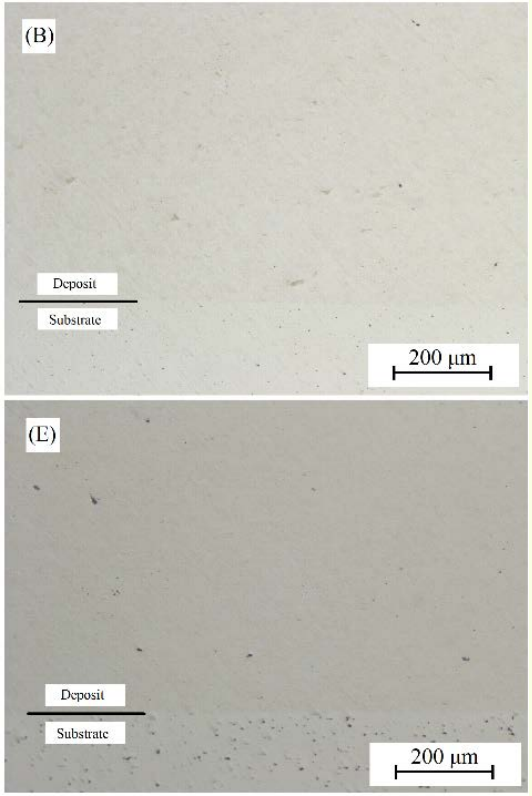
Re-fill depth (mm)	Fraction plate thickness	Refill diameter (mm)	Surface Area/Volume	Sample Name
1.02	0.16	16.5	1.84	“Small”
2.54	0.4	25.4	1.26	“Medium”
4.06	0.64	38.1	0.86	“Large”

Sprayed material in fastener hole-repair



Optical micrograph showing interface between repaired plate (AA7075-T651) and deposited material (AA7075) (4.06 mm thick deposit). Note that the sloped interface is indicative of blend out with cubic spline geometry. Bottom of plate is horizontal.

AA7075



Gas Type	Gas temperature (°C)	Gas pressure (MPa)	Standoff distance (mm)	Powder feed rate (g/minute)	Gun velocity (mm/s)
helium	415°C ± 5°C	3.2	15	13	100

AA2024

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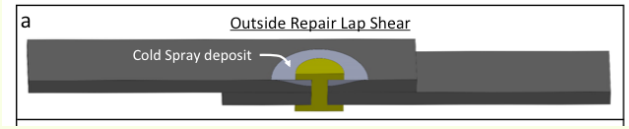
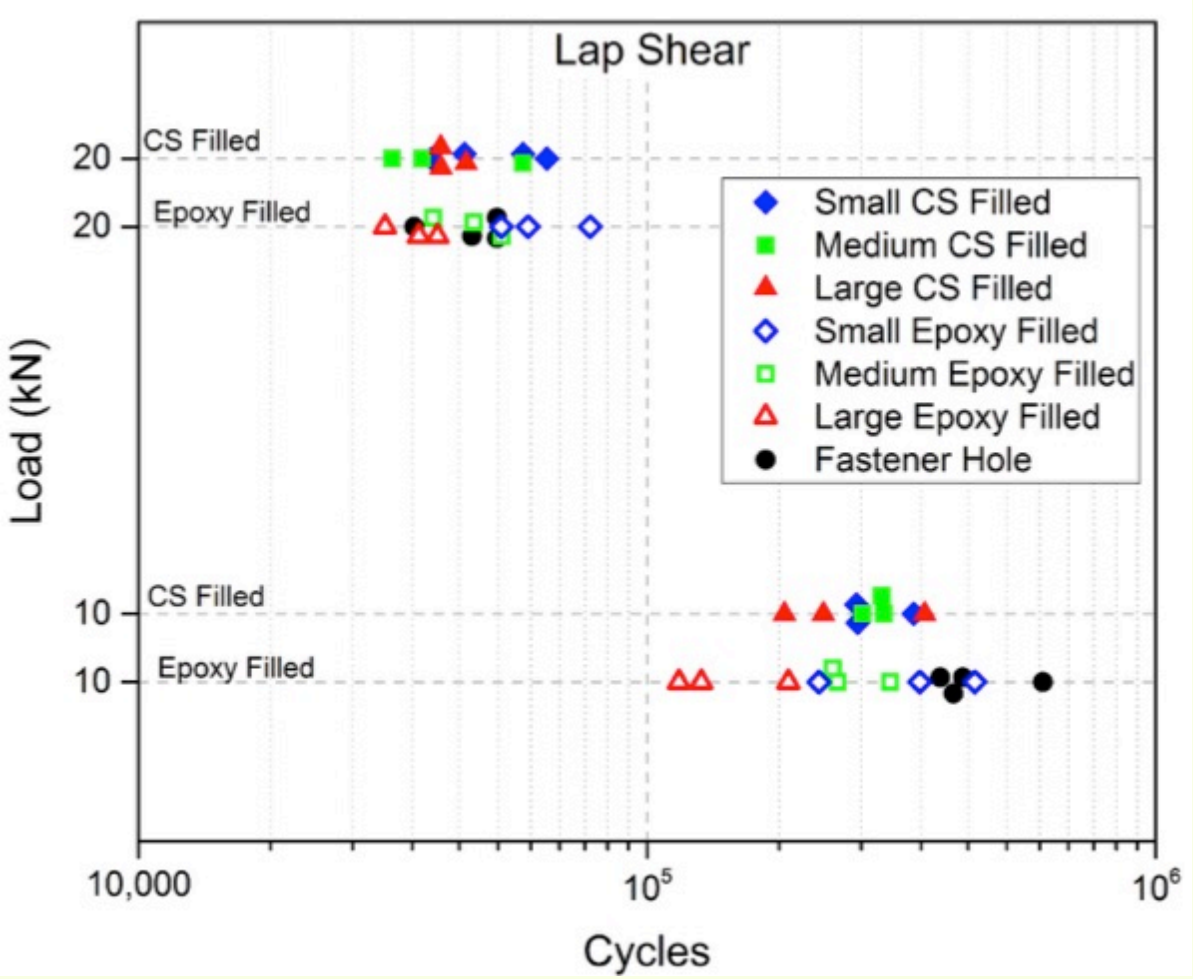
Fatigue Testing of Lap Shear Joints Shows Promise for ARCS

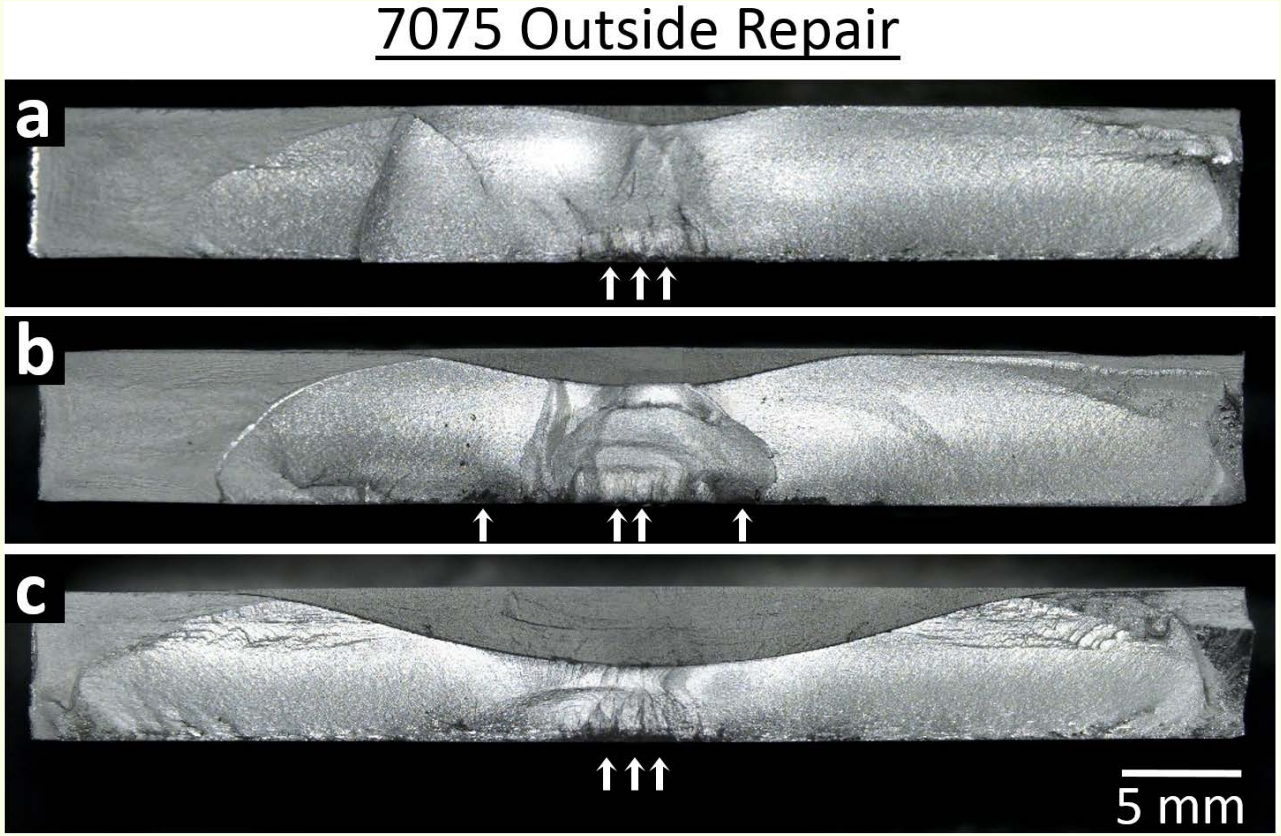
AA7075





- In LCF regime (20 kN), all of the fatigue data overlaps, even with the control.
- In HCF regime (10kN), CS-filled better than epoxy filled, but not quite as good as control.
- Note lack of sensitivity to size of fill for CS repair.
- <u>No spallation of CS material for any fatigue test.</u>

Fatigue Cracking Nucleates through Fretting on the Mating Surfaces of the Joint

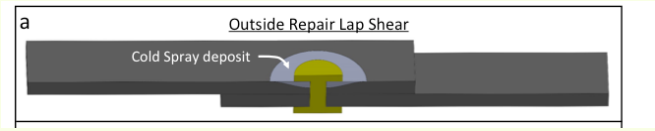


small

medium

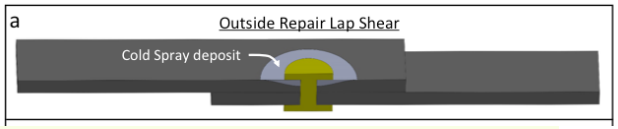
large

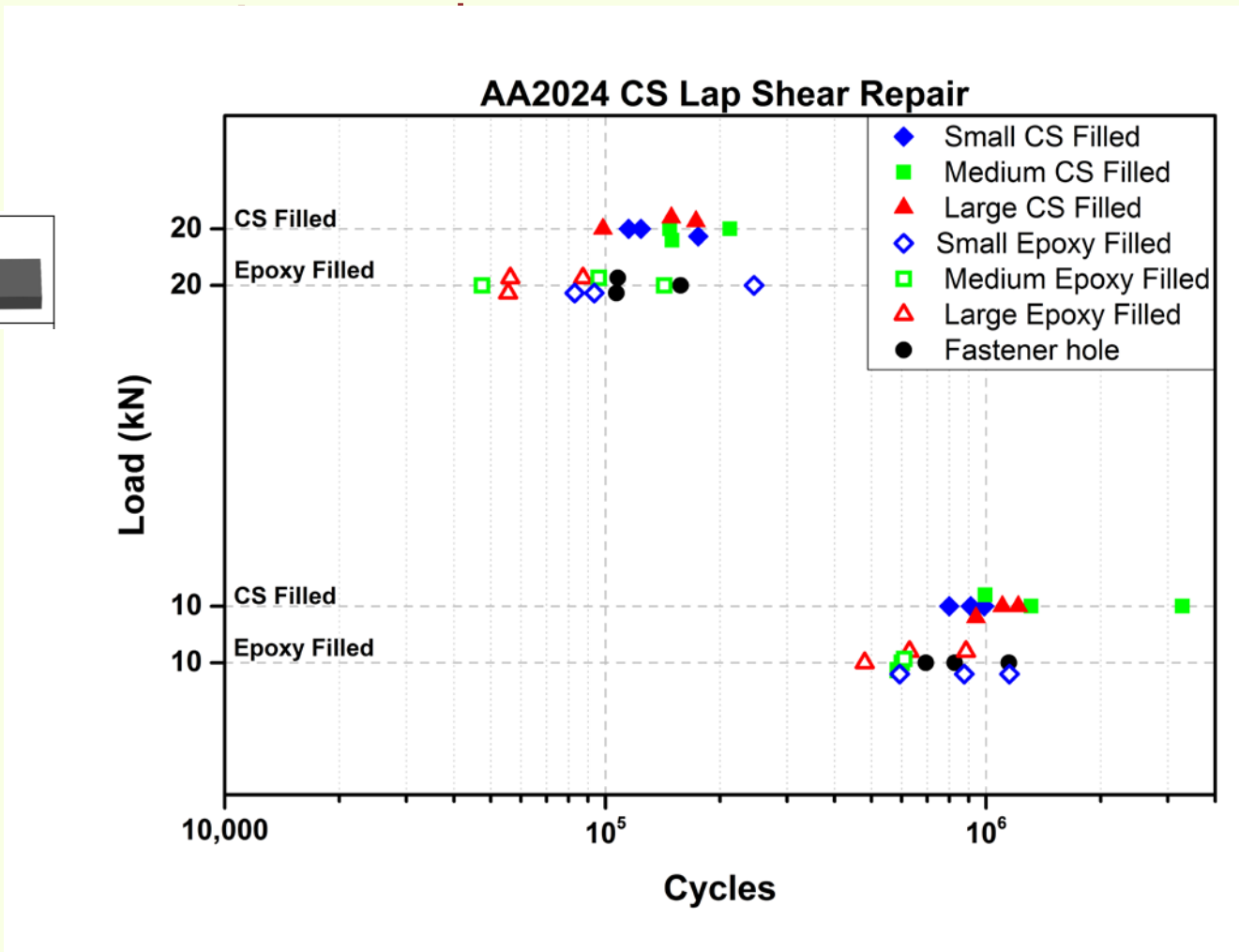
- Fatigue cracks nucleate at mating surfaces of joint and propagate towards outer surface of lap joint--fretting.
- <u>No spallation of CS material for any fatigue test.</u>



Fatigue Testing of Lap Shear Joint Show Promise for ARCS

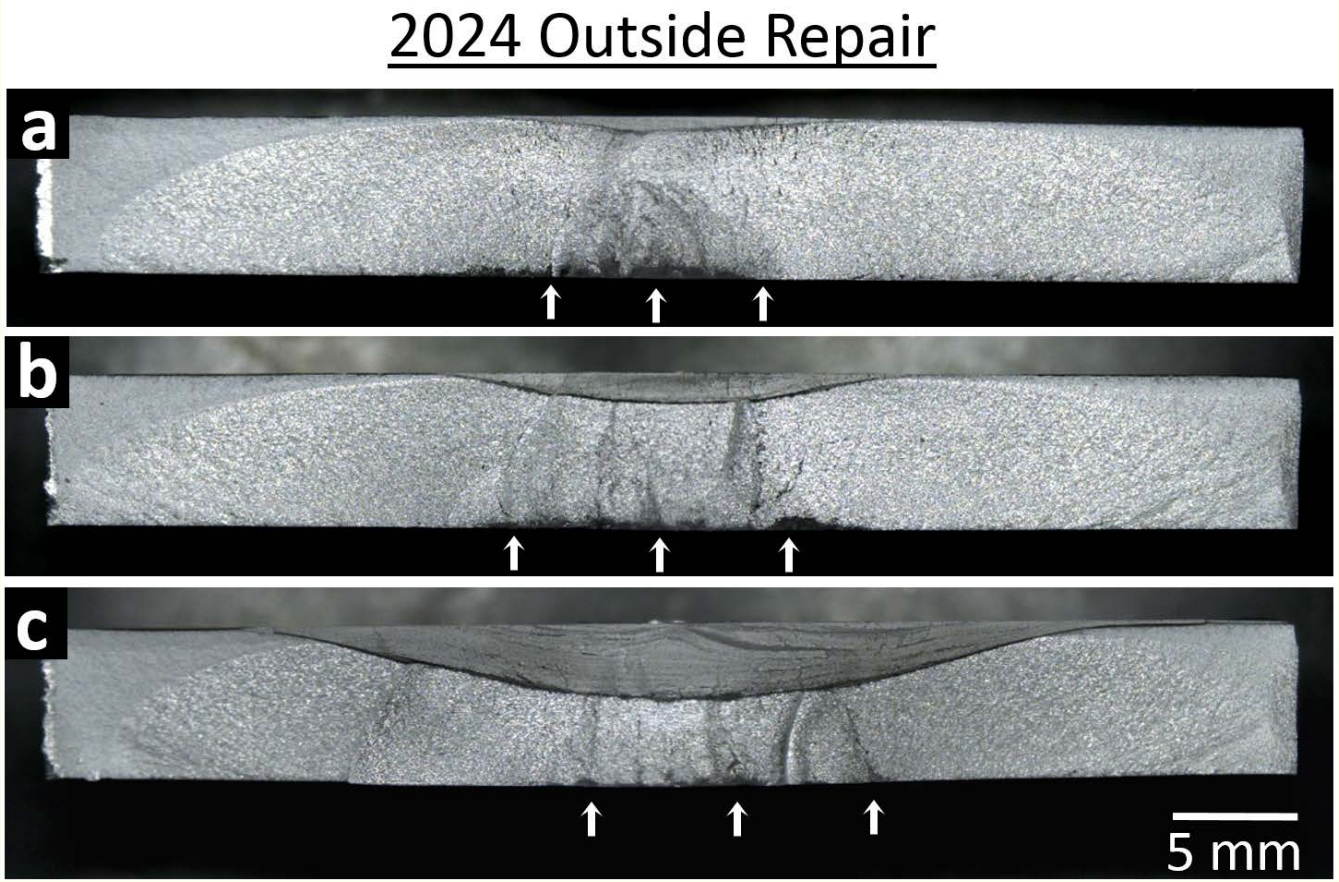
AA2024





- In LCF regime (20 kN), CS fatigue data overlaps or even better than the control.
- In HCF regime (10kN), CS-filled data overlaps control fastener hole.
- Note lack of sensitivity to size of fill for CS repair.
- <u>No spallation of CS material for any fatigue test.</u>

Fatigue Cracking Nucleates through Fretting on the Mating Surfaces of the Joint

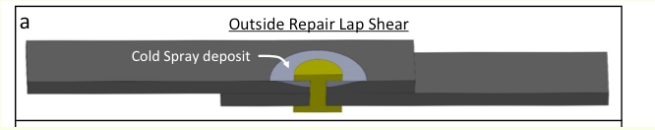


small

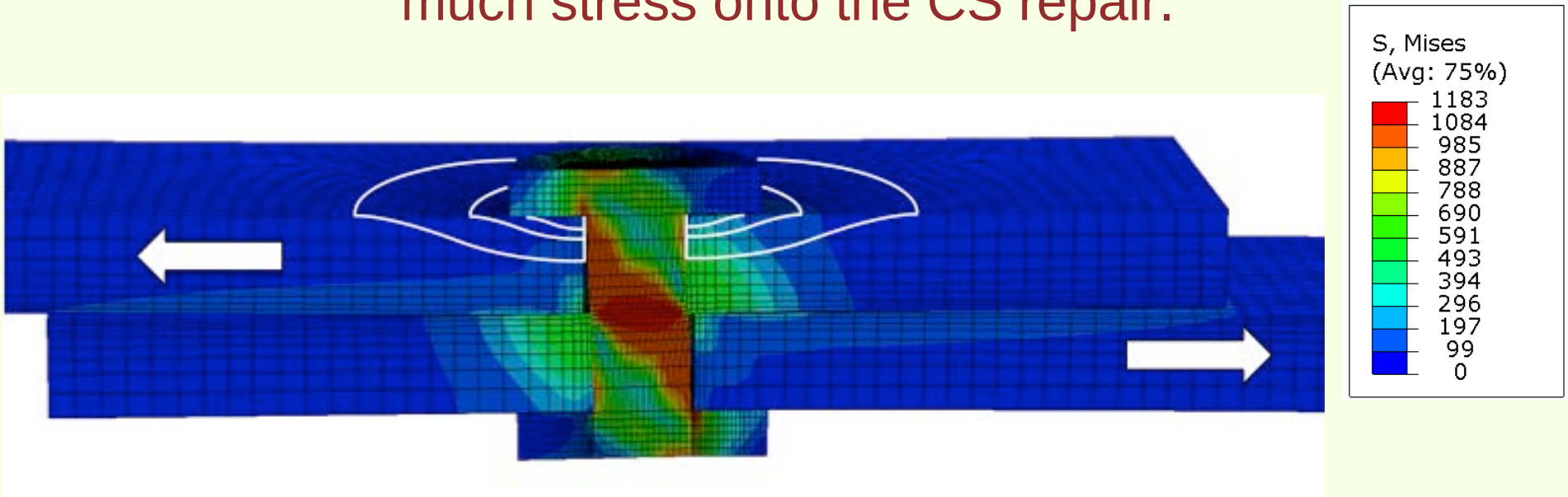
medium

large

- Fatigue cracks nucleate at mating surface of joint and propagate towards outer surface of lap joint.
- <u>No spallation of CS material for any fatigue test.</u>



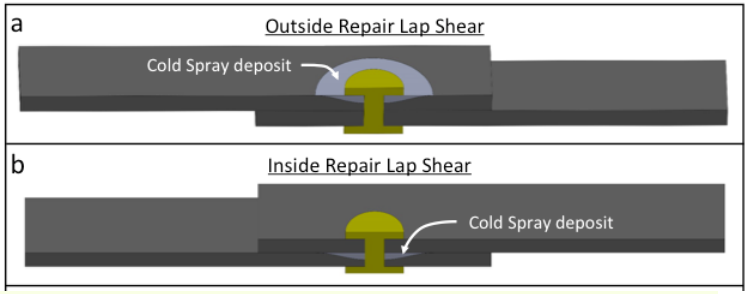
FEA of lap shear shows that this joint design does not put much stress onto the CS repair.

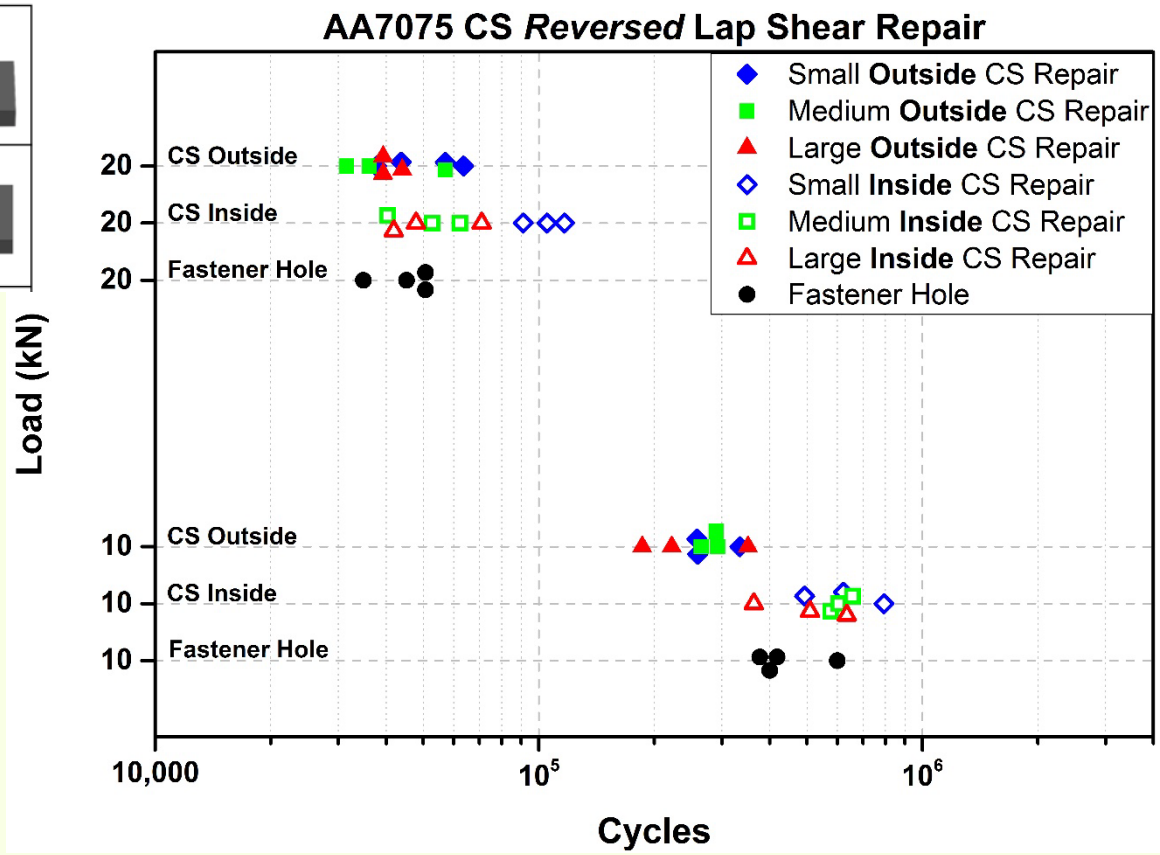


- Highest stresses in fastener and at corners of plate right next to fastener
- The regions with the cold spray experience much lower stresses.

Reversing the position of the CS repair increases the number of cycles to failure…

AA7075

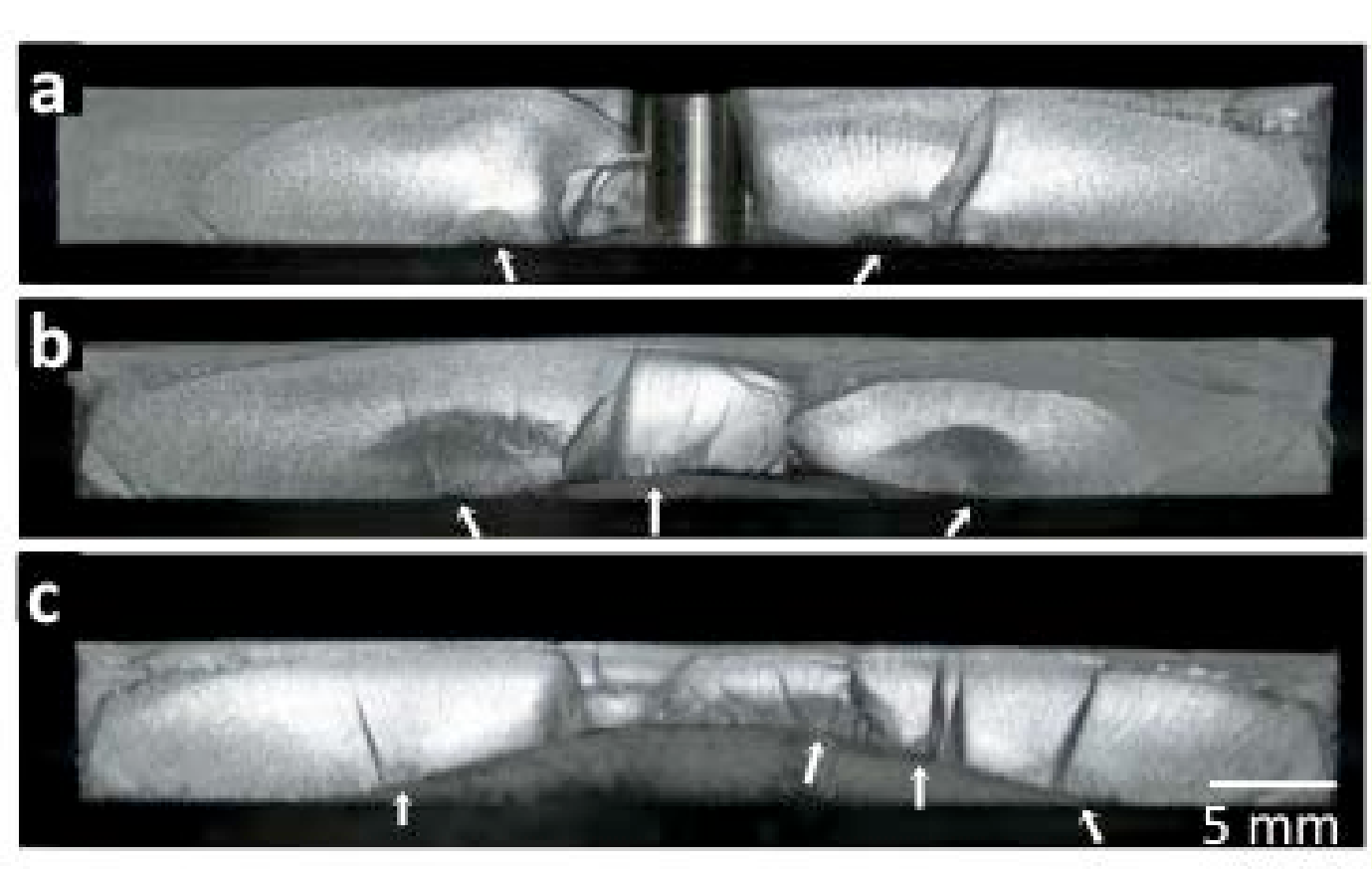




- In LCF regime (20 kN), most of the fatigue data overlaps, small <u>reversed</u> repairs even out-perform controls
- In HCF regime (10kN), all <u>reversed</u> repairs perform equivalently with controls

Fatigue cracks nucleates through fretting on the mating surfaces of the joint—even when repair reversed

AA7075

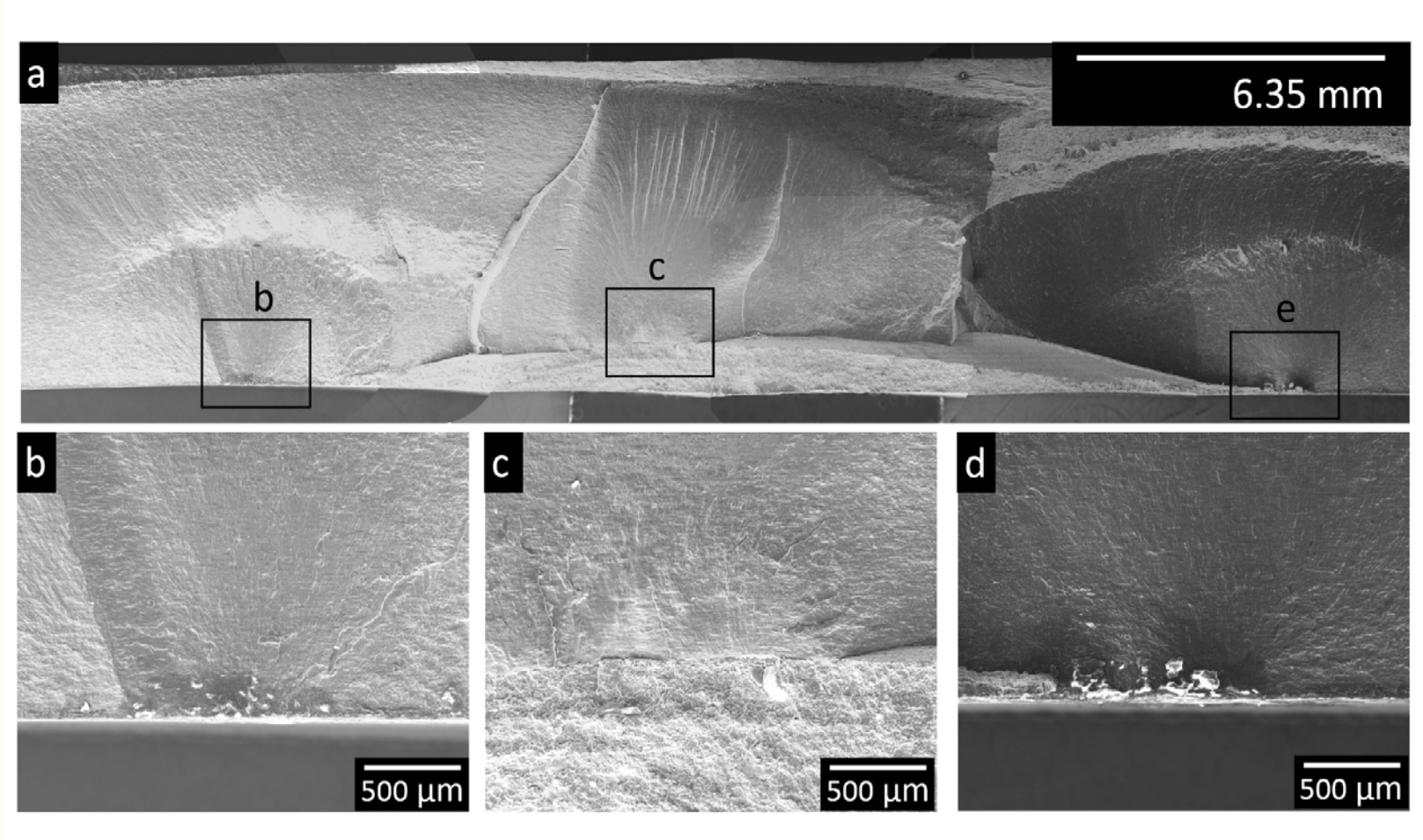


small

medium

large

Fatigue cracks are nucleating due to fretting between plates (medium repair)



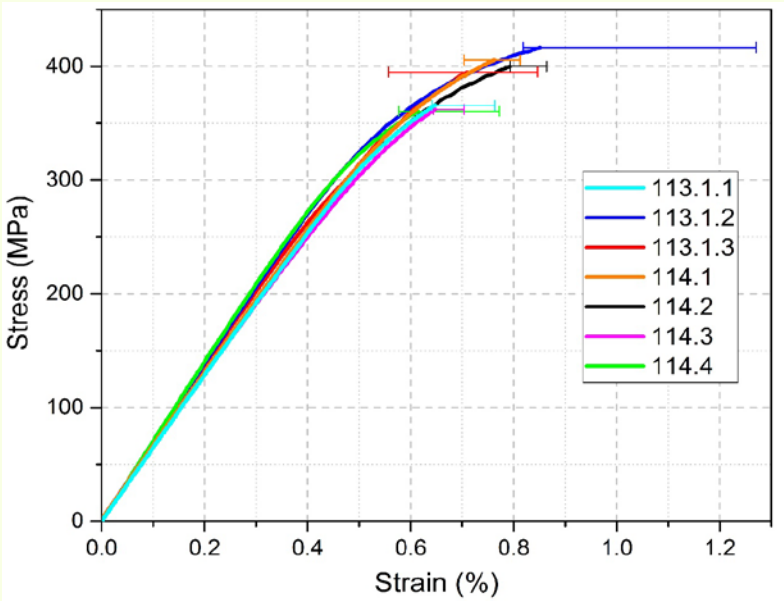
- SEM fractography shows that largest cracks are nucleating through fretting between plate surfaces <u>outside</u> of CS repair.
- Two smaller crack initiation sites observed at the CS/substrate interface.

Highlights from the ARCS Program (2015-2018)

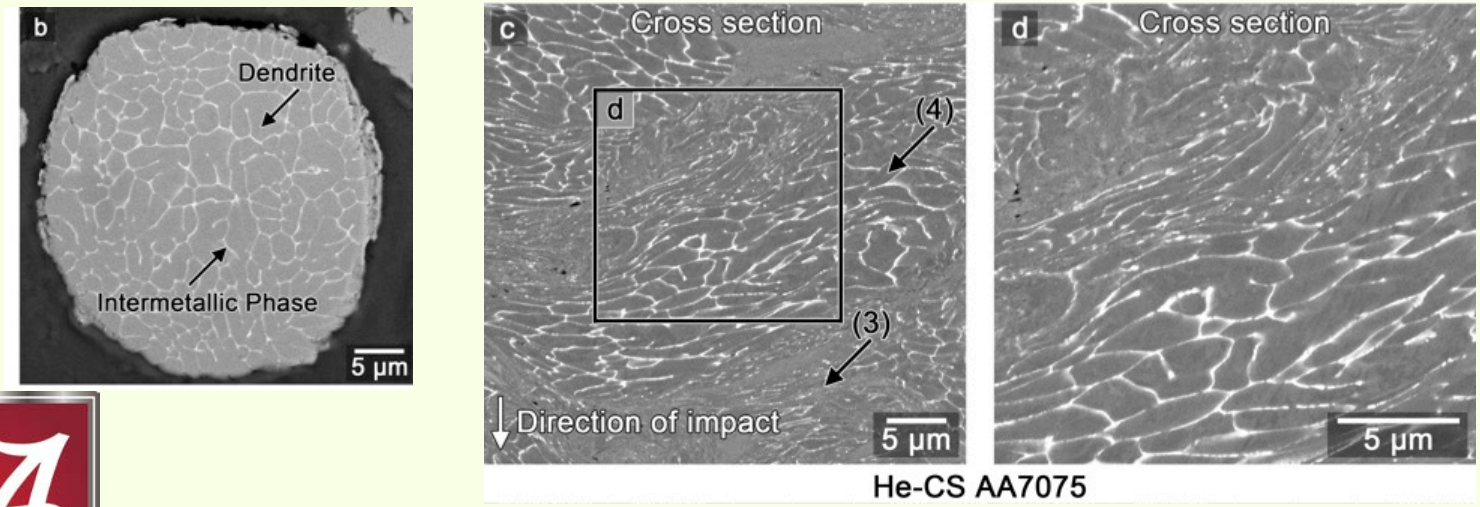
(ONR-SBA Project N00014-15-1-2133)

- Optimized high pressure cold spray (HPCS) processes for AA7075 and AA2024
- Developed initial additive repair method for fastener holes
- Demonstrated good adhesion and develop new methods for characterizing interfacial fracture toughness
- Measured residual stresses in repaired sections using neutron diffraction
- Quantified fatigue behavior of lap shear joints with ARCS around fastener holes
- Invented new method for heat treating cold spray powders

So what needs to be improved?



- We need the ductility to go up (also a higher strength would be better).
- We need the fatigue performance for LCF and HCF to match the wrought plate.
- We need the microstructure <u>and</u> nanostructure of cold sprayed material to match the wrought plate
- We need to apply the ARCS method to other repair geometries.



Project Objectives for ARCS-HT
(ONR-SBA Project N00014-18-1-2519)

- Use new rotary furnace approach to solutionize cold spray feed-stock powder to thereby increase deposition efficiency, tensile properties, and fatigue characteristics.

- Develop laser-assisted cold spray (LACS) to demonstrate increased deposition efficiency, tensile properties, and fatigue characteristics.

- Demonstrate and quantify enhanced fatigue resistance in structural repairs using solutionized powder and/or LACS.

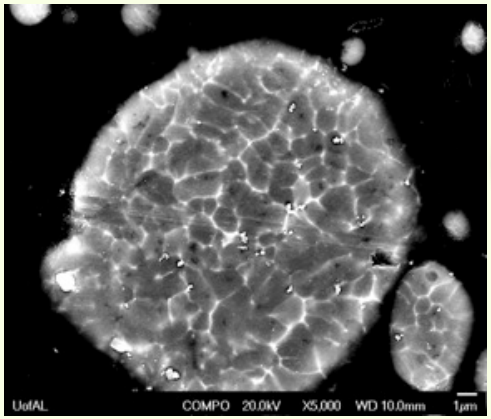
- Demonstrate and quantify corrosion mitigation and enhanced mechanical performance in functional repairs using solutionized powder and/or LACS

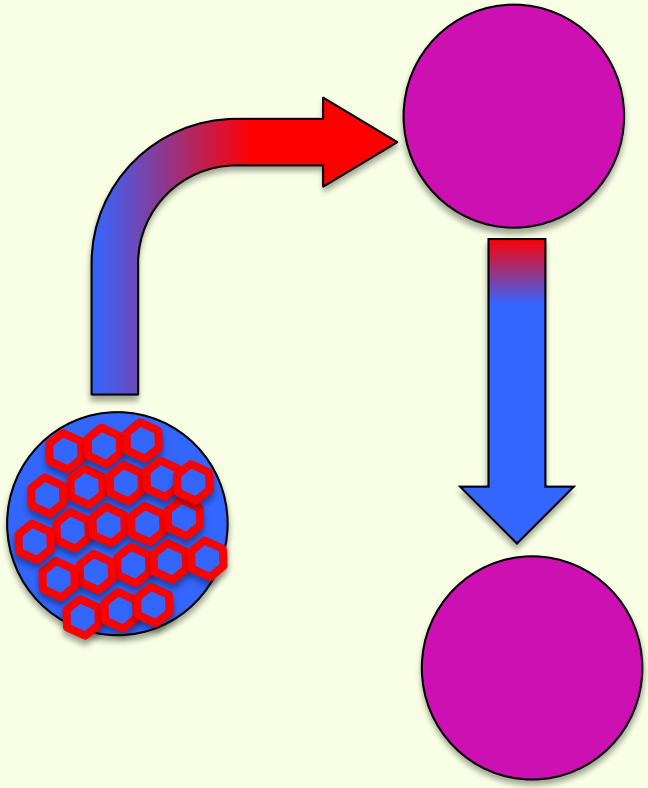
Heat treatment of high strength aluminum powders for enhanced deposition characteristics and improved mechanical properties

Heating of powders

Need to:

- Dissolve intermetallics
- Avoid melting
- Avoid sintering between particles.
- Avoid oxidation

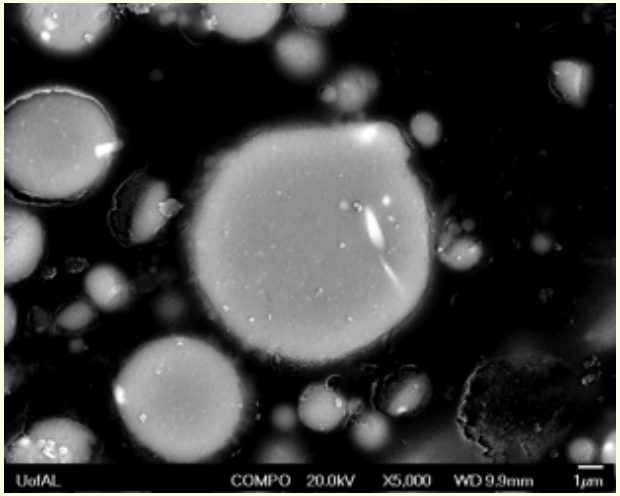




Rapid cooling "quenching"

Need to:

- Avoid re-precipitation of intermetallics
- Avoid oxidation of powder particles



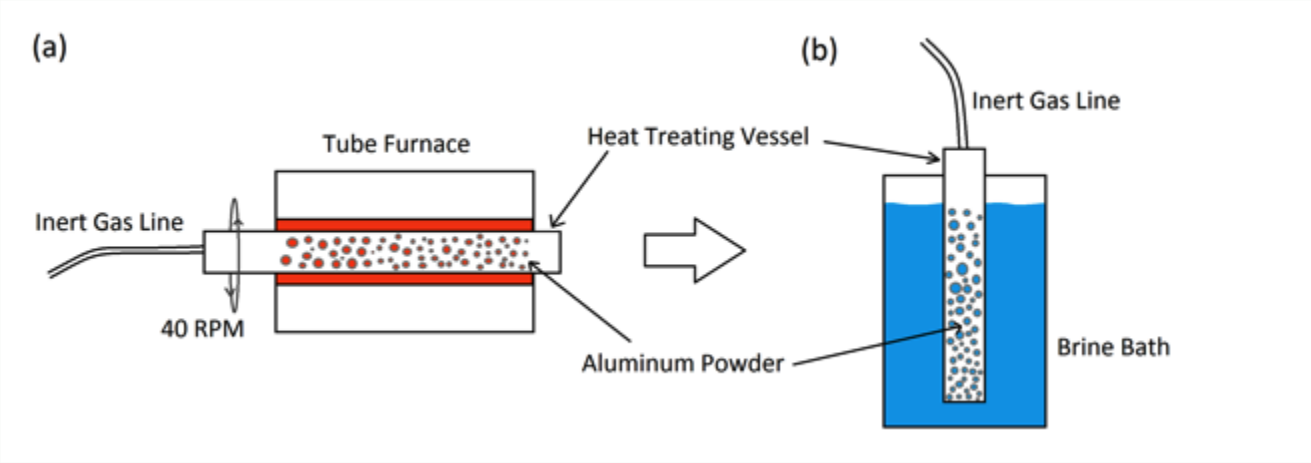
W.A. Story and L.N. Brewer, "Heat Treatment of Gas Atomized Powders for Cold Spray Deposition," Metallurgical and Materials Transactions, 2018.

W.A. Story and L.N. Brewer "METHOD AND APPARATUS FOR HEAT TREATING FEEDSTOCK POWDER." U.S. patent application (16/041,420)

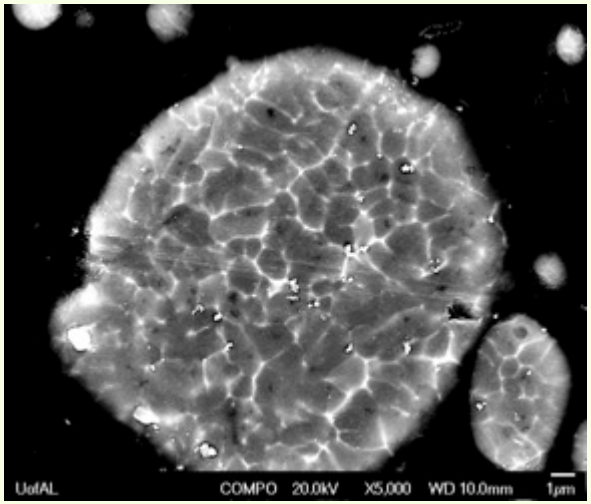
23

Demonstration of Concept—it works!

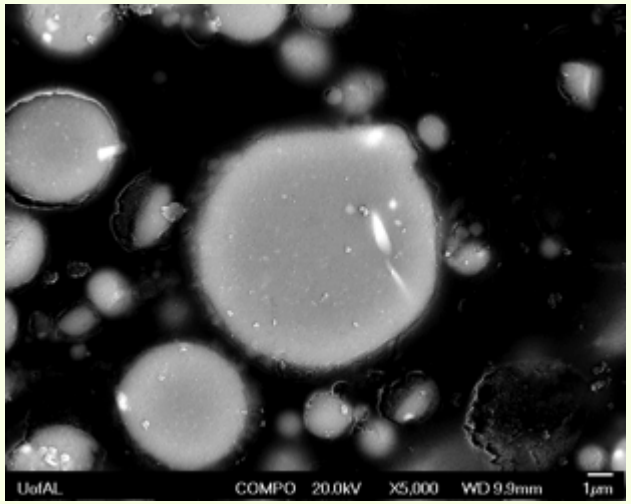
A two- step process (heating and rapid quenching) is used to dramatically reduce undesirable intermetallic microstructures, thereby nearly doubling the deposition efficiency.



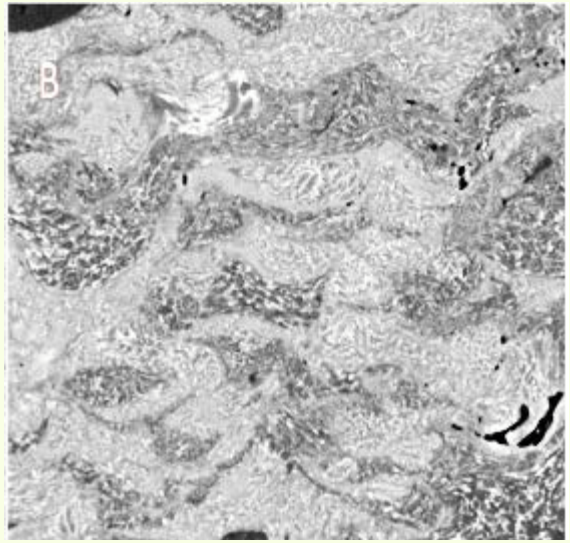
Demonstration of improved particle microstructures.

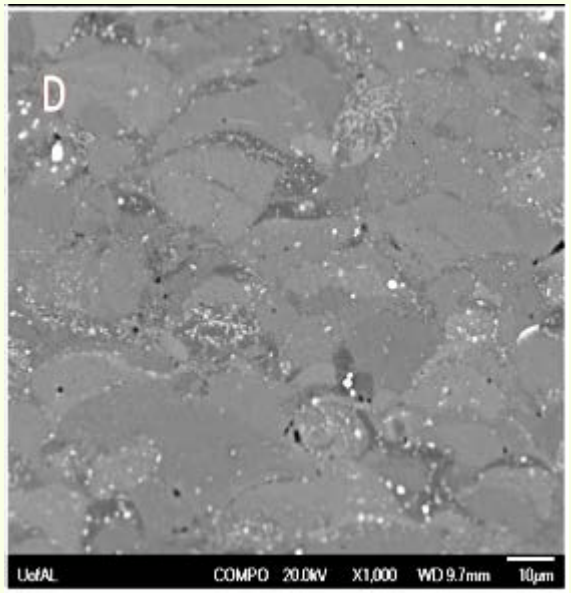


Before heat treatment



after heat treatment

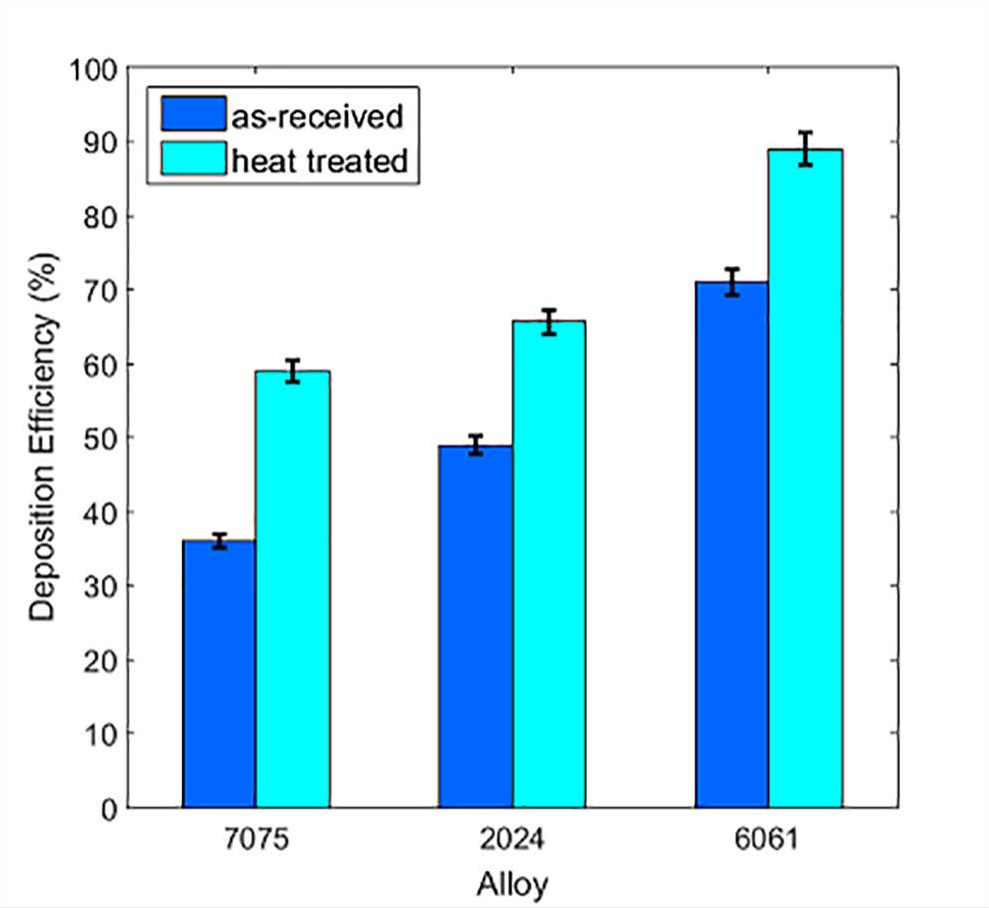




<u>Deposition efficiency improved from 35% → 60%</u>

No reduction in powder flowability—sintering controlled

Demonstration of improved cold spraying after powder heat treatment…

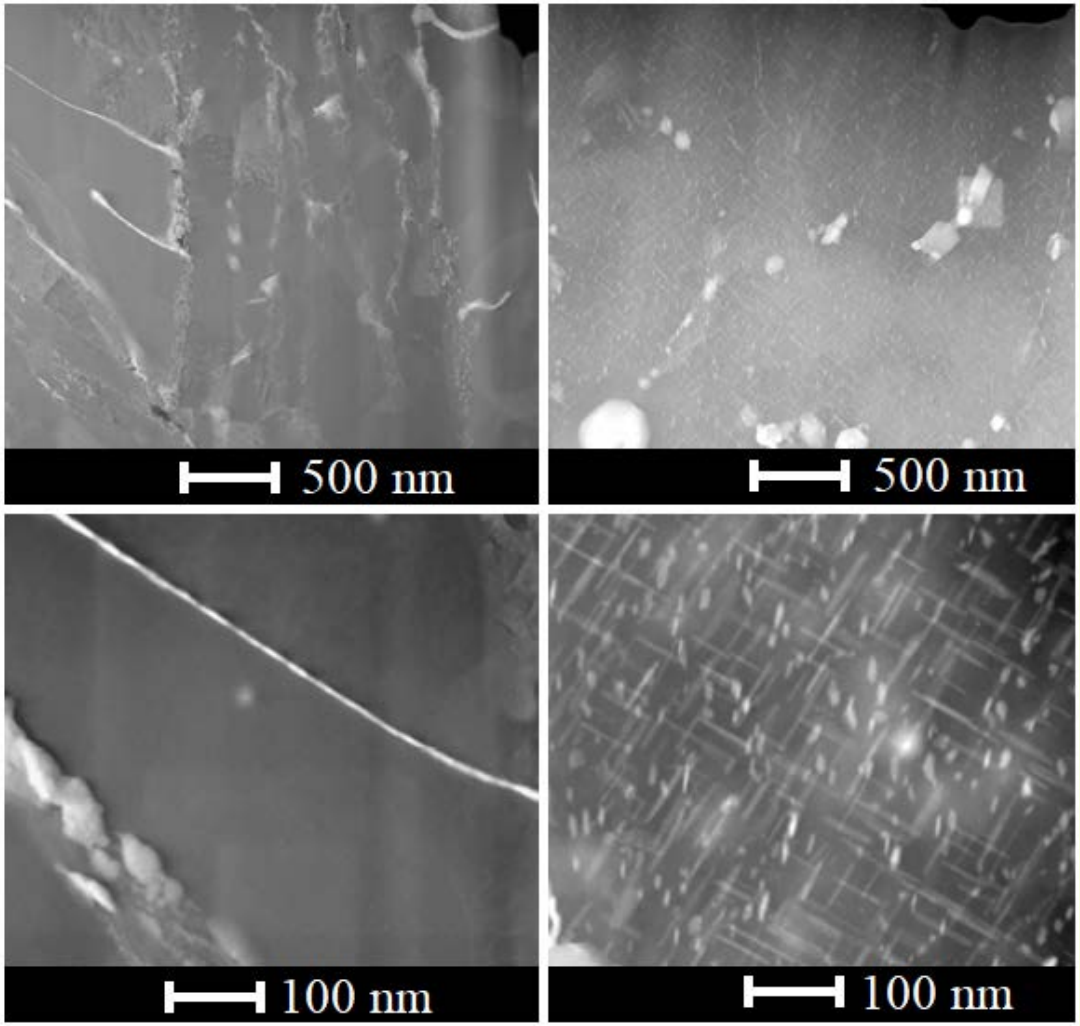


<u>Deposition efficiency improved for AA7075 from 35% → 60%</u>

No reduction in powder flowability—sintering controlled

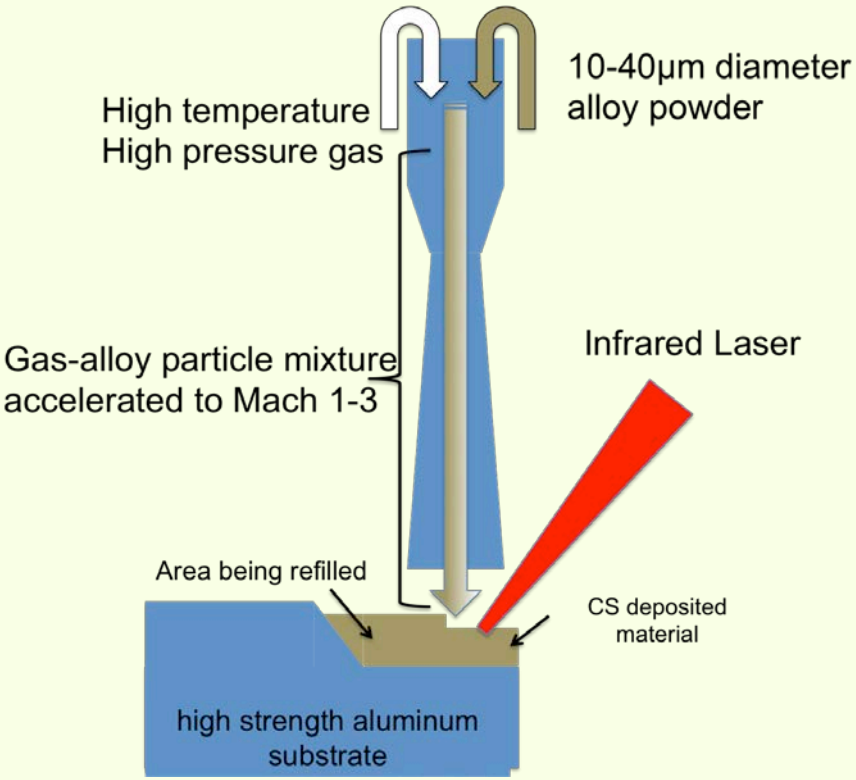
Initial results show the reappearance of nanoscale precipitates in the coating using solutionized/quenched powder.

As Atomized SQ



STEM-HAADF images of S phase precipitates in AA2024 powder

Laser Assisted Cold Spray (LACS) Deposition



1. Allow the use of N_2/ compressed air as a carrier gas for the cold spray deposition of aluminum alloys.
2. Enhance the ductility in high strength aluminum alloy coatings.
3. Enable optimization of the microstructure and strength of high strength aluminum alloy deposits.

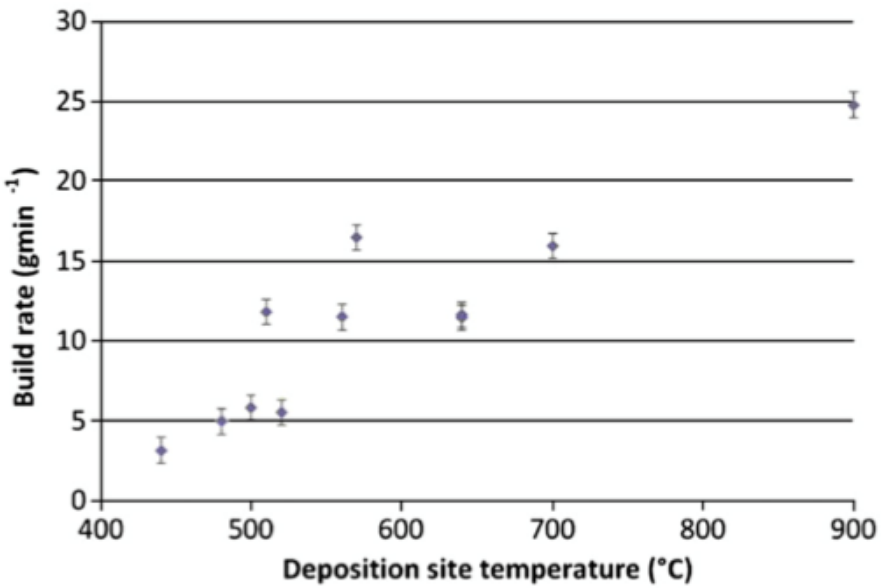
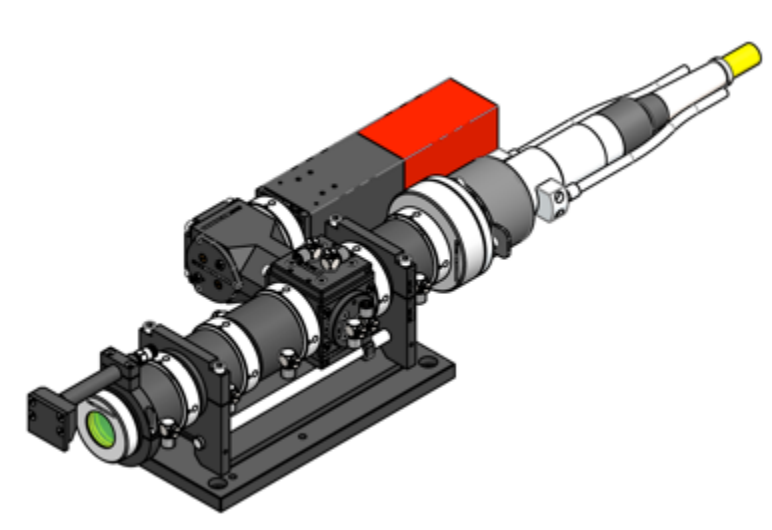


Fig. 9. Build rate versus deposition site temperature for LCS-deposited titanium.

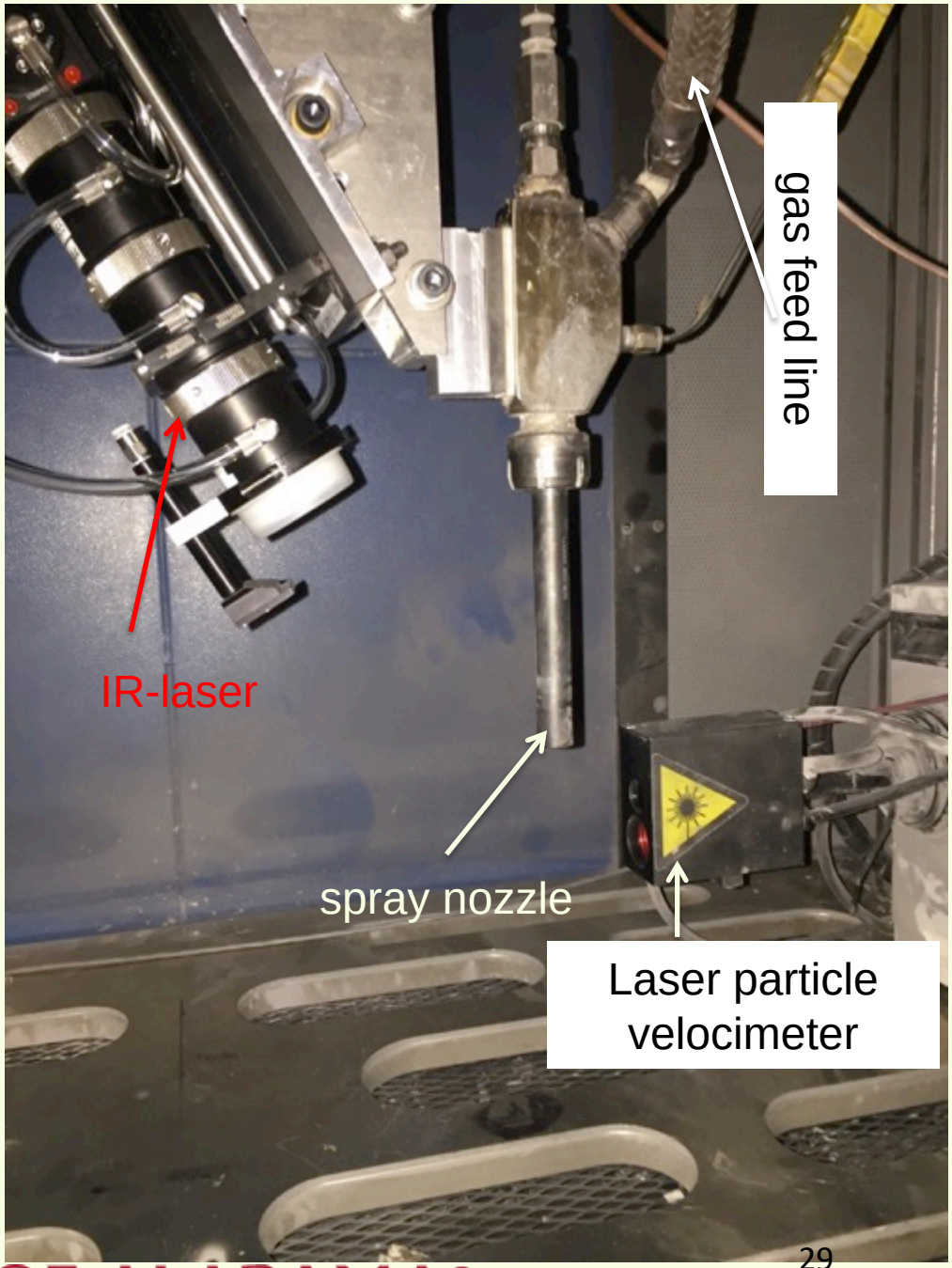
Increased build rate for CS of titanium from Bray et al., Surf. Coat. Tech., 2009

LACS System at UA

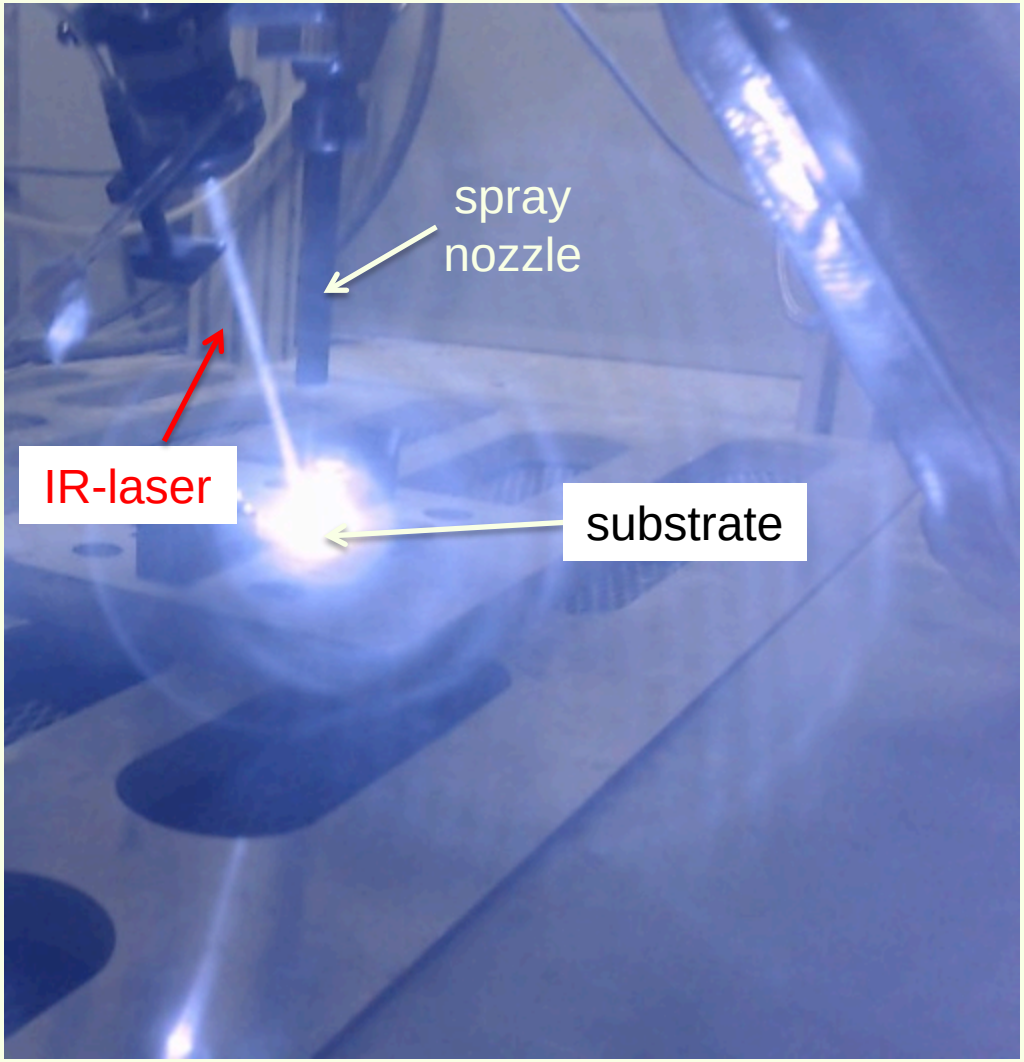
Laserline LDM-4000
4kW infrared diode laser (940 nm)
Optical pyrometer in beam line



Laser purchased through
ONR-DURIP N00014-16-1-2576



Laser Assisted Cold Spray in Operation



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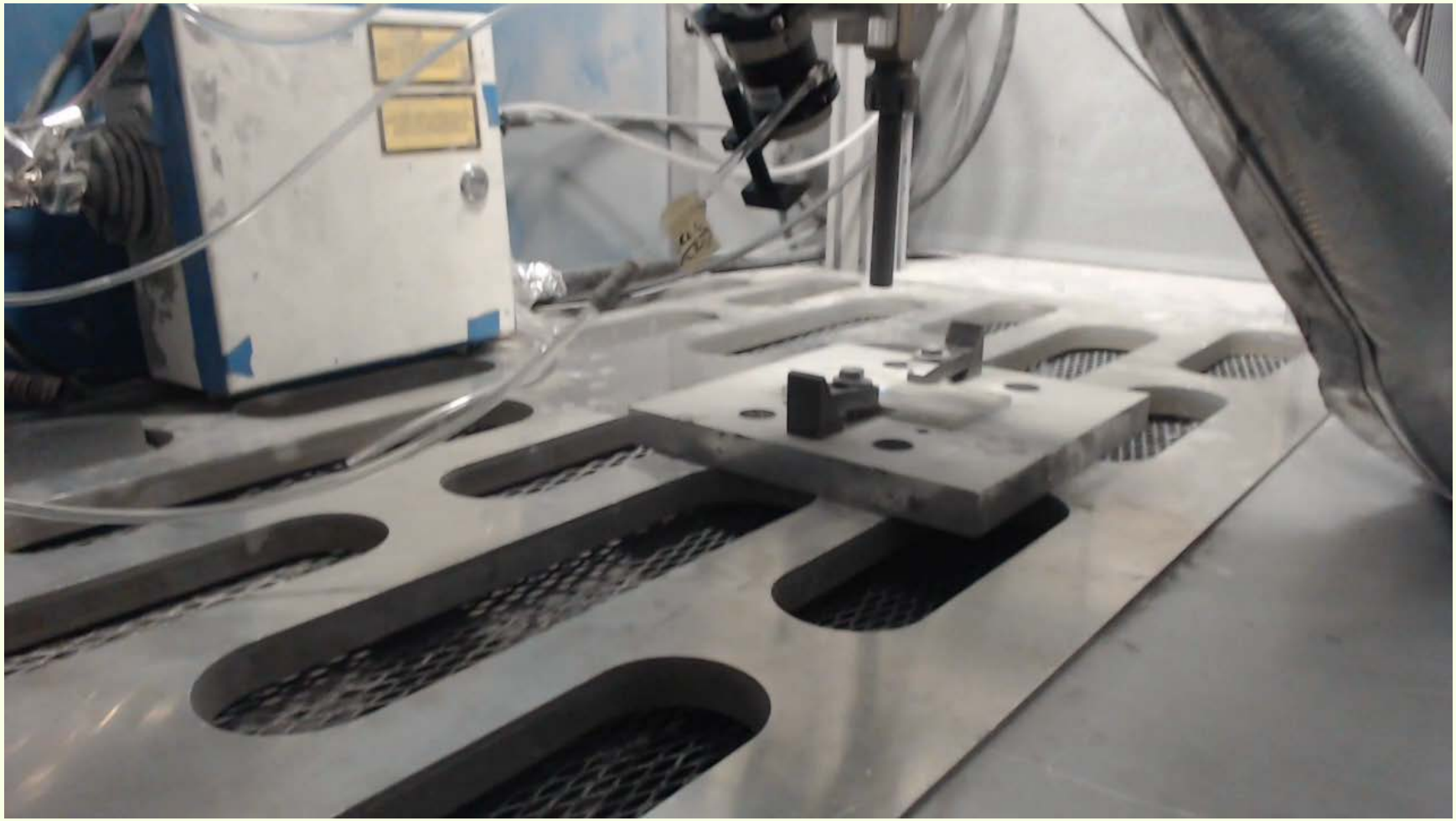
Laser Assisted Cold Spray in Operation



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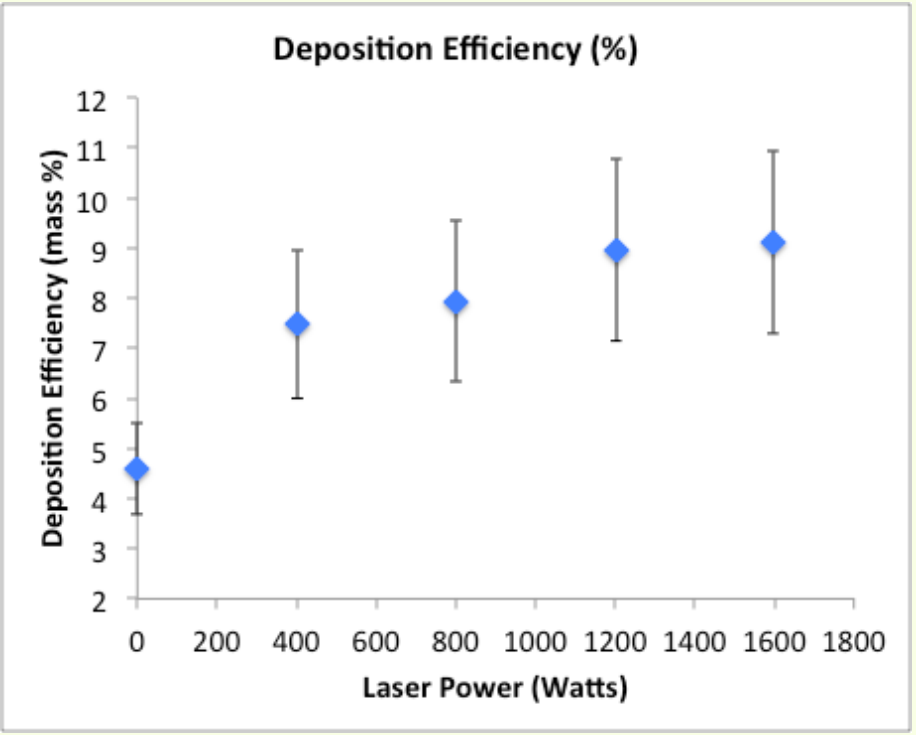
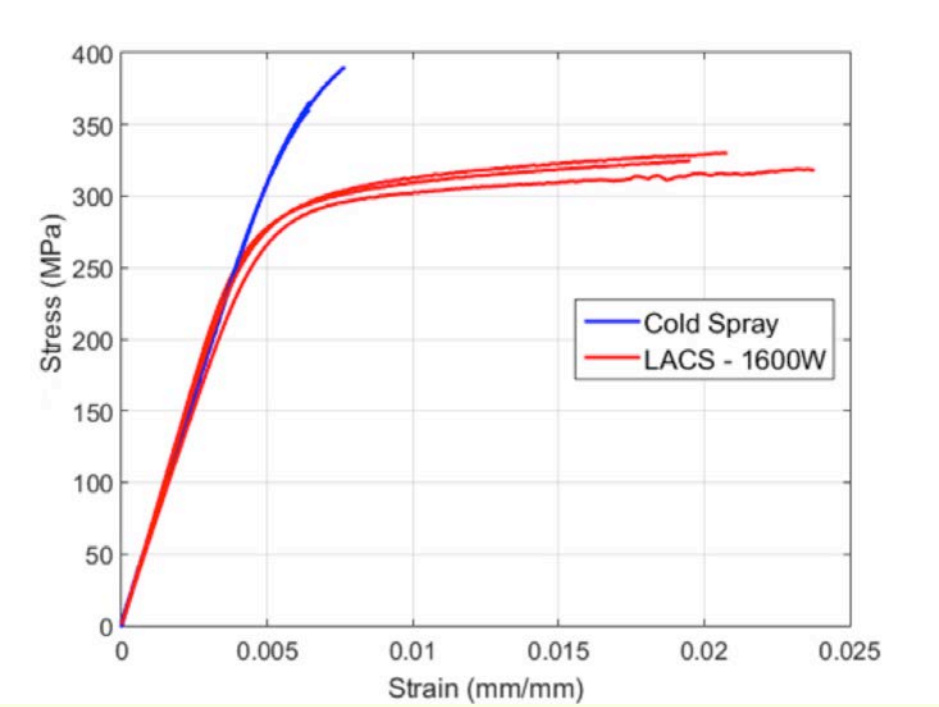
Initial results on LACS applied to AA7075 are promising…



DE for AA7075 powder sprayed with N_2 gas doubles with application of laser.



AA7075 powder sprayed with He gas has lower yield but high elongation with application of laser.

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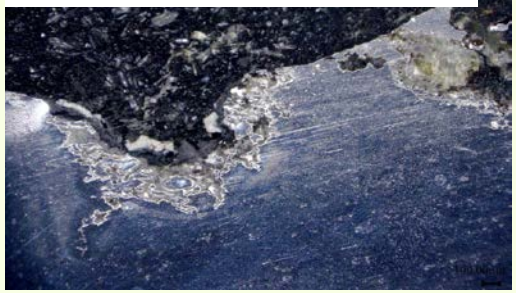
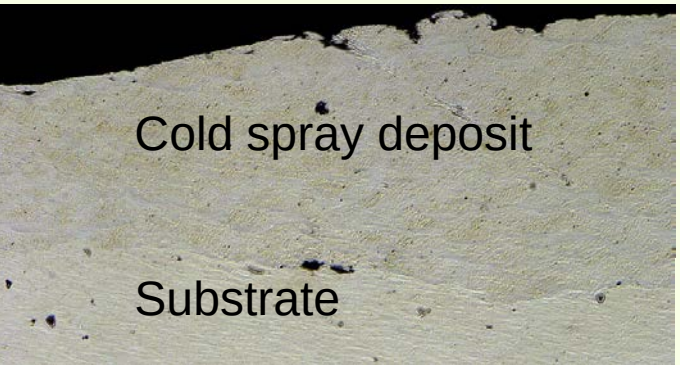
Applying Additive Repair by Cold Spray (ARCS) to AA7050 Sill Repair.

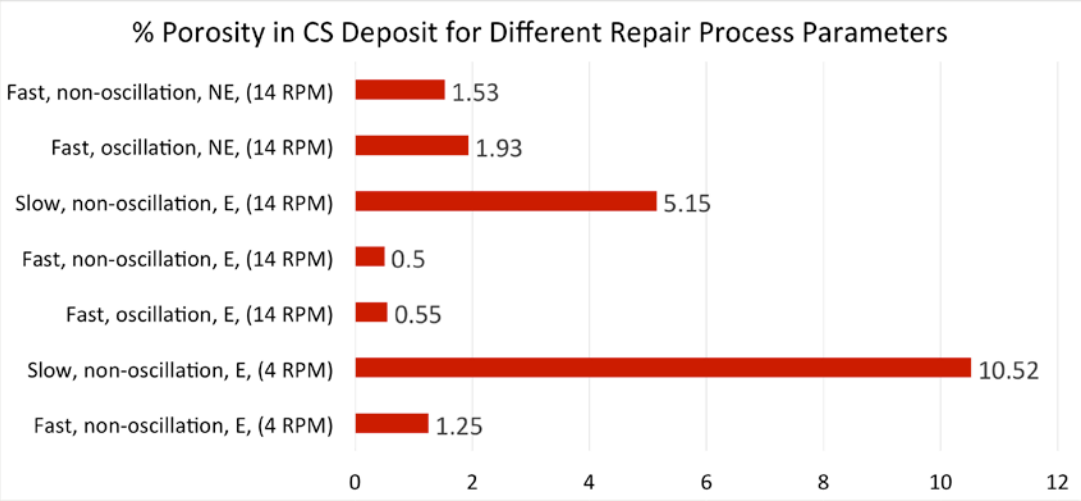
Outside of AA7050 sill

Optical images of pits to be repaired.



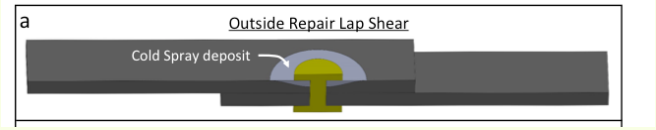


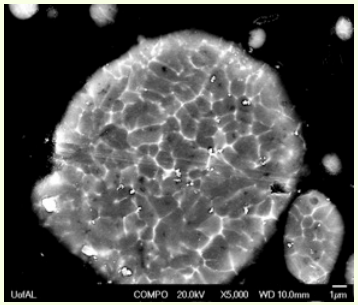
- Deep corrosion pitting in aircraft sills is a prevalent problem in naval aviation
- Working with F. Lancaster (NAVAIR-NAWCAD) and R. Kestler (NAVAIR-FRC-East) to extend the approach AA7050 sill repairs.
- This geometry presents different challenges for ARCS when compared with doubler or fastener repairs—spraying into a 90° bend
- Performed initial Gage R&R study to look at the influence of hand spray parameters and operators on porosity levels for sill repair--achieved conditions with 0.5% porosity.

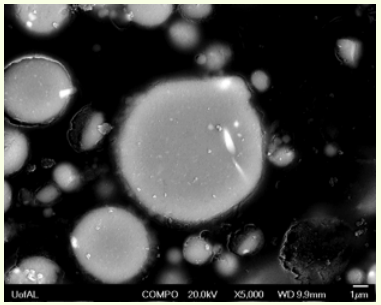


Conclusions:

- Developing Solid State Structural Repair (S3R) for application to functional (sill) and structural (fastener hole) repairs on high strength aluminum alloys components (AA2024 and AA7075)
- Previous program developed optimized spray conditions for these alloys and a repair strategy for fastener holes—initial testing was promising.
- Now developing heat treatment methods to improve deposition characteristics, mechanical behavior, and fatigue performance of S3R
  - Heat treatment of feed stock powders
  - LACS for *in situ* laser heating
- Applying these methods to functional repairs on AA7050 sills.







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