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Cold Spray for Additive Manufacturing

CSAT 2016

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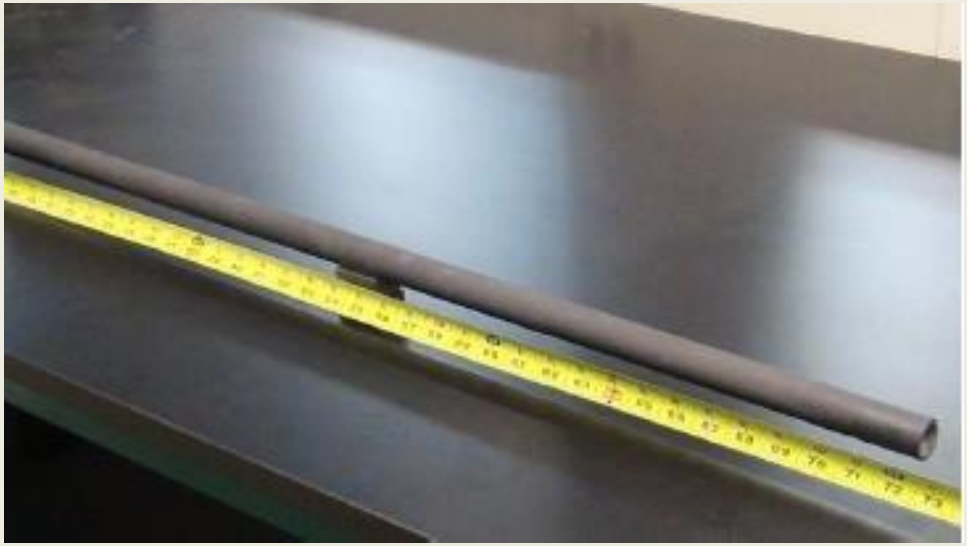
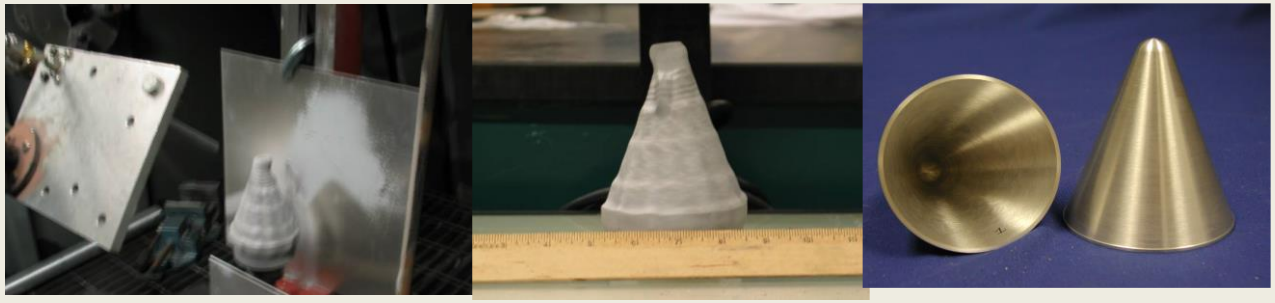
Outline

- AM Comparison
- Cold Spray Applications
  - Sputter Targets
  - Shaped Charge Liners
  - Donor Tubes
    - Objectives
    - Approach
    - Results & Future Work





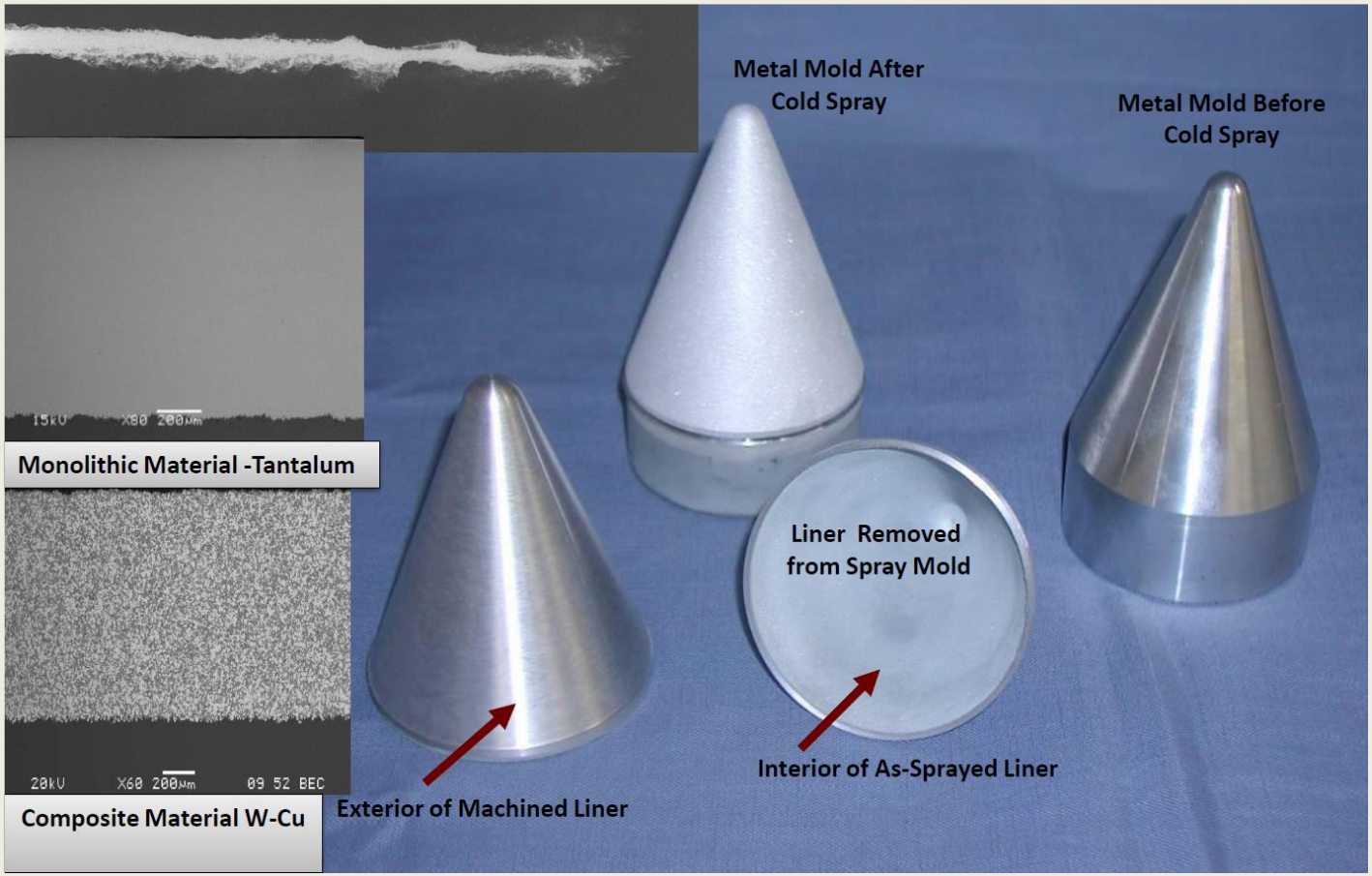
Cold Spray for AM

Cold Spray vs. Powder Bed Fusion Properties

	Cold Spray[1]	PBF (E-Beam)[2]
Build Rate, lbs/hr	20	<0.6
Post-Processing	Machining	Machining, Heat Treat/HIP
Layer Thickness, in.	.002-.010	.002-.008
Atmosphere	Air	Vacuum
Maximum Part Size	Unlimited	Machine-Dependent
Microstructure	Retained from Feedstock	Process Dependent (Solidification Kinetics)
Target Geometries	Axisymmetric Shells	Lattices, Internal Features

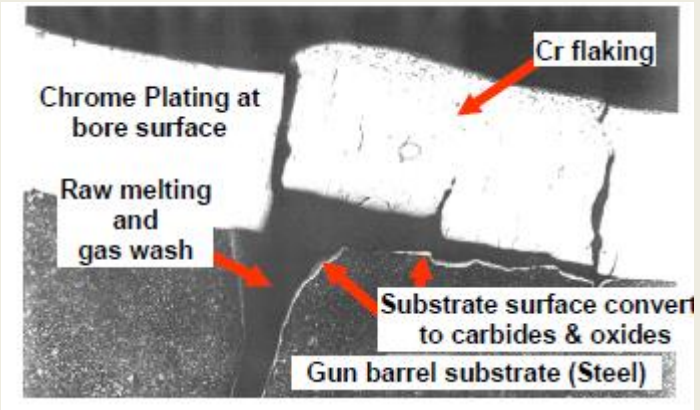
[1] V.K. Champagne, A. Nardi, D. Cote. “Materials Characterization of Advanced Cold Spray Aluminum Alloys” In S.R. Bingert, S.H. Luk. *Advances in Powder Metallurgy & Particulate Materials—2015.* Paper Presented at Powdermet 2015, San Diego, CA (10-15—10-29). Metal Powder Industries Federation, Princeton, NJ.
[2] J. Hiemenz. “Electron Beam Melting” *Advanced Materials & Processes* vol. 165, pp. 45-46. Mar. 2007

Shaped Charge Liners



Donor Tube Objectives

- **Extend Cannon Life & Accuracy**
  - **Chrome-Plated Steel Wear**
  - **Refractory Metals for Reliability**



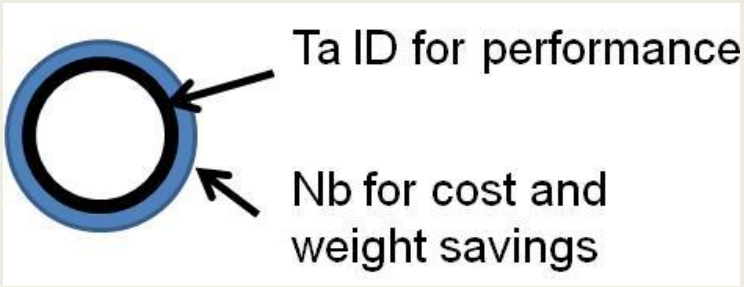
"Elimination of Chromium Electrodeposition from Large Caliber Launch Systems", *Krystyna Truszkowska,* US Army Benet Laboratories (ARDEC), Hard Chrome Alternatives Team, 20-21 July 2004, Utah

- **Reduce Manufacturing Costs Associated w/ Chrome Plating**
  - **Hex Chrome Bath Hazards**
    - **Occupational**
    - **Environmental**
  - **Hex Chrome Bath Costs**
    - **Industrial Hygiene & Engineering Controls**
    - **Hazardous Waste Disposal**

Chrome Plating Bath
Northwest Chrome, http://www.nw-chrome.com/chrome-plating/

Why Cold Spray?

- Geometry
  - Materials Savings over subtractive methods
    - Tantalum ore near $200/kg in June 2016[3]
  - Design Flexibility
    - No dies required to adjust diameter & wall thickness
    - Extreme aspect ratios possible without high-cost tooling
- Materials Flexibility
  - Tantalum
  - Tungsten
  - Niobium
  - Alloyed & Blended Feedstock
  - Functionally Graded and Concentric Multi-Layer Systems

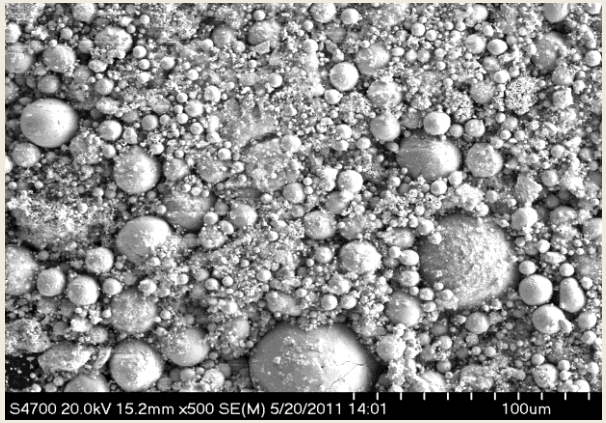


[3] http://www.infomine.com/investment/metal-prices/tantalite-ore/6-month/

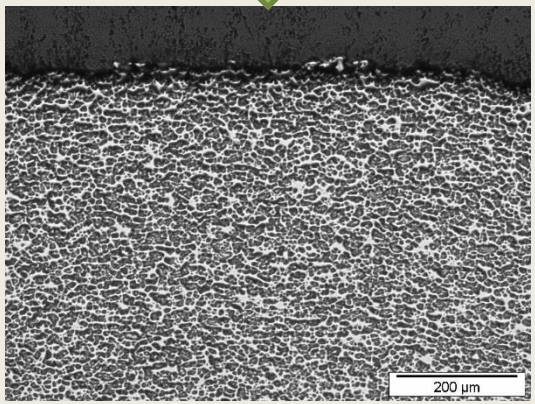
Approach

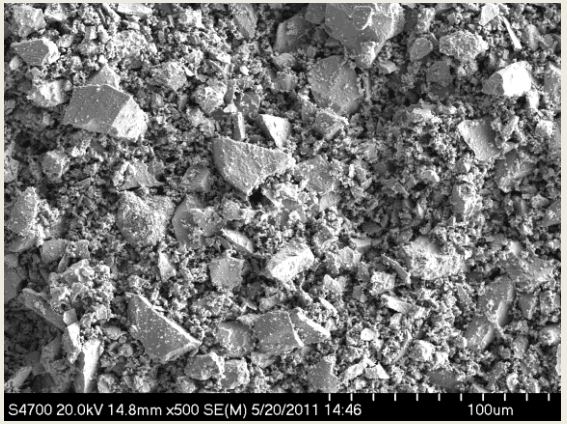
Develop Refractory CS Materials & Demonstrate Feasibility

Medium & Small Caliber Donor Tubes

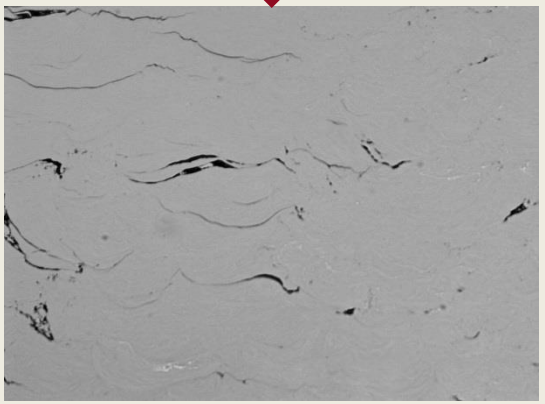


ARL1 10W-Ta Blended Powder





ARL2 (HC Starck 10W-Ta Alloy)



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Alloy Material Optimization

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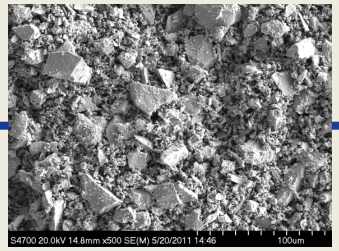
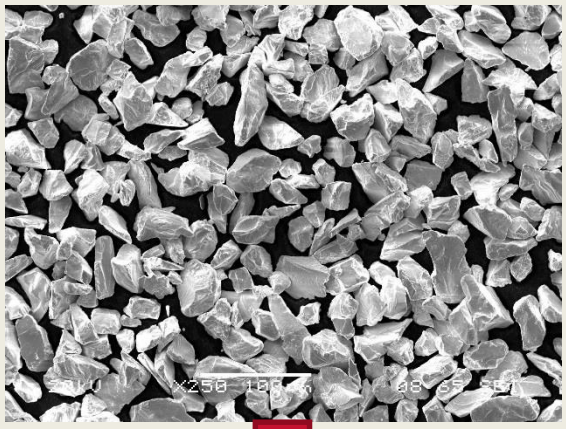
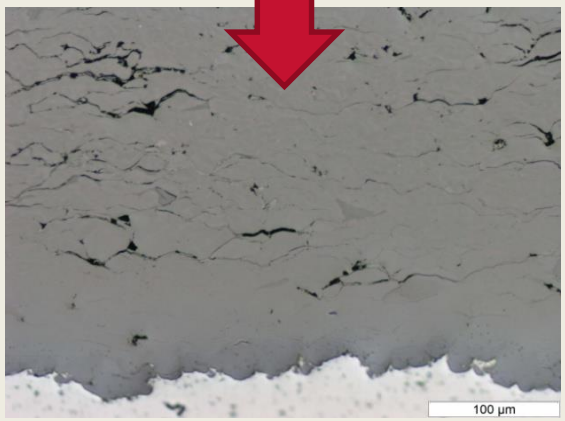
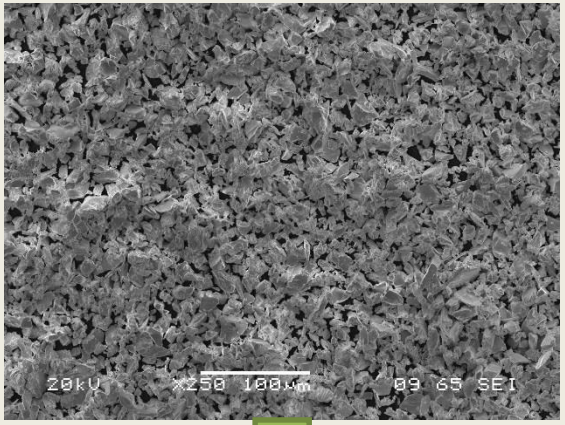


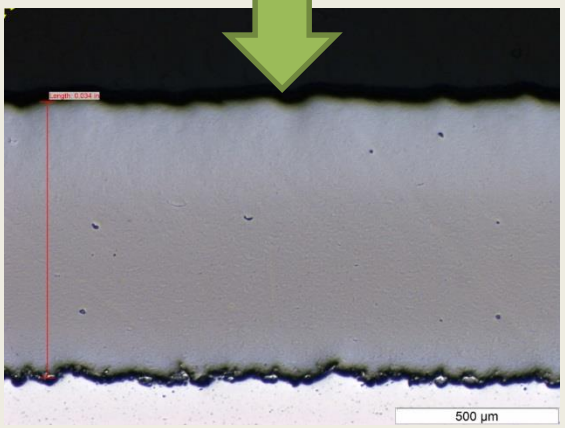
Coarse Fraction





Fine Fraction





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Fabrication

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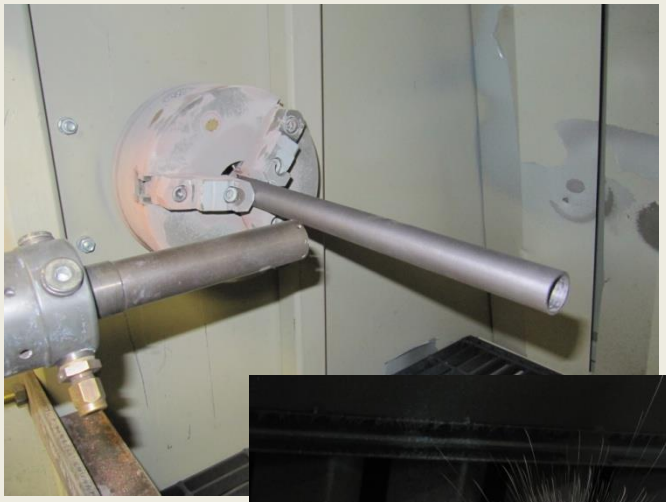
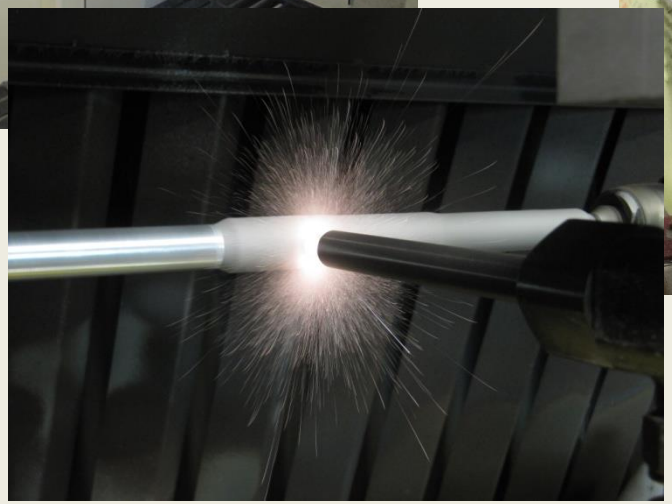
Medium Caliber

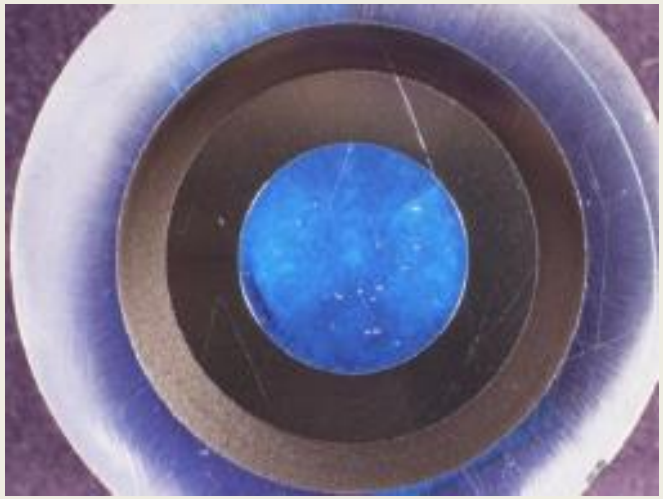




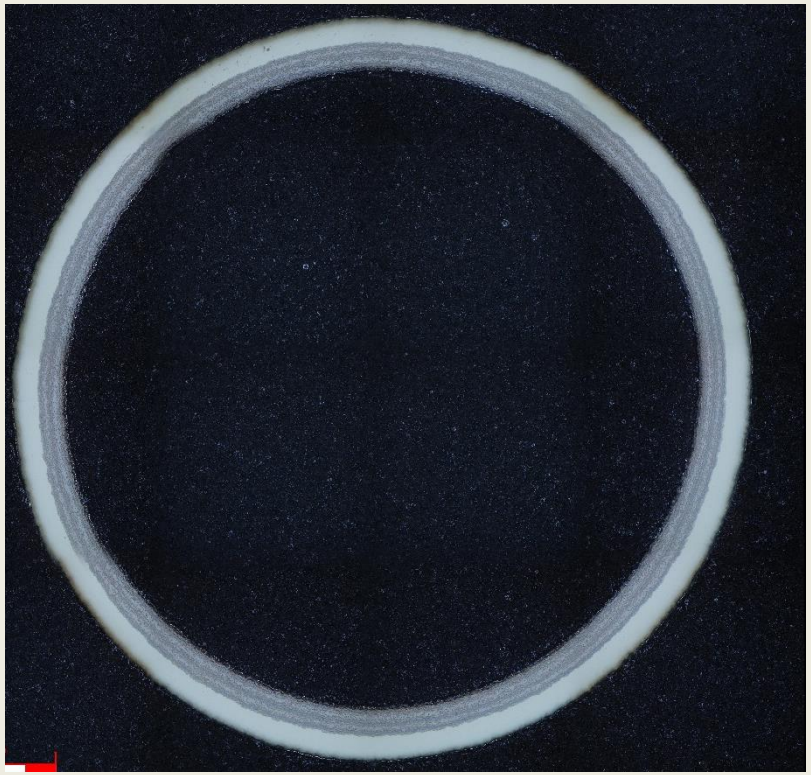
Small Caliber

Donor Tube Cross Sections

Medium Caliber (with mandrel)

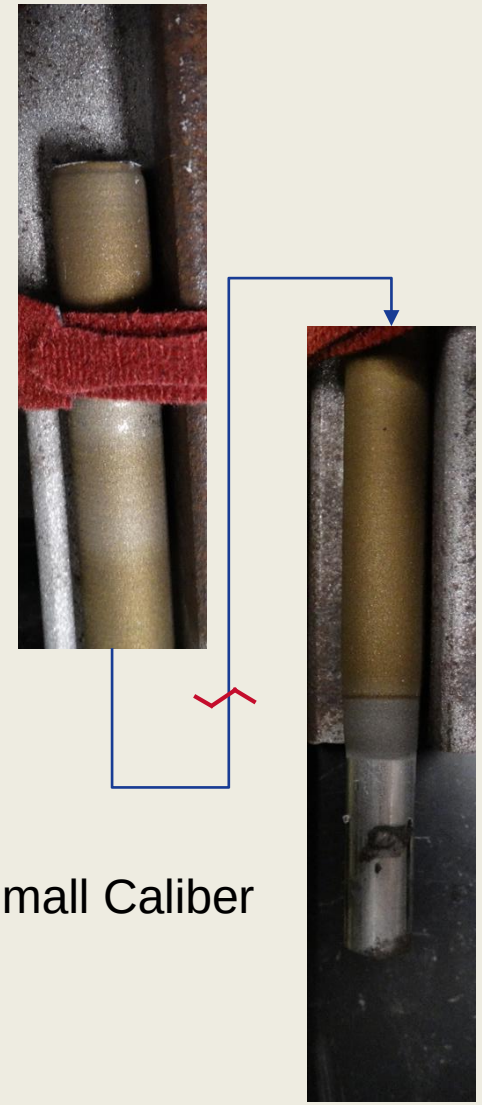


Small Caliber (Bilayer)



Full Scale Donor Tubes

Medium Caliber (3 ft length)



Small Caliber

Conclusions

- Cold Spray AM demonstrated for axisymmetric structures
  - High throughput, low resolution
  - Compatible with a wide range of materials
  - Minimal post-deposition processing

- Future Work
  - Dimensional Studies
  - Residual Stress Analysis and Predictive Distortion Tools
  - Automated Path Planning
  - Capillary Cold Spray for fine features

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Cold Spray Testing for Structural Repair

CSAT 2016

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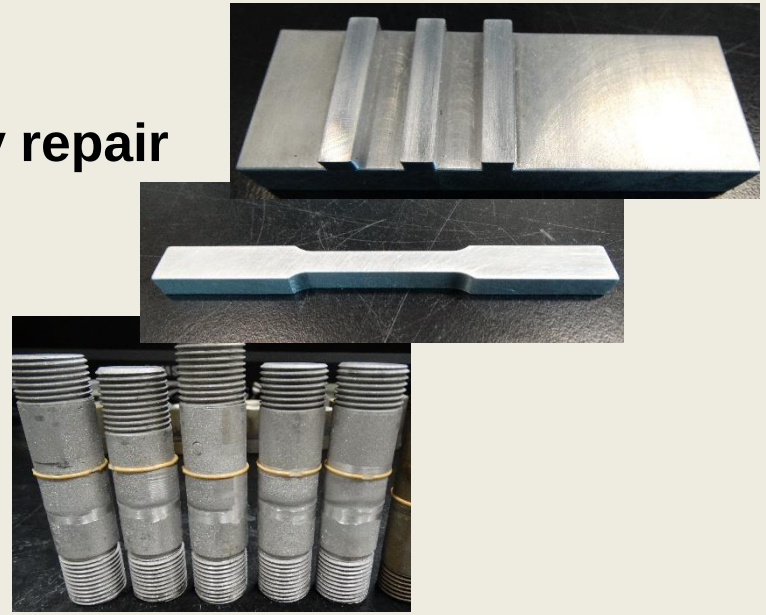
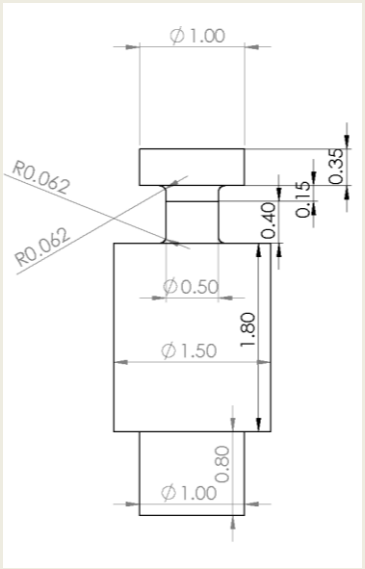
Non-structural Repair

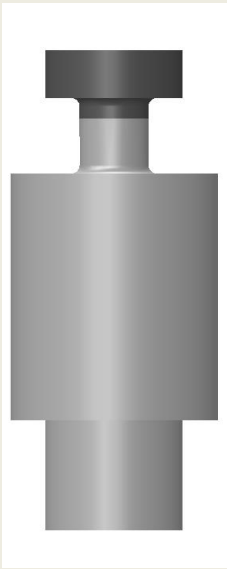
- Cold spray materials well established for non-structural repair
  - Aerospace Al alloys on cast Al and Mg
  - Bronze component repair
  - CrC NiCr for high hardness steels
  - Ti, SS, Cu, Ni, and other materials
- Common mechanical tests for cold spray repair
  - Triple lug shear
  - Tensile
  - Fatigue
  - Adhesion via ASTM C633 “bond bar test”
- ASTM C633 adhesion test constraints
  - Test capability limited by glue properties
  - FM1000 glue 10,000 psi @ RT
  - Successful test result typically listed “glue failure @ > 10,000 psi”
  - Structural repair: need accurate adhesion strength at 10-30,000 psi

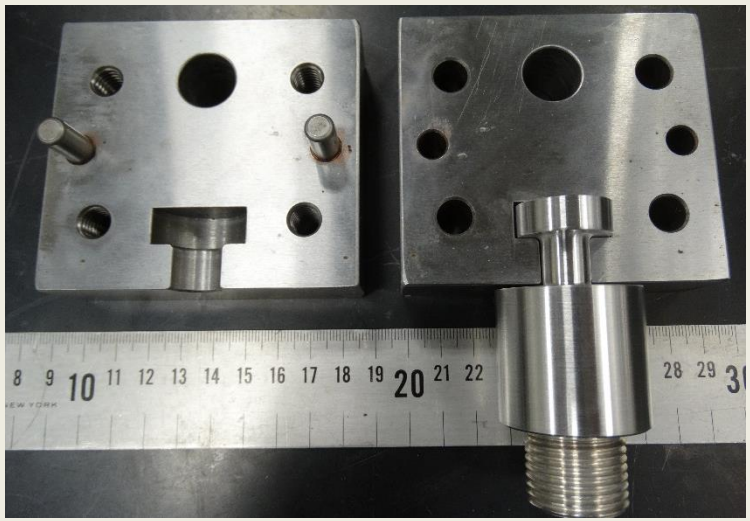


Modifying ASTM C633

- **Glueless Adhesion Test**
  - Evaluate full adhesion strength
  - Enables elevated temp testing
- **Specimen Design**
  - Neck and cap design based on Huang and Fukanuma[1]
  - Cold spray / substrate interface located in neck
  - 1.5” substrate bar diameter to accommodate cold spray taper
- **Fixturing Design**
  - Dual plate fixture accommodates varying cap thicknesses
  - Couples to load frame similar to ASTM C633 uniaxial loading design



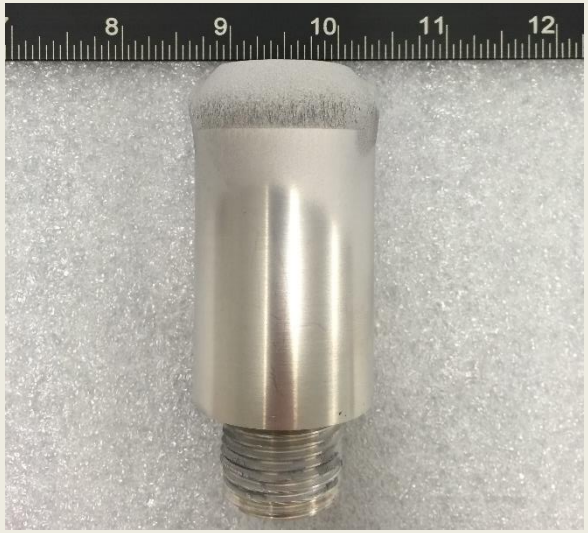


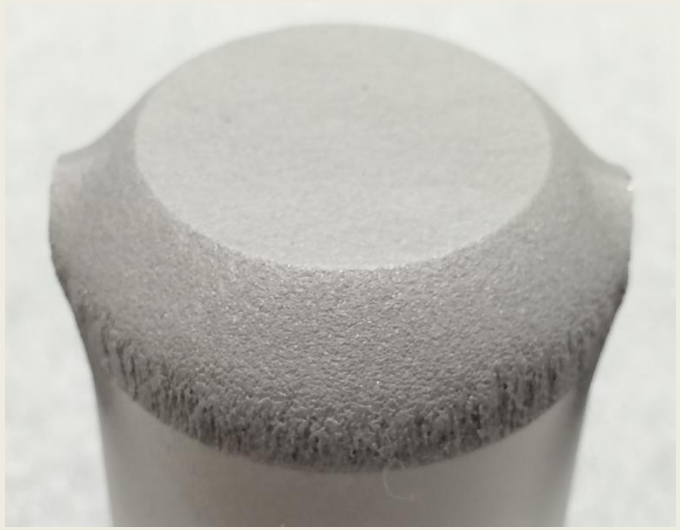


[1] Huang, R., Fukanuma, H. J. Thermal Spray Tech. 2012, 21, 3, 541.

Glueless Adhesion Test

Al 6061 cold spray on cast Al C355-T6 test specimens: as sprayed condition





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Glueless Adhesion Test

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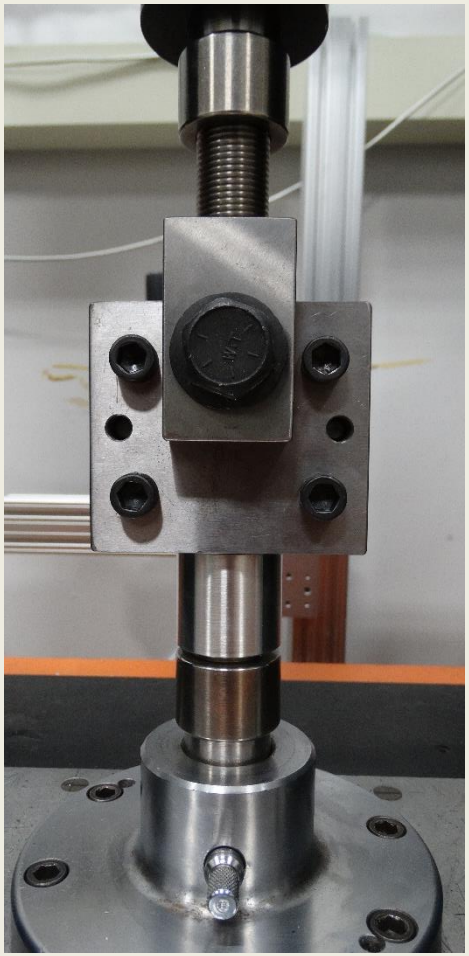
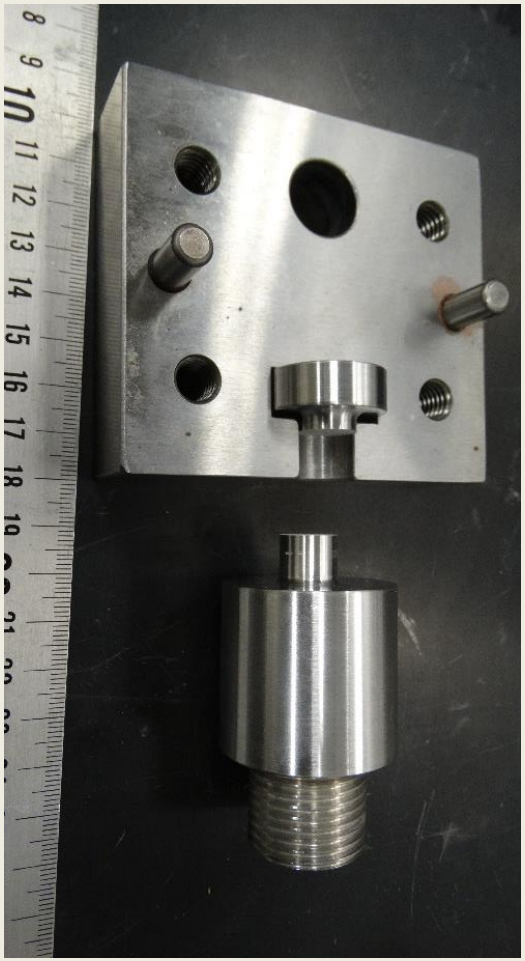
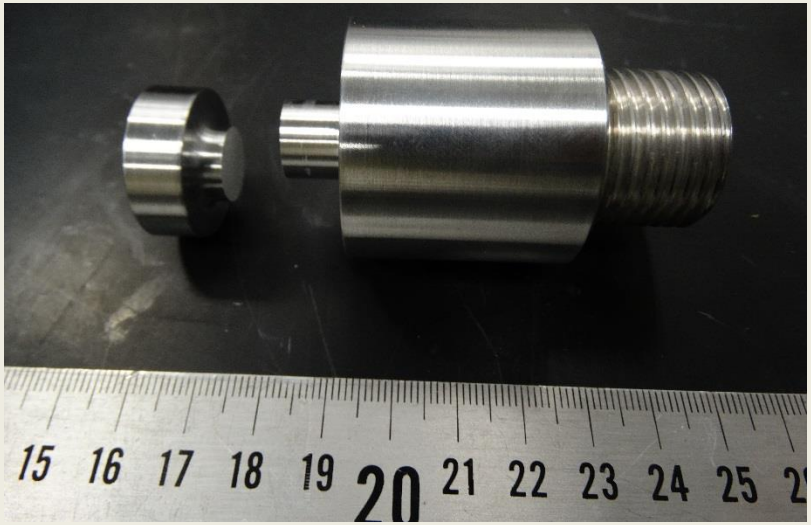
Fixturing for uniaxial loading



Tested specimen



Failure at deposit/substrate interface



Glueless Adhesion Test

Cold Spray Al 6061 on Cast Mg ZE41A-T5 and Cast Al C355-T6 Glueless Adhesion Test Results

Substrate	Max Load (lbf)	UTS (ksi)	Failure Mode
Mg ZE41A-T5	4810	24.5	Adhesion to substrate failure
Mg ZE41A-T5	4664	23.8	Adhesion to substrate failure
Mg ZE41A-T5	4710	24.0	Adhesion to substrate failure
Mg ZE41A-T5	4551	23.2	Adhesion to substrate failure
Mg ZE41A-T5	4508	23.0	Adhesion to substrate failure
Mg ZE41A-T5	4621	23.5	Adhesion to substrate failure
Al C355-T6	3583	18.2	Adhesion to substrate failure
Al C355-T6	4057	20.7	Adhesion to substrate failure
Al C355-T6	5039	25.7	Adhesion to substrate failure
Al C355-T6	3886	19.8	Adhesion to substrate failure
Al C355-T6	4727	24.1	Adhesion to substrate failure
Al C355-T6	5492	28.0	Adhesion to substrate failure

Triple Lug Shear

Cold Spray Al 6061 on Cast Mg ZE41A-T5 and Cast Al C355-T6
Triple Lug Shear Test Results

Substrate	Max Load (lbf)	Ult. Shear Stress (ksi)	Failure Mode
Mg ZE41A-T5	4653	24.8	Substrate failure
	4484	23.9	Substrate failure
	4493	24.0	Substrate failure
Mg ZE41A-T5	4654	24.8	Substrate failure
	4553	24.3	Substrate failure
	4473	23.9	Substrate failure
Mg ZE41A-T5	4488	23.9	Substrate failure
	4413	23.5	Substrate failure
	4301	22.9	Substrate failure
Al C355-T6	4218	22.5	Adhesion to substrate failure
	4410	23.5	Adhesion to substrate failure
	4654	24.8	Adhesion to substrate failure
Al C355-T6	4842	25.8	90% adhesion 10% cohesion
	5049	26.9	75% adhesion 25% cohesion
	5104	27.2	75% cohesion 25% adhesion
Al C355-T6	4715	25.1	50% adhesion 50% cohesion
	5088	27.1	25% substrate 75% adhesion
	4966	26.5	Adhesion to substrate failure

Future Work

- Evaluation of full adhesion strength for bronze, CrC NiCr, and Al 5056 cold spray deposits on various substrates
- Further testing to identify the lowest deposit thickness required for production of cold spray neck and cap
  - 0.5” thickness deposit currently requires long spraytimes, powder, and process gas
- Establish glueless adhesion test as a MIL specified adhesion test for cold spray or addendum to ASTM C633
- Design further tests to accommodate structural repair requirements such as tensile specimens formed in the build direction

Acknowledgments

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