
# Cold Spray Developments at UTRC

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# UTRC Cold Spray Development

## Additive Manufacturing

- UTRC entered into a 5 year Collaborative Research Agreement with ARL in 2010
  - The use of cold spray for additive manufacturing
    - Spray forming entire parts
    - Spray forming added features on existing parts
- Benefits to cold spray formed materials
  - Unique microstructures possible with powder feedstock and processing
    - Fine crystallites for nano-scale structure
    - Traditional phase metallurgy possible
    - Larger micro scale structures with unalloyed powder blends
    - Macro-scale structures in as sprayed deposits
  - Plastic working of materials with benefits to strength, density, and microstructure
  - Potential for post processing like heat treatment or HIP to recrystallize, diffusion bond or otherwise change the microstructure
  - Spray form potentially complex shapes

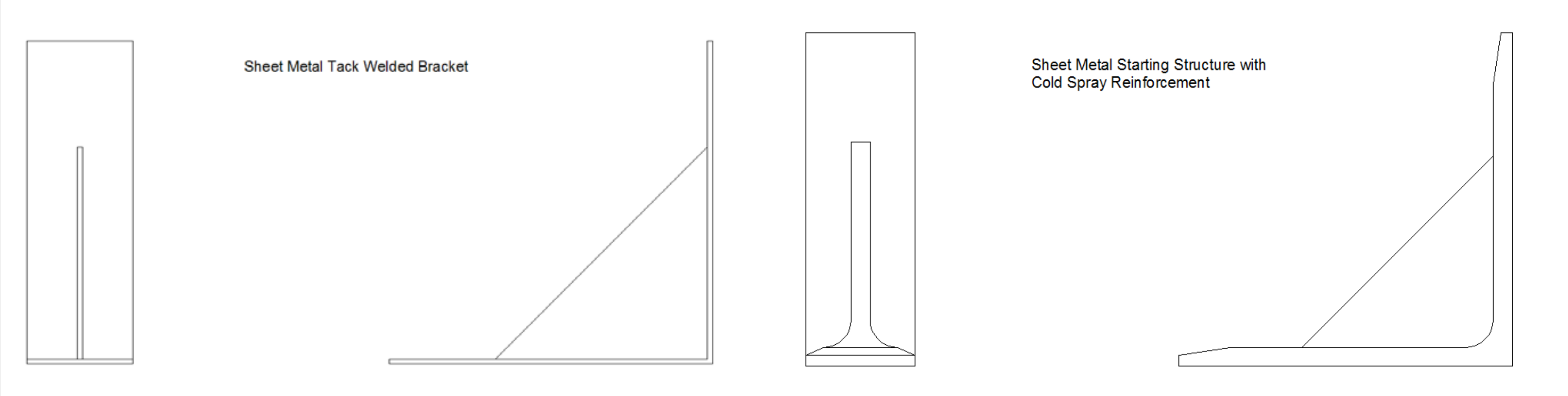
~~Coatings~~ →

•Structural Deposits
•Consolidated Materials

# UTRC Cold Spray Development

## Additive Manufacturing for Addition of Material to Existing Hardware

- Many applications or proposed applications of functional material additions have been considered or are in use today
  - Repair of aerospace hardware with minimal fatigue impact*
  - Addition of metals with specific physical, electrical, or chemical properties (ferro-magnetic, copper, aluminum, etc.)*
- Potential applications of interest in this project are deposits added in order to increase load carrying or part stiffness
  - Plastic components with a metallic reinforcement shell
    - Added strength, stiffness, and potentially erosion or impact performance
  - Sheet metal structure with added structural reinforcement

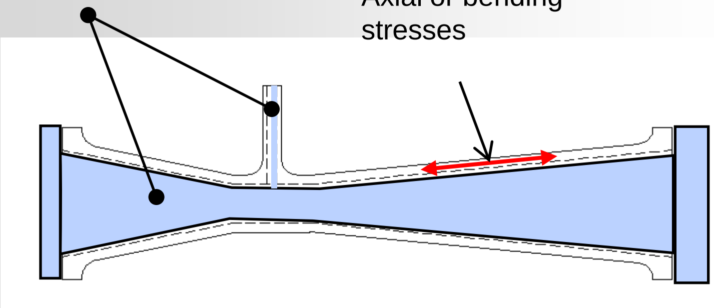



*Numerous examples provided at 2010 ASM cold spray conference and available on the internet

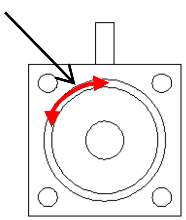
# UTRC Cold Spray Development

## Additive Manufacturing for Complete Part Fabrication

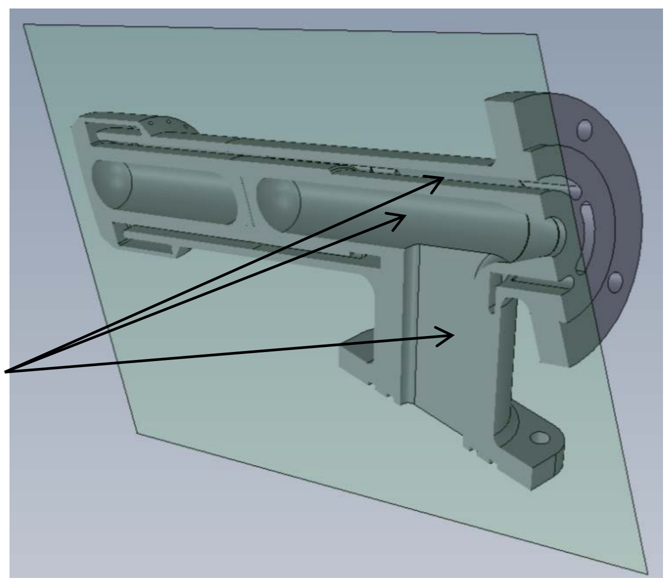
- Potential additive manufacturing applications include complete part production of varying part complexity
- Greatest potential from spraying onto removable mandrel or core
  - Generally properties in plane will be greater than out of plane
  - Internal feature geometry will be reproduced much more accurately
- Potential for varying materials or properties through wall thickness or location (Tribological inner surface strong outer surface)




**Simple Flange Mounted Venturi**




**Generic Temperature Probe Mounting Hardware**

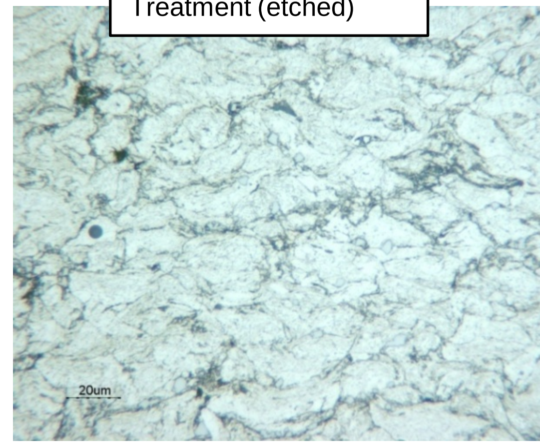


# UTRC Cold Spray Development

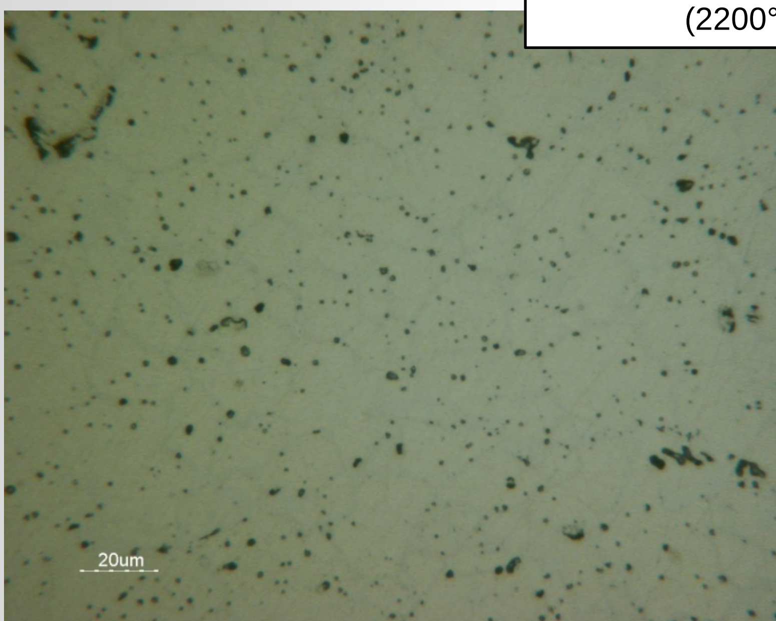
## Additive Manufacturing – Heat Treatment

- Heat treatments can be used after partial or full part fabrication to augment properties
  - Full Annealing or recrystallization annealing and Homogenization
  - Solution and precipitation treatments
  - HIP Treatments (without can to aid in consolidation of voids)
  - Stress Relief and/or partial anneal for ductility enhancement

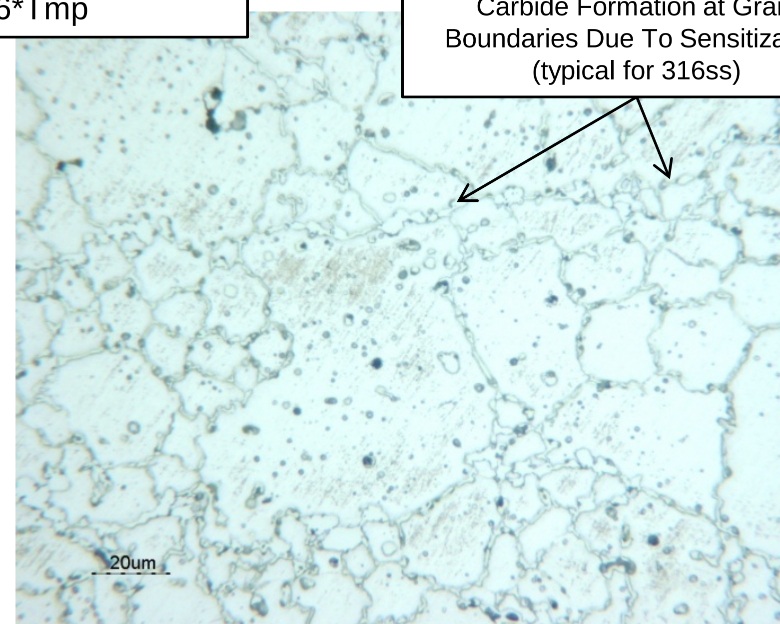
316 SS Before Heat Treatment (etched)




Heat Treatment 1 hour at 1205°C (2200°F) or 0.86*Tmp




Carbide Formation at Grain Boundaries Due To Sensitization (typical for 316ss)



# UTRC Cold Spray Development

## Mechanical Properties for Additive Manufacturing

- Properties of interest are those required for any structural component
  - Monotonic Loading
    - Tensile
    - Compression
    - Shear
  - Cyclic Loading
    - Fatigue Crack Initiation
    - Fatigue Crack Growth
  - Directional property bias
    - Depending on post processing material selection and deposition
- Mechanical Property Goals
  - Achieving properties comparable to wrought in a process with some of the manufacturing benefits of castings
  - Exceed those properties of wrought
    - Higher levels of work
    - Finer grain structure
    - Improved alloys not amenable ingot metallurgy

# UTRC Cold Spray Efforts

## Mechanical Properties for Additive Manufacturing

- Mechanical Property Characterization of Cold Spray Formed Blocks to be Discussed
  - Tantalum Sprayed with CGT4000 at ARL
    - Nitrogen Accelerating Gas
    - As Sprayed
    - Duplex Annealed
    - Tensile and Bend Evaluations
  - Nickel Sprayed with CGT4000 at ARL
    - Helium Accelerating Gas
    - As Sprayed
    - Tensile and Bend Evaluations
  - CP Aluminum with K-Tech at ARL
    - Helium Accelerating Gas
    - As Sprayed
    - Hot Isostatic Pressed
    - Tensile and Crack Growth Evaluations

# UTRC Cold Spray Efforts

## As Sprayed and Duplex Annealed Tantalum Material Evaluation

- Flat tensile specimens made per ASTM E8 (Subsize Flat Tensile)
- Brittle nature of the material in as sprayed condition was the cause of low and scattered tensile strength values
- 3 point bend tests determined optimal for determination of monotonic properties of as sprayed deposit

- Duplex heat treatment resulted in reduction in tensile strength with significant improvement in ductility
- Modulus of elasticity low compared to nominal value of 27 msi

**Tensile Testing Data Reduction**

| Specimen # | Width (in) | Thickness (in) | Peak Load (lbf) | Peak Stress (ksi) | Strain At Break (%) | Modulus (msi) | Comments |
|---|---|---|---|---|---|---|---|
| CS-AS-1 | 0.249 | 0.232 | | | | | Broke in Grip |
| CS-AS-2 | 0.248 | 0.124 | 1601 | 52.1 | 0.296 | 18.70 | Broke at Fillet |
| CS-AS-3 | 0.248 | 0.124 | 1810 | 58.6 | 0.315 | 21.63 | Broke at Fillet |
| CS-AS-4 | 0.248 | 0.124 | 1827 | 59.1 | 0.351 | 19.30 | Broke at Fillet |
| CS-AS-5 | 0.249 | 0.124 | 1572 | 50.7 | 0.261 | 22.25 | Broke at Fillet |
| CS-AS-6 | 0.249 | 0.124 | 1384 | 45.0 | 0.202 | 23.48 | Broke at Fillet |
| **Mean** | | | **1639** | **53.1** | **0.285** | **21.07** | |
| **Std. Dev.** | | | **184** | **5.9** | **0.057** | **2.02** | |

**3 Point Bend Data Reduction**

| Specimen # | Width (in) | Thickness (in) | Peak Stress (ksi) |
|---|---|---|---|
| CS-AS-1 | 0.249 | 0.232 | 125.4 |
| CS-AS-2 | 0.248 | 0.124 | 115.7 |
| CS-AS-3 | 0.248 | 0.124 | 115.7 |
| CS-AS-4 | 0.248 | 0.124 | 124.9 |
| CS-AS-5 | 0.249 | 0.124 | 115.8 |
| CS-AS-6 | 0.249 | 0.124 | 115.8 |
| **Mean** | | | **117.6** |
| **Std. Dev.** | | | **4.9** |

**Tensile Testing Data Reduction**

| Specimen # | Width (in) | Thickness (in) | Peak Load (lbf) | Yield Strength (ksi) | Ultimate Strength (ksi) | Starting Gage Length (in) | Ending Gage Length (in) | % Elongation | Modulus (msi) |
|---|---|---|---|---|---|---|---|---|---|
| CS-AN-1 | 0.248 | 0.124 | 2213 | 63.5 | 72.1 | 0.9675 | 1.3845 | 43% | 25.49 |
| CS-AN-2 | 0.248 | 0.123 | 2279 | 66.1 | 74.9 | 0.9925 | 1.394 | 40% | 22.75 |
| CS-AN-3 | 0.248 | 0.123 | 2280 | 69.6 | 74.7 | 0.975 | 1.401 | 44% | 24.00 |
| CS-AN-4 | 0.248 | 0.124 | 2301 | 69.7 | 75.3 | 0.9845 | 1.404 | 43% | 27.61 |
| CS-AN-5 | 0.248 | 0.124 | 2312 | 70.3 | 75.5 | 0.9695 | 1.378 | 42% | 20.10 |
| CS-AN-6 | 0.248 | 0.126 | 2359 | 69.9 | 75.5 | 0.973 | 1.365 | 40% | 22.64 |
| **Mean** | | | **2291** | **68.2** | **74.7** | | | **42%** | **23.42** |
| **Std. Dev.** | | | **48** | **2.8** | **1.3** | | | **1.5%** | **2.74** |

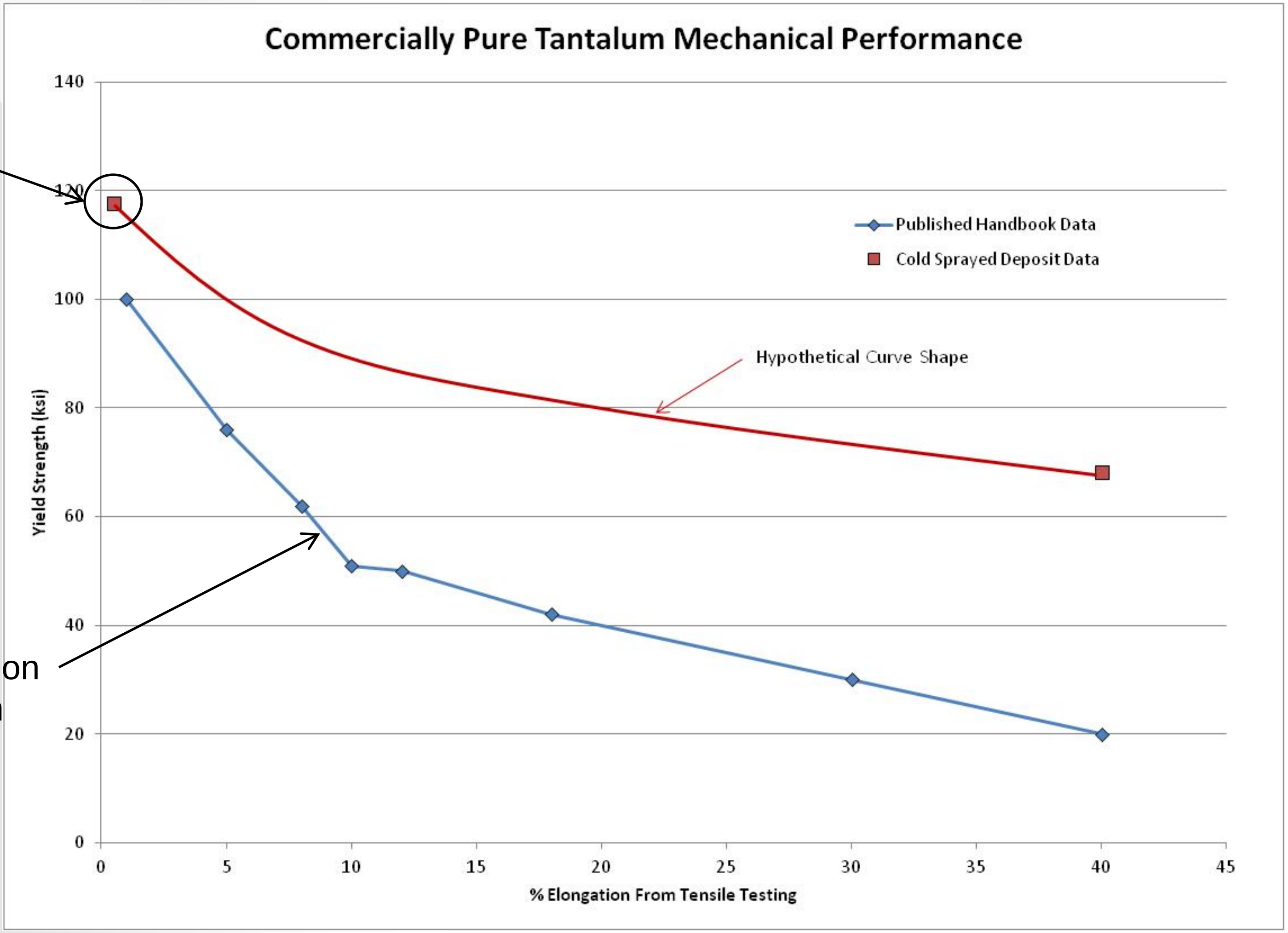
# UTRC Cold Spray Efforts

## As Sprayed and Duplex Annealed Tantalum Material Evaluation

- Tensile properties of annealed cold sprayed tantalum far exceed those published for annealed tantalum with comparable ductility.

Demonstrated Through Bend Testing

Reproduced from available Literature on Unalloyed Tantalum



# UTRC Cold Spray Efforts

## As Sprayed Nickel Material Evaluation

- Flat tensile specimens made per ASTM E8 (Subsize Flat Tensile)
- Brittle nature of the material again favors 3 point bend configuration for monotonic properties
- Modulus values comparable to theoretical values of nickel
- No heat treatment performed
- When highly worked the materials ultimate strength increases exponentially similarly to tantalum

**ARL Cold Sprayed Nickel Data (12/3/2010)**

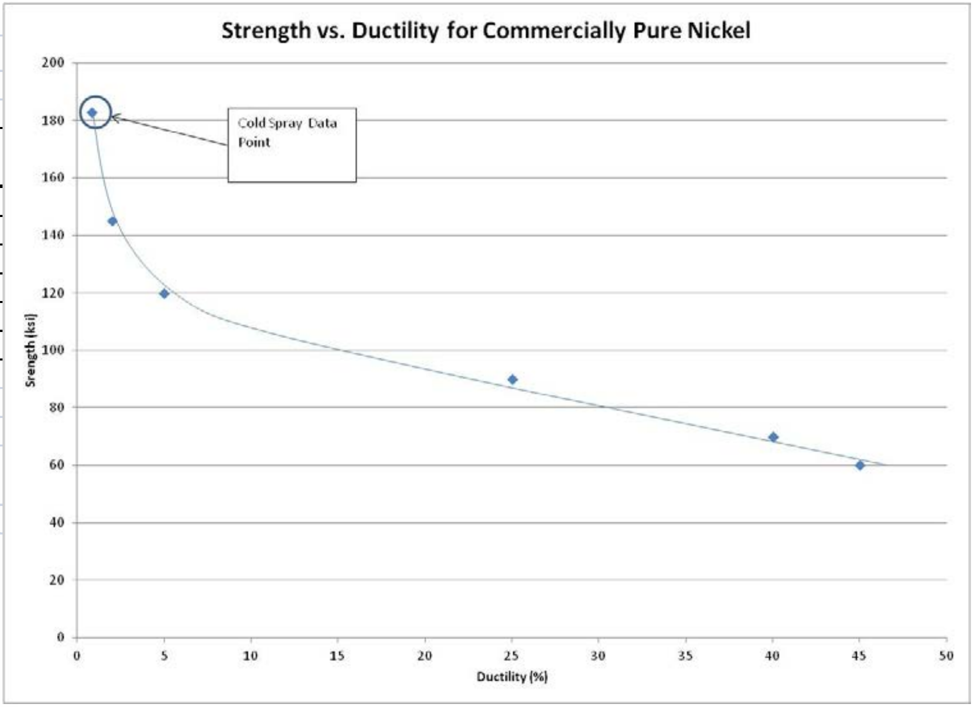
**As sprayed Tensile Tests**

All Specimens failed in fillet area

| Specimen# | UTS (ksi) | YS (ksi) | Modulus of Elasticity (msi) | Plastic Strain at Break |
|---|---|---|---|---|
| CS-NI-AS-1 | 92.7 | n/a | 26.04 | 0.09% |
| CS-NI-AS-2 | 101.2 | n/a | 29.09 | 0.15% |
| CS-NI-AS-3 | 105.4 | 104.8 | 28.7 | 0.21% |
| CS-NI-AS-4 | 117.3 | 106.3 | 27 | 0.73% |
| CS-NI-AS-5 | 114.2 | 106.6 | 28 | 0.53% |
| CS-NI-AS-6 | 114.0 | 104.6 | 28.25 | 0.72% |

**As Sprayed Bend Specimen**

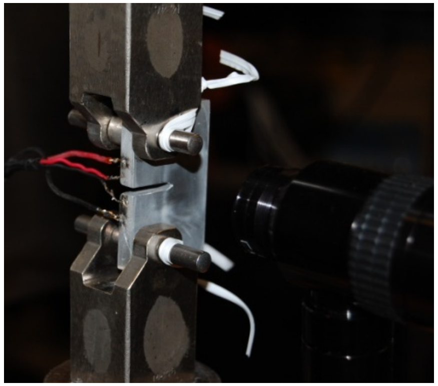
| Specimen# | UTS (ksi) | YS (ksi) | Modulus of Elasticity (msi) | Plastic Strain at Break |
|---|---|---|---|---|
| CS-NI-3pt-1 | 183.3 | 151.0 | 29.45 | 0.85% |



# UTRC Cold Spray Efforts

## As Sprayed and HIP'ed Commercially Pure Aluminum

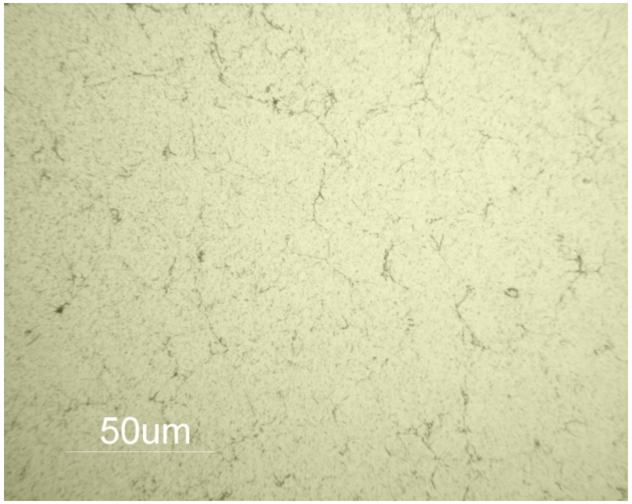
- Blocks manufactured 0.75 inches thick and measuring ~6 inches square
- Blocks sectioned to produce mechanical test specimens
  - 3 - ASTM E8 Round Tensile extracted in the x-direction
  - 2 – CT crack growth specimens x-direction loading
    - Extended specimen length to facilitate Compression Pre-cracking
    - ACPD system to monitor crack length
    - Y-Z specimen plane, Y growth direction (group A)
  - 2 samples made from 1100 Aluminum for comparison to Group A results
- Initial data suggests anisotropic properties
  - 4 additional CT specimens removed
    - Y-direction loading, X-Z crack plane, X direction growth (group B)
    - Z-direction loading, X-Y crack Plane, X direction growth (group C)
  - 2 three point bend crack growth specimens removed
    - Y-direction loading, Y-Z crack plane, Z direction growth (group D)
    - X-direction loading, X-Z crack Plane, Z direction growth (group E)
- SEM imaging and chemistry performed as well as EBSD grain mapping on samples removed from blocks



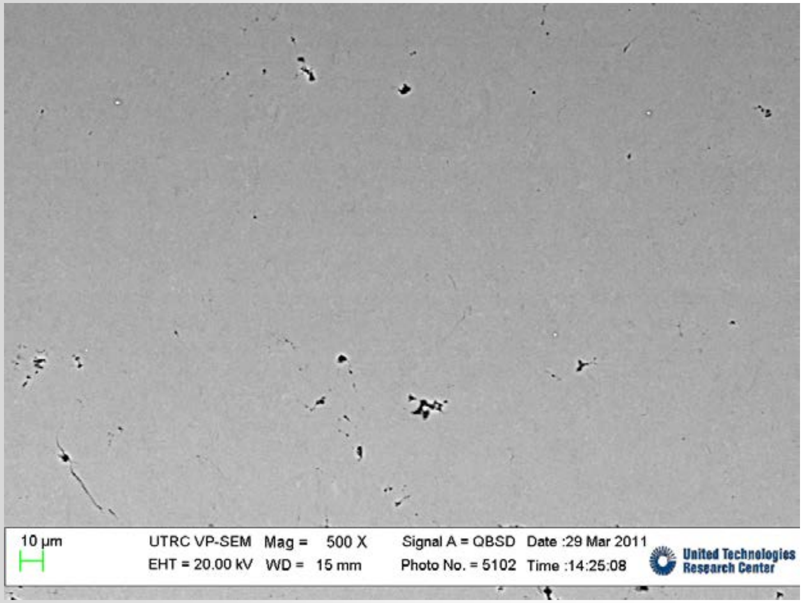
# UTRC Cold Spray Development

## Hot Isostatic Pressing of CP Aluminum

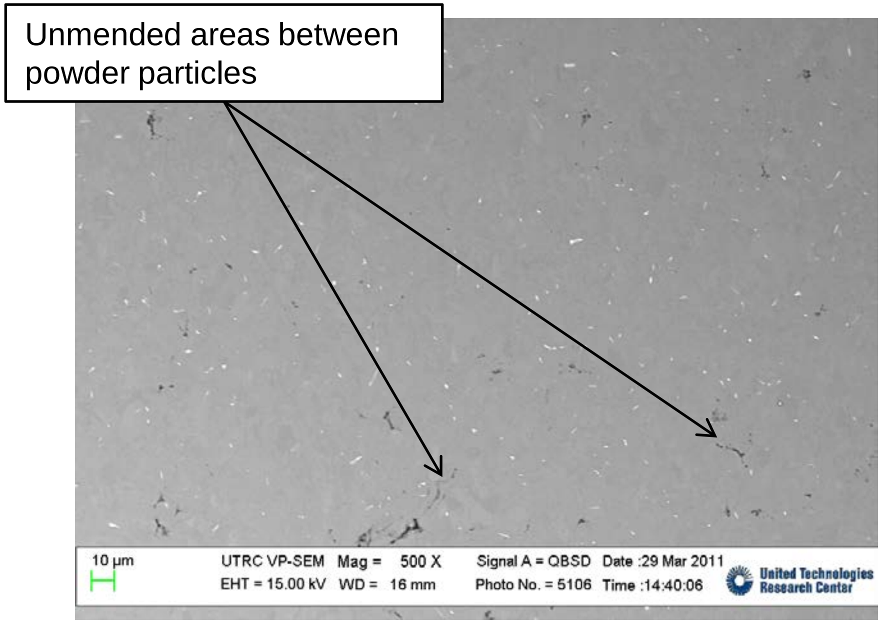
- Heat treatment allowed sufficient diffusion to promote secondary phase formation
- HIP process did not effectively consolidate all of the powder particle gaps and/or porosity from the spray process




As Sprayed Deposit




Deposit After HIP Operation

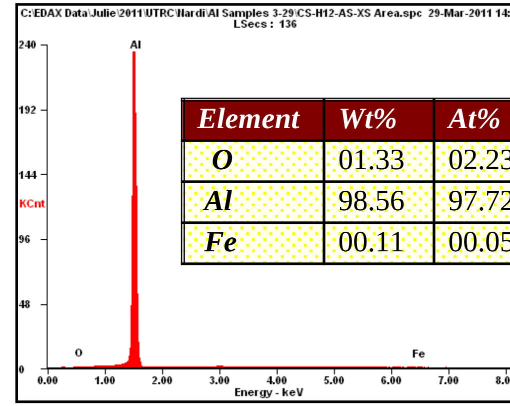


# UTRC Cold Spray Efforts

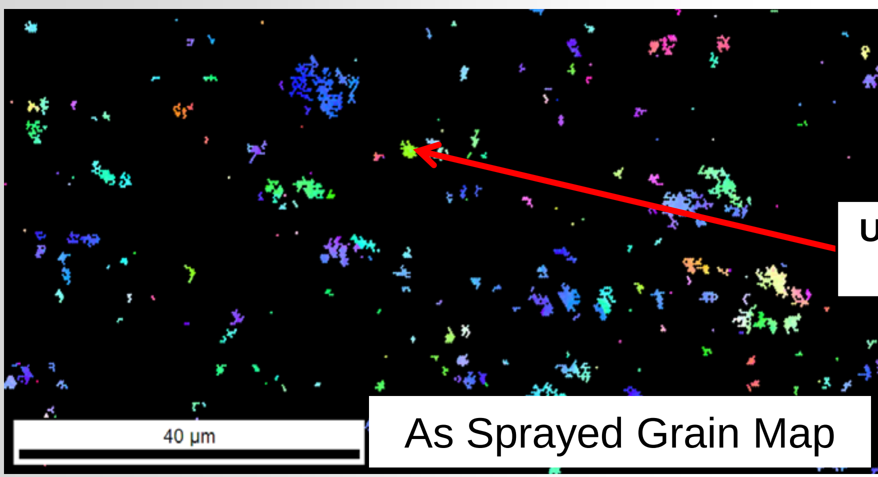
## Commercially Pure Aluminum

- EBSD Data Generated for as sprayed Deposit and HIP'ed deposit
- Clean grain maps generated for HIP'ed samples
  - Very few strained grains
- Grain maps for as sprayed materials exhibit very few resolvable grains
  - Unresolved areas black
    - Lattice strain beyond physical limits of equipment
    - Grain sizes below probe tip diameter (~20-50nm)

Chemistry consistent with CP aluminum except oxygen higher than specified



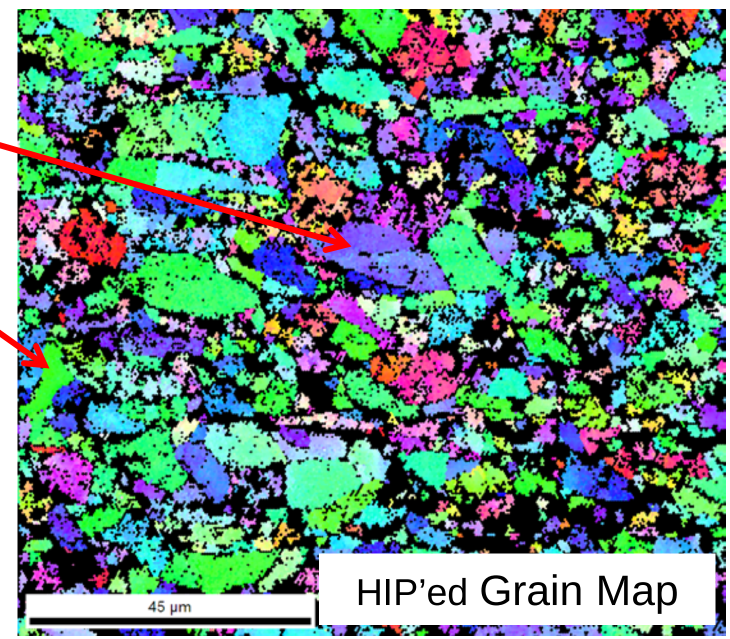

| Element | Wt% | At% |
|---|---|---|
| O | 01.33 | 02.23 |
| Al | 98.56 | 97.72 |
| Fe | 00.11 | 00.05 |




As Sprayed Grain Map

Strained Grain

Unstrained Grain




HIP'ed Grain Map

Most visible grains show evidence of strain

# UTRC Cold Spray Efforts

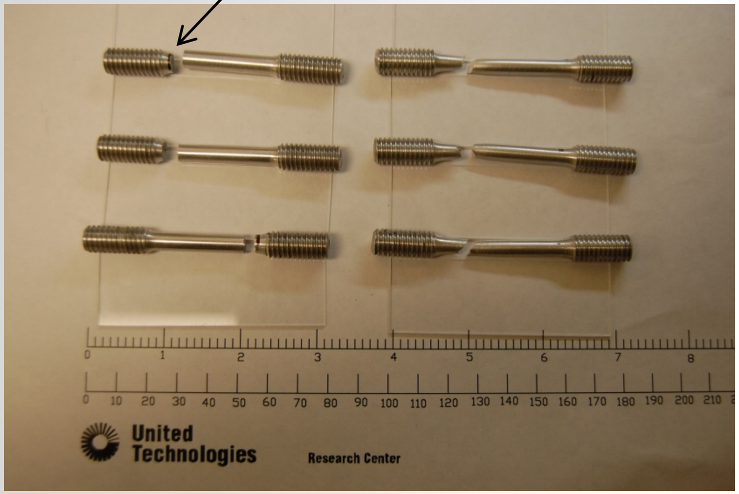
## Commercially Pure Aluminum Results

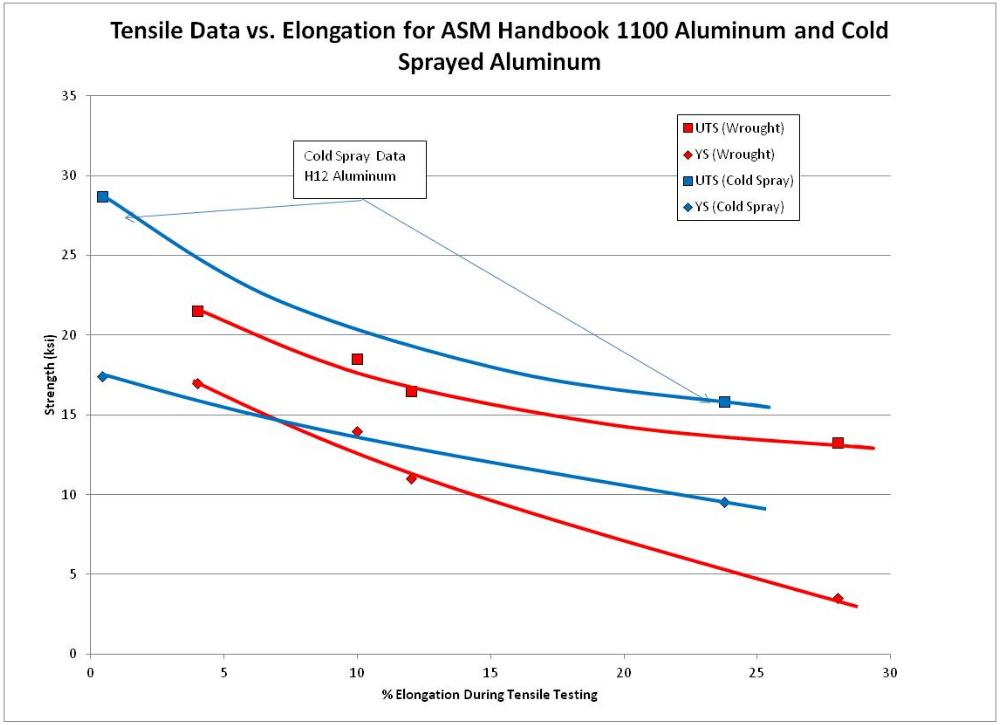
- Tensile test results with round samples were better than previous flat tensile because bending could be better controlled
- HIP heat treatment produced relatively high ductility while reducing the UTS and Yield strengths
- Strength values relative to % elongation tend to exceed handbook wrought properties

| | | | | Fillet Measurement | | |
|---|---|---|---|---|---|---|
| Specimen S/N | Diameter Center of Specimen (in) | Diameter Near Fillet (in) | % El | UTS (ksi) | YS (ksi) | Plastic Strain to Fail (%) |
| CS-CP-H12-AS-1 | 0.249 | 0.2475 | n.a. | 30.200 | 26.348 | 0.59 |
| CS-CP-H12-AS-2 | 0.2485 | 0.2455 | n.a. | 26.542 | -1.025 | 0.22 |
| CS-CP-H12-AS-3 | 0.25 | 0.2465 | n.a. | 29.413 | 26.996 | 0.47 |
| | | | Average | 28.72 | 17.44 | 0.42 |

| | | | | Fillet Measurement | | |
|---|---|---|---|---|---|---|
| Specimen S/N | Diameter Center of Specimen (in) | Diameter Near Fillet (in) | % El | UTS (ksi) | YS (ksi) | Plastic Strain to Fail (%) |
| CS-CP-H12-HP-1 | 0.249 | 0.247 | 24% | 15.916 | 9.737 | 25.31 |
| CS-CP-H12-HP-2 | 0.25 | 0.2485 | 18% | 15.704 | 9.573 | 23.36 |
| CS-CP-H12-HP-3 | 0.249 | 0.2465 | 21% | 15.851 | 9.389 | 22.57 |
| | | | Average | 15.82 | 9.57 | 23.75 |

Fillet Failures indicate that bend testing may still be needed

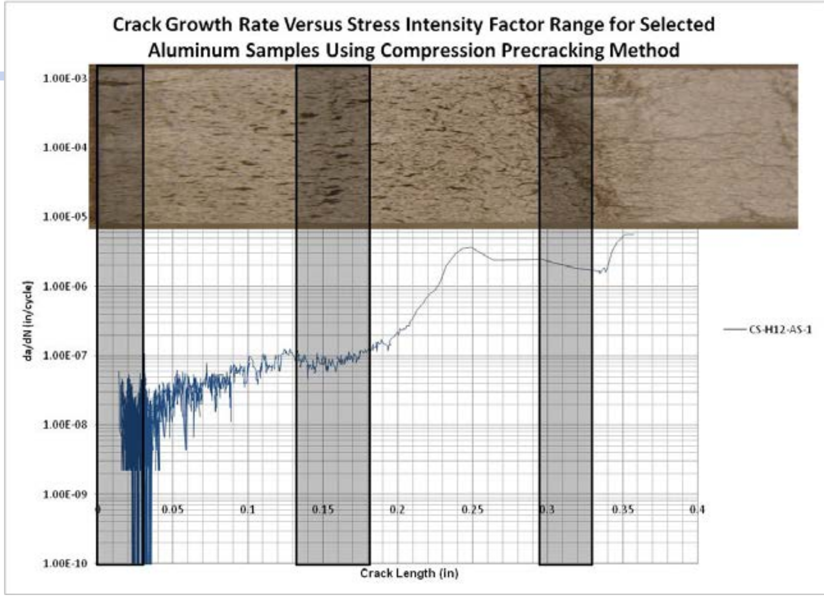


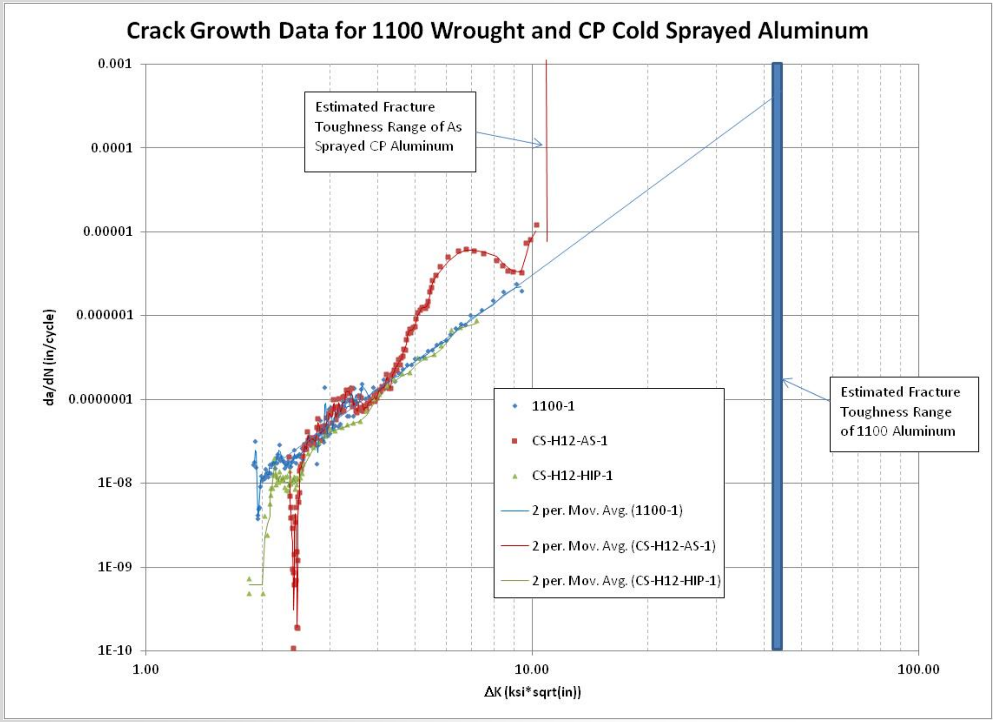



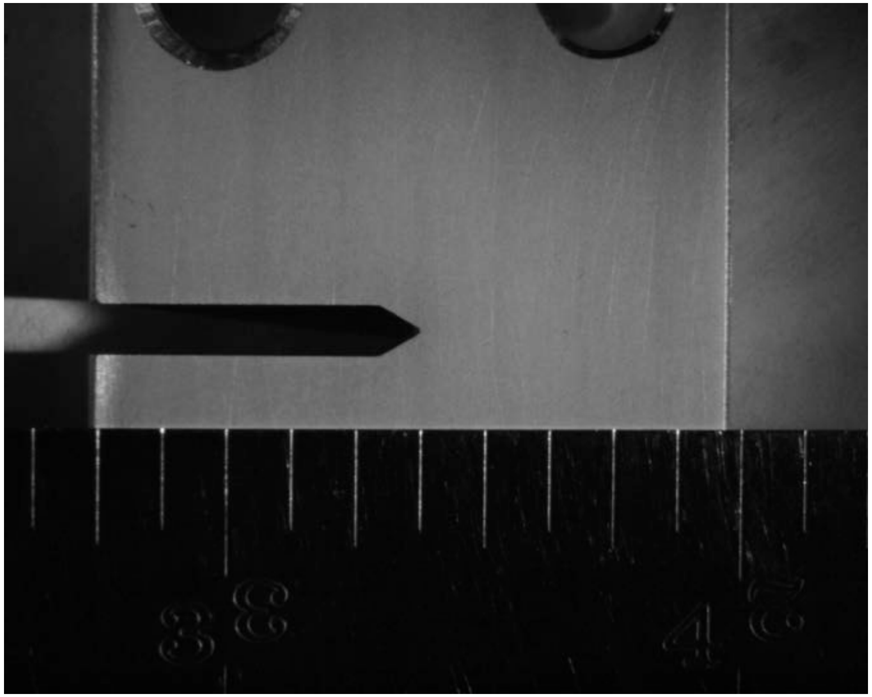
# UTRC Cold Spray Efforts

## Commercially Pure Aluminum Results

- Compressive pre-cracking constant amplitude testing produced good threshold values by minimizing the effects of plasticity induced closure
- HIP’ed material performs similarly to Wrought 1100
- As sprayed material exhibits texture effects



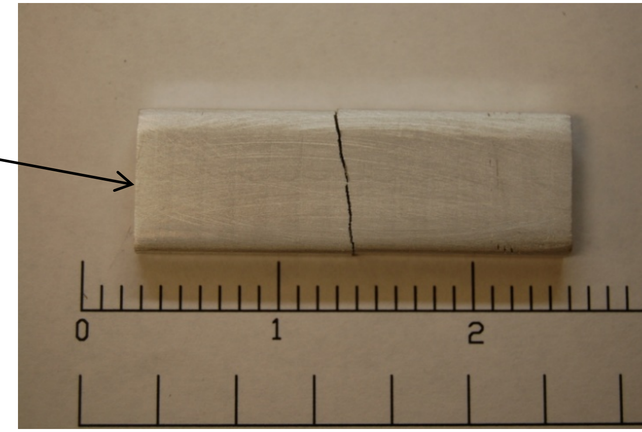



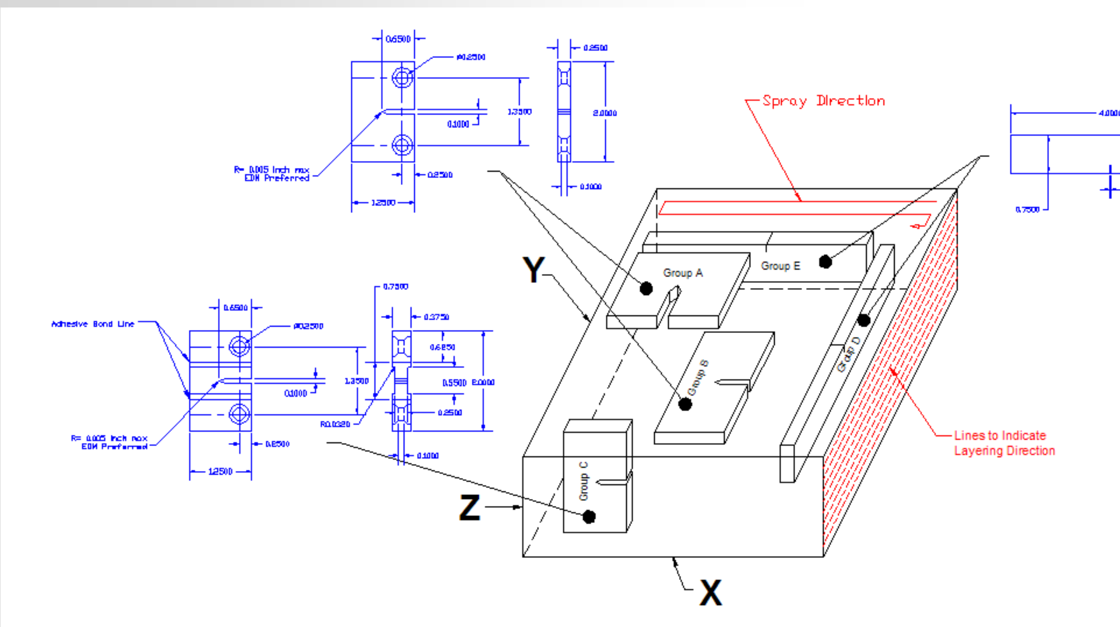



# UTRC Cold Spray Efforts

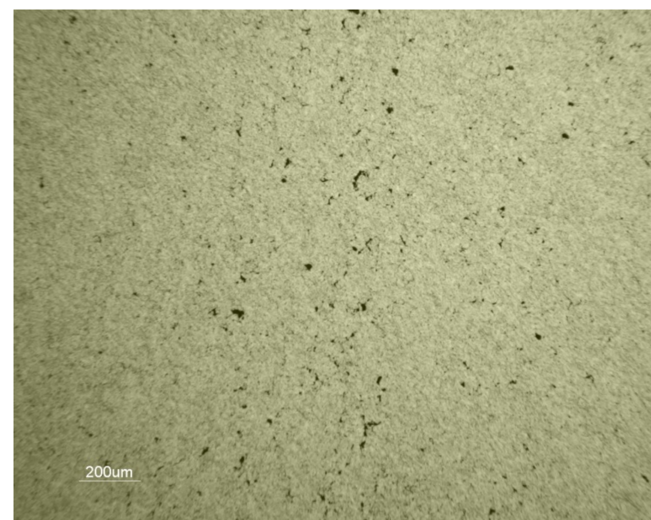
## Commercially Pure Aluminum Texture Effects

- Steps being taken to evaluate texture effects
  - Monotonic 3 point bend testing of beam specimen in Y orientation
    - 20% debit compared to X direction UTS data
  - Metallographic section to understand microstructure variations
  - Evaluate Crack Growth Specimens




Higher than average density of micro-structural porosity in dank band region



# UTRC Cold Spray Efforts

## Summary

- Cold spray shows great potential for additive manufacturing through material addition to existing hardware as well as total part fabrication
- Mechanical properties will likely be comparable or exceed those of their wrought counterpart
- Spray texture may play a very important role in as sprayed materials

## Next Steps

- Complete installation of a CGT 4000 system provided by ARL on site at UTRC
- Select an appropriate structural alloy for further characterization
- Work to develop more complete mechanical property data for the alloy
- Manufacture several simple dummy parts using a sprayed mandrel or core approach
- Evaluate the dummy part destructively, non-destructively and mechanically

# UTRC Cold Spray Efforts

## Acknowledgements

The author would like to thank the staff at the Army Research Laboratory for consulting on test results obtained and for providing the deposits used to generate the test results herein.