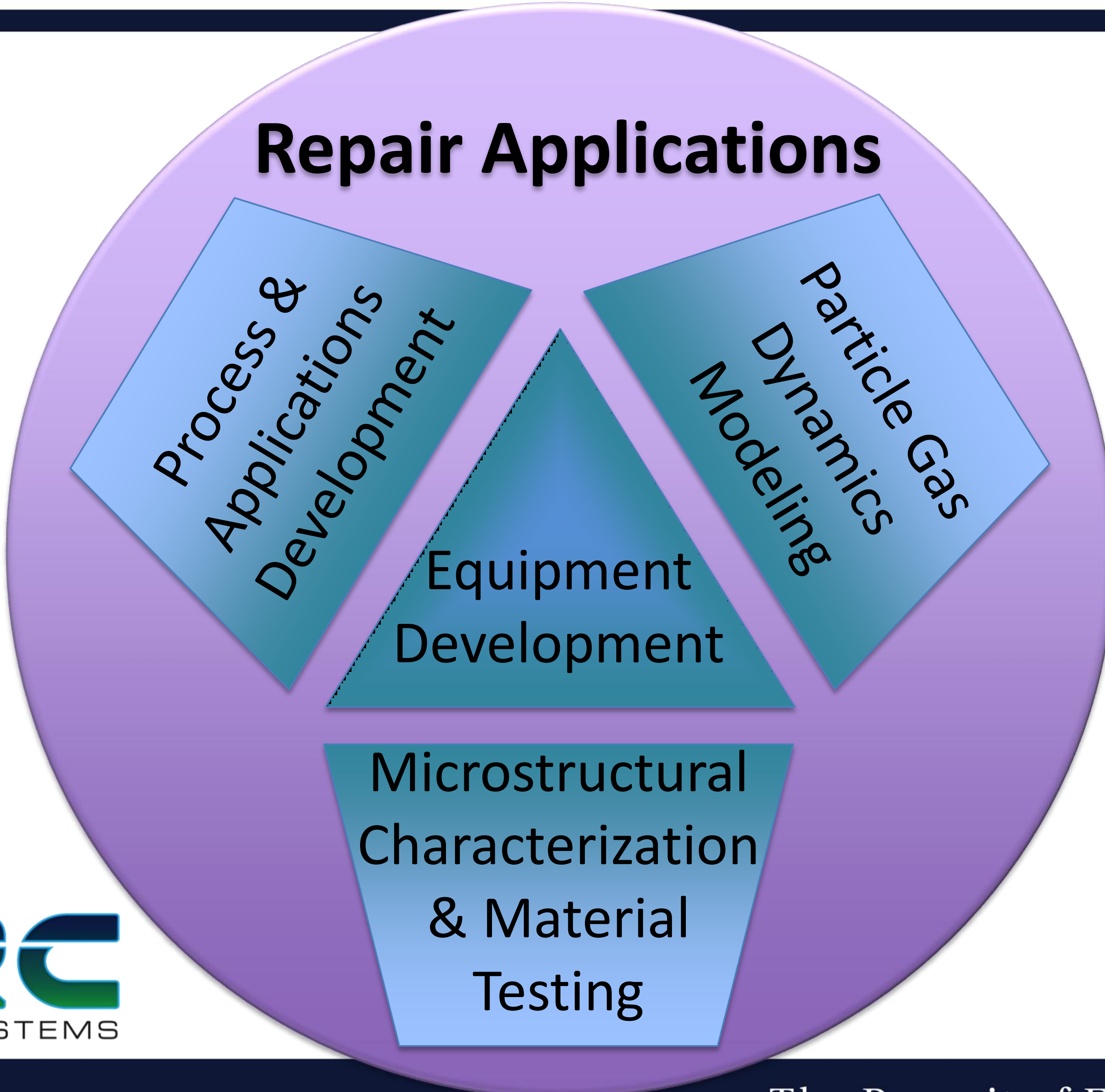
CS Repair and Refurbishment Developments at SDSM&T

Christian Widener, Ph.D.
South Dakota School of Mines and Technology
& VRC Metal Systems

Michael Carter, Todd Curtis, Ozan Ozdemir, Reza Rokni,
Dr. Grant Crawford, Dr. Bharat Jasthi, Dr. Marius Ellingsen
South Dakota School of Mines and Technology

VRC METAL SYSTEMS

SOUTH DAKOTA M SCHOOL OF MINES & TECHNOLOGY


Repair Applications
Process & Applications Development
Particle Gas Dynamics Modeling
Equipment Development
Microstructural Characterization & Material Testing

Applied Research Efforts Underway

- **Microstructural Investigation & Material Testing**
  - Emphasis on understanding metallurgy of powders & coatings
  - Aluminum & other structural alloys
- **Computational Fluid Dynamics Modeling**
  - Nozzle Design & Parameter Prediction
  - Gas Mixing
- **Equipment Development**
  - VRC Gen III
  - Supporting Equipment: Nozzles, Motion Systems, Powder Processing
- **Applications Development**
  - Repair for DOD components
  - Cold Spray as Coating & Additive Process for new parts

SOUTH DAKOTA M SCHOOL OF MINES & TECHNOLOGY

Microstructure

- **Lessons Learned**
  1. Cold Spray retains the microstructure of the powder material.
     - Solid state
     - Minimal time for diffusion
     - Addition of plastic strain
  2. Better properties can be achieved through optimization of powder material conditions and process parameters.
     - Structural properties are possible…

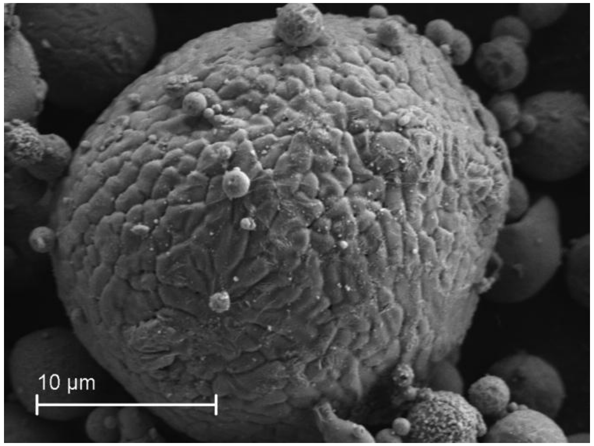
SOUTH DAKOTA SCHOOL OF MINES & TECHNOLOGY

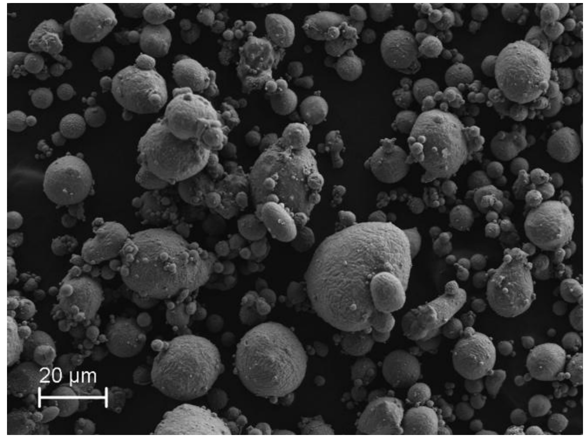
Powder Characterization

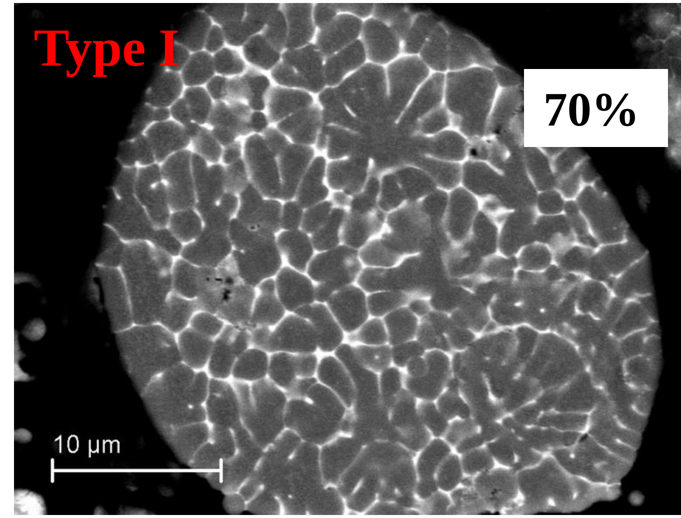
- Standard Testing
  - **Hardness** – needed for modeling
  - **SEM images** – understand morphology
  - **Microtrack particle analysis** – understand size distribution
    - Fines – clogging – deposition quality
    - Size range – deposition efficiency
  - **DSC** – understand material condition (temper & thermal sensitivity)
  - **EBSD** – understand elemental distribution, grain size, etc.

SOUTH DAKOTA SCHOOL OF MINES & TECHNOLOGY

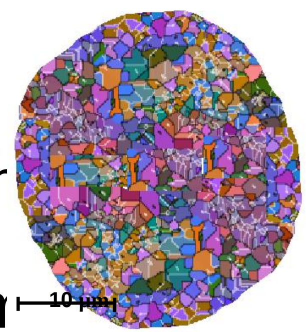
Al 7075 Powder Microstructure

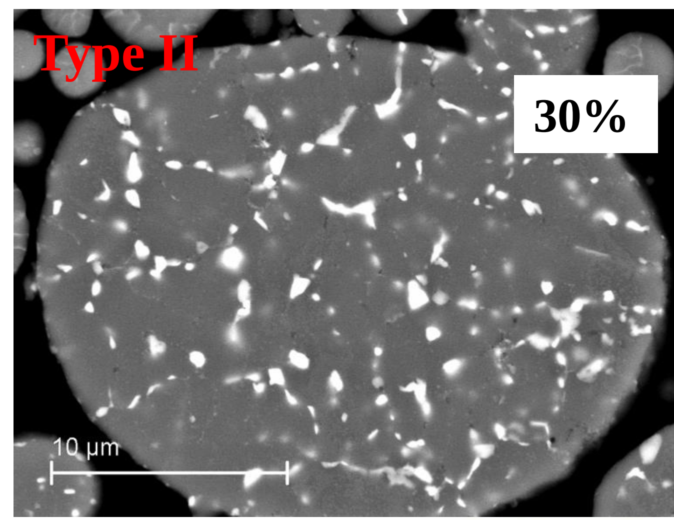




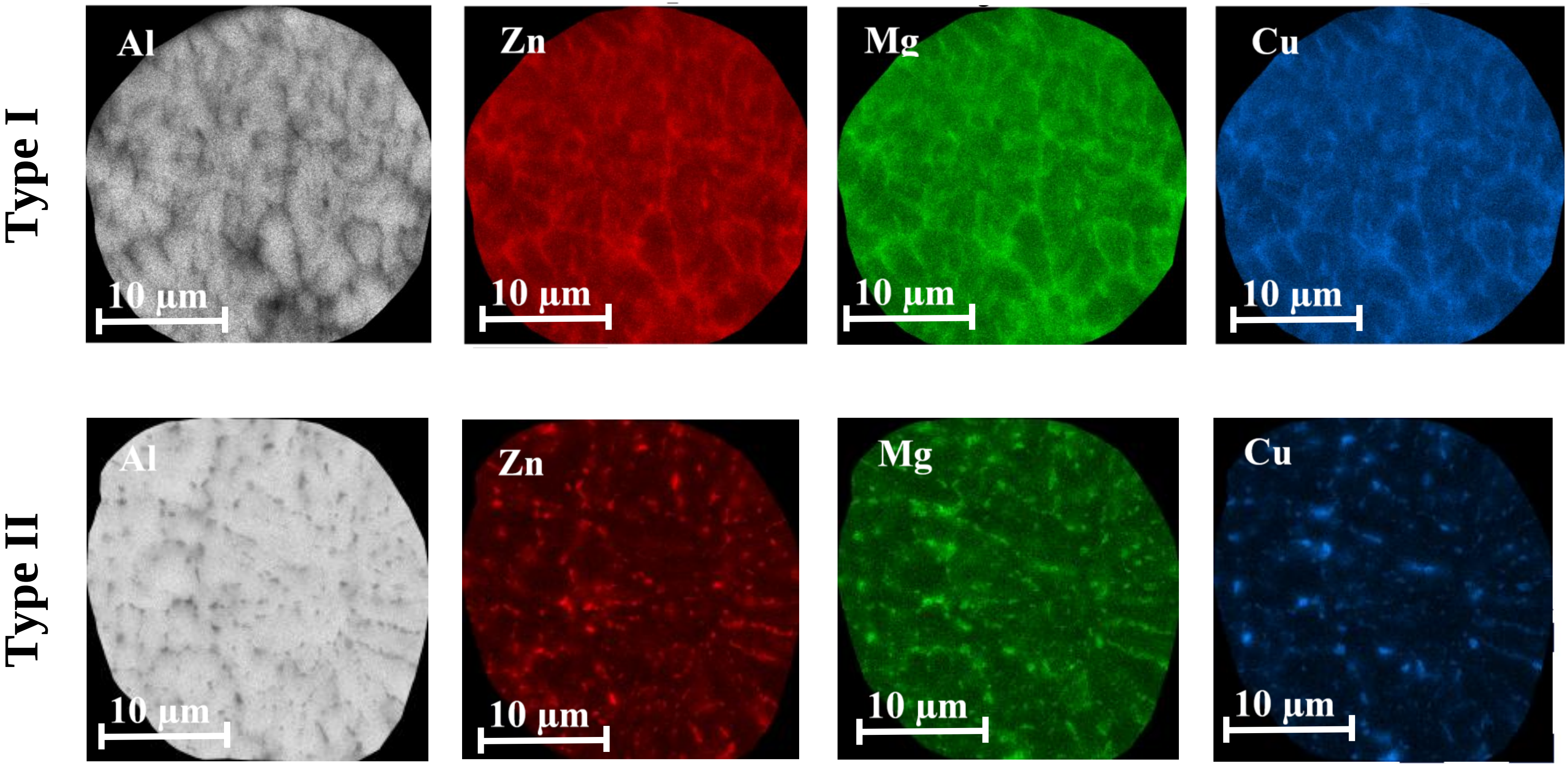


- Valimet 7075 -325 Mesh powder
- Variable particle size
- Particle Dia: 18.6 ± 8.2 µm
- Powder grain size: 1-4 µm
- Two particle microstructure types

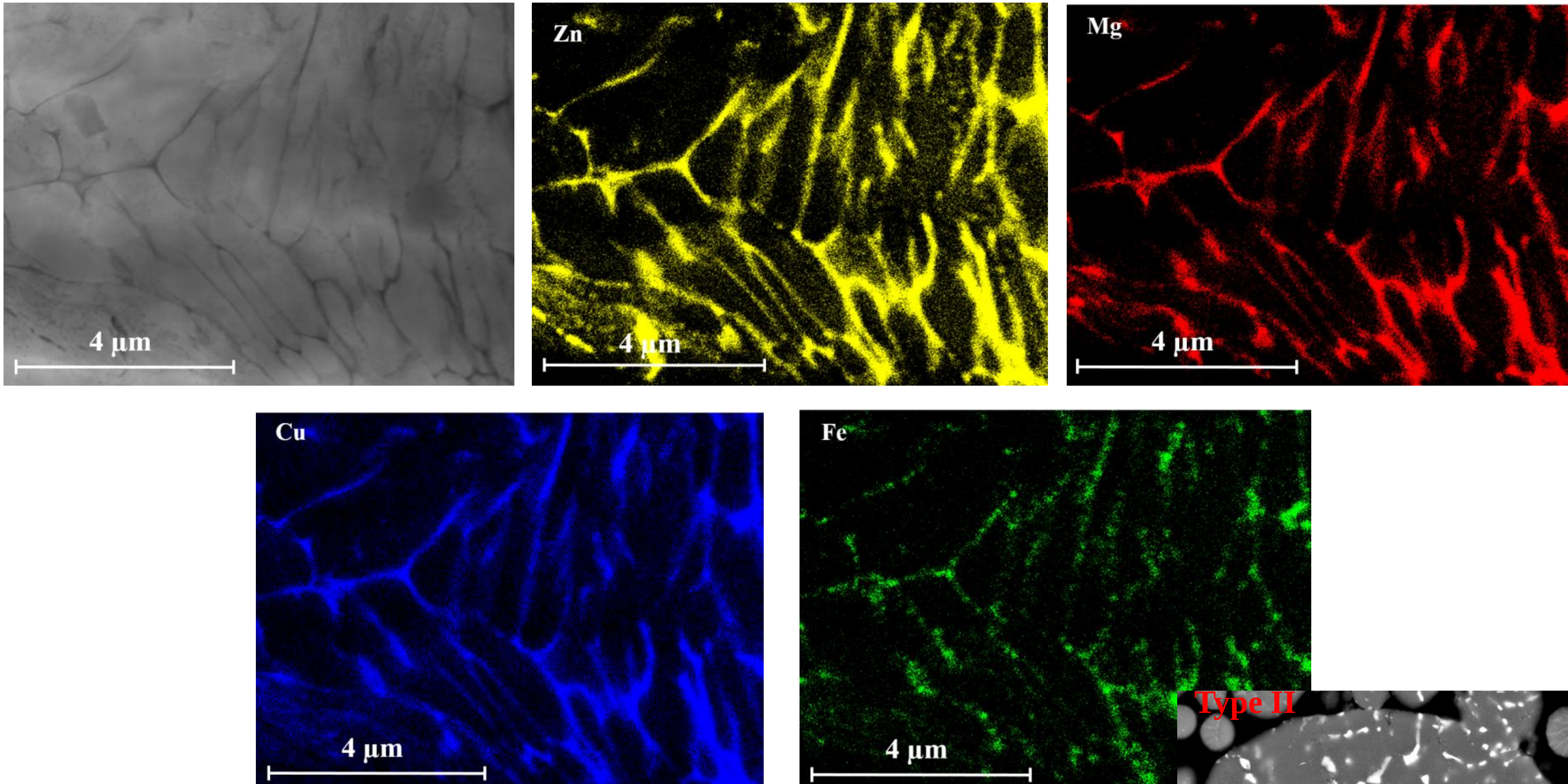


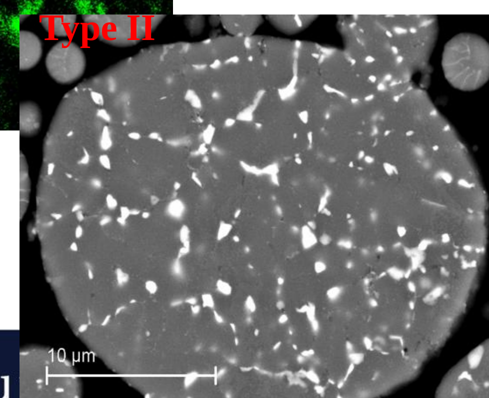


EDS Map of Al 7075 Powder Cross Section



Segregation at GB's

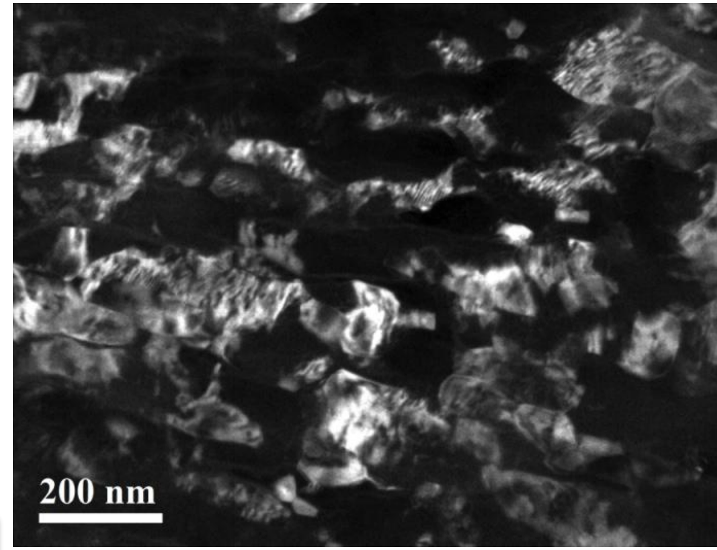




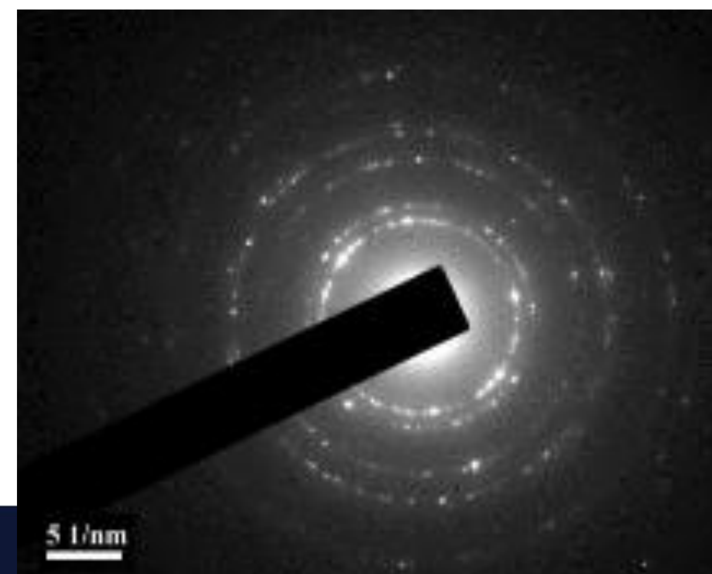
- ✓ Solute segregation at the grain boundaries
- ✓ Demonstrates powder condition is retained in the deposition

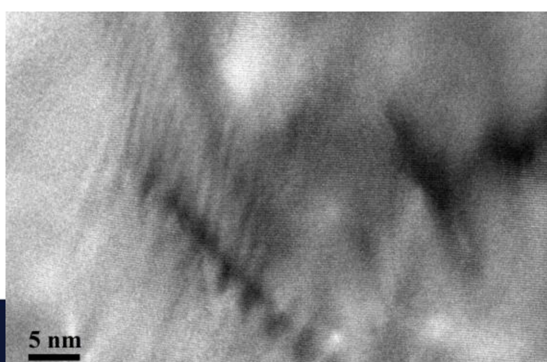
TEM study of the powder

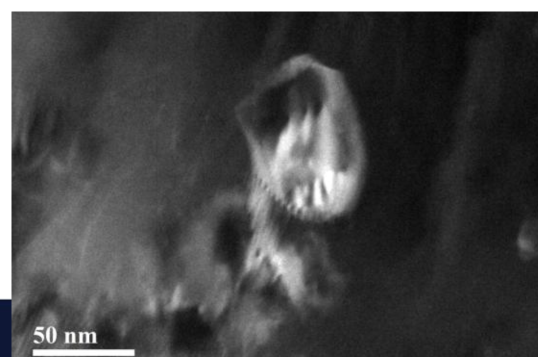
- Internal UFG and even nano structures in powder particles
- Residual stress shown in SADP
- Moderate dislocation density, concentrated near



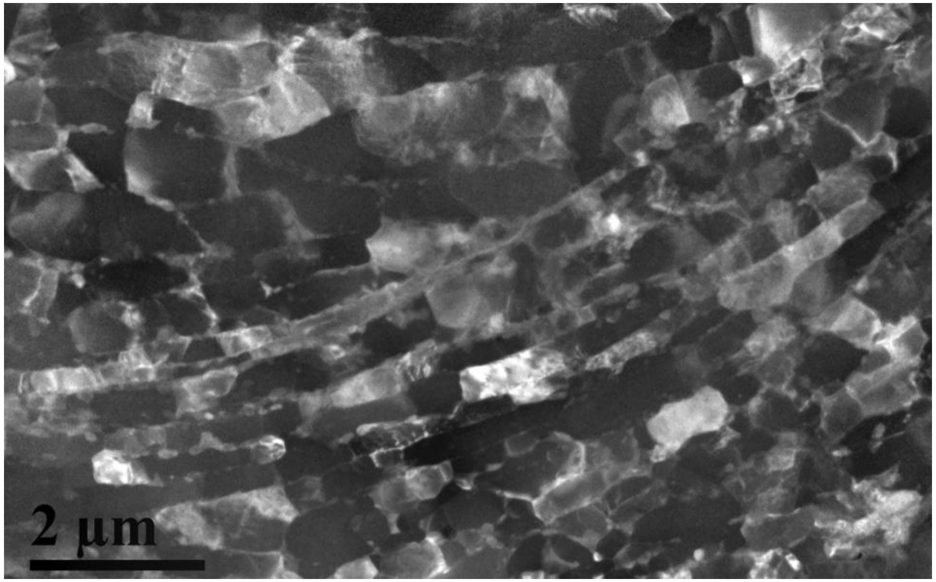
Studying the powder helps to better interpret the microstructures in CS

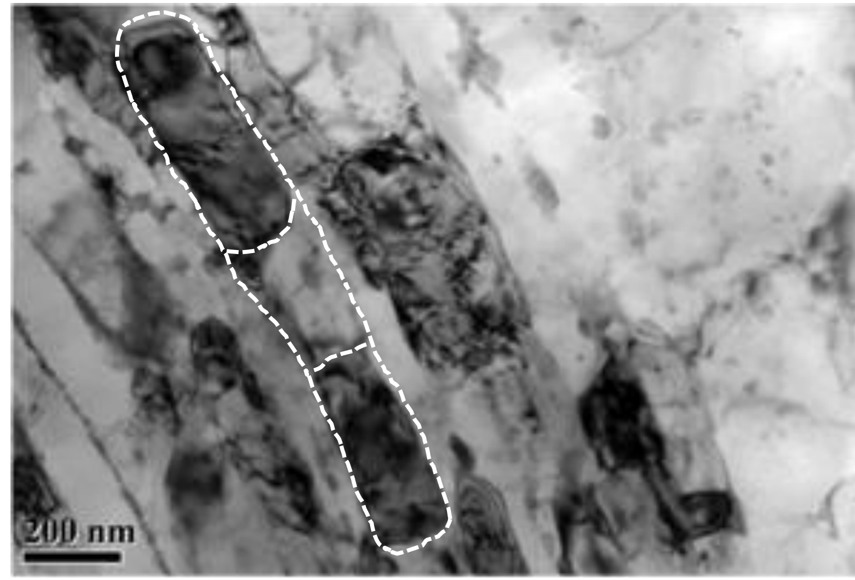


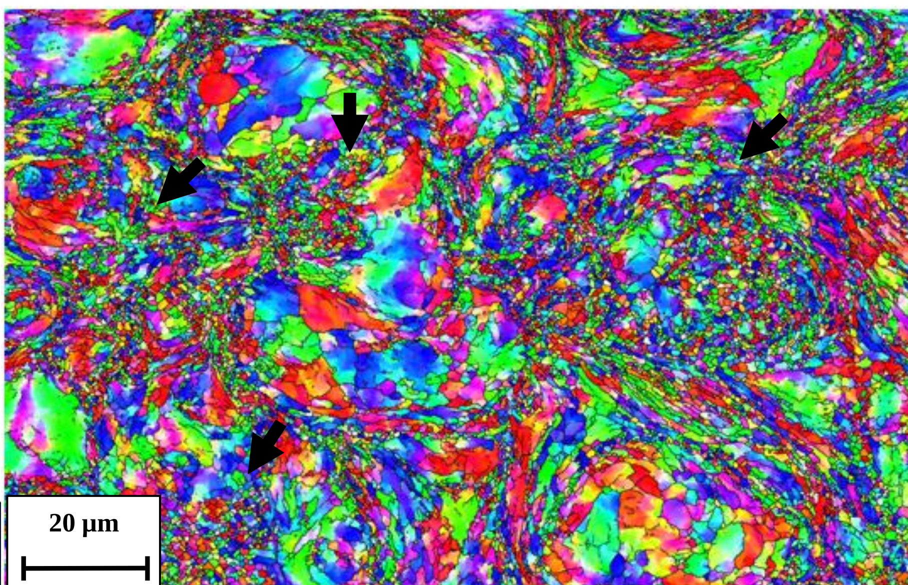


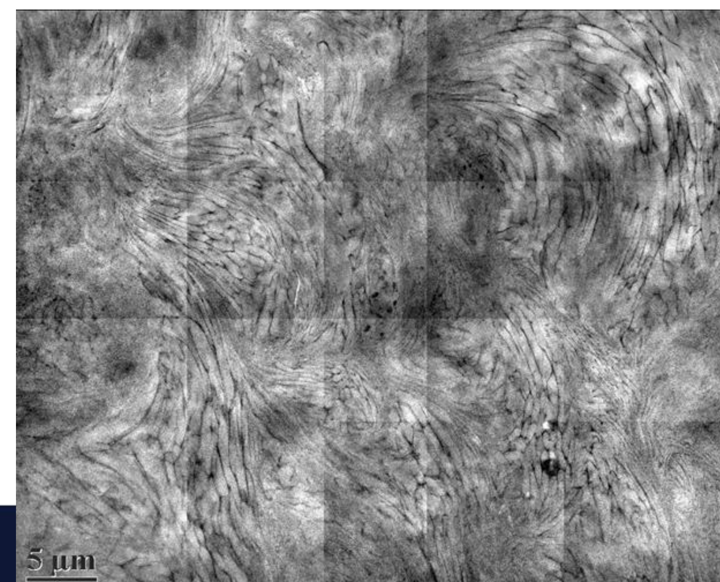


In-depth Characterizations

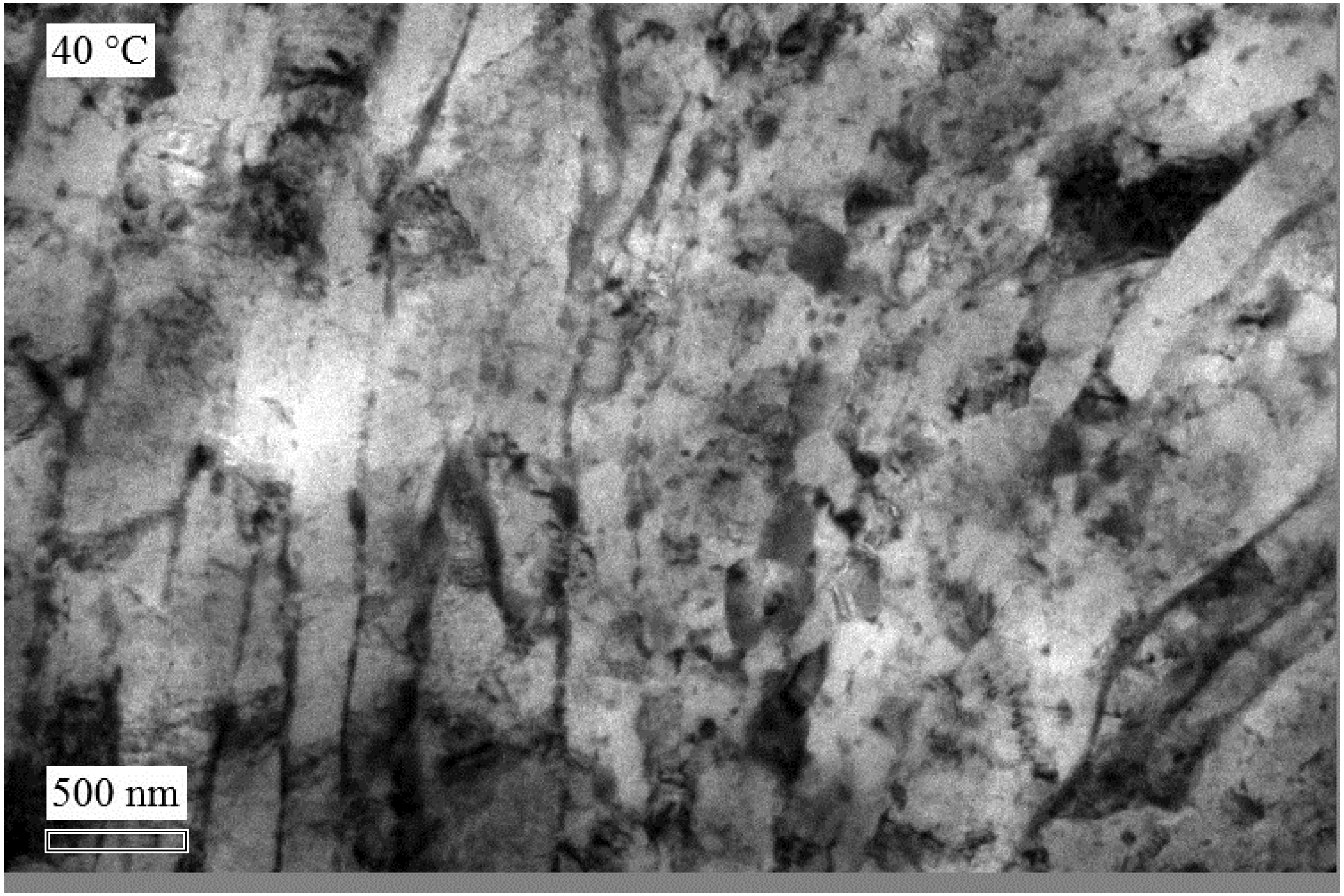








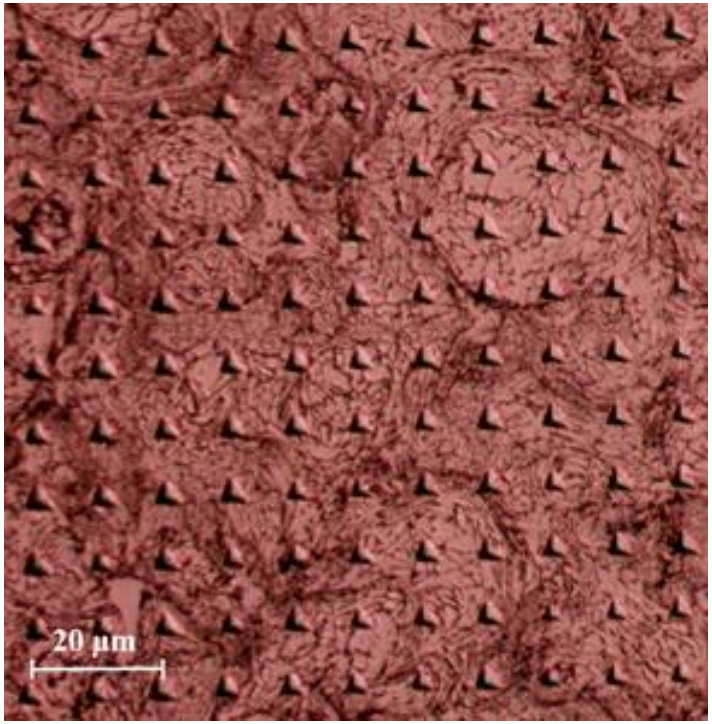
Non-isothermal HT

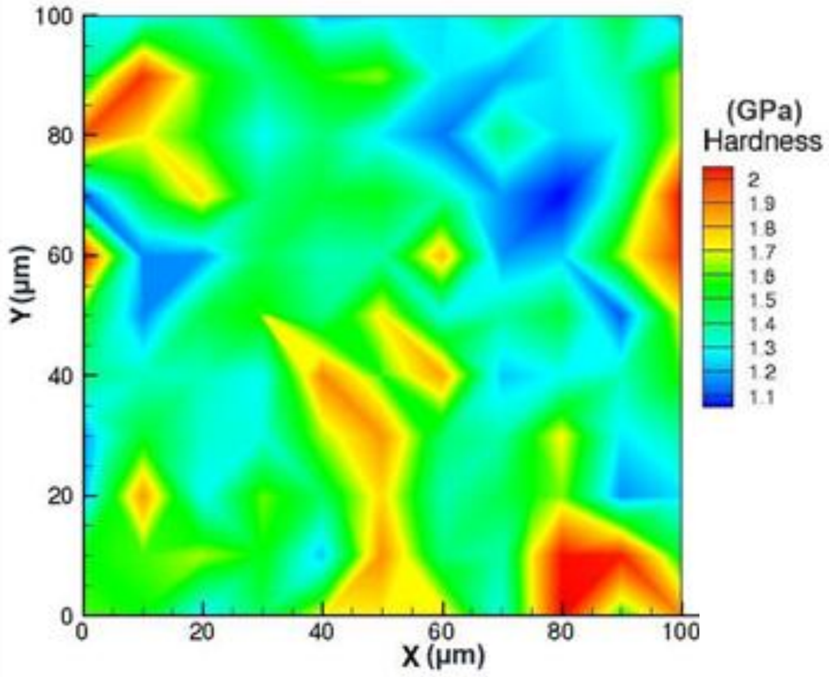


Microstructural Characterization Work Performed by SDSM&T Ph.D. Graduate – M. Reza Rokni

SOUTH DAKOTA SCHOOL OF MINES & TECHNOLOGY

Nanoindentation



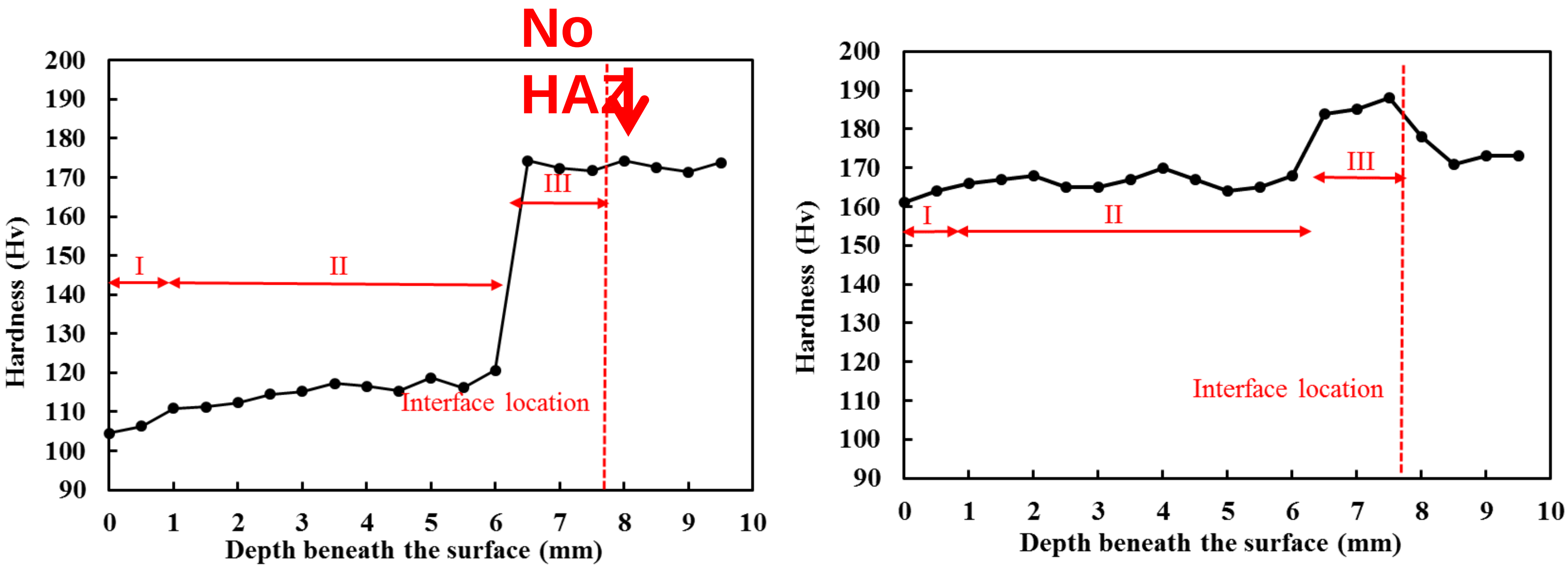


Material	CSP 7075	
Hardness (GPa)	particle interior	particle interfaces
	1.53±0.30	2.01±0.09

- ✓ 100 µm square array of nanoindentations (121 indents)
- ✓ Regions of high and low hardness associated with particle impacts

SCHOOL OF MINES & TECHNOLOGY

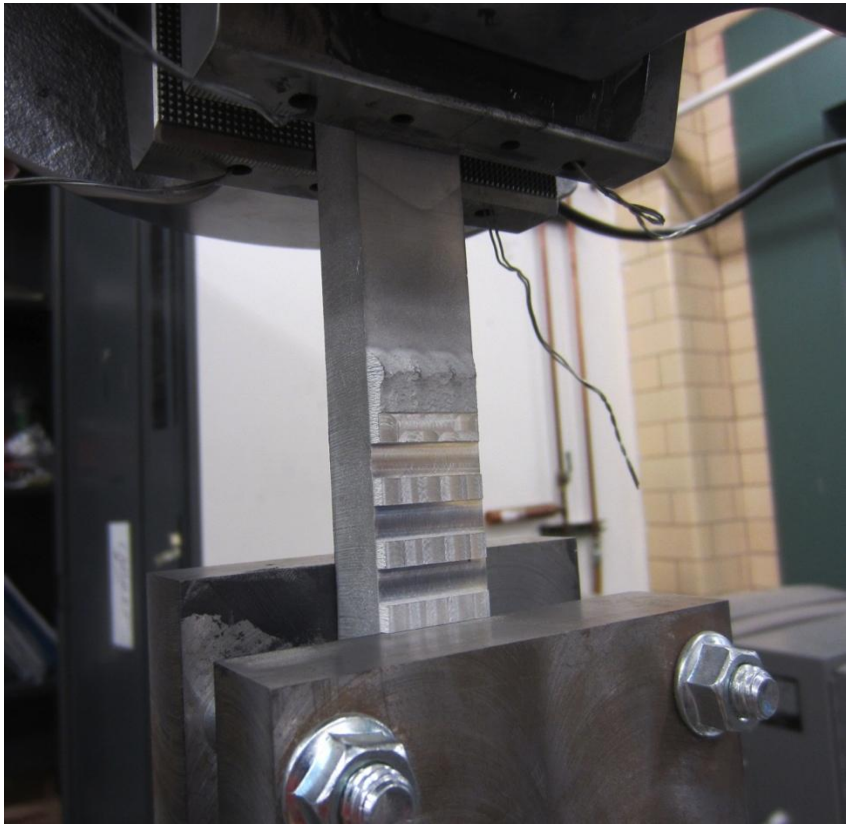
Al 7075 Cold Spray with PWAA

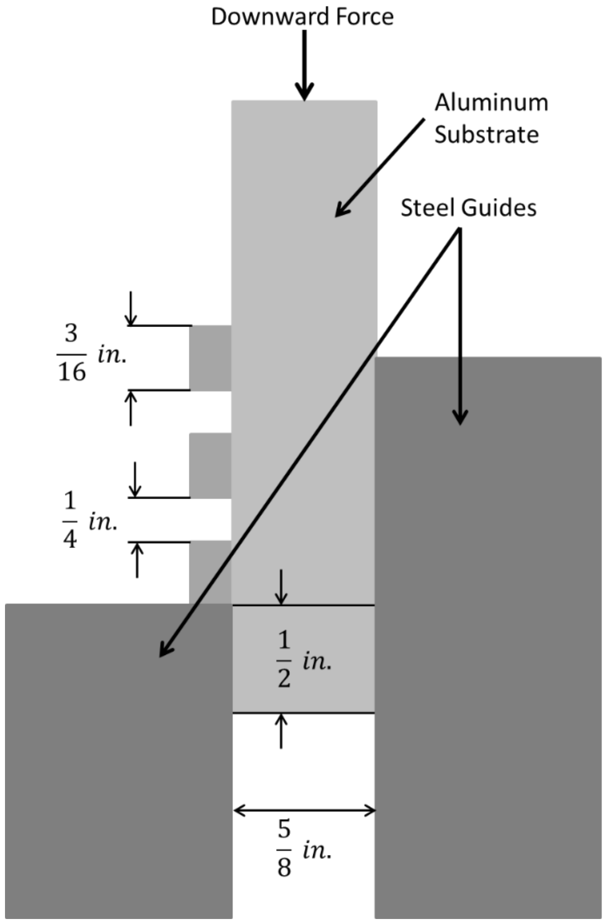


- Vickers microhardness distribution from the top of the CSP 7075 layer to the substrate: before T-73 heat treatment (left) and after T-73 heat treatment (right).
- The dashed red line represents the location of the deposit/substrate interface.

Mechanical Testing

- **3-Lug Shear Testing – per *MIL-J-24445A***

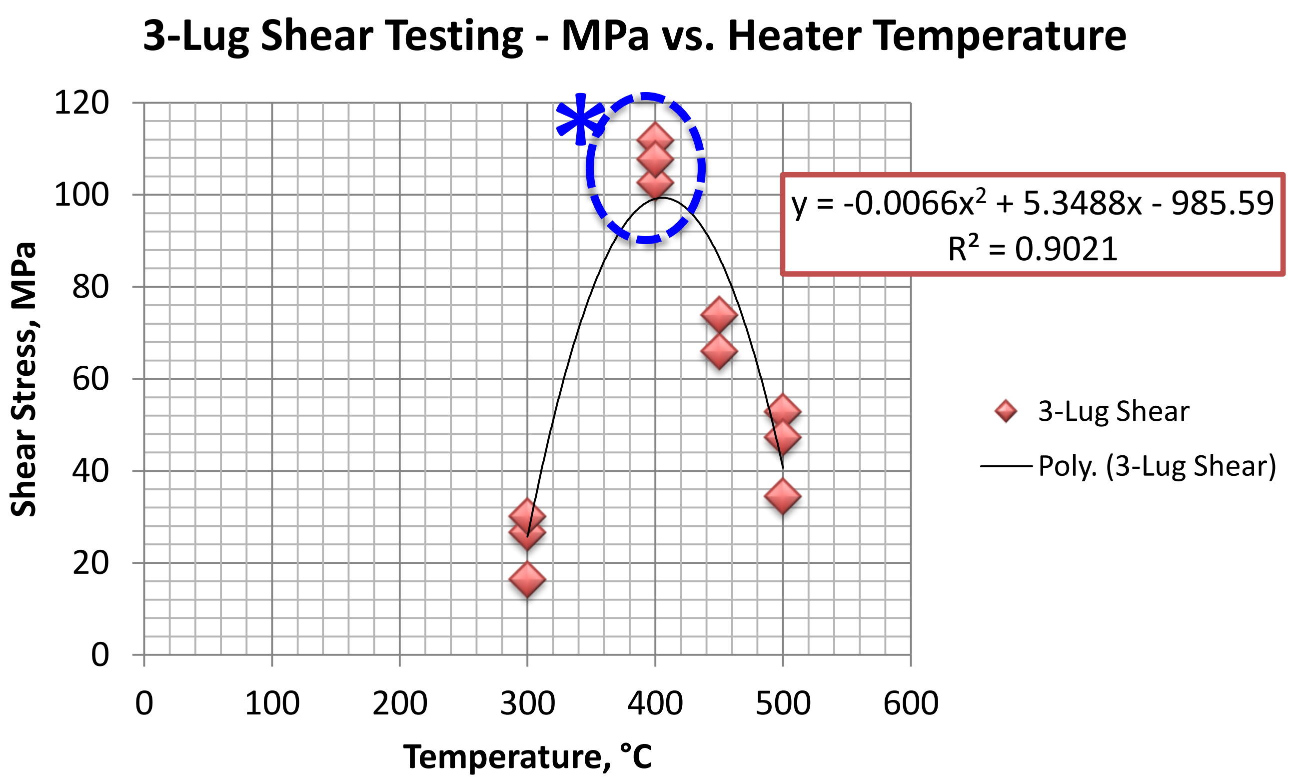




SOUTH DAKOTA SCHOOL OF MINES & TECHNOLOGY

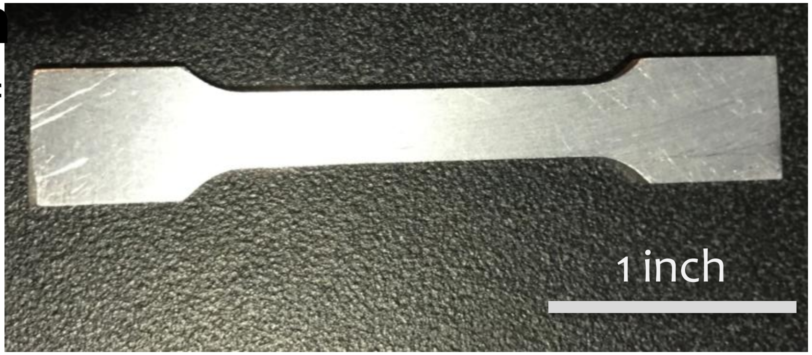
Al 6061 Mechanical Testing – Internal Bore Application

- ASTM C633 Testing – Masterbond EP15 – glue failures >10 ksi
- Three Lug Shear = 107.4 ± 4.60 Mpa
- Lower, but still very high strengths were achieved with the sh … nes).



Tensile Strength

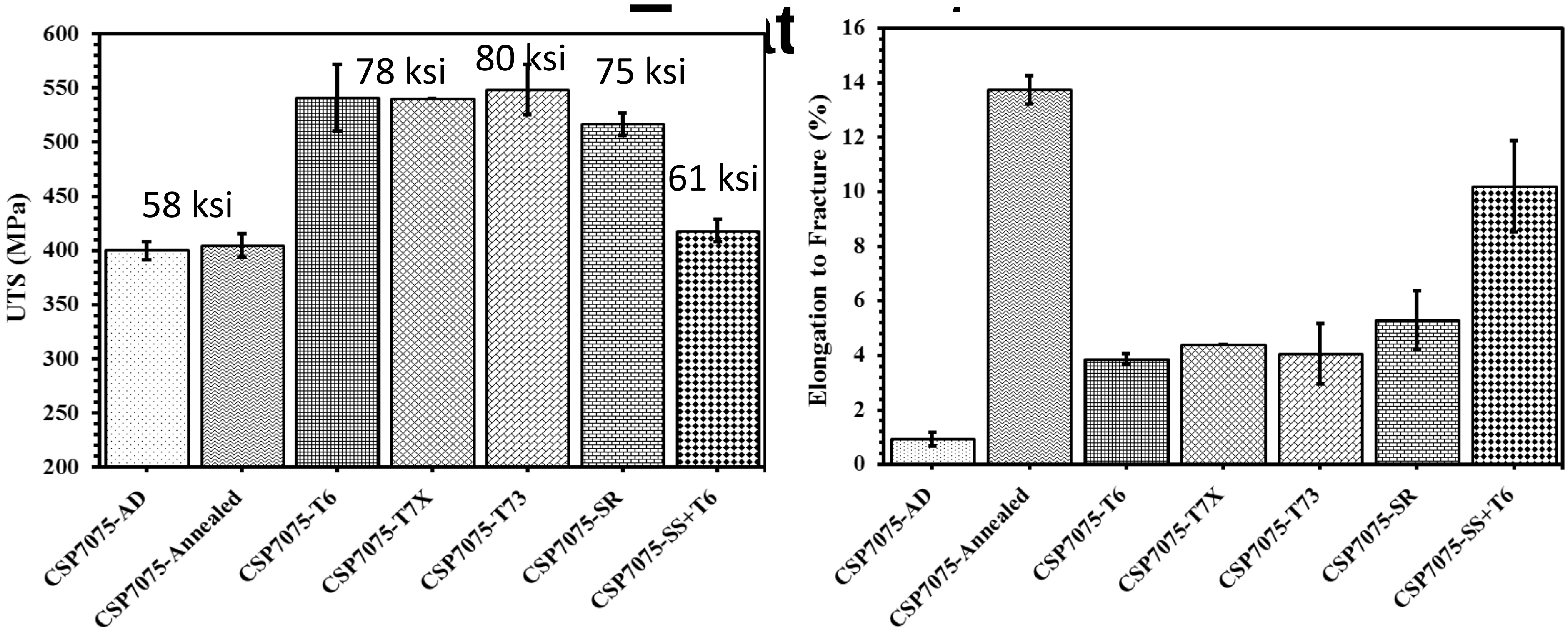
- **ASTM E8 – Subscale Coupon**
  - Machined from a large build-up of cold spray material.
  - Substrate material is not included



- **Al 6061**
  - Yield Strength = 35.5 ± 1.05 ksi
  - UTS = 45.4 ± 0.37 ksi
  - %EL = 5.5% ± 0.77%
  - Hardness = 90 HV
- **Al 2024**
  - Yield Strength = 45.9 ksi
  - UTS = 50.1 ksi
  - %EL = 5.5 ksi
  - Hardness = 167 HV

SOUTH DAKOTA SCHOOL OF MINES & TECHNOLOGY

Al 7075 Mechanical Properties vs. Heat Treatment



✓ Superior mechanical properties in the heat treated conditions (samples were microtensiles 10mm x 1mm x 1mm)

Due to grain boundary strengthening and metallurgical Bonding

SOUTH DAKOTA SCHOOL OF MINES & TECHNOLOGY

Fluid Dynamics Modeling

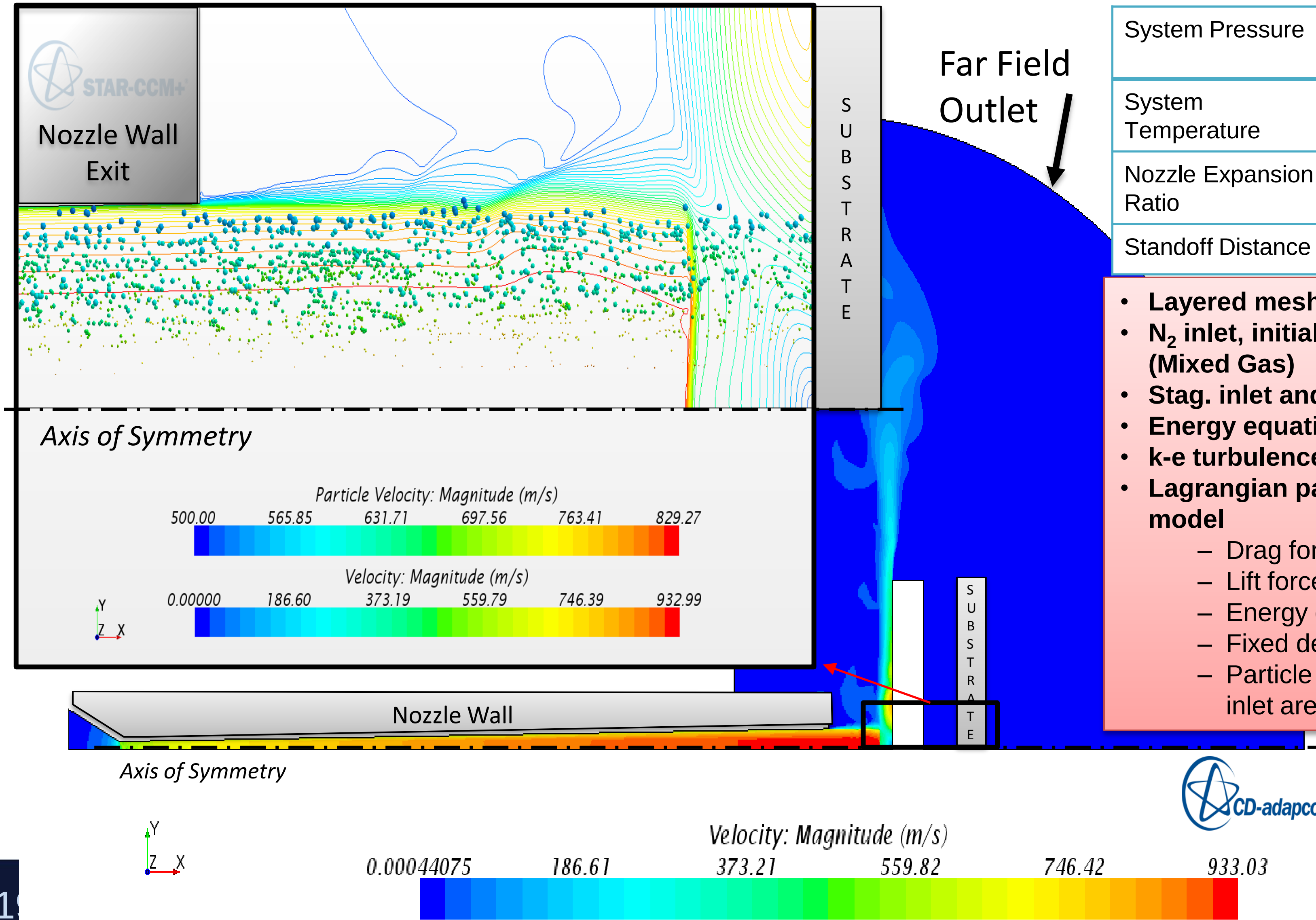
1. **Process modeling is maturing.**
2. Particle **velocities and temperatures** can be **accurately predicted** for a range of process conditions.
3. **Still requires experimentation**, and bonding is not just a function of process parameters, but much better than a shot in the dark.

Modeling Work Performed by SDSM&T Ph.D. Candidate – Ozan Ozdemir

SOUTH DAKOTA SCHOOL OF MINES & TECHNOLOGY

2D Axisymmetric CFD Model

Variability of Particle Impact Velocity



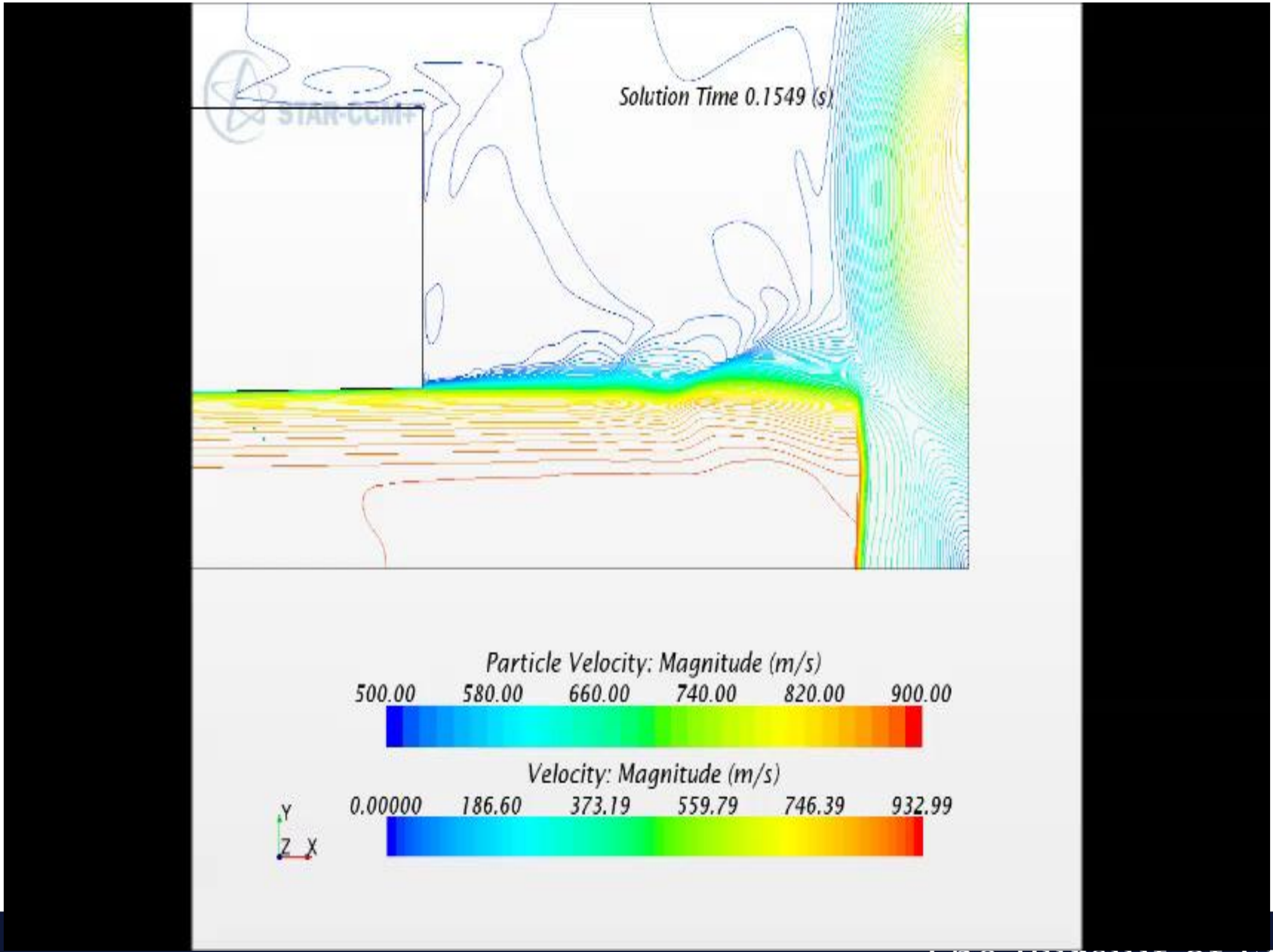
System Pressure	4.83 MPa (700 psi)
System Temperature	350 C (662 F)
Nozzle Expansion Ratio	5
Standoff Distance	10 mm

- **Layered meshing**
- **N_2 inlet, initialization with air (Mixed Gas)**
- **Stag. inlet and press. outlet**
- **Energy equations**
- **k-e turbulence model**
- **Lagrangian particle injection model**
  - Drag force
  - Lift force
  - Energy equations
  - Fixed density particles
  - Particle conditions at inlet are same as gas

CD-adapco

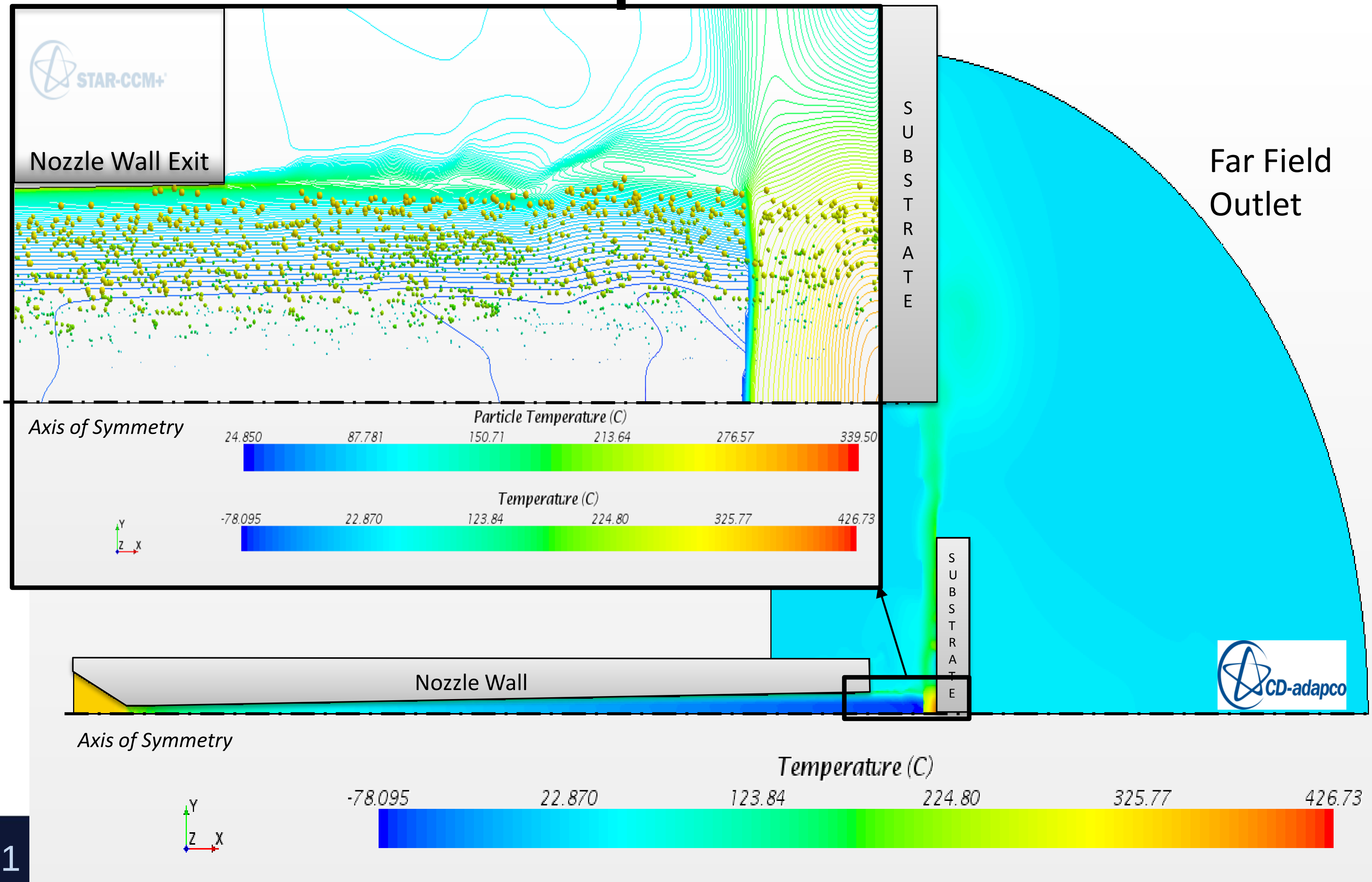
SCHOOL OF MINES & TECHNOLOGY

Transient Behavior of Particles

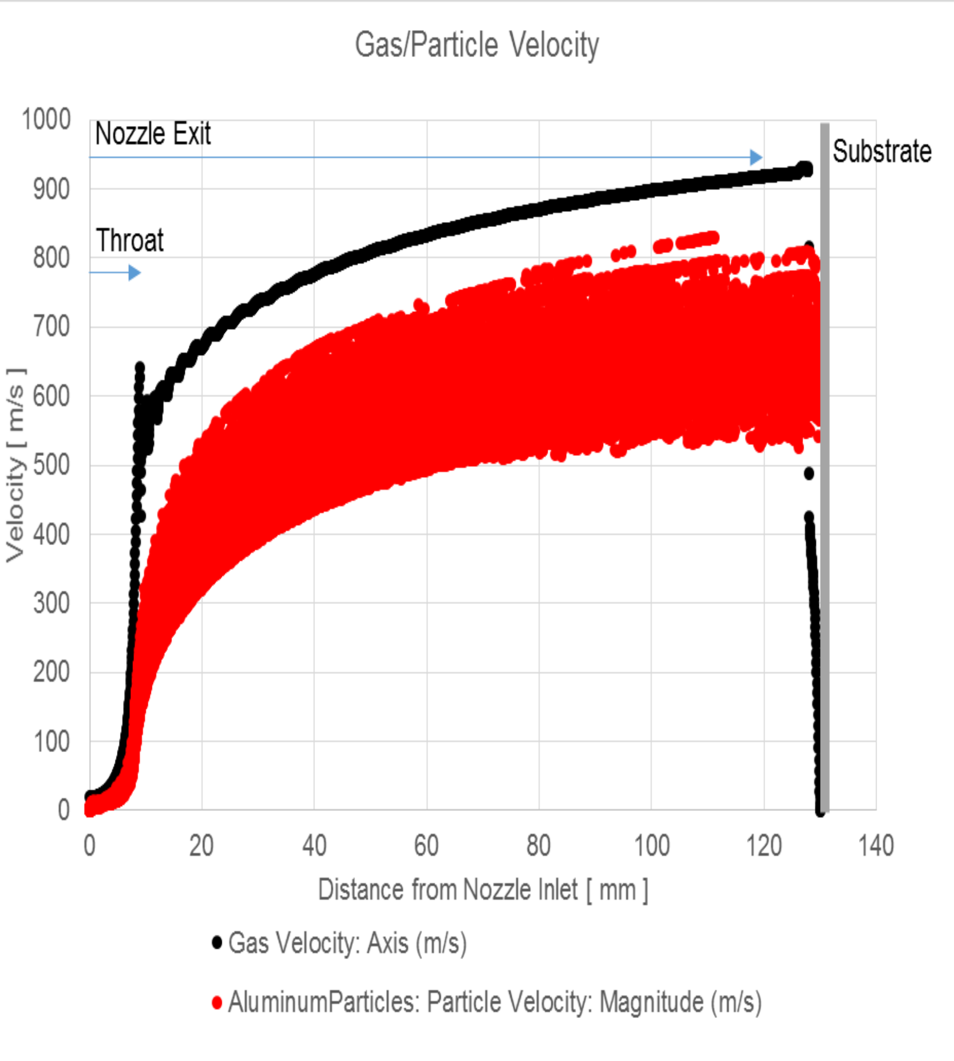


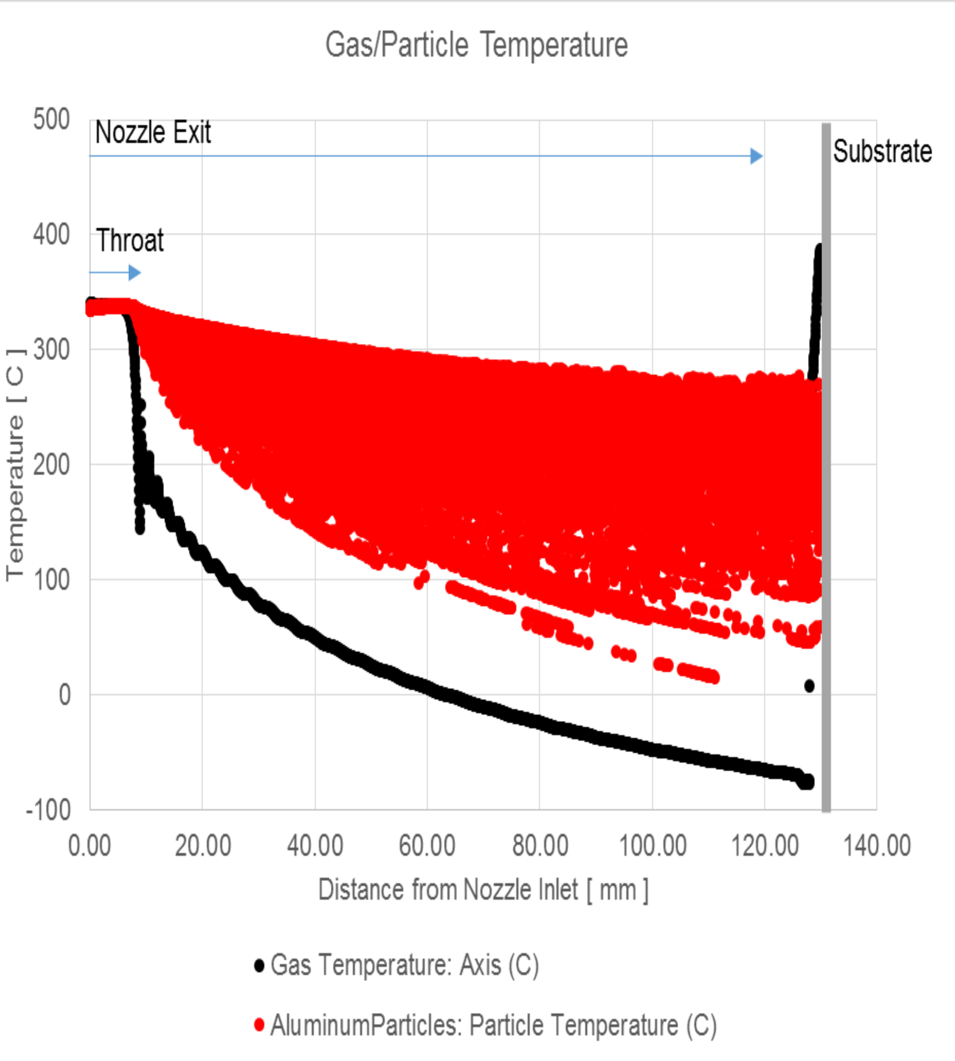
SOUTH DAKOTA SCHOOL OF MINES & TECHNOLOGY

Variability of Particle Impact Temperature



Velocity and Temperature Variation Plots
Injection to Impact



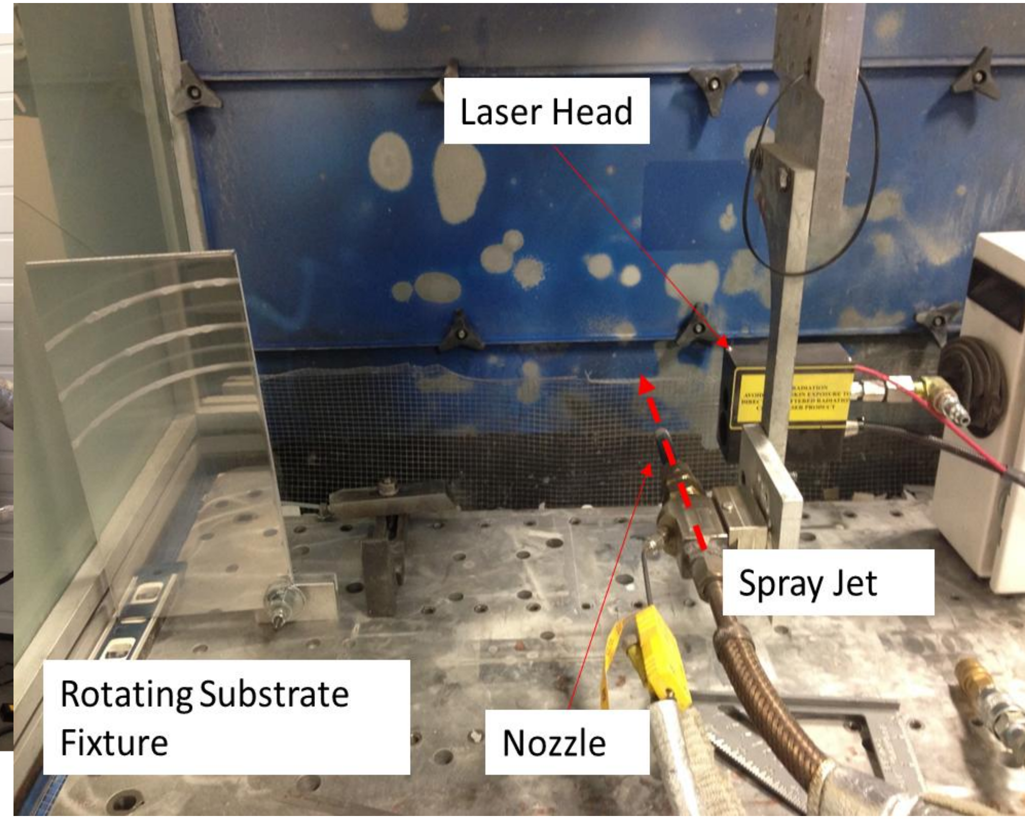


Preliminary Calculations
Selection of Spray Condition

Select a system pressure and temperature He mixing can improve.

T [C] \ P [psi]	**500**	**600**	**700**	**800**	**900**	**1000**
300	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
350	0.00%	0.00%	0.00%	0.00%	0.00%	0.10%
400	52.56%	63.80%	73.22%	82.13%	86.71%	91.12%
450	92.52%	96.82%	98.56%	99.54%	99.93%	99.93%
500	100.00%	100.00%	99.97%	99.97%	99.97%	99.97%

Experimental Setup

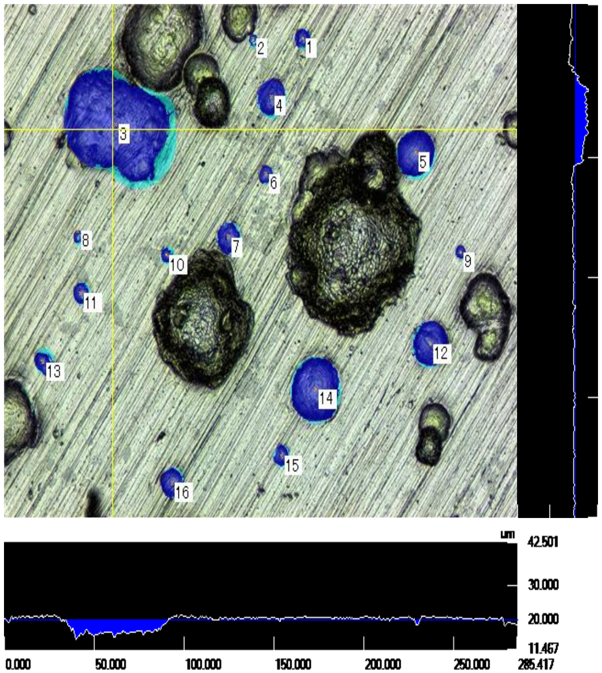


5 Different Conditions

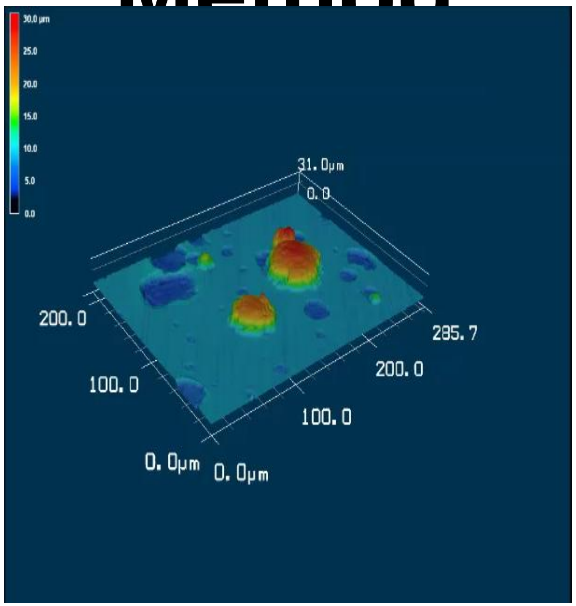
0% - 70% Helium Mixing into Nitrogen

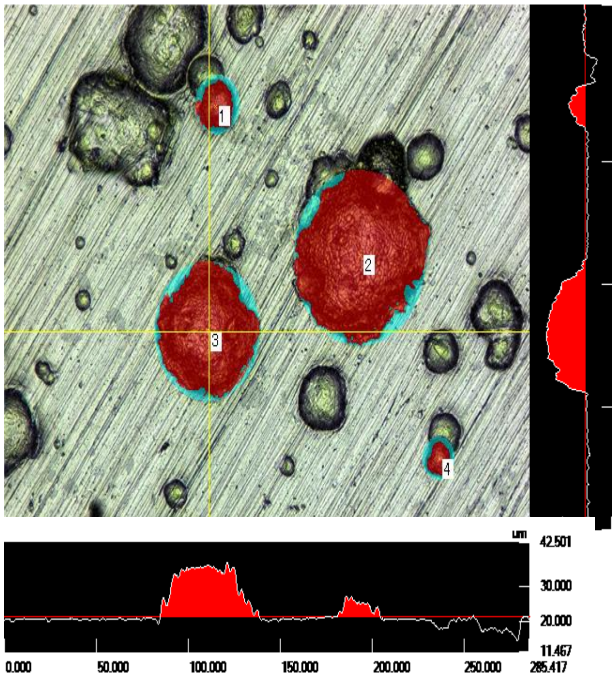
SCHOOL OF MINES & TECHNOLOGY

Deposition Efficiency Measurement Method

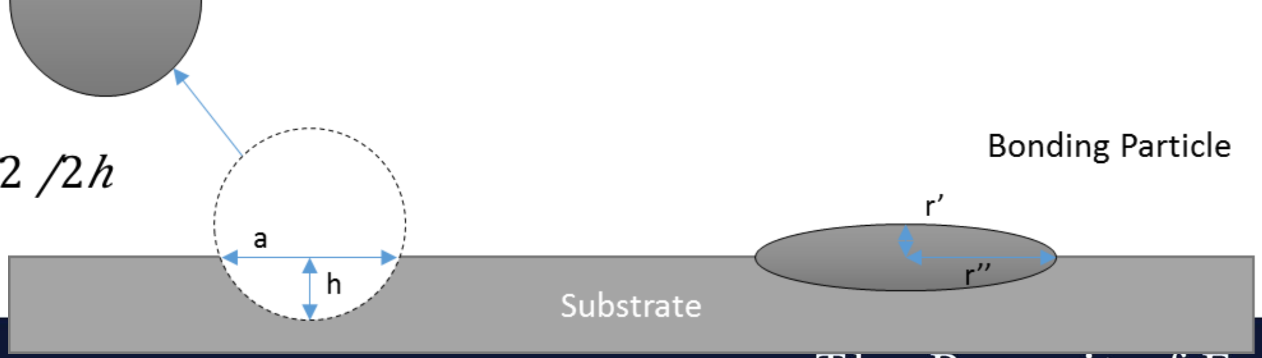


CRATERS





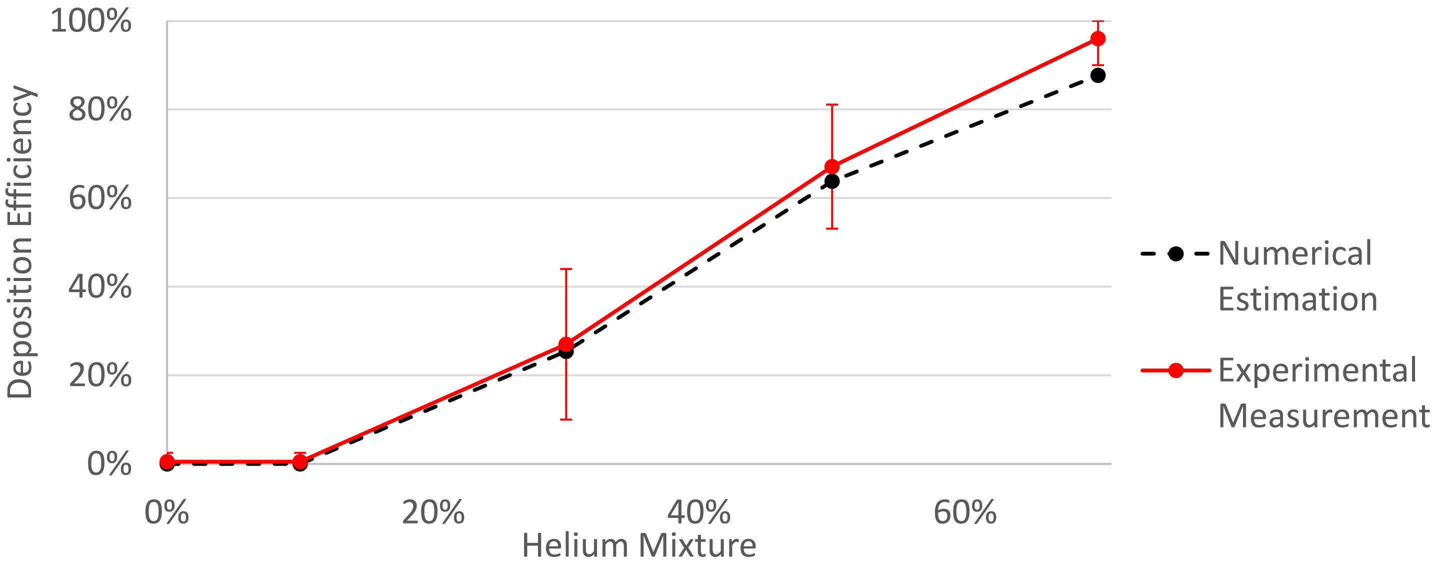
DEFORMED PARTICLES



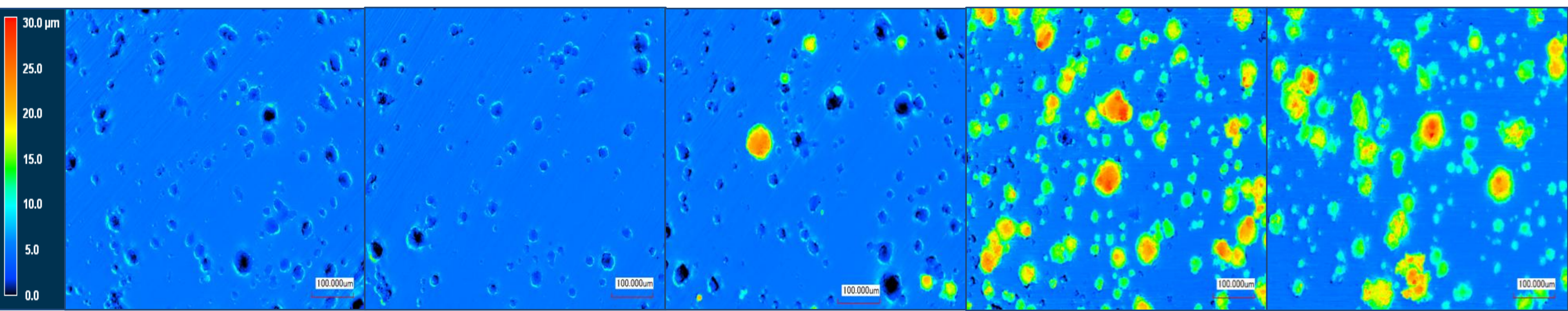
$r=a^{2}+h^{2}/2h$

SOUTH DAKOTA SCHOOL OF MINES & TECHNOLOGY

Improving Deposition Efficiency with Helium Mixing



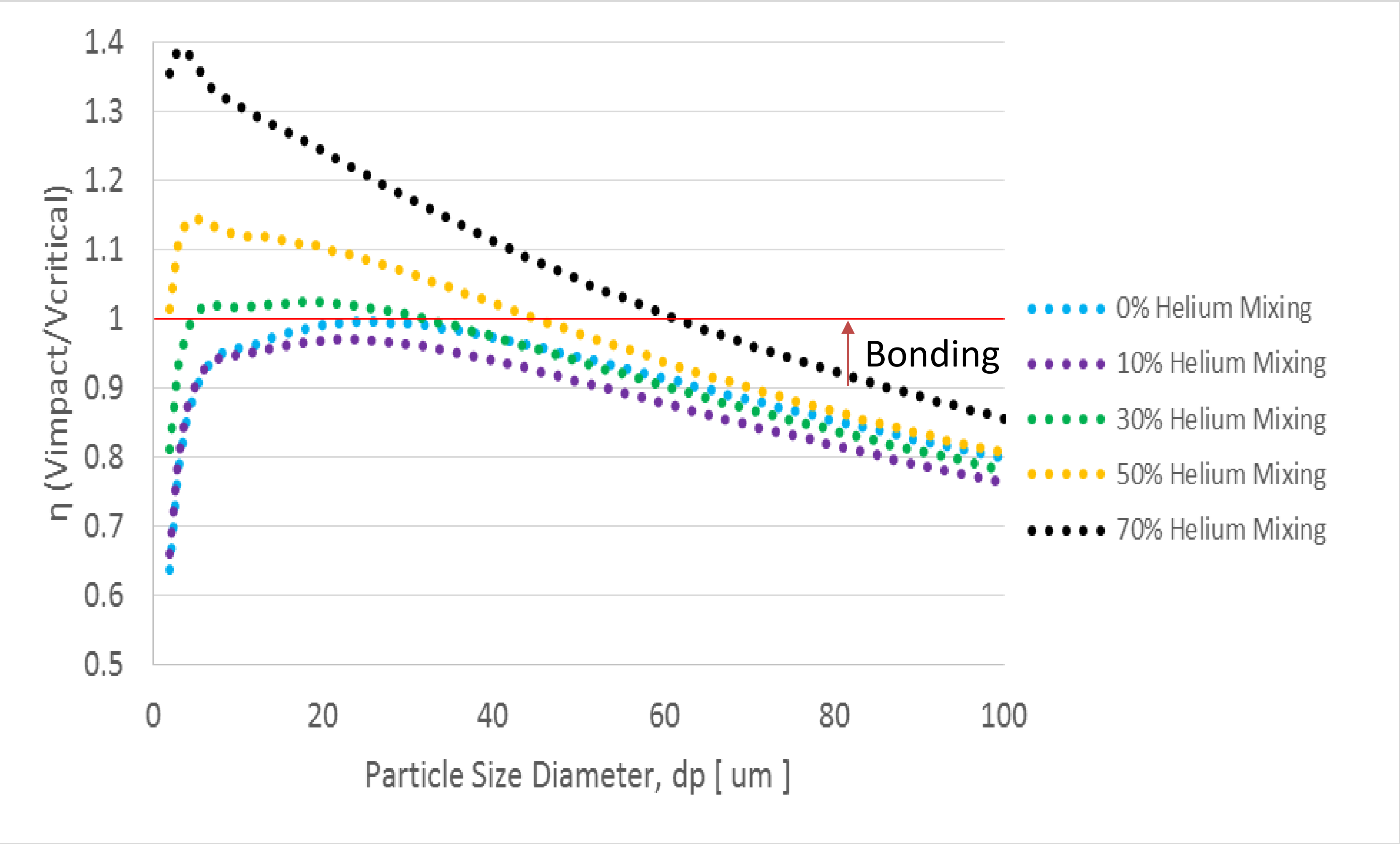
SDSU METLAB MATERIALS EVALUATION AND TESTING



0% He 10% He 30% He 50% He 70% He

SCHOOL OF MINES & TECHNOLOGY

What does Helium Mixing in N_2 Do?



SOUTH DAKOTA
SCHOOL OF MINES & TECHNOLOGY

Equipment Development

- **Efforts Underway**
  1. VRC Gen III
     - Gas mixing
     - 1000 psi for Nitrogen is helpful
     - Shorter nozzles for internal bores & confined areas
     - Upstream feed option for particle heating
  2. Supporting Equipment:
     - Motion Systems
     - Powder Processing

SOUTH DAKOTA SCHOOL OF MINES & TECHNOLOGY

VRC Gen III Cold Spray System

VRC METAL SYSTEMS

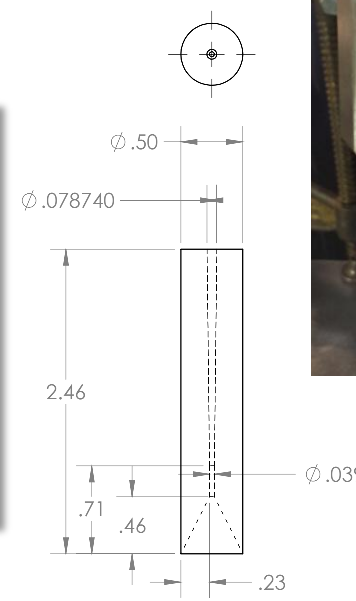
Hand-Held Capable

- Working with VRC Metal Systems to develop cold spray equipment solutions
- The Goal is to support and accelerate cold spray implementation for suitable applications.
- Operates at 1000 psi to enable more with N_2.

Development for Internal Bores

VRC METAL SYSTEMS

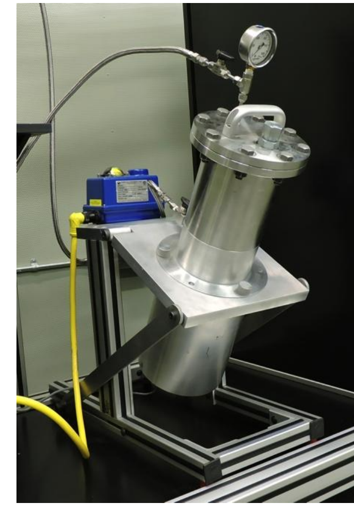
- Worked with ARL and MOOG to develop a repair process for a valve body internal bore.
  - Made a shortened nozzle (75 mm) with internal bore 45° gun
  - Turn table rotating at 60 rpm with 3-axis robot with downdraft



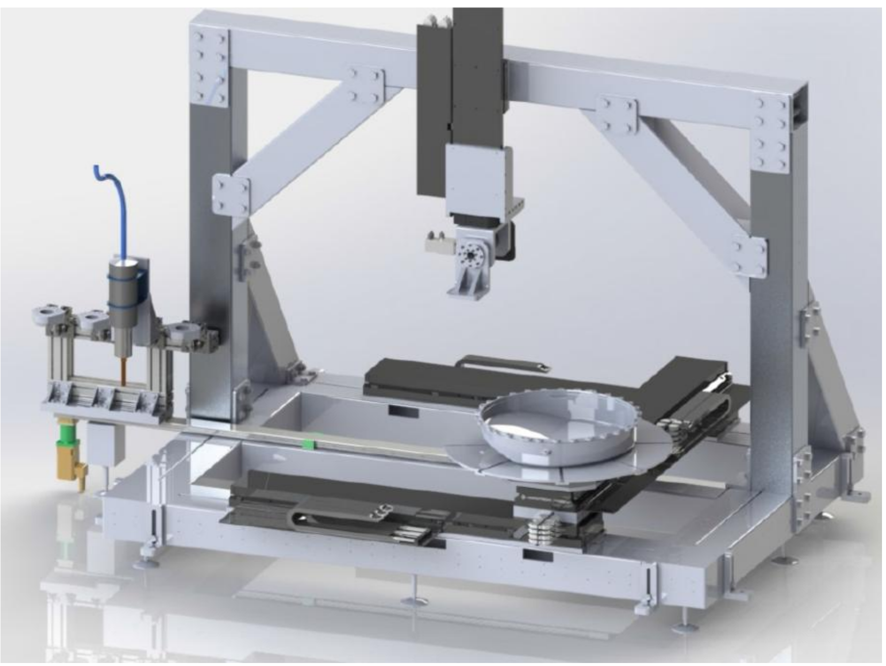
[Dimensions in inches]

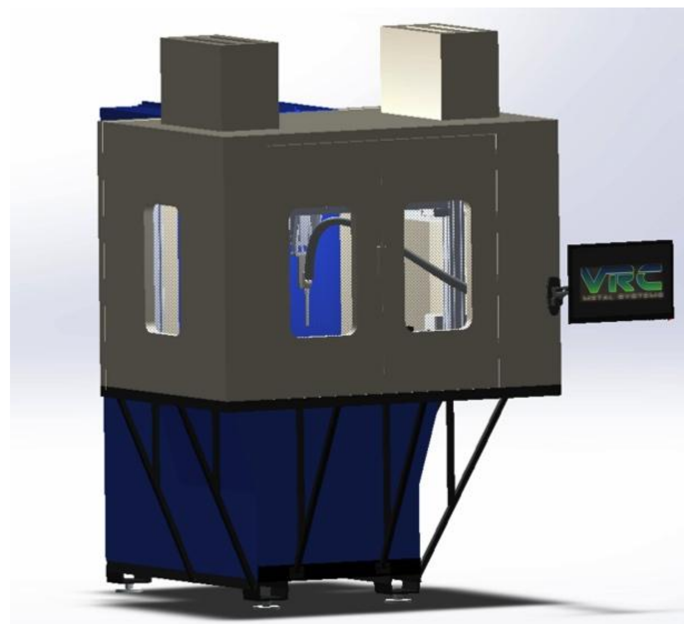
SOUTH DAKOTA SCHOOL OF MINES & TECHNOLOGY

Other Equipment



- **Powder Processing**
- **Motion Systems**





SOUTH DAKOTA
M
SCHOOL OF MINES
& TECHNOLOGY

Application Development

- **Lessons Learned**
  1. Repair is a great ROI opportunity.
     - Many replaced for form/function defects not failure.
     - Minimal impact to finished part with repair.
  2. Need to understand microstructures and properties.
  3. Modeling is a valuable development tool.
  4. Some applications will require custom equipment solutions
  5. Requirements should be based on repair zone needs, not material spec minimums

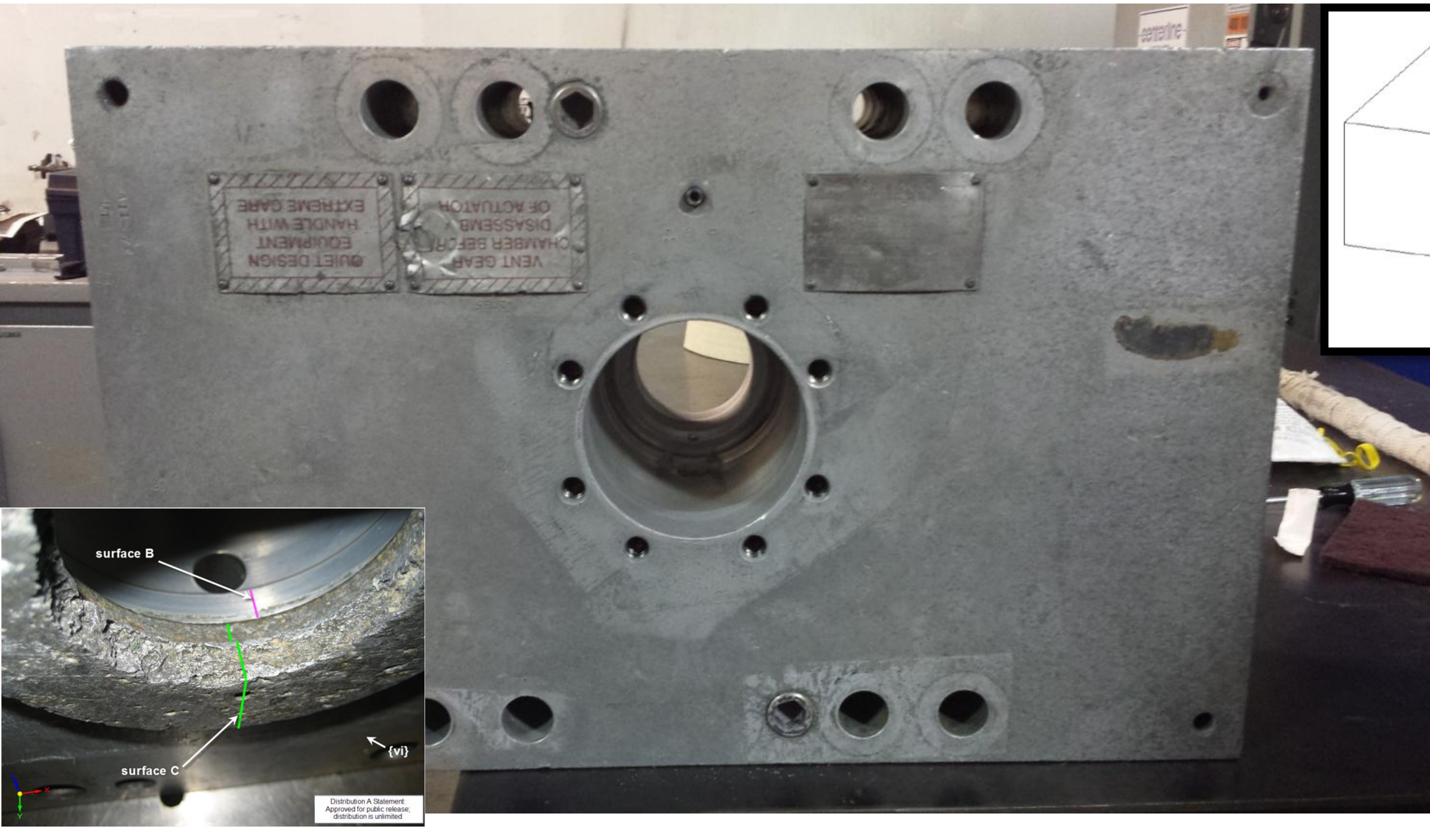
SOUTH DAKOTA
SCHOOL OF MINES & TECHNOLOGY

Implications for Repair

- Ideal for parts that are heat sensitive
  - can avoid creating a heat-affected zone
- Powder microstructure is essentially preserved
- Some applications may require pre or post-heat treat
  - to achieve a desired microstructure in the deposited

SOUTH DAKOTA SCHOOL OF MINES & TECHNOLOGY

Corrosion / Sealing Surface Repair



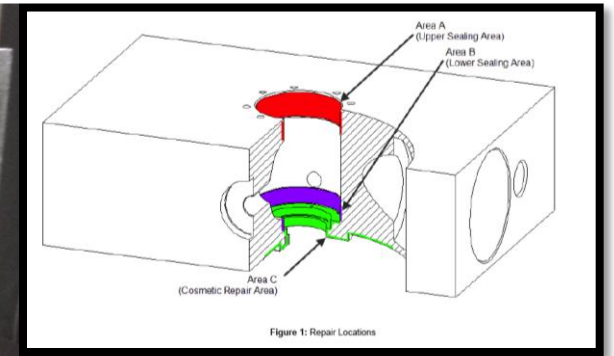


Figure 1: Repair Locations

Puget Sound Naval Shipyard & Intermediate Maintenance Facility

VRC METAL SYSTEMS

Mid-America AVIATION

MOOG

ARL

SOUTH DAKOTA SCHOOL OF MINES & TECHNOLOGY

Mechanical Testing

Requirements

1. Min. 10 ksi adhesion
2. <5% Porosity
3. Machinable

ASTM C633 – Adhesive Bond Test

✓ **Avg. >10 ksi (glue failures)**

Average Porosity = 2.9% ± 2.10%

Critical Surface Porosity < 1%

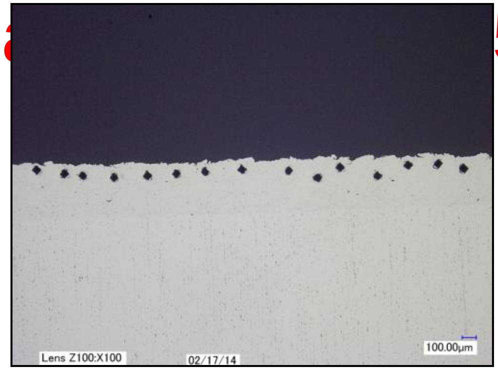
SCHOOL OF MINES
& TECHNOLOGY

Other Mechanical

- **ASTM E8 Tensile Strength**

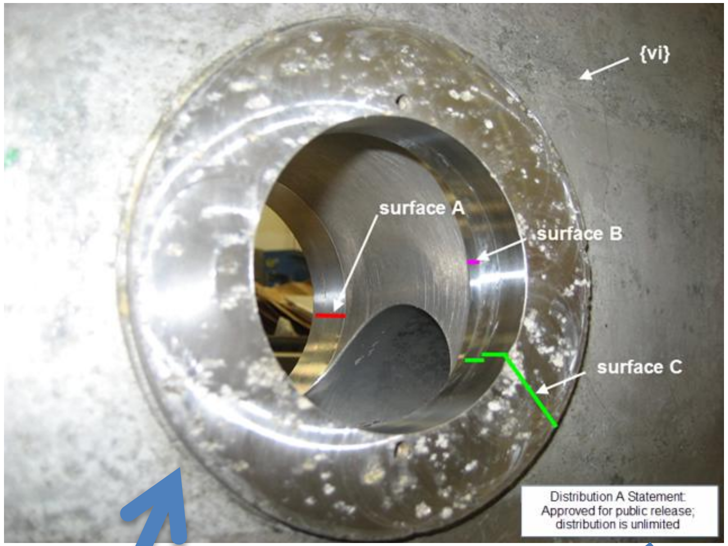
Sample #	UTS (MPa) [ksi]	% Elongation
1	272	2.91
2	251	3.02
Average	**261.5 [37.9]**	**2.97**

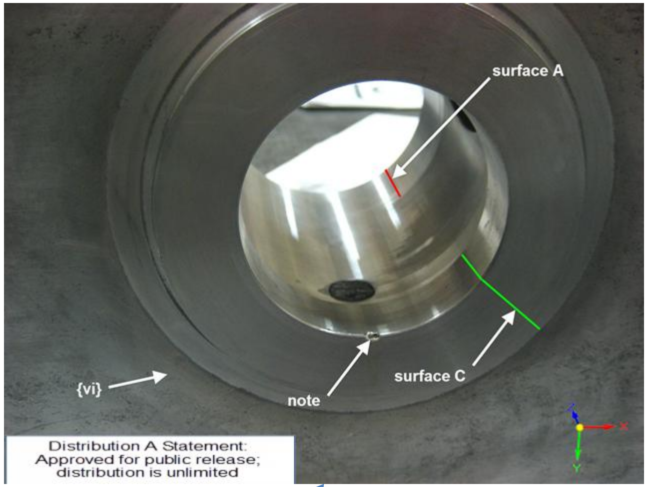
- On a 2nd set Puget Sound measured avg. = 247 MPa
- Min tensile strength of the actu 5 Mpa
- Microhardness = 87 ± 3.3 HV

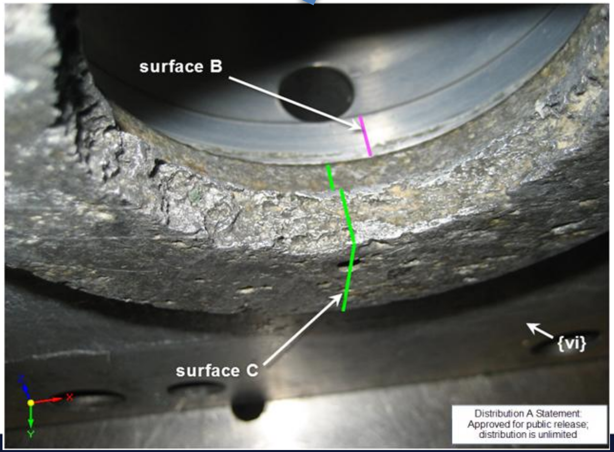


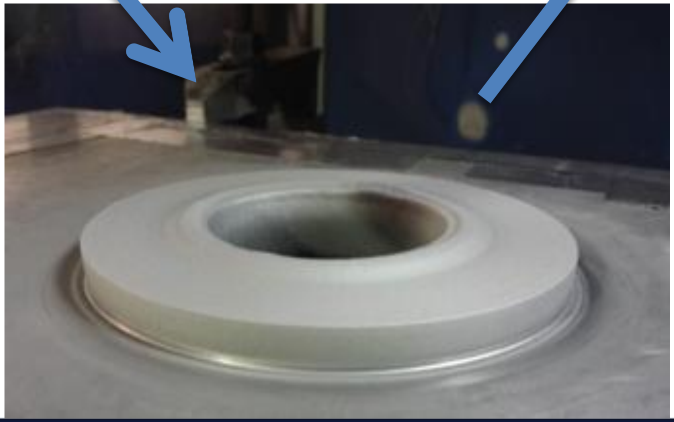
SOUTH DAKOTA SCHOOL OF MINES & TECHNOLOGY

Repairing Non-Critical Corrosion



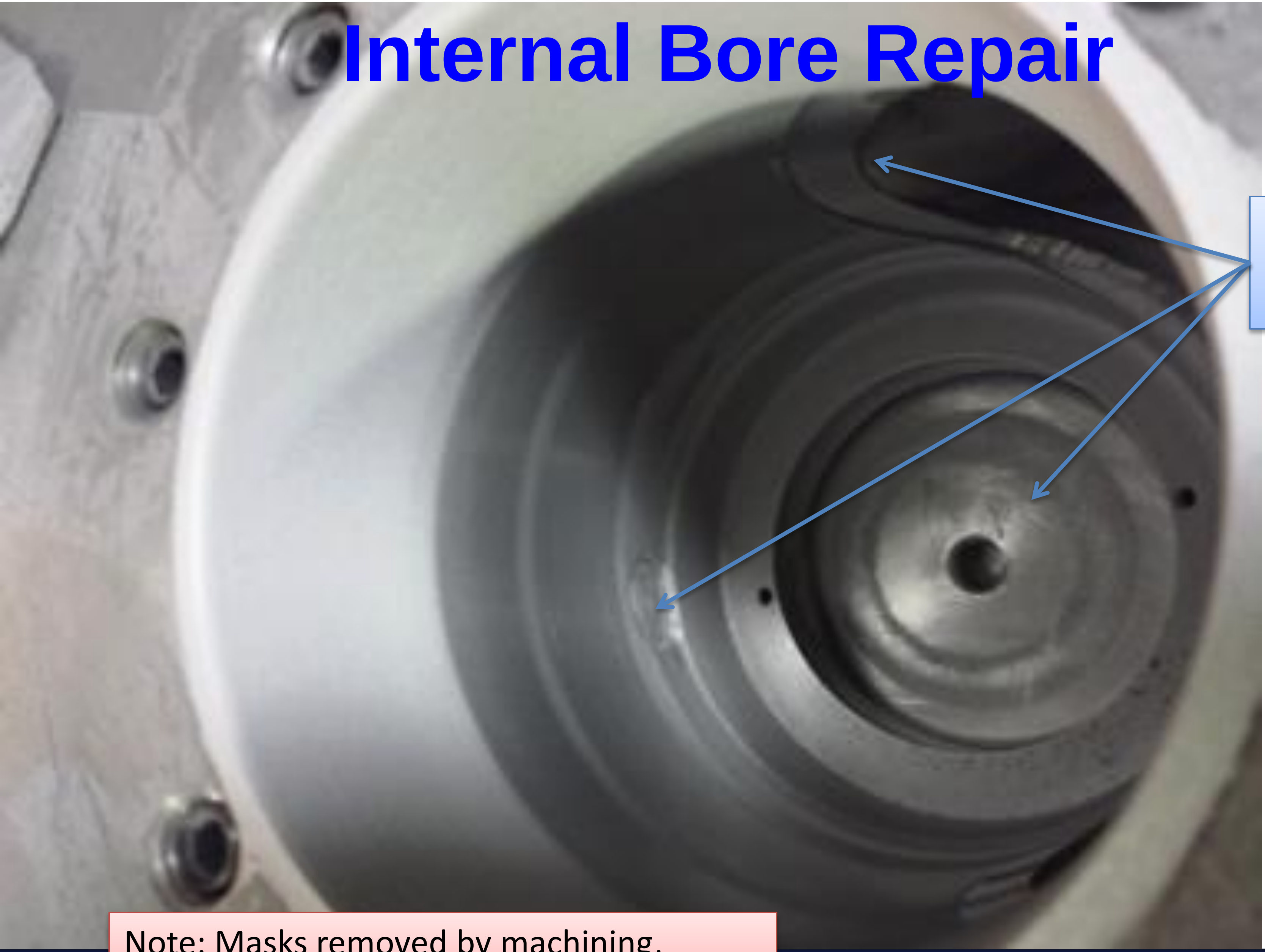






SOUTH DAKOTA SCHOOL OF MINES & TECHNOLOGY

Internal Bore Repair



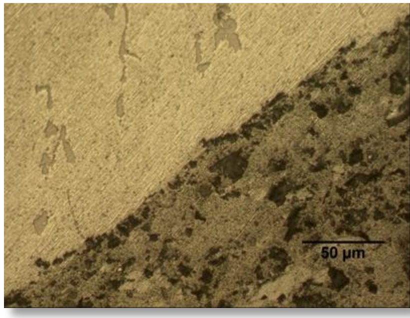
Note: Masks removed by machining, otherwise damage to cold spray can occur.

Repair Application Example

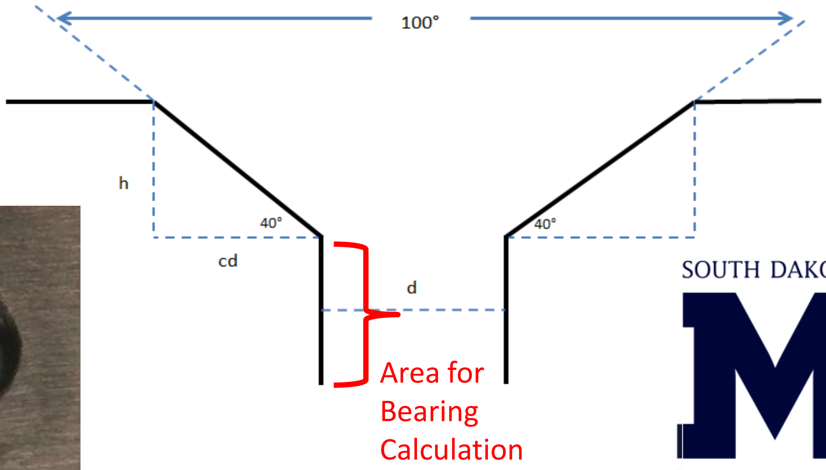
- **B1 Bomber Skin Panel Repair**
  - Wear at fastener holes
  - Replacement Cost >$200K each (Fleet liability: $50M)
  - Access panel not designed to be load carrying
  - Part lead time > 18 months

A cold spray repair solution has been developed… ROI > 10:1

Mechanical Testing



- Realistic requirements developed with Tinker AFB cognizant engineer
- Fatigue
  - 500K Cycles At 15 ksi
- Three lug shear testing
  - (Avg. 5681 psi ± 729)
- **Static Guided lap shear**
  - Carried full Mil-HDBK fastener bearing yield load of 3400lbs.
  - Tested up to failure at 5600 lbs – **no delamination at failure**

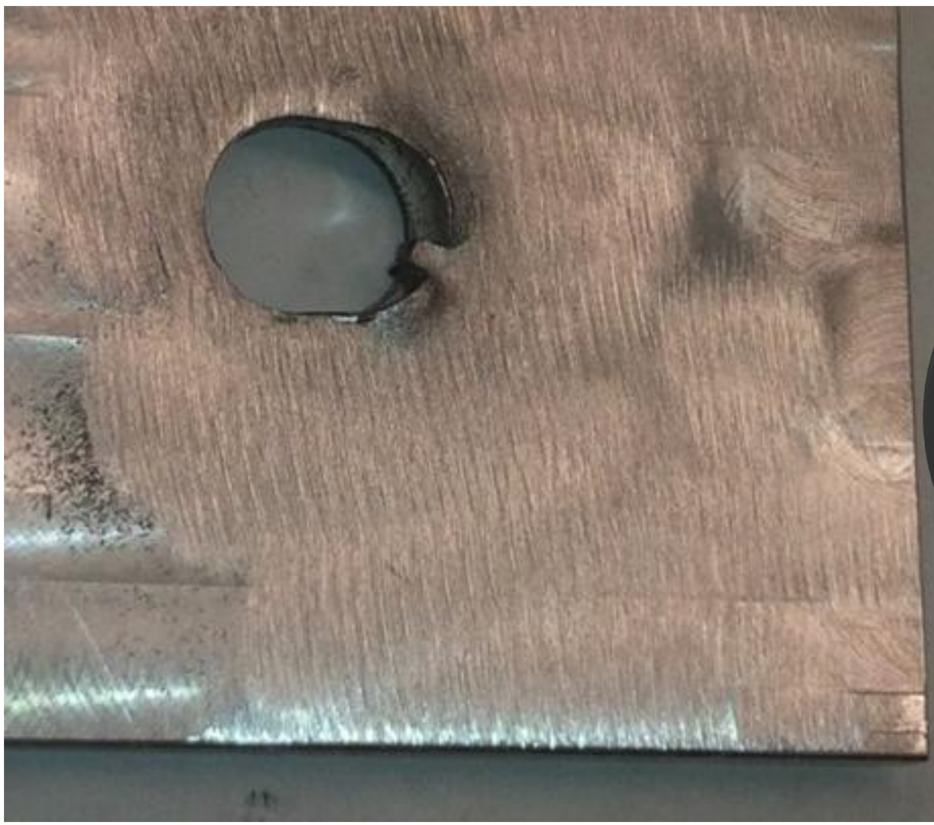


No evidence of cold spray material failure observed up to full bearing

SOUTH DAKOTA
SCHOOL OF MINES & TECHNOLOGY

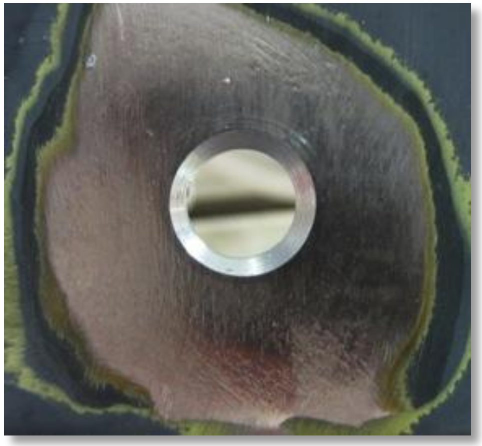
Failure Load Testing

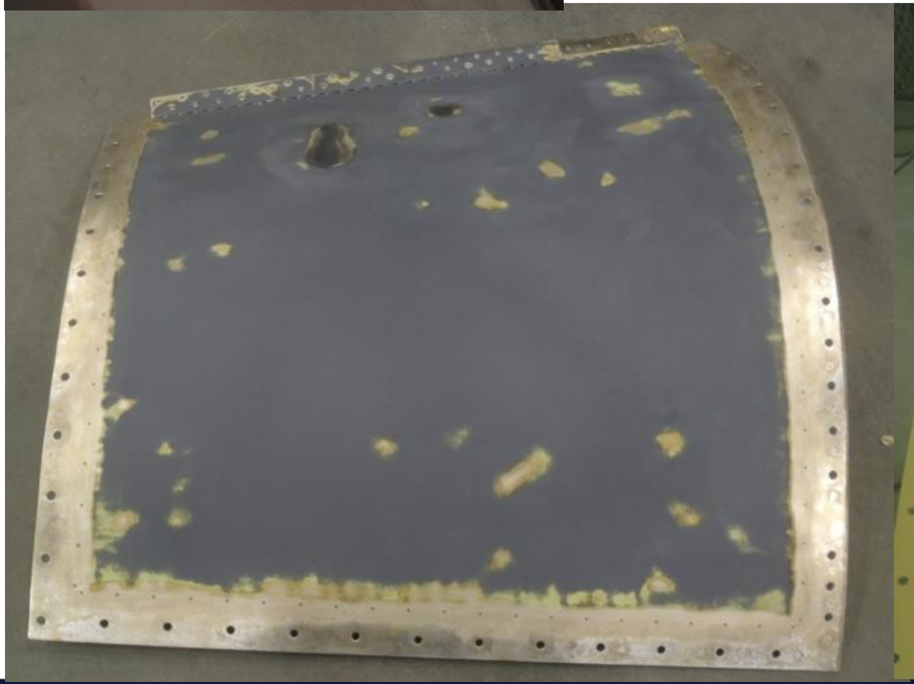
- **Even tested up to failure at 5600lbs, the cold spray material did not separate from the coupon.**

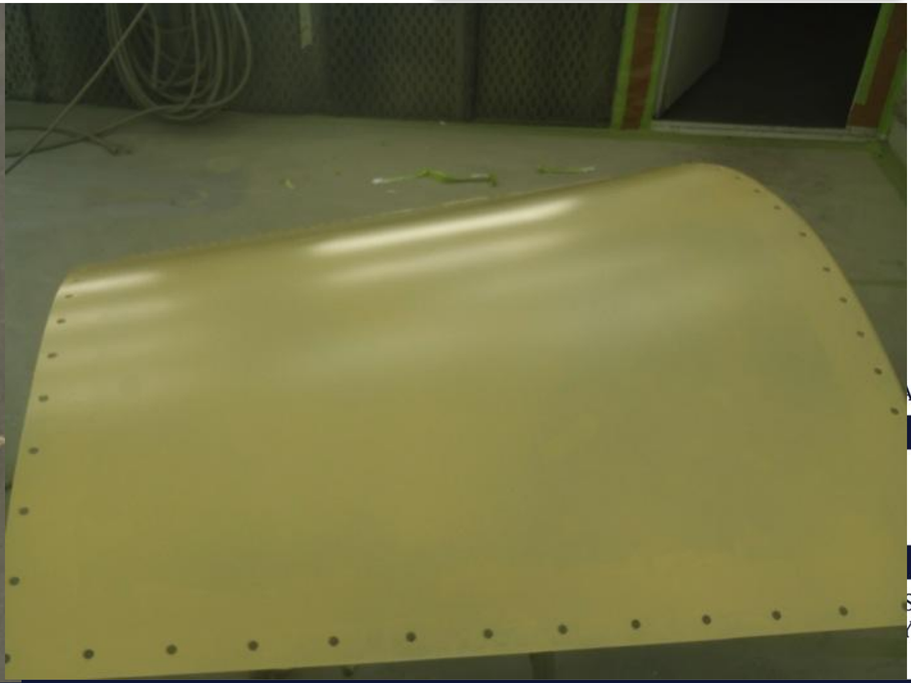


Repaired Panel

Panel temperatures did not exceed 100°C.







Fully Restored Panel vs. Legacy Repair

- *The repair is currently flying on a B1 under an ETAR (August 2012)*
  - Still no sign of degradation or repair failure
- Total development time (with Tinker AFB support): 250 days
- Repair time: 2 weeks --- Savings >$200K + Availability

SOUTH DAKOTA
SCHOOL OF MINES & TECHNOLOGY

Acknowledgements

- **These research projects have been made possible with funding from:**
  - The State of South Dakota (Governor’s Research Center and Office of Economic Development)
  - The Army Research Lab (contract #W911NF-11-2-0014)
  - H.F. Webster Engineering Services
  - VRC Metal Systems

SOUTH DAKOTA
SCHOOL OF MINES & TECHNOLOGY

Thank you for your attention!

- **Dr. Christian Widener**
  - Director/ Associate Professor
    Arbegast Materials Processing Lab
    South Dakota School of Mines & Technolog
    Ph. 605-394-6924
    Email: christian.widener@sdsmt.edu
    http://www.sdsmt.edu/amp
  - Chief Technical Officer
    VRC Metal Systems
    http://www.vrcmetalsystems.com