Structure/Property Relations for CS-5056 Al vs Wrought

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CSAT 2017, Boston, MA

USC and Viterbi School of Engineering

USC

- Founded in 1880
- 2nd largest private university in the US
- 44 000 students (19K undergrad), 4000 full-time faculty
- 18 schools
- Largest number of international students (China 39%, India 17%)
- Endowment \$4.7B, Budget \$4.2B, Sponsored Research \$691M
- Largest employer in Los Angeles

Viterbi

- Top 10 Engineering School in the US
- 2600 undergrad, 5200 graduate students
- 185 faculty
- 8 academic departments
- 45 Research Centers and Institutes
- Annual Research Expenditures \$185M

M.C. Gill Composites Center

Leadership and Personnel

Steven R. Nutt, Ph.D.
M.C. Gill Professor
Founder and Director
Co-Director, EM Lab

+

1 research professor
1 postdoc
15 PhD students
3 master's students
7 undergraduates

Focus Areas

Fundamental and Applied Research

- Composite processing/mfg
- Microstructural analysis
- Mechanical performance
- Recycling and reuse

What about cold spray? Hybridization of materials & processes → CS onto composites

Select Sponsors

kaneka, AIRBUS, JPL, NASA, CYTEC, M.C. GILL CORPORATION, Henkel, NORTHROP GRUMMAN

Presentation Overview

- Introduction and background
- Motivation – CS of 5056 Al
- Results
  - Microstructural analysis
  - Mechanical properties
  - Fractography
- Conclusions

Spoiler Alert

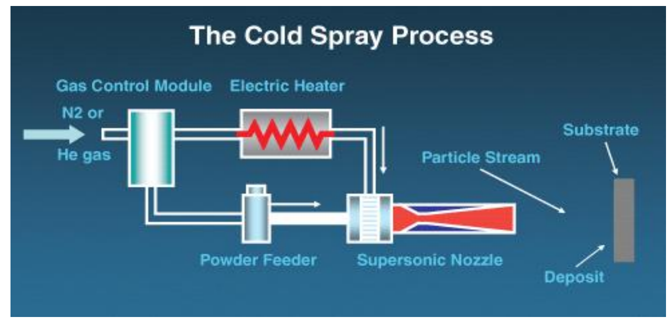
By preprocessing powder, can achieve CS strength and ductility = wrought

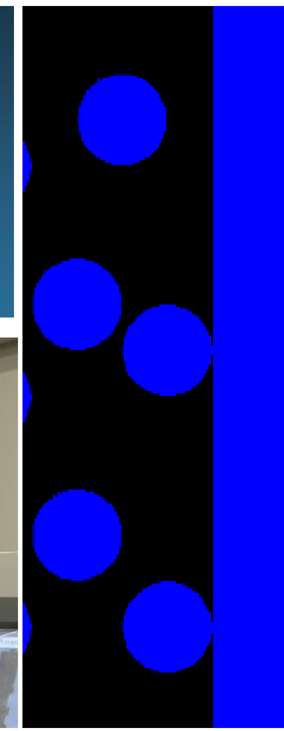
Overview of CS Process

Cold spray (CS) is a deposition/consolidation process in which powder particles are accelerated by preheated, high-pressure carrier gas as the gas expands in the divergent section of a nozzle.

Applications for Cold Spray:

- ✓ Repair & refurbishment
- ✓ Wear- & corrosion-resistant coatings
- ✓ Additive Manufacturing



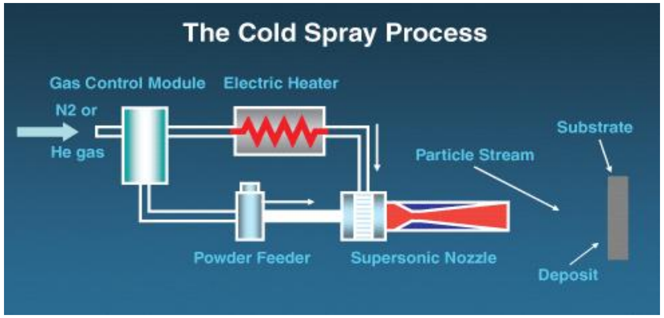


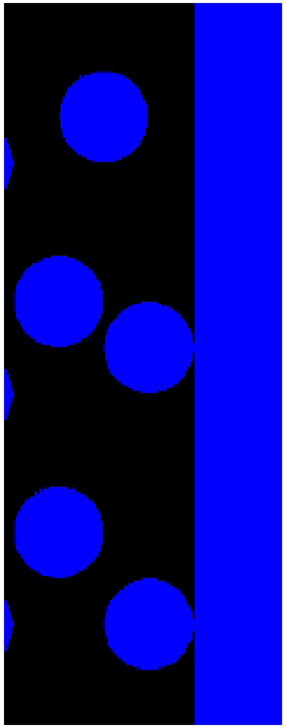
Overview of CS Process

Cold spray (CS) is a deposition/consolidation process in which powder particles are accelerated by preheated, high-pressure carrier gas as the gas expands in the divergent section of a nozzle.

Key Parameters:

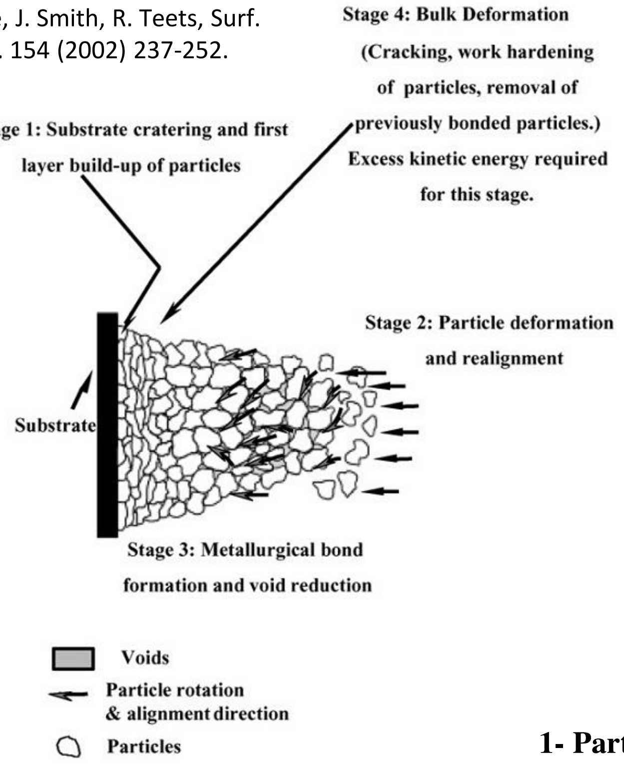
- ✓ Gas pressure (1 to 4 MPa)
- ✓ Gas temperature (up to 900°C)
- ✓ Particle velocity (300-1400 m/s)
- ✓ Particle size (typically 5–50 µm)

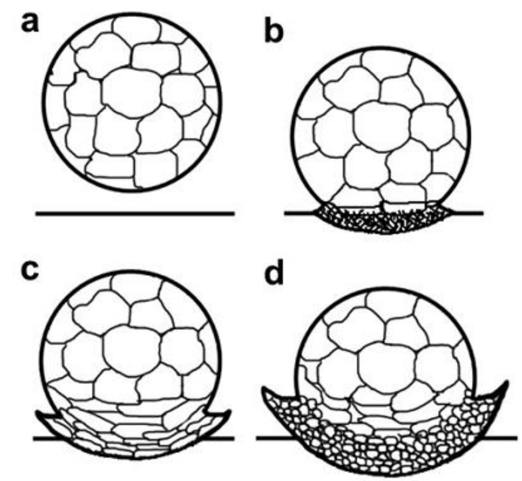




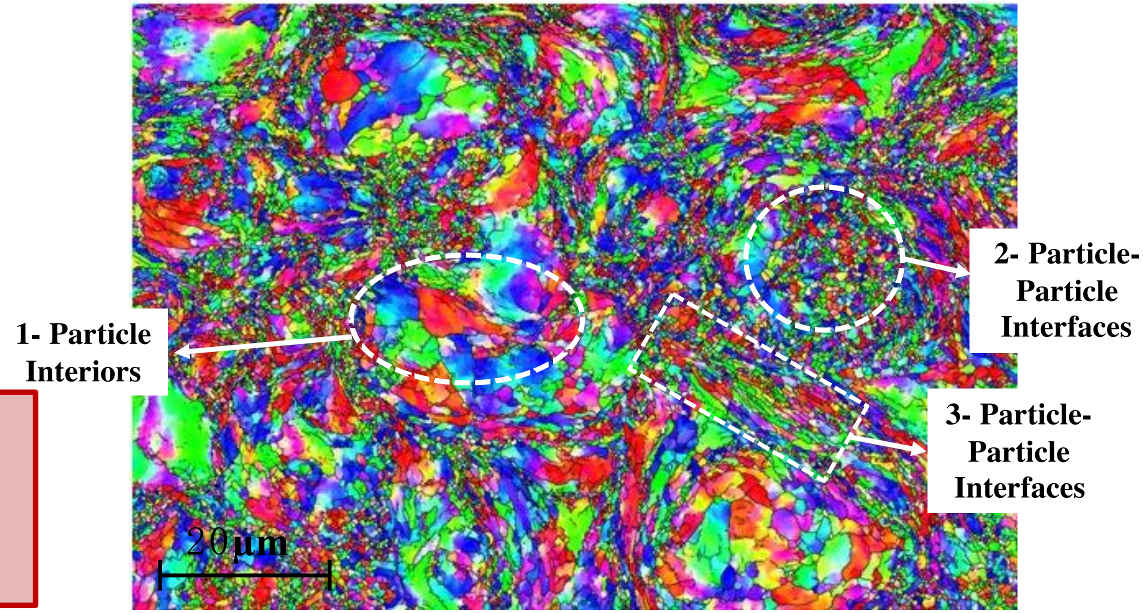
Background

T. Van Steenkiste, J. Smith, R. Teets, Surf. Coat. Technol. 154 (2002) 237-252.





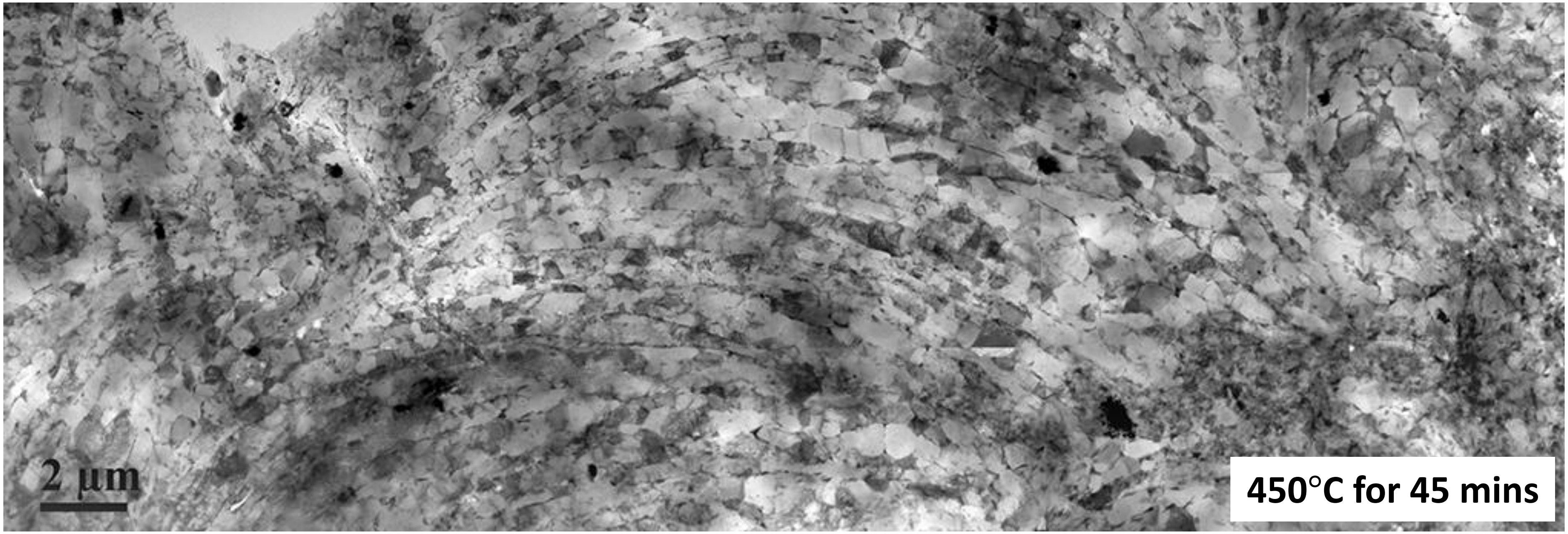
K. Kim, M. Watanabe, S. Kuroda, Surf. Coat. Technol. 204 (2010) 2175–2180.



M.R. Rokni, C.A. Widener, C.A. Crawford, Surf. Coat. Technol. 251 (2014) 254-63.

CS imposes high strains in particles, yielding a heterogeneous microstructure

Post-CS heat treatment- Microstructure

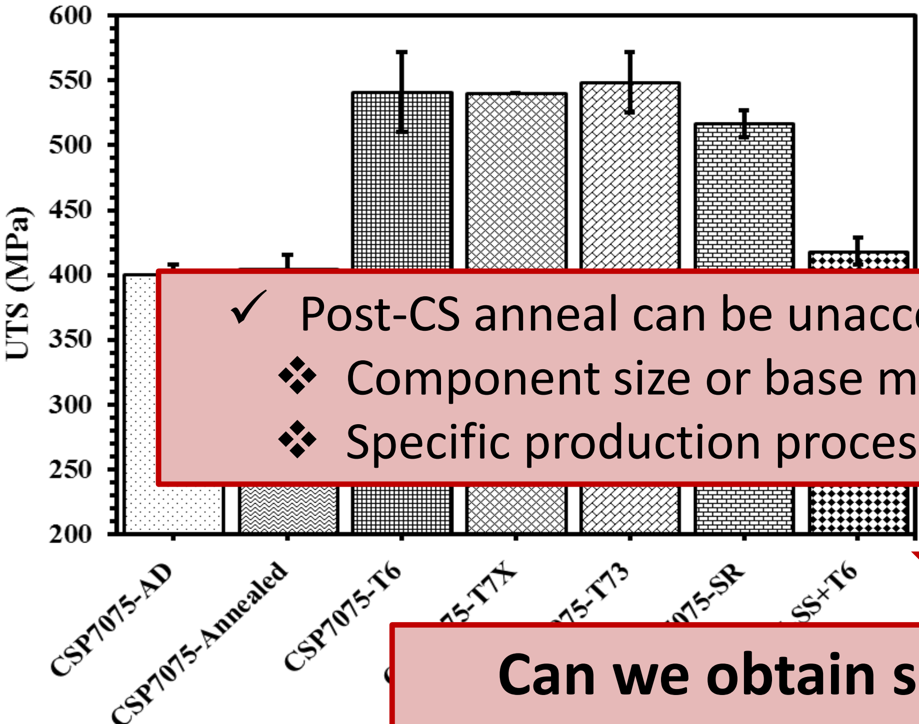


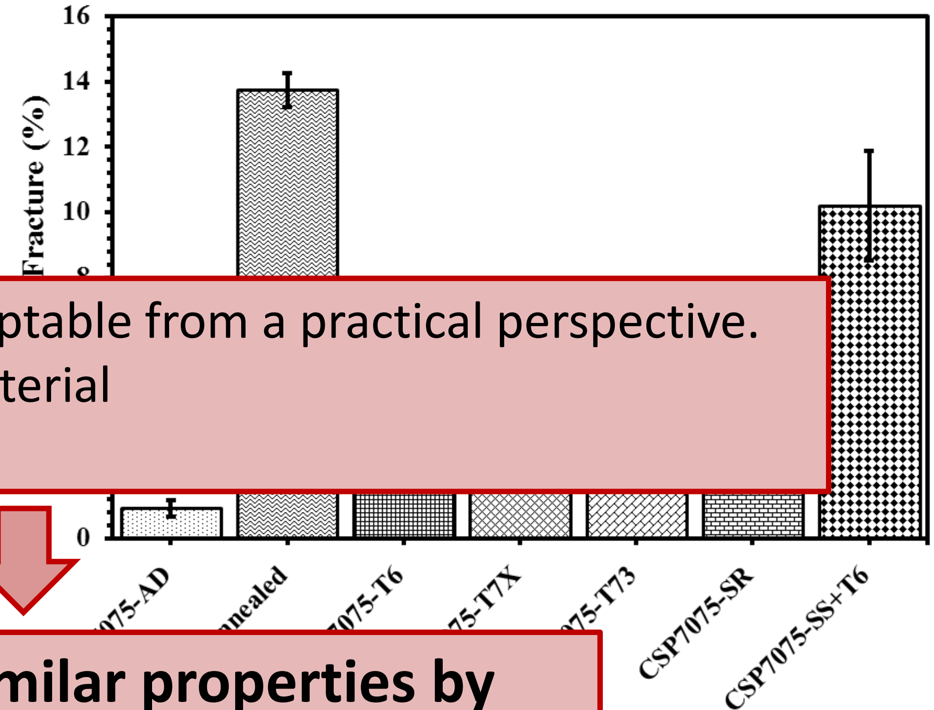
- Well-defined, straight grain boundaries – equi-axed grains
- Unlike heterogeneous microstructure of as-deposited material

Post-processing CS deposits can homogenize microstructure

MR Rokni, CA Widener, VK Champagne, GA Crawford, Surf. Coat. Technol. 276 (2015) 305-315

Post-CS heat treatment- Properties





- ✓ Post-CS anneal can be unacceptable from a practical perspective.
  - ❖ Component size or base material
  - ❖ Specific production process

Can we obtain similar properties by preprocessing the powder?

Post-deposition anneal can increase ductility and strength of CS deposits.

“Review of Particle Deformation-Structure-Properties relations in High Pressure Cold Spray”
R Rokni, C Widener, R Hrabe, V Champagne, and S Nutt, *J Thermal Spray Tech* 1-48 June (2017) DOI

MR Rokni, CA Widener, VK Champagne, GA Crawford, SR Nutt, Surf. Coat. Technol. 310 (2017) 278-285

Motivation/Objectives

Determine effects of powder preprocessing (degassing) on microstructure and properties of 5056 Al deposits

(1) Evaluate microstructure and mechanical properties of preprocessed 5056 Al alloy powder

(2) Evaluate microstructure and mechanical properties of the resultant deposit, benchmark to wrought 5056

(3) Determine causes of observed variations in microstructure and mechanical properties

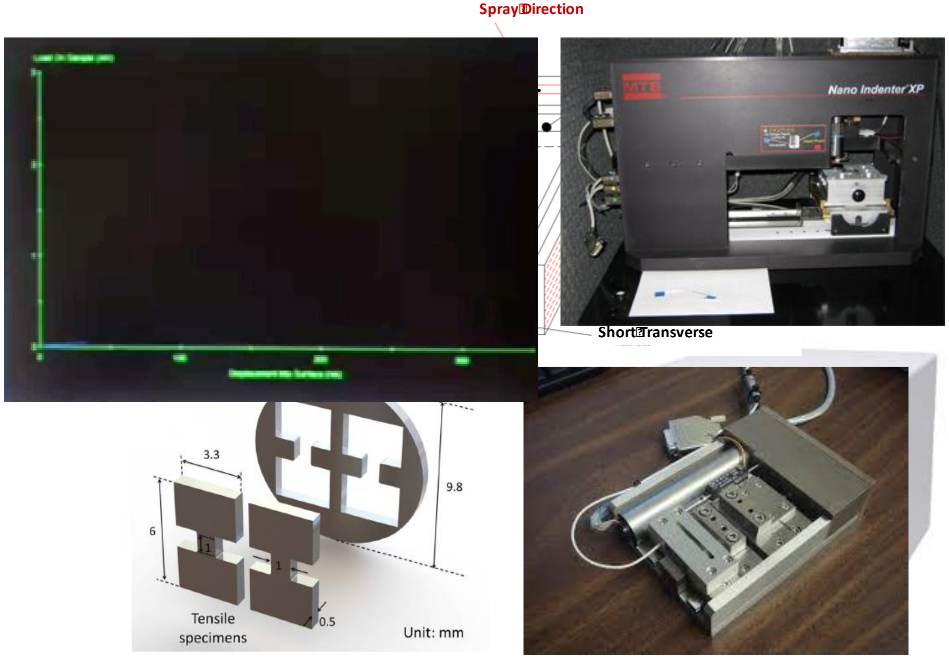
Experimental procedure

(1) Microstructure & mechanical properties of pre-processed 5056 Al powder

- LM, SEM, EBSD, and TEM
- Nanohardness (5 times loading)

(2) Microstructure & mechanical properties of resultant CS deposit

- LM, SEM, and EBSD
- Nanohardness
- Microtensile testing
  - ➢ L, LT, ST, and 45°



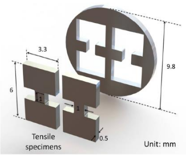
Why 5056 Al?

- Low density, cost
- Ballistic properties
- Weldability
- Corrosion resistance

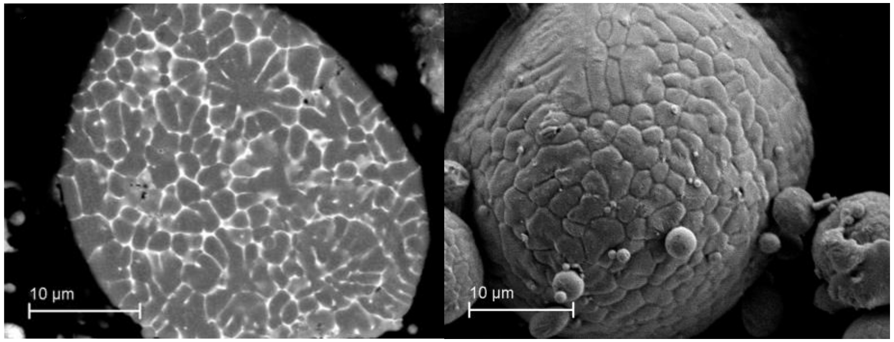
Element	Content (%)
Aluminum, Al	95.0
Magnesium, Mg	5.0
Manganese, Mn	0.12
Chromium, Cr	0.12

These features allow consistent design/production of lightweight, reliable, and cost-efficient DoD parts/systems.

		Tensile Strength	Yield Strength	Elongation (%) for the following gauge ranges:	
Alloy	Temper	(ksi)	(ksi)	0.010-0.050″	0.051-.125″
5056	O	42	22	23	24
	H38	60	50	6	13



Powder production



Typical gas-atomized Al powder

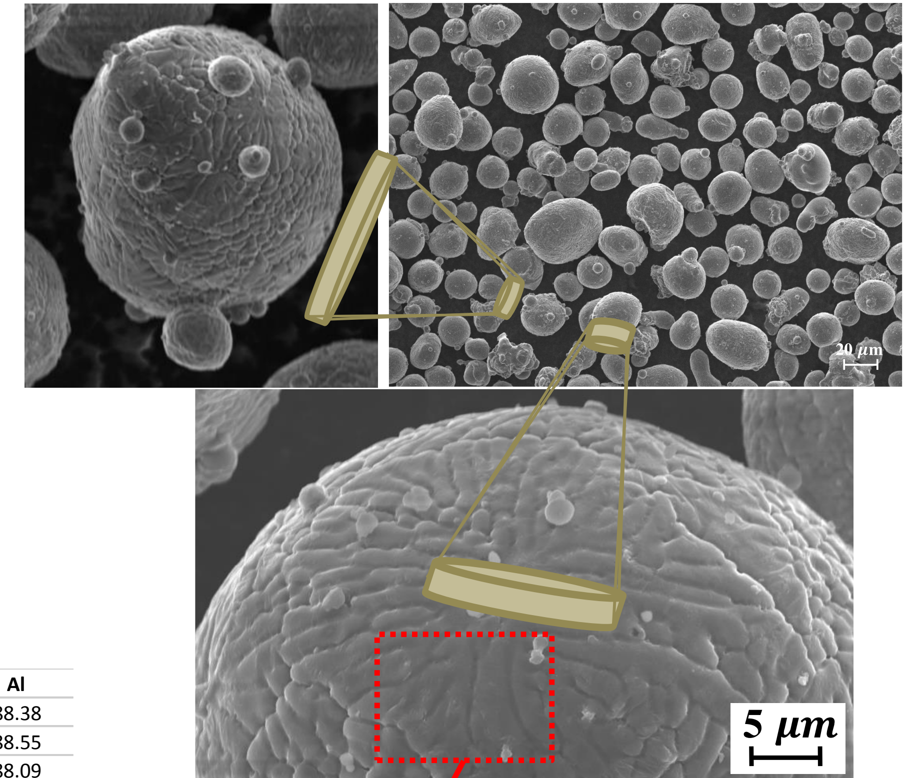
1. Melting in vacuum
2. Atomization by gas jet
3. Rapid quenching
4. Powder collection

Solute segregation at GBs

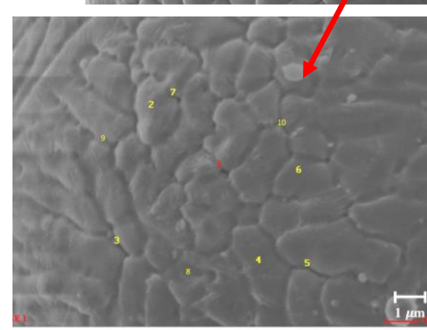
Major concern with feedstock gas-atomized alloy powders

Preprocessed powder

- ✓ Spherical particles
- ✓ Particle sizes ~24 µm (± 8 µm)
- ✓ Smaller particles agglomerate around larger particles
- ✓ Surface grain structure 1-4 µm
- ✓ No Mg segregation on particle surface



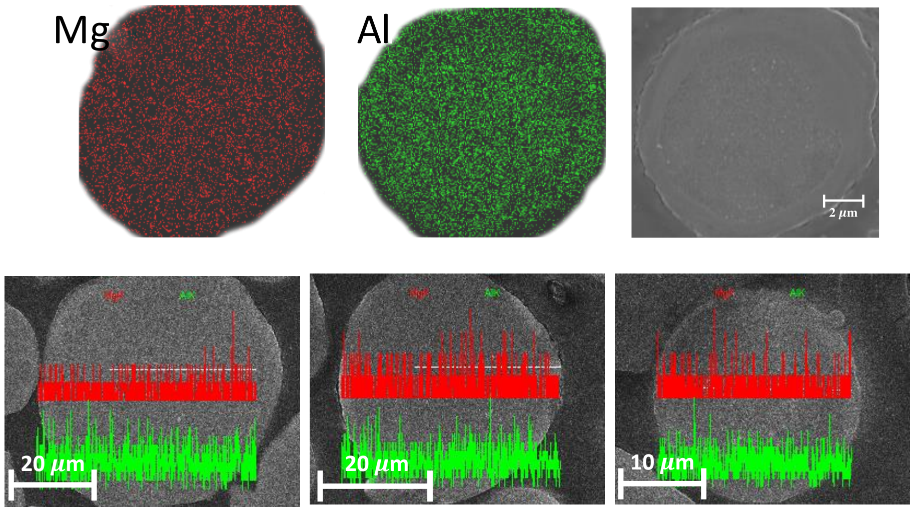
Point/Wt%	O	Mg	Al
1	2.47	9.15	88.38
2	2.45	9.00	88.55
3	2.61	9.30	88.09
4	2.50	8.90	88.60
5	2.81	9.30	87.89
6	2.60	9.18	88.23
7	2.60	8.78	88.62
8	2.75	8.72	88.53
9	2.12	9.29	88.59
10	2.33	8.78	88.99
STDEV.P	0.19	0.22	0.30
AVE	2.52	9.04	88.45



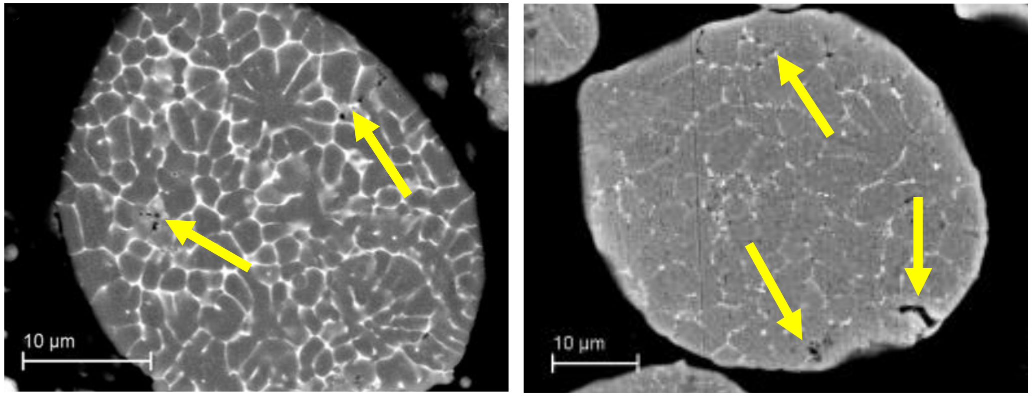
Preprocessed powder- degassed

- ✓ Uniform concentration of Mg
- ✓ No GB segregation within particle
- ✓ Confirmed with EDS mapping, line profiles
- ✓ Fewer pores compared to typical gas-atomized powder

Degassed gas-atomized particle structure

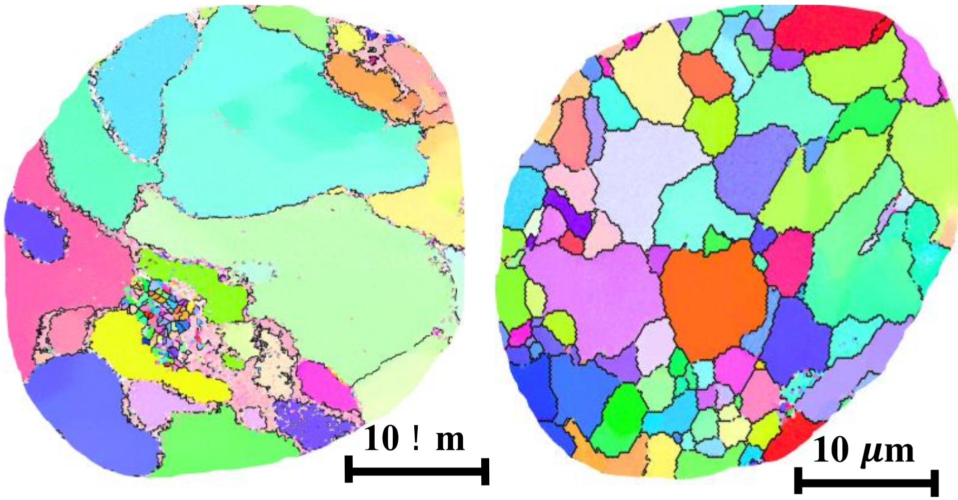


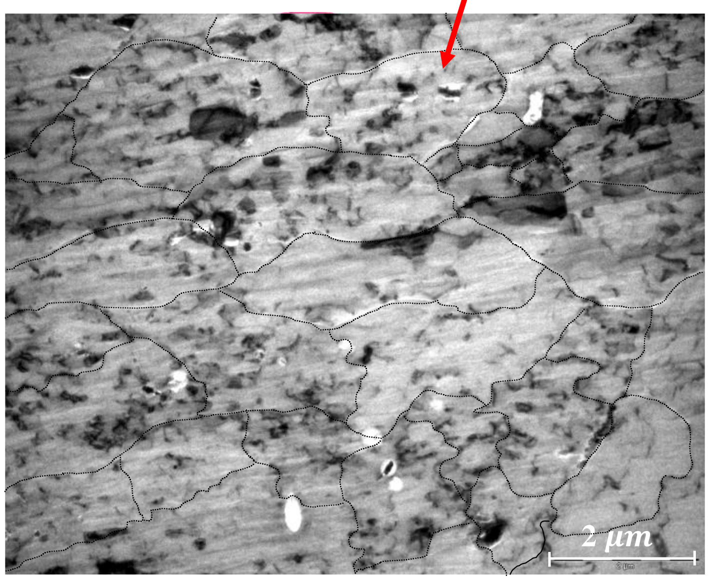
Typical structure of gas-atomized particle



Preprocessed powder- degassed

- ✓ Different types of interior grain structures
  - Large particles:
    - Similar grain structure as surface
    - Abnormal grain growth during degassing
  - Small particles:
    - All with abnormal grain growth
- ✓ Same grain structure under TEM
- ✓ Nanohardness of 0.66 ± 0.04 GPa

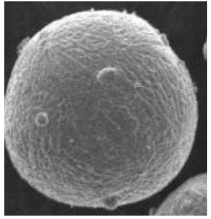


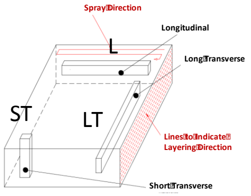


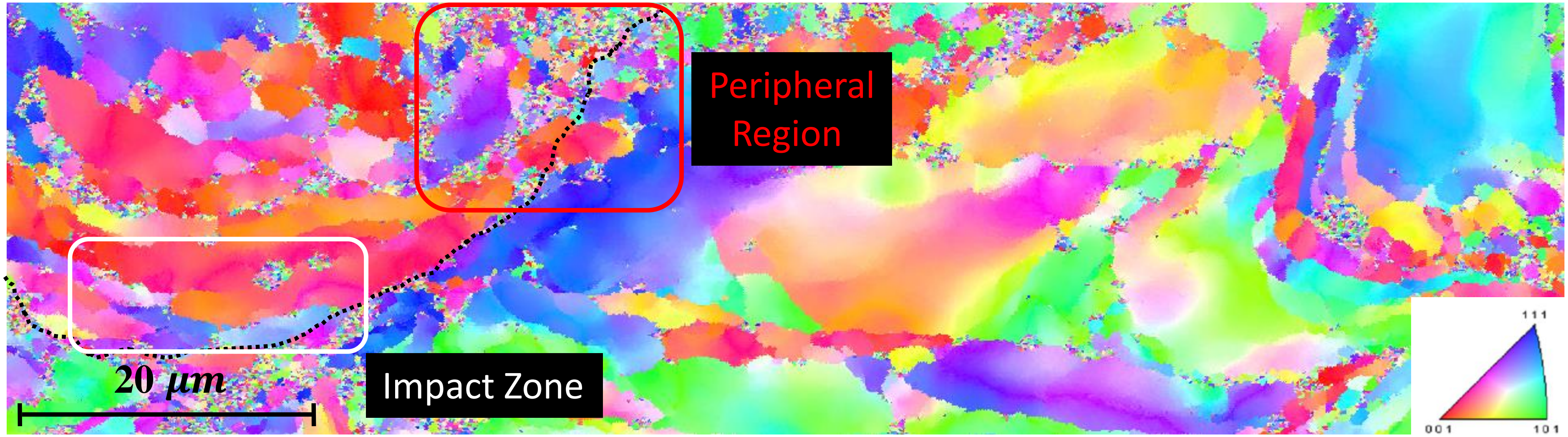
Nominal temperature (°C)	Actual maximum temperature (°C)
–	–
400	415 for 5.5 h
450	440 for 10 h
500	500 for 2 h

B. Ahn, A.P. Newbery, E.J. Lavernia, S.R. Nutt, Effect of degassing temperature on the microstructure of a Al–Mg alloy, Mater. Sci. Eng. A 463 (2007) 61–66

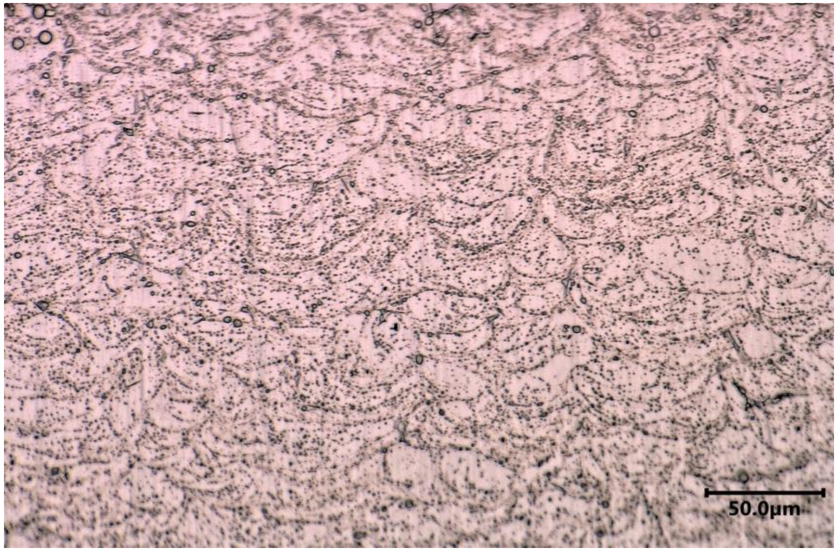
Deposit microstructure





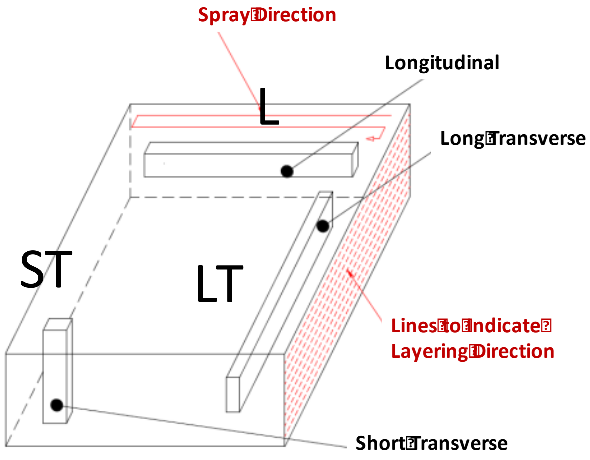


- ✓ Severe deformation of spherical particles
- ✓ No evidence of porosity
- ✓ No crystallographic texture
- ✓ Light deformation in the particle interiors
- ✓ Recrystallization at interfaces (PPB’s)
- ✓ More recrystallization in peripheral regions
- ✓ Enhanced bonding at these regions (?)



Deposit properties

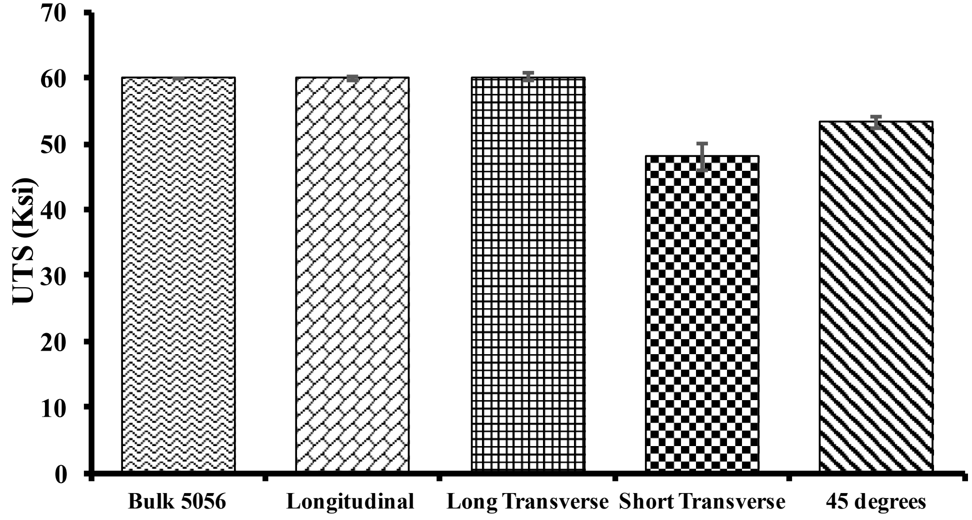
Specimen	Thickness (mm)	Initial Guage length (mm)	Final Gauge length (mm)	%El	Peak Load (lbf)	UTS (Ksi)
L1	0.5	1	1.055	5.52	46.00	59.36
L2						
L3	0.5	1	1.053	5.34	46.30	59.80
L4	0.5	1	1.062	6.21	46.95	60.58
L5	0.5	1	1.055	6.07	45.98	59.11
L6	0.49	1	1.073	6.19	47.04	60.92
				5.87	**46.45**	**59.95**
				5.87	**46.45**	**59.95**
LT1	0.48	1	1.029	2.91	44.77	60.17
LT2	0.47	0.985	1.021	3.64	43.49	60.61
LT3	0.48	1	1.028	2.78	43.49	57.90
LT4	0.47	0.99	1.020	3.05	44.00	60.46
LT5	0.48	1	1.032	3.21	45.66	61.37
				3.19	**44.34**	**60.10**

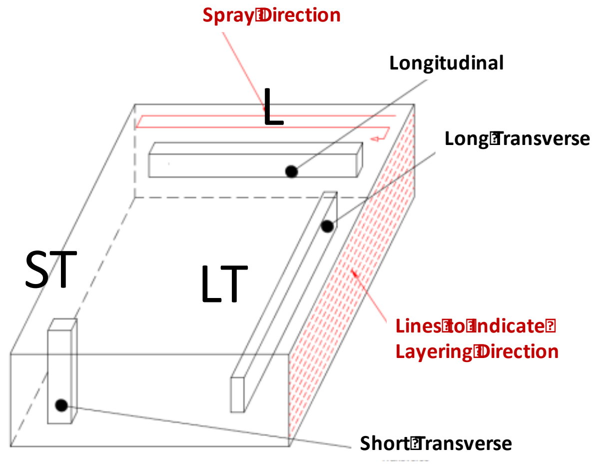


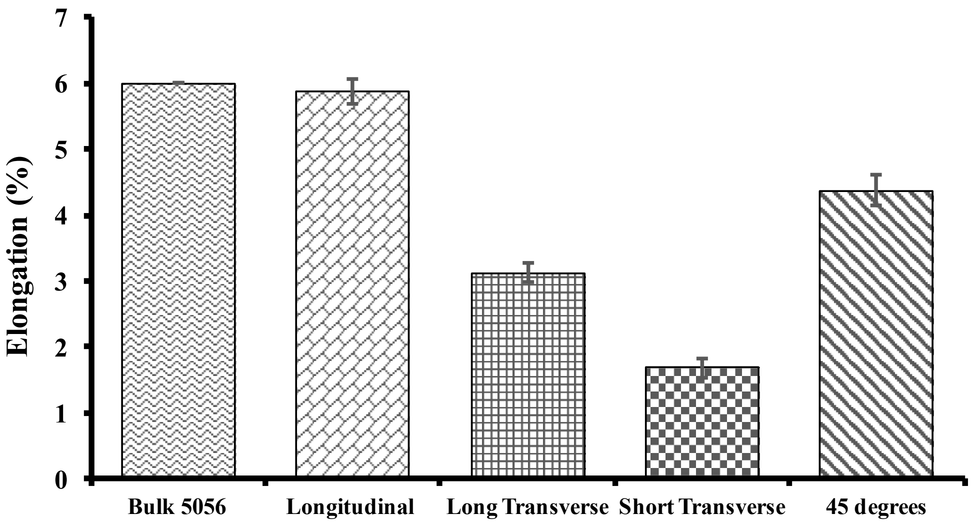
Red highlights: sample broke during the setup.

Specimen	Thickness (mm)	Initial Guage length (mm)	Final Gauge length (mm)	%El	Peak Load (lbf)	UTS (Ksi)
ST1	0.47	1	1.013	1.26	134.02	41.36
ST2	0.48	1	1.017	1.73	166.67	50.36
ST3	0.48	1	1.019	1.91	162.02	49.95
ST4	0.48	0.99	1.016	1.65	164.87	48.97
ST5	0.5	1	1.031	1.87	163.31	49.54
				1.68	**158.18**	**48.04**
				1.68	**158.18**	**48.04**
45-1	0.48	1	1.037	3.65	175.51	53.03
45-2						
45-3	0.48	1	1.039	3.92	167.10	50.49
45-4	0.47	1	1.045	4.54	167.35	51.64
45-5	0.48	1	1.048	4.81	182.56	55.16
45-6	0.49	1	1.056	4.93	183.61	55.96
				4.37	**175.23**	**53.26**

Deposit properties

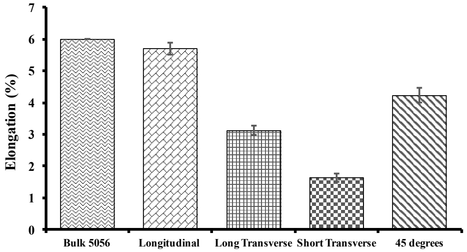


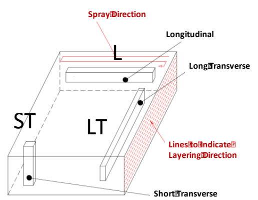




- ✓ Wrought strength in almost all directions
- ✓ Wrought El in L direction
- ✓ Minimum El and UTS in ST direction
- ✓ Average properties in 45° direction

Fracture Surfaces

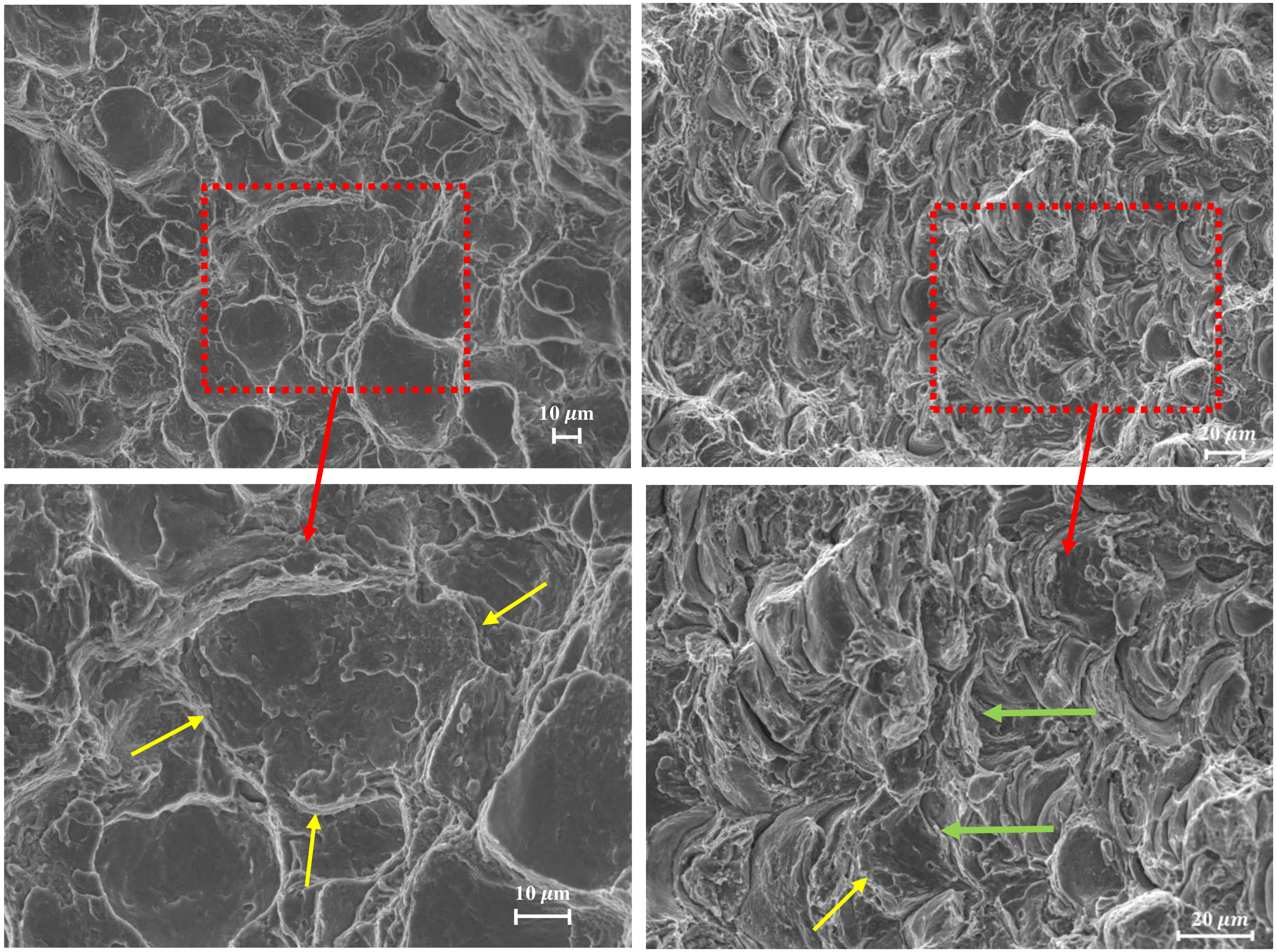




ST samples fracture at particle/particle interfaces (PPB'S)

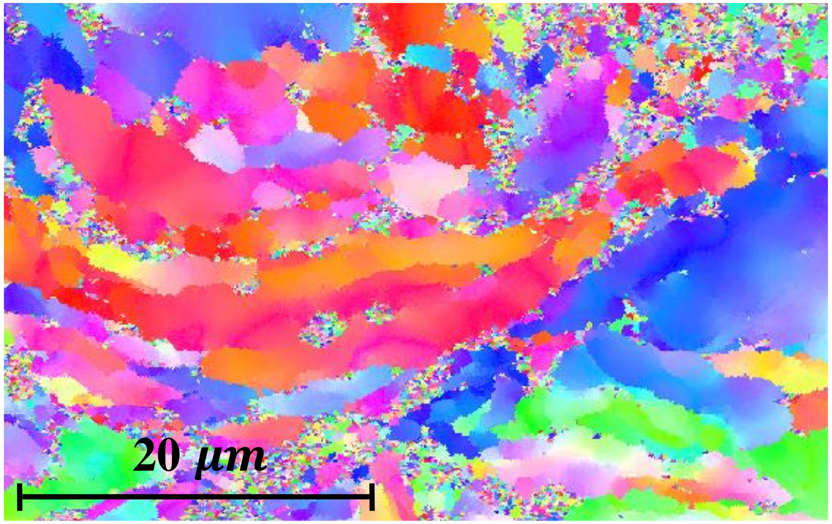
L samples fracture mostly through particles

Short Transverse **Longitudinal**

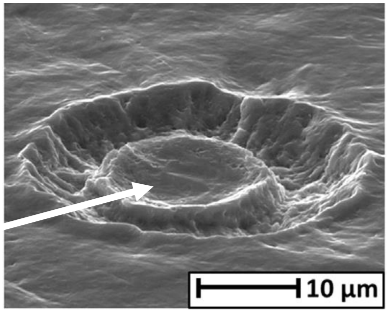


Causes of property variations

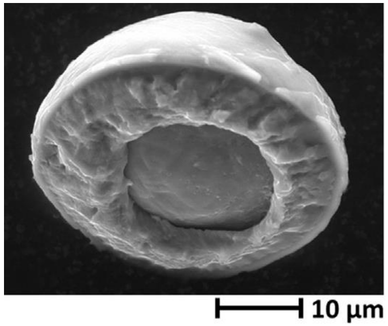
- Bonding occurs initially at the periphery of the contact zone
- Consistent with large-scale impact tests and simulations
- Maximum hydrostatic pressure at the center of impact



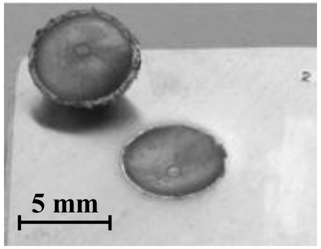
- Transition of bonding mechanism from mechanical interlocking to metallurgical, yielding ~wrought mechanical properties, through recrystallization at highly strained interfaces

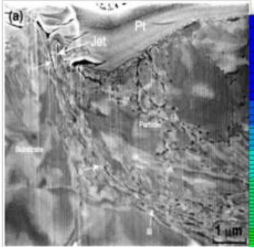


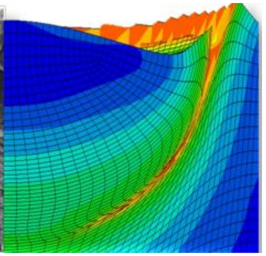
Potential defect site known from models



Superior properties in Longitudinal directions, inferior in Short Transverse directions.

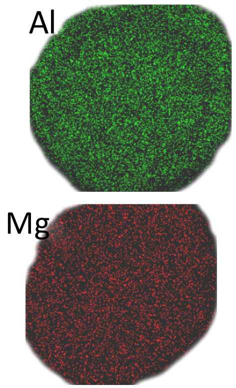


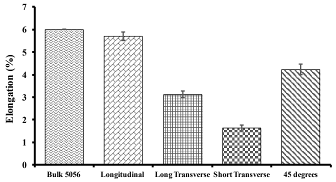


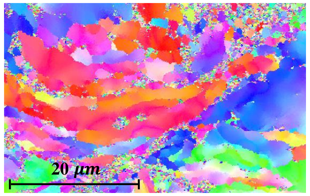


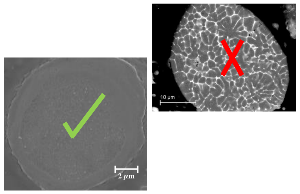
Conclusions

1) Preprocessing powder homogenizes solute distribution.
2) With proper preprocessing, strength and ductility = wrought achievable.
3) Strong bonding at periphery of contact zone because of intense shear → extensive recrystallization.
4) Yields superior properties in longitudinal and 45° directions.
5) Insights gained → optimization of preprocessing treatments for cold spray deposits.









Thank You

Questions?

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Thank You

"If you ask me a question I don't know, I'm not going to answer."

After a rough game, any questions seem like tough ones. Sometimes you just don't feel like talking about it. But like it or not, you have to face the press.