Structural Aluminum Cold Spray Development

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Summary

- 5056 Cold Spray Test Results
  - Multiple Cold Spray systems
  - Multiple nozzle configurations
  - Various tensile geometries
- Advances in heat treatable aluminum alloys
  - 6061, 2024, and 7075 results from STA conditioning
  - Powder characterization
- Nano-materials extrusion

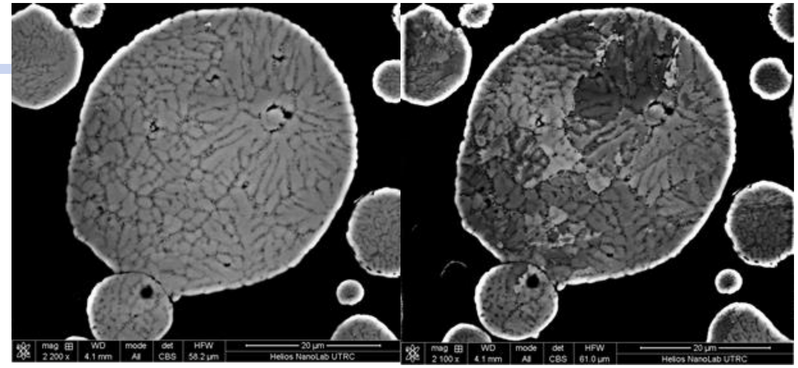
5056 Aluminum Cold Spray Test Results

- Tensile testing of 5056 aluminum has consistently provided high strength and good ductility
- Tensile tests have been performed primarily with ASTM E8 Sub-size flat tensile coupons, but similar results can be obtained from smaller round coupons
- Small test coupon advantages
  - Evaluating material from actual parts
  - Evaluating deposits in multiple directions
- Smaller coupon results are more sensitive to measurement accuracy
- Critical development aspects enabling high properties
  - Powder processing
  - Spray parameter development

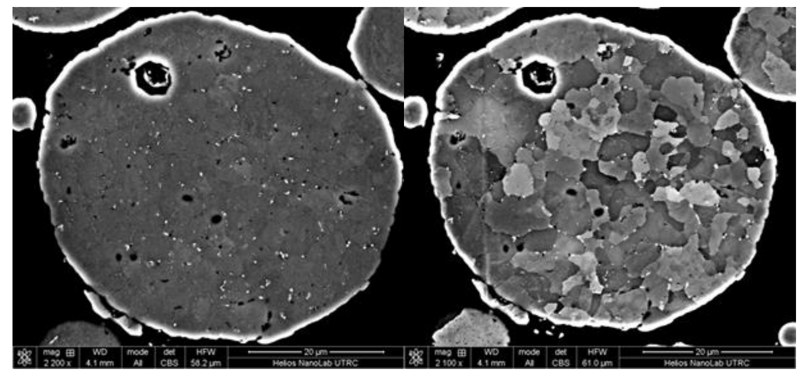
	Standard Coupon	Micro coupon
UTS (ksi)	58.3	58.4
%el ASTM E8	12.4	10.9

5056 Powder Processing

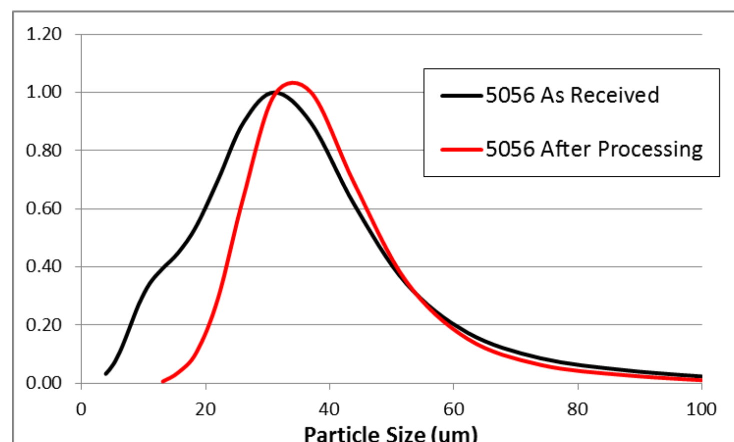
- In Cold Spray powders must undergo significant plastic deformation
- Powder particles are castings
  - Segregation in castings can lead to poor ductility
- Aluminum powders adsorb significant amounts of moisture which can lead to problems during or after consolidation
- Aluminum powders size classification is critical to allowing particles to feed properly, heat sufficiently, and not foul equipment
- UTRC has developed equipment for processing aluminum powders to achieve the desired goals or Cold Spray (PA-0025560-US)



5056 powder as received before and after ion etching

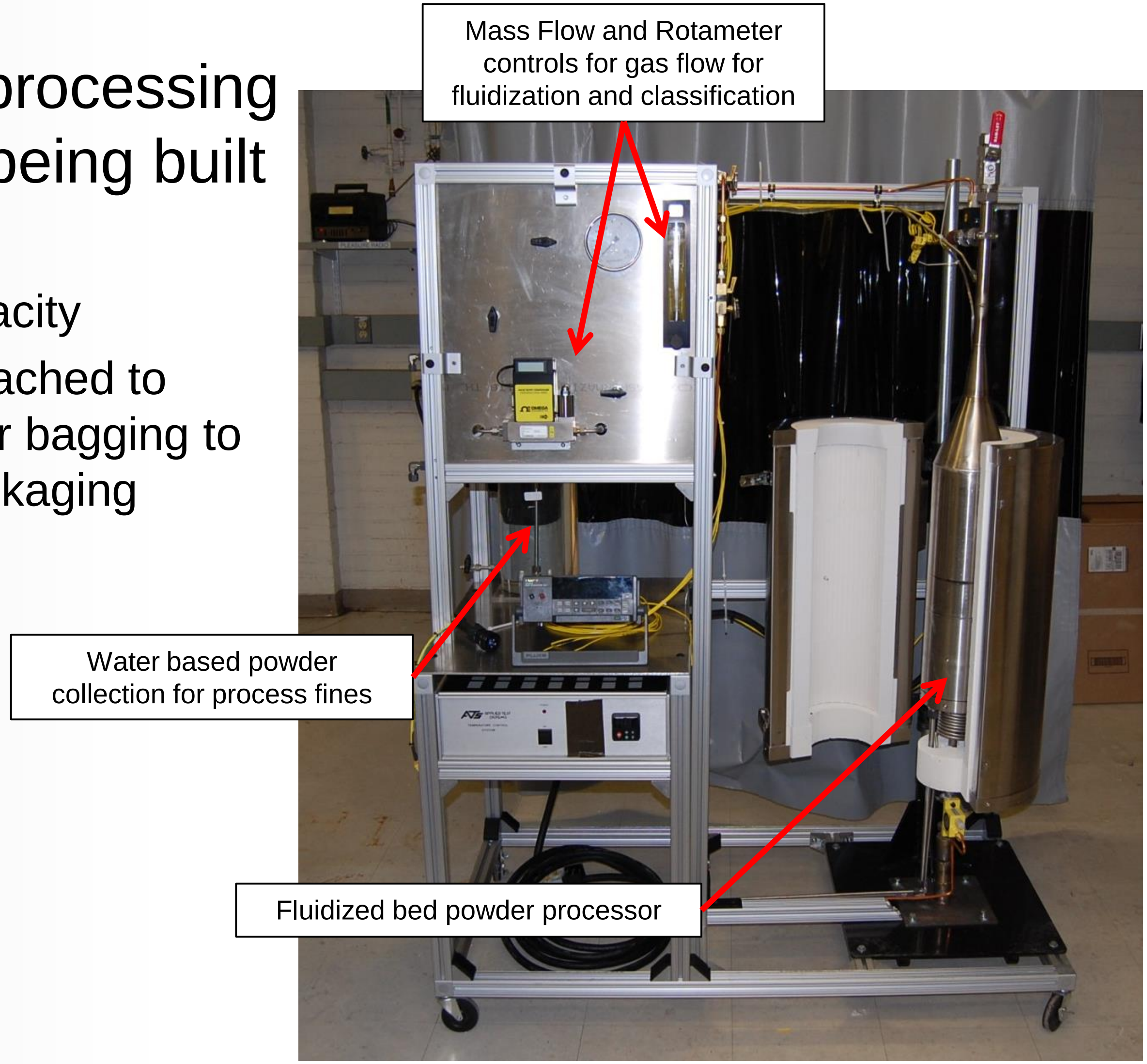


5056 powder processed before and after ion etching



5056 Powder Processing

- Scaled up powder processing unit Designed and being built for ARL
  - 10 lb processing capacity
  - Collection system attached to processing system for bagging to allow for inert dry packaging



Expected system completion date 7/15/2016

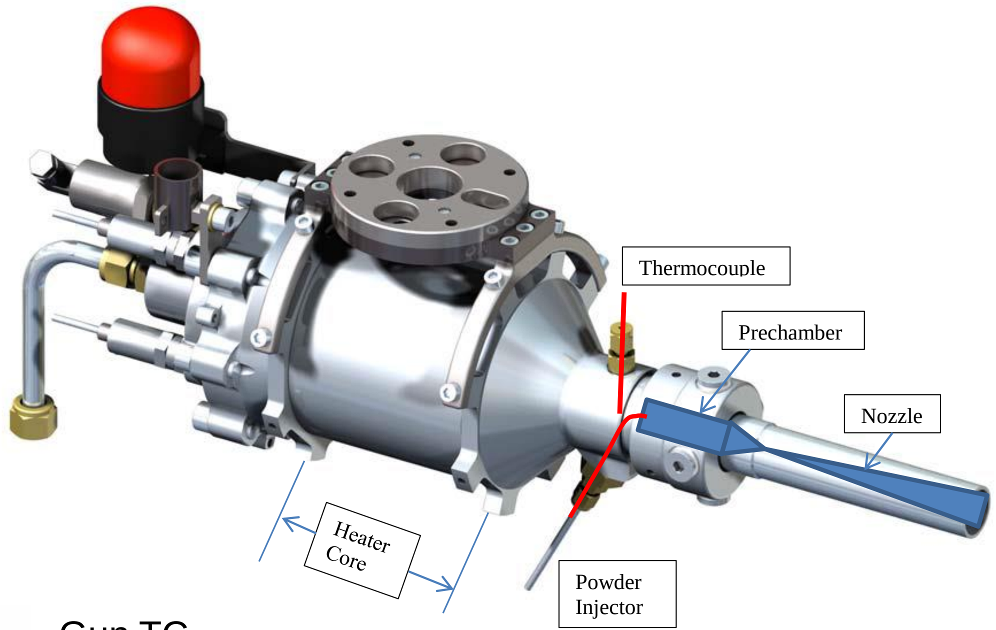
Understanding True Spray Conditions

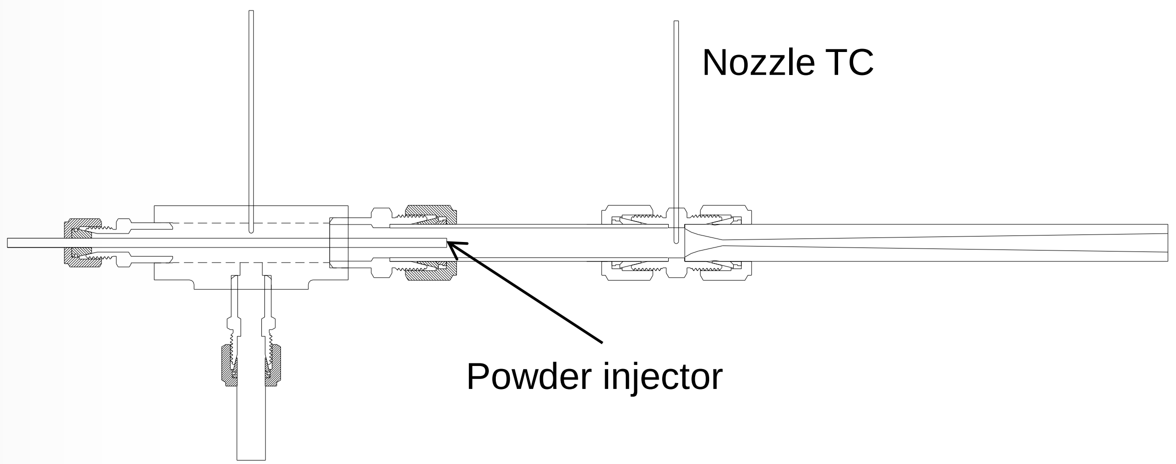
<u>What you need to know</u>

- Temperature of the powder as it enters the nozzle
- Pressure and temperature of the gas as it enters the nozzle
- Nozzle geometry
- Powder size distribution

<u>Related items</u>

- Actual powder injection location
- Temperature measurement location
- Main gas flow rate
- Carrier gas flow rate





Relative Critical Velocity Ratio Calculations

- Critical velocity ratio allows for comparison between varying velocities and temperatures
  - Should be used as a relative number not absolute

$$V_{crit} = \sqrt{\frac{4F_1\sigma_{uts}\left(1-\frac{T_i}{T_{MP}}\right)}{\rho} + F_2C_p\left(T_{MP}-T_i\right)}$$

- Actual powder size distribution can be used to determine mass averaged velocity

Size	%chan	Normalized Fraction
Powder Distribution for Averages*		Normalized Fraction
104.6	0.1	0.001
87.99	0.61	0.006
73.99	1.44	0.014
62.22	3.49	0.035
52.32	8.03	0.080
44	15.7	0.157
37	22.94	0.229
31.11	22.77	0.228
26.16	14.83	0.148
22	6.71	0.067
18.5	2.42	0.024
15.55	0.83	0.008
13.08	0.13	0.001
11	0	0.000
total of %	100	

* #'s read off microtrac graph

Particle Diameter (um)	Impact Temp (°c)	Impact Velocity (m/s)	Critical Velocity Ratio
104.6	387	662	1.3
88	376	726	1.4
73.99	362	794	1.5
62.22	346	867	1.5
52.32	326	944	1.6
44	304	1025	1.7
37	280	1109	1.8
31.11	254	1195	1.9
26.16	230	1283	1.9
22	210	1371	2.0
18.5	197	1459	2.1
15.55	196	1543	2.2
13.08	210	1623	2.4
11	239	1696	2.6

Average CVR
1.805

Average Velocity
1143

Average Temperature
271

Process

Gas Selection	1	0 if N2, 1 if He	
Pressure (bar)	40	Pressure (psi)	580
Gas Temperature (°C)	430		
Standoff Distance (in)	1		

Type 24 | Type 33 | K-Tech Long | Innovati | 0.068 x 0.2 x 6 | 0.078 x 0.25 x 6 | 0.078 x 0.11 x

Nozzle Dimensions

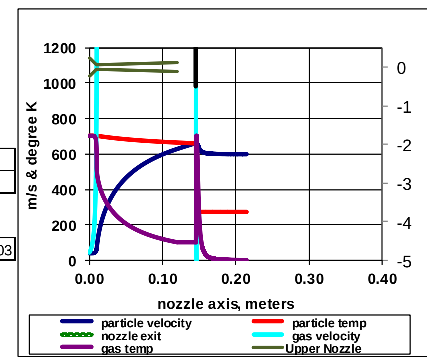
		Mach Number at nozzle inlet		
Throat Diameter (in)	0.078	0.028	Vp, m/s (at impact)	662
Exit Diameter (in)	0.196	Expanding Length (in)	Tp, C (at impact)	387
Entrance Diameter (in)	**0.350**	4.327		
Converging Length (in)	0.393	Expanding Angle (2Θ) Degrees	Ve, m/s (at nozzle exit)	628
Area Ratio	**6.31**	**1.562**	Te, C (at nozzle exit)	391
Overall Length	**4.72**			

Powder Information

Particle density (g/cc)	2.64	Material	Critical Velocity (m/s)	519
Particle Specific Heat, Cp J/kg-K	910		Critical Veocity Ratio	**1.2742**
Particle Size (microns)	104.6		Max Particle Temperature (°C)	**430**
UTS (Mpa)	290	UTS (ksi)	Erosion Velocity (m/s)	**1038**
Melting Point (°c)	630	42.1	Erosion Velocity Ratio	**0.637**

Apply Downstream Injection | Remove Downstream Injection

Injection Powder Temperature (°c)	565
Initial Powder Temperature (°c)	430
AR / ΔL	1.459271303



Material being sprayed

5056	2.64	630	290	910

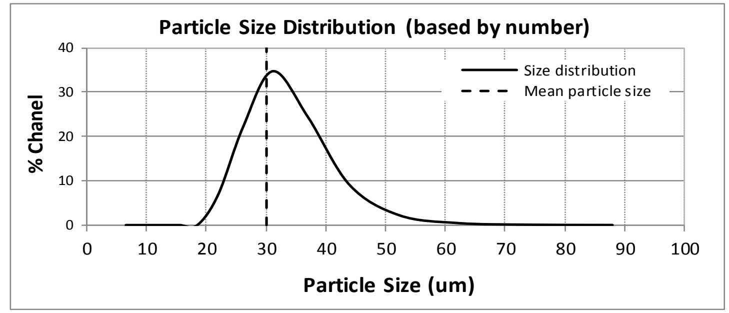
Particle Velocities: Predicted *vs.* LDV Measured

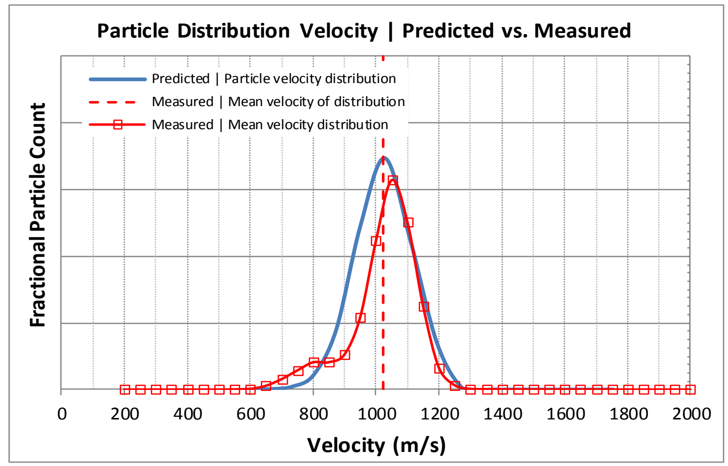
Velocity calculations calibrated with Laser Doppler Velocimeter

Aluminum prediction on average predict 4.8% higher than measured velocity

Cobalt alloy prediction on average predicts 2.8% lower than measured velocity

	Run ID		LDV-017	
POWDER	Powder type		Al 5056	
POWDER	Manufacturer		Valimet	
POWDER	Classification		10 LPM	
POWDER	Sieving		-400/+500	
POWDER	Mean particle size, mm		30.08	
POWDER	Powder density, g/cm3		2.618	
COLD SPRAY CONDITIONS	System		CGT	
COLD SPRAY CONDITIONS	Nozzle material		PBI	
COLD SPRAY CONDITIONS	Nozzle		SM-0007, Type 33	
COLD SPRAY CONDITIONS	Throat diameter, in	Exit diameter, in	Converging length, in	Expanding length, in
COLD SPRAY CONDITIONS	0.106	0.381	1.155	7.39
COLD SPRAY CONDITIONS	Gas 1		Helium, 100%	
COLD SPRAY CONDITIONS	Gas 2		---	
COLD SPRAY CONDITIONS	Distance from end of nozzle, in		1	
COLD SPRAY CONDITIONS	Pressure, bar		20	
COLD SPRAY CONDITIONS	Gun temperature, °C		300	
COLD SPRAY CONDITIONS	Nozzle temperature, °C		---	
COLD SPRAY CONDITIONS	Calculated | Nozzle Temperature, °C		291	
COLD SPRAY CONDITIONS	Gas flow, LPM		---	
COLD SPRAY CONDITIONS	Calculated | Gas flow, m3/h		182	
COLD SPRAY CONDITIONS	Predicted | Velocity of mean diameter particle, m/s		1056	
COLD SPRAY CONDITIONS	Predicted | Mean velocity of distribution, m/s		1029	
COLD SPRAY CONDITIONS	Measured | Mean velocity of distribution, m/s		1023	
COLD SPRAY CONDITIONS	Deviation, %		0.63%	





Legend:

- (green) Calculated using rule of mixtures
- (blue) Predicted using 'Velocity Calcs 1.4 + Log Book' Excel file
- (red) Measured values from LDV laser system
- (yellow) Deviation between predicted and measured velocity

Additional information:

* Particle size distribution was measured using Microtrak S3500

* Powder density was measured using pycnometer

--- : not available

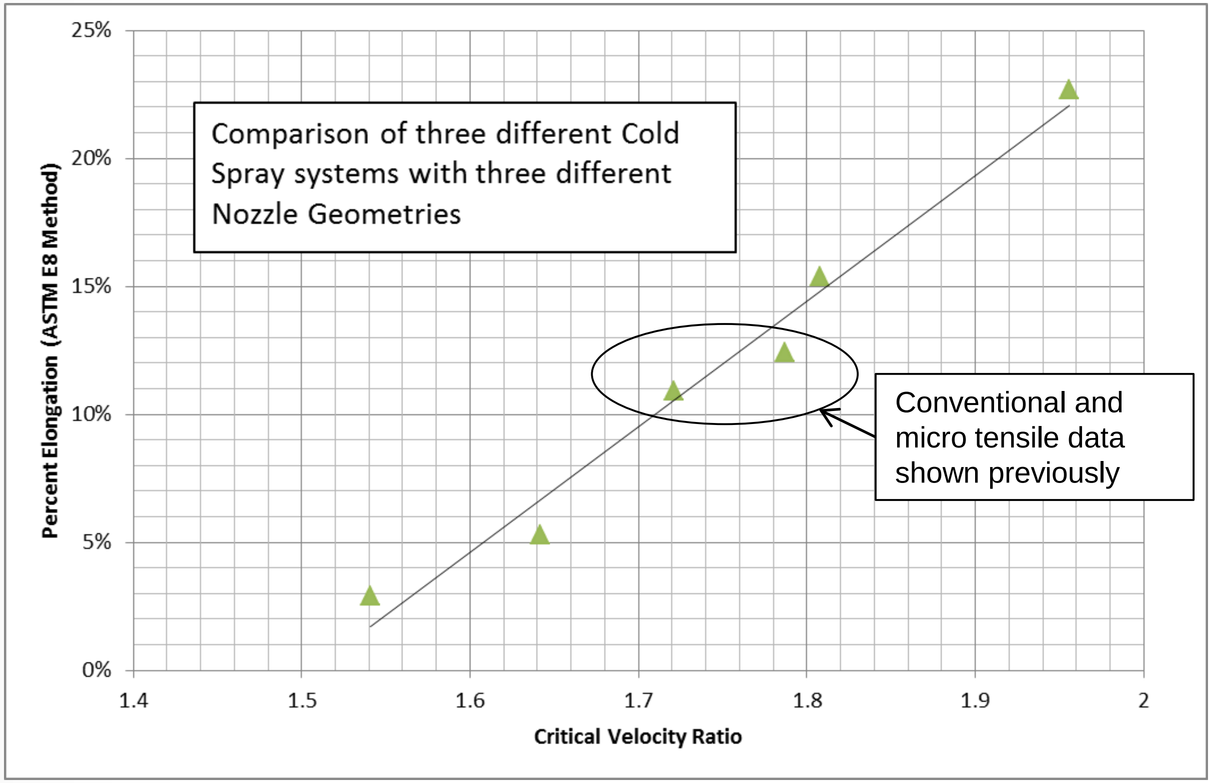
5056 Aluminum Cold Spray Test Results

5056 Results Comparison

- All results are made using powder processed per the UTRC developed Degassing and homogenization method
- Tensile strength can vary slightly with spray condition
- Tensile elongation can vary dramatically with spray condition

Results shown include 3 data points from the CGT system, 1 from the VRC system, and 2 using a system designed at UTRC

All results follow the same trend when final spray conditions are determined



5056 Aluminum Cold Spray Test Results

Summary

- Aluminum alloys like 5056 have the tendency to adsorb moisture, maintain a high fraction of fines even after room temperature sieving and traditional gas classification, and tend to be highly segregated as atomized
- UTRC and ARL are working together to scale up and ultimately license powder processing technology developed at UTRC to address all of these issues in Cold Spray powders
- ARL's goal is to have production sources of powder ready to supply powders to the Cold Spray industry some time in 2016

Advances in Heat Treatable Aluminum Properties

Processing of 6061, 7075, and 2024

- Processes have been developed to achieve homogenization of 7075, 6061, and 2024 powders
- Homogenization temperatures result in significant overaging in heat treatable alloys requiring materials to be re-solutioned in order to achieve good mechanical properties

Materials shown have been homogenized, solution treated, Cold Sprayed, then aged

7075 Cold Spray			
	UTS (ksi)	YS (ksi)	%el
Averages	68.19	57.32	5.8%
Typical Wrought	72.22	59.73	4.7%
Spec Minimum Wrought	67.00	54.00	3.0%

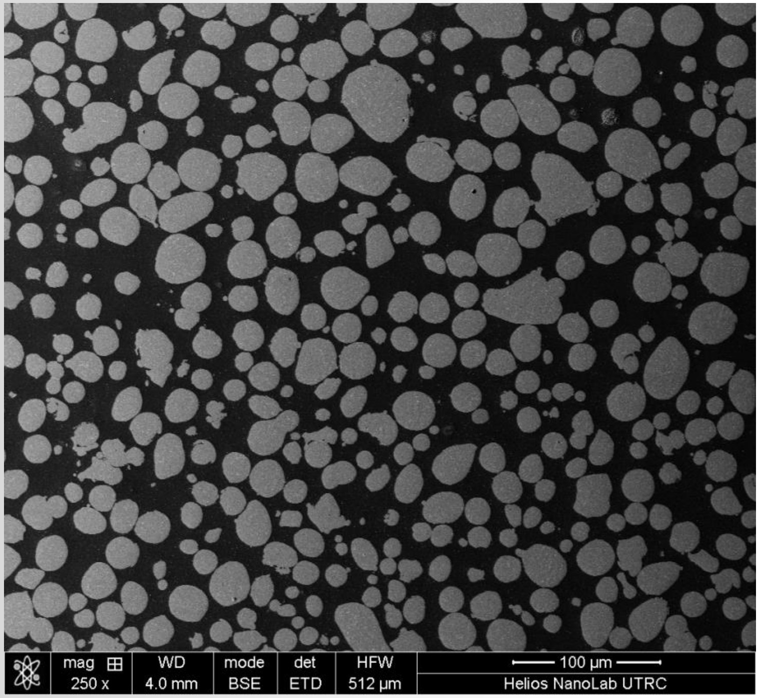
6061 Cold Spray			
	UTS (ksi)	YS (ksi)	%el
Averages	43.70	40.38	11.5%
Typical Wrought	45.00	40.00	14.5%
Spec Minimum Wrought	42.00	35.00	10.0%

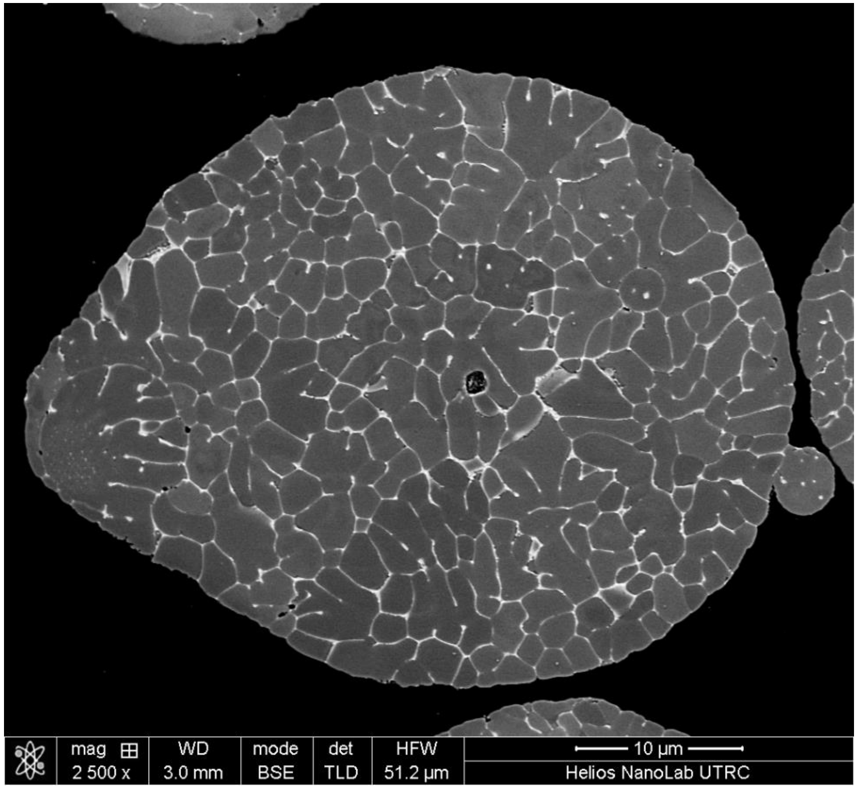
2024 Cold Spray			
	UTS (ksi)	YS (ksi)	%el
Averages	72.20	62.58	3.9%
Typical Wrought	75.00	71.00	5.0%
Spec Minimum Wrought	70.00	64.00	4.0%

Typical and specification minimum values determined for comparable heat treatment condition

As-Received AA7075 Feedstock Powder

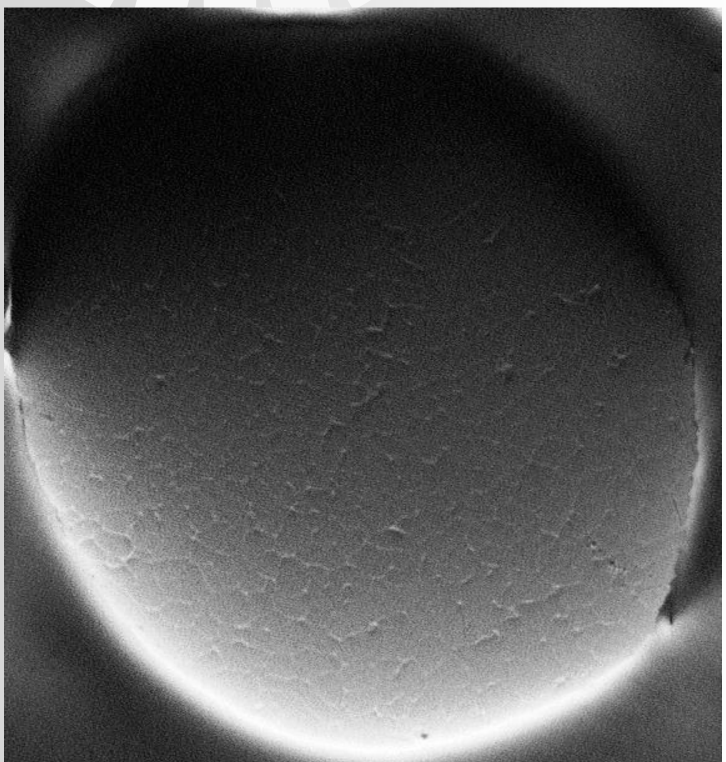
- Gas atomized AA7075 has a cellular dendritic structure.
- Cell size appears to be ~1.5 to 3.0μm
- <u>Question</u>: *Does each cell have a unique crystallographic direction such that it constitutes a grain?*

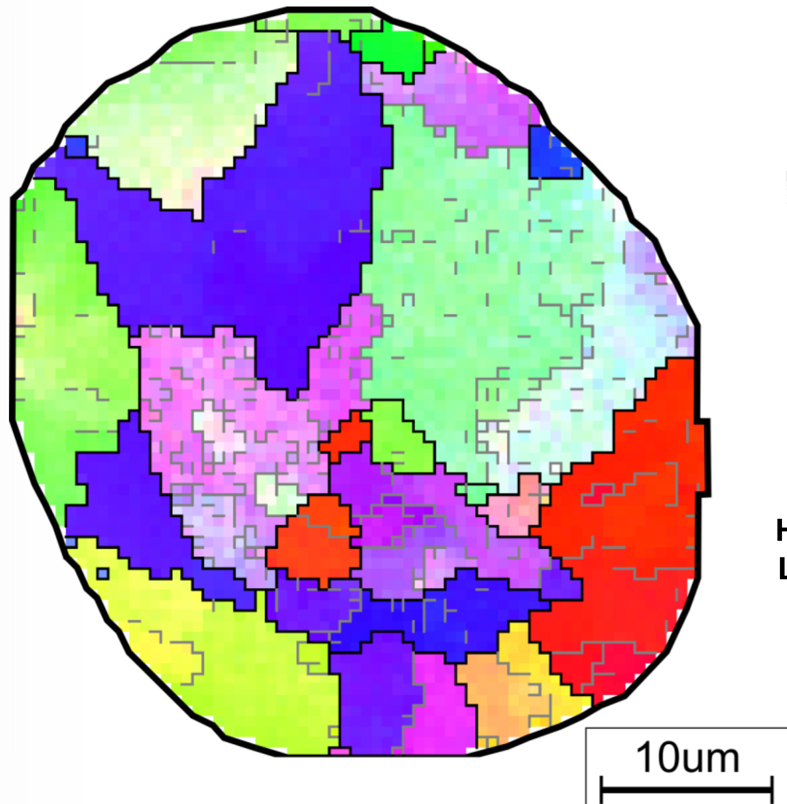


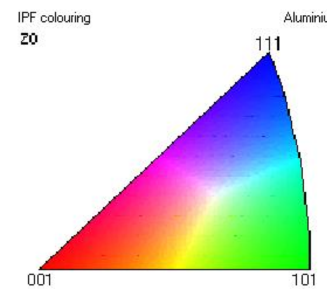


EBSD of AA7075 As-Received Powder Particle

- Investigate a ~40μm diameter x-section of a powder particle
- FSD image on lower left shows cellular dendritic structure of the powder particle.
- Particle contains 24 grains, 2.3 to 18.7μm in size. Grains contain several LAGB segments.
- Dendritic cell size appears < grain size i.e. one grain contains several cells.







HAGBs (> 15°) in black
LAGBs (2°-15°) in grey

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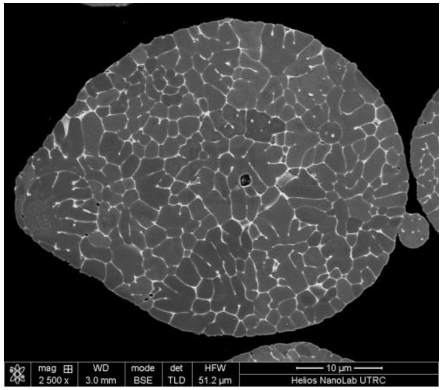
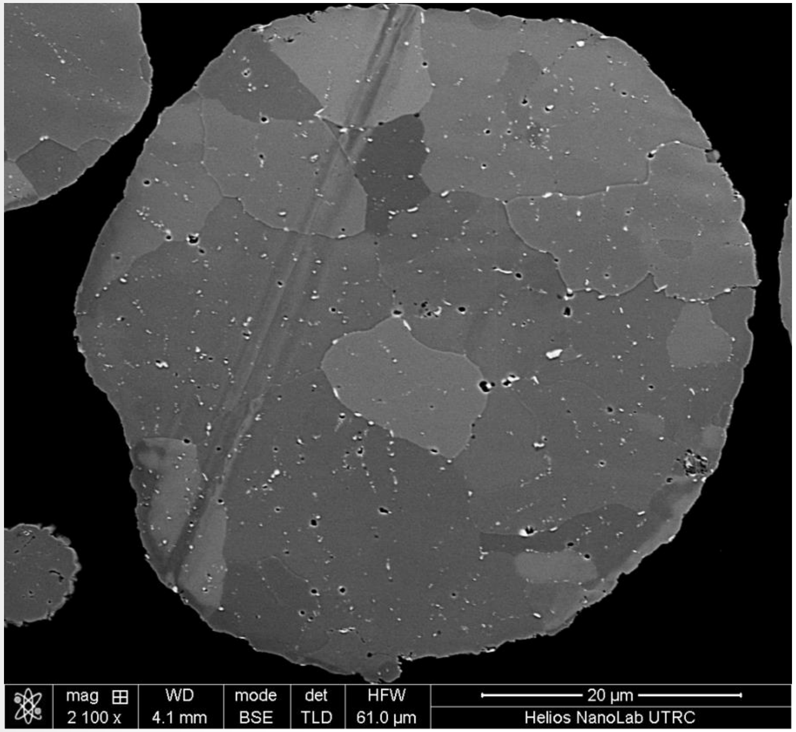
Explore Impact of Heat Treating Powder Particles

- Powder put through a heat treatment to homogenize → solutionize → quench
- Heat treatment eliminates the cellular dendritic structure and segregation

As-Received Powder Particle

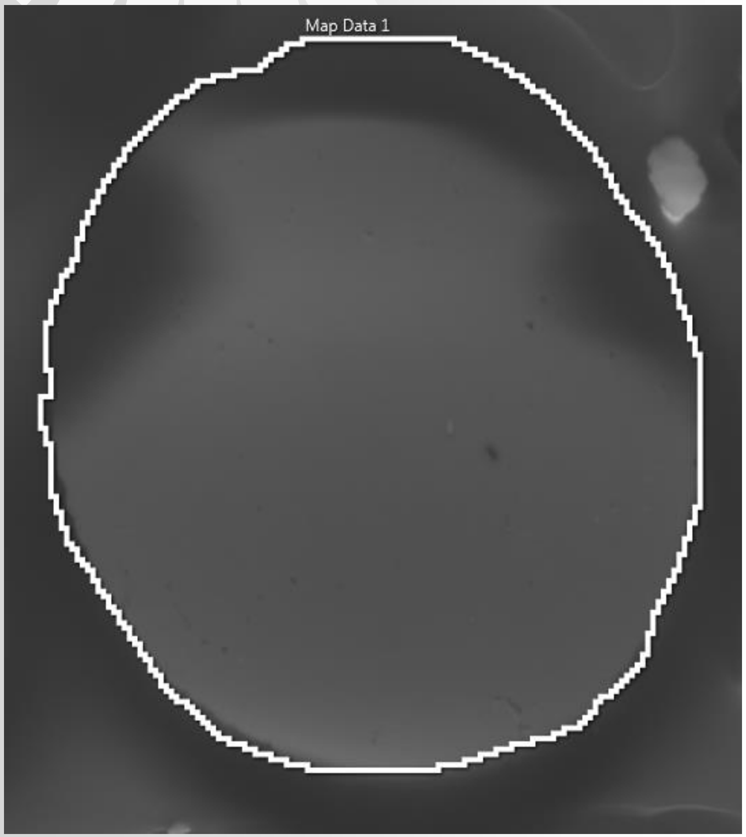


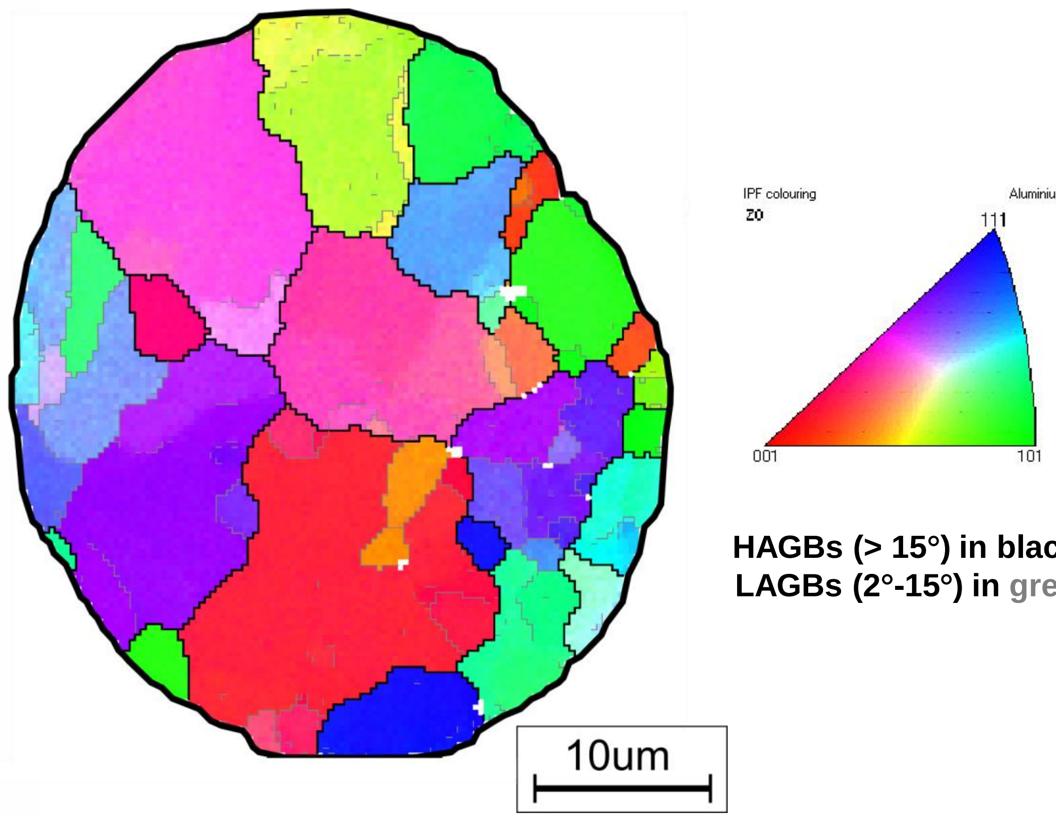
Heat Treated Powder Particle



EBSD of AA7075 Heat Treated Powder Particle

- Investigate a ~39μm diameter x-section of a powder particle
- Particle contains 34 grains, 1.4 to 15.3μm in size.
- Grain appear to have less LAGB content





HAGBs (> 15°) in black
LAGBs (2°-15°) in grey

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Heat Treatable Aluminum

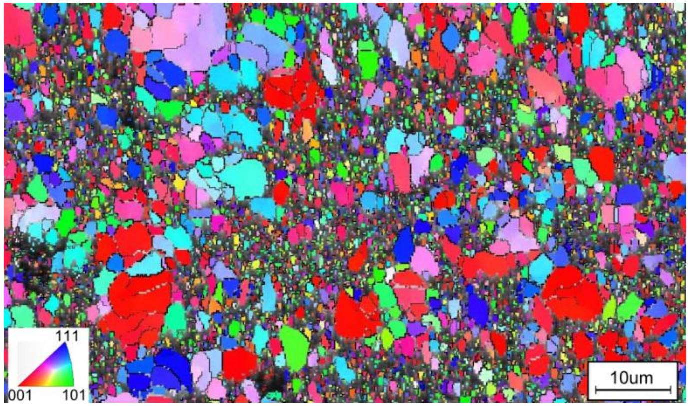
Summary

- Heat treatable alloys experience similar segregation to non-heat treatable alloys like 5056 but cannot be processing in the same way
- A process has been developed which can attain properties comparable to wrought versions of the materials
- Further development is needed to understand implications of final heat treatments on various hardware and properties of Cold Spray without final heat treatments

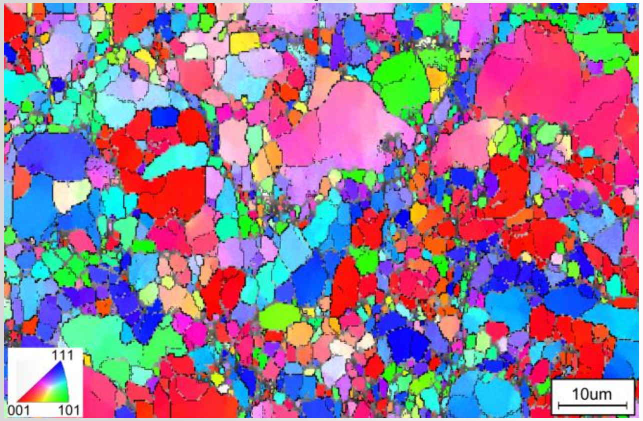
AA5083 Nano-materials development

- Goal: Evaluate potential of Cold Spray for billet consolidation followed by extrusion for wrought nanomaterial production
- Sample 1: Conventional (coarse grain) AA5083 powder consolidated via cold spray then machined into a slug with 0.825” dia. and 1” height
- Sample 2: 50-50 wt.% blend of conventional AA5083 & Nwerkz 5083 powder
- Sample 3: Nwerkz AA5083 powder was cold spray consolidated and then machined into a slug with a 0.825” dia. and 0.94” height for extrusion
- Prior to cold spray this -325 mesh powder was classified to remove fines less than ~20μm, and then de-gassed in the UTRC fluidized bed.

Sample 2



Sample 1



- Temperature: 425°C
- Ram displacement rate: 0.12 inch per sec
- Graphite lubrication

1

2

3

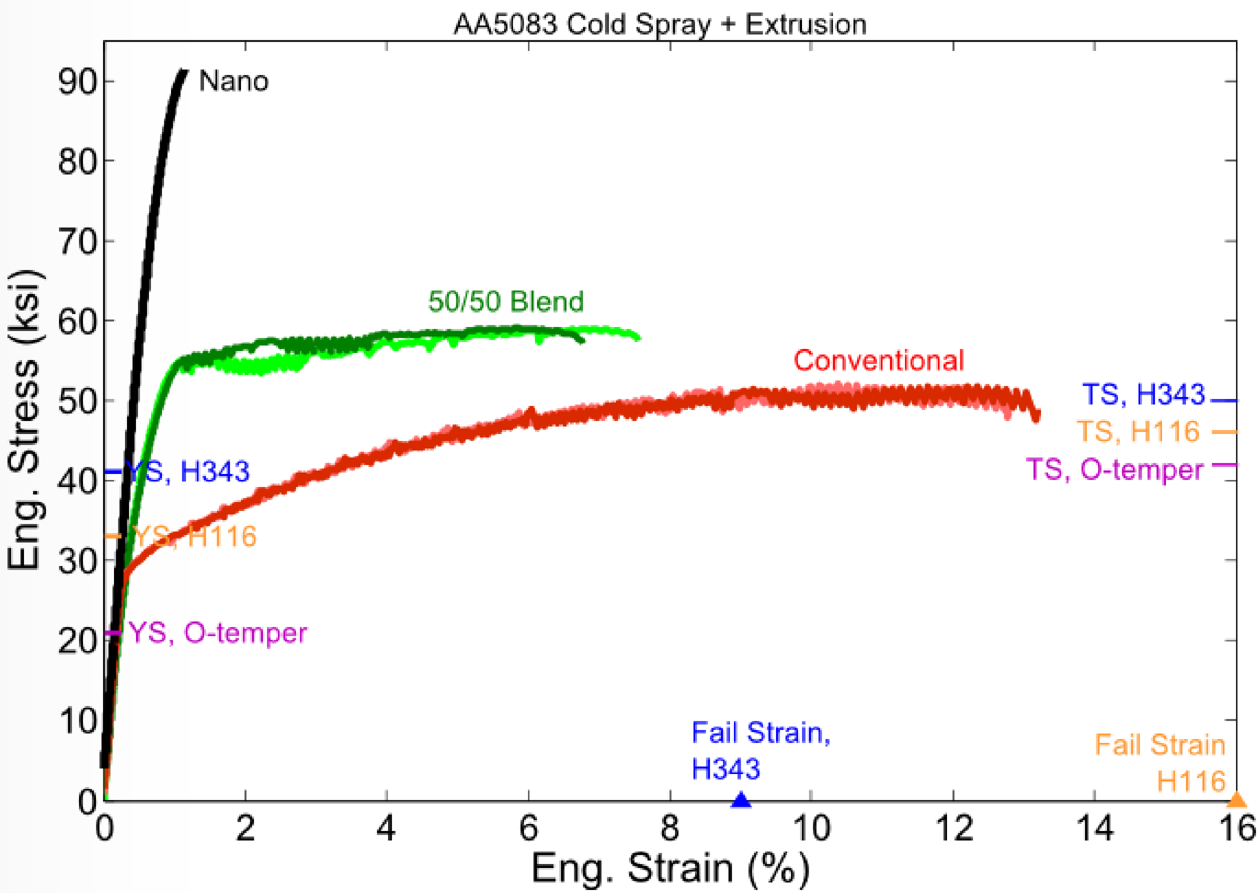
AA5083 Cold Spray + Extrusion Comparison

- Cold spray extrusions are plotted along with some nominal values for wrought AA5083 of different tempers

- The conventional extrusion has strength and ductility akin to H343 which is logical as the cold spray process is analogous to the work hardening step of this temper.

- The nano extrusion has the highest strength but this comes at the expense of elongation

- The blended extrusion has the balance of strength and ductility. Compared to H343, it has more strength with similar elongation.



Nano-Materials Development

- Mechanical properties of the three cold spray + extruded samples follow the logical trend:
  - Nano AA5083 is the strongest with the lowest ductility
  - Blended AA5083 has a strength-ductility balance
  - Conventional AA5083 is the weakest with highest elongation at fracture.

- Extrusion after cold spray consolidation erases the ‘splat’ microstructure

- The elevated temperature employed for extrusion does not
  - Fully eliminate work hardening → the conventional coupon had behavior comparable to the H343 temper of wrought AA5083
  - Does not substantially grow the nano-grains in the nano and blended coupons.