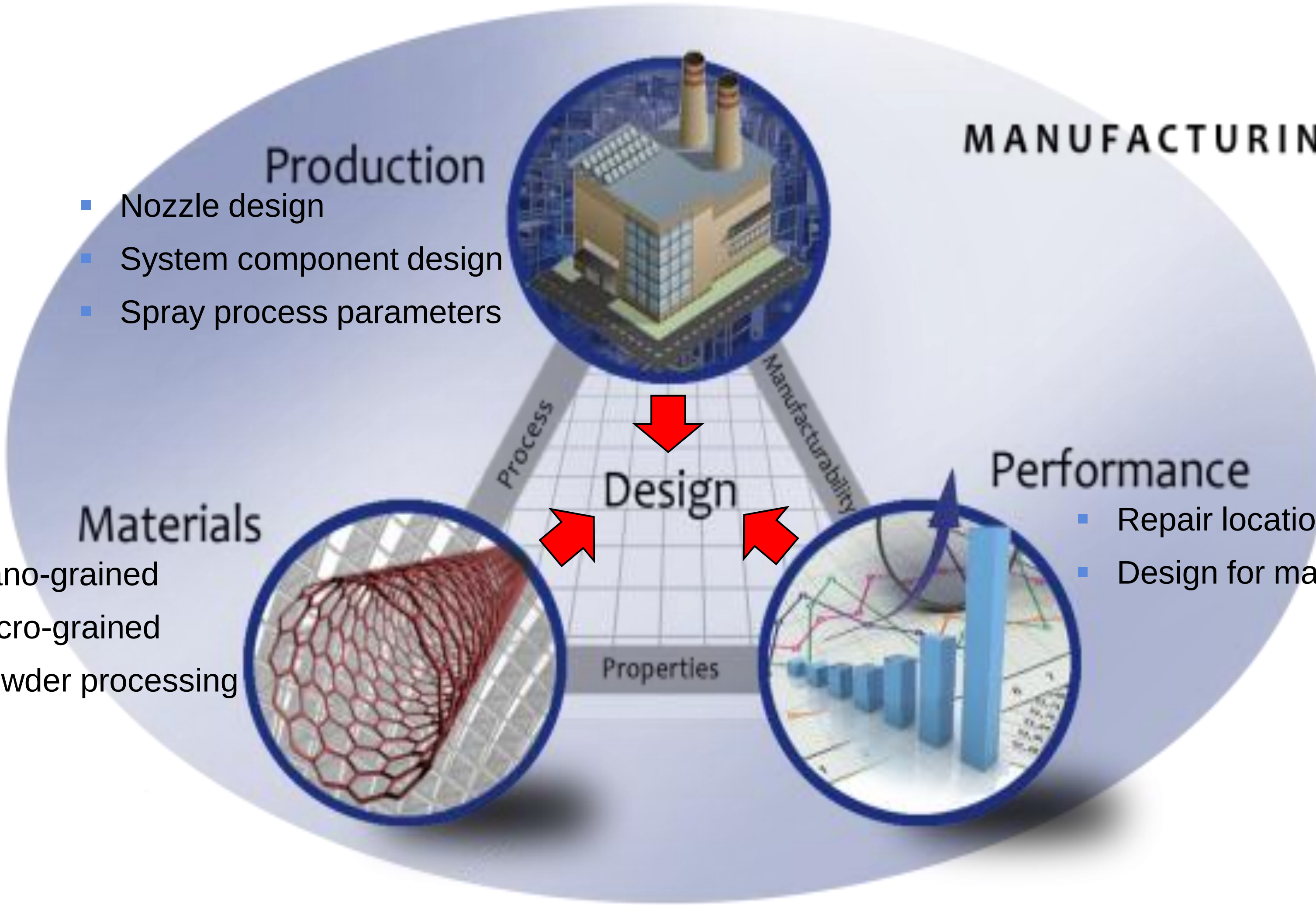
Cold Spray Materials and Process Development at UTRC

A. Nardi, X. Wang, J. Sharon, M. Mordasky, A. Espinal

United Technologies Research Center

Manufacturing Paradigm



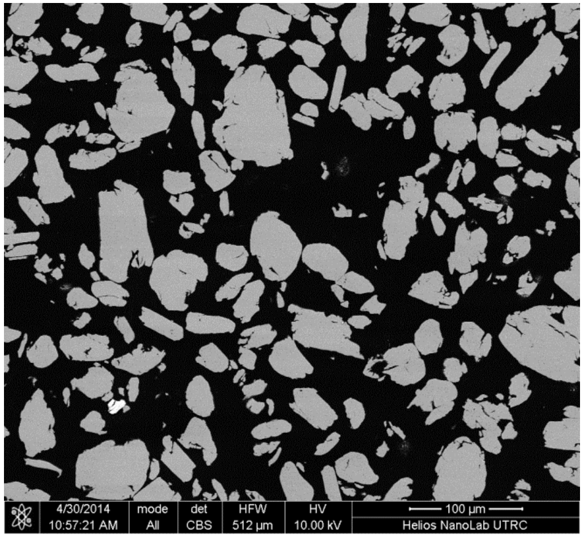
Production
- Nozzle design
- System component design
- Spray process parameters

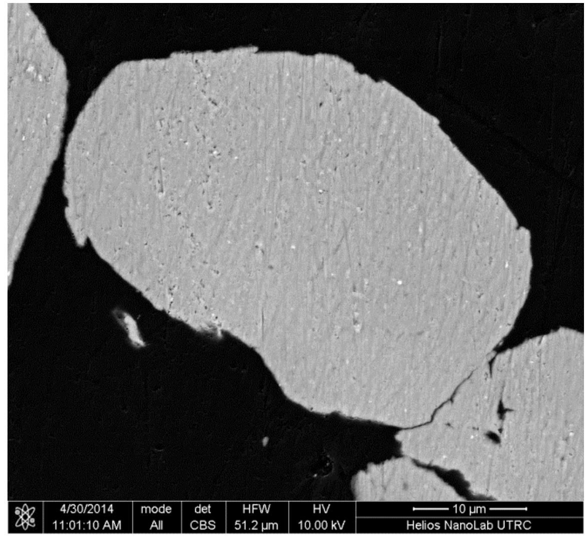
Materials
- Nano-grained
- Micro-grained
- Powder processing

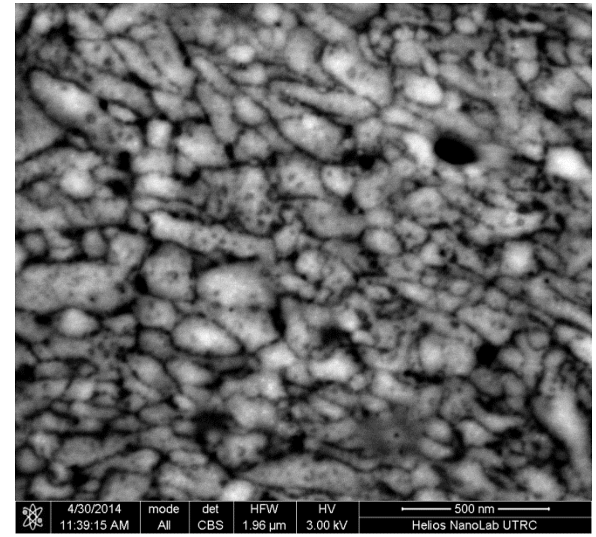
Performance
- Repair location design
- Design for manufacturing

Effect of Degassing on Nano-Materials

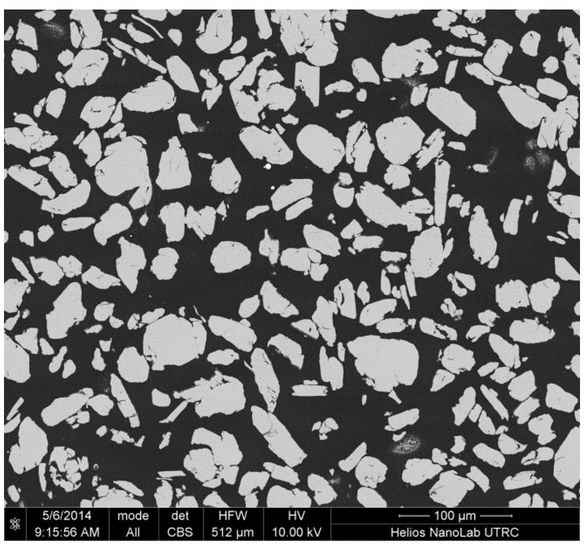
Nano 6061 Powder As-Received

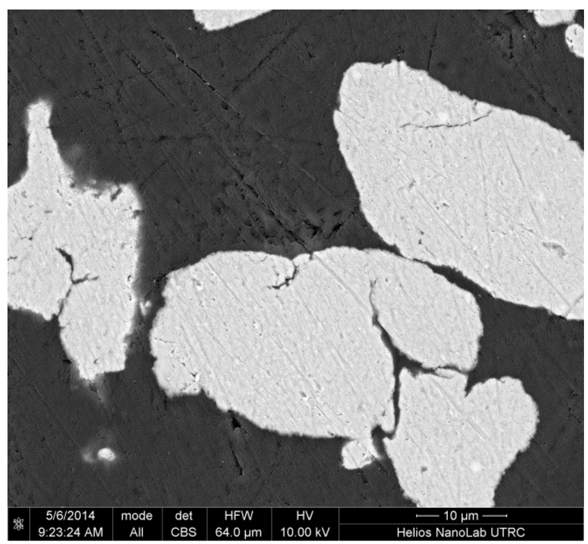


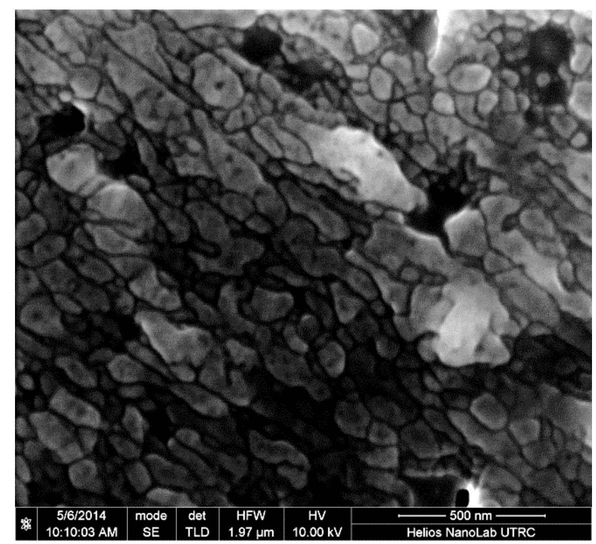




Nano 6061 powder after Degass



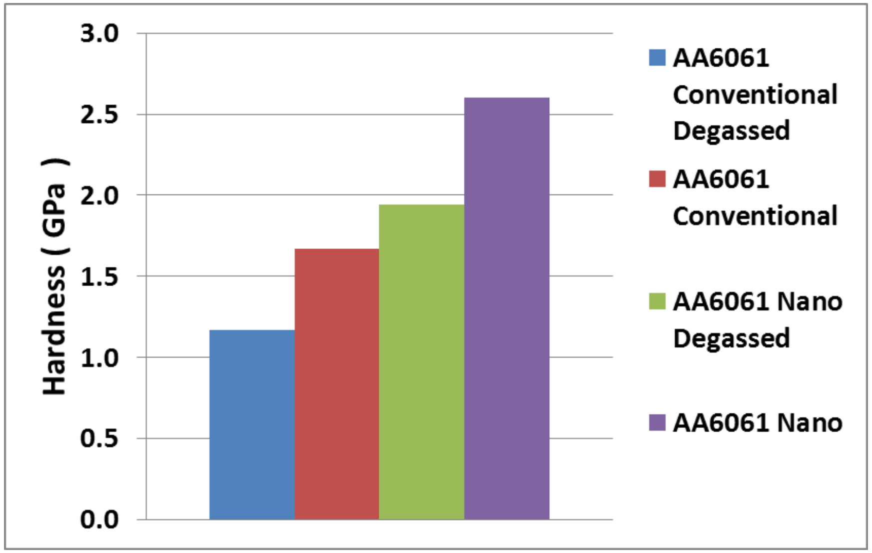




Effect of Degassing on Nano-Materials

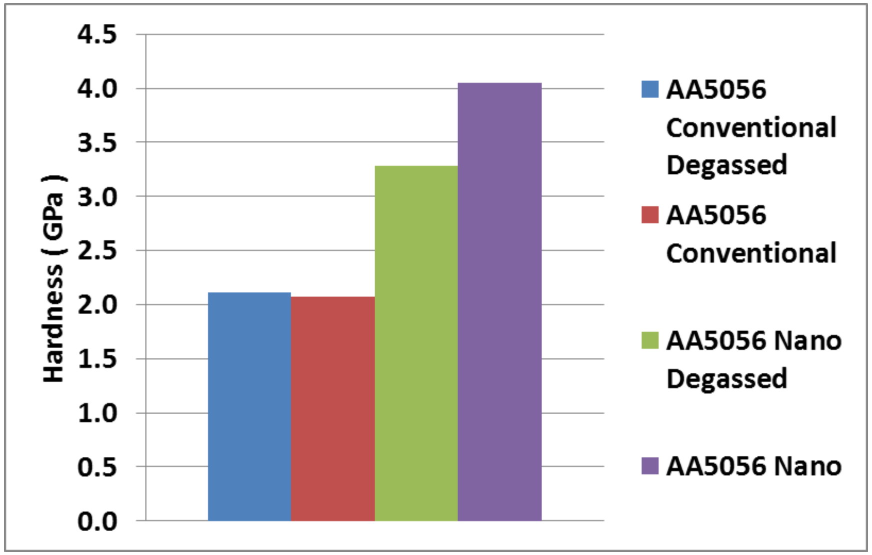
- Nano-indentation experiments
  - Berkovich tip
  - Displacement controlled 750nm deep indents

AA6061



Key strengthening mechanisms will be grain size and precipitates. Degassing impacts both grain size and aging of precipitates.

AA5056



Key strengthening mechanisms will be grain size and solid solution. Degassing primarily impacts grain size.

Material Strength Prediction

Developed strength model and initial validation

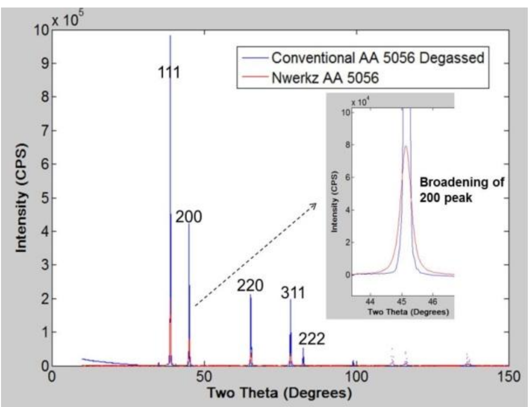
AA5056	Grain Size (nm)	Dislocation Density (cm^{-2})	Hardness, *H* (GPa)	Estimated Yield (MPa)
As-received	67	1.3×10^{11}	4.05	544
De-gassed	110	5.5×10^{10}	3.28	447

XRD data

19%

18%

Strength model



Grain Size Strengthening					
Grain size (um)	0.11		k (MPa - um$^{0.5}$)	Grain sizes covered	Reference
			113.74	35um to 220nm	Mukai et al., Acta Metall., 1998
Hall-Petch slope	113.74				
Increase in Yield (MPa)	342.94				

Increase in yield due to grain size reduction

$$\Delta\sigma = kd^{-0.5}$$

k = strengthening slope { MPa - m$^{0.5}$ }

d = grain size in microns

Solute Strengthening	
Concentration, C (at.%)	5.4
H	12.10
a	1.14
Uniaxial Yield Increase (MPa)	82.74

Increase in yield due to solutes

$$\Delta\sigma = HC^{a}$$

H = constant (MPa/at%^{a})

C = concentration of solute (at.%)

a = constant

Reference: Ryen et al., Metall And Mat. Trans A, 37A, 2006

Dislocations Density Strengthening	
Dislocation Density, r	5.51E+10
FCC factor, α	0.3
Matrix Shear Modulus, G (Pa)	2.50E+10
Matrix burgers vector, b (m)	2.86378E-10
Shear Strength Increase (Pa)	5.04E+05
Uniaxial Yield Increase (MPa)	1.54
Yield, 99% Al, annealed (MPa)	20
Estimated Al-Alloy Yield (MPa)	447.22

Increase in yield due to dislocation density:

$$\Delta\sigma = 3.06 * Gb\alpha\sqrt{\rho}$$

Model predicts the reduction in mechanical properties after degassing based on grain size and dislocation density

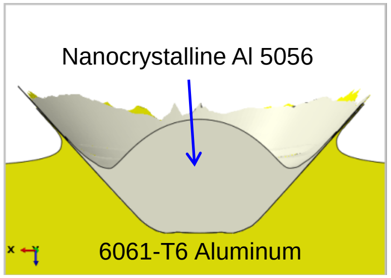
- Grain size effects
- Solute strengthening
- Dislocation density

Nano-Materials Development

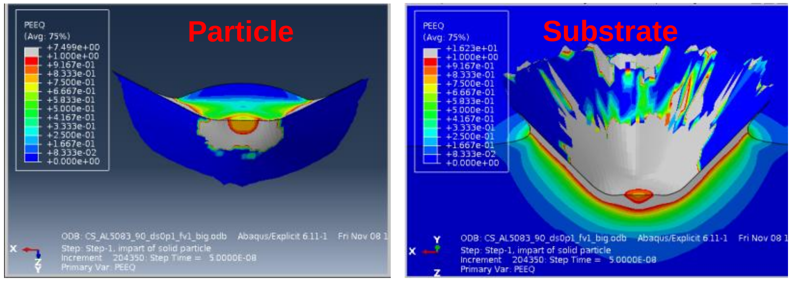
Summary

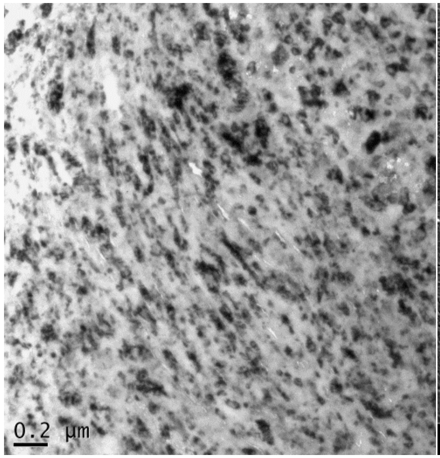
- Nano-crystallinity can be maintained through degasing and Cold Spray
- The Cold Spray process imparts substantial plasticity to the powder surface creating high inter-particle bonds strength
- The Milled powders evaluated contain internal defects which are not as significantly affected by compaction process
- Defects will drive low ductility and low strength even with good spray process parameters

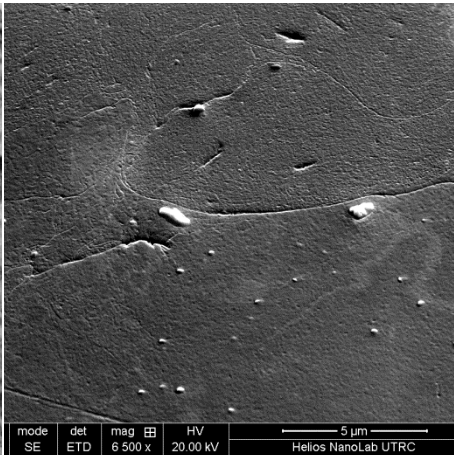
Deformed shapes



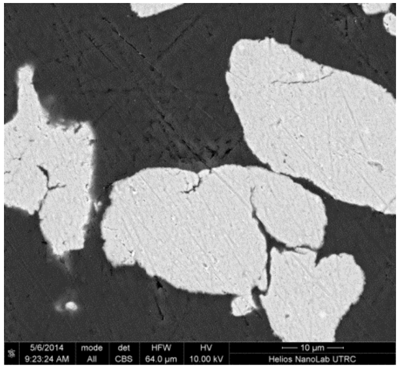
Plastic contours







Actual Powder Shape



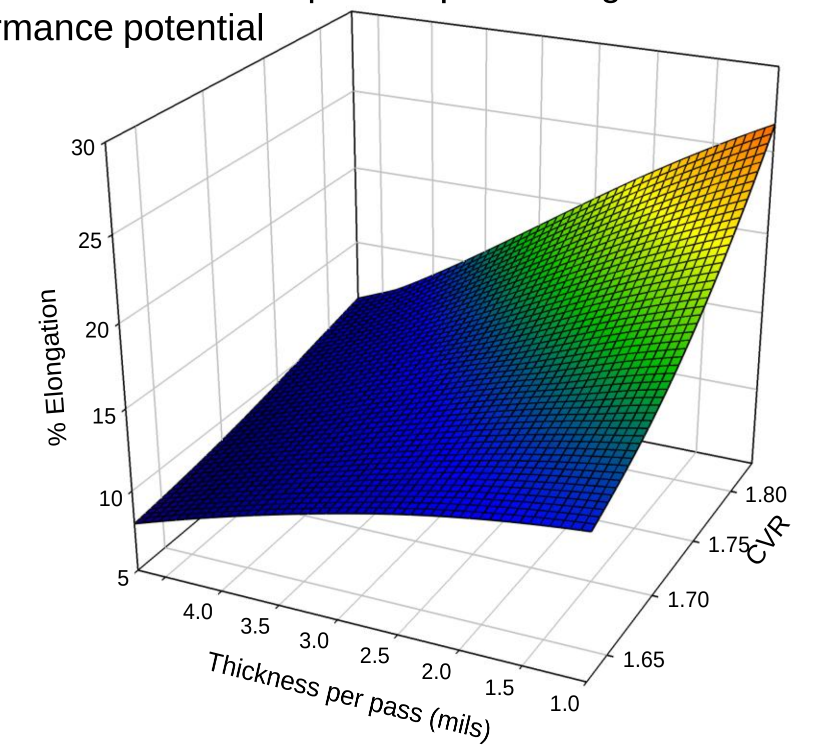
Cold Spray Process Development

Developed cold spray process parameters for several high strength aluminum alloys

- Process parameters developed for sustained cold spray operation
- Powder processing including over-aging for heat treatable powders and full annealing for non-heat treatable powders
- Data generated to date provides insight into the effect of processing parameters on ductility
- Alternate processes developed to achieve extreme properties including ultimate strength and elongation
    - Processes are currently not sustainable due to nozzle materials and powder processing needs, but small batch processing confirms performance potential

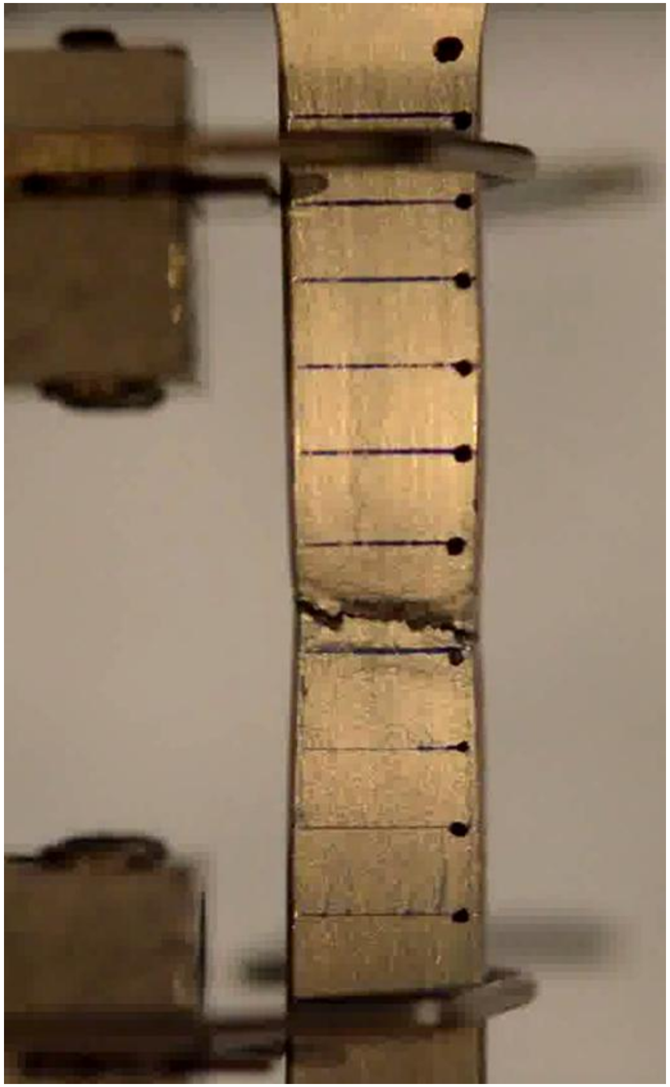
	UTS	YS	%El
6061	45	39	4.5
7075	59	43	5.5
2024	55	41	5
5056	58	46	12

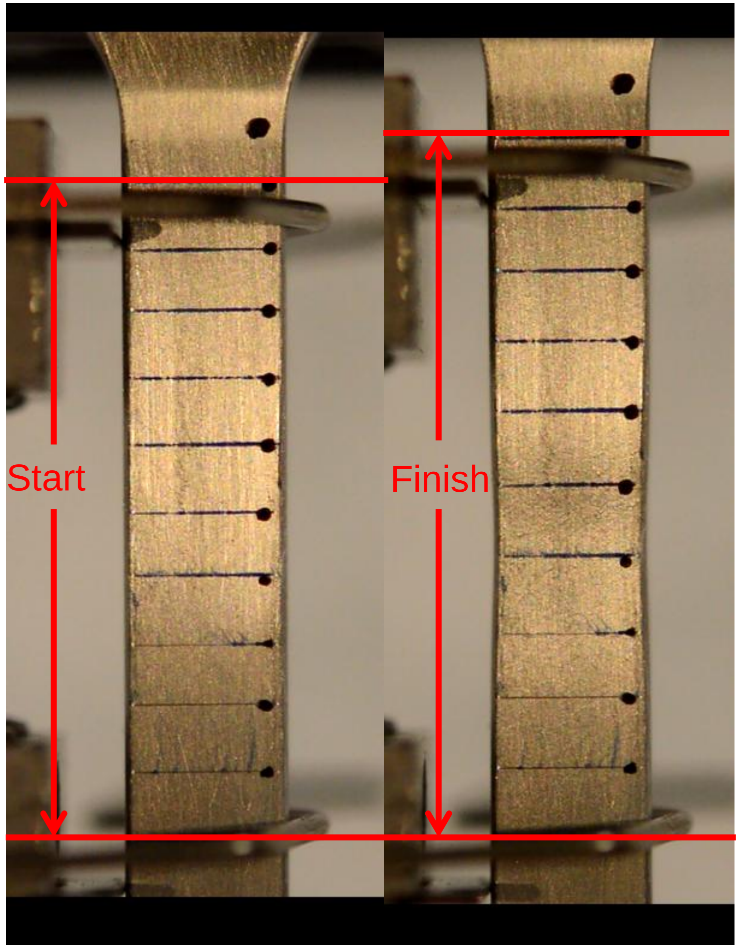
	UTS	YS	%El
7075-HU	69	58	5.3
5056-HE	58	45	22



5056 Aluminum Development

Tensile Testing of 5056 Dogbones



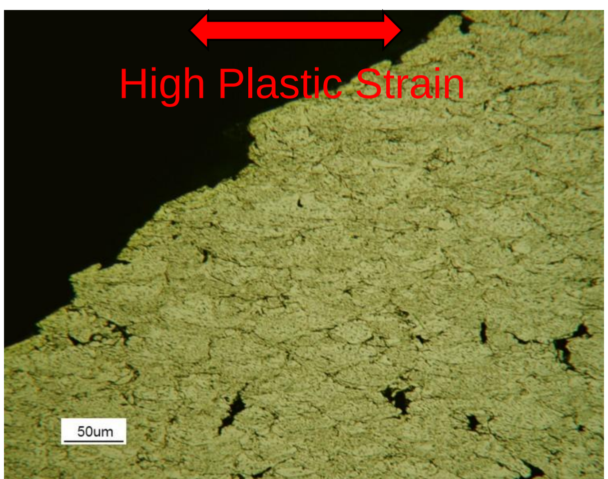


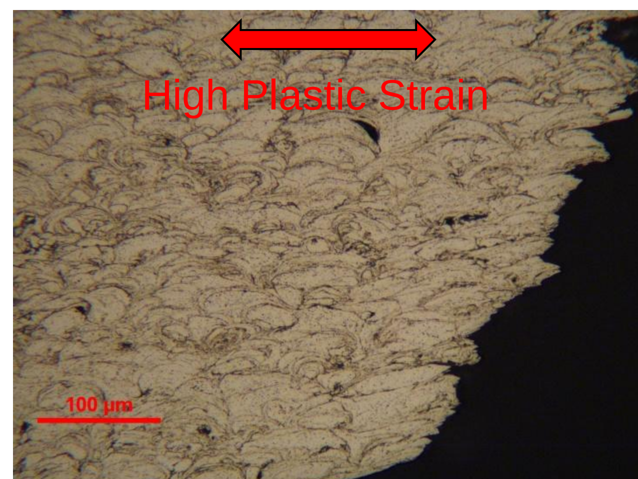
Cold Spray Process Development

Micro-structural evolution of inter-particle defects during static testing

CS6061, UTS = 45ksi, % El = 3.5%

CS5056, UTS = 58ksi, % El = 22%



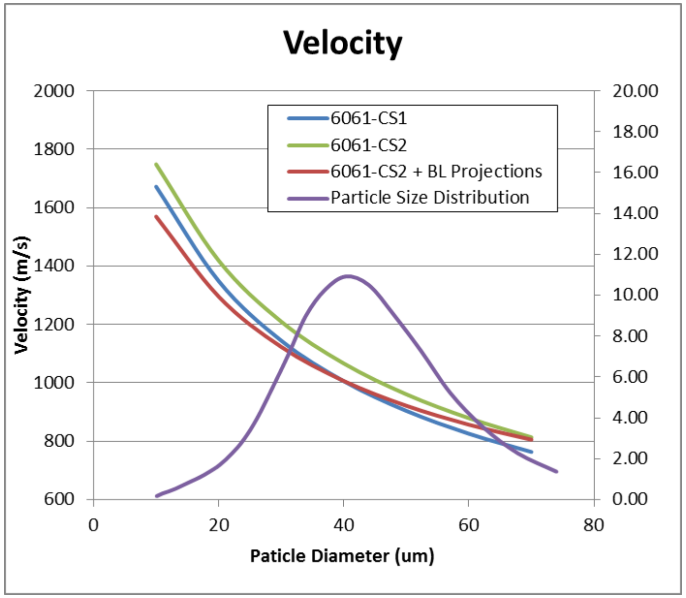


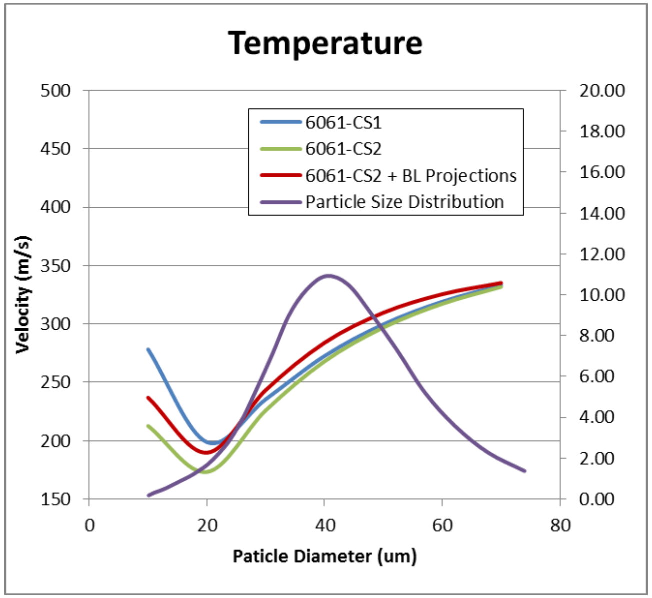
Cold Spray Process Development

Developing Process Parameter Translation Capability

- Cold Spray System 1 (CS1) - CGT 4000 spray system
  - Nozzle with 0.102 in throat
  - ~4 inches pre-chamber
- Cold Spray System 2 (CS-2) - Generic high pressure Cold Spray system
  - Nozzle with 0.068 inch throat
  - ~3.5 inches pre-chamber

	UTS	YS	%El
6061 - CS1	45	39	4.5
6061 - CS2	40	34	7.4





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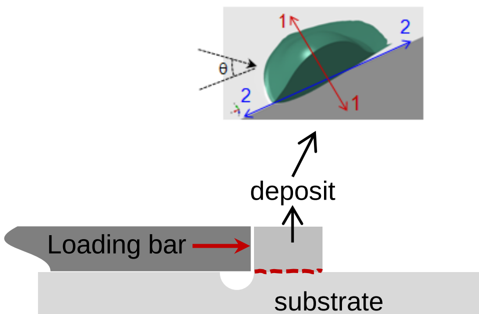
Effect of Deposition Angle

Lower angles provide improved bonding in some cases

Experimental Results

Lug shear test



Effect of spray angles on bond Strength

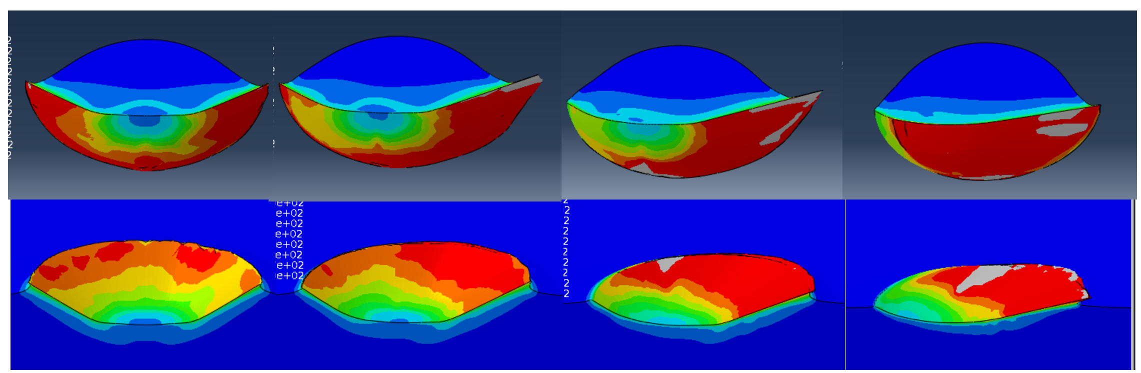
Spray Angle (degree)	% of 90° Deposition Efficiency	Bond Strength (1-1) (ksi)	Hardness 30T
90	100	5	57.7
75	85	8.5	57.8
60	65	12	57.2
45	41	20	55.5

- Bond strength↑
- Deposition efficiency ↓
- Hardness, strength, and ductility ↓

Modeling Results

- Increased influence of frictional dissipation energy
  - Temperature rise at the interface
- More temperature uniformity along the interface
  - Increasing the bond area
- Lower DE increases probability that high bond strength particles remain

Modeling Results for 6061-T6 Impacting on 6061 T6 Showing Temperature at the Particle-Substrate Interface



90° impact | 75° impact | 60° impact | 45° impact

Acknowledgments

We would like to thank the Army Research Labs and other collaborating institutions for supporting this research

Portions of this Research were sponsored by the Army Research Laboratories and was accomplished under Cooperative Agreement Number W911NF-14-2-0011. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the Army Research Laboratory or the U.S. Government. The U.S. Government is authorized to reproduce and distribute reprints for government purposes notwithstanding any copyright notation herein.