A Comparison of Low and High Pressure Cold Spray Systems

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United Technologies Research Center

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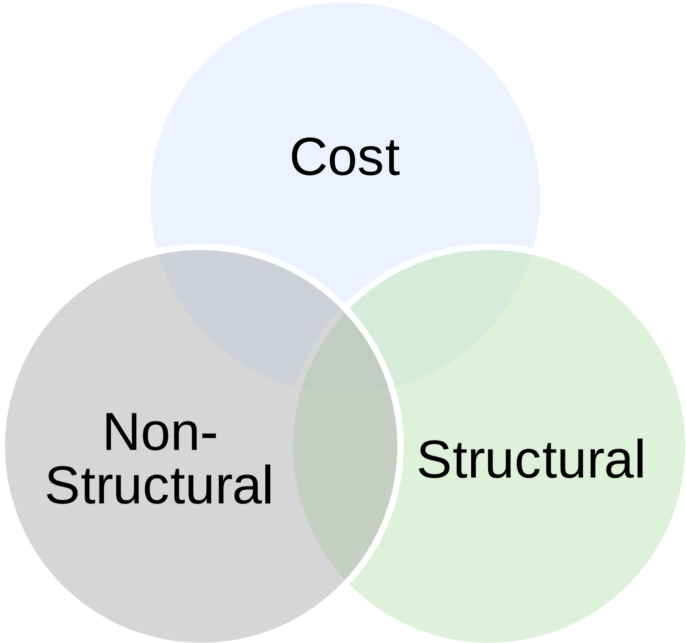
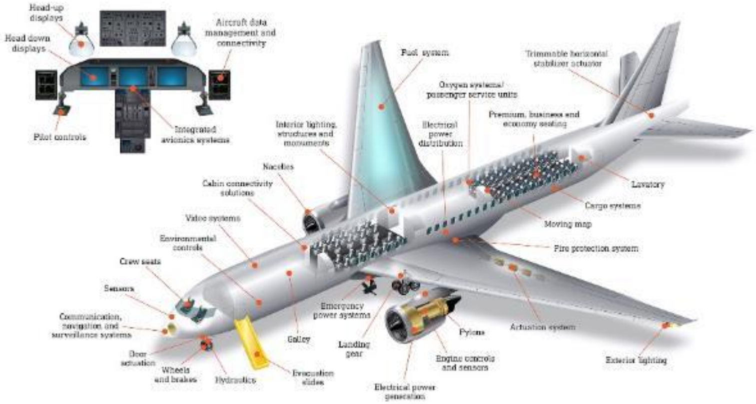
Why Does the Cold Spray System Matter?

- Application Requirements
  - Non-Structural: Dimensional restoration
  - Structural: Deposit needs to carry load
- Cost
  - Capital Investment
  - Cost per Spray ($ / Volume)
- Misc. Cold Spray System Requirements
  - Size, weight, etc.



Current UTC Business Needs

- United Technologies Corporation
  - Pratt & Whitney
    - Aircraft Engines
  - Collins Aerospace
    - Aerostructures, Avionics, Interiors, Mechanical Systems, Mission Systems, and Power and controls



High Value Structural Repairs
Materials with High Strength and High Ductility

Cold Spray for Non-Structural & Structural Repair

Spray Process Conditions

Low Nitrogen → High Nitrogen → Low Helium → High Helium

Non-Structural	Structural

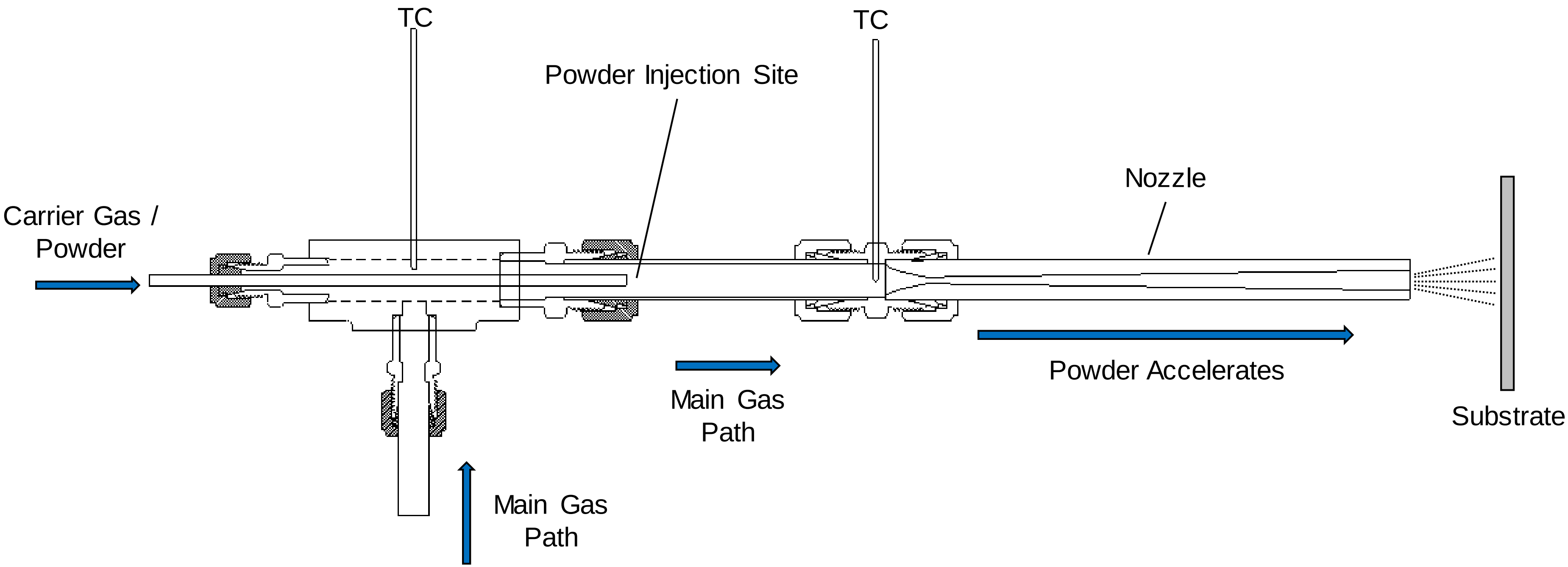
Non-Structural

- Typically for geometry restoration
  - Moderate strength
  - Low ductility (<1%)
- Lower spray process conditions
  - Nitrogen
- Feedstock/Powder
  - Pure metals or alloys
  - Blends with hard phase

Structural

- Partial load carrying capability
  - High strength
  - Moderate to high ductility (>5%)
- High spray process conditions
  - Helium, high pressure (>35 Bar)
- Feedstock/Powder
  - Pure metals or alloys

Cold Spray Process Conditions



- Pressurize and heat gas (Nitrogen or Helium)
- Choke the flow and expand gas (Converging – Diverging Nozzle)
- Inject powder upstream or downstream
- Accelerate the powder using aerodynamic drag

Process Conditions

Particle Velocity Calculator

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 | 0.068 x 0.2 x 6 | 0.078 x 0.25 x 6 | 0.078 x 0.11 x

Nozzle Dimensions

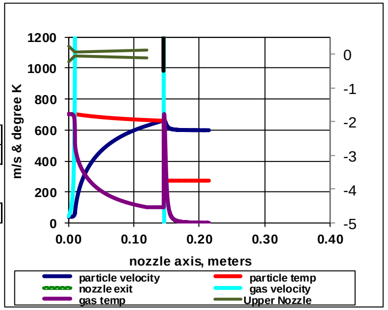
		Mach Number at nozzle inlet		
Throat Diameter (in)	0.078	0.028	**Vp, m/s (at impact)**	**662**
Exit Diameter (in)	0.196	**Expanding Length (in)**	**Tp, C (at impact)**	**387**
Entrance Diameter (in)	**0.350**	4.327		
Converging Length (in)	0.393	**Expanding Angle (2Θ) Degrees**	**Ve, m/s (at nozzle exit)**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

Powder Particle Distribution

Size	%chan	
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

Impact Velocity & Temperature

Particle Diameter (um)	**Impact Temp (°c)**	**Impact Velocity (m/s)**
104.6	**387**	**662**
88	**376**	**726**
73.99	**362**	**794**
62.22	**346**	**867**
52.32	**326**	**944**
44	**304**	**1025**
37	**280**	**1109**
31.11	**254**	**1195**
26.16	**230**	**1283**
22	**210**	**1371**
18.5	**197**	**1459**
15.55	**196**	**1543**
13.08	**210**	**1623**
11	**239**	**1696**

Impact velocity and temperature are controlled by process conditions, nozzle geometry, powder material properties and particle size distribution

Critical Velocity Ratio

Critical Velocity

$$V_{crit} = \sqrt{\frac{4F_1\sigma_{uts}\left(1-\frac{T_i}{T_{MP}}\right)}{\rho} + F_2 C_p (T_{MP} - T_i)}$$

T. Schmidt, F. Gartner, H. Assadi, and H. Kreye, Development of a Generalized Parameter Window for Cold Spray Deposition, Acta Mater., 51 (2003) 4379-4394.

σ_{UTS}	Ultimate Tensile Strength
ρ	Density
T_i	Impact Temperature
T_{MP}	Melting Point
C_P	Specific Heat
F_1, F_2	Empirical Factors

Critical Velocity Ratio

$$\text{CVR} = \frac{V_{impact}}{V_{critical}}$$

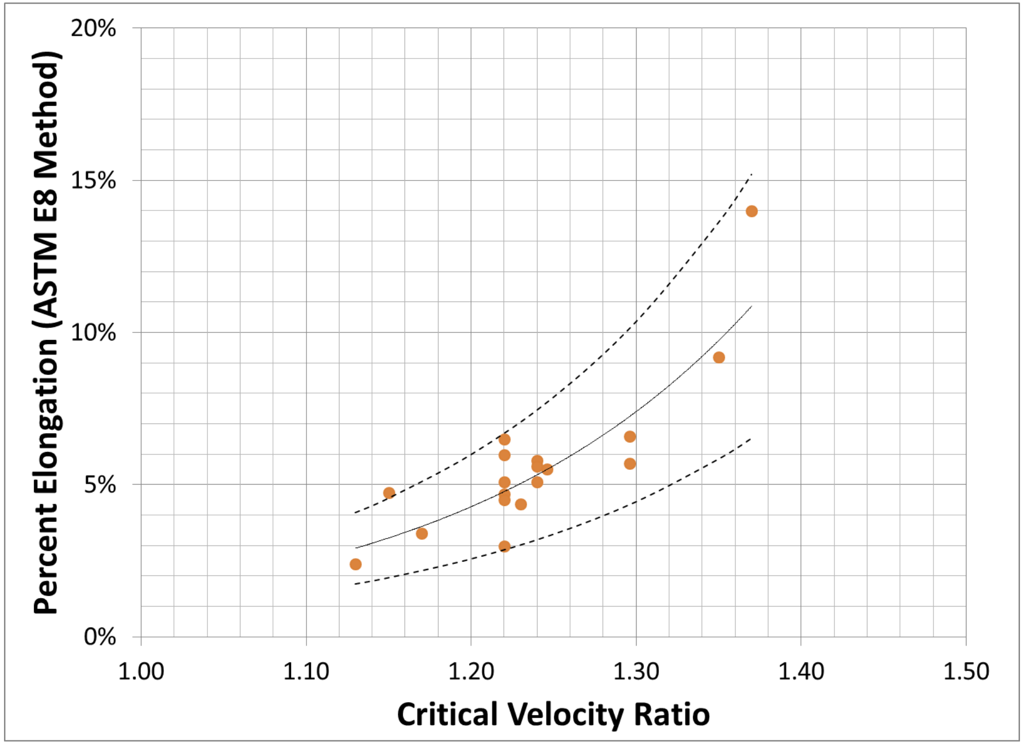
$$\text{CVR} > 1.0$$

- CVR is equivalent to the term, η which is used in numerous German Cold Spray publications
- CVR > 1.0 can be correlated to improved ductility in Cold Spray aluminum alloys

Critical Velocity Ratio & Mechanical Properties

- Compiled Aluminum Alloy Data
  - 2xxx, 5xxx, 6xxx, 7xxx series
- Powder Feedstock
  - Preprocessed (HT, Classified)
- Critical Velocity Ratio (CVR)
  - = 1.0 results in bonding
  - > 1.0 improved ductility
- Structural Repair
  - Higher CVRs, >1.21

Compiled Data from Cold Sprayed Aluminum Alloys



Case Study: Cold Spray for Structural Repair

- Compare three Cold Spray OEM systems
  - Centerline
  - Inovati
  - VRC Metal Systems

- Assumptions
  - Spraying a 6061 aluminum alloy for structural repair
    - Material has been preprocessed and classified
  - Process gas is Helium
  - Nozzle geometry is defined by each OEM
  - Process temperature is limited by nozzle material, PBI at 450°C
  - Process pressure is limited by OEM system capability

- Evaluate Critical Velocity Ratio capability and cost of each system

Cold Spray OEM – Centerline SST

Centerline – SST

- EPX System
  - Automatic Spray Gun (50 lbs)
  - 100 – 500 psi (7 – 35 Bar)
  - RT – 550°C
  - Helium, Nitrogen, or Air
  - Dimensions: 27” x 22” x 44”

- PX System
  - Manual (4.5 lbs) or Automatic (5 lbs) Spray Guns
  - 100 – 250 psi (7 – 17.2 Bar)
  - RT – 550°C
  - Helium, Nitrogen, or Air
  - Dimensions: 23” x 20” x 44”

EPX Robotic Spray Gun

PX Robotic Spray Gun

Manual Spray Gun

FEEDSTOCK

Centerline
SST-A5012: AA6061 Powder
$127 per pound

Cold Spray OEM – Inovati

Inovati

- KM Coating Development System – HDR
  - KM Raster Gun (5 lbs)
  - 50 – 130 psig (3.4 – 9 Bar)
  - RT – 1000°C
  - Helium, Nitrogen, or He/N2 mixture
- Spray Enclosure
  - Dimensions: 62” x 62” x 76”

The Raster Gun

Powder Fluidizing Units

Spray Enclosure

FEEDSTOCK

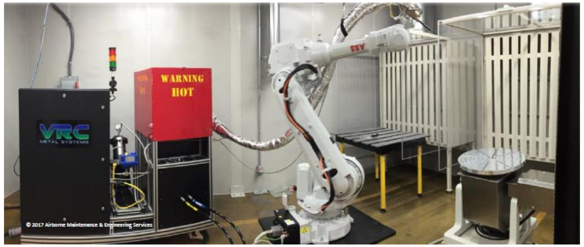
Inovati
6061 Powder
$126 per pound

Cold Spray OEM – VRC Metal Systems

VRC Metal Systems

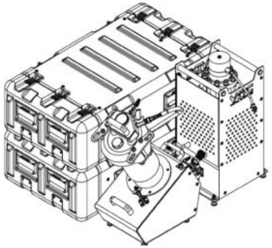
- Gen III
  - Nozzle Applicator (4.4 lbs)
  - 80 – 1000 psig (5.5 – 69 Bar)
  - RT – 800°C @ heater
  - Helium or Nitrogen
  - Dimensions: 72” x 34” x 72”
- Raptor
  - Nozzle Applicator (4.4 lbs)
  - 80 – 1000 psig (5.5 – 69 Bar)
  - RT – 800°C @ heater
  - Helium or Nitrogen
  - Dimensions: 68” x 32” x 65”
- Dragon Fly
  - Nozzle Applicator (4.4 lbs)
  - 80 – 1000 psig (5.5 – 69 Bar)
  - RT – 800°C @ heater
  - Helium or Nitrogen
  - Dimensions: 12” x 22” x 40” (2x)
    28” x 16” x 13” (1x)

Gen III



Raptor

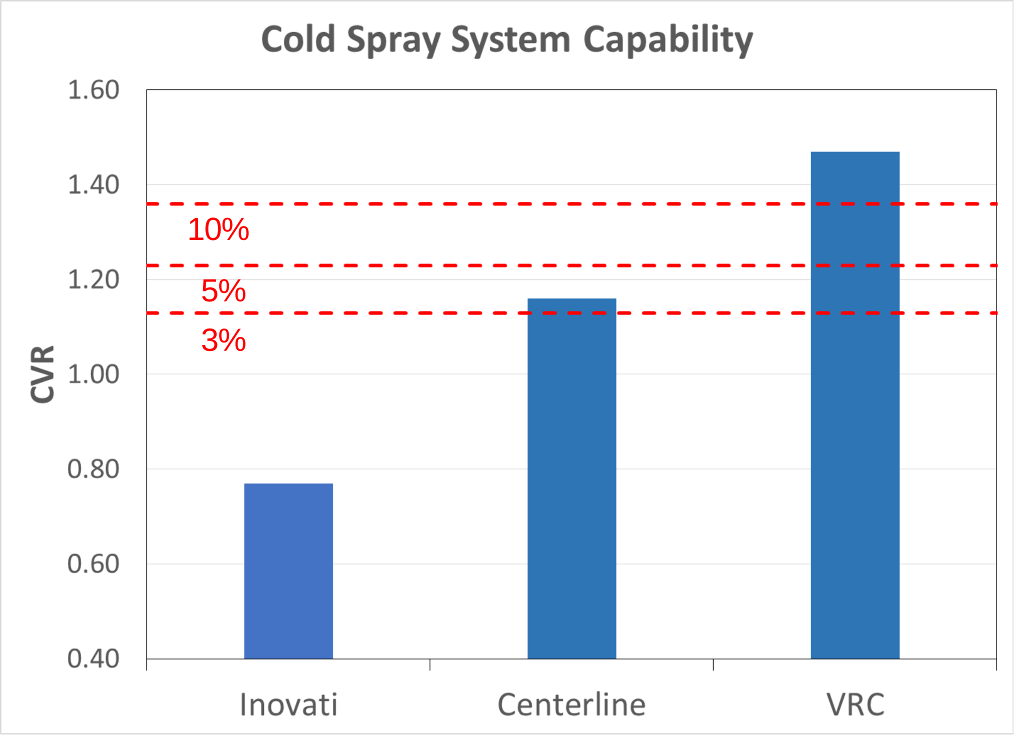
Dragon Fly



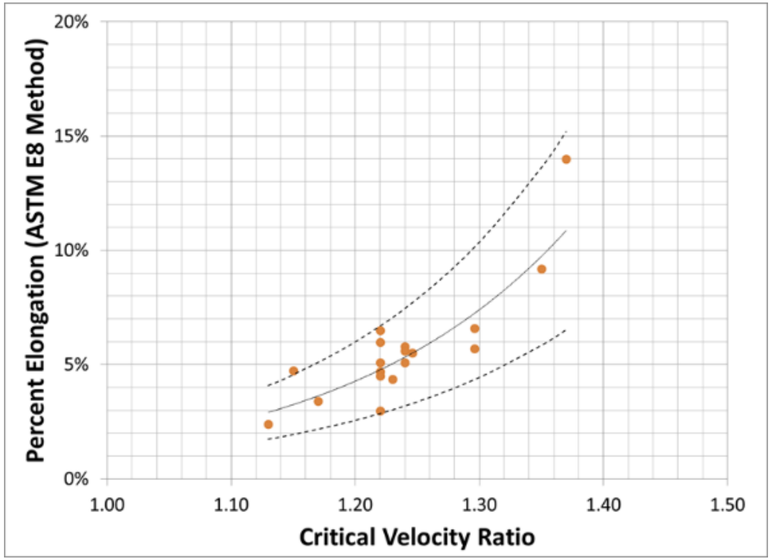
FEEDSTOCK

Solvus Global – Powders on Demand
SAAM-AL6061-G1H1
$125 per pound

Cold Spray System vs. CVR, Helium



Cold Sprayed Aluminum Alloys

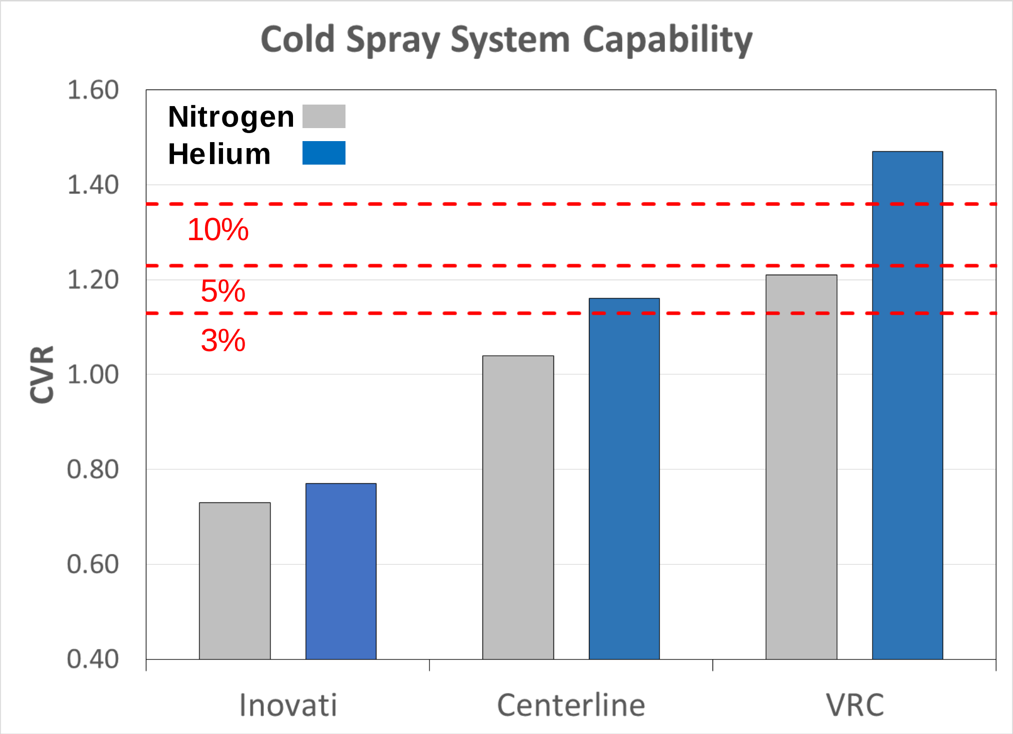


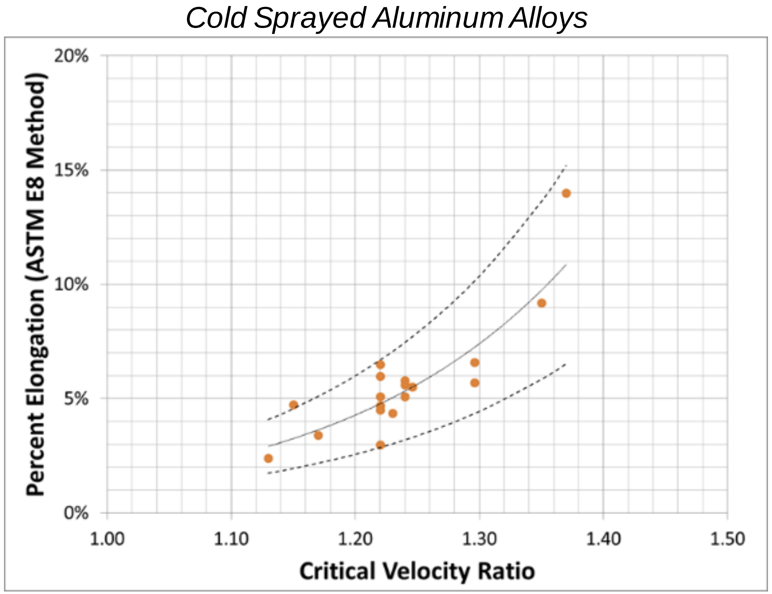
CVR of 1.13, ~3% elongation

CVR of 1.23, ~5% elongation

CVR of 1.36, ~10% elongation

Cold Spray System vs. CVR, Helium vs. Nitrogen



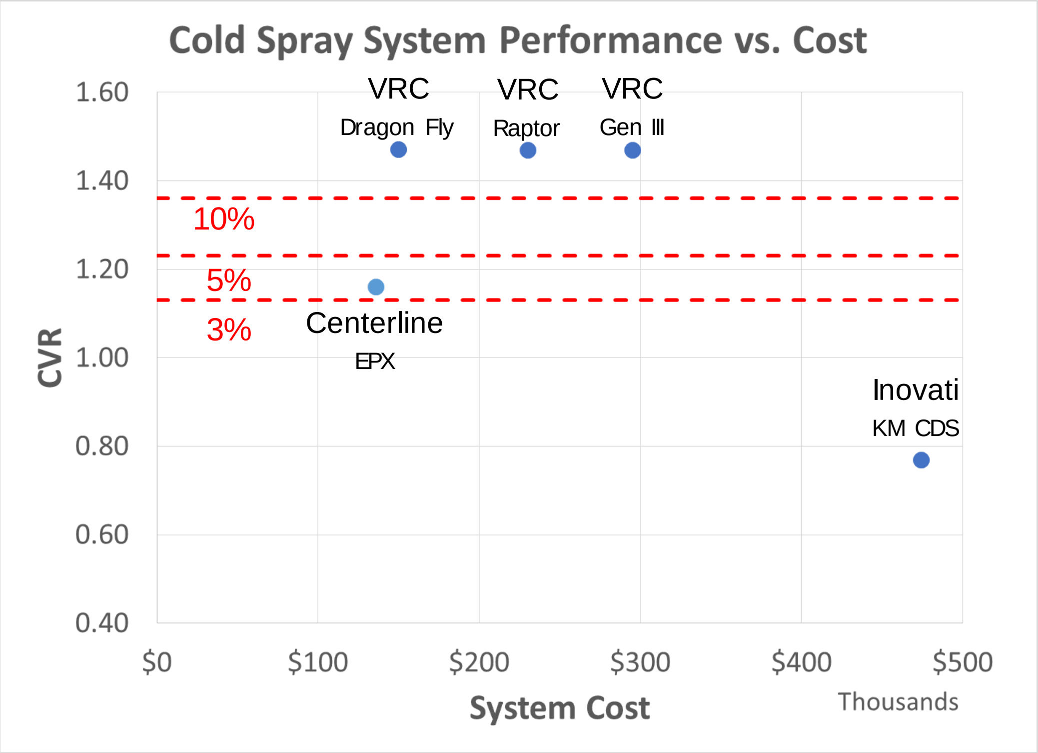


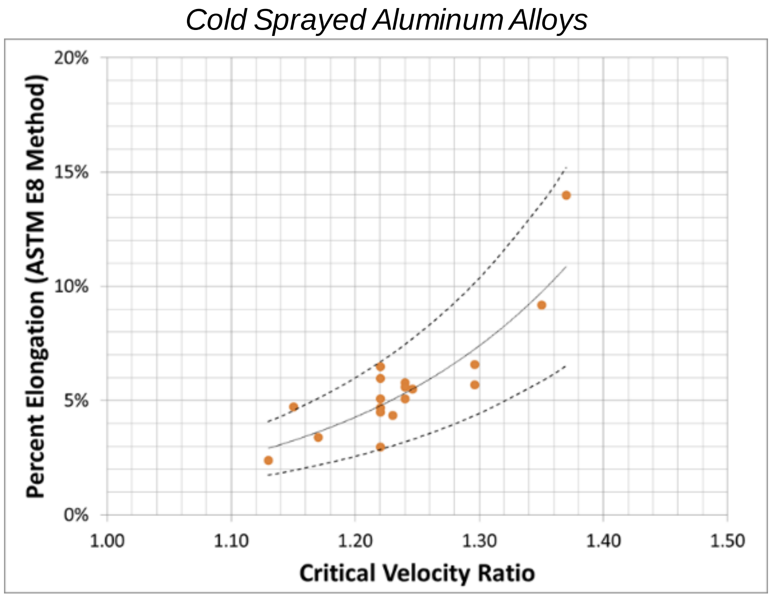
CVR of 1.13, ~3% elongation

CVR of 1.23, ~5% elongation

CVR of 1.36, ~10% elongation

Cold Spray System CVR vs. Cost





CVR of 1.13, ~3% elongation

CVR of 1.23, ~5% elongation

CVR of 1.36, ~10% elongation

Summary

- There is a need for structural repair of high value aerospace parts
- Spray process conditions and powder feedstock are key to structural repair
- High pressure cold spray systems are necessary to achieve the CVRs (critical velocity ratios) required for structural repair
- Cold spray system capability and capital cost should be considered before purchasing a system

Thank You