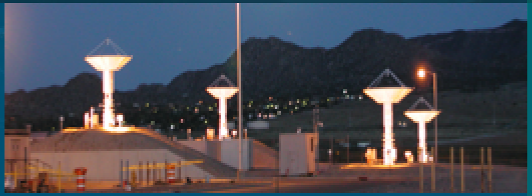
SAND2020-13560PE

Overview of Kinetic Spray Processing of Metallic and Ceramic Films



PRESENTED BY

Jacob Mahaffey (1834)

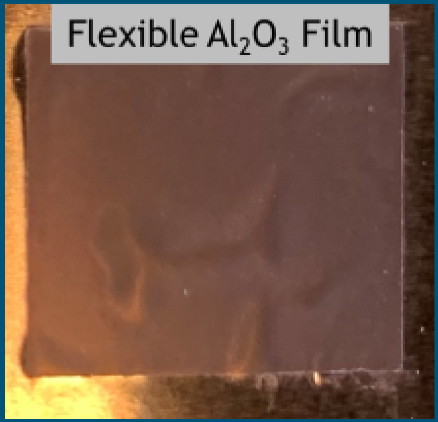
Materials Science R&D

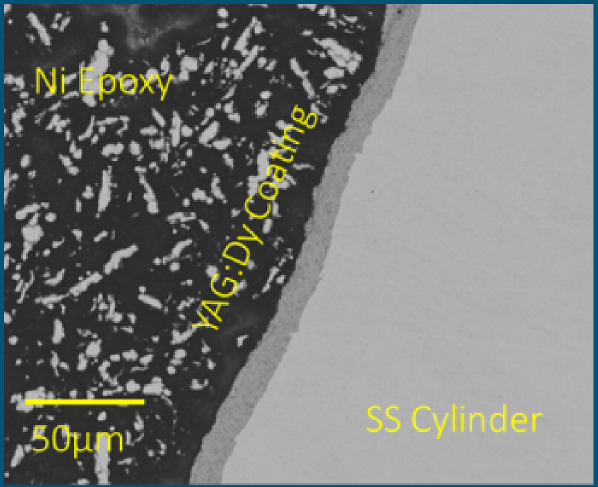
Thermal Spray Technologies

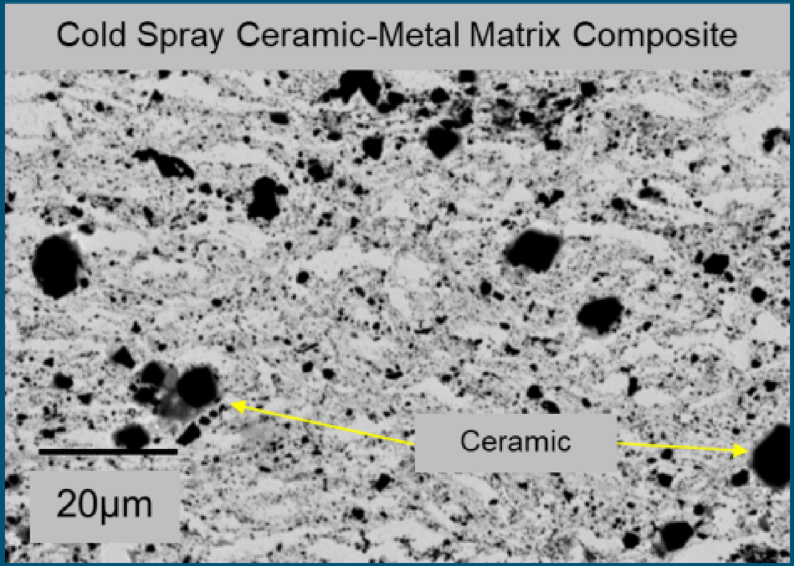
Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Outline of Talk

1. Overview of Thermal Spray processing
2. Gas and particle dynamics of kinetic spray
3. Cold Spray metal particle deformation mechanism
4. Cold Spray example
5. Aerosol Deposition ceramic particle deformation mechanism
6. Aerosol Deposition example

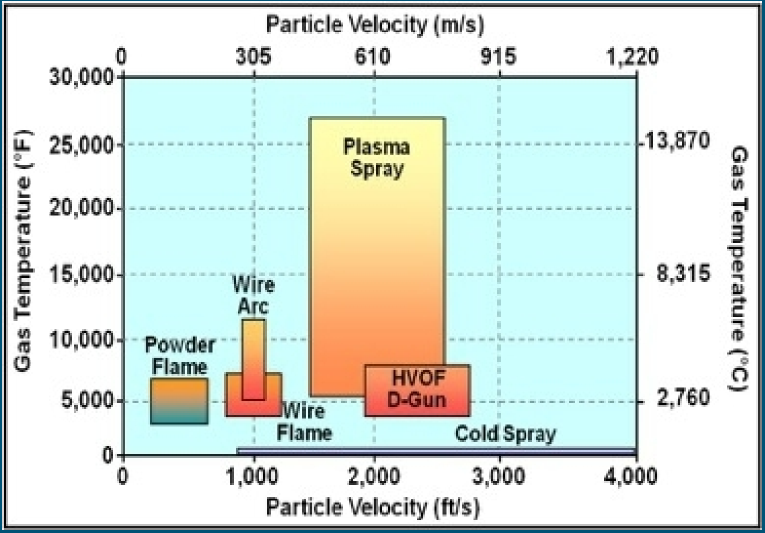






Thermal Spray Coating Techniques – Melt and Kinetic Deposition

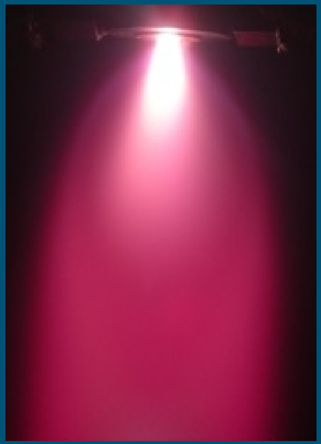
- Thermal Spray encompasses many techniques used to produce coatings of Metals, Ceramics, and CerMets
- These technologies span a wide variety of particle states (temperature and velocity)



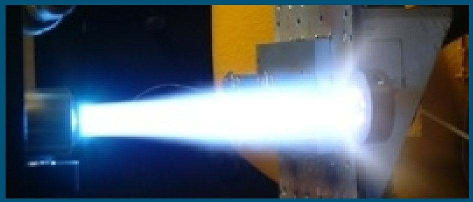
*Adapted from plots by R.C. McCune, Ford Motor Co. & A. Papyrin, Ktech Corp.

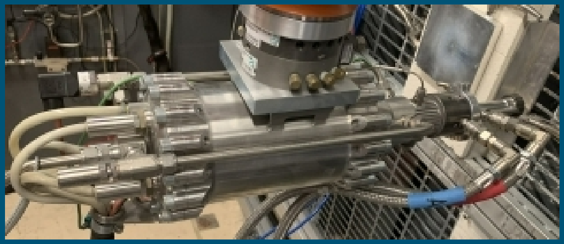
Air Plasma Spray

Inert atmosphere, low pressure, and very low pressure plasma spray

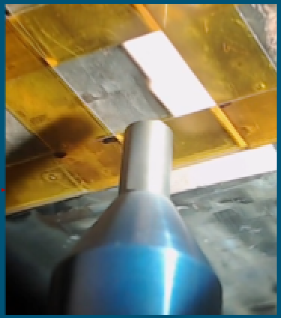


Powder Flame Spray



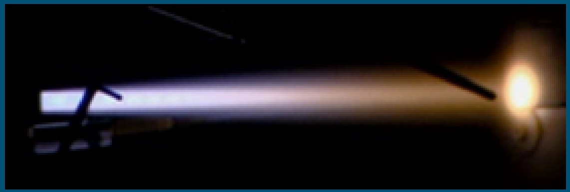


Cold Spray



Aerosol Deposition

Twin Wire Arc Spray



High Velocity Oxy-Fuel (HVOF)

Thermal Spray Coating Techniques – Melt and Kinetic Deposition

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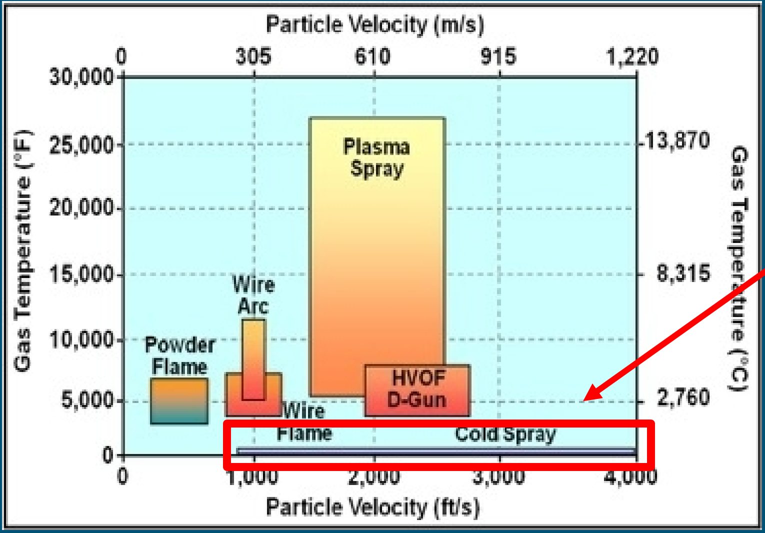
- These technologies span a wide variety of particle states (temperature and velocity)



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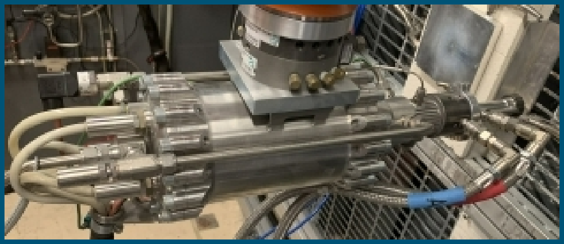
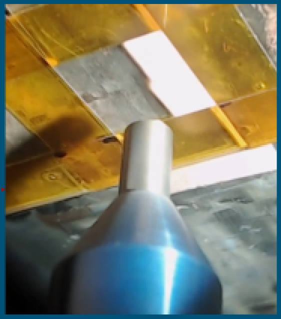
- Kinetic spray processes rely on high particle velocity instead of high temperature to produce coatings
- Cold Spray and Aerosol Deposition are both considered kinetic spray processes
- Both techniques rely on plastic deformation of the materials during impact with the substrate to produce a coating

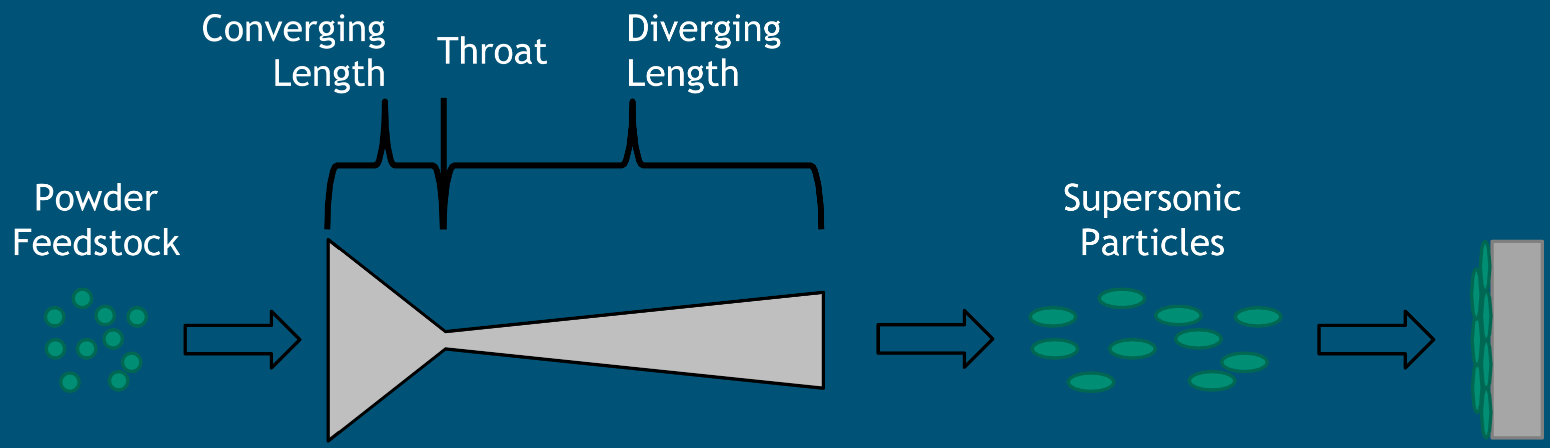


Cold Spray



Aerosol Deposition

Gas and Particle Dynamics of Kinetic Spray



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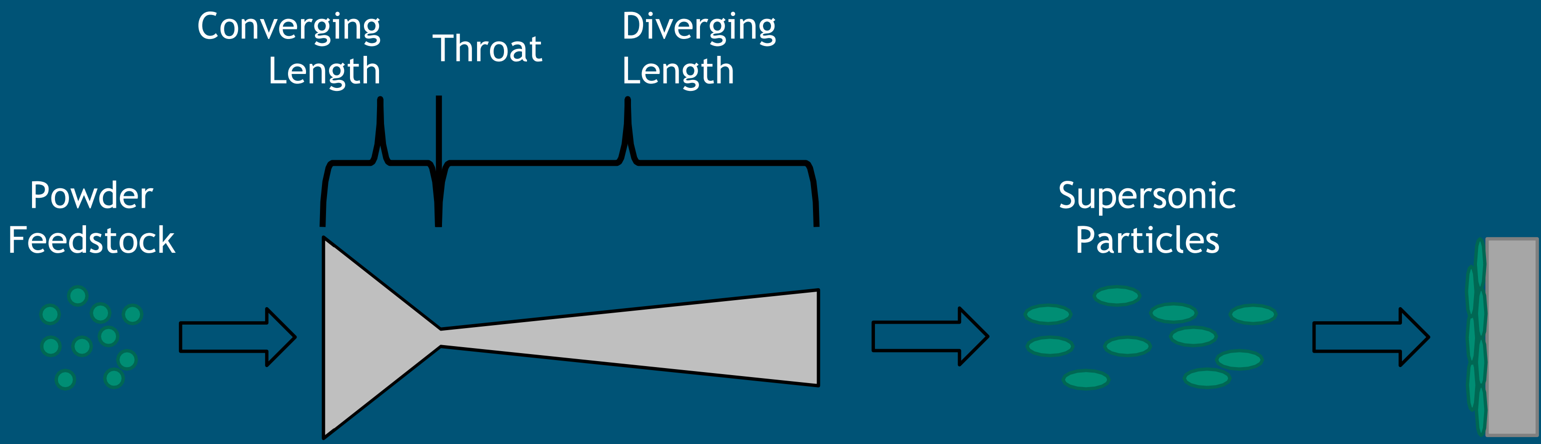


Gas Velocity:

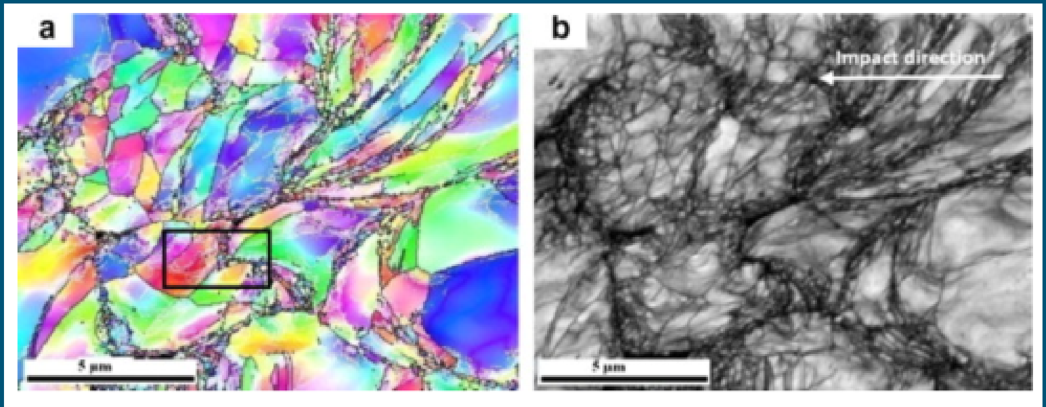
$$v_e = \sqrt{\frac{TR}{M} * \frac{2\gamma}{\gamma - 1} * \left[1 - \left(\frac{P_e}{P}\right)^{\frac{\gamma-1}{\gamma}}\right]}$$

Particle Velocity:

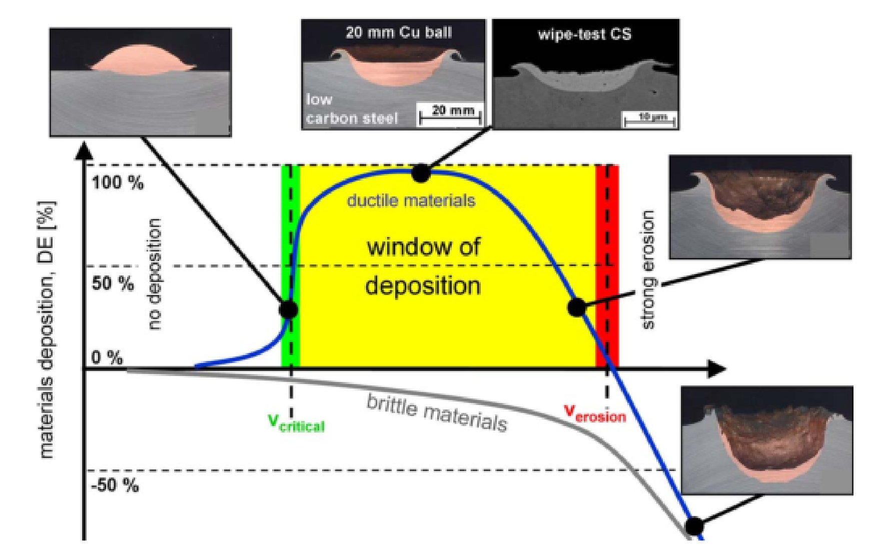
$$m\frac{dV_p}{dt} = \frac{D_D A_p \rho (V - V_p)^2}{2}$$

- Nitrogen and Helium are common gasses for kinetic spray processing
- Particles accelerated through DeLaval Nozzle
- Gas velocity is determined by pressure drop across the throat as well as gas properties
- Particle velocity is a function of material properties and geometric parameters

Zou, Yu, et al. "Dynamic recrystallization in the particle/particle interfacial region of cold-sprayed nickel coating: Electron backscatter diffraction characterization." Scripta Materialia 61. 9 (2009): 899-902



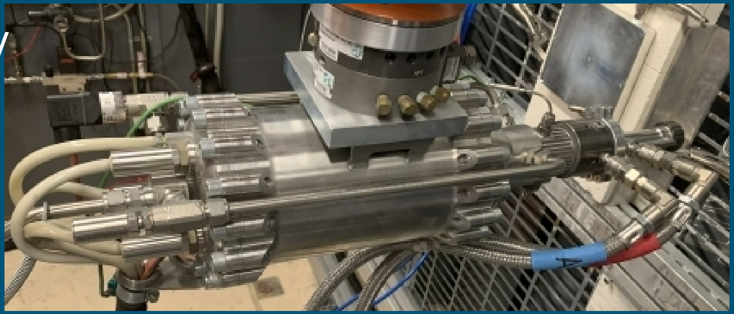
Cold Spray Mechanism



Schmidt, Tobias, et al. "From Particle Acceleration to Impact and Bonding in Cold Spraying." Journal of Thermal Spray Technology 18 (2009): 794-808.

Cold Spray – Standard Processing Conditions

Impact 5/11 Cold Spray System at Sandia



An impact consolidation technique which utilizes a supersonic gas stream laden with metallic feedstock powder to produce thick, highly dense, work hardened coatings without melting of particles.

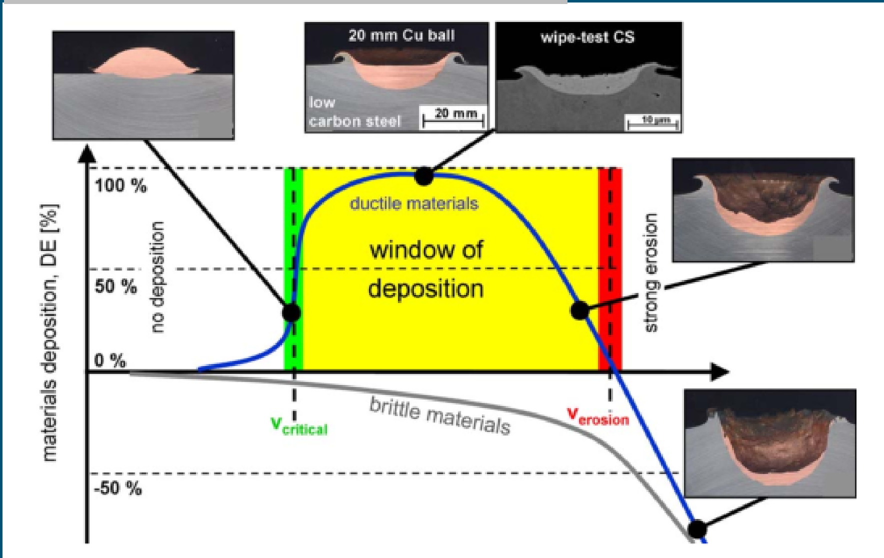
Common materials include: Copper (and Alloys), Aluminum (and Alloys), Titanium (and Alloys), Tantalum, Stainless Steels, Nickel Based Alloys

*From Work at Sandia	**Cold Spray**
Operating Temperature	Up to 60% melting point
Operating Pressure	Ambient
Particle Size	15-45 microns
Coating Materials	Metals, CerMets
Coating Thickness	20-10,000 microns
Thickness per Pass	30-200 microns
Coating Density	Typically >90%

Critical Velocity for Cold Spray Mechanism

- Particle state (velocity) is important in determining wheather a material will have enough energy to bond
- If velocity is too low to induce deformation/oxide shearing, coatings will not form (critical velocity)
- If velocity is too high, particles will erode the substrate and coatings will not form (erosion velocity)

Example Critical Velocity Curve:



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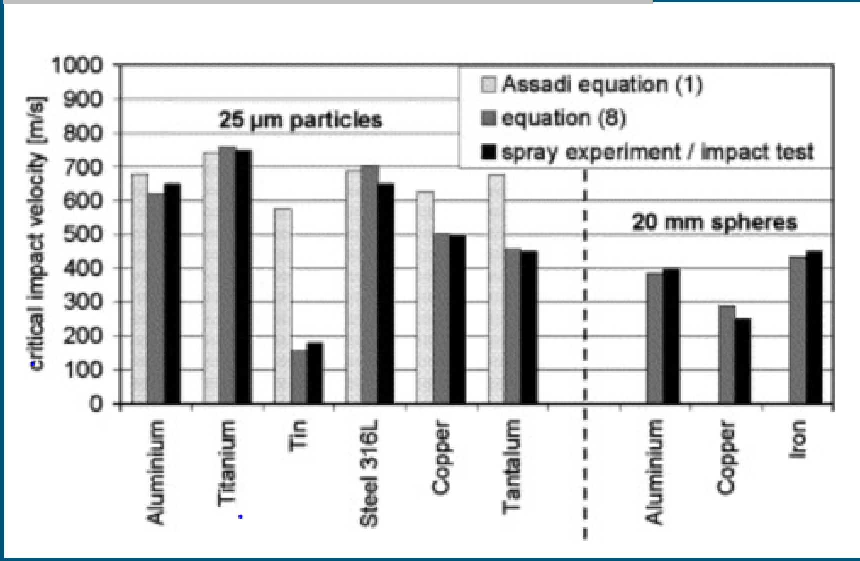
Calculated and Measured Critical Velocities:



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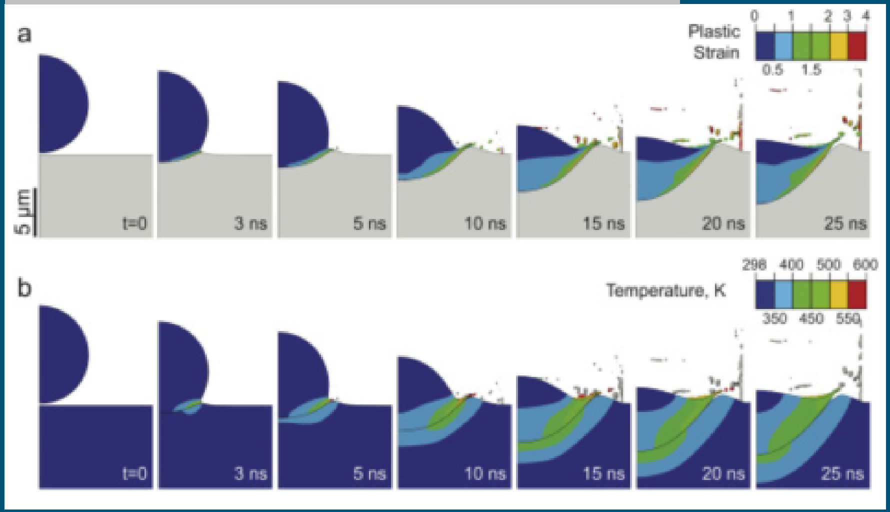
High Velocity Impact on Microstructural Changes

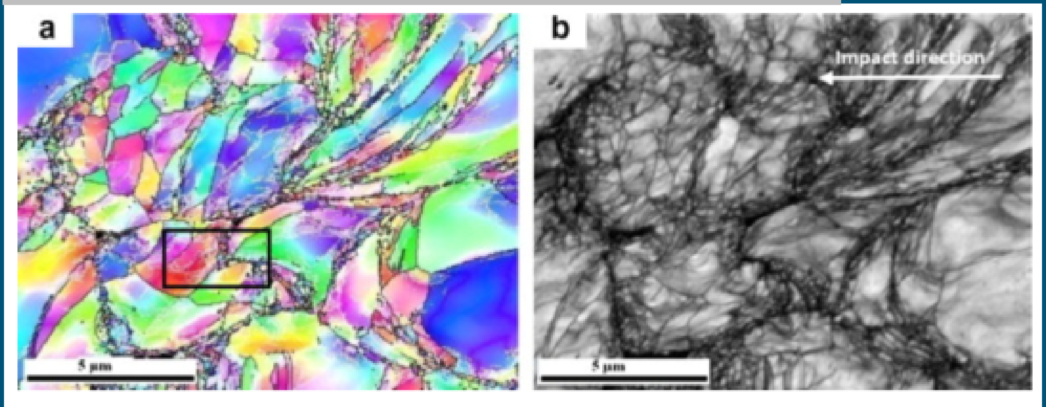
- High velocity impacts from the metallic particle results in high strain and rapid temperature rise (right figure)
- The impact therefore results in plastic deformation, shearing of the native oxide, and fusing of the particle to the substrate (right figure)
- Due to high temperature from impact, adiabatic shear instability can result in higher deformation of the particle
- Resulting microstructures at the interface are generally recrystallized, nano-grained, and highly work-hardened (bottom picture)

Simulated particle impact during Cold Spray:



Hassani-Gangaraj, Mostafa, et al. "Adiabatic shear instability is not necessary for adhesion in cold spray." Acta Materialia 158.1 (2018): 430-439.

EBSD Microstructure of Cold Sprayed Nickel Coating:



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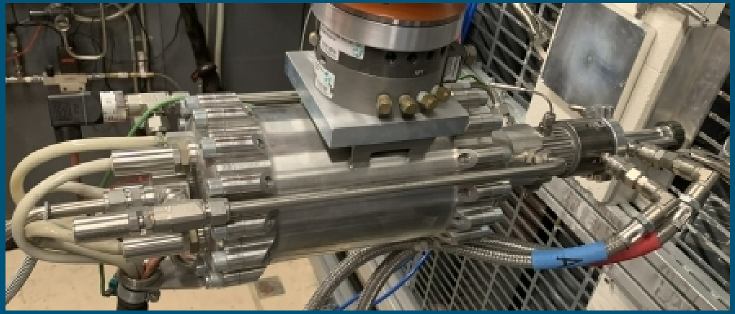
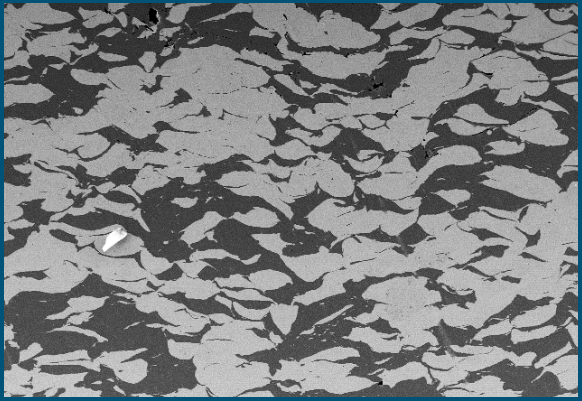
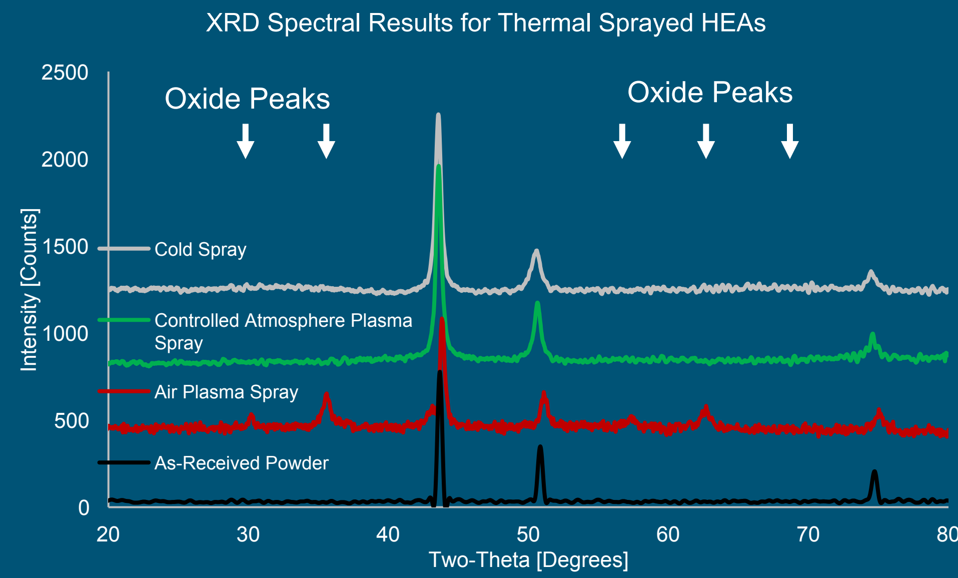
Cold Spray Example



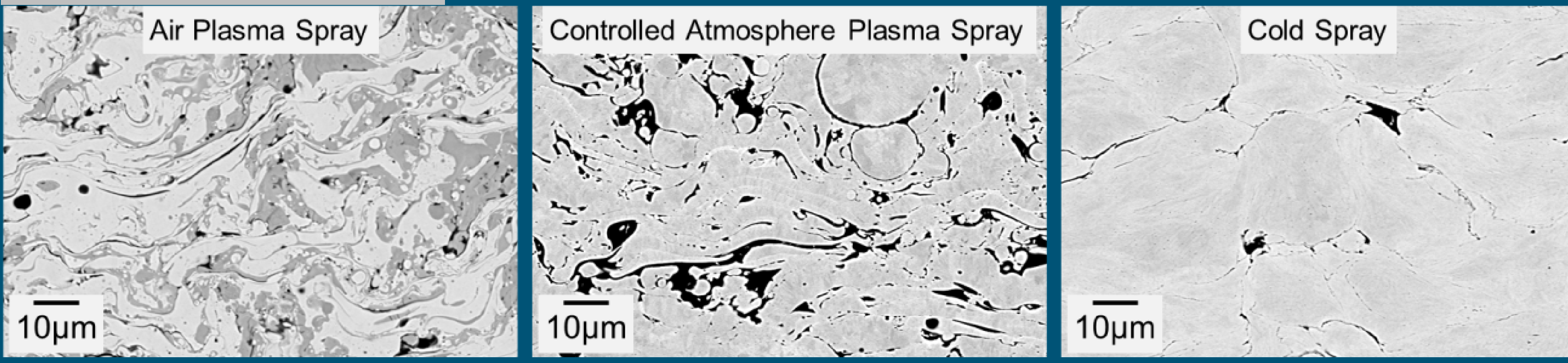


Cold Spray – High Entropy Alloy (CoCrFeMnNi)

- High entropy alloys have gained interest due to mechanical properties and chemical stability
- Due to low processing temperatures, no oxidation is observed in final coatings
- Phase retention of as-received powder
- Manganese depletion observed in ... sing

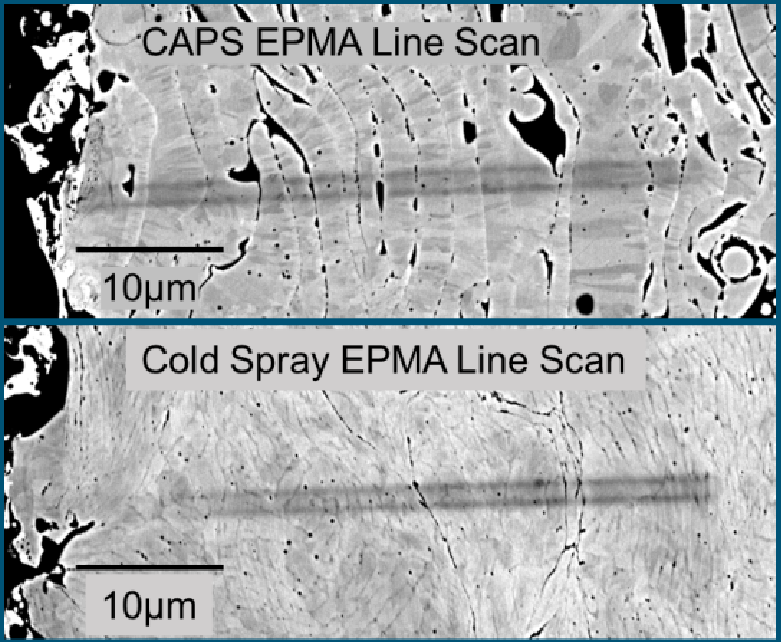


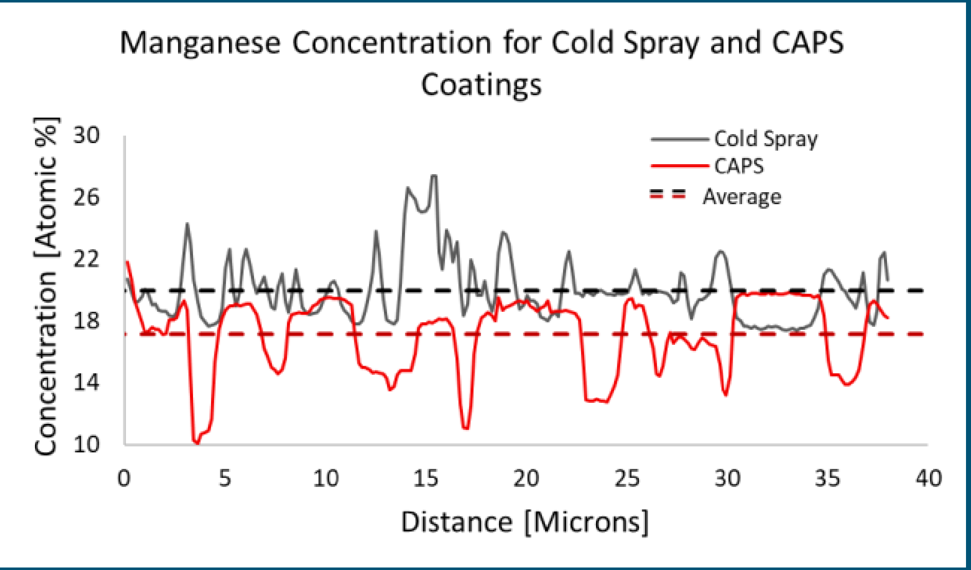
Backscatter SEM Imaging:



Advantages of Cold Sprayed High Entropy Alloy Over Plasma Spray

- Hardness values show severe work hardening of the cold spray samples (Bottom)
- Manganese depletion observed along boundaries in Plasma Sprayed samples (Right)
  - Due to differences in boiling point of the individual metals
- Low temperature of kinetic processing prevents manganese boiling (Right)





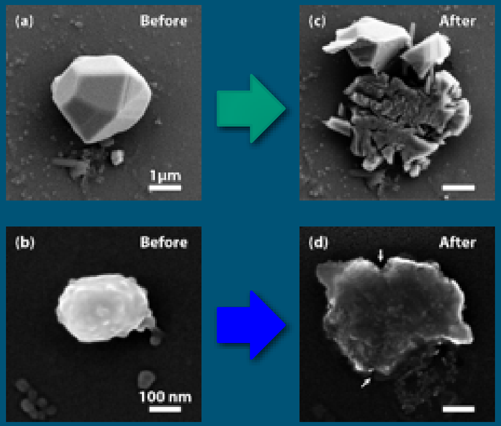
Vickers Hardness Data:

	Powder (10 values)	CAPS (25 values)	CS (25 values)
Average	163	196	351
St Dev	19	18	32

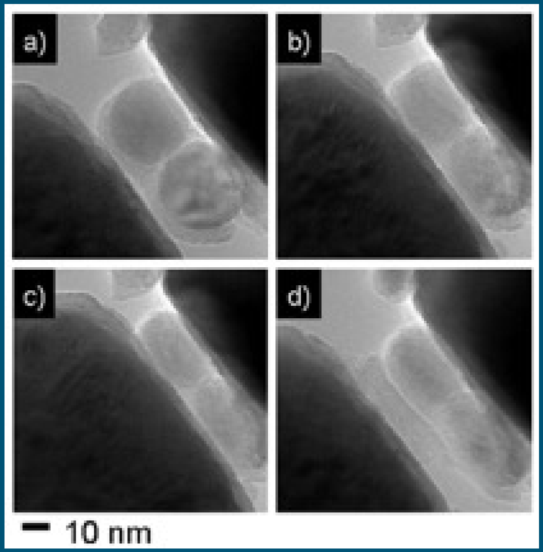
Sarobol, Pylin, et al. "Room temperature deformation mechanisms of alumina particles observed from in situ micro-compression and atomistic simulations." Journal of Thermal Spray Technology 25.1-2 (2016): 82-93.

3.0 µm

0.3 µm

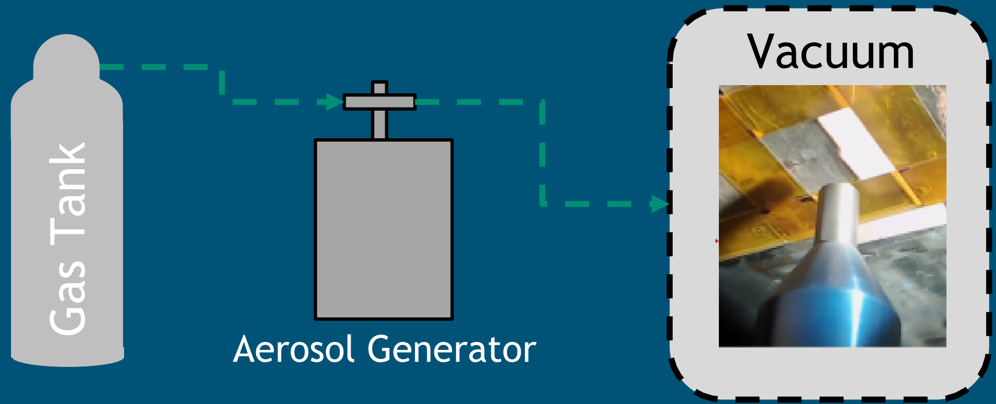


Aerosol Deposition Mechanism



Calvié, Emilie, et al. "Real time TEM observation of alumina ceramic nano-particles during compression." Journal of the European Ceramic Society 32.10 (2012): 2067-2071.

Kinetic Processing – Aerosol Deposition



An impact consolidation technique which utilizes a supersonic gas stream laden with metallic or ceramic feedstock powder to produce thick, highly dense, work hardened coatings without melting of particles in vacuum.

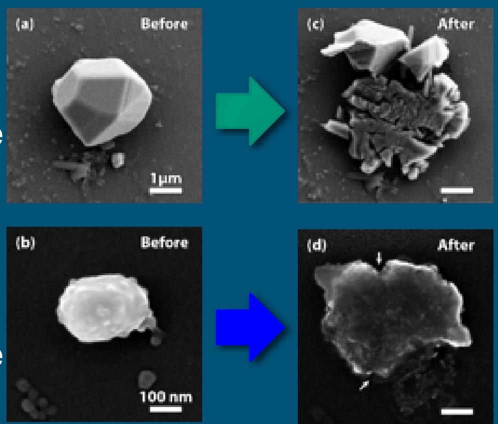
Common materials include: Al_2O_3, $BaTiO_3$, YAG, Zr_2O_3, TiO_2, Y_2O_3, piezoelectric materials, Copper, Tantalum

*From Work at Sandia	**Aerosol Deposition**
Operating Temperature	Room Temperature
Operating Pressure	Vacuum
Particle Size	<2 microns
Coating Materials	Metals, Ceramics, CerMets
Coating Thickness	1-1000 microns
Thickness per Pass	1-20 microns
Coating Density	Typically >90%

Nano-Crystalline Plasticity (In-Situ TEM Compression Tests)

3.0 µm Particle

0.3 µm Particle



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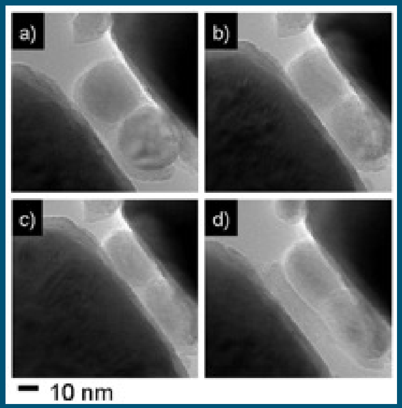
0.04 µm Particle



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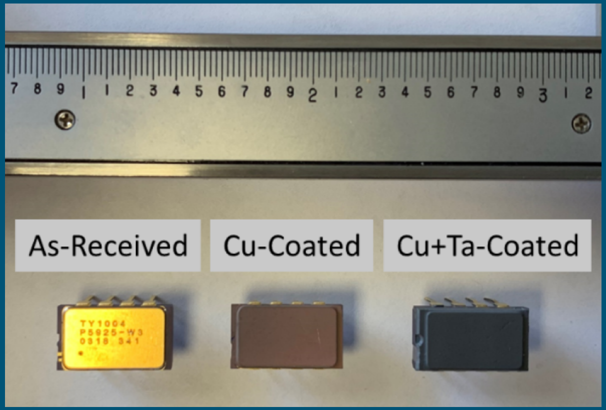
- Aerosol Deposition relies on ductility of ceramic and metallic materials
- Ceramic materials exhibit ductile behavior when particle size becomes small enough
  - Ductile behavior is typically observed when particle size reaches 10-30nm
- Theorized to occur when the fracture energy surpasses the energy required for defect formation and migration
- Particle momentum during impact is very important to reach critical energy to fracture particles to ductile regime
- Ball Milling and heat treatment can help reduce starting crystallite size without sacrificing particle size and hence momentum

Aerosol Deposition Example

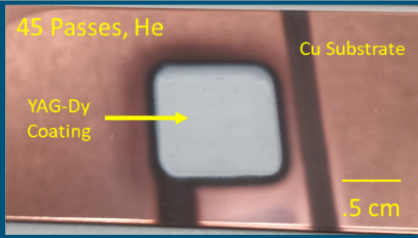
High Velocity



2-Dimensional Analysis of Aerosol Deposited YAG:Dy

Aerosol Deposition (500°C) | Epoxy (400°C)

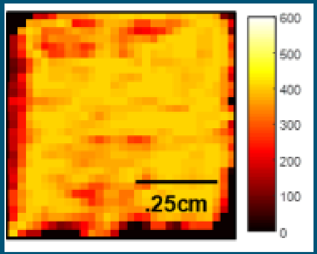
A)



Extreme substrate oxidation at ~550C prevented higher temperature testing

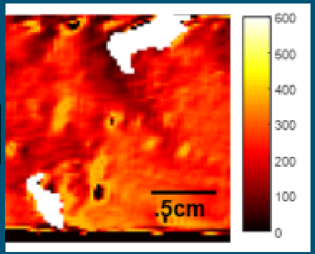
B)

C)



~250µm/pixel

D)



A. Aerosol Deposited YAG:Dy coating on copper substrate exposed to 500°C.

B. Epoxy-YAG:Dy coating exposed to 400°C.

C. 2-D temperature profile for AD YAG coating.

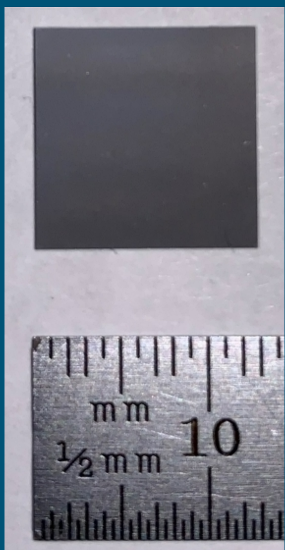
D. 2-D temperature profile for Epoxy coating.

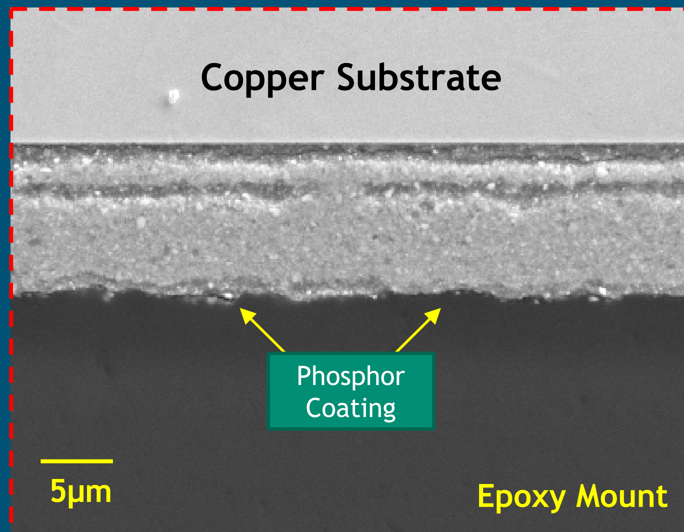
- 2-D Temperature profile obtained for AD phosphor coatings using two color pyrometry
- Measurement stopped at 500°C due to extreme oxidation of copper substrate
- Ceramic substrates and coatings have survived thermal cycling up to 1000°C
- ngs pyrolyzed at 400°C.

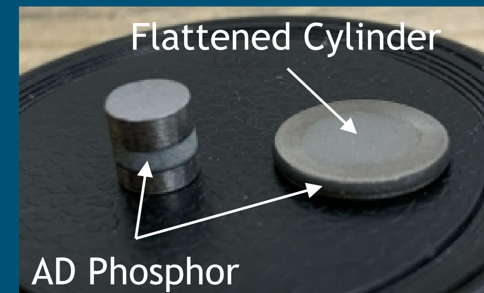
*Temperature profiles courtesy of Wendy Flores-Brito and Kate Hoffmeister

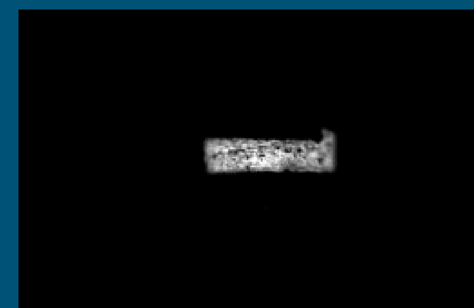
Mechanical Testing of AD Phosphorescent Coatings

AD Film







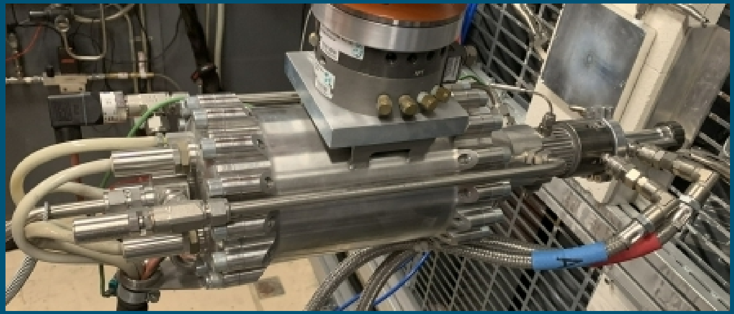


- Higher phosphor density promises thinner coatings→ faster thermal response time
- Thermal conductivity As-Sprayed: 1.43 W/mK, bulk thermal conductivity: 9.9 W/mK
- Robust coating, improved stability in extreme mechanical and thermal

*Mechanical Testing courtesy of Caroline Winters and the Thermal Test Facility

Summary of Kinetic Processes

- Kinetic spray processing utilizes high velocity instead of melting to produce thick films of metallic, cer-met, and ceramic coatings
- Only velocity is considered for particle state compared to temperature and velocity for melt deposition techniques, therefore reducing manufacturing complexity for thermal spray technologies
- Kinetic spray can be used for a wide variety of applications due to ability to deposit many different materials
- Thermo-mechanical properties are typically lower than bulk values, but the lack of input heat during deposition allows phase retention, lack of oxidation, and ability to couple high melting point coatings with low melting point substrates



Vacuum

References

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