Cold Spray Deposition Process Control Guided by Predictive Models

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Cold Spray Action Team Meeting
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Worcester, MA
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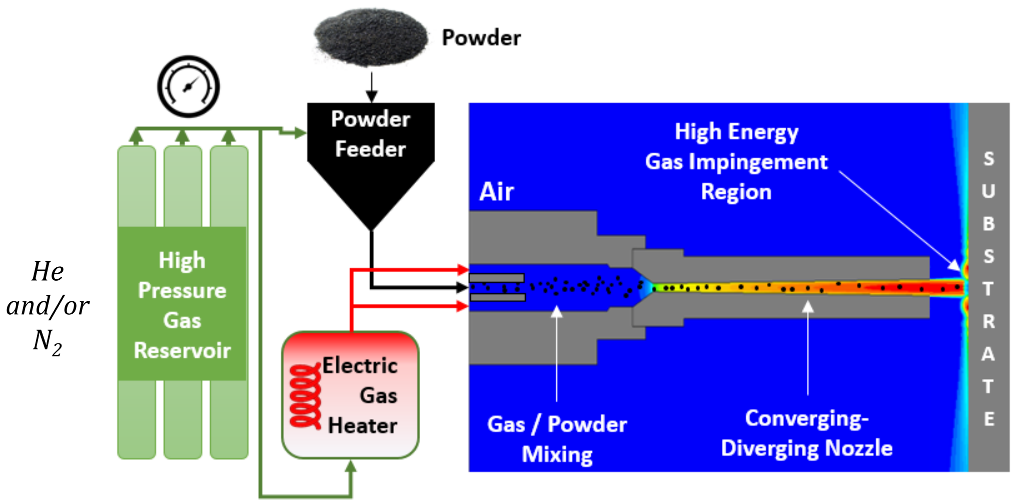
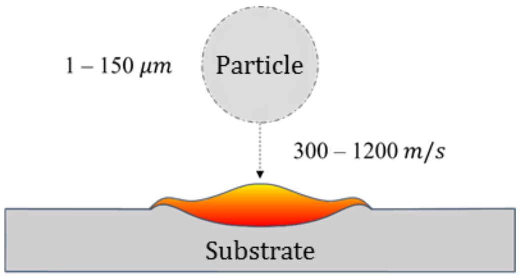
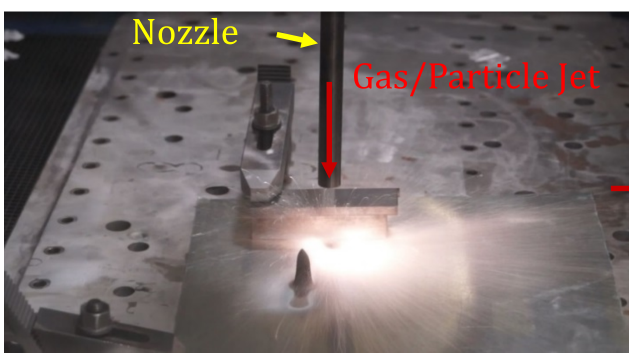
Cold Spray



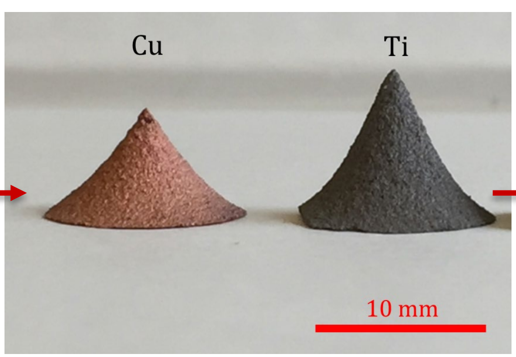


Materials

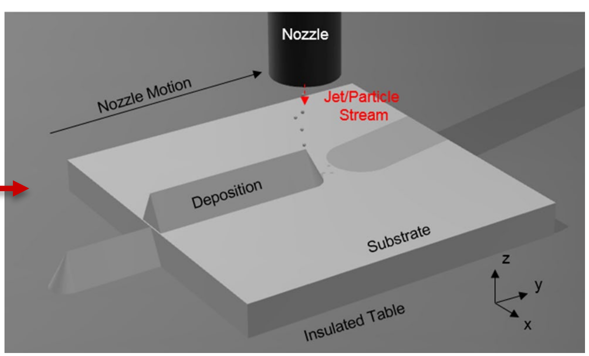
Predominantly **metals**, but **ceramics**, **polymers**, **composites**, and **dissimilar materials** have been successfully demonstrated.



Spray Process



Deposition Process



Building Process

Process Variables

Gas Dynamic Variables, Powder Properties, Powder Injection Variables, Substrate Variables, Building Strategy

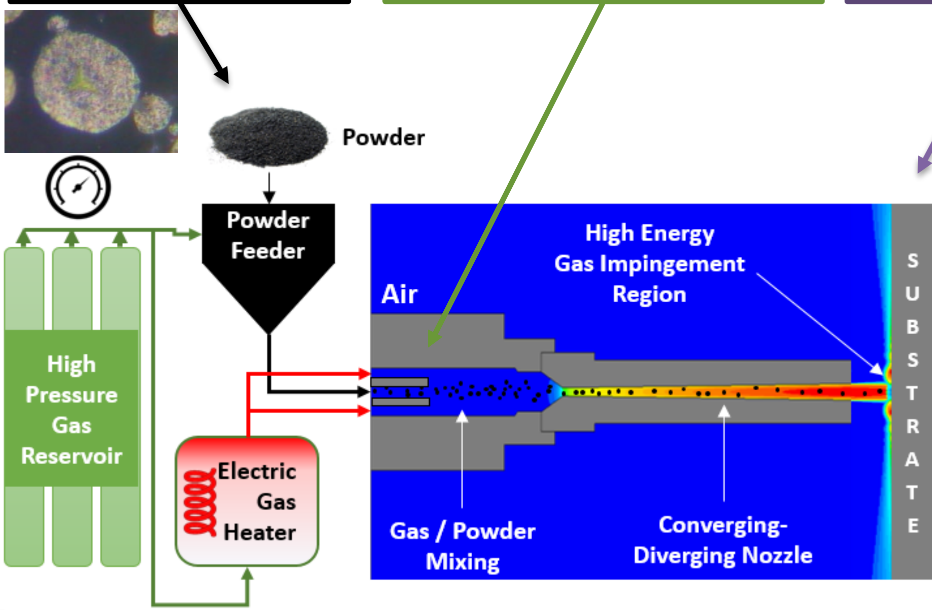
Powder Variables
- Size Distribution
- Morphology
- Microstructure and chemistry

Powder Injection Variables
- Injector type
- Injection location
- Injector geometry
- Injection consistency

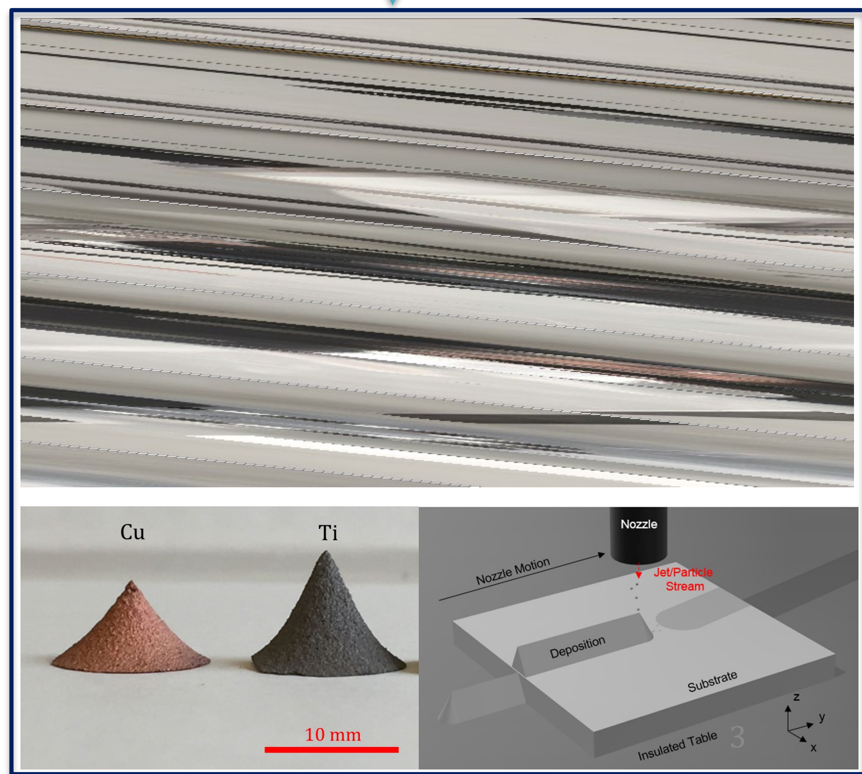
Substrate Conditions
- Properties
- Surface chemistry
- Morphology
- Geometry

Spray Control Parameters
- Building strategy
- Associated motion controls

CS Product



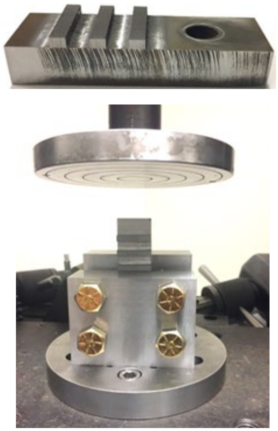
Gas Dynamic Variables
- Nozzle geometry
- Gas type
- Gas pressure & temperature
- Substrate distance and geometry
- Powder characteristics



Product

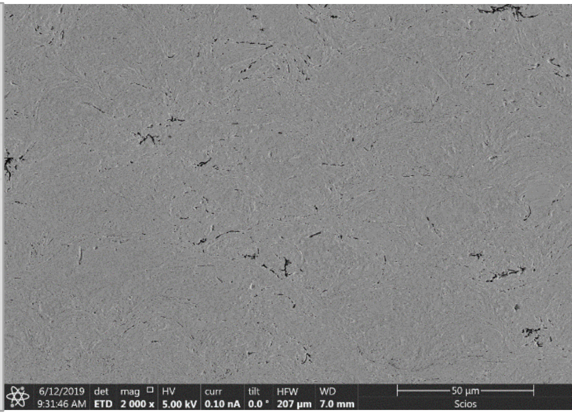
- Product of a unique combination of variables with tolerance
- Resultant properties
- How do we dial and refine our process variables?

Machinable Coatings



Adhesive Strength Test

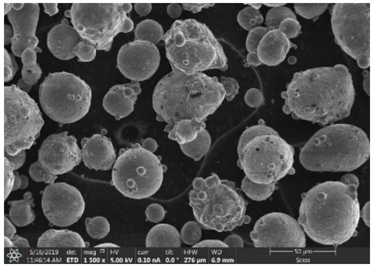
CS Deposited Tantalum Optical Image

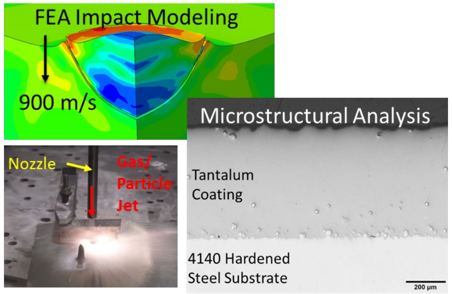


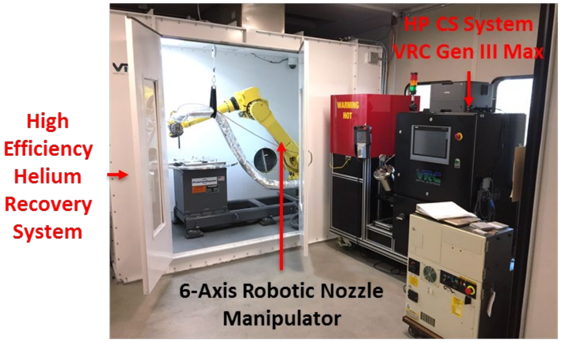
CS Deposited Tantalum SEM Image

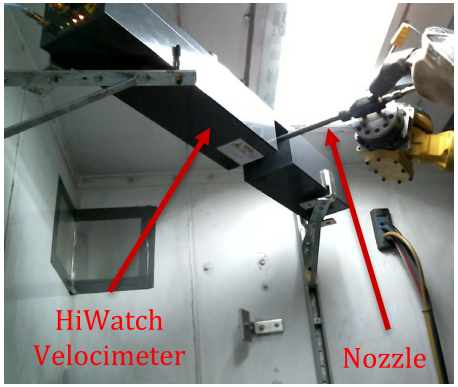
NU CS Research Group

- CSRG works on fundamentals of Cold Spray
- Consist of 7 faculty, 3 research scientists/engineers and 9 graduate students
- Combined Experimental-Theoretical Approach
- Materials modeling for understanding fundamentals
- CFD for process optimization and novel systems level design
- Mechanical testers
- SEM, TEM and indentation of interfaces to investigate materials underpinnings of bonding









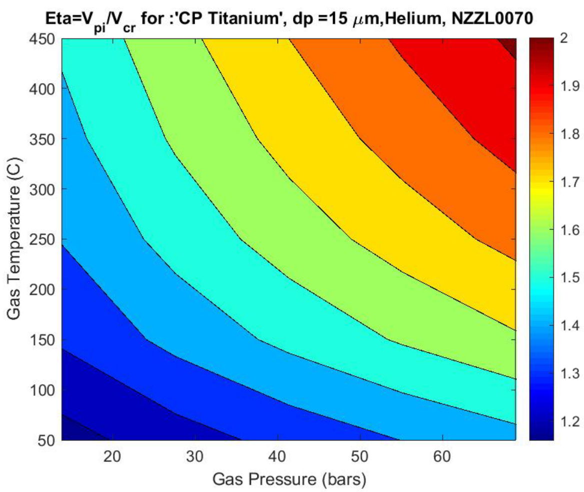
6 kW Laser
IPG Photonics Donation

Guidance by Models

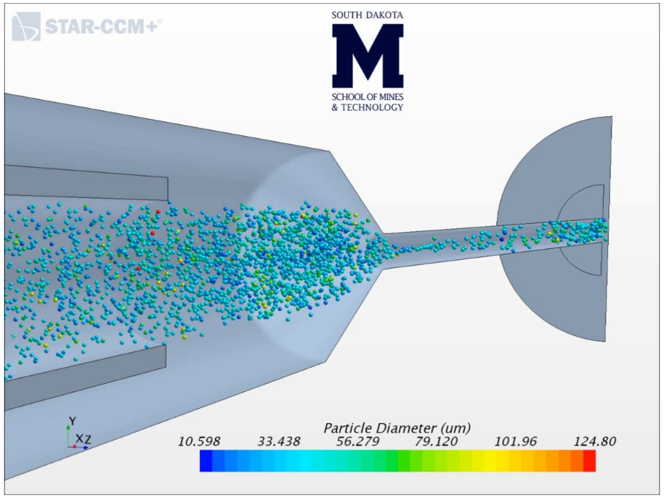
How do we dial and refine our process variables?

- Requested information ⟷ • Model complexity

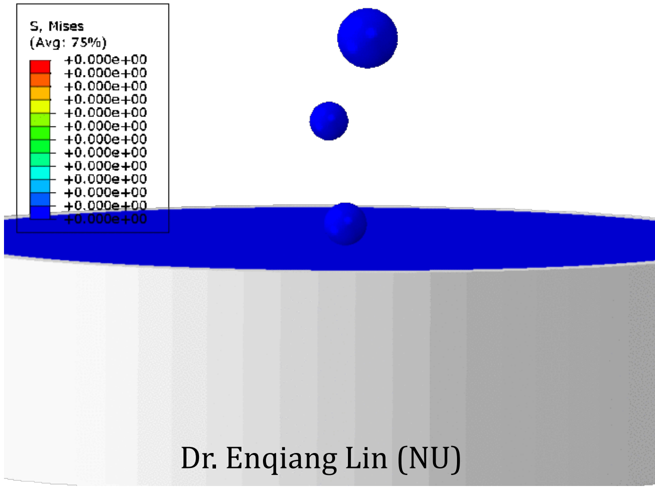
Complexity of the model is driven by the expected answers from the models.
So, what can we expect from available today?



1D CFD Model
Parameter Window for
15 µm Titanium Particle



3D CFD Model
Particle Impact Conditions
and Build Profile



FEA Model
Multi-Particle Impact

- Gas & Powder Flow Modeling
- Impact process modeling
- Material buildup process modeling
- Manufacturing process modeling
- Validation & integration

- Gas & Powder Flow Modeling
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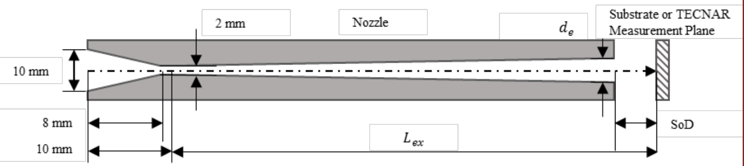
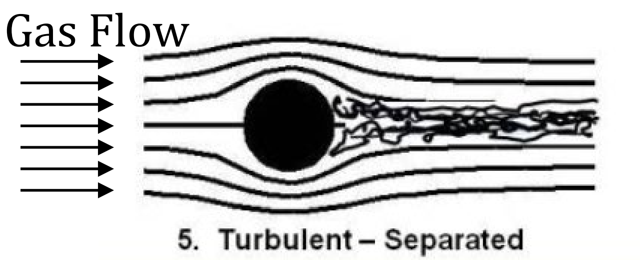
Parametric Modeling

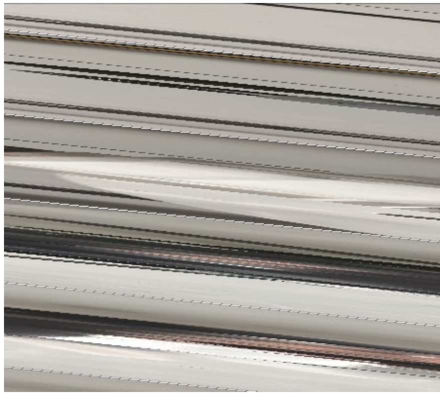
- 1D Isentropic CFD Models Test Parameter Windows
- Helps us quickly select spray parameters for metal and metal alloys.

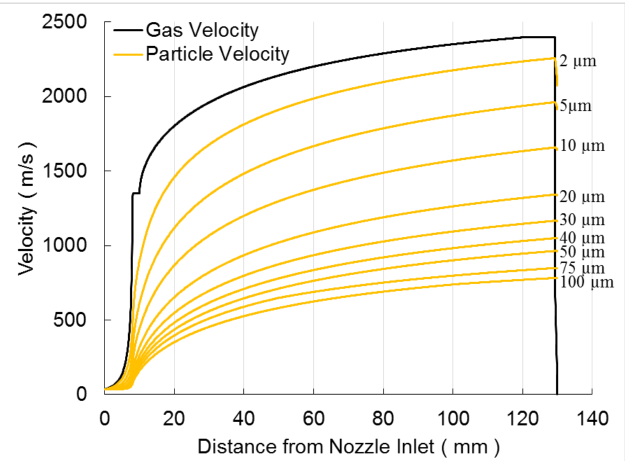


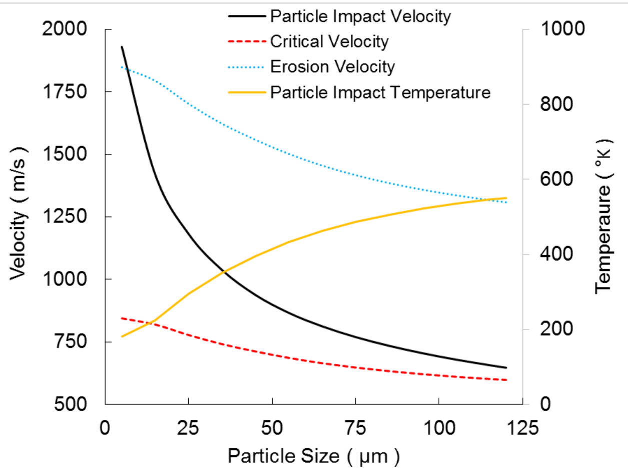


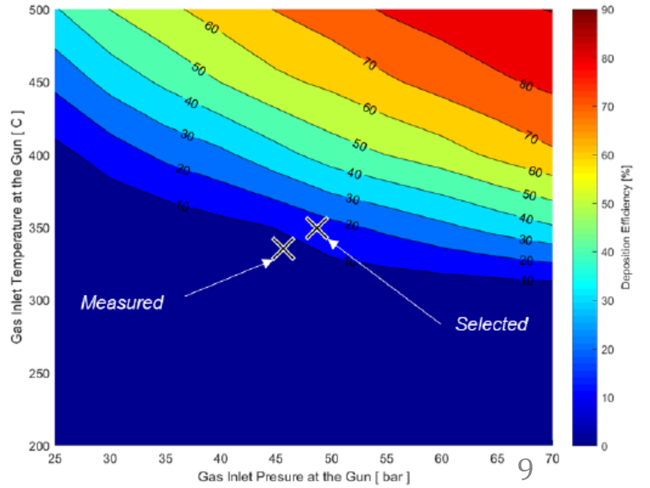
Advantages
- Fast
- Builds parameter windows
  - Dozens of cases per minute
- Daily use for spray parameters

Disadvantages
- 3D gas dynamic effects not captured
  - Variability in spray not captured.
- Semi-empirical bonding equation used. Not accurate for everything.









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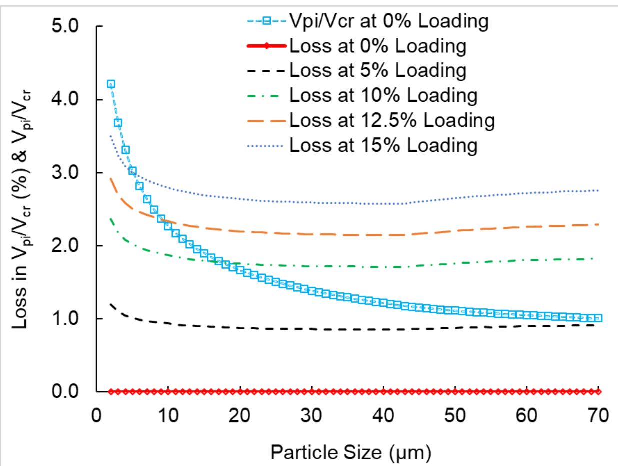
Fully Coupled Quasi 1D Multiphase CFD

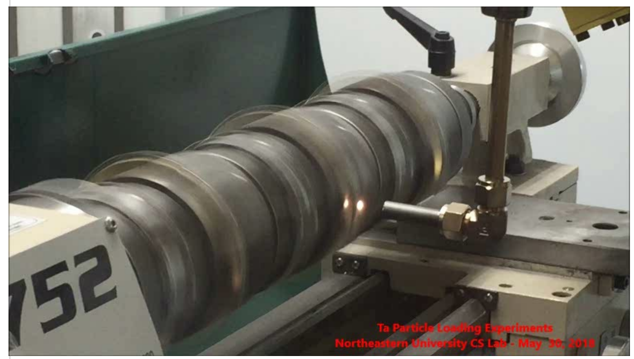
- Interactions of particles and gas
- Thermal losses in nozzle (gas to nozzle)
- Frictional losses in nozzle (gas to nozzle)

Loss in CVR



Particle loading study

- Increase efficiency and speed of deposition



Increase efficiency and speed of deposition.

No measurable effects for:
- 3X Increase in deposition rates
- Minimal change to velocity.
- 3X Savings in time
- 3X Savings in helium usage

Continuity

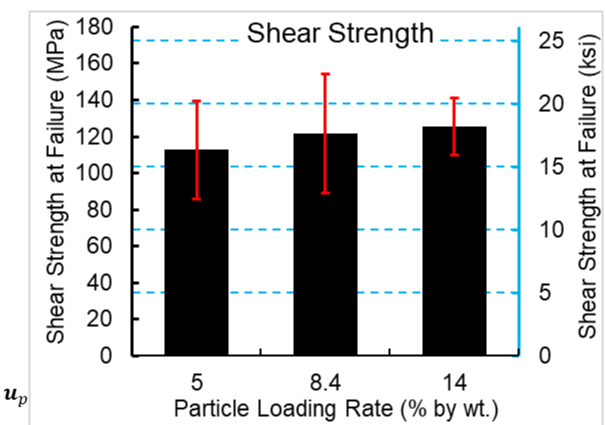
$$\frac{\partial}{\partial t}\iiint \rho \, dV + \oiint \rho \, \boldsymbol{u} \cdot \boldsymbol{dS} = 0$$

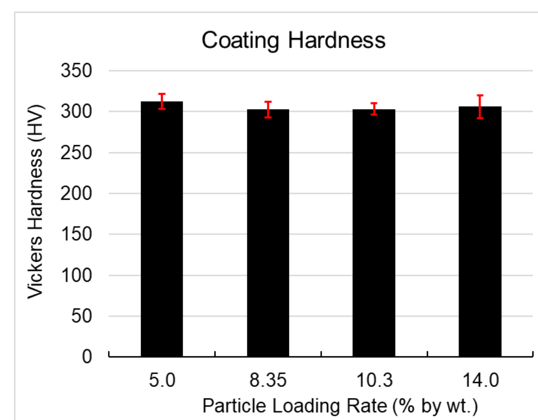
Momentum

$$\frac{\partial}{\partial t}\iiint (\rho u) \, dV + \oiint (\rho u \boldsymbol{u}) \cdot \boldsymbol{dS} = -\oiint (p \; dS)_x + \boldsymbol{F}_p$$

Energy

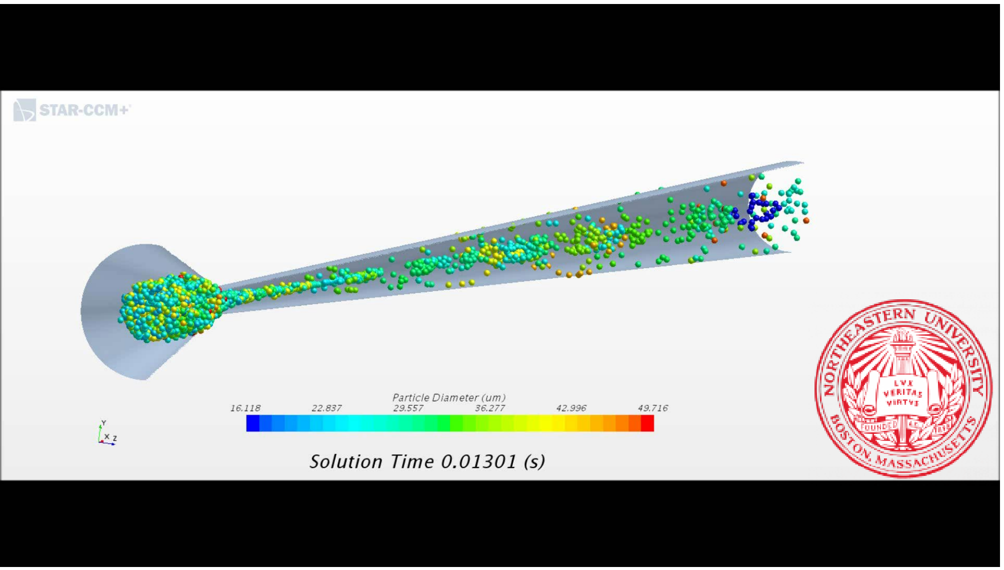
$$\frac{\partial}{\partial t}\iiint \rho\left(e + \frac{u^2}{2}\right) dV + \oiint \rho\left(e + \frac{u^2}{2}\right)\boldsymbol{u} \cdot \boldsymbol{dS} = -\oiint (p\boldsymbol{u}) \cdot \boldsymbol{dS} + \dot{Q}_p + \boldsymbol{F}_p \cdot \boldsymbol{u}_p$$





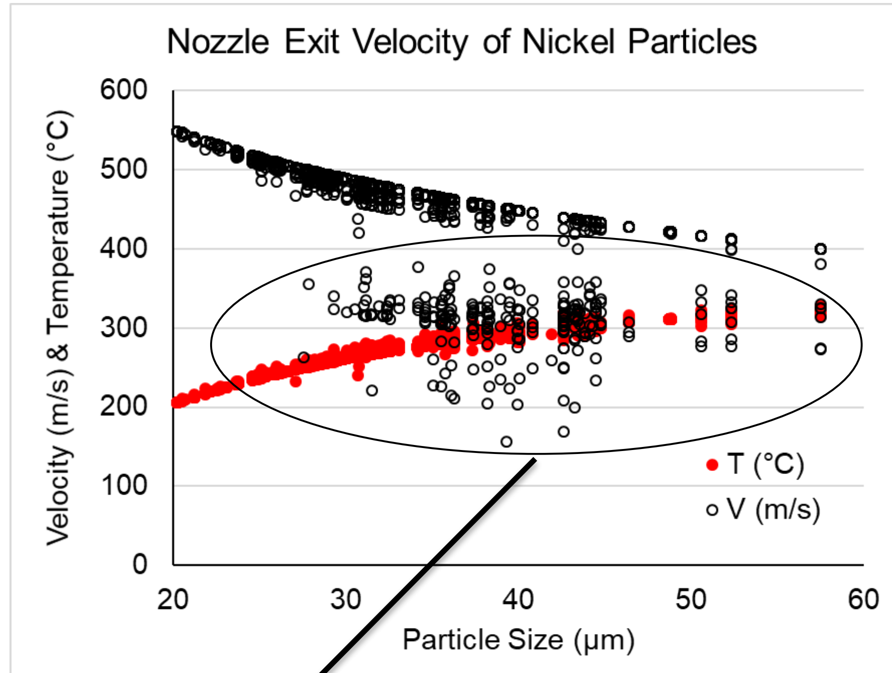
Multidimensional CFD Models

Fully-coupled Simulation of Nickel in a VRC Nozzle



Captures:

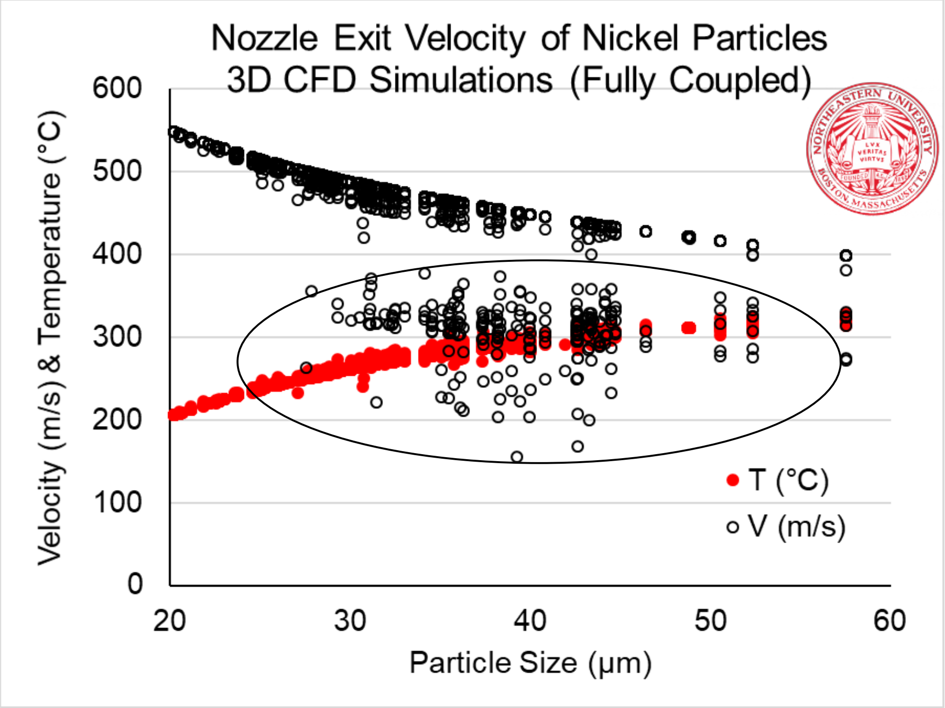
- Complex gas behavior (shock waves)
- Stochastic nature of particle flow and impact.
- Particle/nozzle interactions.
- Particle/particle interactions
- Flow of irregularly shaped particles.
- Prediction of deposition footprint.
- Proven models reduce cost of experimentation.

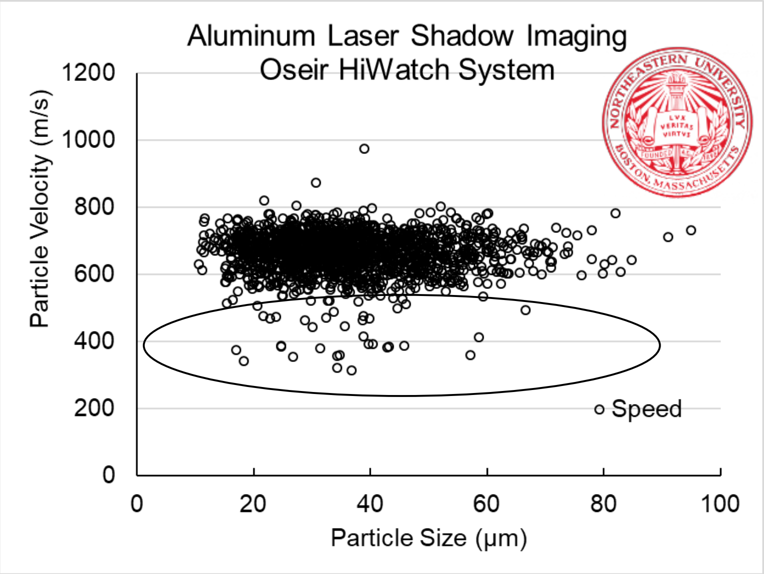


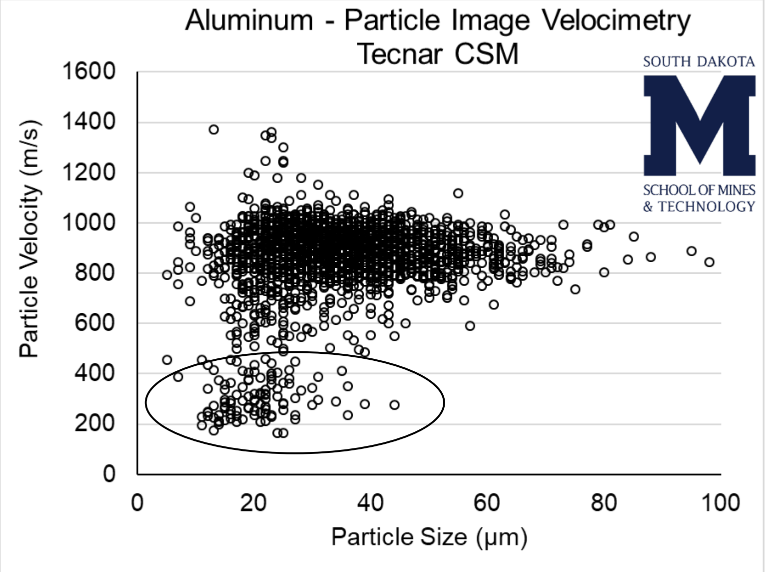
Interaction of nozzle and nickel particles cause reduction of particle velocity. Severe in some cases.

Model behavior observed in particle image velocimetry measurements.

Replicating Real-Time Experiments







- Understanding the required level of complexity in models can help reproduce experiments in a timely manner.
- Validated models reduce experimentation costs in industrial applications.
- In cold spray, the efforts put into modeling over the years are paying off. (ARL Team)

- Gas & Powder Flow Modeling
- Impact process modeling
- Material buildup process modeling
- Manufacturing process modeling
- Validation & integration

Single Particle Impact Modeling

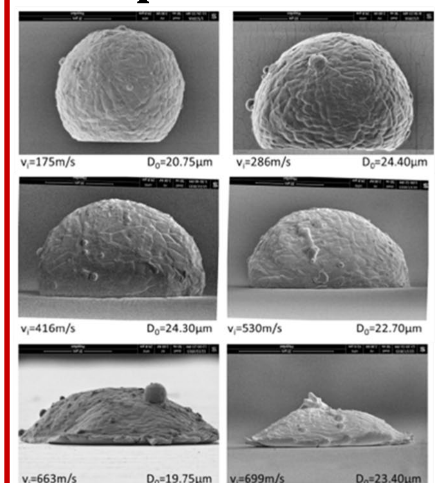
Finite Element (FEM) and Smooth Particle Hydrodynamics (SPH) Modeling
Property related deformation behavior.

Calibrated models can provide

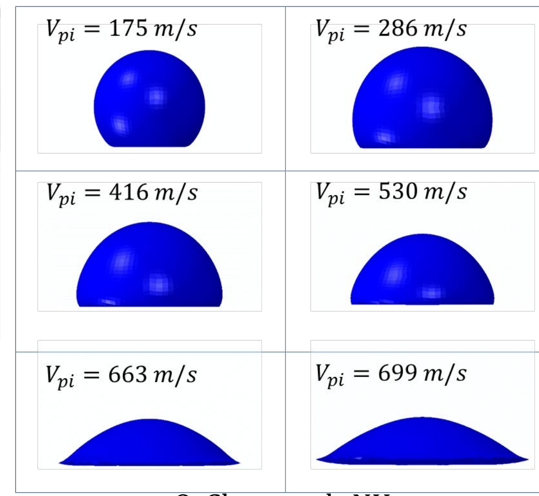
- Interface energy needed for bonding
- Heat generation from impacting particles
- Parametric effects of:
  - Effects of impact velocity/temperature
  - Substrate/particle morphology
  - Surface oxidation
  - Porosity

ARL CS Modeling Team

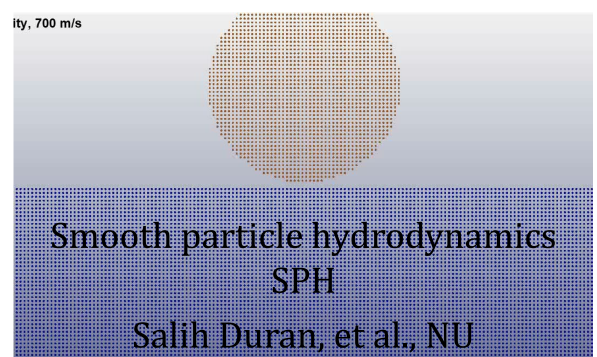
experiments | **FEM model results**



W. Xie, J.-H. Lee, UMASS



Q. Chen, et al., NU



Calibrated Models Provide Interfacial Energy and Thermal Energy Rise During Impact

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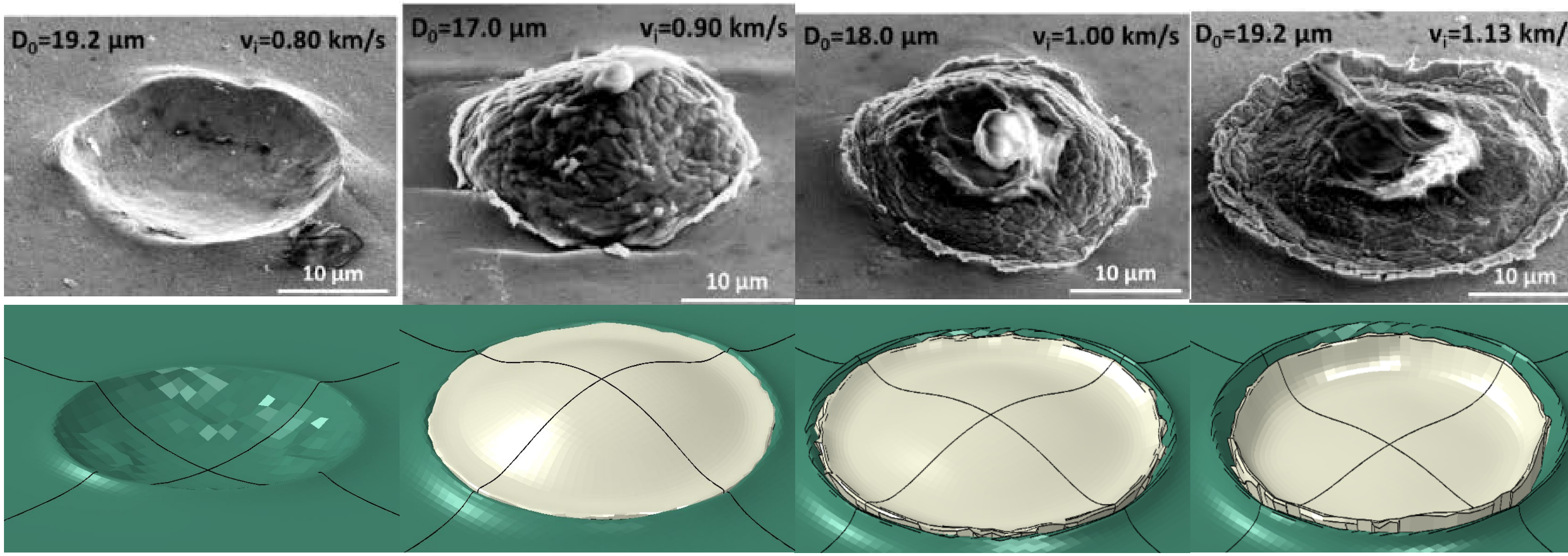
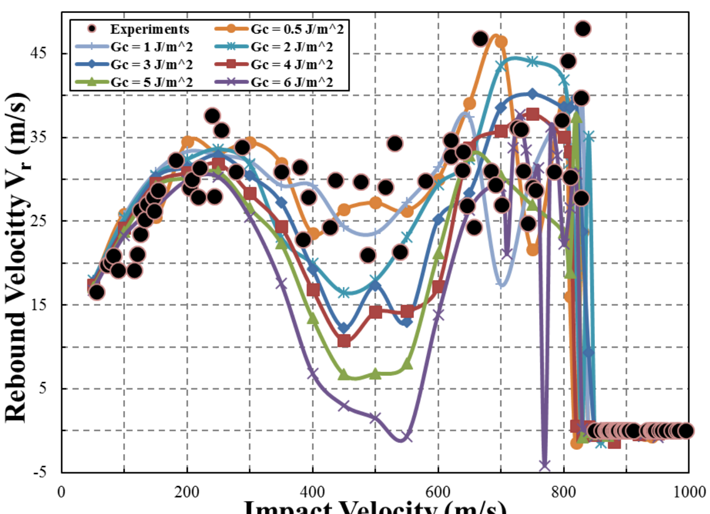
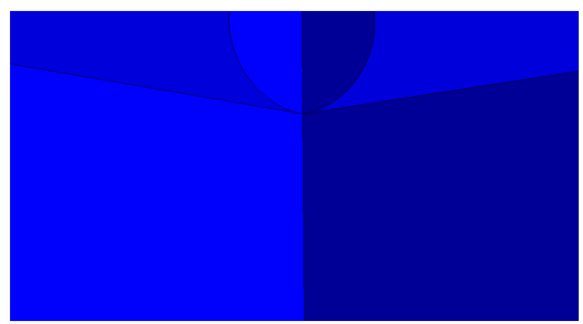






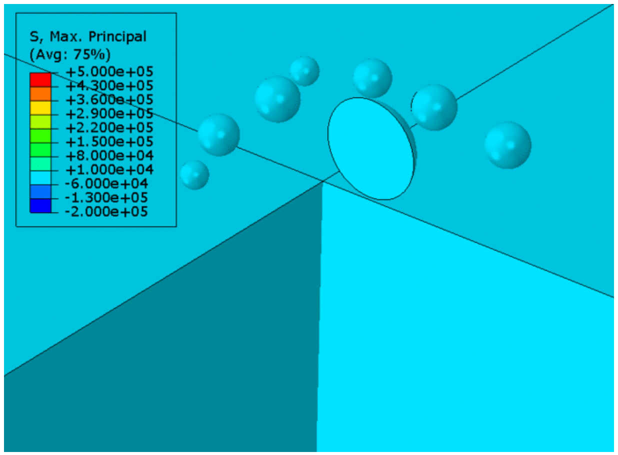
V_c = 884 m/s
G^{Al} = 25 J/m²

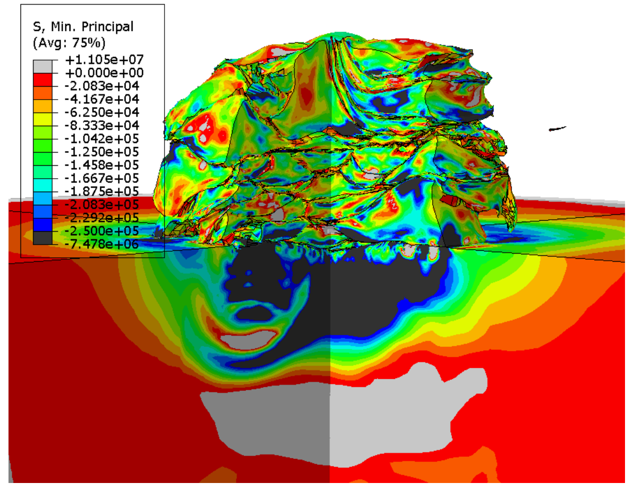
Thermal energy conversion to kinetic energy

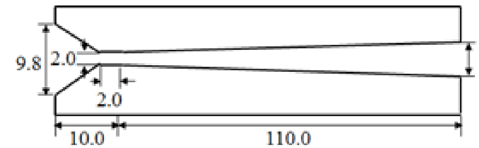
$$TE_{particle} = 0.34 \cdot KE$$

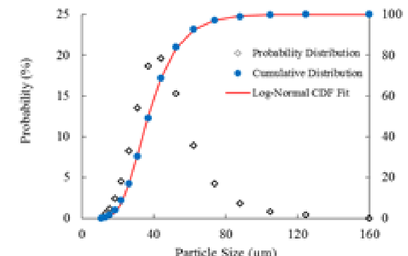
$$TE_{substrate} = 0.45 \cdot KE$$

Multiparticle Impact Simulations
Residual Stress and Porosity Estimations







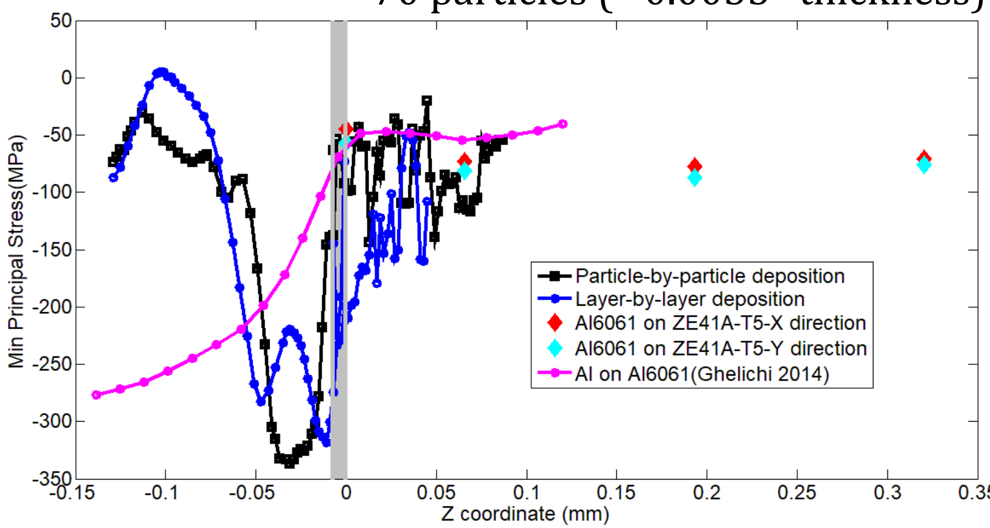


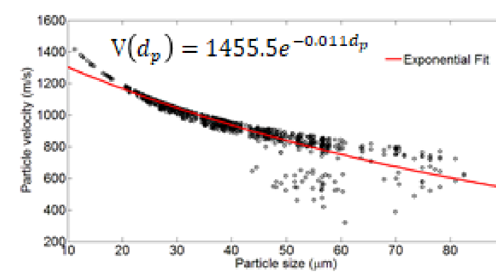
$$f(d_p) = \frac{100}{2}\left[1 + \mathrm{erf}\left(\frac{ln(d_p) - ln(\bar{d_p})}{\sigma_{log}\sqrt{2}}\right)\right]$$

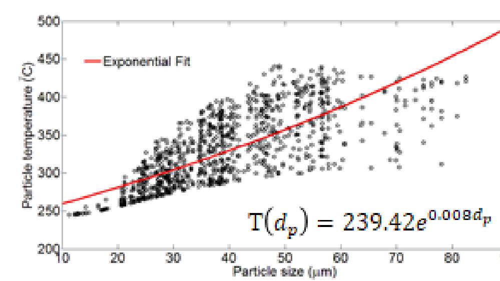
70 particles (~0.0035” thickness)

Al 6061 on Al6061

35 bar
400 °C
Helium Spray



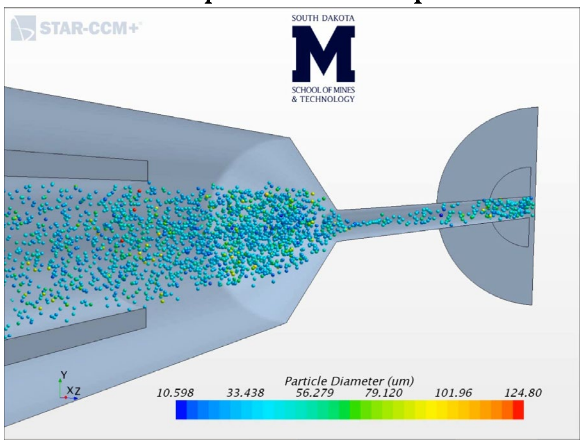


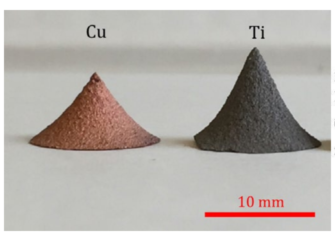


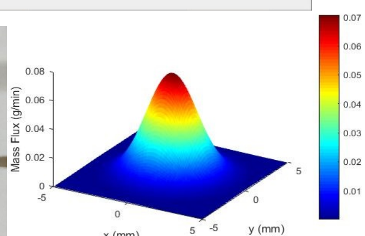
- Gas & Powder Flow Modeling
- Impact process modeling
- **Material buildup process modeling**
- Manufacturing process modeling
- Validation & integration

Combining Multiscale Models for Deposition Process Simulation

3D CFD Model
Particle Impact Conditions and Deposition Footprint







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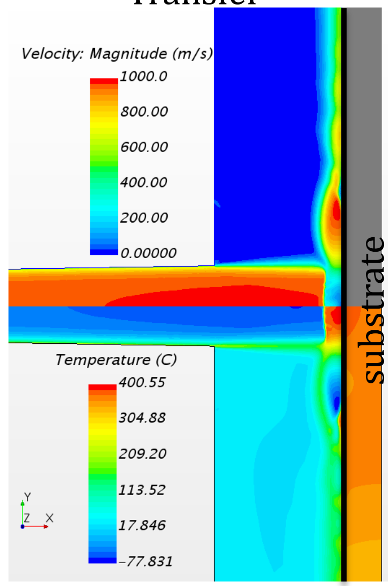
Axisymmetric CFD Model
Jet Impingement Heat Transfer



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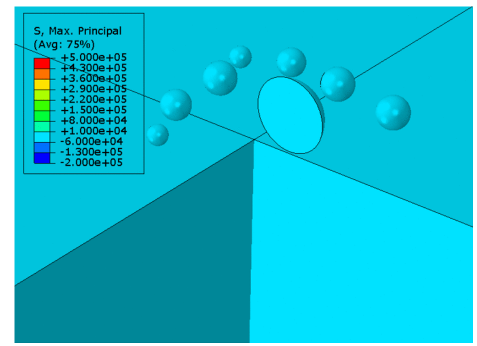
FEA Model
Particle Impact

Kinetic Energy to Thermal Energy Measured from FEA



$$TE_{particle} = 0.34 \cdot KE$$

$$TE_{substrate} = 0.45 \cdot KE$$

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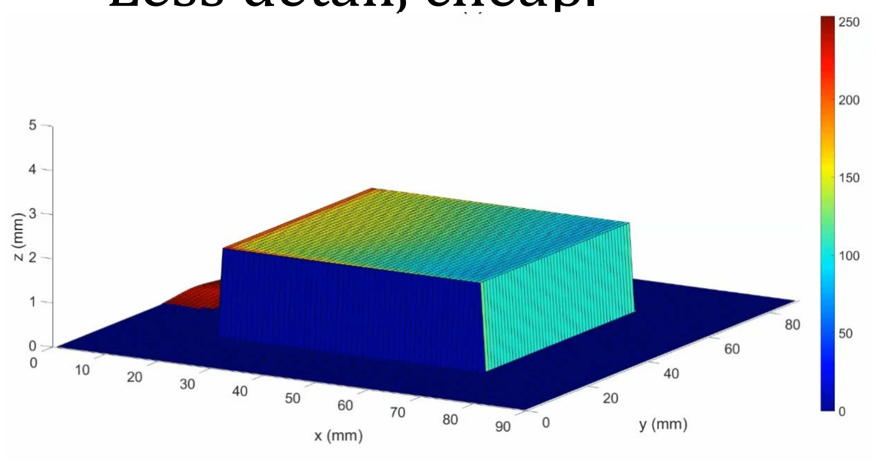
E. Lin, NU

Transient 3D Finite Volume Representation or 3D Finite Element Representation

Bulk Deposition Simulation

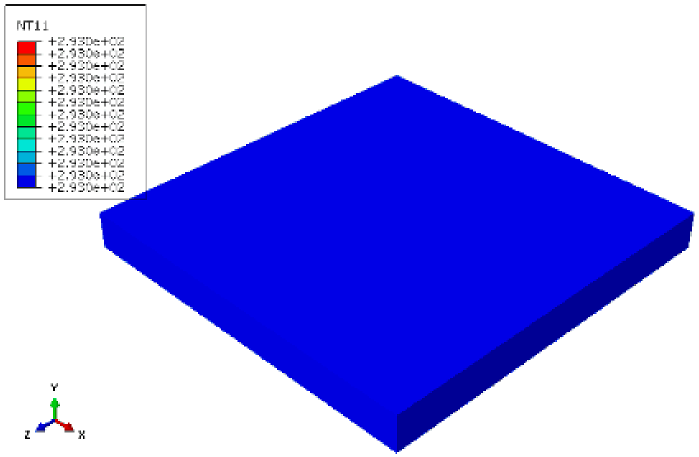
Finite Volume Method (FVM)

- Track thermal history and deposition profile.
- Less detail, cheap.

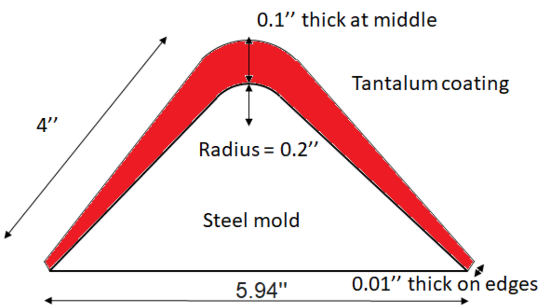


Finite Element Methods (FEM)

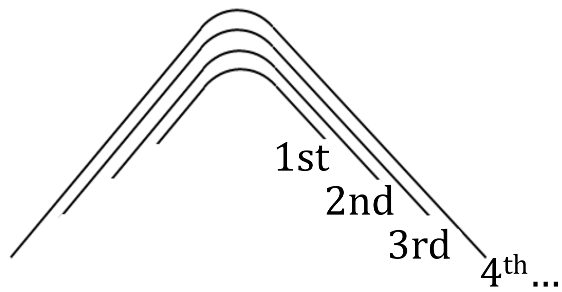
- Track deposition, thermal history, and stress.
- More detail, increased cost.



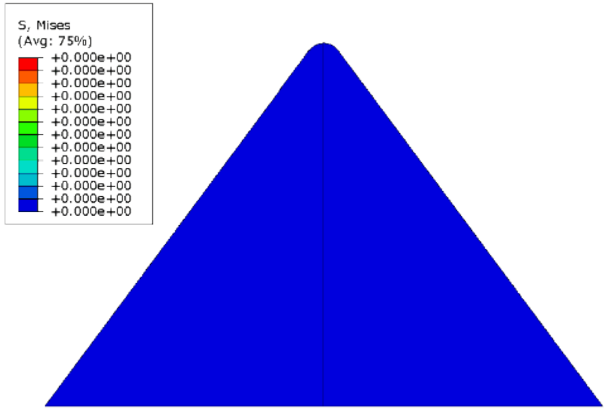
Strategy to Prevent Coating Fracture
Transient Deposition Simulation by FEM



Stragegy-1



Tip First

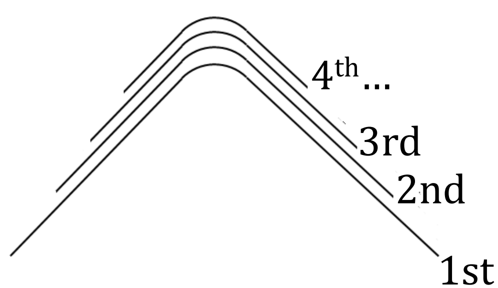


Strategy-2

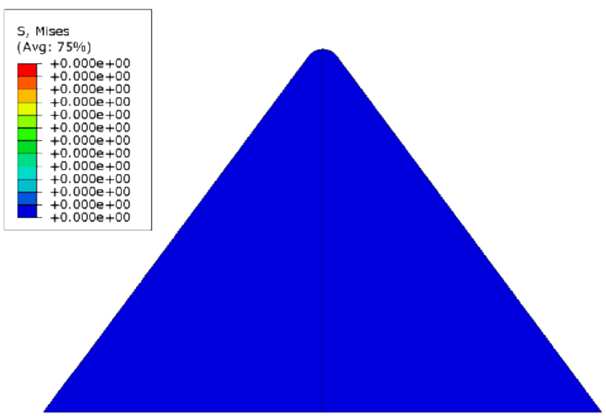
1. Provides lower stress
2. Provides lower maximum temperature

Dr. Enqiang Lin, NU
Dr. Isaac Nault, ARL

Stragegy-2

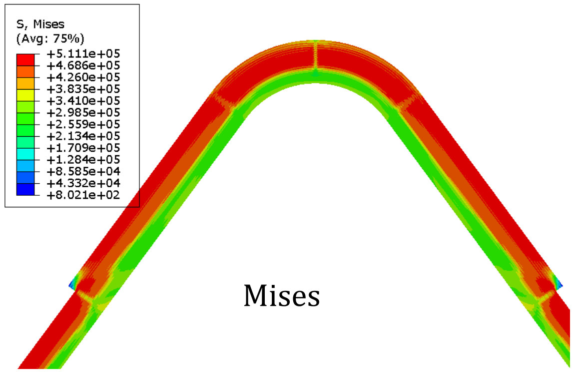


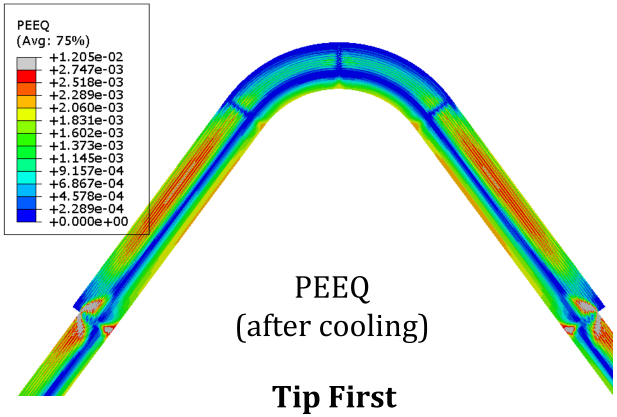
Edges First



Plastic Deformation After Deposition

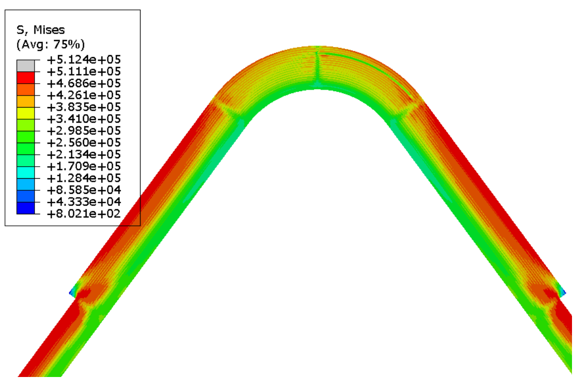
Strategy 1

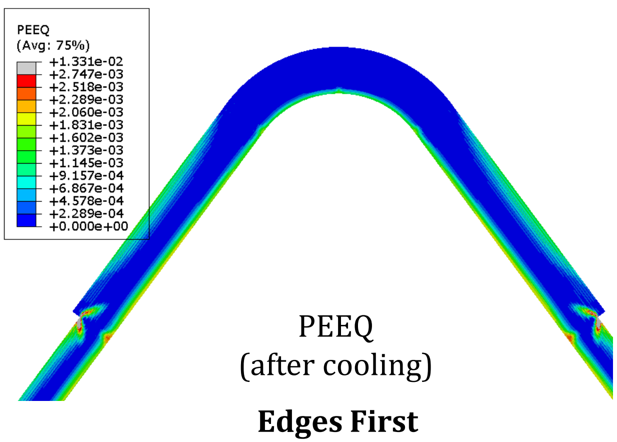




Shows more distributed high plastic deformation in coating.

Strategy 2

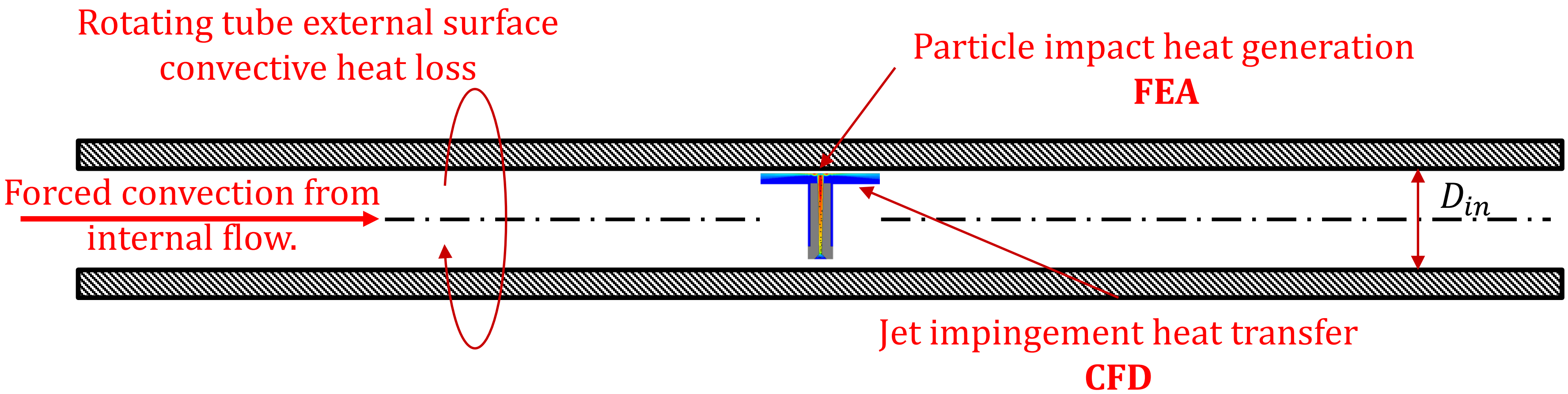


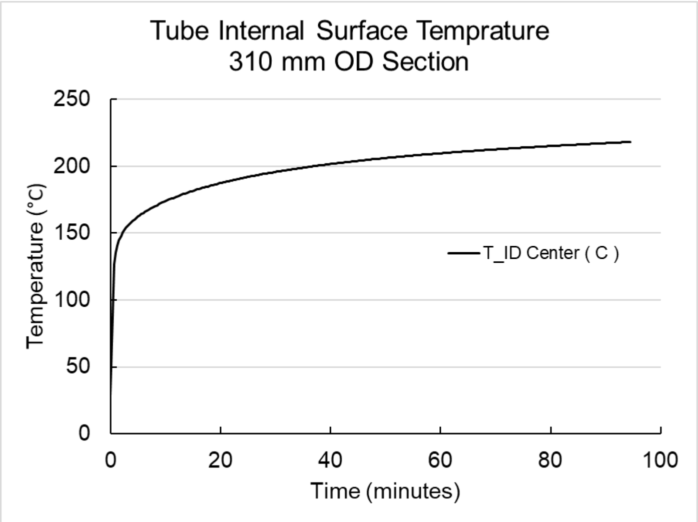


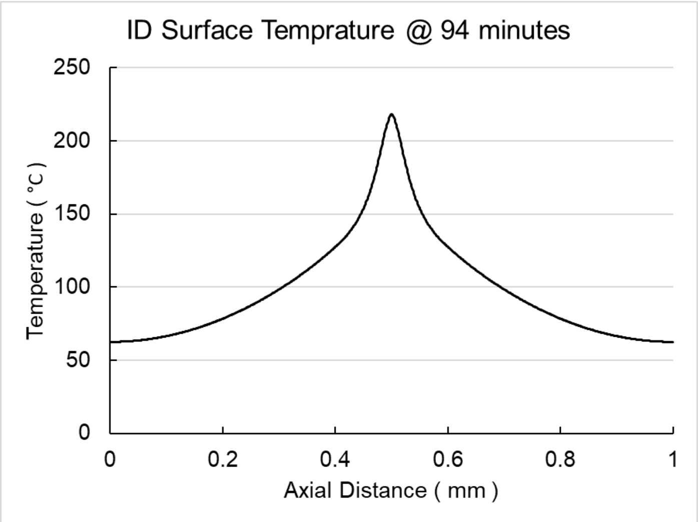
- Preferable
- Less plastic deformation after deposition and cooling.
- Less likely to fail.

Thermal Modeling of a Tube Internal Surface Coating Comprehensive FVM

Estimate worst case scenario maximum temperature in a steel tube.



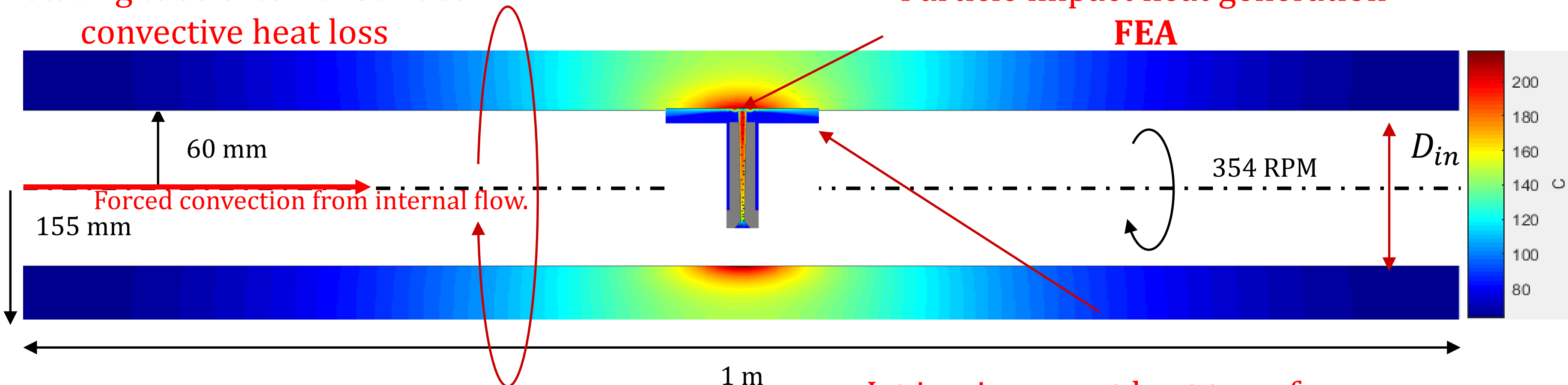




Thermal Modeling of a Tube Internal Surface Coating

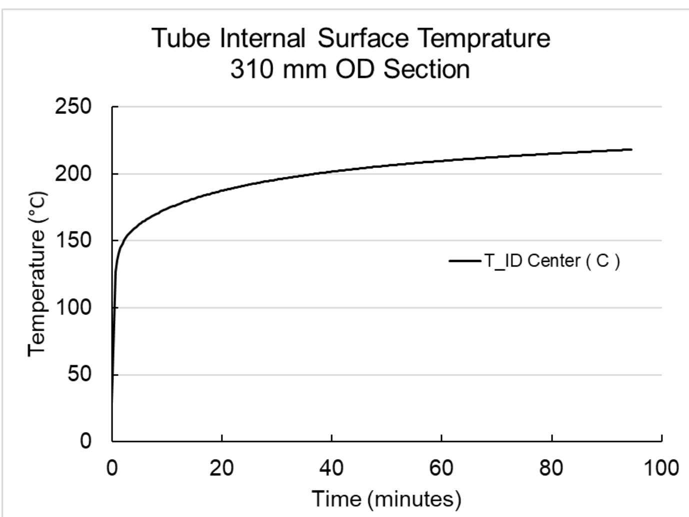
Rotating tube external surface convective heat loss

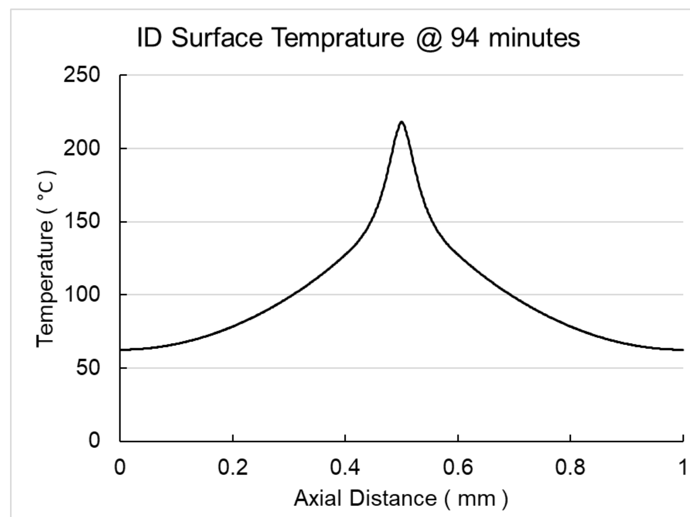
Particle impact heat generation
FEA



Jet impingement heat transfer
CFD

After 94 minutes

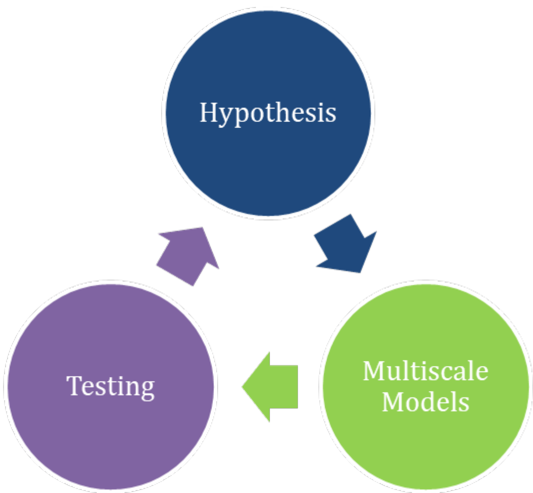


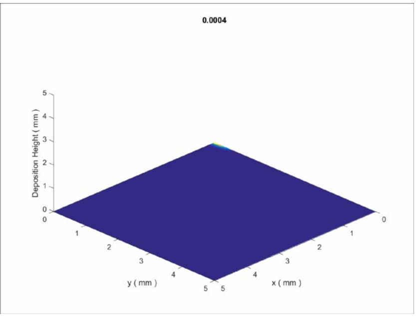


- Gas & Powder Flow Modeling
- Impact process modeling
- Material buildup process modeling
- Manufacturing process modeling
- Validation & integration

Motion Strategy and Integration

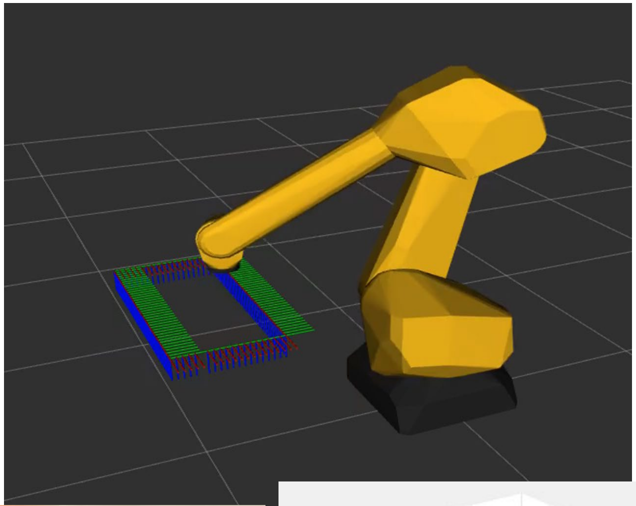
Modeling Favorable Patterns

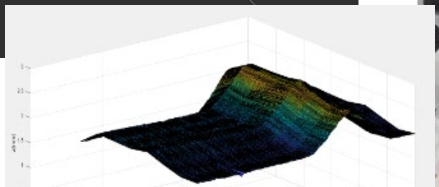




Robotic Path Generation

Dr. Taskin Padir
Joseph Lynch





Deposition profile from integrated sensor

In-Situ Process Monitoring

Design Team
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Ozan Ozdemir, Andrew Gouldstone

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- Manufacturing process modeling
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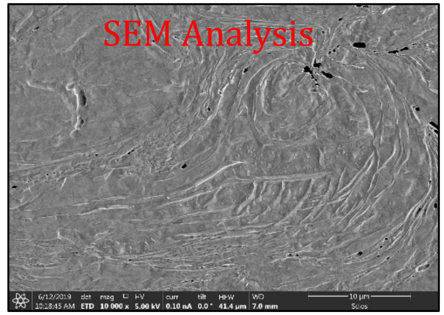
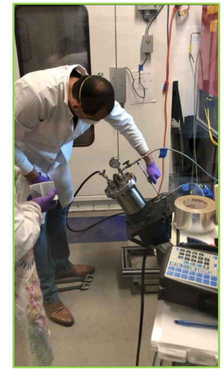
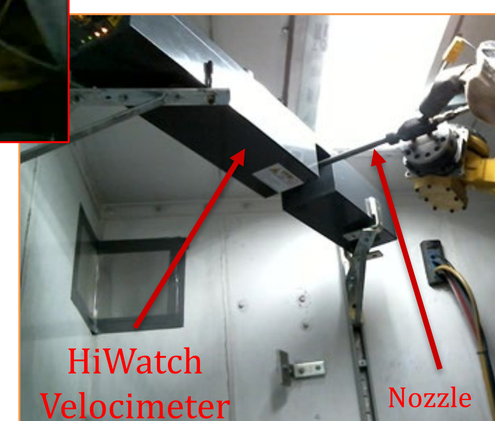
Validation & Integration



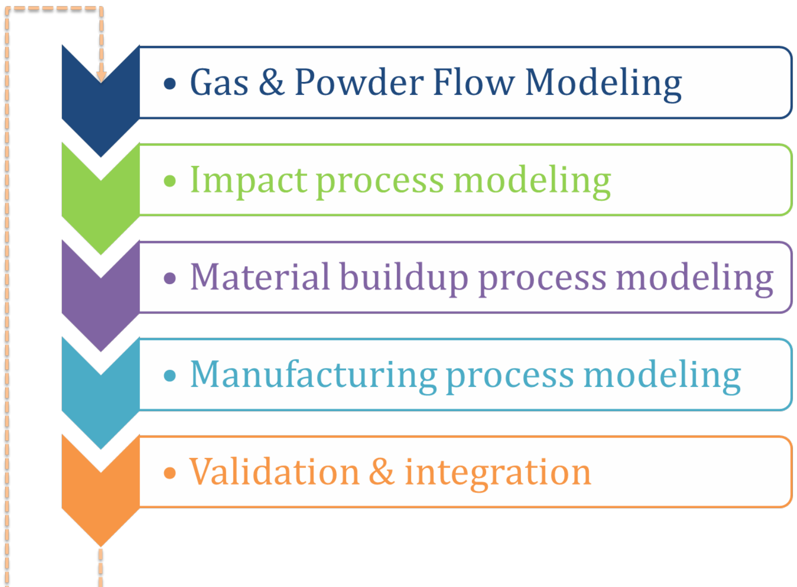


NU CS Laboratory
VRC Gen III Max
Quantum He Recovery
6 kW Laser (Donated by IPG Photonics)
Inert Powder Processing Unit
Testing & Analysis Laboratories



Takeaways

- Target focused modeling approaches help us refine our daily cold spray operations.
- Validated modeling tools (as shown here) can help reduce experimentation costs significantly.
- Help determine the direction we should go with variables to improve systems and procedures.



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Sponsors
Army Research Laboratory

Partners
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United Technologies Research Center
VRC Metal System

Thank you!
Questions?

Acknowledgements

Further Questions?

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