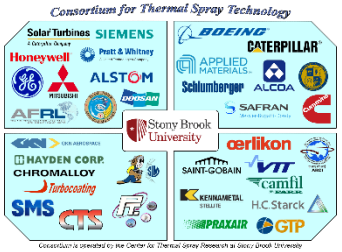
Methodologies to Interpret Properties of Sprayed Materials

Andrew Vackel, Gregory Smith, Brian Choi,
Prof Toshio Nakamura, Prof. Sanjay Sampath

CSAT June 23rd 2015



Center for Thermal Spray Research

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Thermal and Cold Spray as Additive Manufacturing

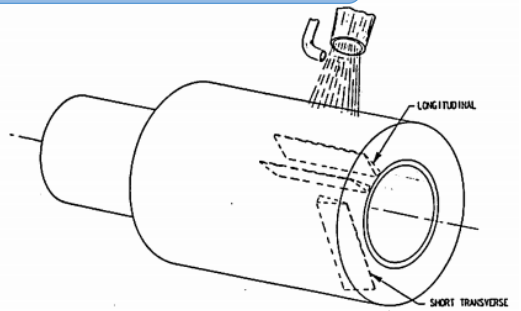
Historical and Present Uses

Spray Forming

- Explored in the 80s and 90s
  - Low Pressure Plasma Spray, Range of Materials – Ceramics, Intermetallics, Super alloys
- Direct and Traditional Testing
  - Freestanding objects

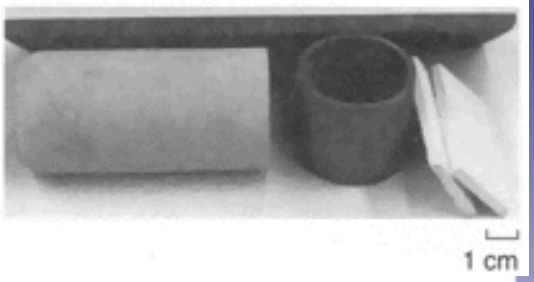
Aircraft Engine Gas Turbine Component Fabrication Concepts using RSPD – Johnson, Kelm, Smashey, Rigney, Wakeman, General Electric Co. 1982

Coatings

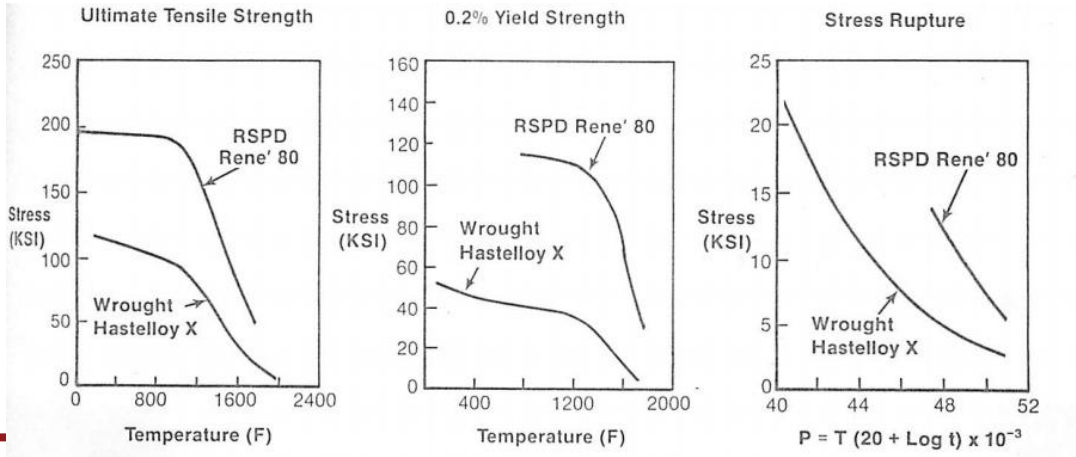


The Mechanical Behavior of RSPD Materials – Jackson, Smashey, Peterson, General Electric

Reclamation



Sampath S, Gansert R, Herman H. JOM 1995;47:30.

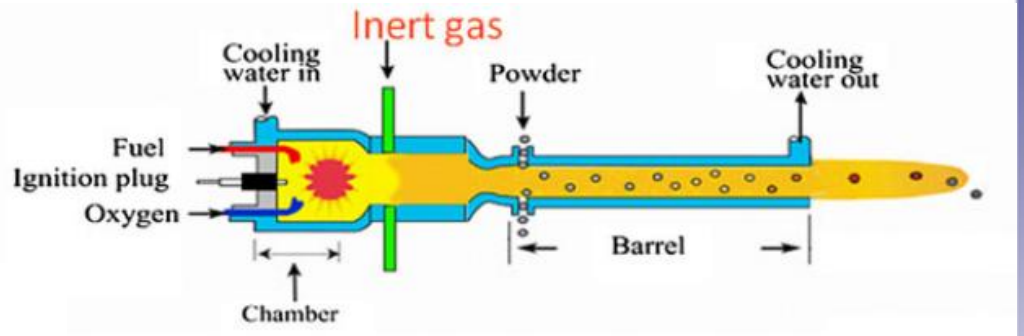


Progression in Spray Forming Technologies

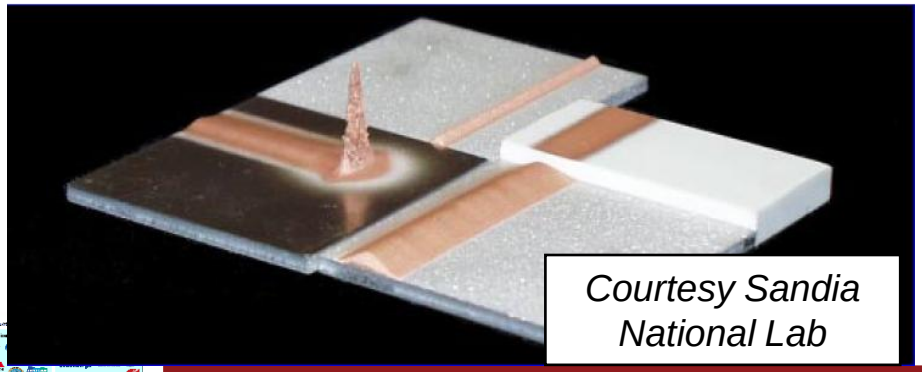
Historical and Present Uses

Spray Forming | Coatings | Reclamation

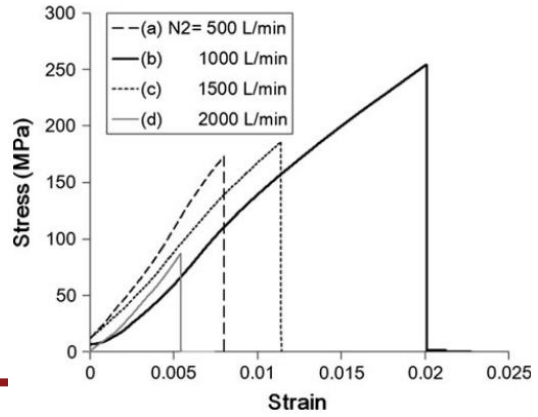
- Presently there is a wider Process Selection
  - Cold Spray, HVAF, Warm Spray
- Opens up application possibilities previously limited by processing limitations



Kuroda, Watanabe, Kim, Katanoda JTST 2011



Courtesy Sandia National Lab



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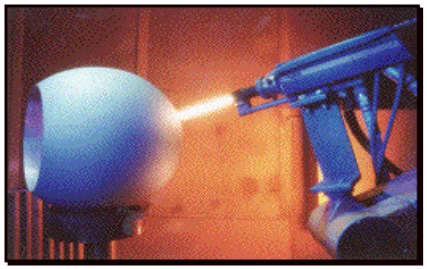
Thermal and Cold Spray as Additive Manufacturing

Historical and Present Uses

Spray Forming



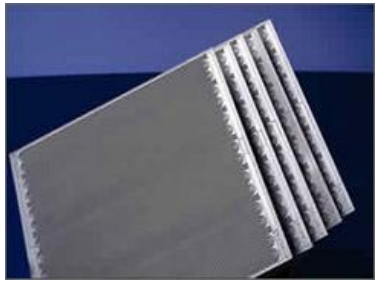
Wear and
Corrosion Protection

Thermal
Insulation

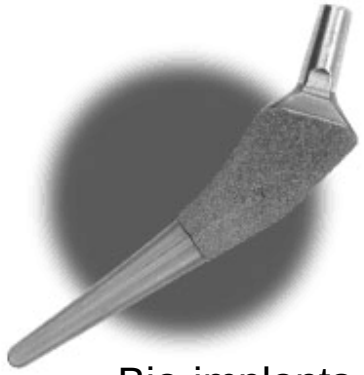
Coatings

- "Bread & Butter" i.e. Conventional deployment of the technology
- Multiple Processes, Materials, and applications
  - Passive Protection for Enhanced Performance (TBCs, Wear and/or control protection, EBCs)
- Value adding or functional materials
- Function Specific Characterization

Reclamation



Advanced oxides
For fuel cells

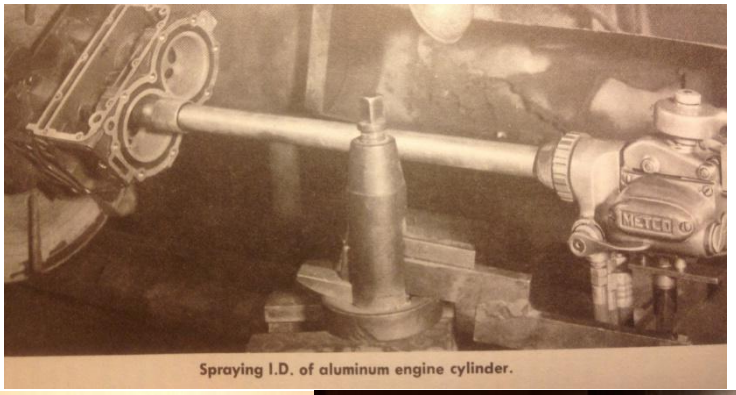


Bio-implants

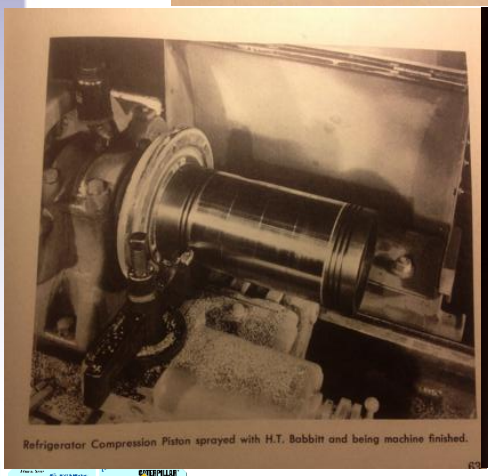
Early Uses for Repair

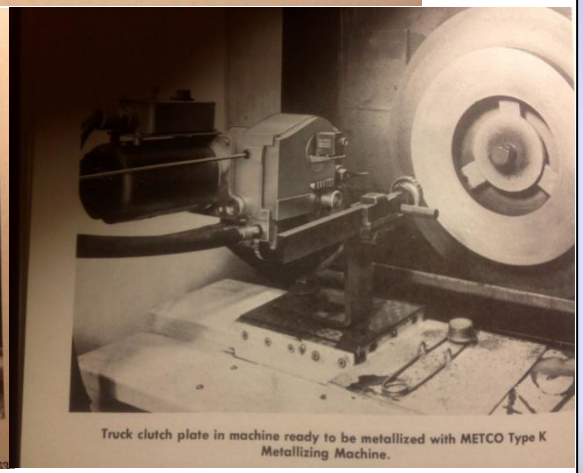
Historical and Present Uses

Spray Forming | Coatings | Reclamation



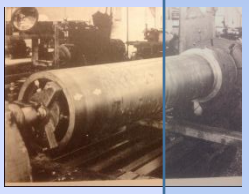
Spraying I.D. of aluminum engine cylinder.


Refrigerator Compression Piston sprayed with H.T. Babbitt and being machine finished.


Truck clutch plate in machine ready to be metallized with METCO Type K Metallizing Machine.

- One of the earliest uses for spray deposition (metalizing)
- New technology advances (HVOF, HVAF, Warm Spray, Cold Spray) open new opportunities
- Hierarchy of Performance Need in Repair
  - Cosmetic
  - Dimensional Restoration
  - **Structure Stabilization**
  - **Load Recovery**
- **How do we address the efficacy of such a composite?**

Timeline of Application Integration



$ Billions since 1900

3.00 -
2.50 -
2.00 -
1.50 -
1.00 -
0.50 -

Material restoration
Corrosion control
Yankee Dryer
Auto Piston Rings
Aerospace WC-Co
Aerospace ZrO2
Steel Mill Rolls
Paper Industry
Implants
IGT TBCs
Auto cylinders
Landing gear
Semi Conductor industry
Functional oxides
Heavy Machinery reman

1910 1930 1950 1970 1990 2010

Approximate time period noted and only exemplary applications are included

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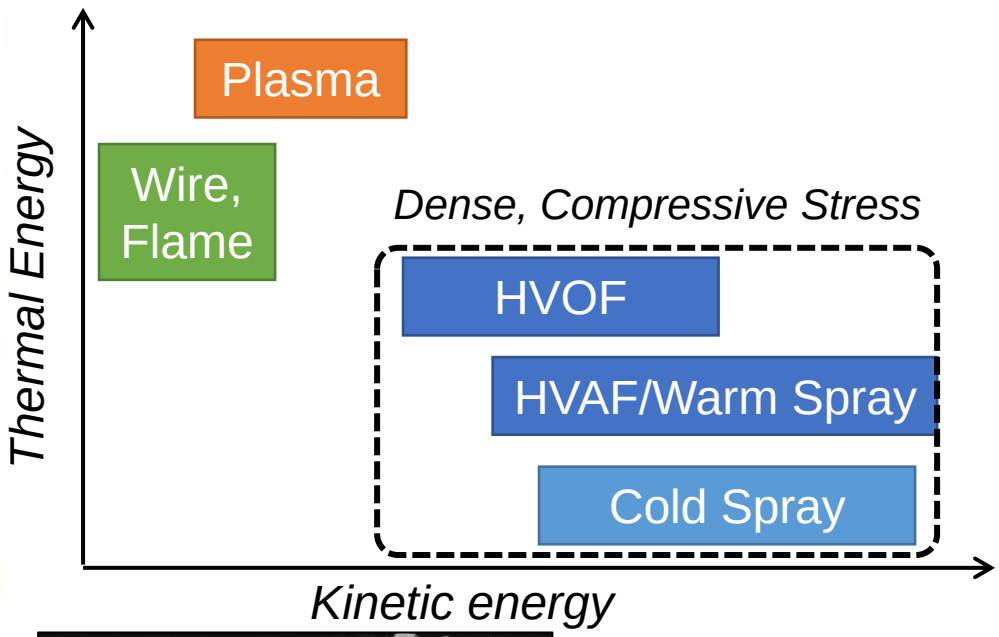
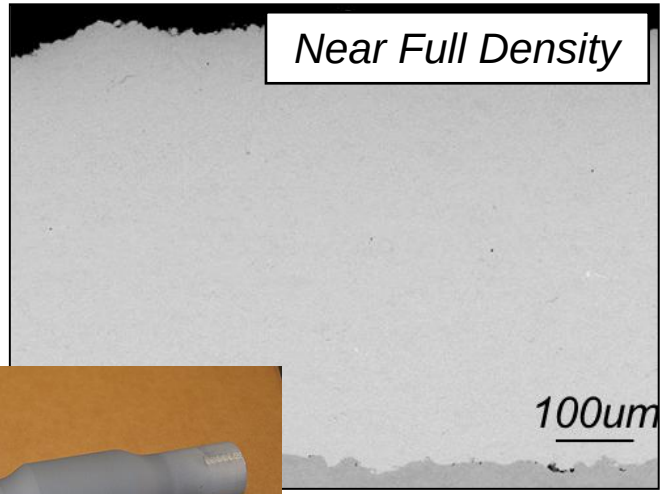
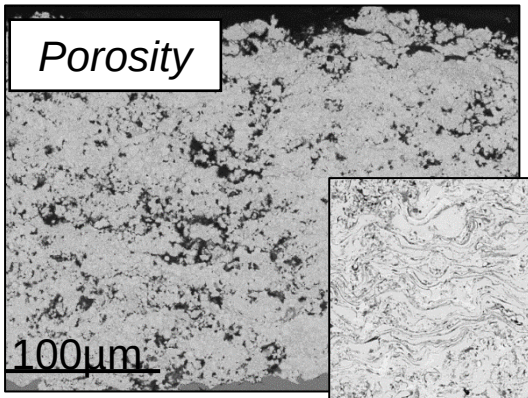
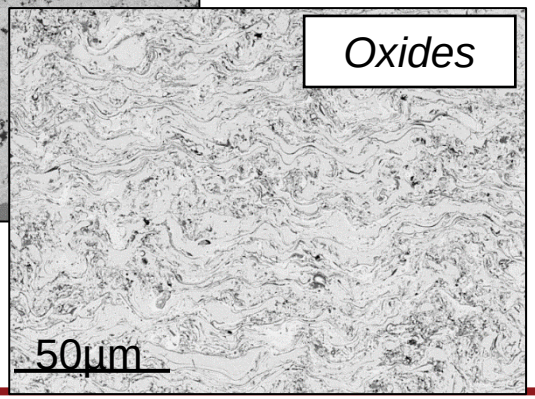
Progression of the Technology









- Hierarchy of Performance Need in Repair
  - Cosmetic
  - Dimensional Restoration
  - **Structure Stabilization**
  - **Load Recovery**

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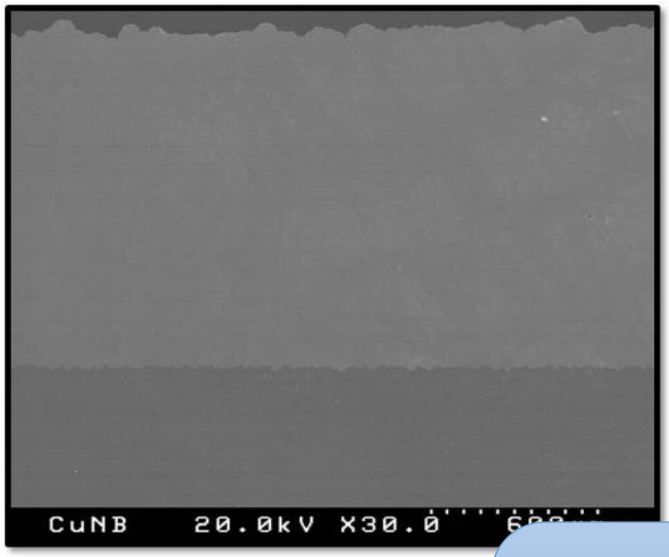
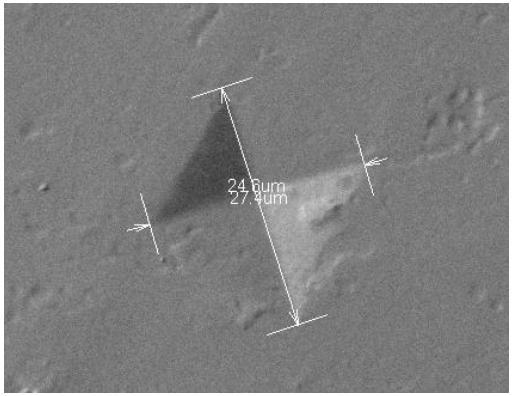
Addressing the Efficacy of Spray Composites for Repair?

- Adhesion
- Microstructure
- Hardness

Bond Strength



%Porosity, Composition

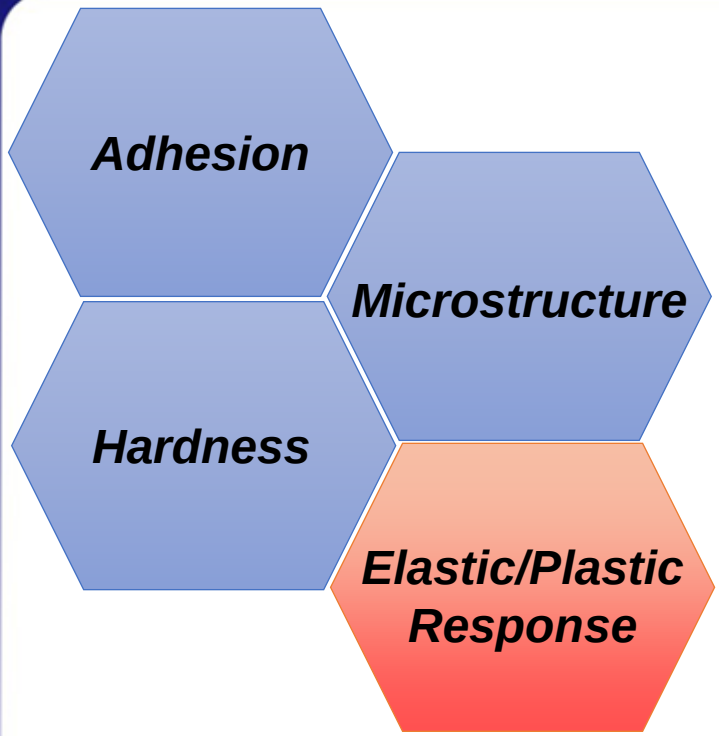


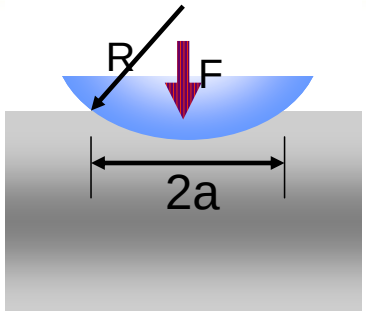
Vickers, Rockwell, Brinell etc.

What do these numbers tell us?

What other information can we use?

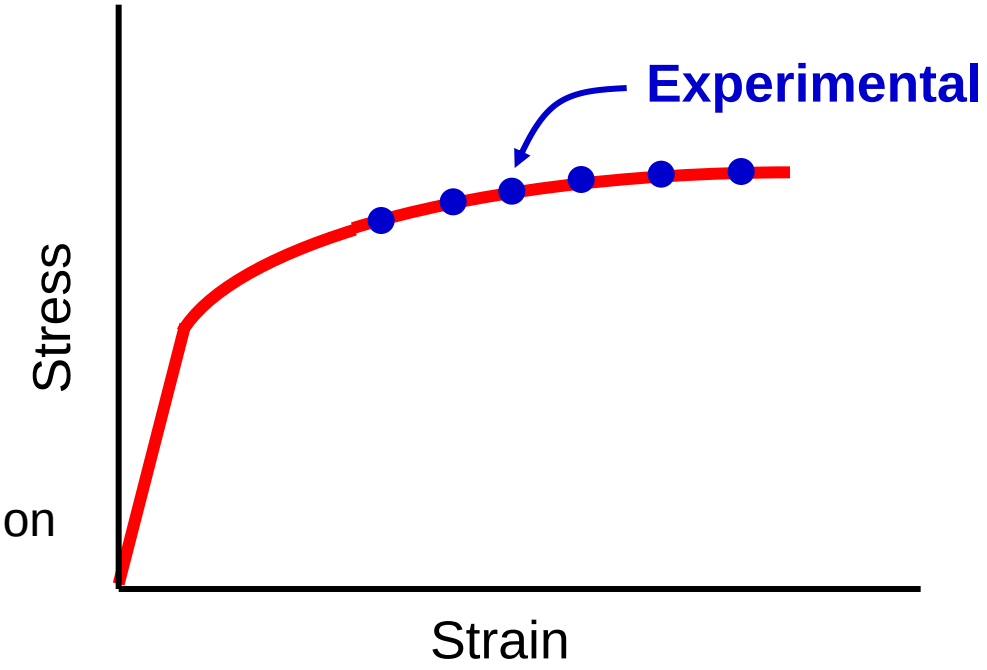
Elastic-Plastic Response via Indentation Stress Strain





$$P_m = \frac{F}{\pi a^2} \qquad P_m = cY \qquad Y \approx 2.6 - 2.9$$

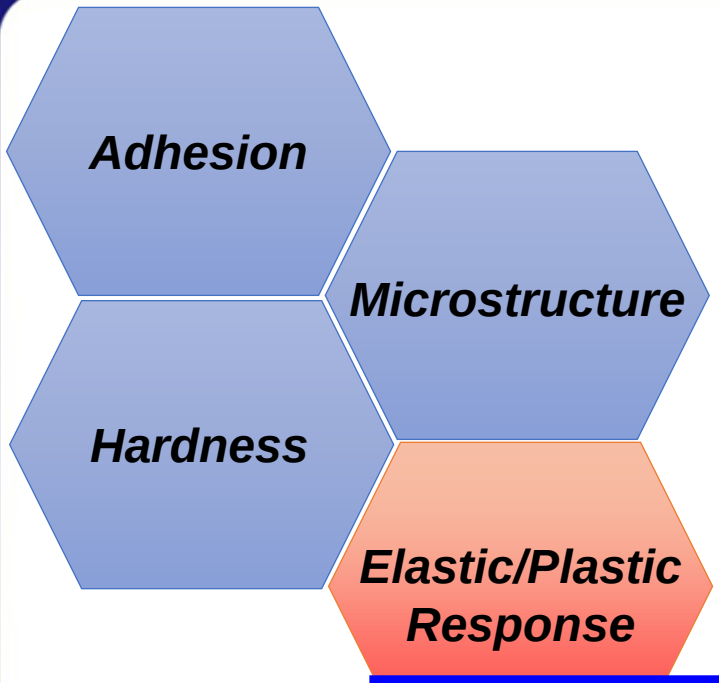
$$\varepsilon_{SPHERICAL} = 0.2\left(\frac{a}{R}\right)$$

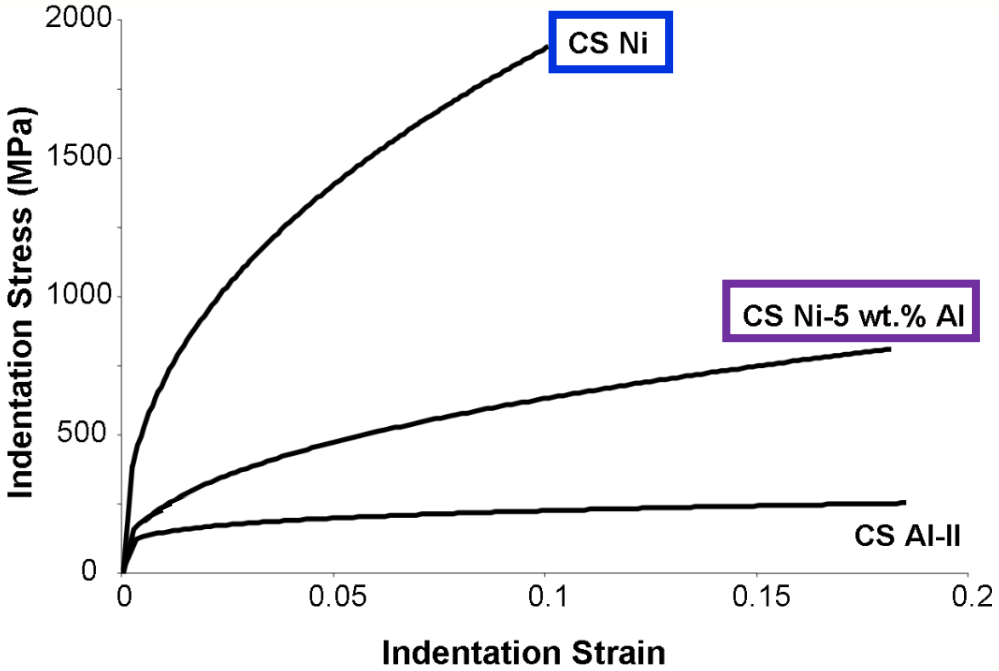


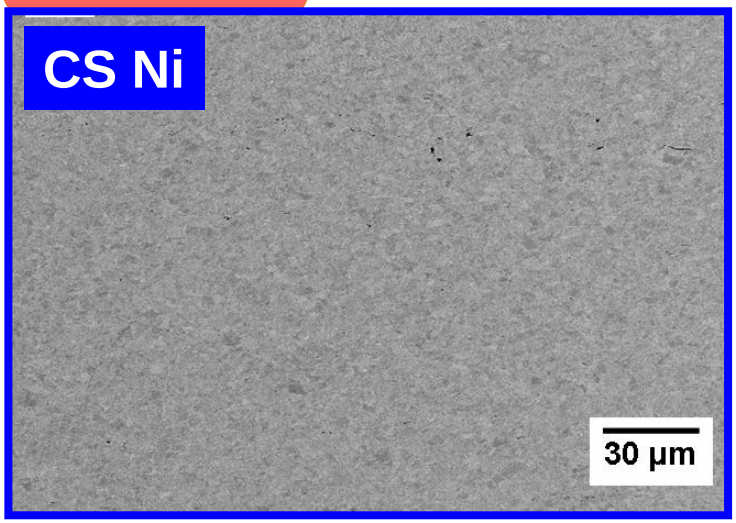
- Minimal Specimen Preparation
- Multi-scale Capability
- Repeatable
- Observe subsurface physics
- Indentation σ – ε

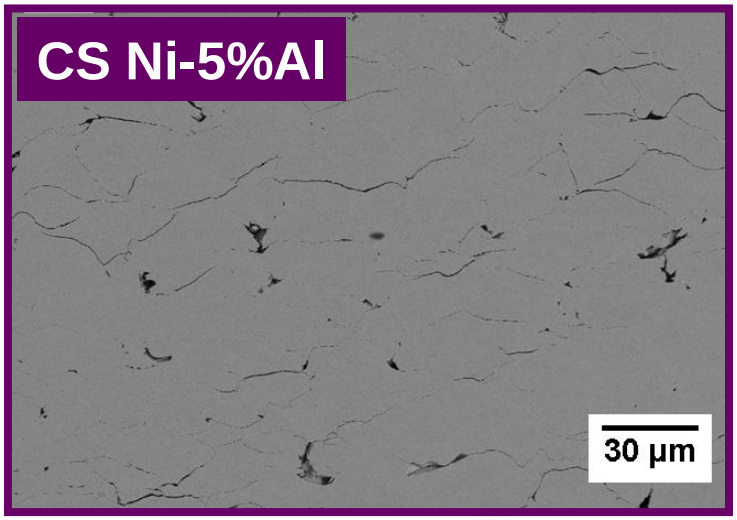
L. Prchlik. Mat. Sci. Eng. A. 360(2003) p. 264

Plastic Indentation Behavior









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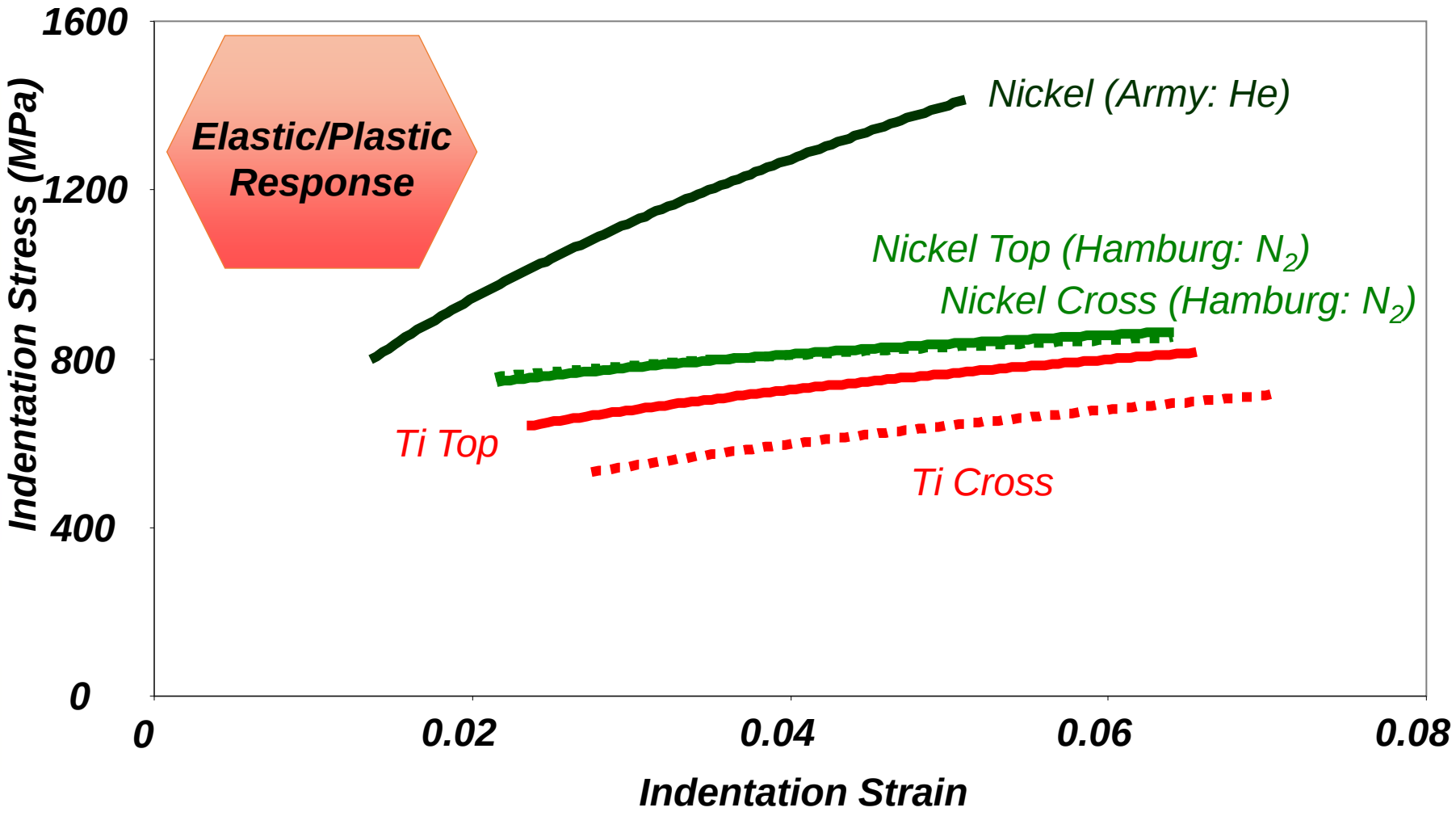
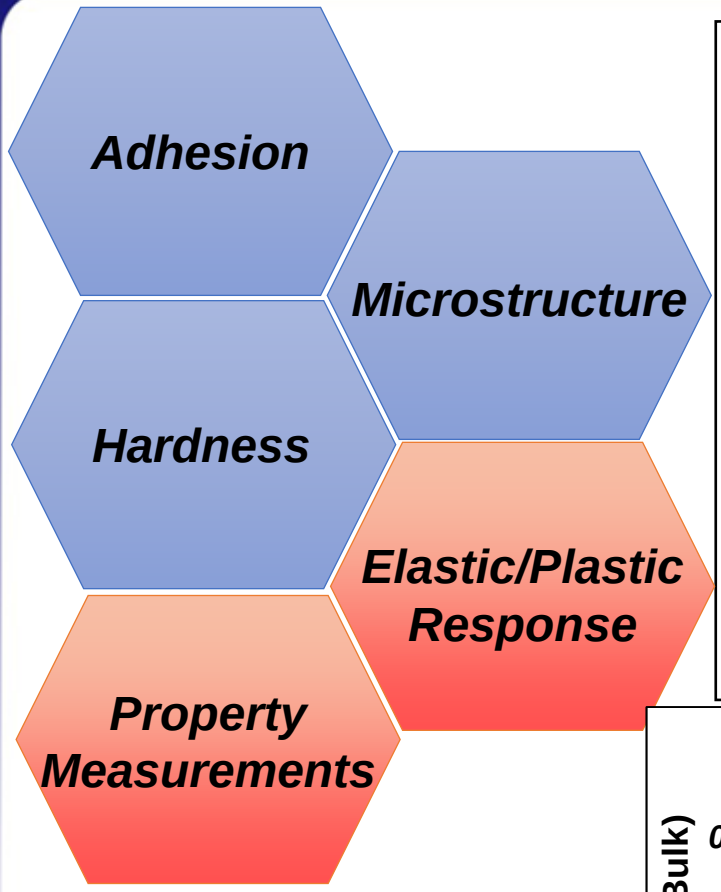
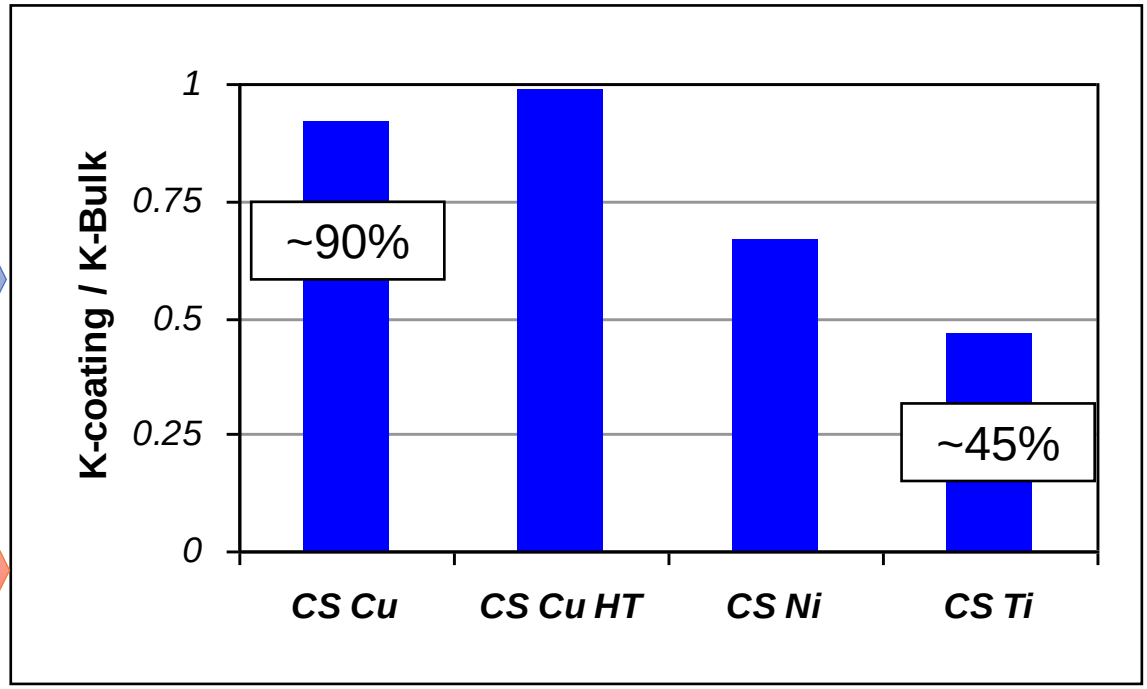
Process Comparing

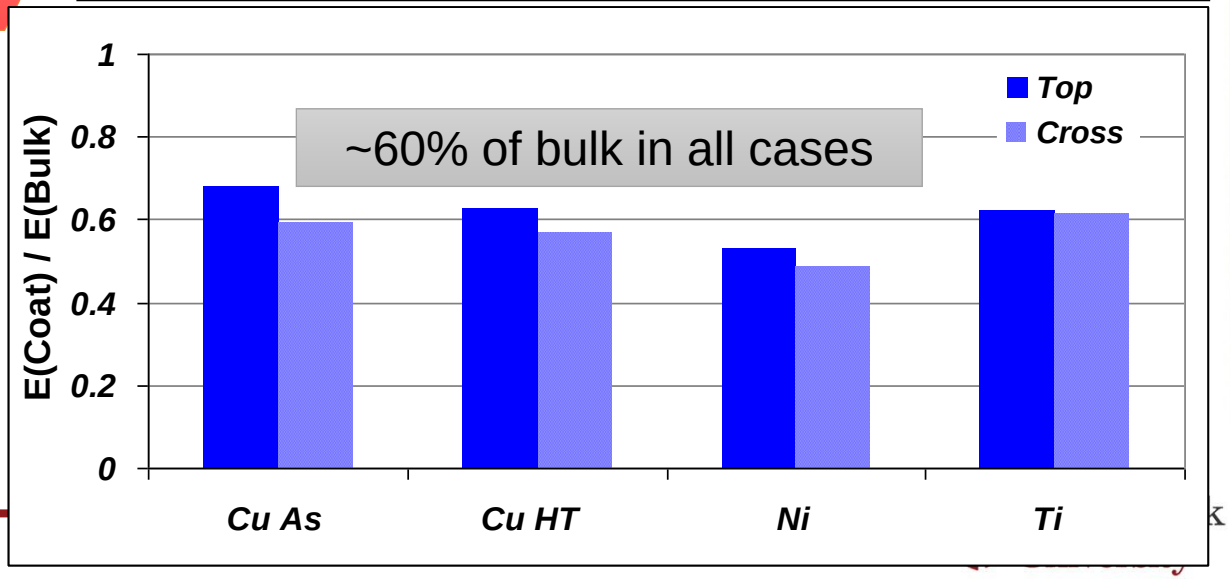


- *Cold spraying using He gas increasing coating strength (better Bonding!)*
- *No plastic anisotropy in Ni coating*
- *Plastic anisotropy in Ti coating*

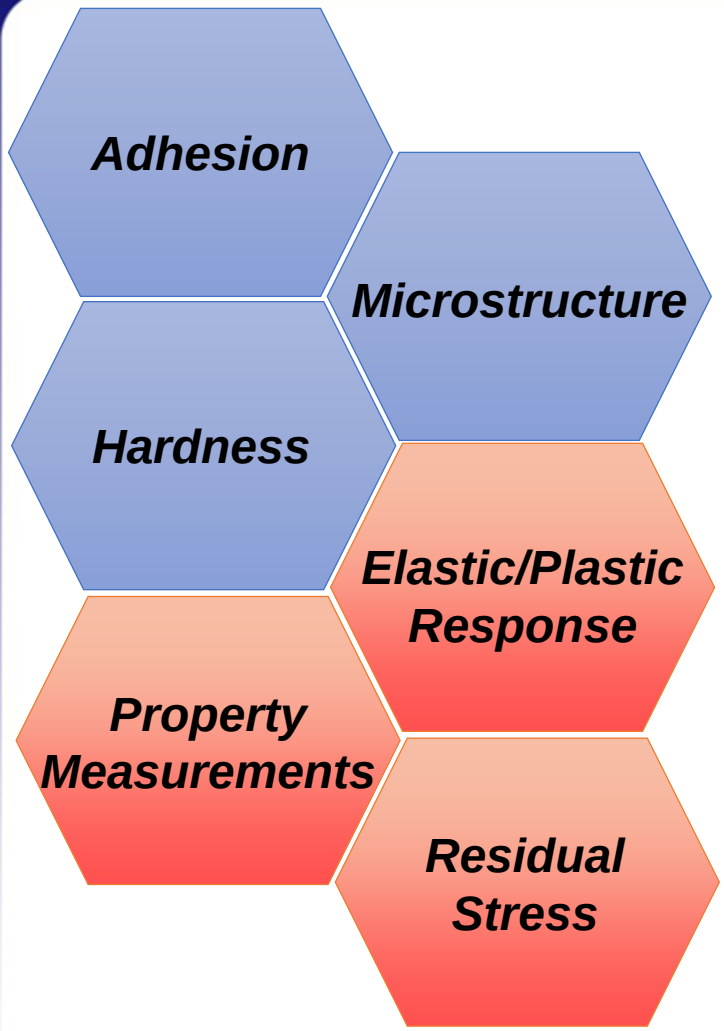
Thermal Conductivity, Anisotropic Moduli

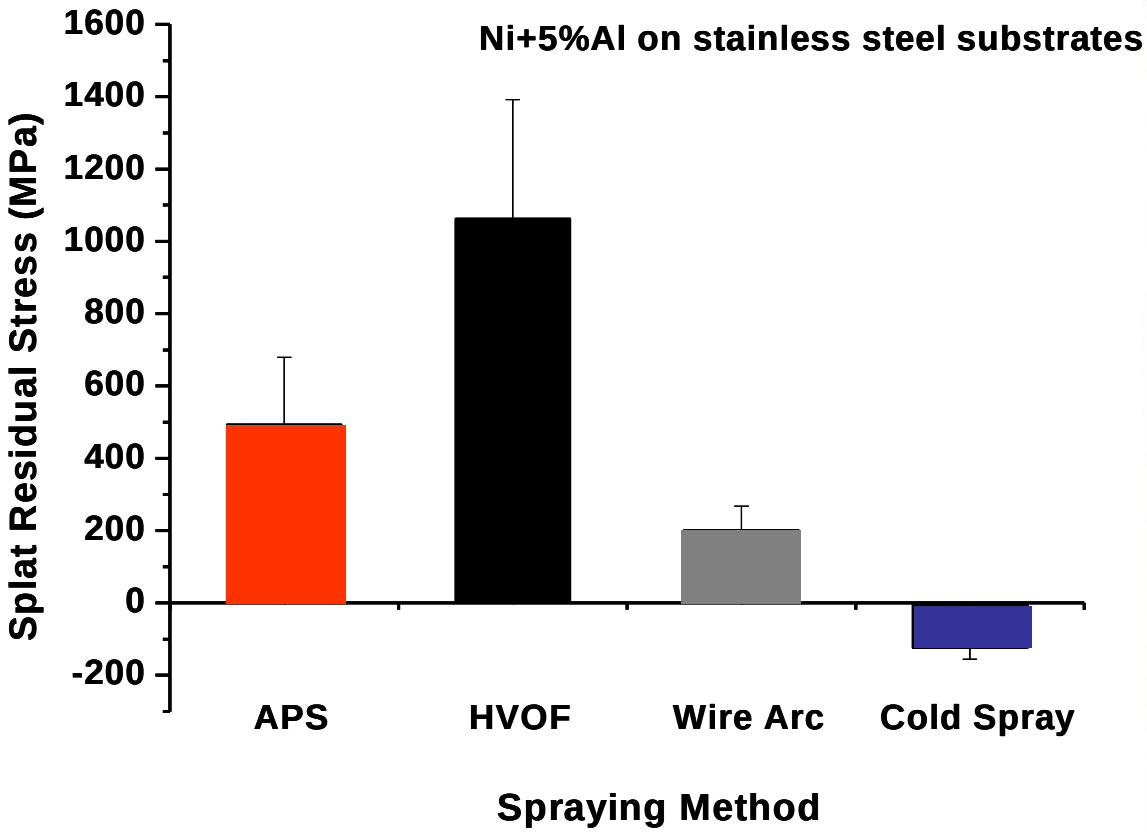




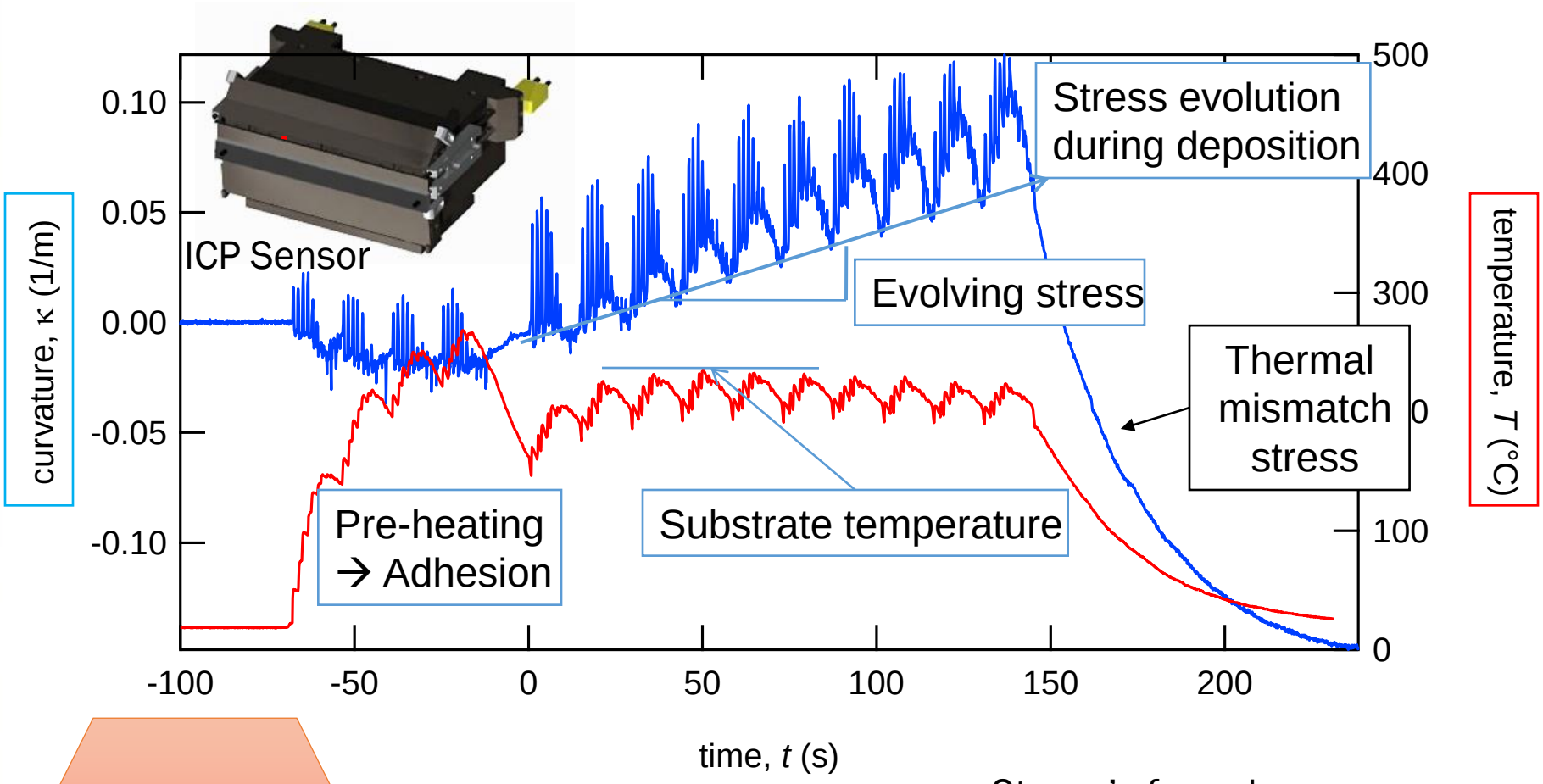


Residual Stress – A Hidden Variable





Curvature Based Stress Measurement



Residual Stress

Stoney's formula

$$\sigma = \frac{E_S' t_S^{\,2}}{6\Delta t_D}\Delta\kappa$$

After Kuroda & Clyne, Thin Solid Films 200 (1991) 49

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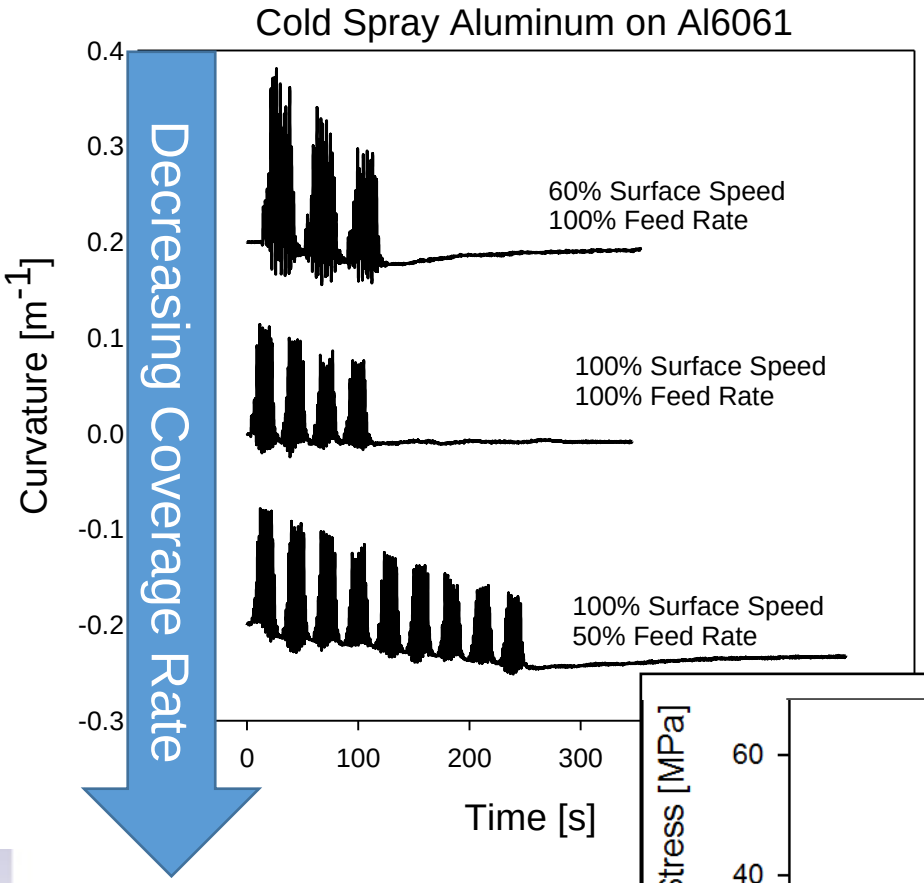
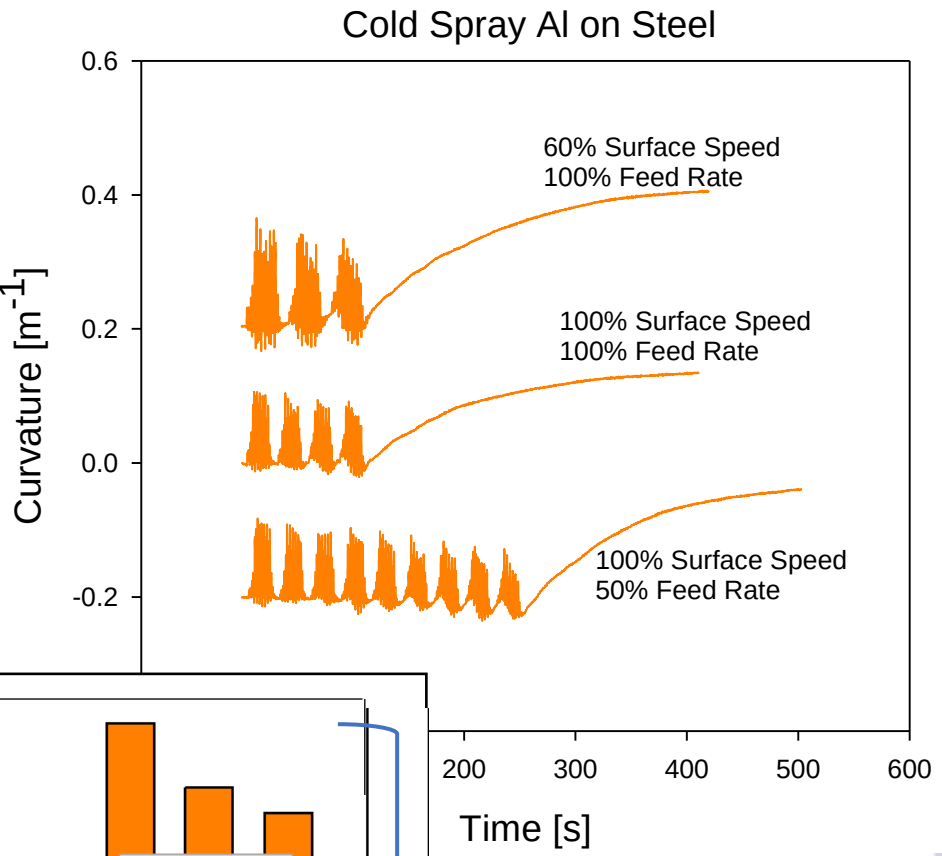
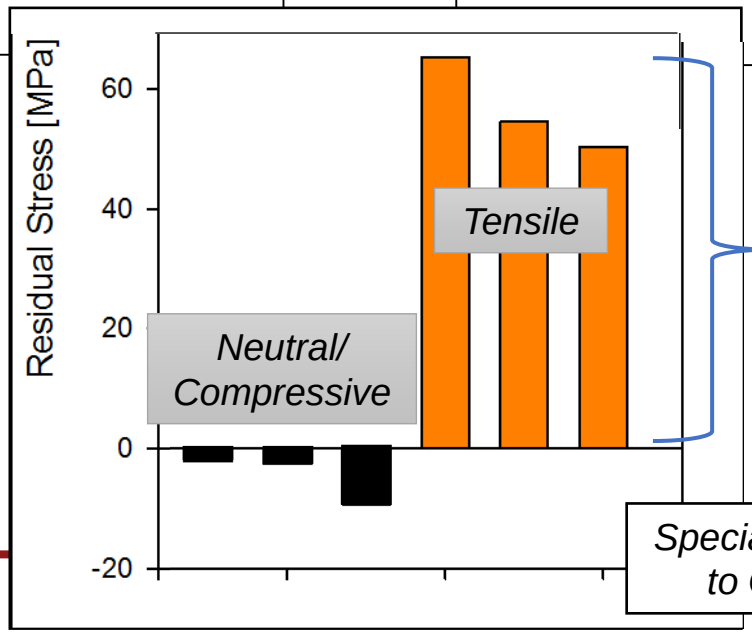
Deposition and Thermal Stresses







Residual Stress

Substrate & Coating Thermal Mismatch

Special Thanks to CNRC

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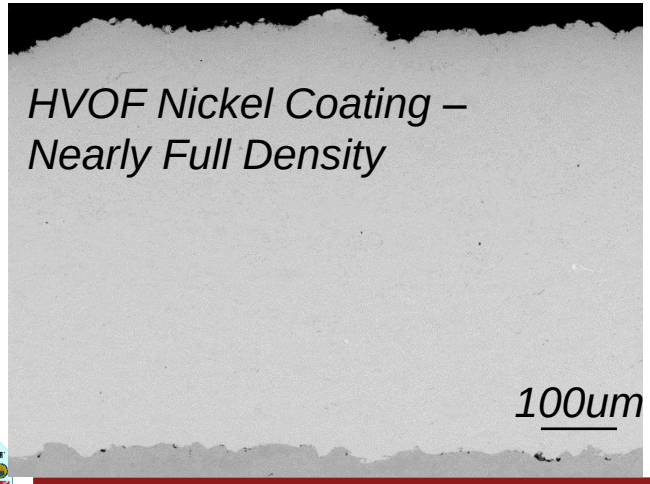
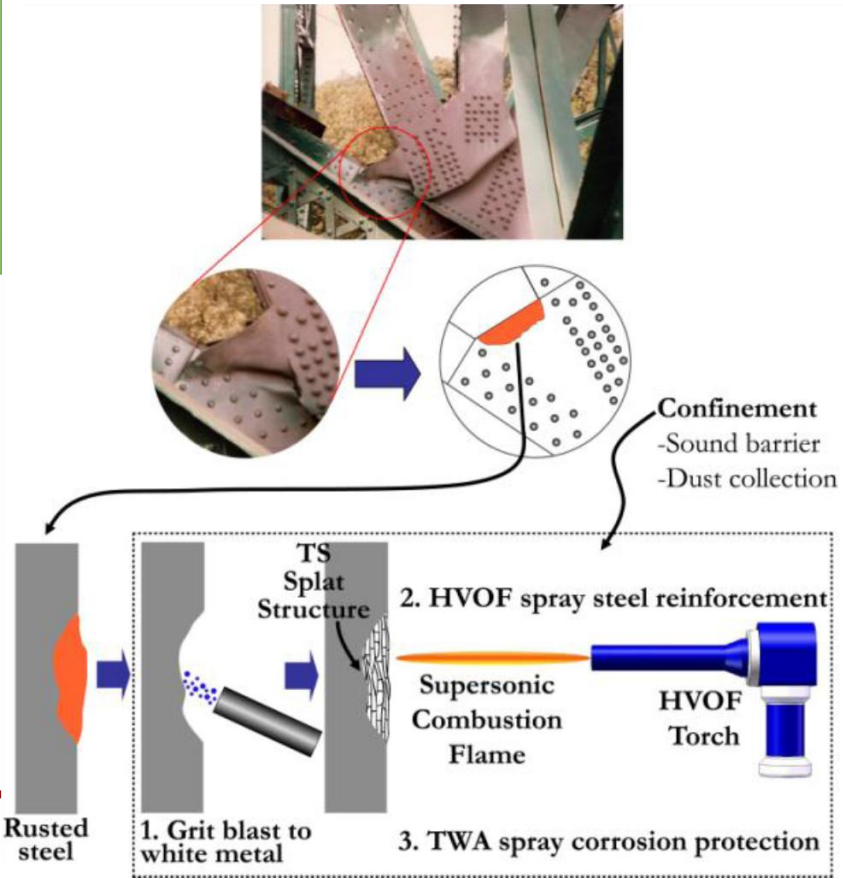
Assessing Load Recovery

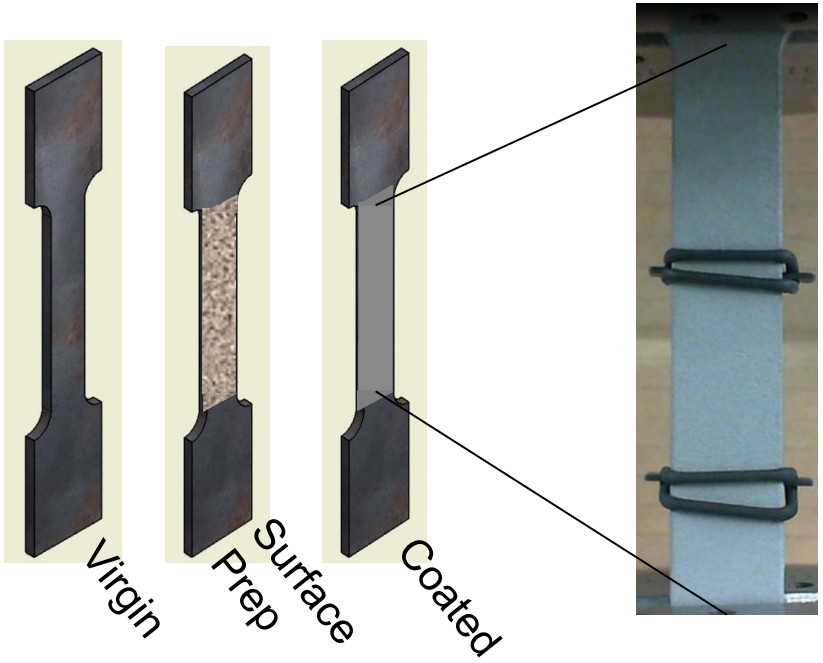
- High Velocity Spray Repair Coatings
  - Produce dense, well adhered coatings with limited phase change in the feedstock material
- Peening mechanism during deposition
  - Compressive residual coating stresses
- **Can it bear load?**

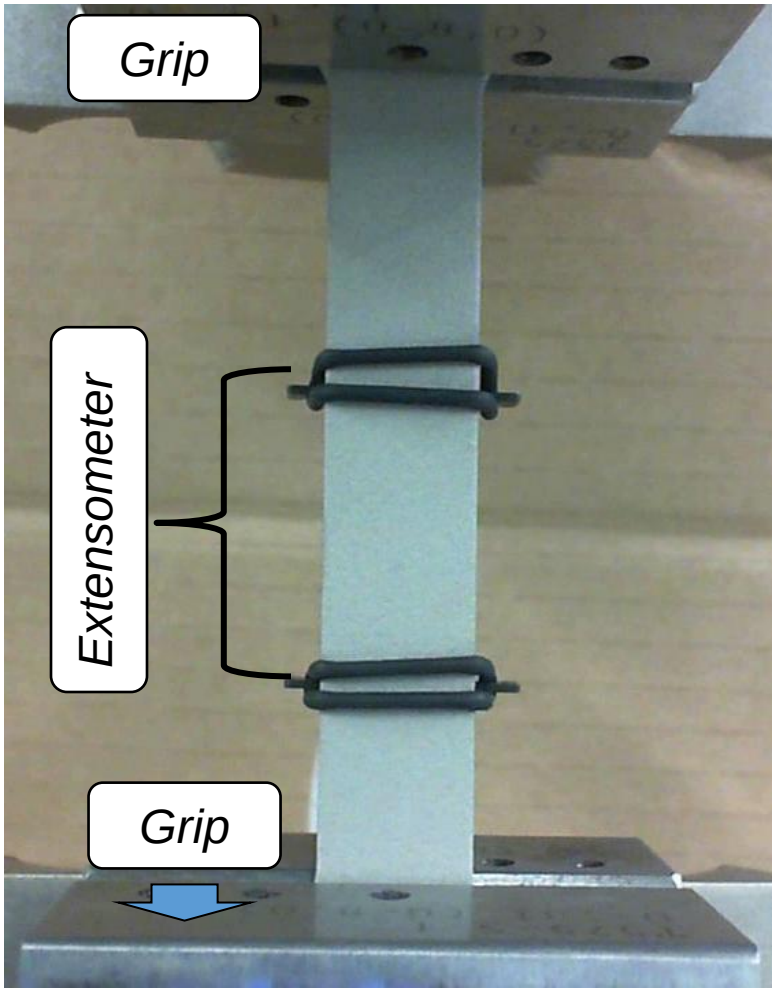
- Hierarchy of Performance Need in Repair
  - Cosmetic
  - Dimensional Restoration
  - Structure Stabilization
  - **Load Recovery**





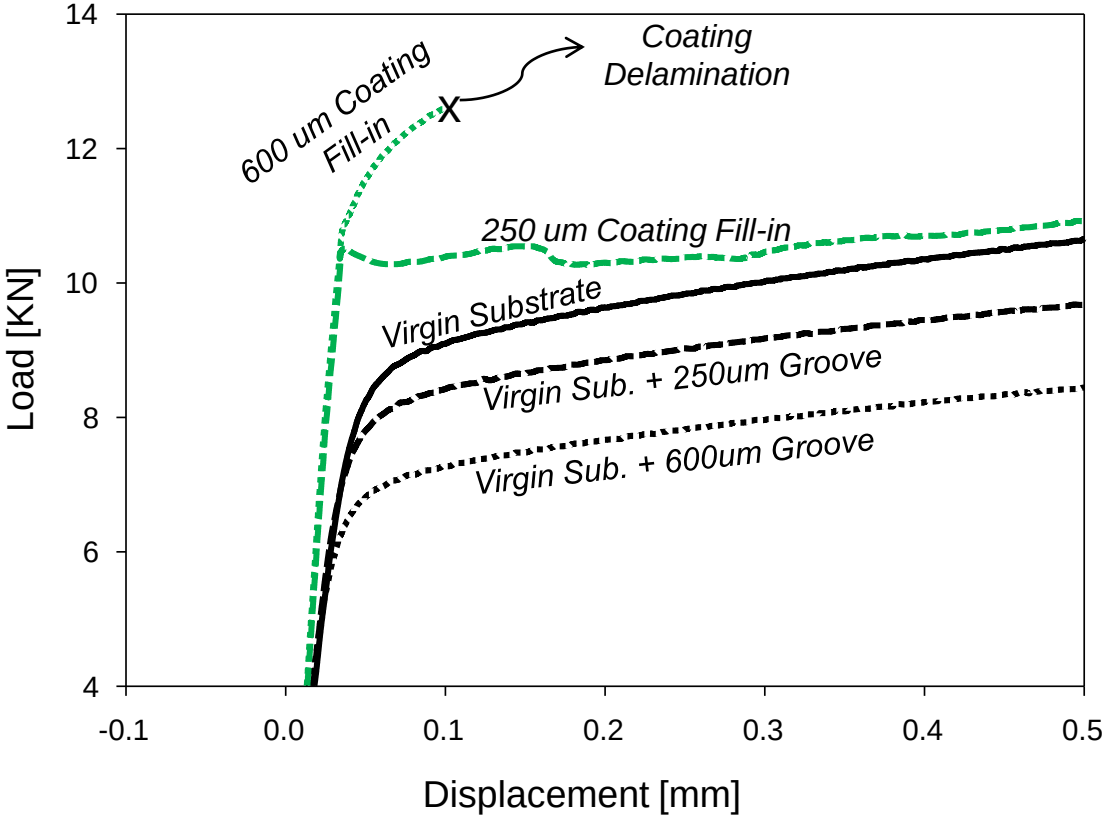
Tensile Behavior of Coated Composites

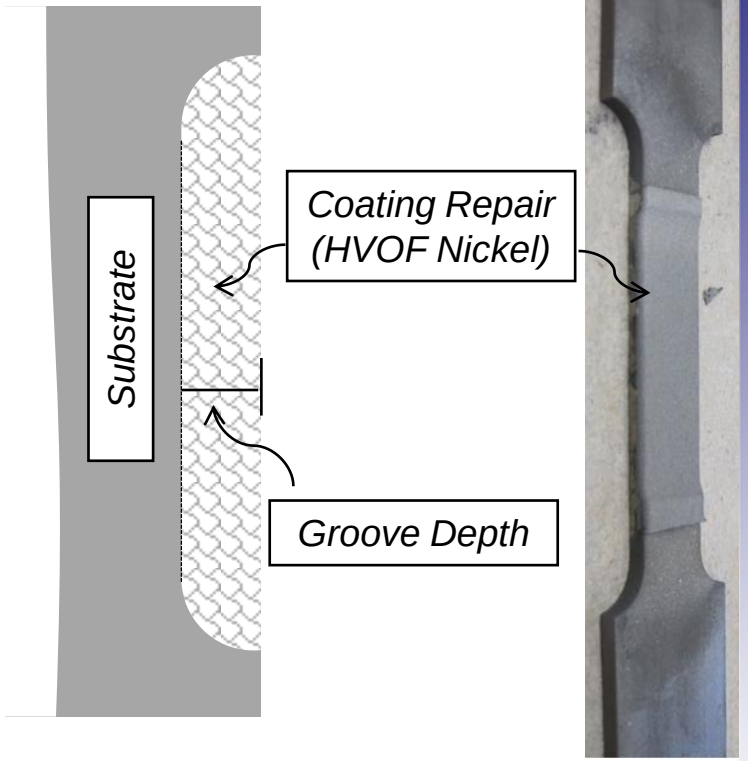




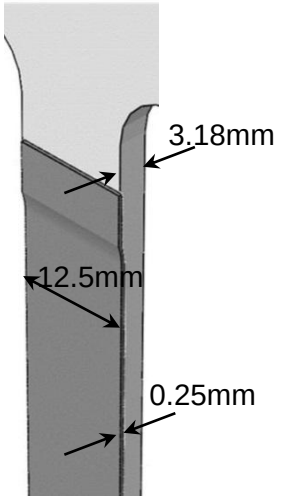
Nickel on Low Carbon Steel at 10% of composite thickness

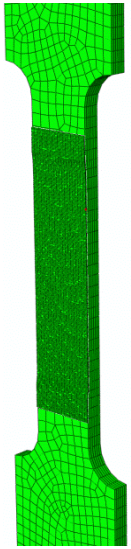
Repairing of "Damaged" Structures

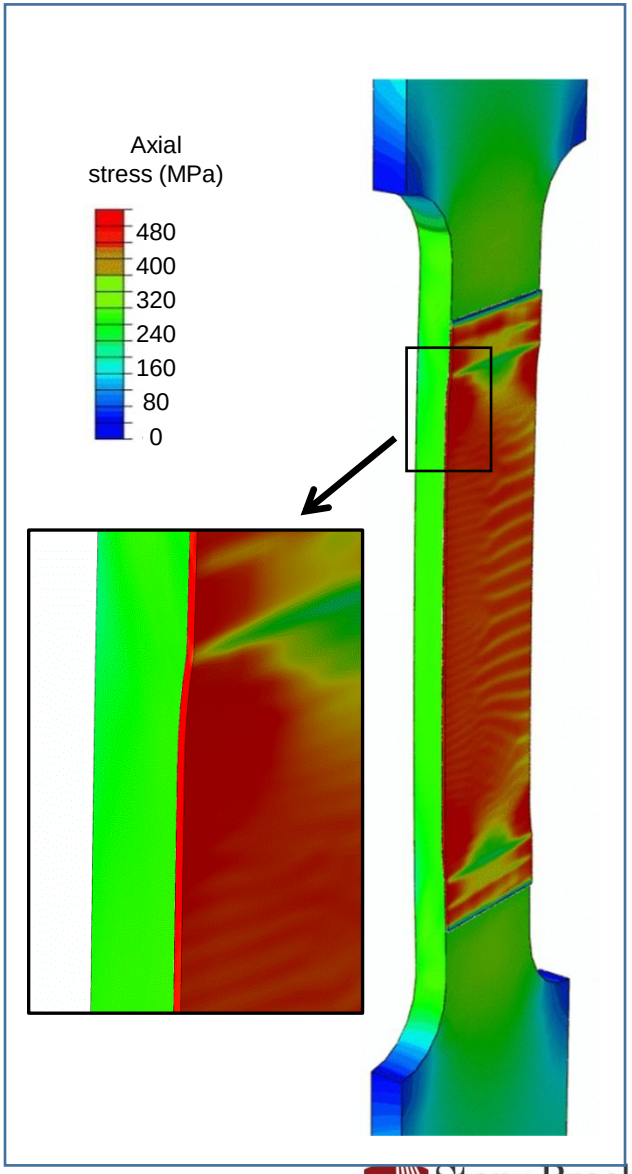


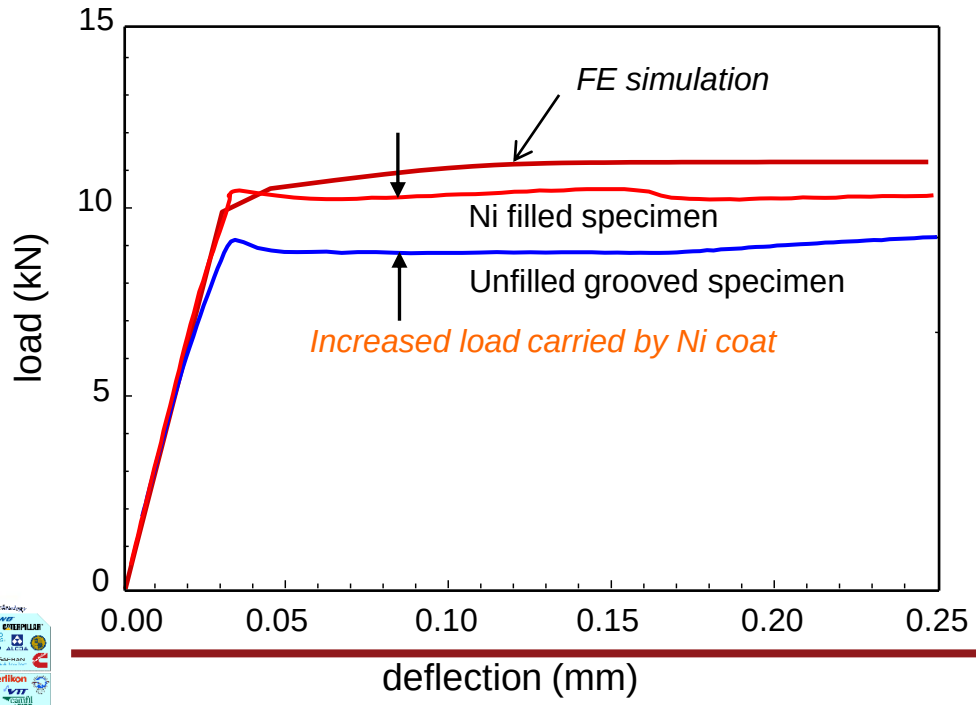


FEM Modeling









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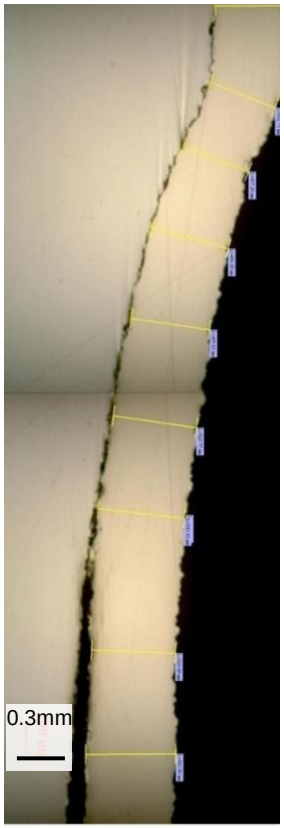
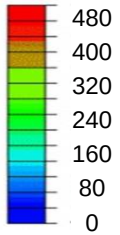
Edges and Groove Corners

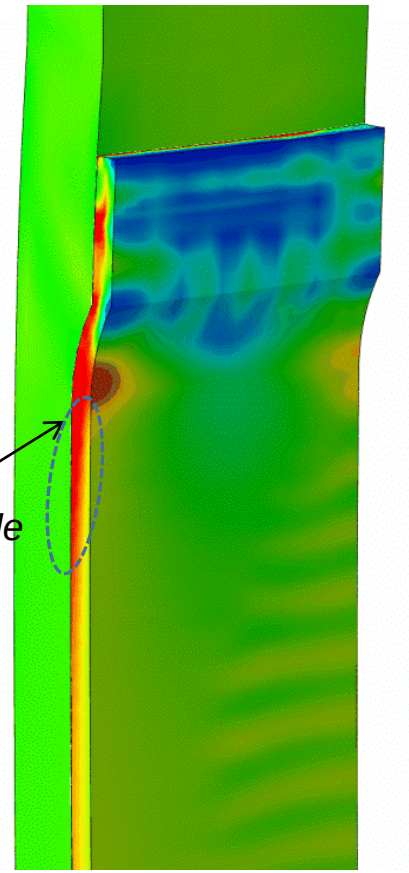
Large stresses develop near the groove and may promote delamination of Ni coating under tensile loading for thick coat.

0.6mm thick

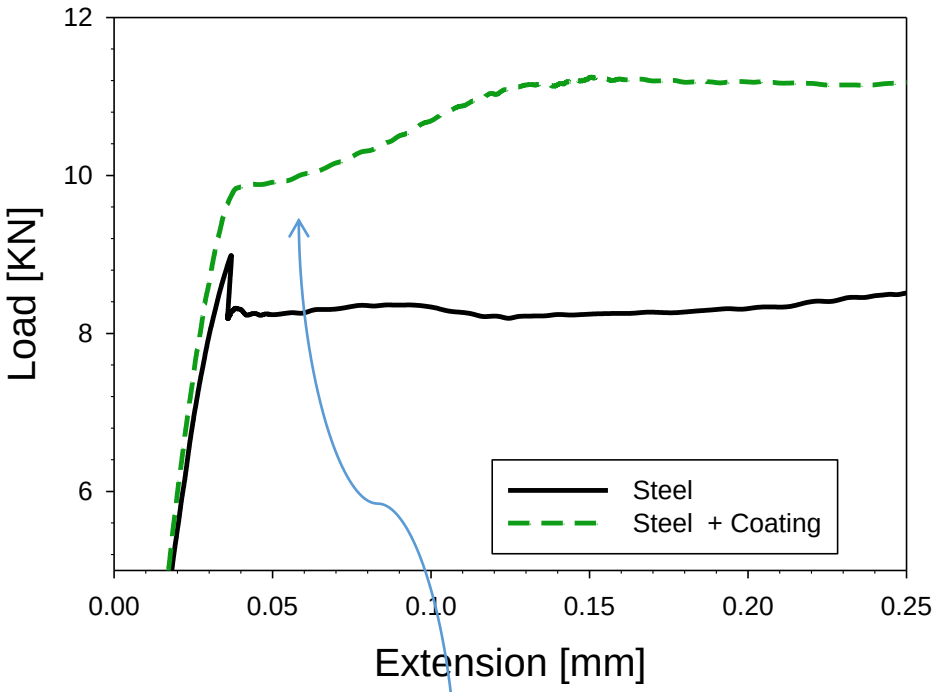


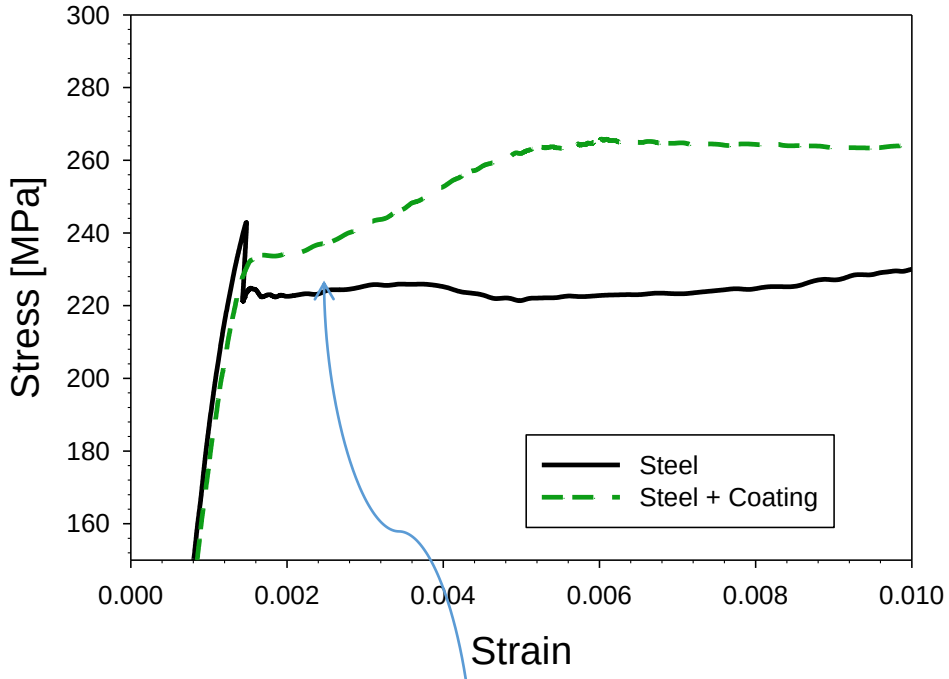
Max Princ. stress (MPa)





Structural Integration





Additional load capability with added cross section

As a Structurally Integrated Repair, the Coating can add strength to the composite

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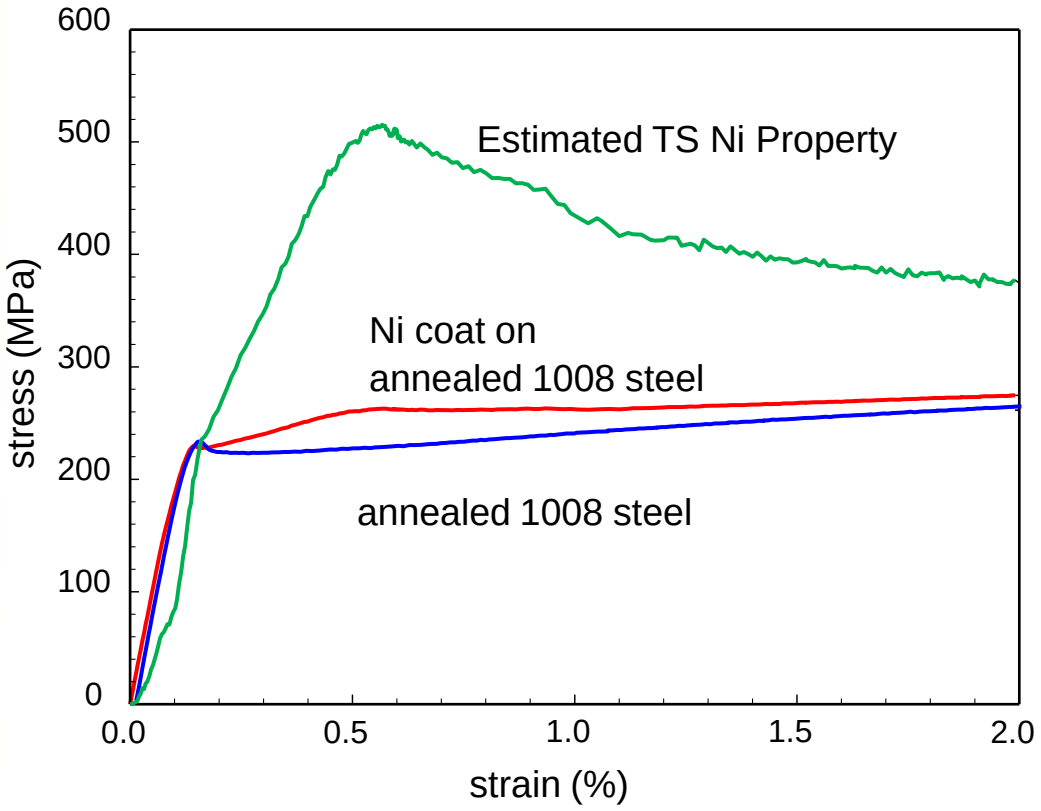
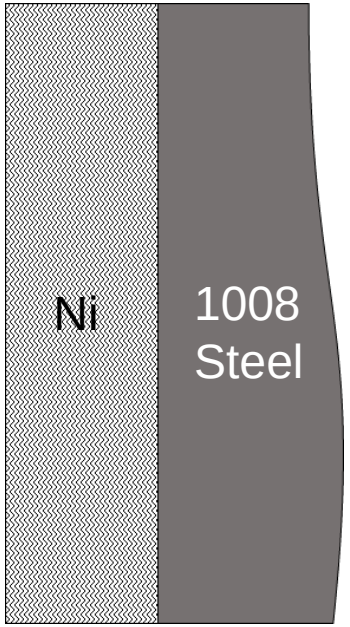
Extracting Coating Properties

From the difference between coated and un-coated specimens



Effect of residual stress is included obtained by the curvature measurement
→ Compressive stress (–85MPa)



E = 121±5GPa

σ_0 ~ 500MPa

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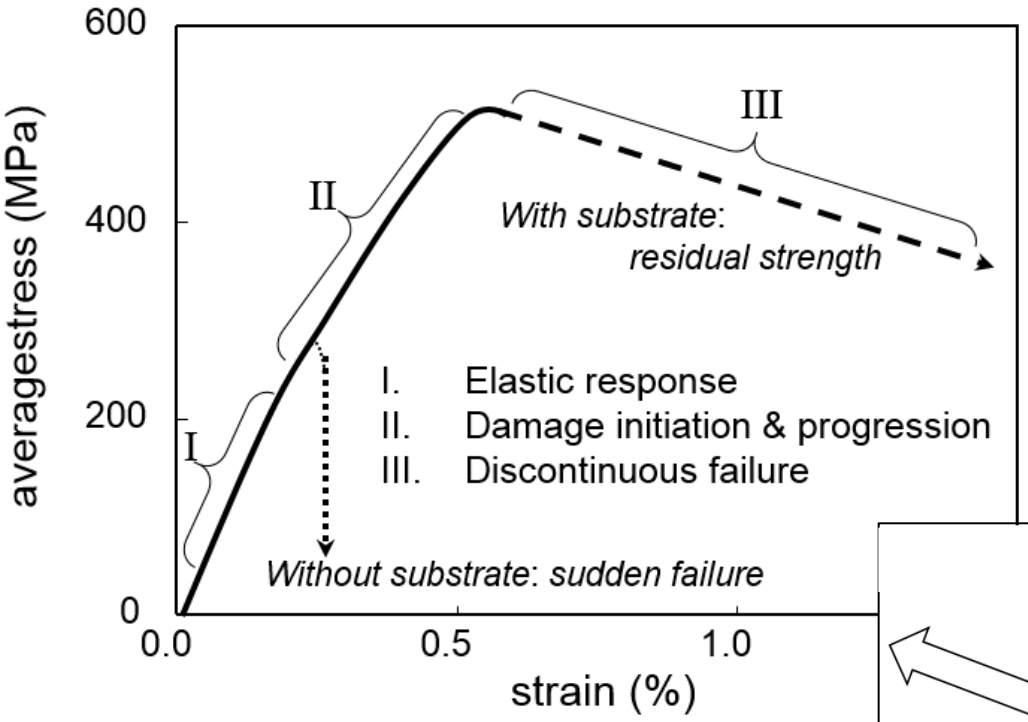
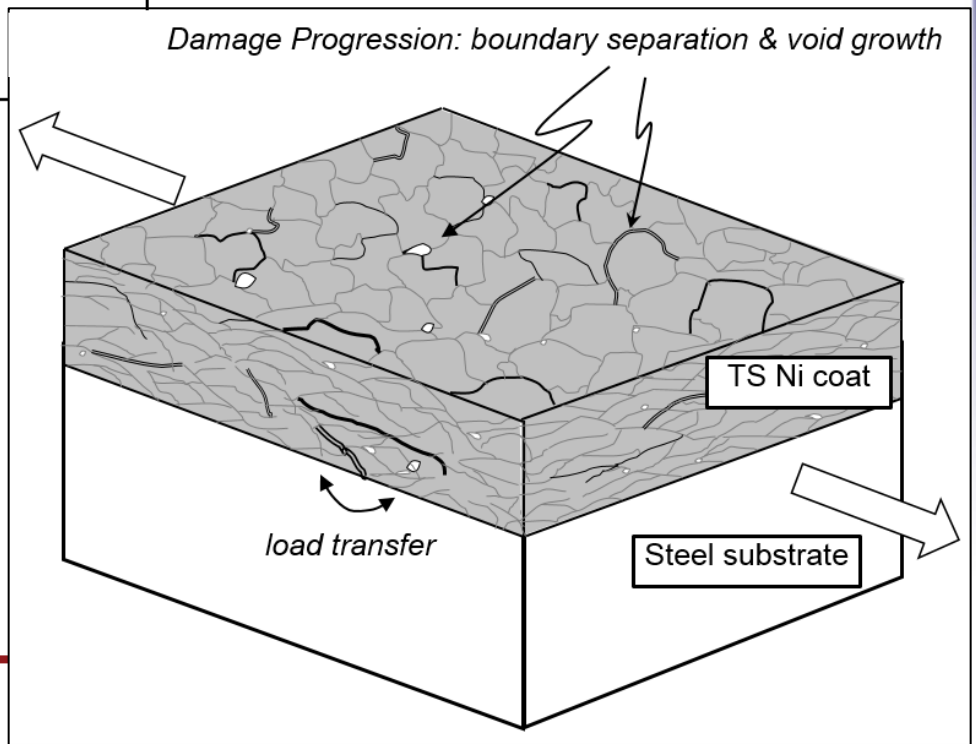
Load Transferring Mechanism

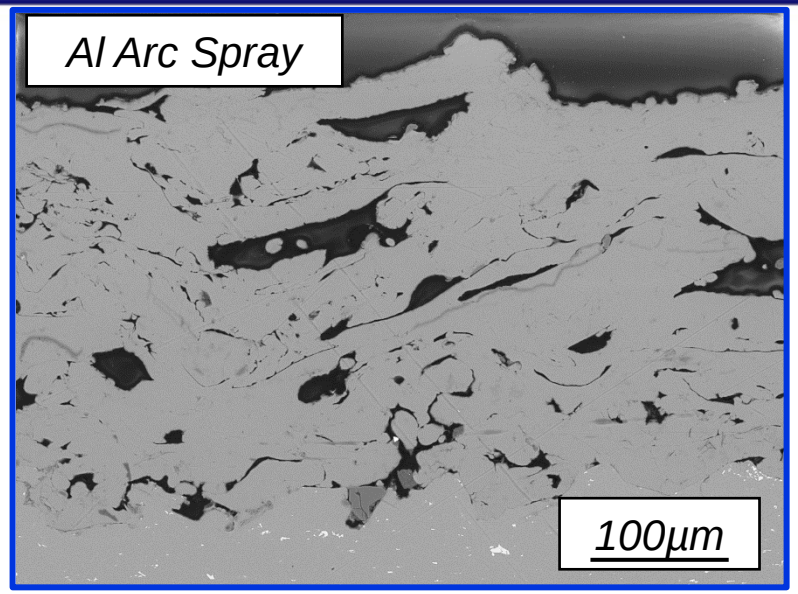


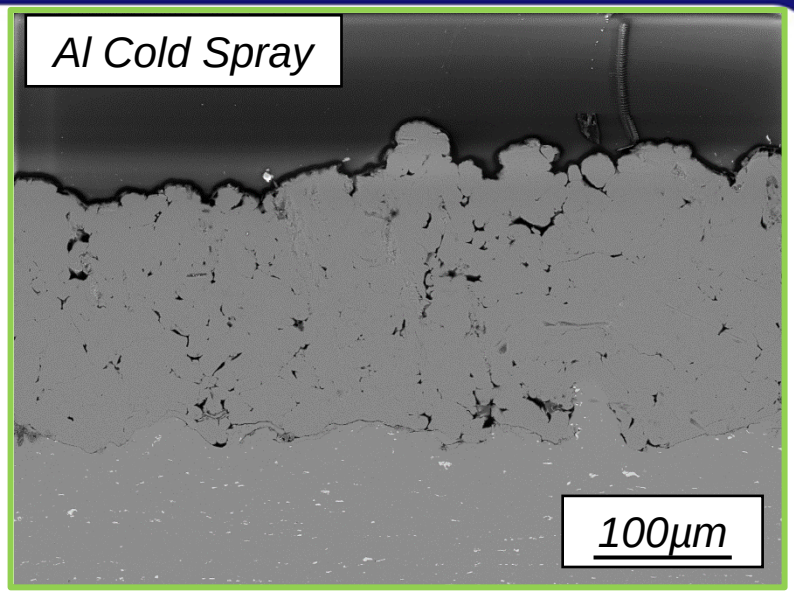
Normally a brittle coating, but combined with substrate offers benefit

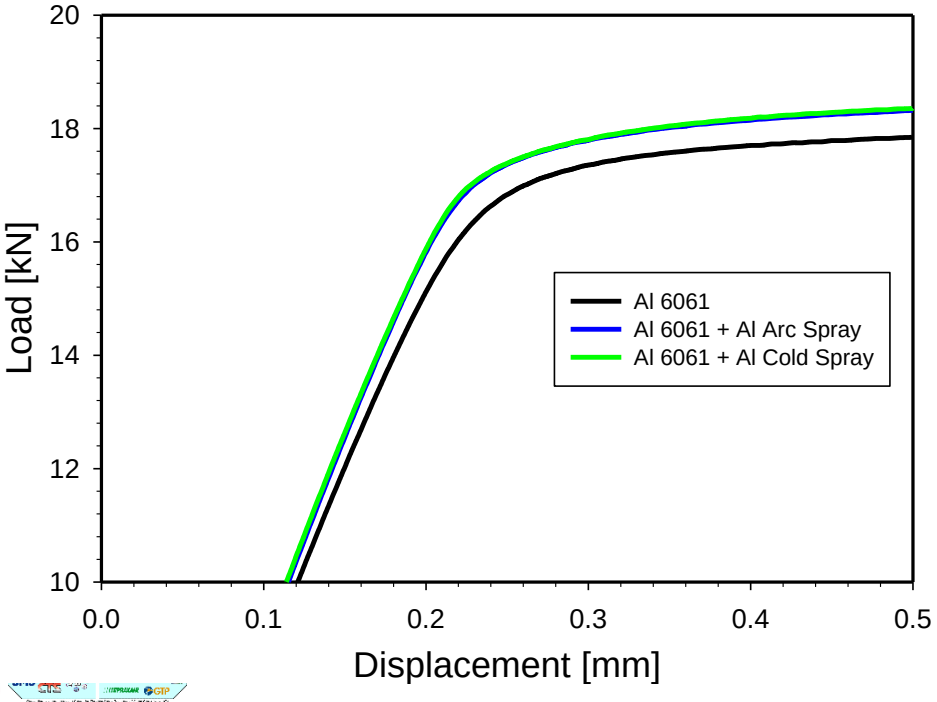
<u>Weakest Link will be exploited</u>
-Inter-splat cohesion (Porosity, Toughness, Ductility)
-Adhesion (Bonding, substrate Preparation, Stresses)

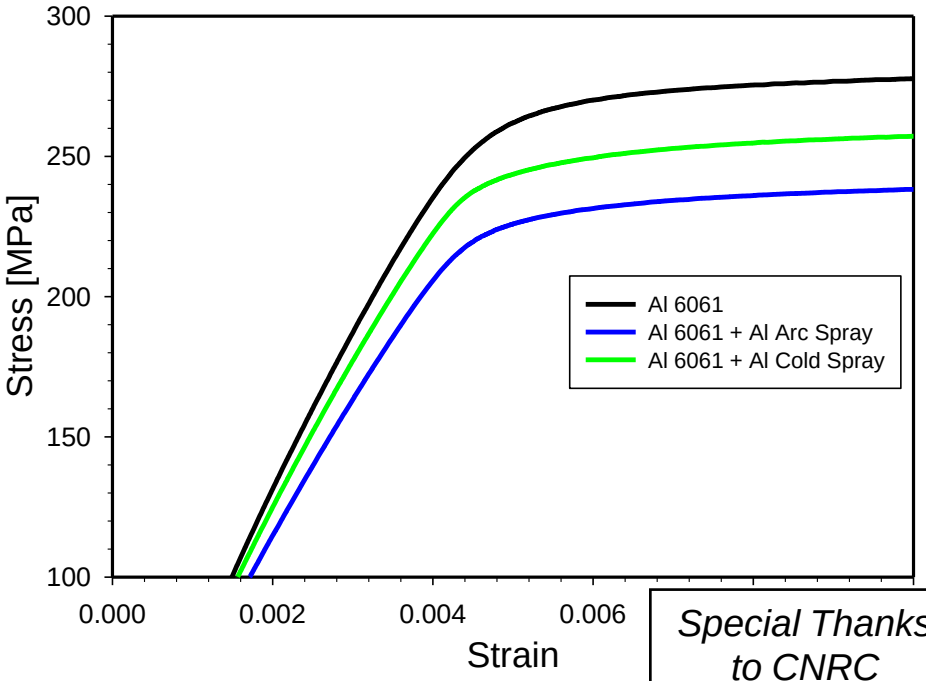


Additive Process Comparison



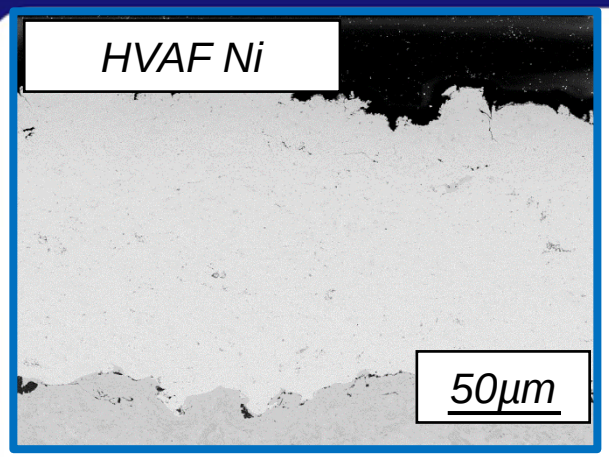


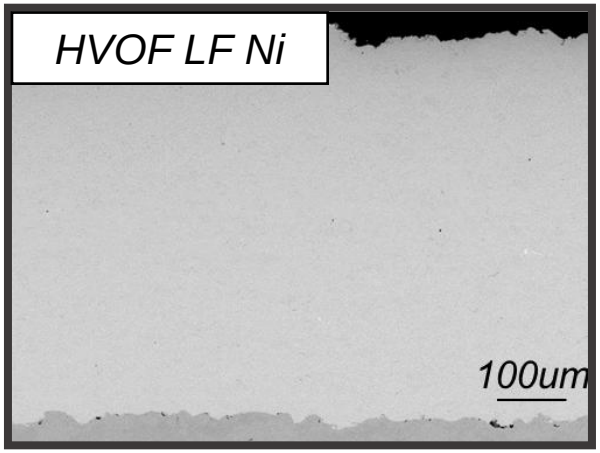


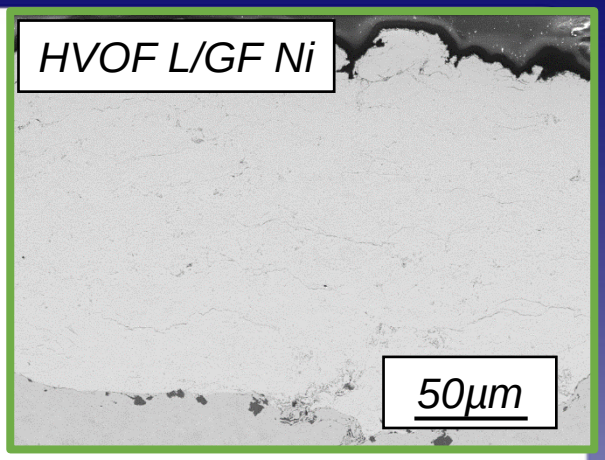


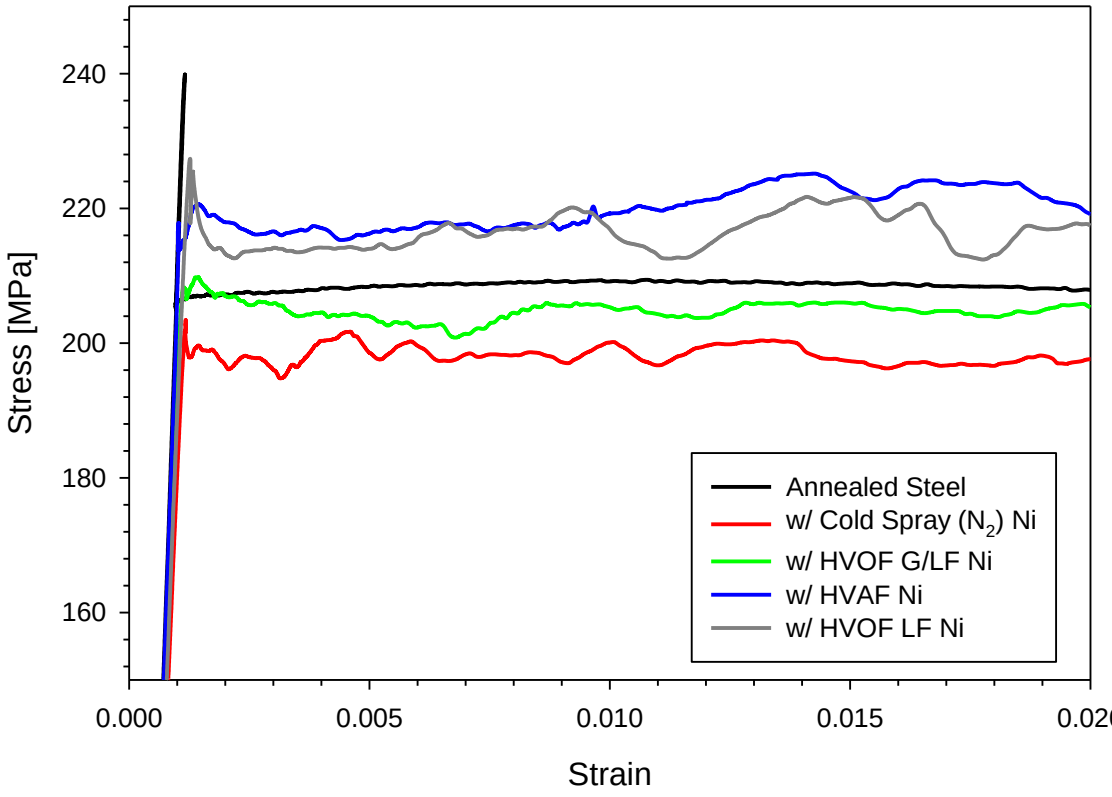
Special Thanks to CNRC

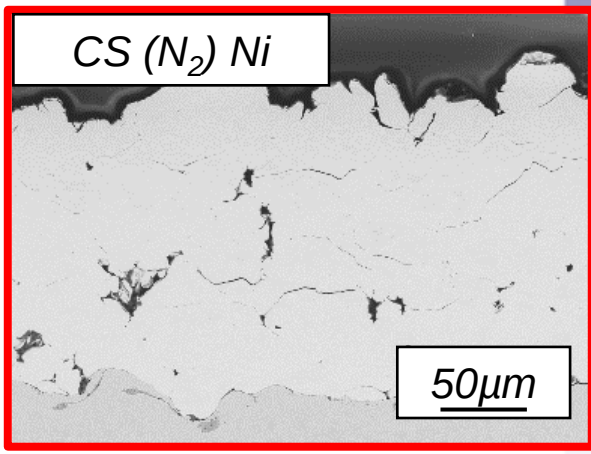
High Velocity Process Compare





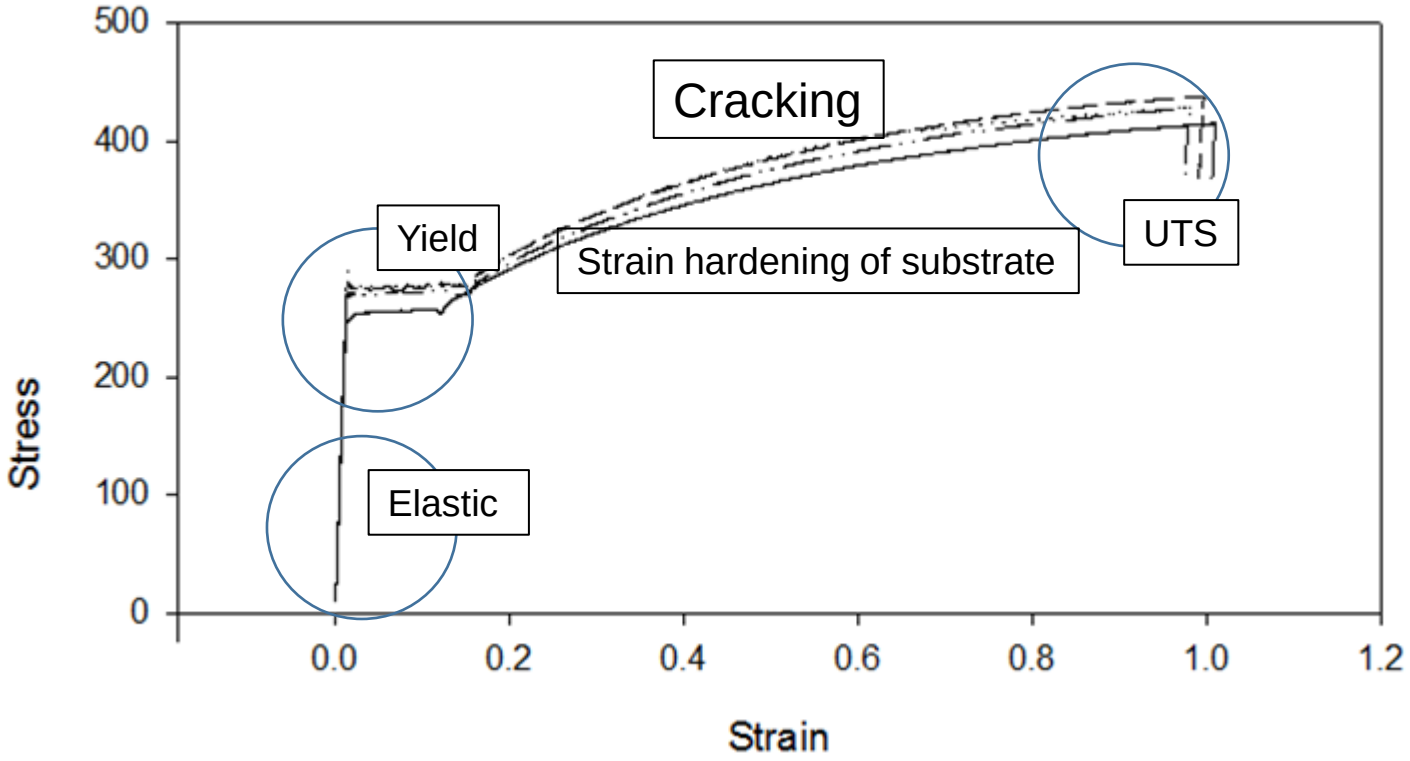


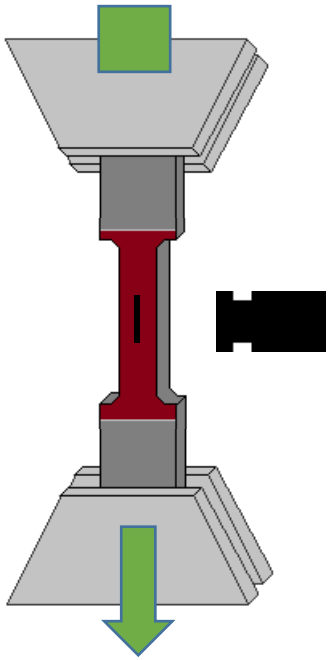


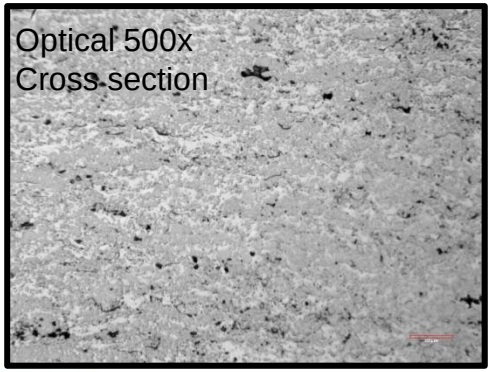


Special Thanks to VTT and CNRC

Outline of Video Observation of Tensile Testing





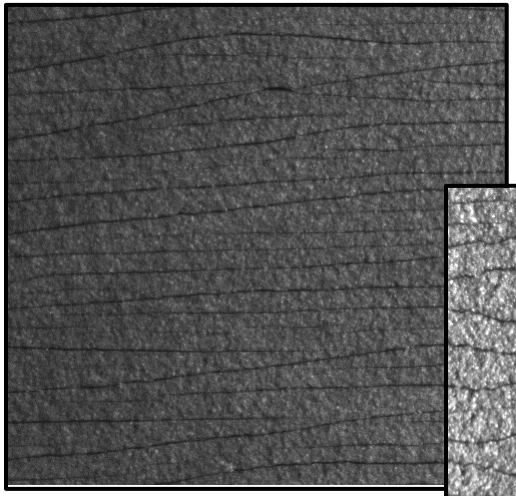


Energy in coating is constantly increasing

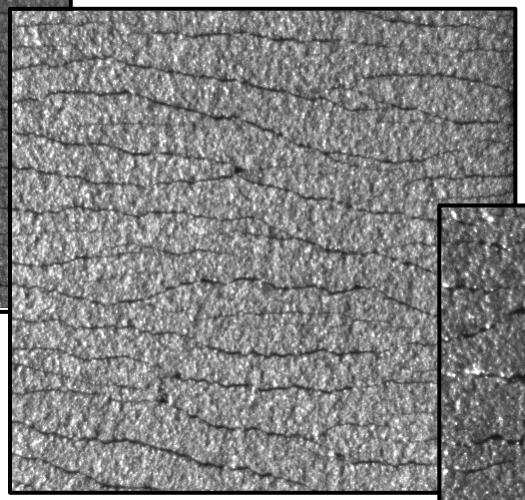
There needs to be mechanisms to release and distribute that energy

→ Cracking

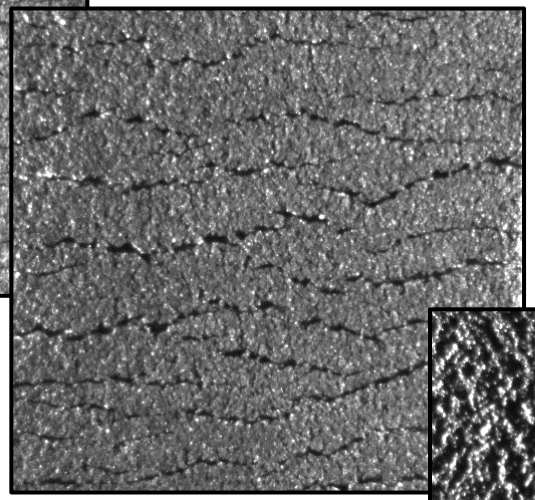
Material ductility/brittleness impact on cracks



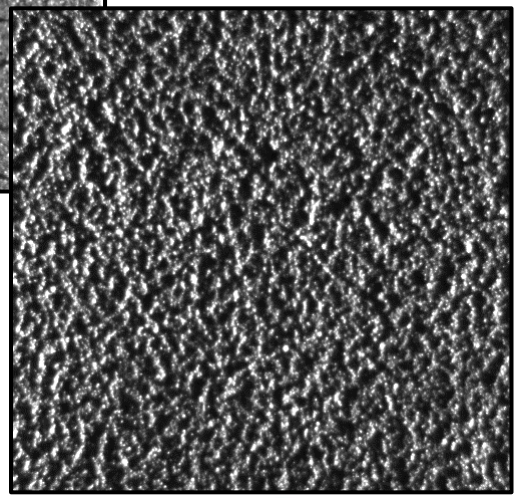
HVOF WC-CoCr



HVOF T800



HVOF (CJS)Ni



Cold Spray Al (N_2)

In general:

Coating material ductility increasing

Crack propagation changes from brittle, rapid failure to a more tumultuous smearing

Related to energy and stress buildup and dissipation

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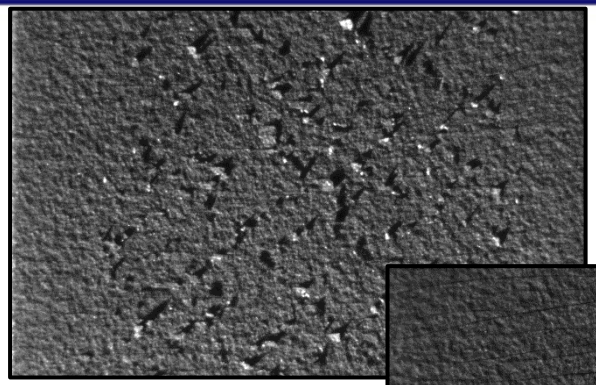
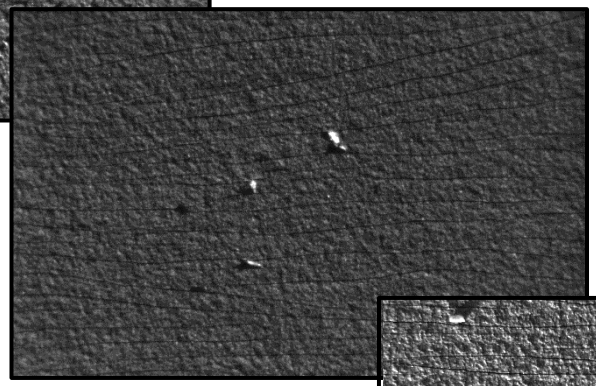
Thickness effect/processing on WCCoCr cracks

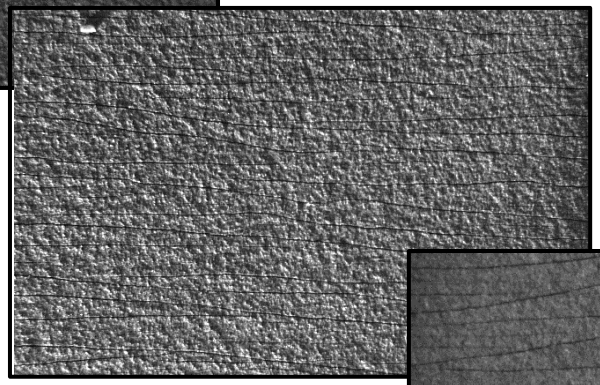
Ordered by thickness



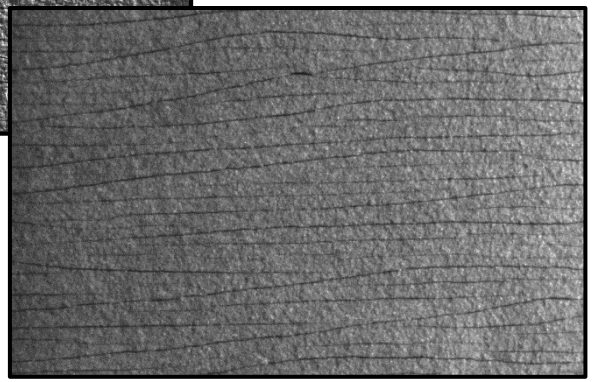
65 µm



125 µm

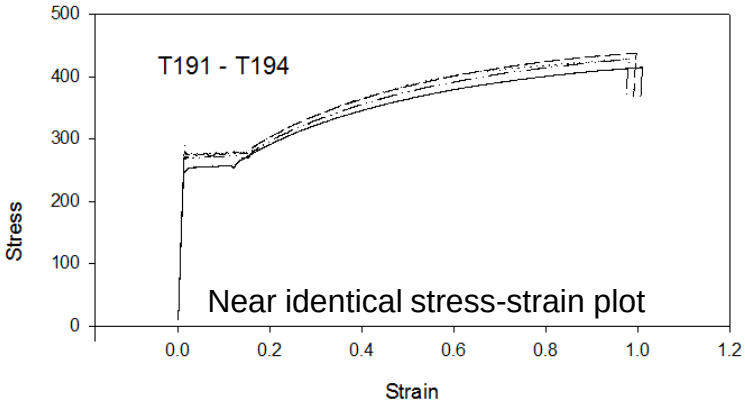


150 µm



200 µm

Increasing thickness



In general:

Change from “popcorn” structure to more horizontal cracks, as a function of thickness increase

More coating thickness results in more energy and stress in the coating, which shifts release from discrete points to higher energy full length cracks

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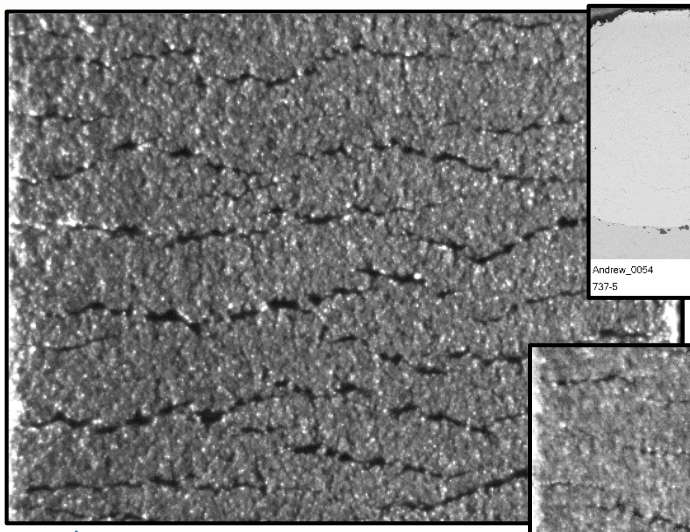
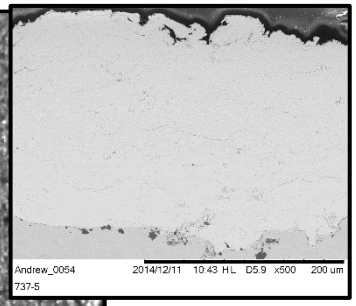
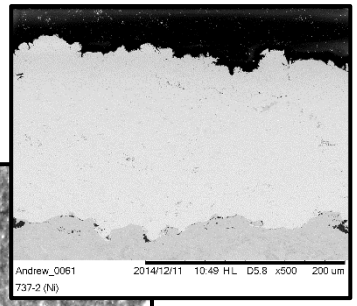
Nickel by Process – Impact on crack shape

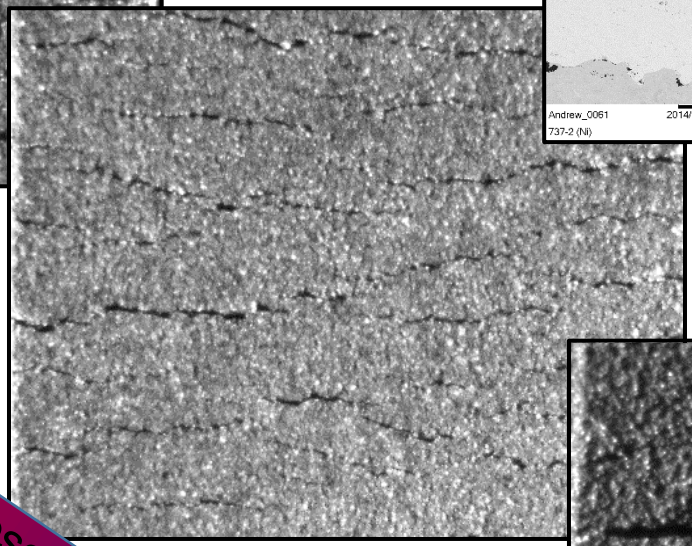




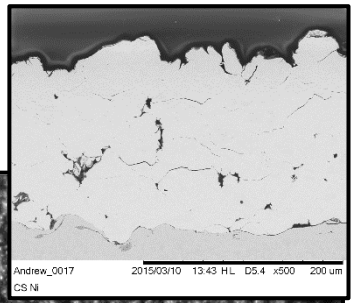
CJS Ni

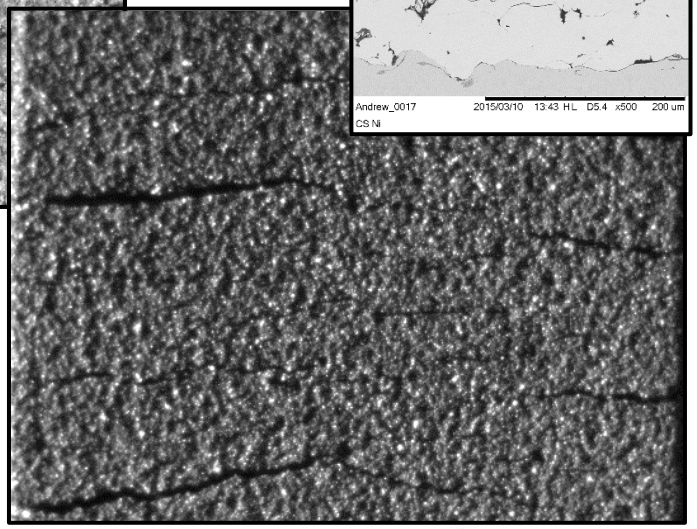
HVAF Ni





Cold Spray Ni (N_2)





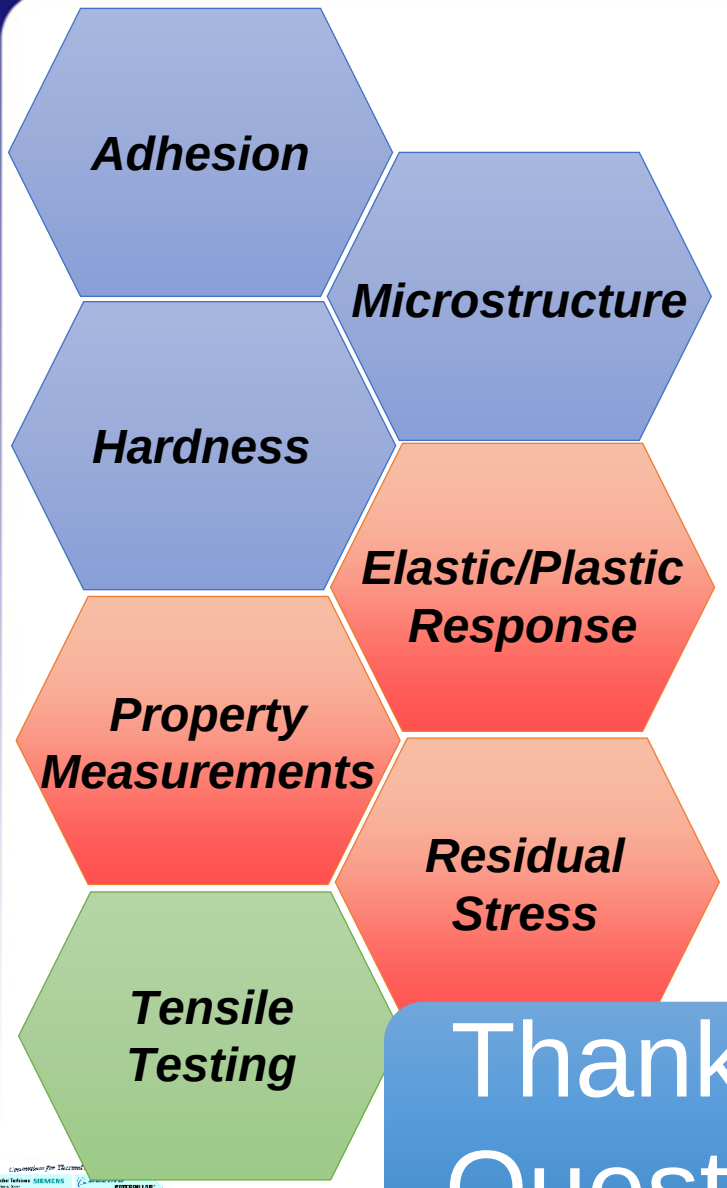
Decreasing process temperature

In general:

Change from ductile smearing to higher energy release horizontal cracks

Relation to processing conditions?

Conclusion



- Expansion of Characterizations to Interpret the Properties and Behavior of Spray Composites
- Towards the full hierarchy of Reclamation and Repair
  - Cosmetic
  - Dimensional Restoration
  - Structure Stabilization
  - Load Recovery
- Broader and Reliable implementation of High Velocity Thermal, Warm, and Cold Spray as Structurally Integrated Materials
  - Repairs/ Reclamations
  - Original Manufacturing

Thank you!
Questions?

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