Microstructure, Processing, Performance Relationships for High Temperature Coatings

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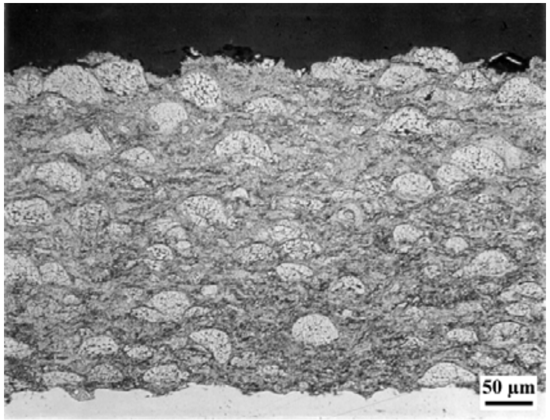
Introduction

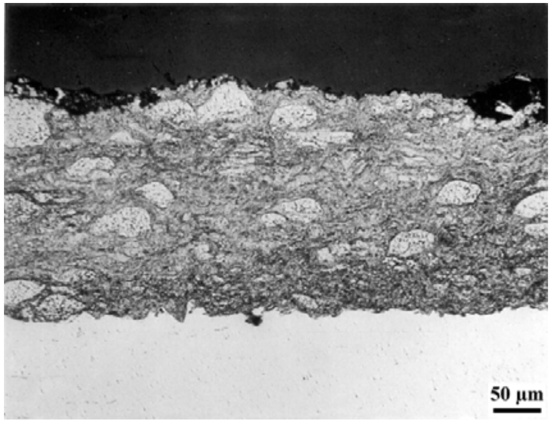
- **Research goal: understand relationships between *coating processes*, *coating characteristics*, and *coating performance***
- **Coating types:**
  - **HVOF Fe_3Al, (alumina former)**
  - **HVOF 316SS (model alloy)**
- **Substrates:**
  - **Low-alloy ferritic steels**
  - **Advanced ferritic-martensitic steels (e.g. Grade 91)**
  - **Austenitic stainless steels**
  - **Ni-base alloys (e.g. alloy 600 or 617)**

Past Results

- **Thermal spray parameters can be used to generate highly dense coating with varying levels of residual stress**
- **Residual stresses in coating arise from three sources**
  - **CTE mismatch between coating and substrate**
  - **Quench stresses**
  - **"Peening" stress**
- **Corrosion resistance of coating is very close to wrought material**
- **Coating failure governed by cracking and delamination**



570 m/s



630 m/s

Particle velocity, m/s	Residual stress, Mpa	Unmelt particles, vol. %	Mean CTE @ 700°C, ppm/°C	Average particle temperature, °C
570	-175	35	14.5	1750
630	-430	20	17.0	1600

Current Project Focus

Goal:

Determine factors affecting the mechanical stability of HVOF thermal spray coatings

Tasks:

- **Develop methods for detecting cracking and delaminations in coatings**
- **Characterize the influence of thermal spray and materials parameters on the mechanical stability of coatings**
- **Define coating failure**

Parameters of Interest

Objective: Identify parameters that result in adherent, high-durability coatings

- Materials parameters
  - CTE of coating and substrate
  - Coating strength/ductility
    - Room temperature
    - Service temperature
  - Microstructure stability
- HVOF parameters
  - Chamber pressure – particle velocity
  - Fuel/oxygen ratio – particle temperature
  - Substrate temperature during spraying – standoff distance, traverse speed, preheat/active cooling
  - Coating thickness - # of passes

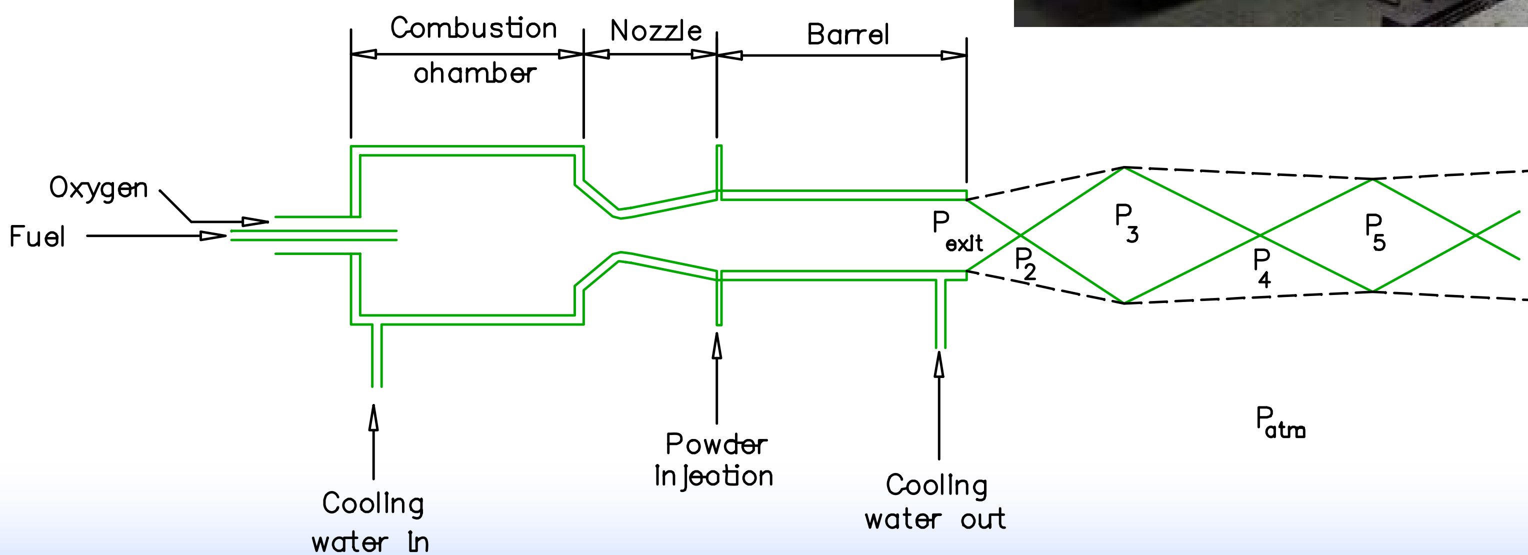
High-Velocity Oxygen Fuel (HVOF) Process

- Equivalence ratio (phi)

$$\Phi = \frac{Fuel / Oxygen}{(Fuel / Oxygen)_{Stoich}}$$

- Combustion chamber pressure

$$P_C \propto Total\ mass\ flow\ of\ O_2\ and\ fuel$$



Control of Residual Stress

Total = Quench + CTE + Peening

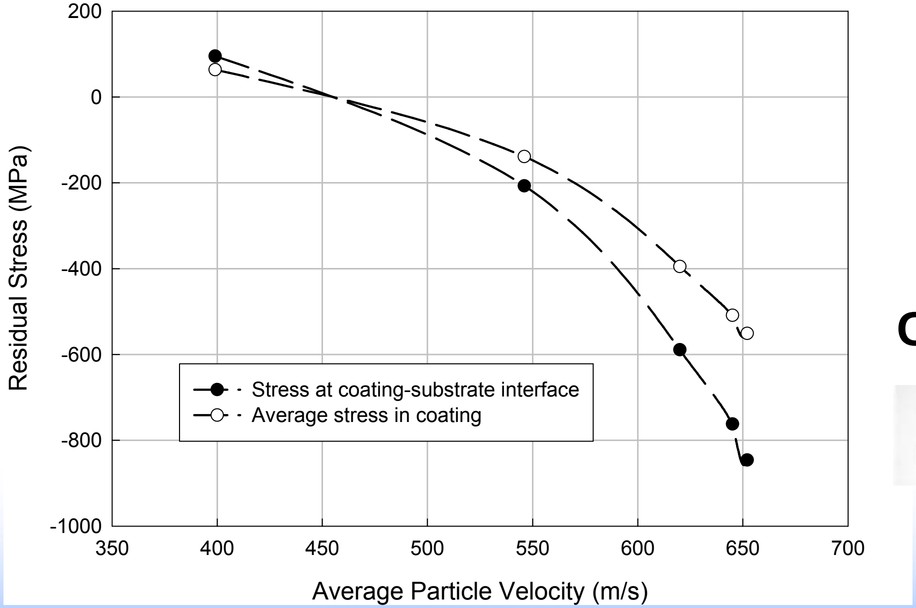
- Substrate temp.
- Particle temp.
- CTE of particle

- Coating CTE
- Substrate CTE
- Processing temp.

- Particle hardness
- Particle velocity
- Particle mass

TENSILE

NEUTRAL



COMPRESSIVE

Materials Systems of Interest

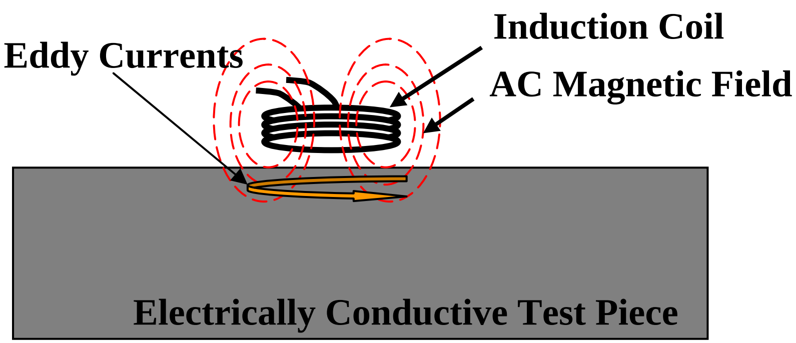
- Coating materials
  - Fe_3Al
  - FeAl

- Substrate materials
  - Carbon Steel
  - Low-alloy ferritic steels
  - Advanced ferritic-martensitic steels (e.g. Grade 91)
  - Austenitic stainless steels
  - Ni-base alloys (e.g. alloy 600 or 617)

Coating Durability Tests

- Coating failure resulting from thermal cycling
  - Optical methods
    - Visual
    - Metallographic methods
  - Real time crack detection using eddy current methods
- Room temperature coating strength/ductility
  - Acoustic emission
  - Eddy current methods

Basics of Crack Detection using Eddy Current methods



<u>Senses Localized Electromagnetic Properties</u>

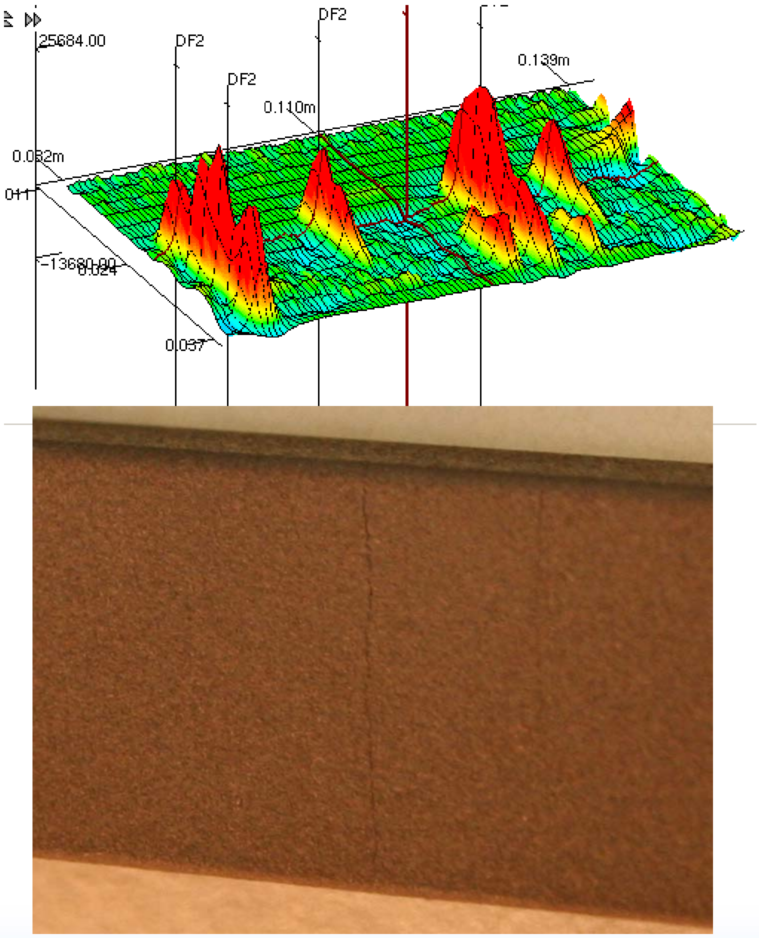
- **Electrical Conductivity**
- **Magnetic Permeability**

Measure Induction Coil Impedance to Detect Defects

- **Disruptions of Eddy Current Field, e.g. cracks**
- **Change In Bulk/Composite Electrical Properties, e.g. coating thickness or phase change**

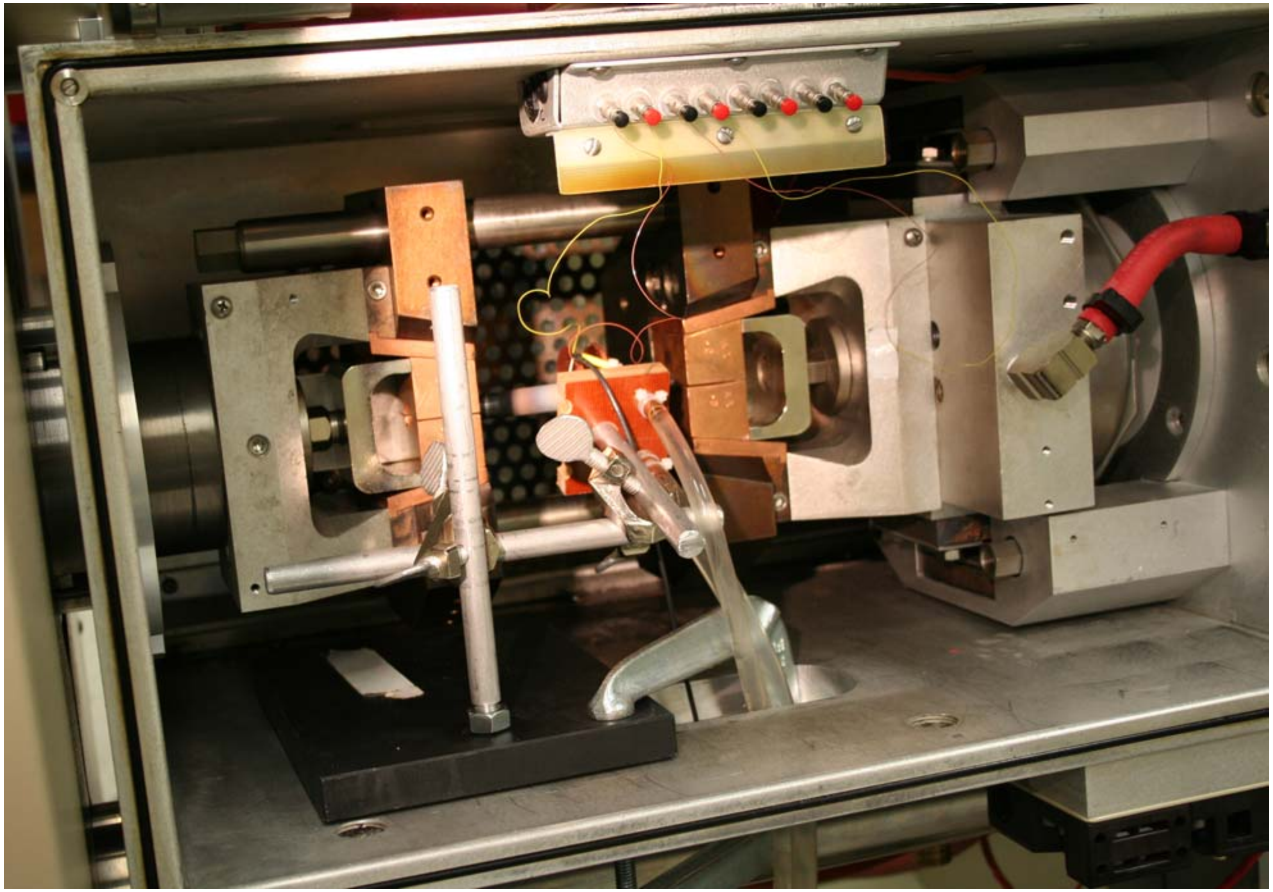
<u>Typical Applications</u>

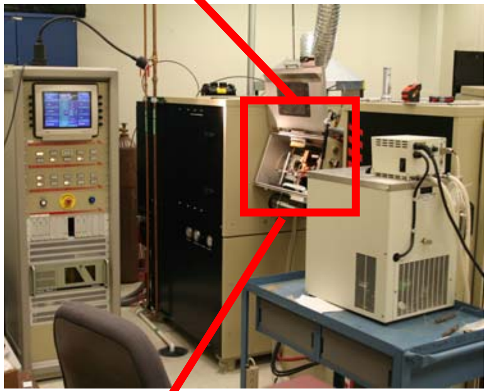
Inspection of Steam Generator Tubing
Weld Inspection
In-service Inspection of Reactor Components and Piping
Inspection of Aircraft Skin and Engine Components



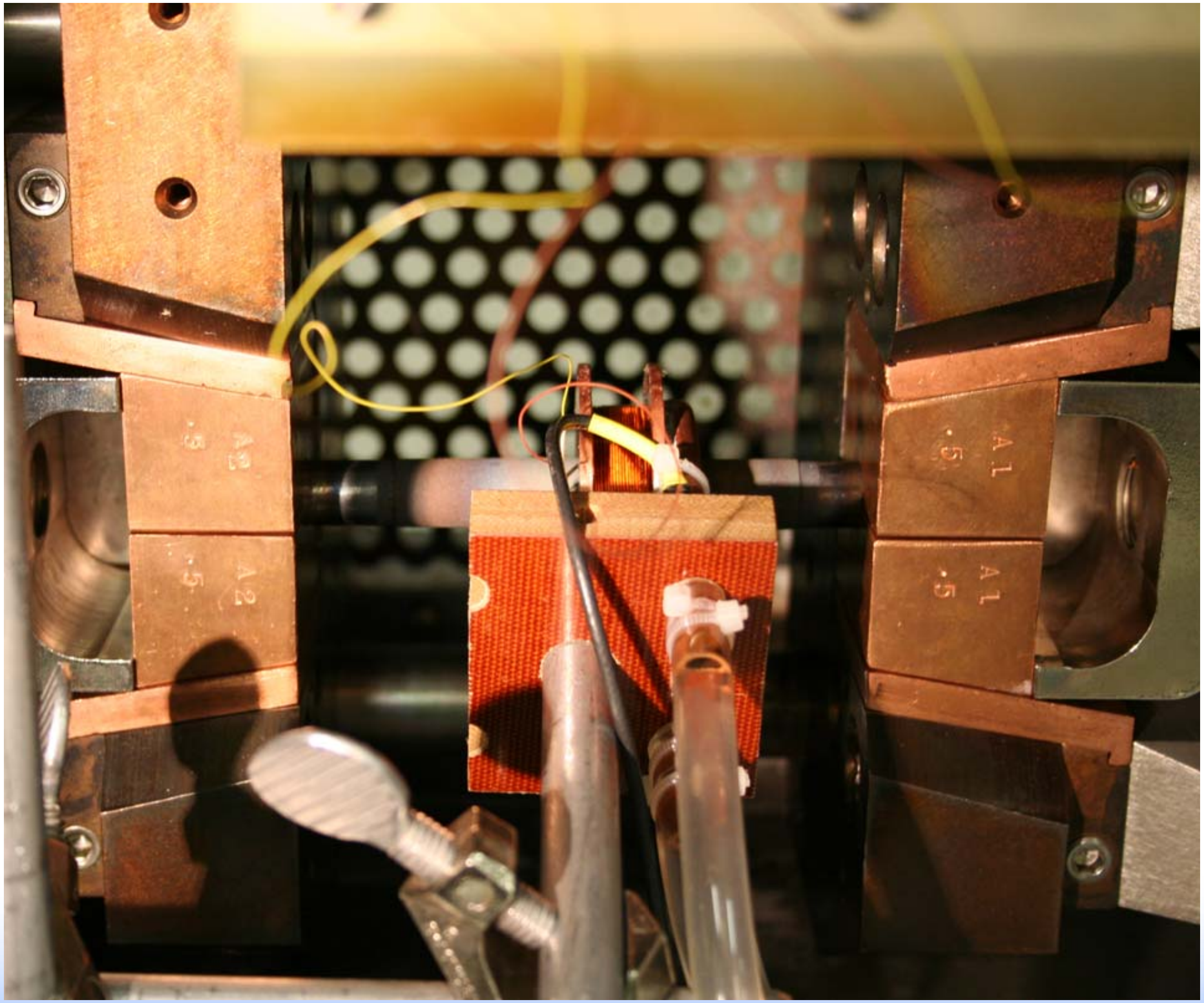
Eddy Current Detection of Cracking in a Coating

Experimental Setup – Thermal Cycling



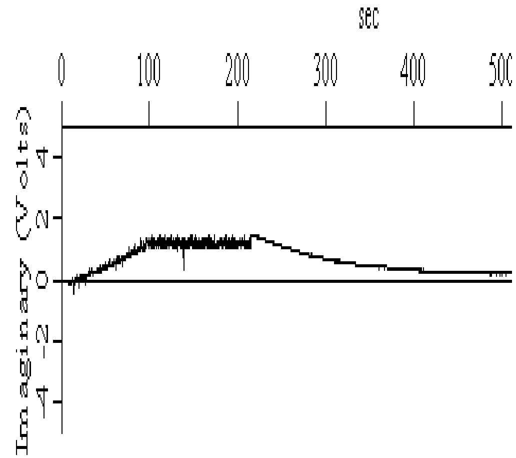


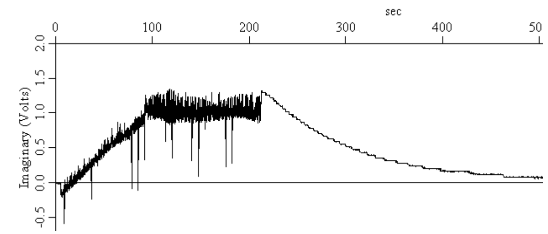
Experimental Setup – Eddy Current

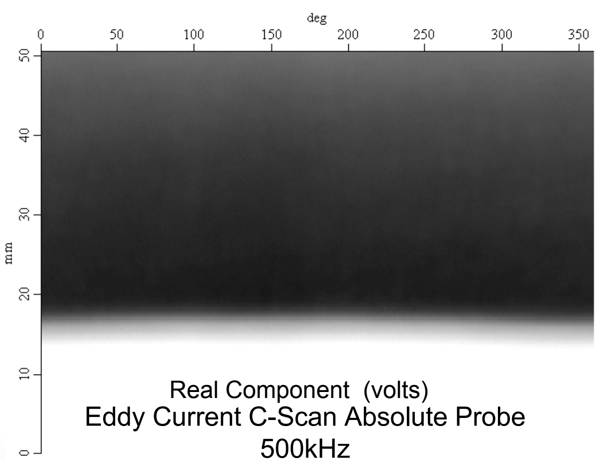


Eddy Current Response During Thermal Cycling

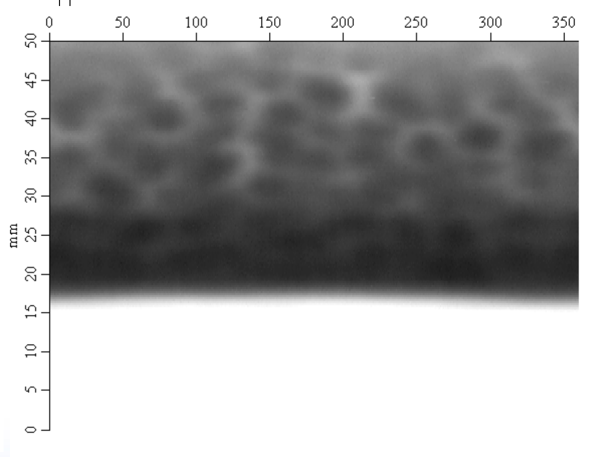
FeAl Coating on Carbon Steel - Thermal Cycle (Room Temp. - 700º C)



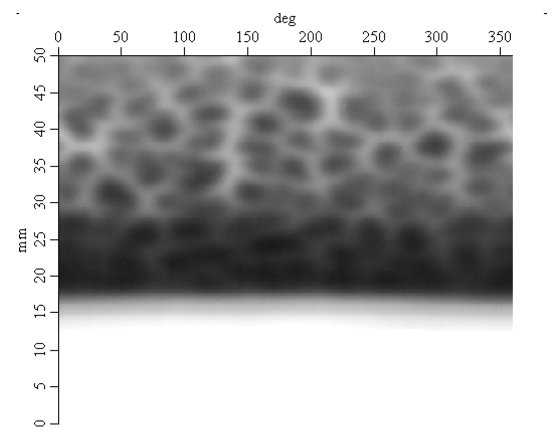




As-sprayed

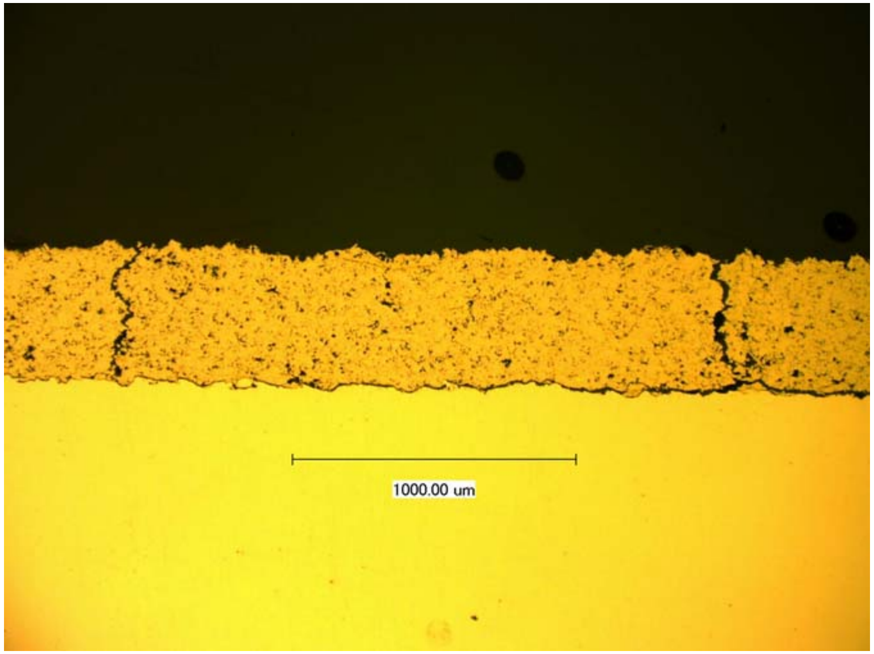


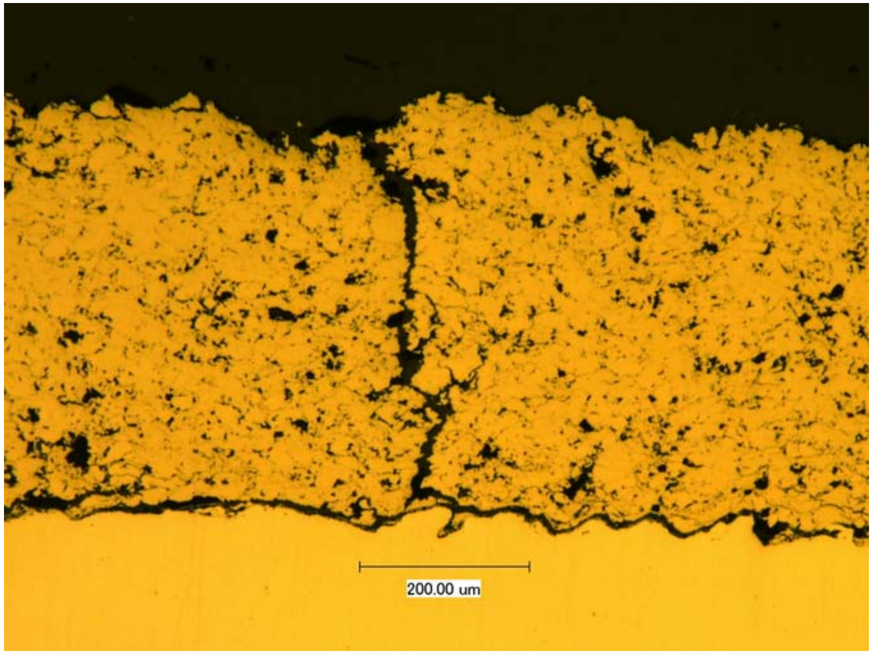
1 Thermal Cycle



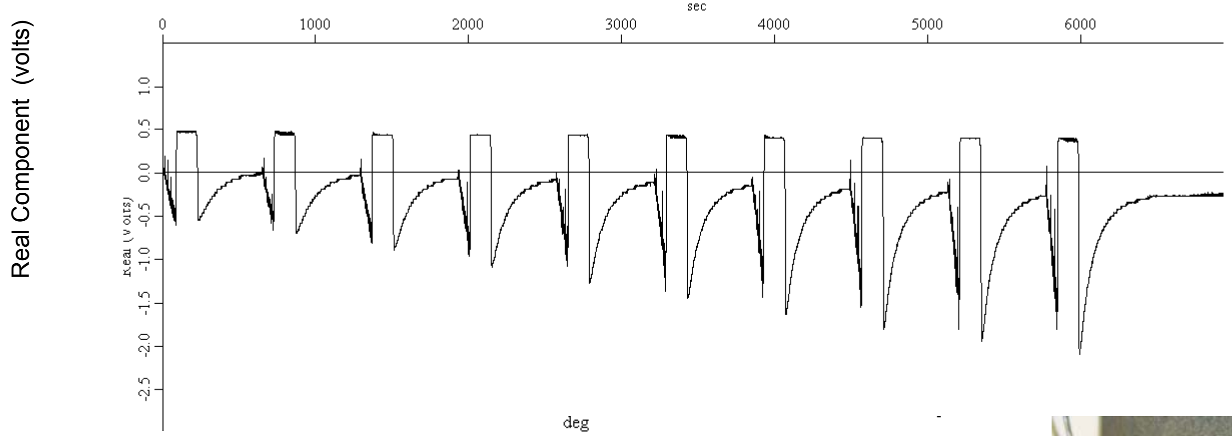
2 Thermal Cycles

Optical Metallography of Thermally Cycled Coating

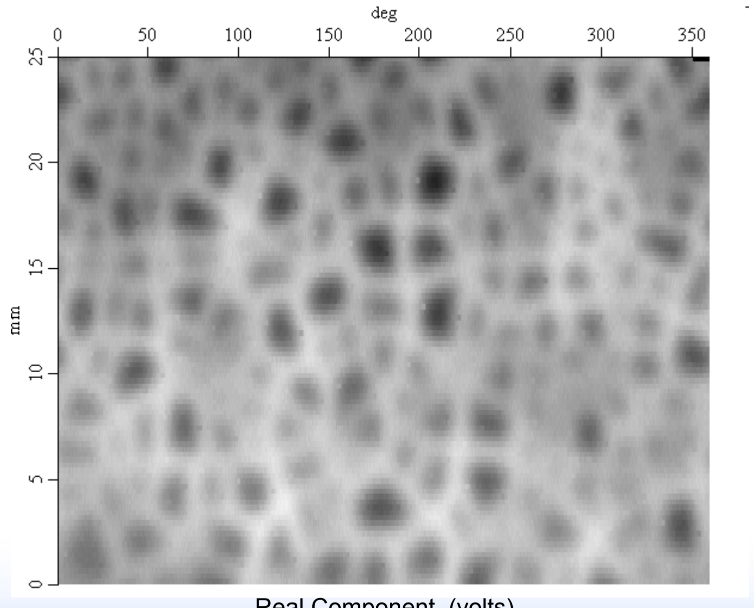




Eddy Current Scans



Encircling Absolute Eddy Current Coil
Ten Cycles: Room Temperature - 800º C



Eddy Current C-ScanAbsolute Probe 500kHz

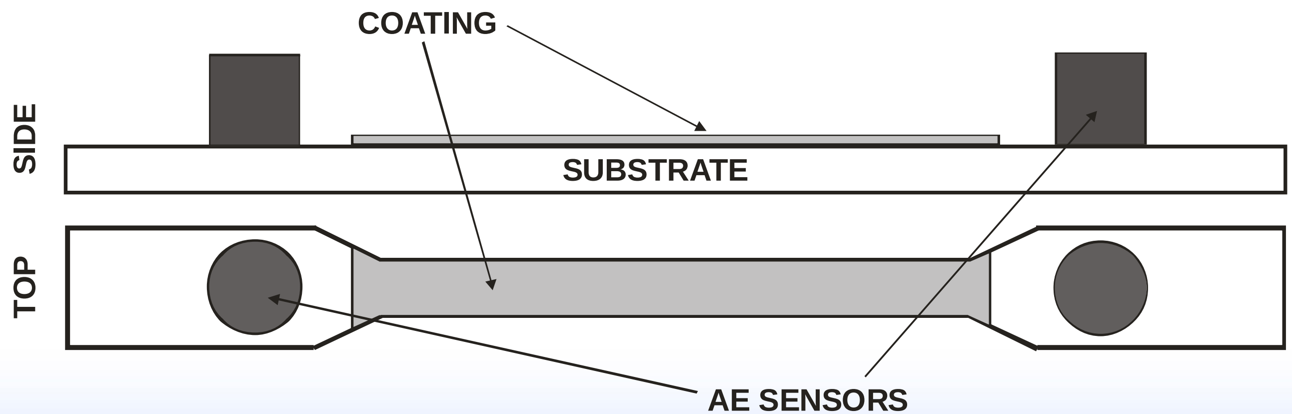
FeAl Coating on Carbon Steel Bar after Thermal Cycling

Future Plans for Thermal Cycling

- Add more eddy current coils to interrogate smaller areas – increased sensitivity
- Measure crack line length/unit area as a function of the number of thermal cycles
- Manipulate HVOF parameters and coating thickness to evaluate the effect on crack line length/unit area
- Address the detection and importance of delamination versus through-coating cracking.
  - Add thermal imaging to look for delamination in real time
- Investigate more relevant coating/substrate systems

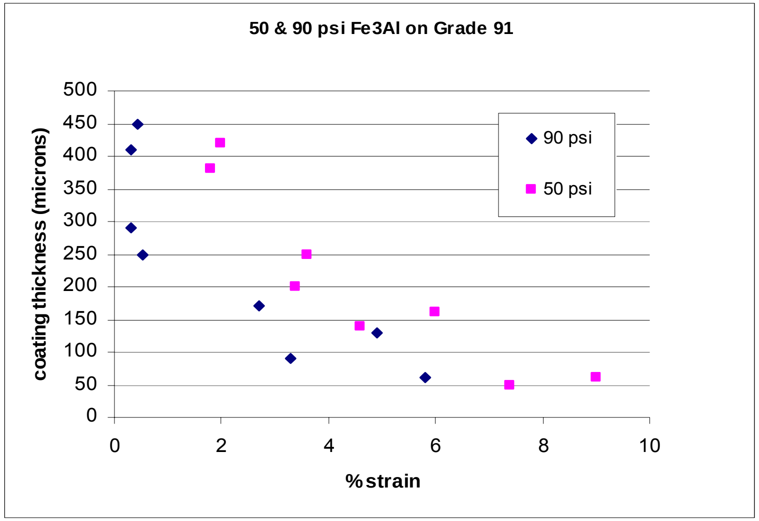
Previous Coating Fracture Testing

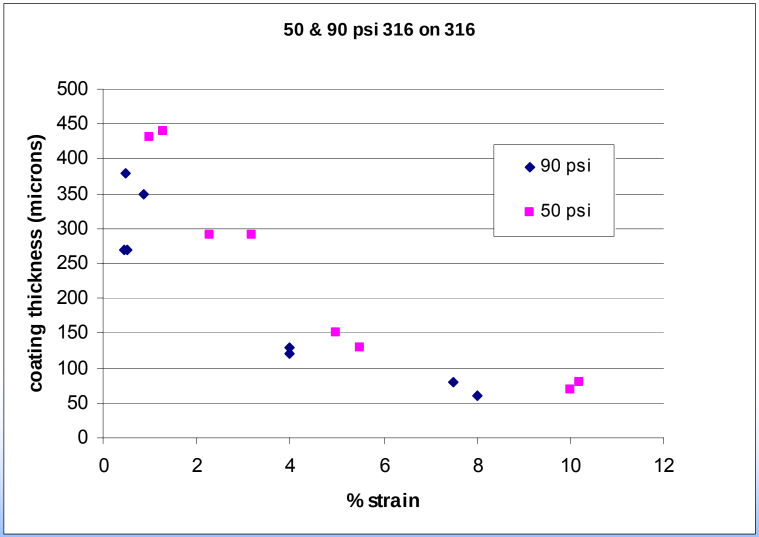
- Coating strain to fracture measured using acoustic emission monitoring
- 500 µm coatings applied to dogbone-shaped tensile specimen substrates
  - Reduced area section
- Two AE sensors attached to each end of substrate near grips
  - Used to locate events within coated gage section
- Coating cracking produces clear AE signals



Strain to failure as function of coating thickness results

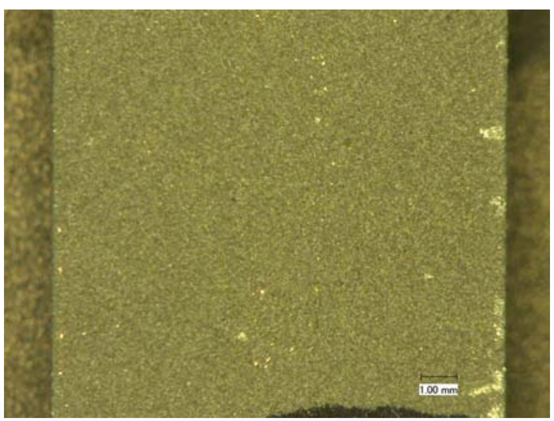
- Both Fe3Al and 316SS coatings showed improved ductility with decreasing thickness.
- Same trend was also seen among different particle spray velocities.
- In a few cases the strain at which the specimen cracked was observed visually as there was little or no acoustic emission.

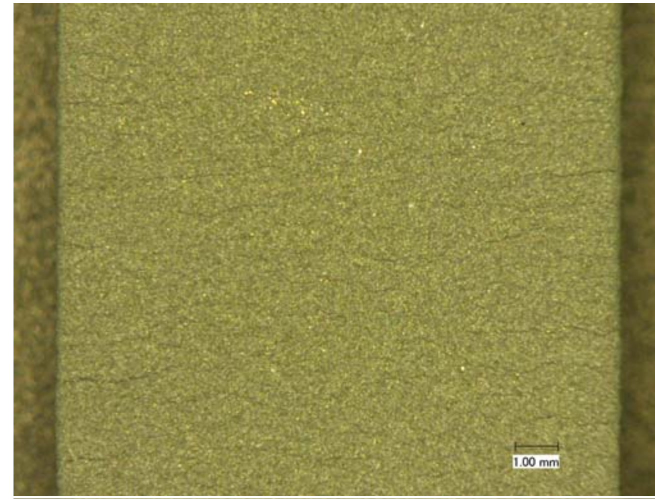


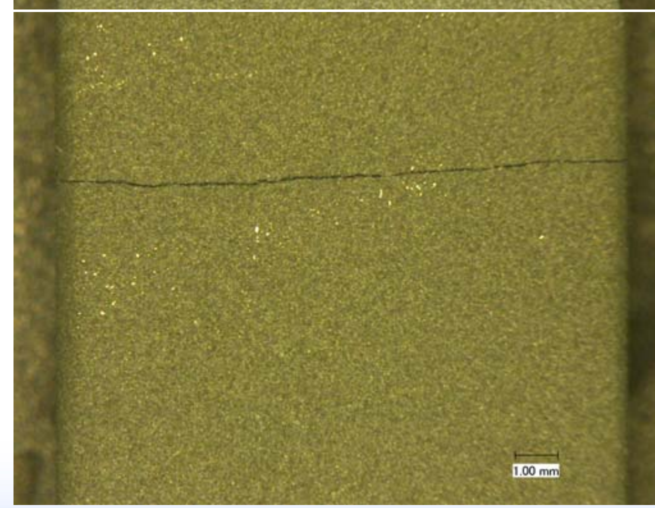


Strain to failure fracture modes

- Thick coatings tend to have one or two large cracking events with de-bonding.
- Thinner coatings fracture and flake.
- Crack initiation appears to be at stress concentrator at 90° edge.
- Bottom left coating is 50μm thick while top right is 130 μm the bottom right is 410 μm.

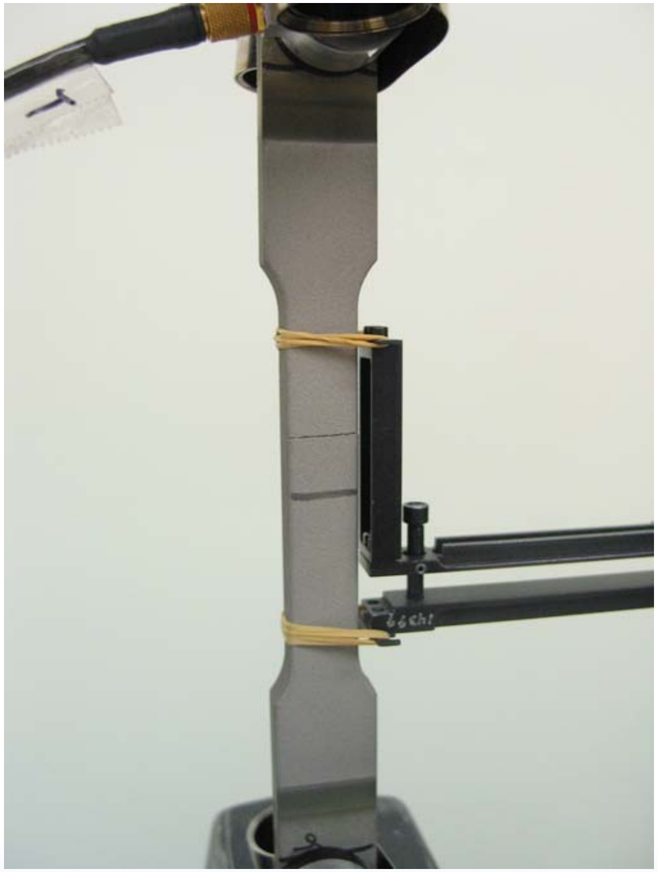






Strain to failure apparatus

- **AE signal was not always consistent with degree of cracking observed in thin coatings**
- **Optical observation of cracking in many cases correlated with observed strain to failure**



Future Strain to Failure Testing

- **Round tensile bars**
  - **Reduced section**
  - **Uniform diameter**
- **Investigate factors affecting sensitivity of crack detection by acoustic emission**
- **Add eddy current for crack detection in thin coatings**
- **Study relevant coating/substrate systems**