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Characterization of High Temp Thermal Sprays for Engine Applications

Nick Jacobs – UDRI

Presented at HCAT – Kennedy Space Center

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Management Structure

- AFRL Program initiated by AFRL/MLSC
  - *Funded by AFMC Weapons Systems Pollution Prevention Program*
  - *Program Manager - Joe Kolek, contractor for AFRL/MLSC*
  - *Technical Aspects – Bob Ware, AFRL/MLSA*
- UDRI Contracted Engineering
  - *Susan Hill - Principal Investigator*
  - *Nick Jacobs, John Ruschau – Testing Engineers*
  - *Dave Stubbs – Acoustic Emission Technical Support*
- (Testing phase) conducted from 11/02 through 9/03
  - *Fatigue Completed 4/03*
  - *Acoustic Emission Completed 7/03*
  - *Adhesion Completed 9/03*

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Program Overview

- Any relative performance differences between HVOF/PS processes with powders suitable for high temp applications?
  - *Fatigue*
  - *Coating Fracture (Acoustic Emission)*
  - *Adhesion/Delamination*
- Substrates (OC-ALC typical workload – TF33)
  - *Inconel 901*
  - *17-22 Low Alloy Steel*
- Spray Processes and Powders
  - *HVOF (High Velocity Oxygen Fueled)*
    - *Ni,Cr (Cr_3C_2-20) Tribaloy 400 WC-Co17*
  - *Plasma Spray*
    - *Tribaloy 400 WC-Co17*

Fatigue

- Directly compare EHC to HVOF and PS coatings
- Specimen Details
  - *Sprayed Shoulder to Shoulder*
  - *Uniform ¼" Gage Diameter, 3/4" Gage Length*
  - *Stress Ratio=0.1, Frequency = 30 Hz*
- Full Matrix vs. EHC baseline
  - *Two Substrates (17-22 Steel; Inconel 901)*
  - *Two Temperatures (300 °F, 750 °F)*
  - *One Thickness (0.010 inches)*
  - *Four Coatings*
    - *HVOF: WC-Co17; Tribaloy-400; Ni,Cr*
    - *PS: WC-Co17*

Not intended to justify processes and powders for use in fatigue critical applications

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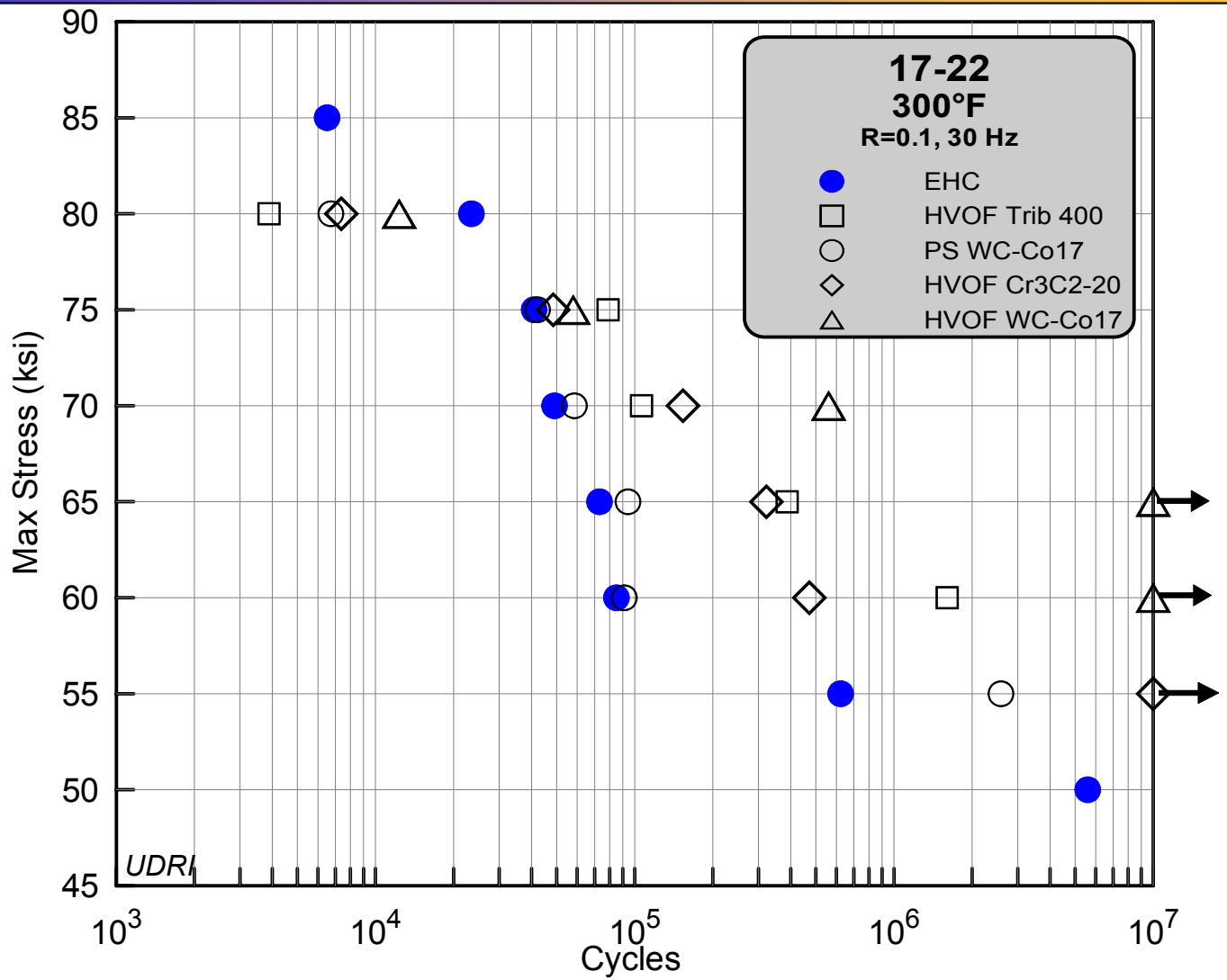
Fatigue Setup

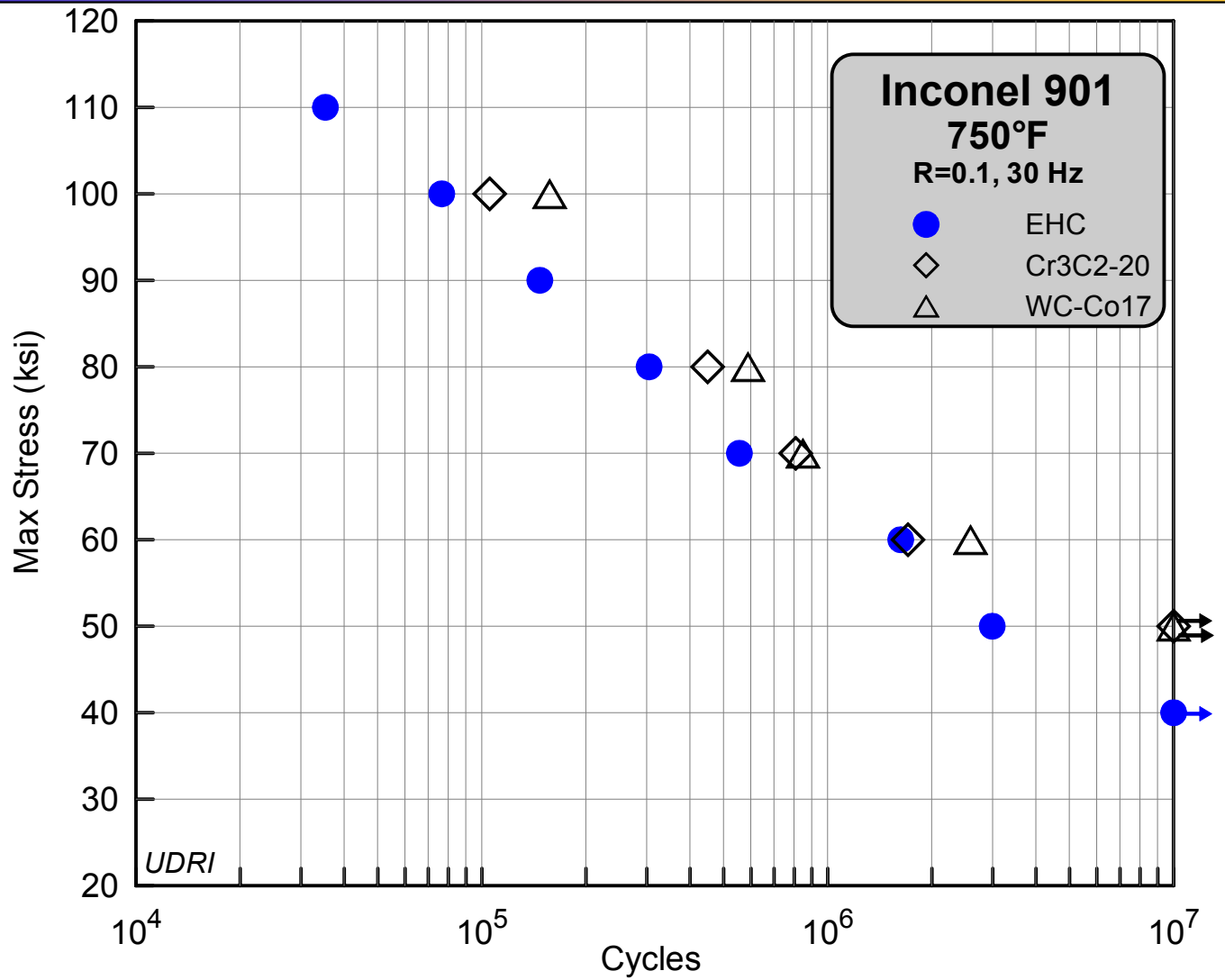
Fatigue Results

17-22 Steel @ 300ºF



Fatigue Results

Inconel 901 @ 750ºF



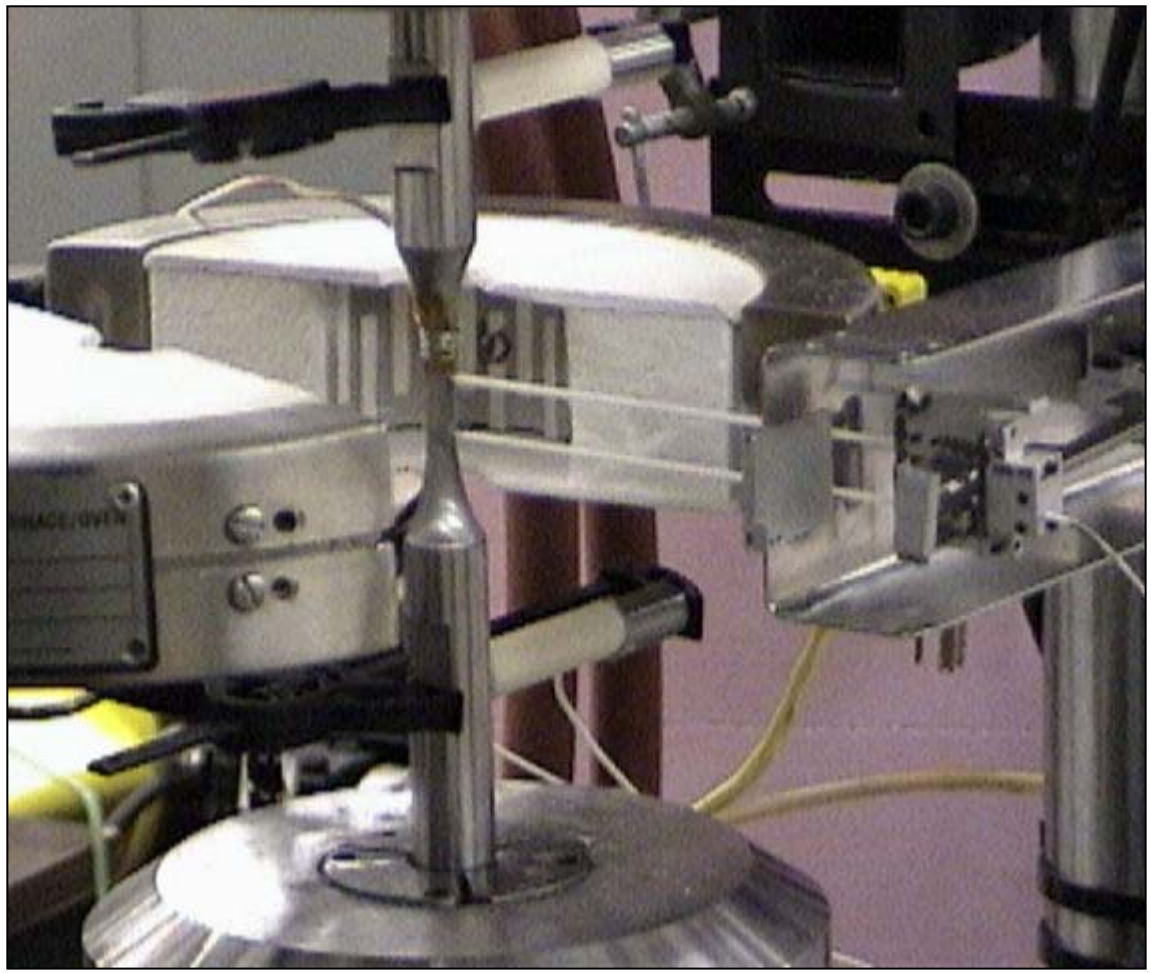
Fatigue Results Summary

- HVOF performed better than or equal to EHC
  - *Difference in Fatigue properties is not statistically significant*
  - *Test used as a performance discriminator, not intended for fatigue critical applications*
- No significant fatigue debit associated with thermal spray coatings as compared with EHC
- In general, HVOF performed better than PS

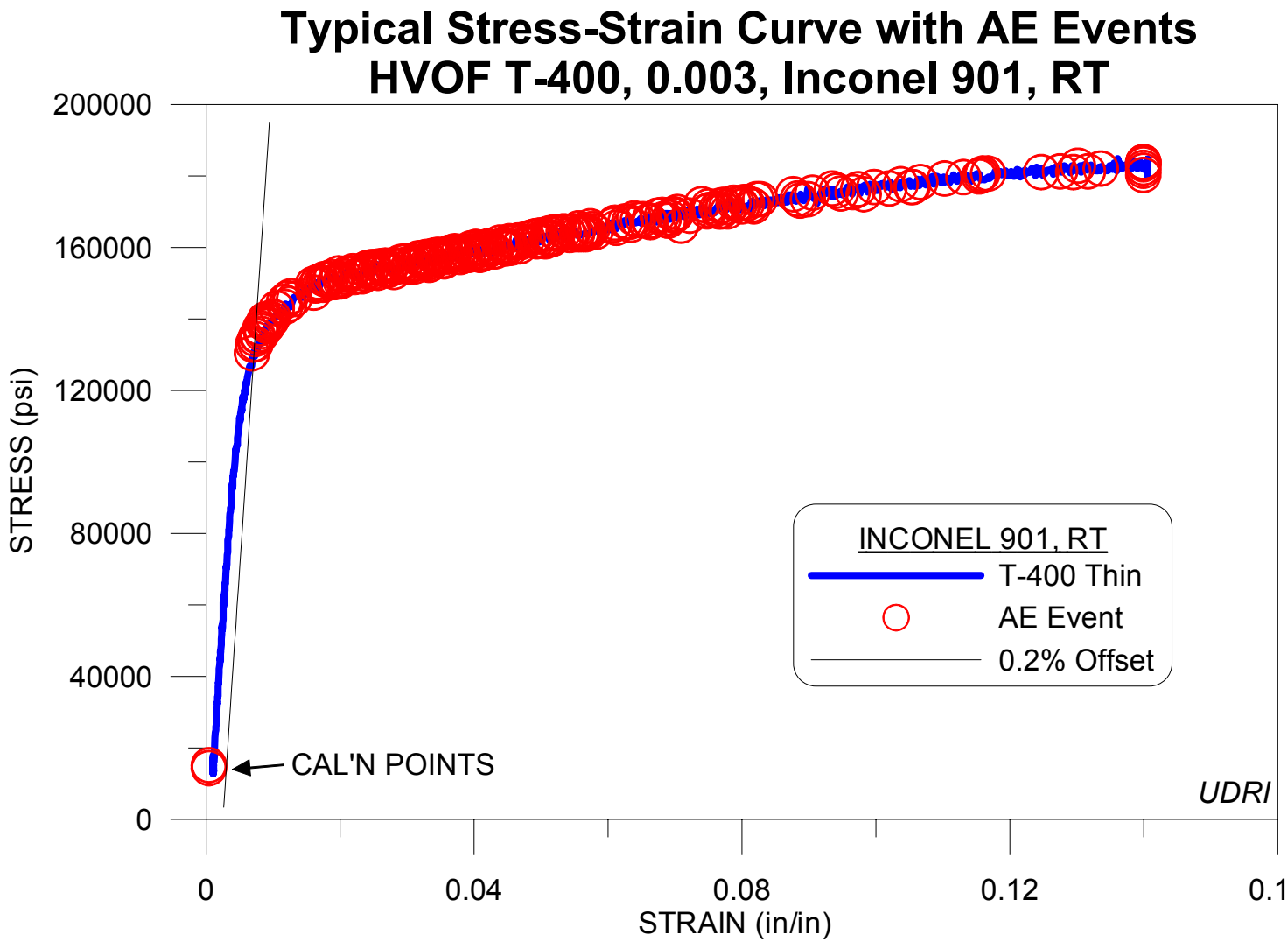
Onset of Cracking – Acoustic Emission

- Strain to Fracture with Acoustic Emission Detection
  - *Detect cracking of coating prior to substrate tensile failure*
    - *Record AE energy, duration, location, load, strain, timestamp*
    - *Record high level signals (Load, Strain) as in typical tensile test*
  - *Goal: Detect minimum strain required to cause cracking in coating*
- Elongated Tensile Specimen modified for AE Sensors
  - *Two Substrates (17-22 Steel; Inconel 901)*
  - *Three Temperatures (R.T., 300 °F, 750 °F)*
  - *Two Thicknesses (0.003 inches, 0.010 inches)*
  - *Five Coatings*
    - *HVOF: WC-Co17; Tribaloy-400; Ni,Cr*
    - *PS: WC-Co17; Tribaloy-400*

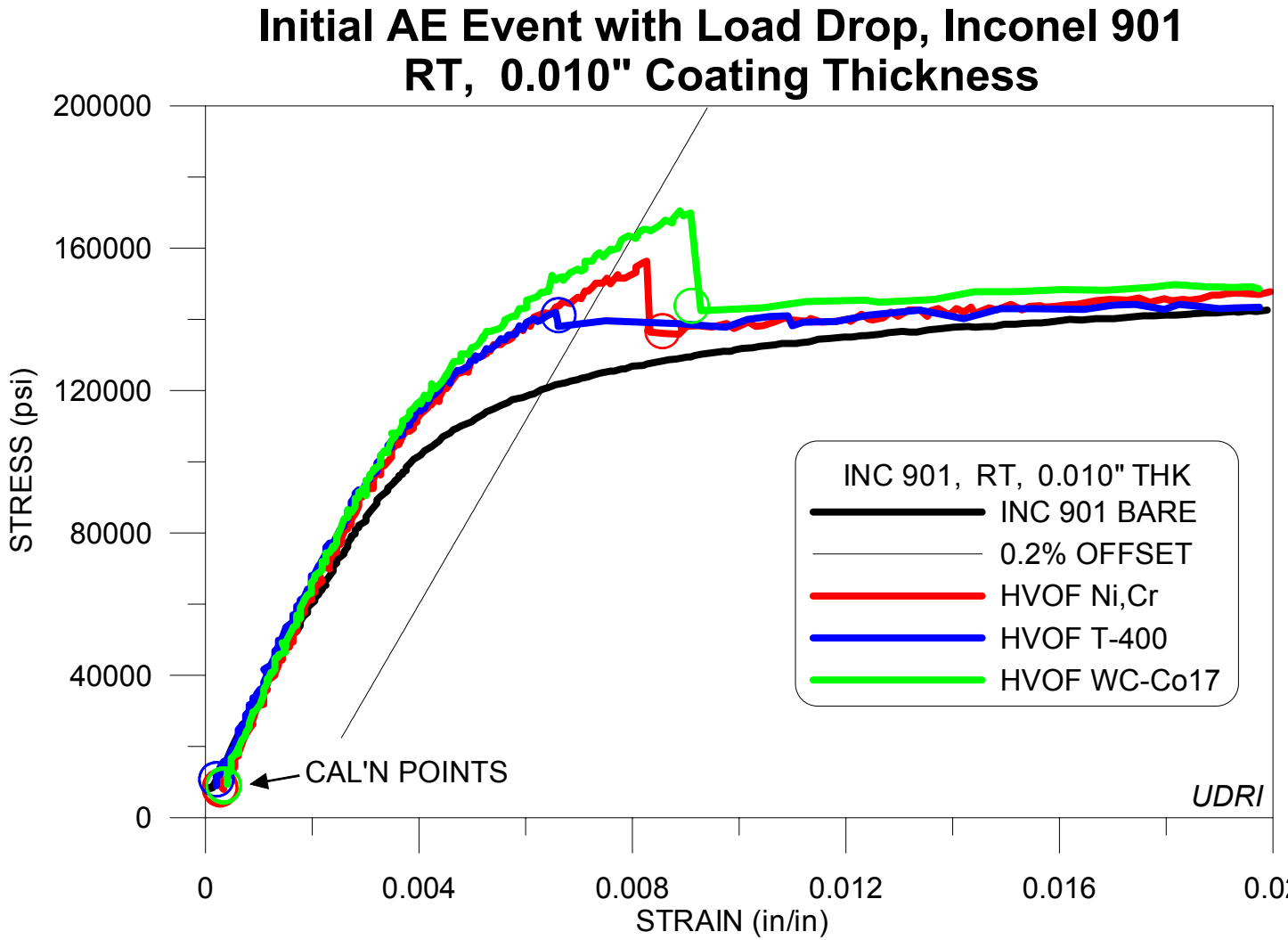
Acoustic Emission Setup



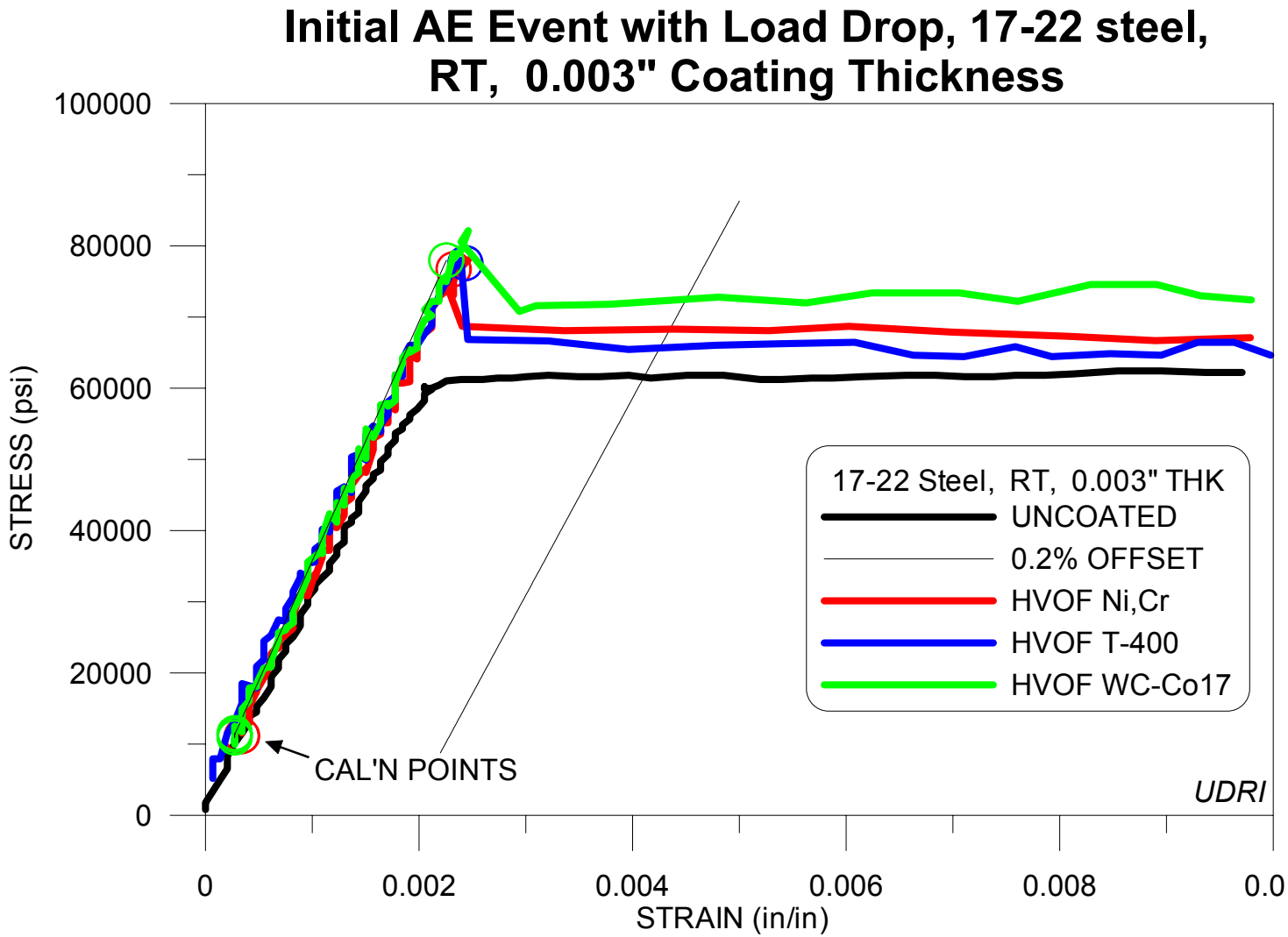
Acoustic Emission Results



Acoustic Emission Results



Acoustic Emission Results



AE – Failure Modes

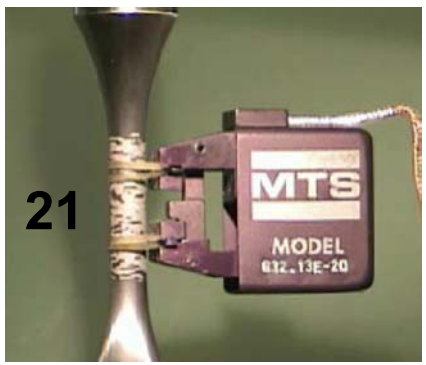
Thin Coatings

Typical Fail Mode:

Spalling/Flaking –

Patch Delamination

(HVOF Ni Cr, 0.003”)
HVOF WC-Co 0.003”
PS WC-Co17 0.003”



AE – Failure Modes

Thick Tribaloy-400

Typical Fail Mode:

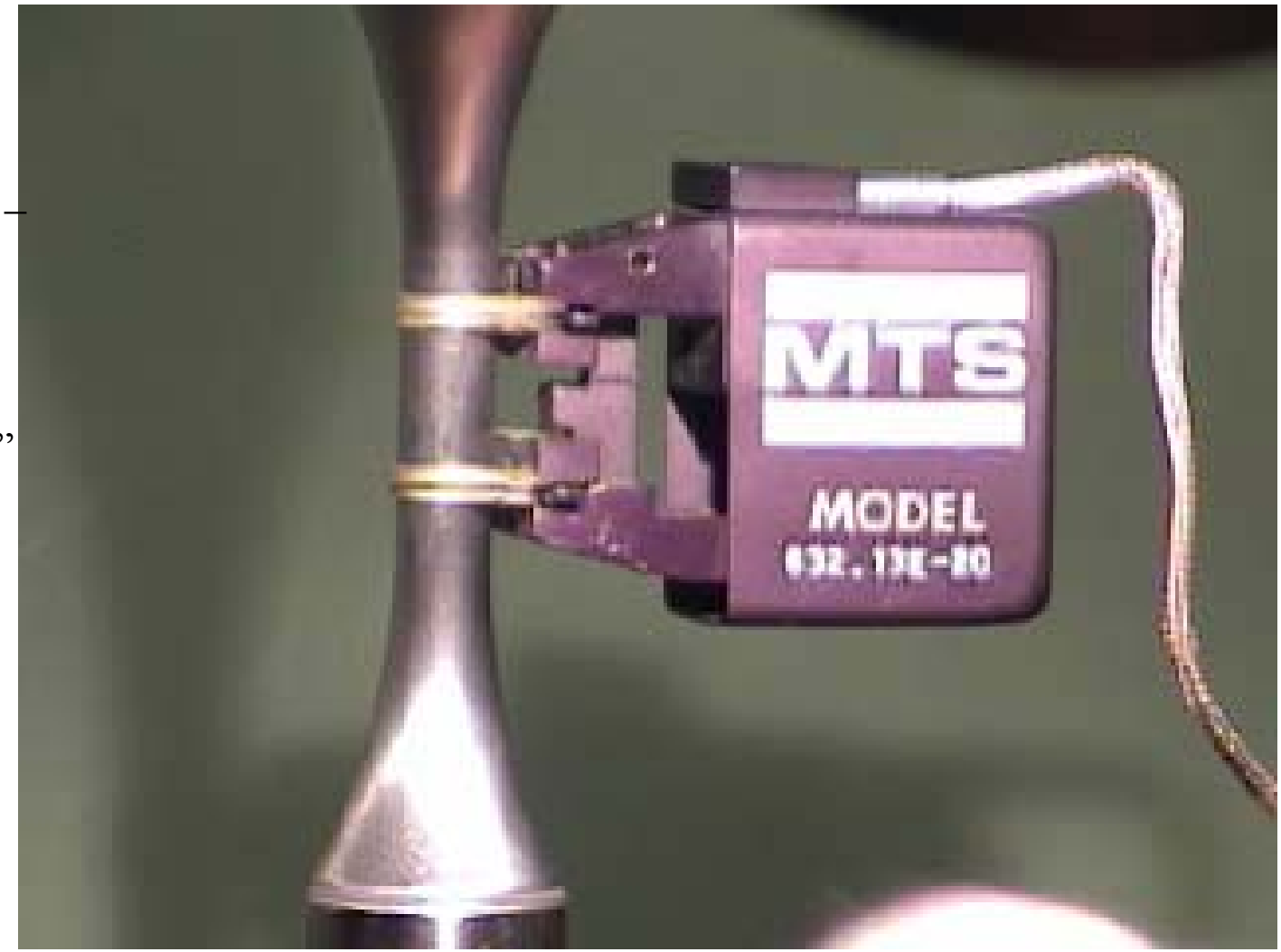
Cigar Band Delam –

Circumferential Cracks –

Lateral Contraction

(HVOF T-400, 0.010”)

PS Tribaloy-400, 0.010”



AE – Failure Modes

Thick WC-Co and Ni,Cr

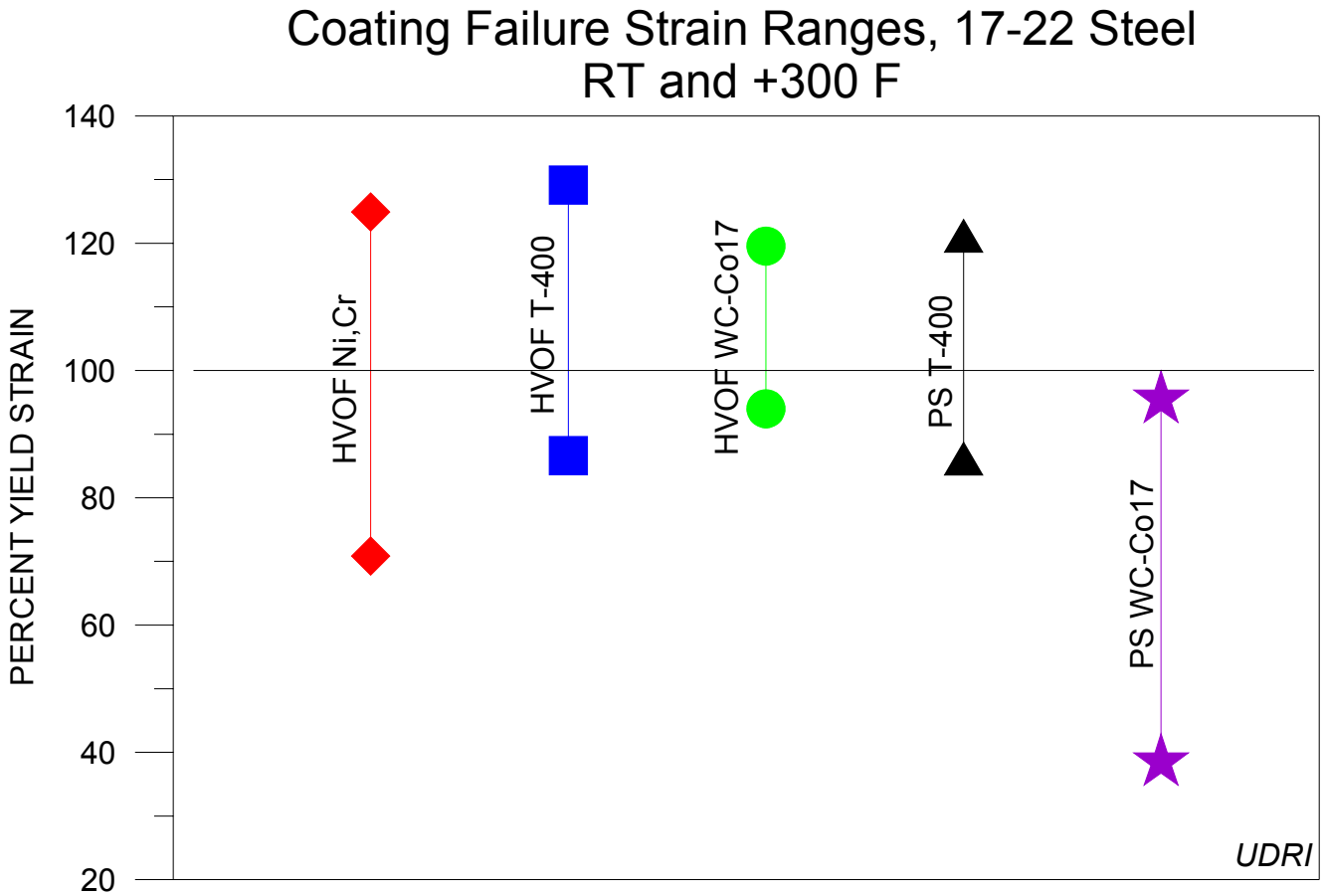
Typical Fail Mode: Coating suddenly shatters – Coating carry load?

(HVOF WC-Co, 0.010”)

HVOF Ni Cr, 0.010”

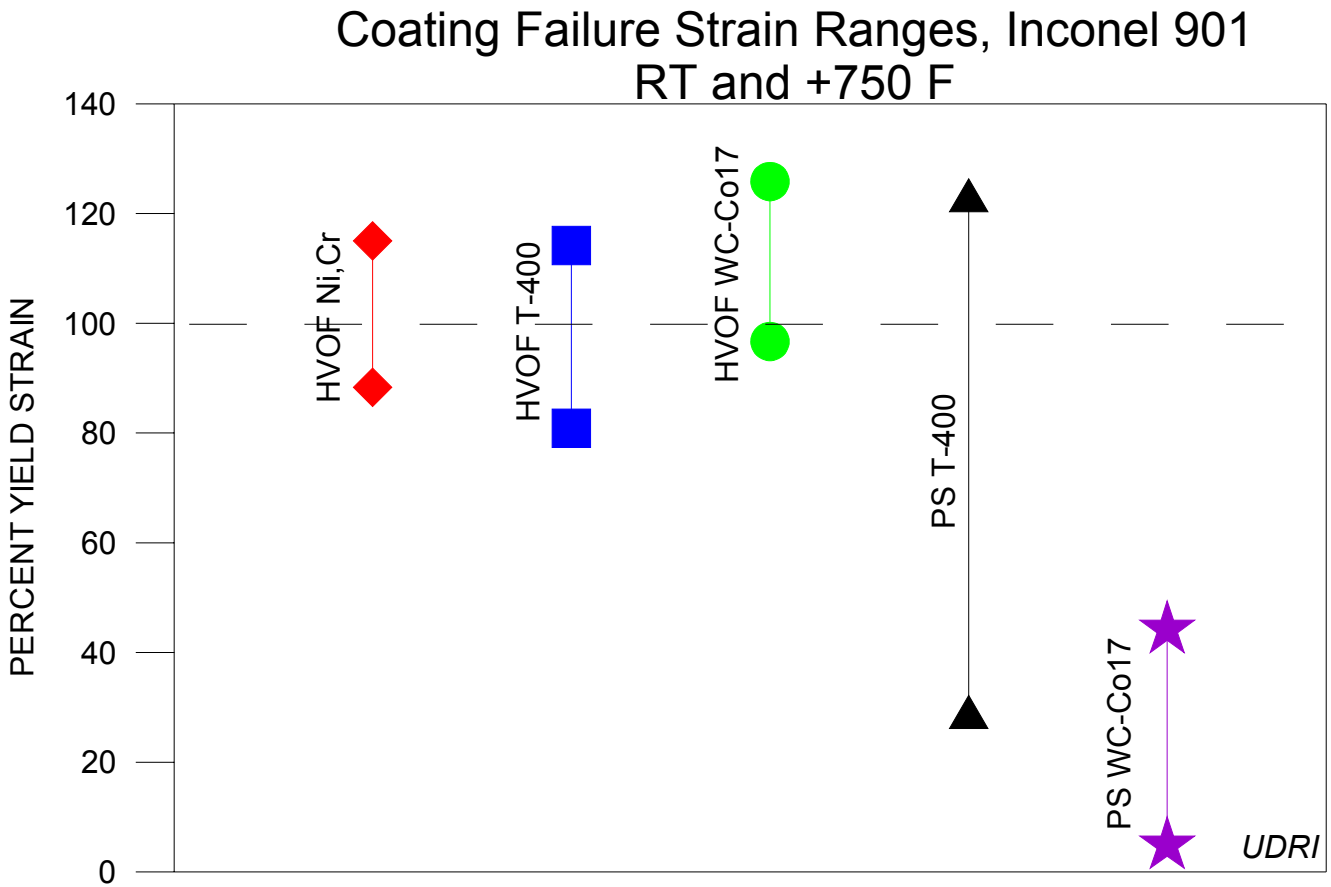
AE Failure Strain

Initial Cracking of Coating



AE Failure Strain

Initial Cracking of Coating



Acoustic Emission Results

Summary

- PS coatings began to crack at far lower stress and strain levels
  - *Tribaloy-400 minimum strain 0.17%* *(32% YS – 750F)*
  - *WC-Co17 minimum strain 0.05%* *(5% YS – 750F)*
- HVOF coatings began to crack near yield point in both substrates
  - *Tribaloy-400 minimum strain 0.54%* *(85% YS – 750F)*
  - *WC-Co17 minimum strain 0.45%* *(90% YS – RT)*
  - *Ni,Cr minimum strain 0.32%* *(80% YS – 300F)*
- Evidence of coating carrying load? In some coating conditions
  - *Most evident in thicker HVOF WC-Co17 and HVOF Ni,Cr coatings, on 17-22 and Inc 901, at RT and elevated temp*
- In general, the HVOF coatings began to fracture near the yield point of the substrate.
  - *Further investigation necessary with higher strength substrates – follow on project*

HVOF coatings performed superior to PS coatings

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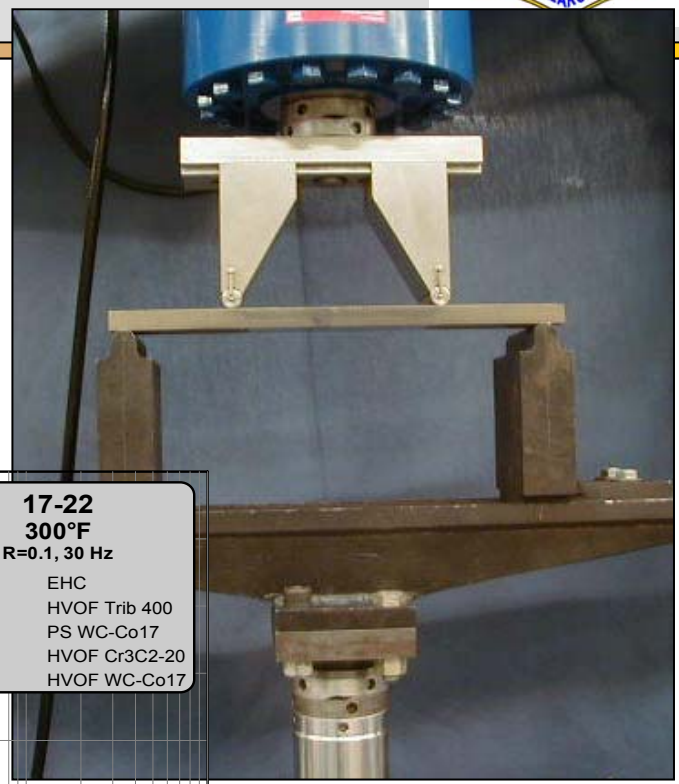
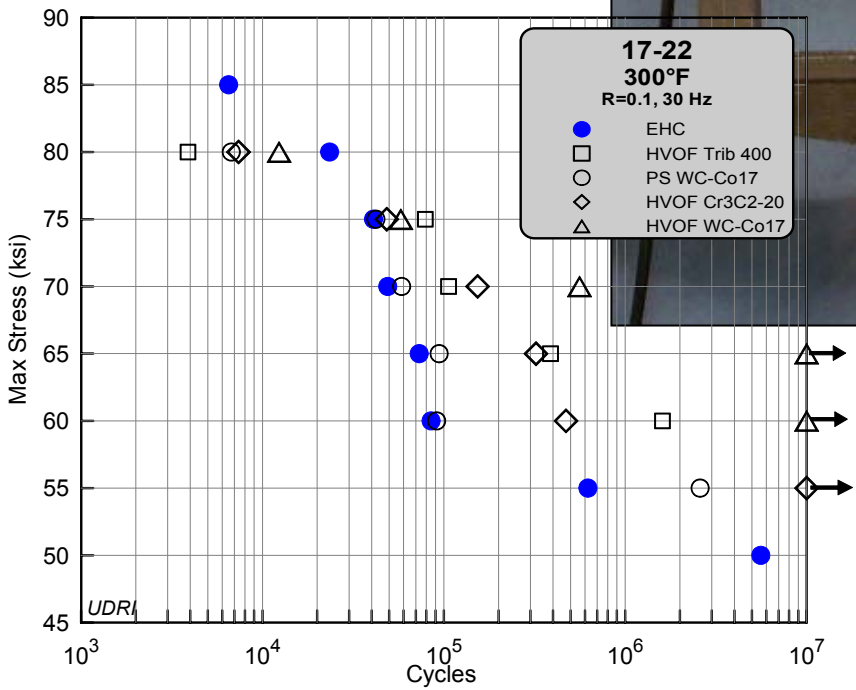
Adhesion

- Create, Detect, and Characterize delamination and coating damage for engine applications
- Correlate known specimen damage to NDI ultrasound scan results and adhesion tests
- Coatings and Conditions
  - *17-22 steel substrate, 12”x1.5”x0.50” bar specimen*
  - *Two Thicknesses (0.003 inches, 0.010 inches)*
  - *Five Coatings*
    - *HVOF: WC-Co17; Tribaloy-400; Ni,Cr*
    - *PS: WC-Co17; Tribaloy-400*

Adhesion Setup

Damage Mechanisms





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Adhesion Setup

Bond Buttons

AIR FORCE RESEARCH LABORATORY

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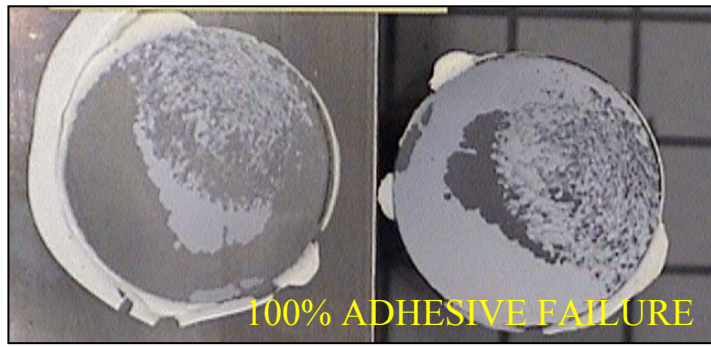
Adhesion

Bond Button Fail Modes

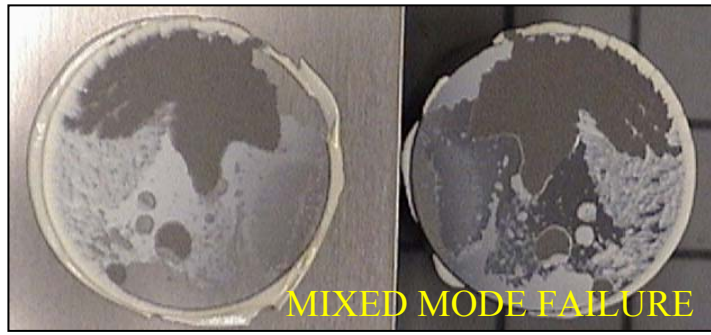
Adhesive failure, ~10 ksi failure stress

HVOF WC-Co17, NiCr



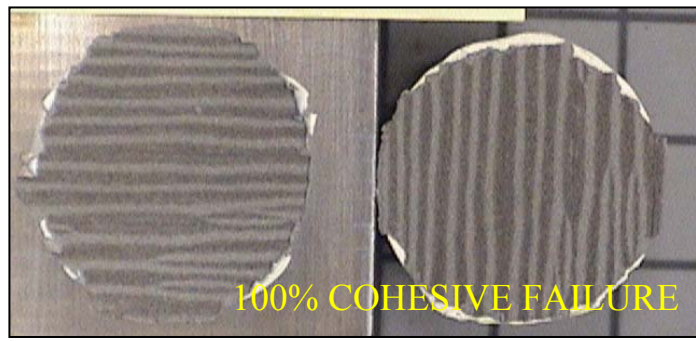
Mixed Mode failure, 4-10 ksi failure stress

HVOF T-400



Cohesive failure, 3-5 ksi failure stress

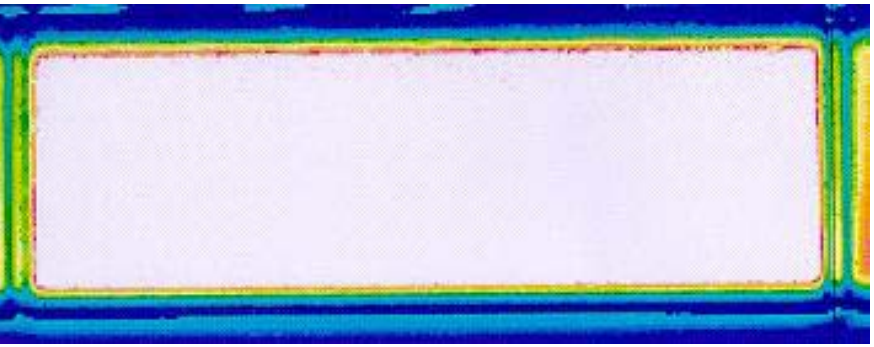
PS T-400, PS WC-Co



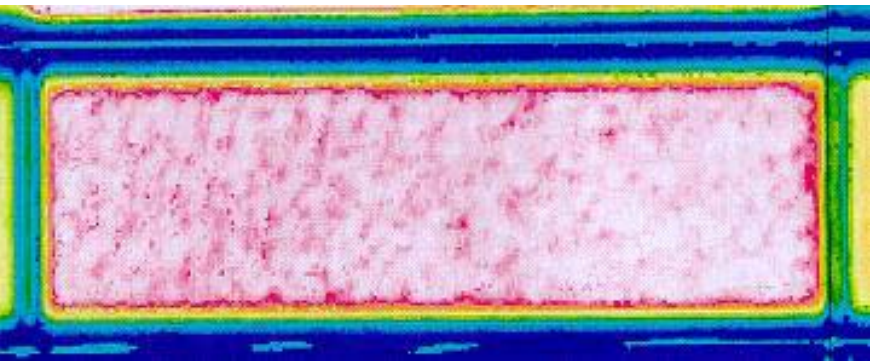
Adhesion

NDI Scan Results

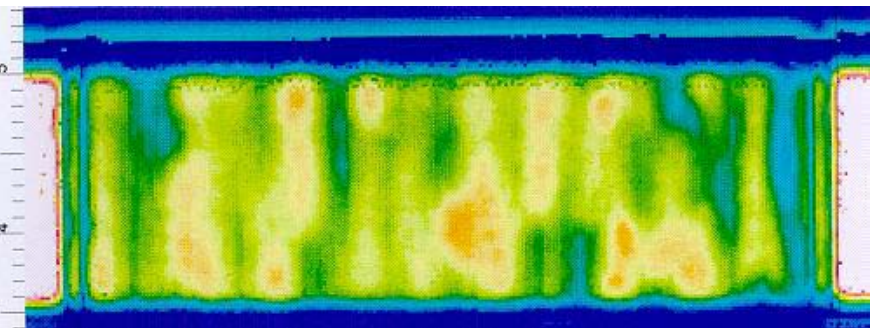
NDI Scans



Baseline NDI scans performed on undamaged specimens, some scans show uniform attenuation (gain issues)



Post Damage, some NDI scans show “Uniform Attenuation” and surface shows no visible coating damage – *Almost all coatings*



Post Damage, *PS WC-Co17* shows visible cracking on coating surface, NDI scans show definite loss of coating integrity

Adhesion Results

- Increasing Damage with constant life or stress
  - *HVOF*
    - *Ni,Cr - maintained 10ksi adhesive strength, >90% adhesive failures*
    - *WC-Co17- maintained 10ksi adhesive strength, >95% adhesive failures*
    - *T-400 - maintained ~10ksi adhesion strength, ~60% adhesive failures*
  - *PS*
    - *WC-Co17 – 10 ksi fell to 6-7 ksi after stress, 90% adhesive fail fell to <10% after stress*
    - *T-400 - constant poor adhesive strength ~4 ksi, constant 0% adhesive fail*

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Adhesion Summary

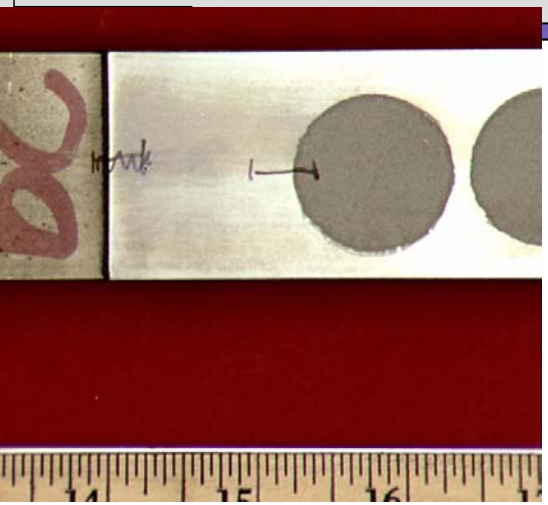
- HVOF sprayed coatings
  - *Tribaloy-400 showed unstressed cohesive failures – increasing with stress*
  - *WC-Co17 showed slight effect of damage increasing with cycles*
  - *Ni,Cr showed slight effect of damage increasing with cycles*
- As-sprayed PS adhesion was poor
  - *WC-Co17 showed effect of damage as cycles and stress increased*
  - *Tribaloy-400 failed as low as 34% of typical HVOF adhesion results*
- NDI results
  - *Ultrasound scans (baseline vs. damaged) only correlated for visibly damaged coatings*

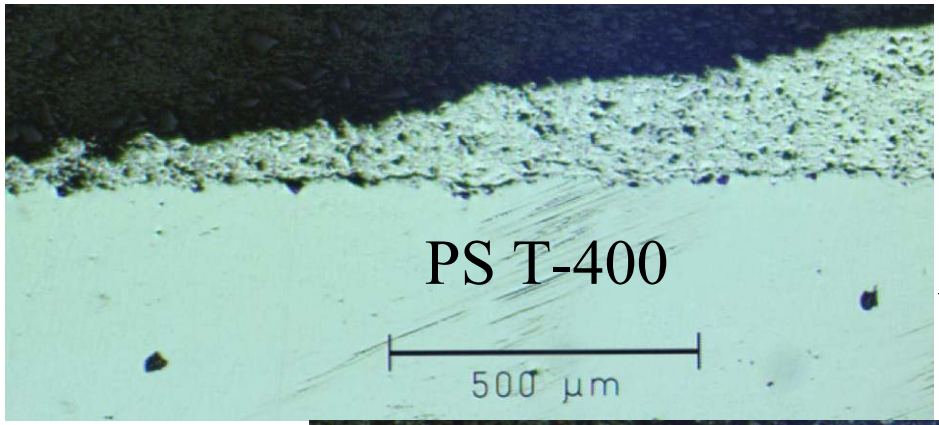
Overall Conclusions

- Fatigue
  - *HVOF performed equal to EHC at both temps, for both substrates*
  - *HVOF performed better than PS*
- AE
  - *HVOF onset of cracking occurred near the substrate yield point*
  - *PS onset of cracking occurred well before yield*
  - *Coating application guidelines should include strain considerations, as coatings may crack within the working strain of the substrate or component*
- Adhesion
  - *HVOF performed better than PS*
  - *Thinner coatings tend to resist damage better than thick*

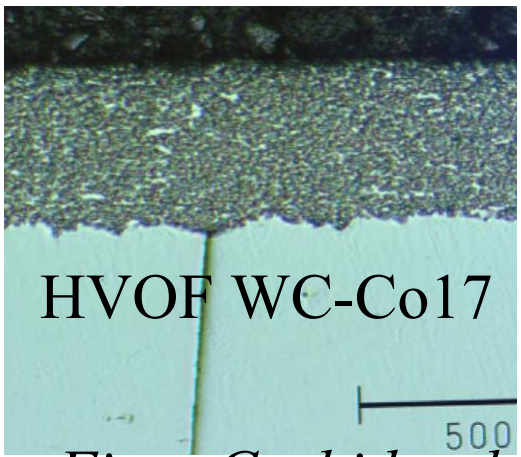
Additional Slides

Metallography
Thick Coatings

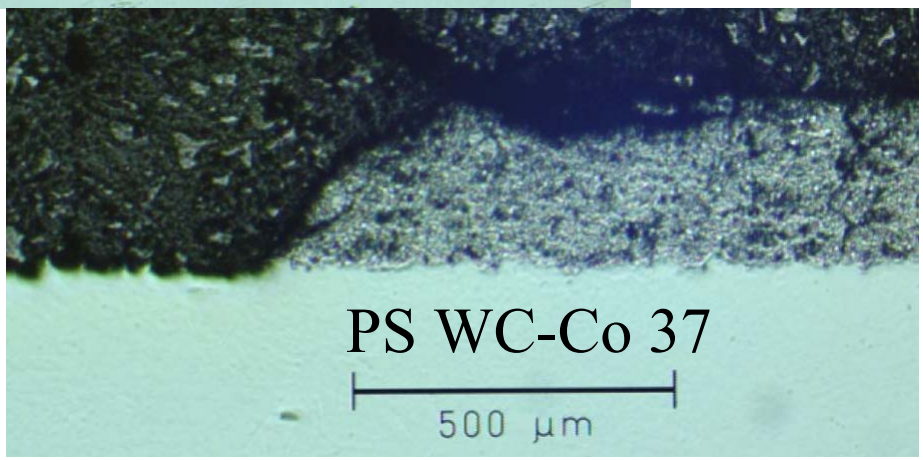




Low angle fail, porosity

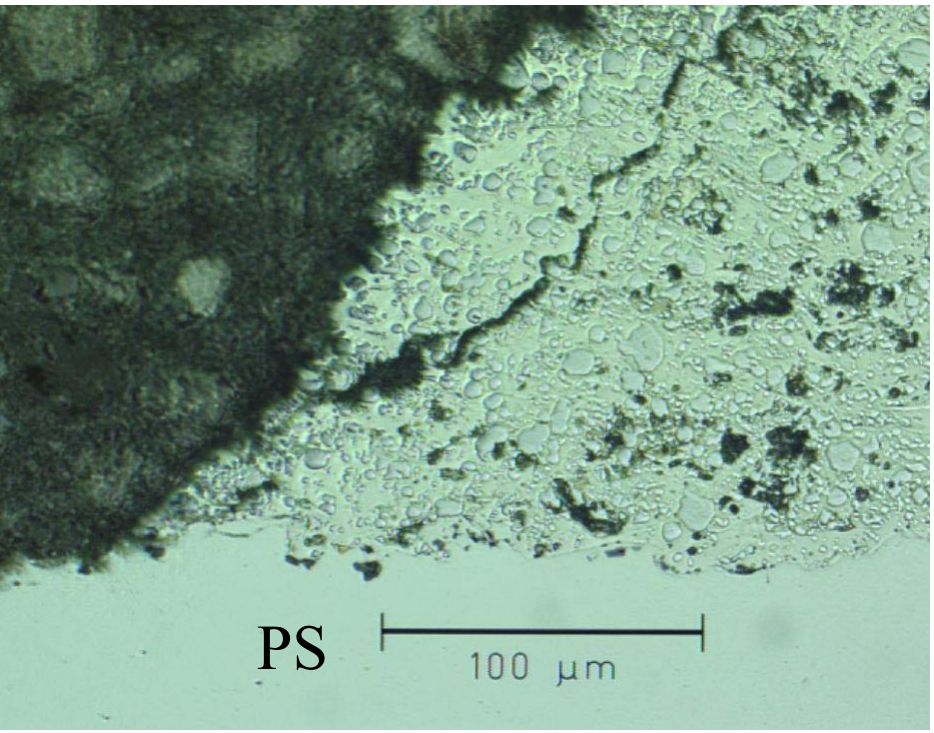


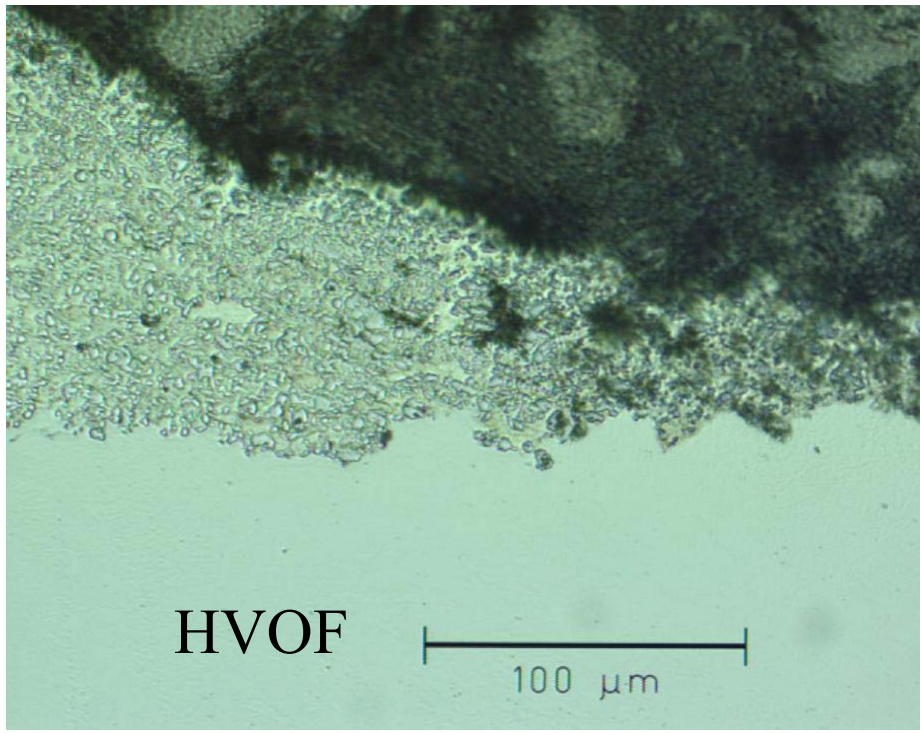
Finer Carbides, less Porosity



Porosity, larger carbides

Metallography
WC-Co17 Coatings





Follow-on Project

- Follow On Project to Acoustic Emission Testing
  - *Intended to detect if coating supports a portion of the load…*
  - *And determine if coating cracking is a function of strain or substrate yield point*
  - *Specimens ordered 9/03, Delivery 11/03*
- Test – Specimens - Condition
  - *Identical Acoustic Emission – Onset of Cracking test*
  - *4340 Steel, HT to ~280ksi, Identical geometry to AE specimens*
  - *Testing will be conducted at room temp*
- Coatings
  - *HVOF WC-Co17 in 0.003”, 0.005”, 0.010” thicknesses*
  - *HVOF Tribaloy 400 in 0.003”, 0.010” thickness*
  - *Bare substrate with same HVOF prep (grit blast, etc)*