Application of High-Temperature Extrinsic Fabry-Perot Interferometer Strain Sensor

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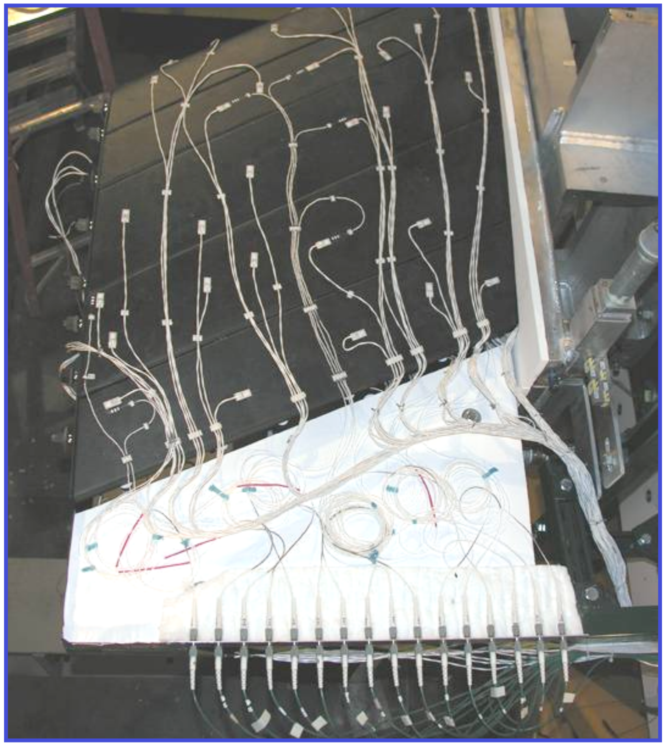
Cleared for public release

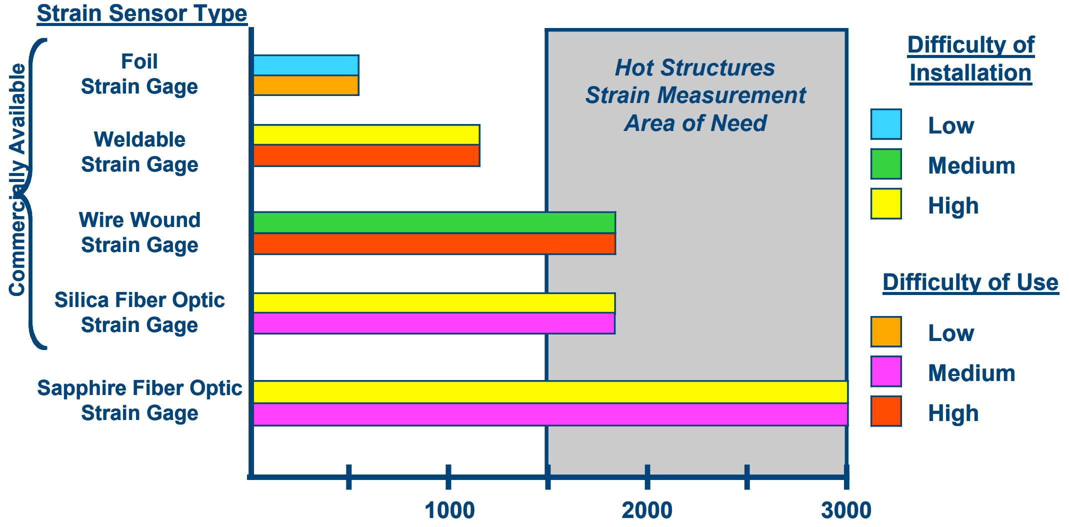
Outline



- Background
- Objective
- Sensor
- Attachment Techniques
  - Sensor Construction
  - Thermal Spray Process
- Evaluation / Characterization
- Future Fiber Optic Testing

Background

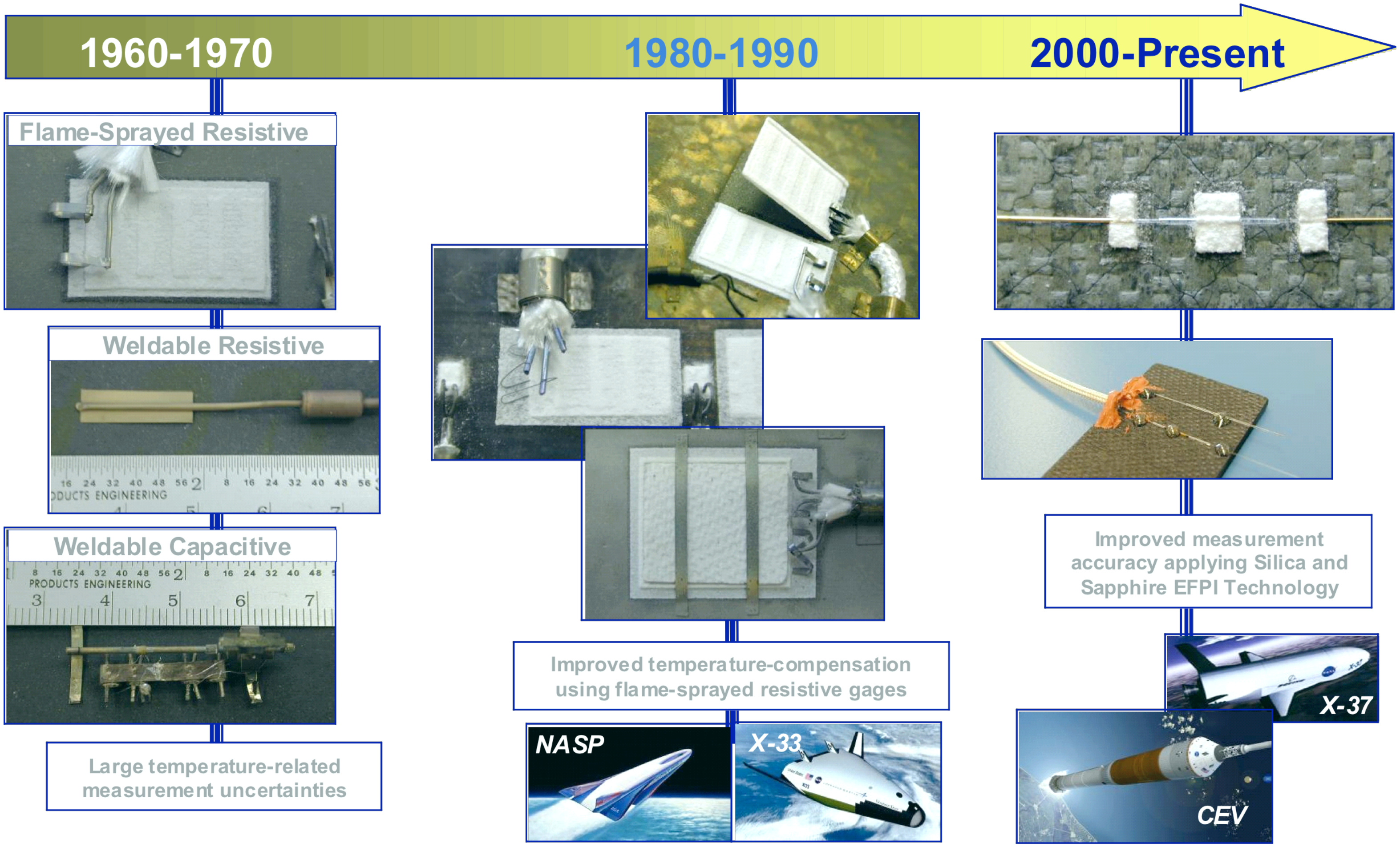
Sensor Development Motivation



- **Lack of Capability**
  - TPS and hot structures are utilizing advanced materials that operate at temperatures that exceed our ability to measure structural performance
  - Robust strain sensors that operate accurately and reliably beyond 1800°F are needed but do not exist
- **Implication**
  - Hinders ability to validate analysis and modeling techniques
  - Hinders ability to optimization structural designs

Background

Strain Sensor Maturation



1960-1970

Flame-Sprayed Resistive

Weldable Resistive

Weldable Capacitive

Large temperature-related measurement uncertainties

1980-1990

Improved temperature-compensation using flame-sprayed resistive gages

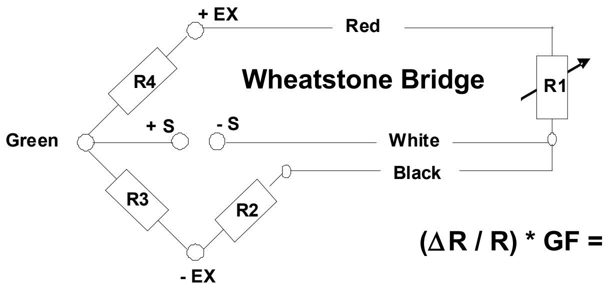
2000-Present

Improved measurement accuracy applying Silica and Sapphire EFPI Technology

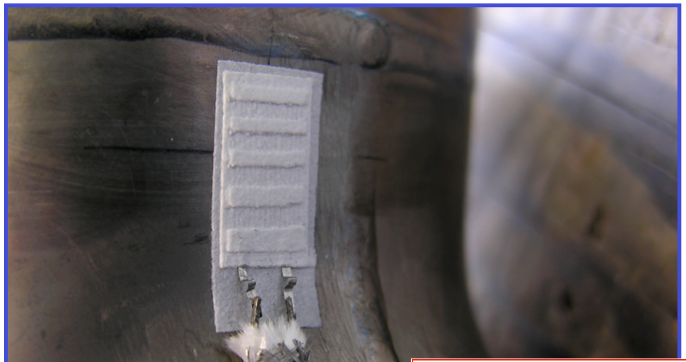
Background

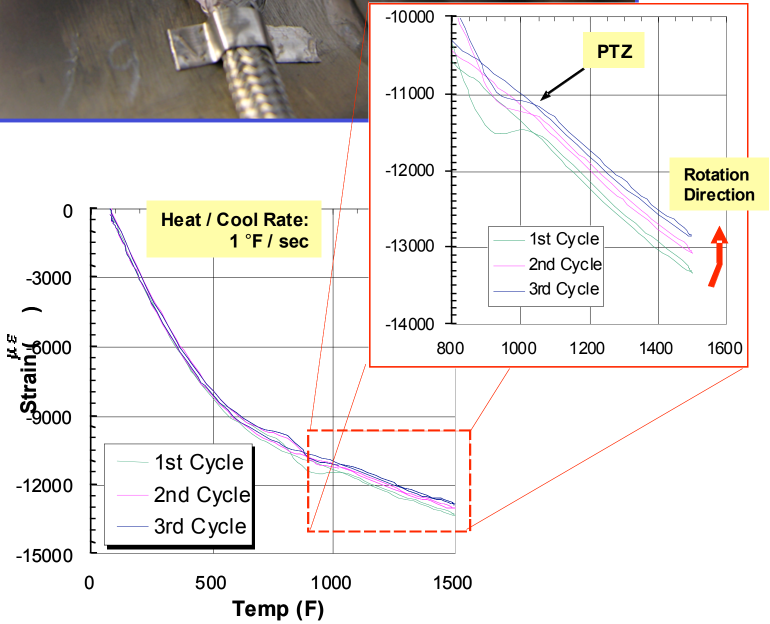
Electrical Resistive Strain Gage

High-Temp Quarter-Bridge Strain Gage



(ΔR / R) * GF = ξ





Pro's

- Sturdy / rugged thermal sprayed installation and spot-welded leadwire stakedown
- Available high sample rate DAS, usually AC coupled to negate large ξapp

Con's

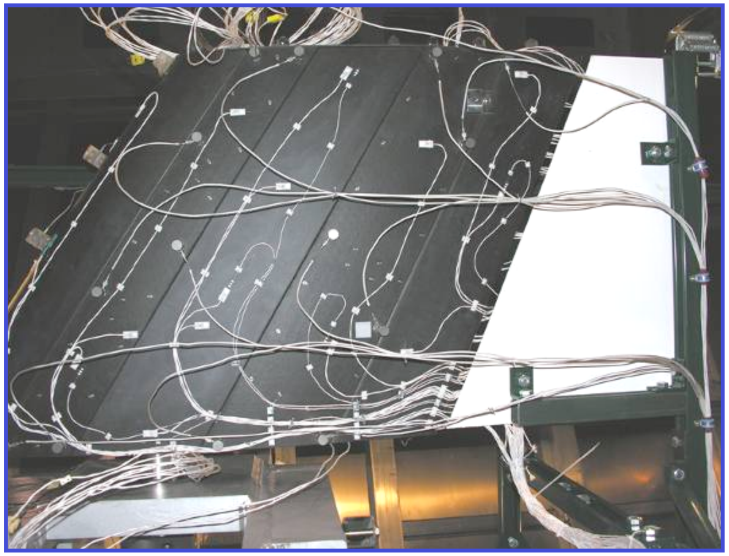
- Large magnitude ξapp primarily due to wire TCR, slope rotates cycle-to-cycle
- Sensitivity (GF): Function of temperature

$$\xi_{app} = [TCR_{gage} / GF_{set} + (\alpha_{sub} - \alpha_{gage})] * (\Delta T)$$

Objective

Provide strain data for validating finite element models and thermal-structural analyses

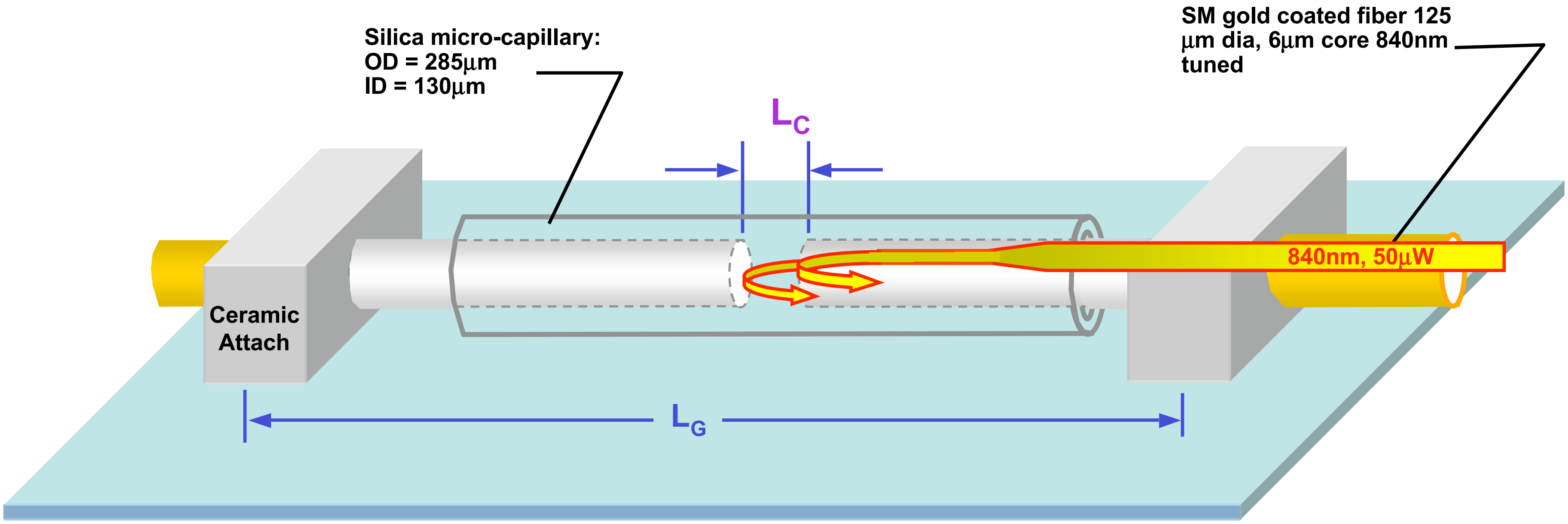
- Develop sensor attachment techniques for relevant structural materials
- Perform laboratory tests to characterize sensor and generate corrections to apply to indicated strains
- Instrument large scale hot-structures test articles



EFPI Strain Sensor

Static Measurement

Extrinsic Fabry-Perot Interferometer (EFPI)



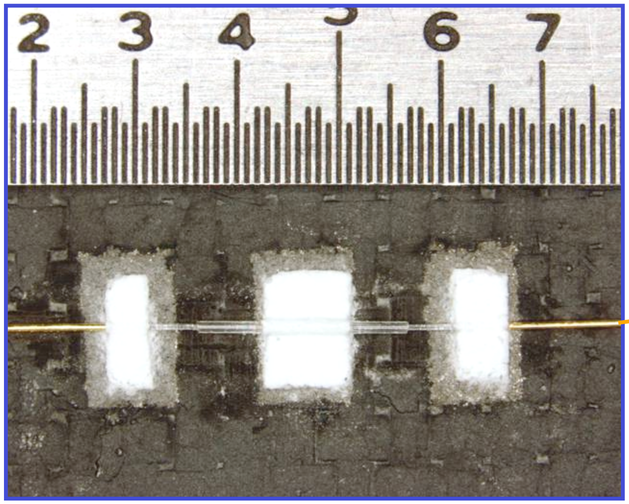
Strain = $\Delta L_C / L_{G\,(initial)}$, where sensitivity = L_G

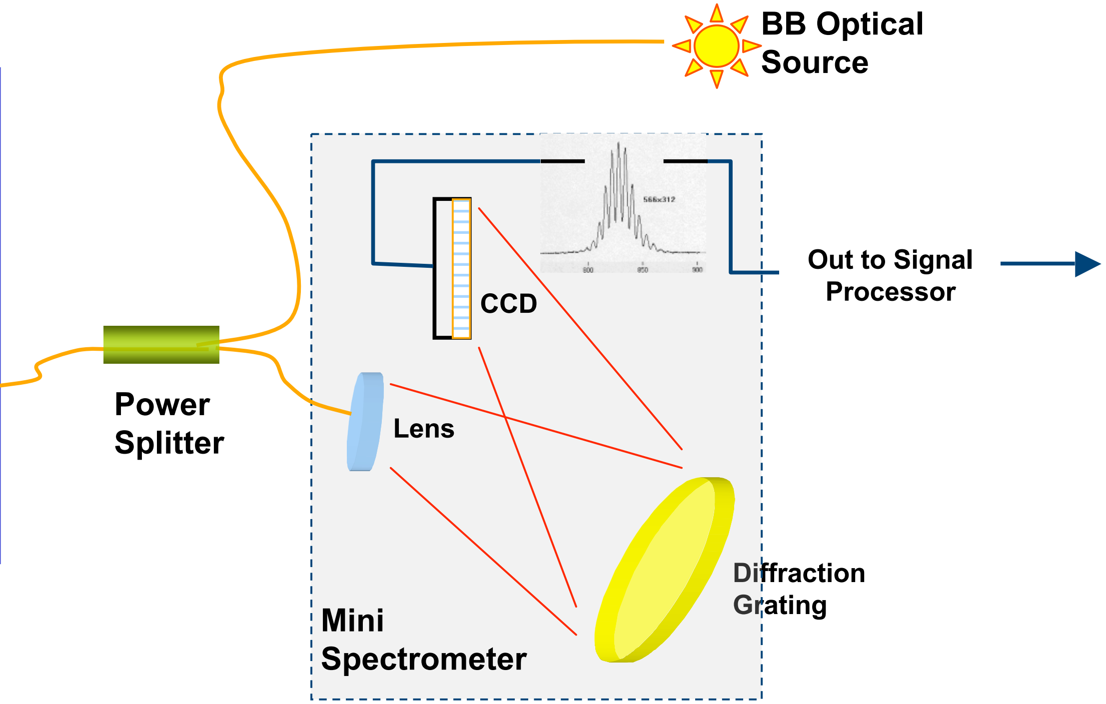
Apparent Strain (ξapp) = $(\alpha_{sub} - \alpha_{fiber}) * \Delta T$

EFPI Strain Sensor

Static Measurement

Single Mode Interferometer Signal Conditioning





BB Optical Source

CCD

Out to Signal Processor

Power Splitter

Lens

Diffraction Grating

Mini Spectrometer

Attachment Techniques

Develop sensor attachment techniques for relevant structural materials

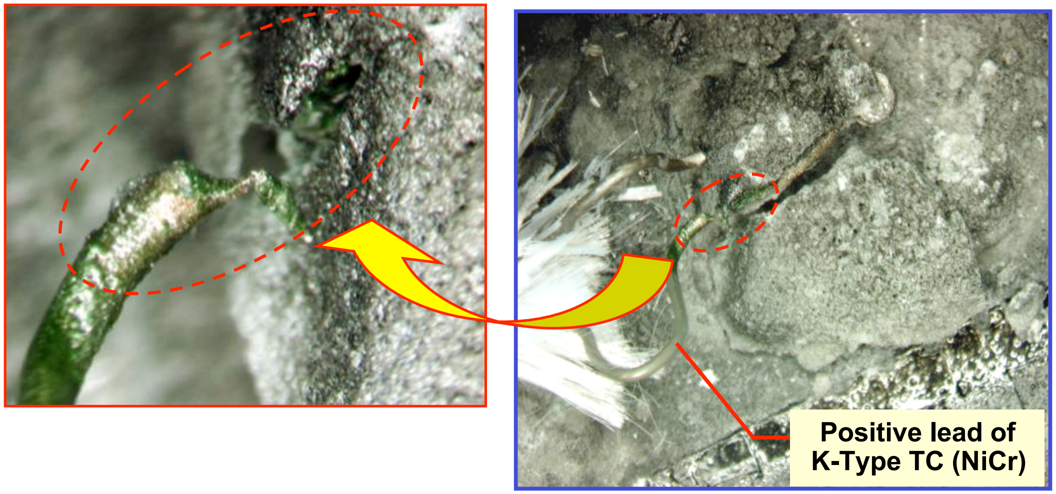
- Derive surface prep and optimal plasma spray parameters for applicable substrate
  - powder media / type, power level, traverse rate, and spraying distance
- Or, optimize / select cement that best fits application
- Improve methods of handling and protecting fragile sensor during harsh installation processes

Attachment Techniques

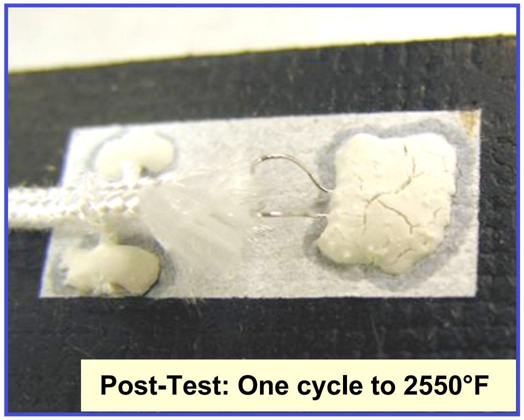
Thermal Spray vs. Cement

Thermal sprayed attachments are preferred even though cements are simpler to apply

- Tests indicate increased gage-to-gage scatter on first cycle
- Cements are often corrosive to TC or strain gage alloys
  - Si / Pt, NaF / Fe-Cr-Al alloys, alkali silicate / Cr
- Cements are more prone to bond failure due to shrinkage and cracking caused when binders dissipate



Positive lead of K-Type TC (NiCr)



Post-Test: One cycle to 2550°F

Attachment Techniques

Thermal Spray Equipment

Thermal Spray Room

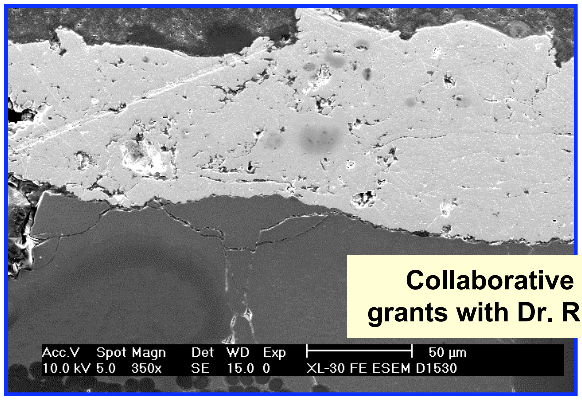
- 80KW Plasma System
- Rokide Flame-Spray System
- Powder Spray System
- Grit-Blast Cabinet
- Micro-Blast System
- Water Curtain Spray Booth

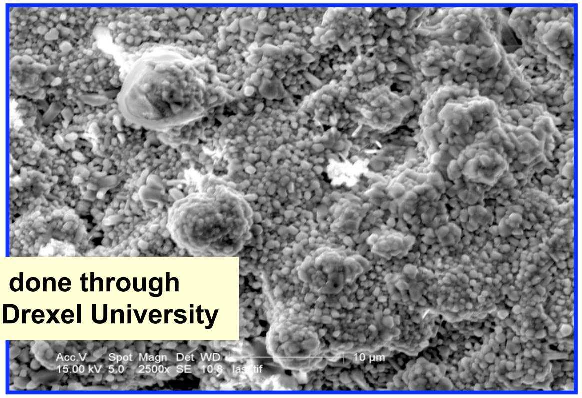
Attachment Techniques

Thermal Spray

Arc-plasma sprayed base coat

- Metallic Substrates: Used to transition high expansion substrate metal with low expansion sensor attachment material (Al_2O_3)
- CMC Substrates (inert testing): High melting-point ductile transitional metals (i.e. Ta, TiO_2, & Mo) more conducive for attachment to smooth surfaces like SiC





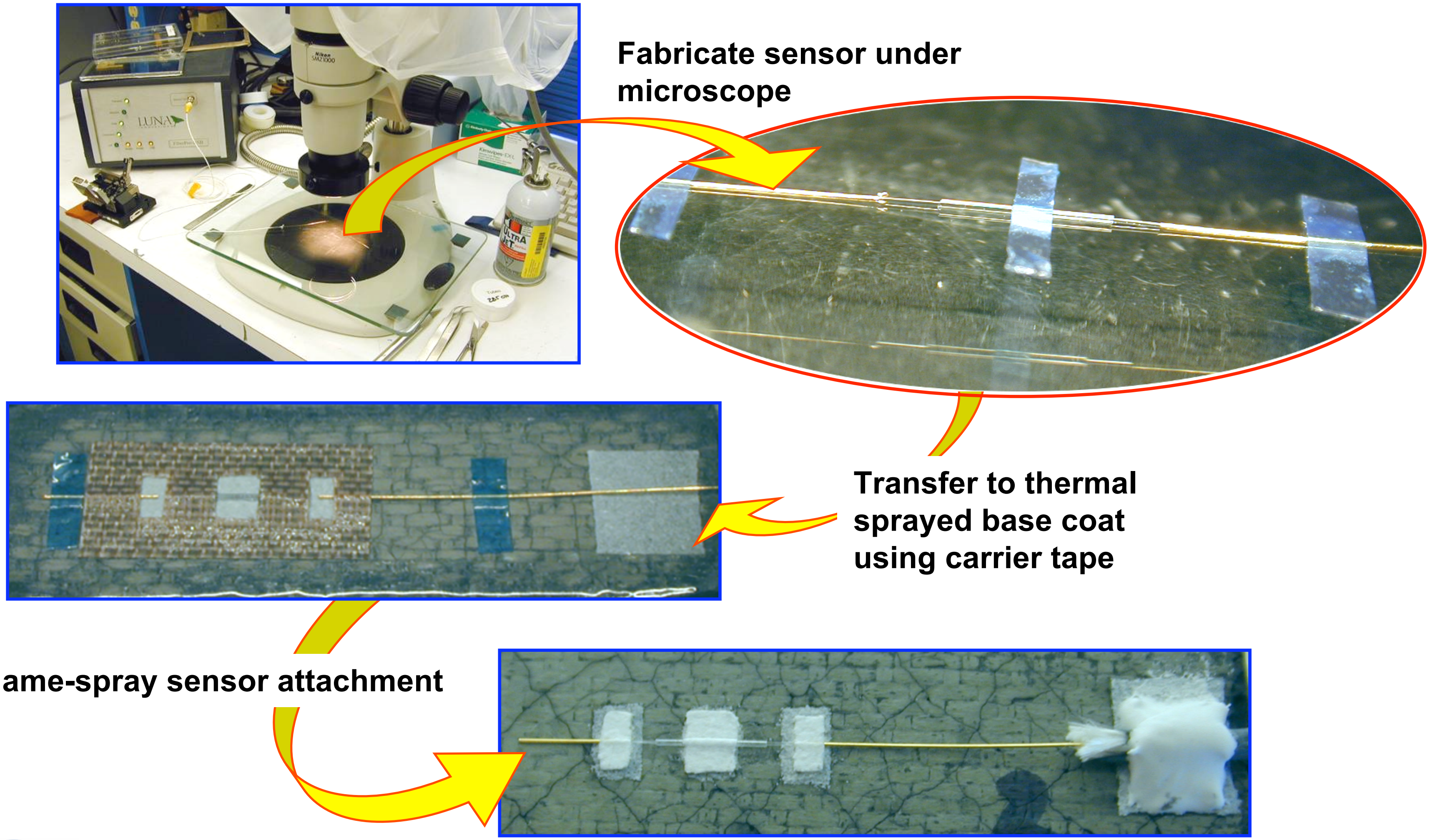
Collaborative work has been done through grants with Dr. Richard Knight, Drexel University

Rokide flame-sprayed sensor attachment

- Applies a less dense form of alumina than plasma spraying
- Electrically insulates (encapsulate) wire resistive strain gages

Attachment Techniques

Fiber Optic EFPI Installation



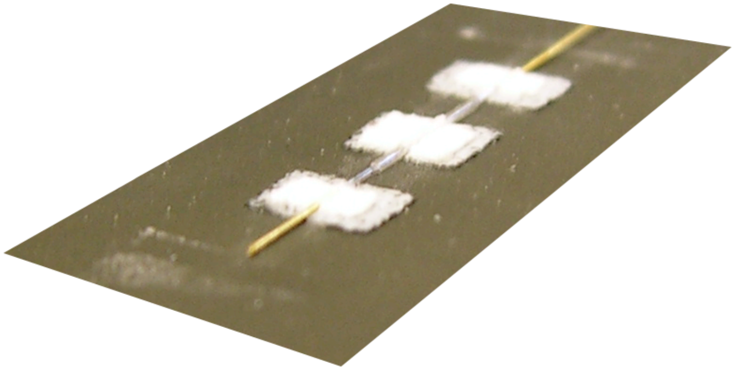
Fabricate sensor under microscope

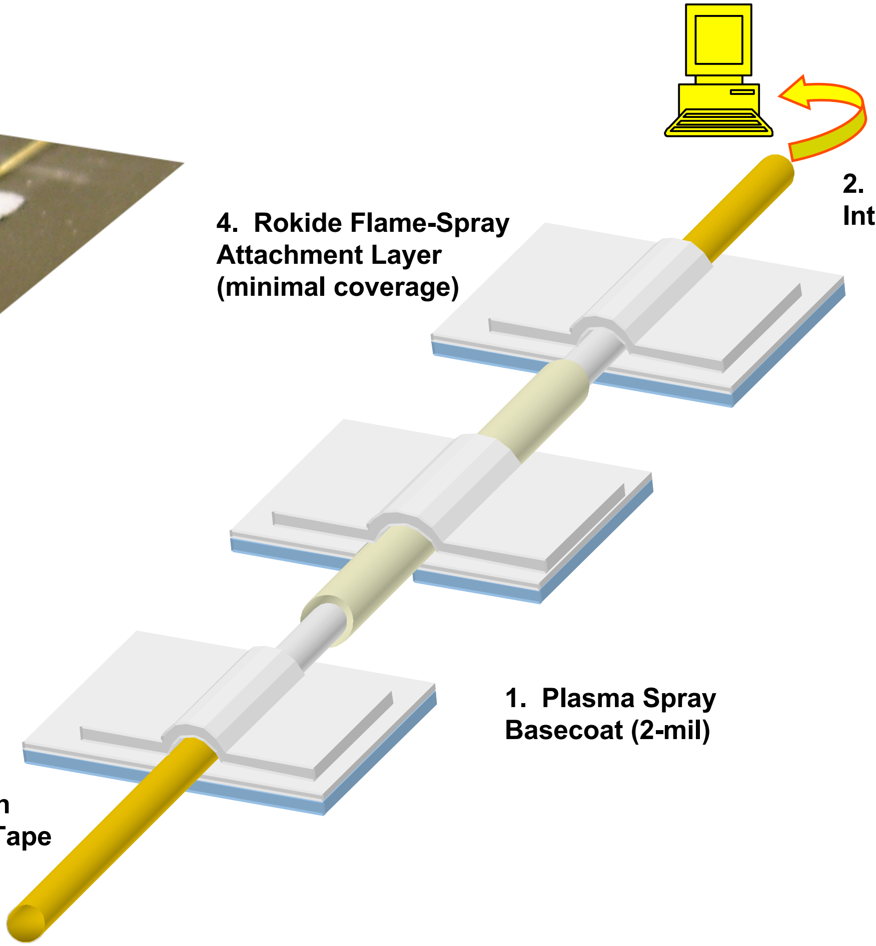
Transfer to thermal sprayed base coat using carrier tape

Flame-spray sensor attachment

Attachment Techniques

Fiber Optic EFPI Installation





2. Rokide Flame-Spray Intermediate Layer (1-mil)

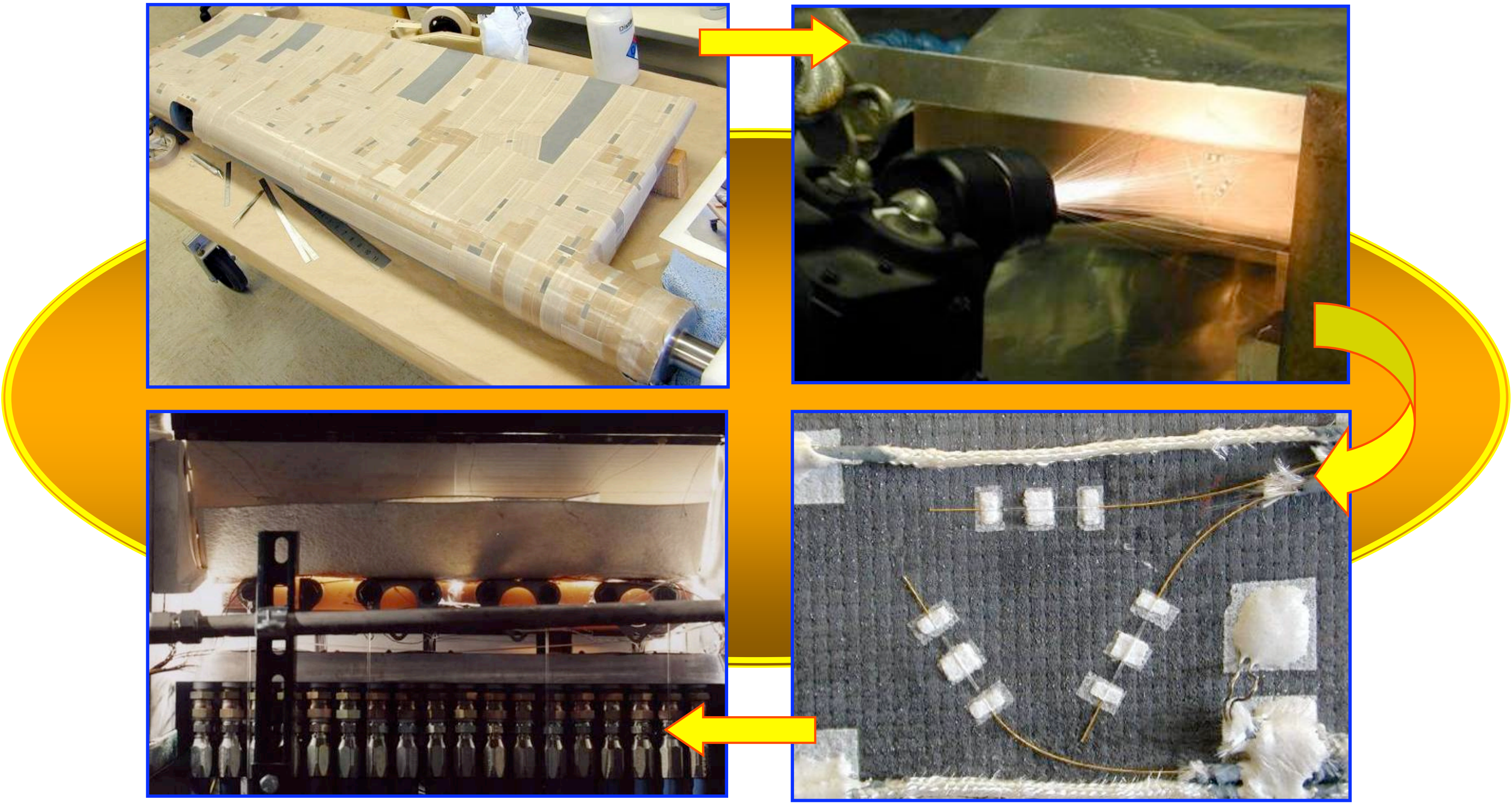
4. Rokide Flame-Spray Attachment Layer (minimal coverage)

1. Plasma Spray Basecoat (2-mil)

3. Set EFPI Sensor in Place Using Carrier Tape

Attachment Techniques

Large-Scale Structures



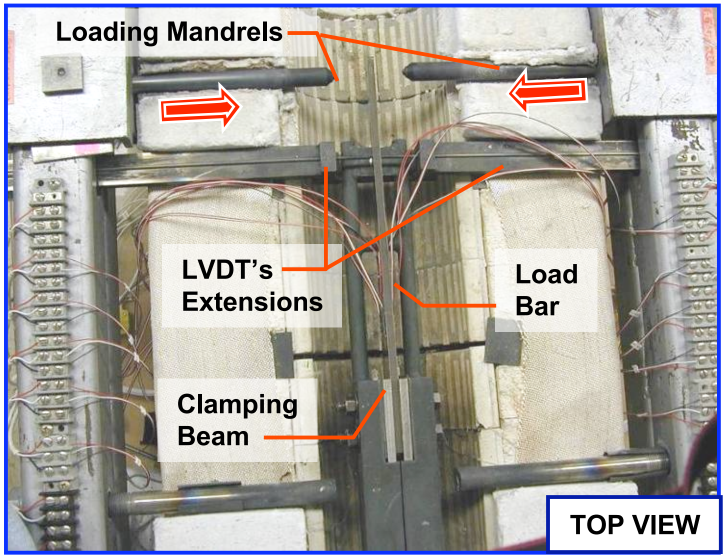
Evaluation / Characterization

Validate and characterize strain measurement

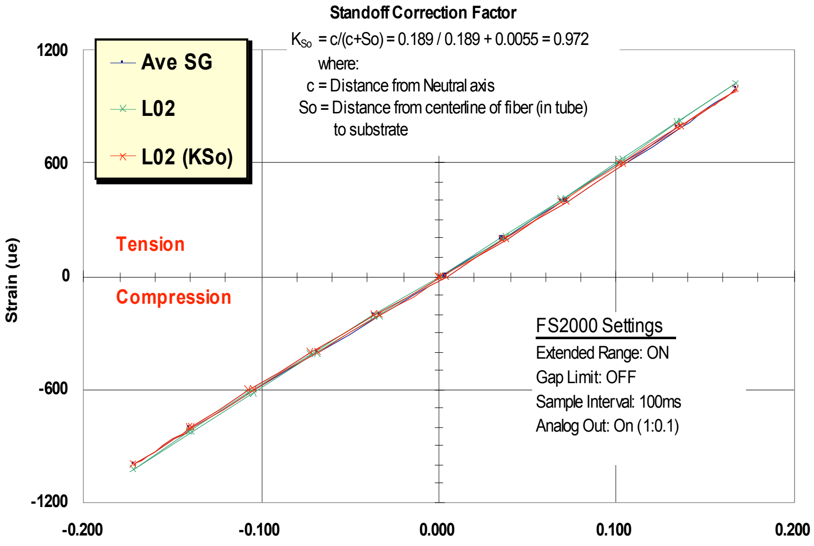
- Base-line / characterize high-temperature strain sensors on monolithic Inconel specimens
  - Known material spec's isolate substrate from inherent sensor traits prior to testing on more complex composites
- Evaluate / characterize sensitivity (GF) of strain sensors on ceramic composite substrates using laboratory combined thermal / mechanical load fixture
- Generate apparent strain curves for corrections on relevant ceramic composite substrates

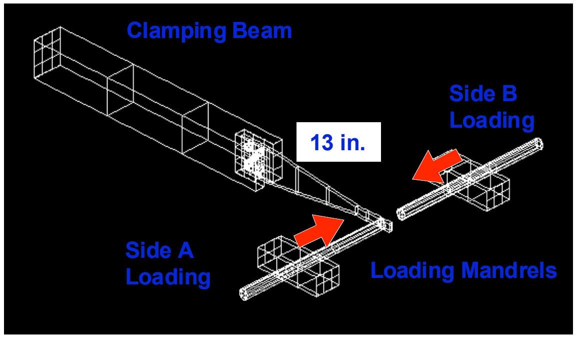
Evaluation / Characterization

Combined Thermal / Mechanical Loading (Obsolete)



EFPI Combined Loading on IN625



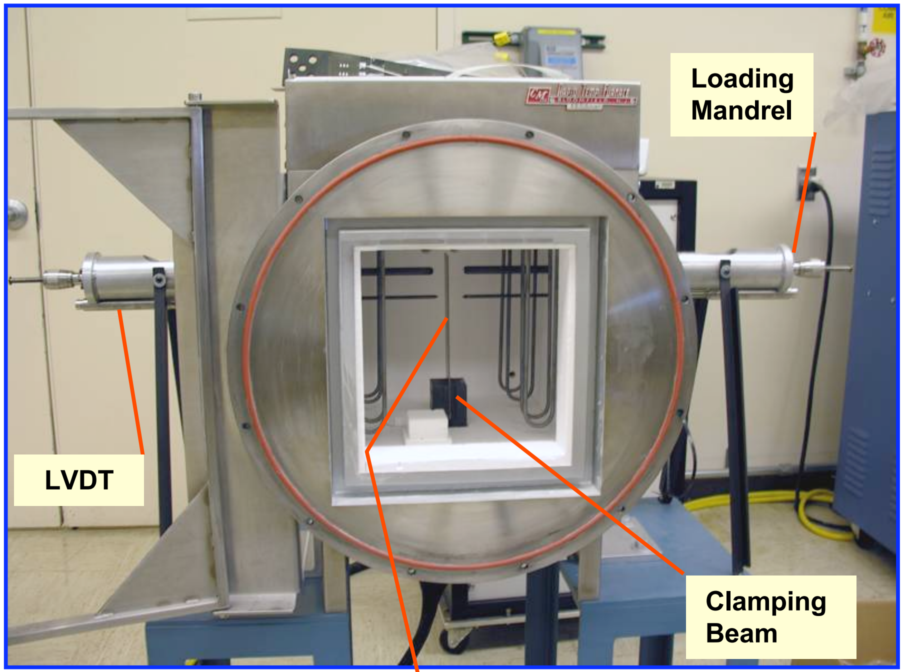


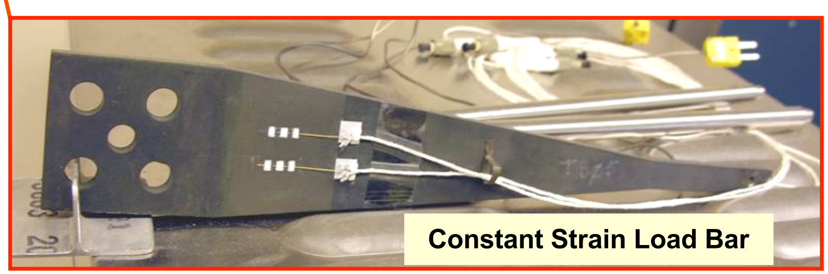
Thermal / Mechanical Cantilever Beam Testing of EFPI's

- Excellent correlation with SG to 550°F (3%)
- Very little change to 1200°F
- Slight drop in output slope above 1200°F
- Maximum gap readability uncertain at upper range temperatures on high expansion material

Evaluation / Characterization

Combined Thermal / Mechanical Loading (Current)





Furnace / cantilever beam loading system for sensitivity testing

- Air or inert (3000°F max)
- 12-in^3 inner furnace with Molydisilicide elements
- Micrometer / mandrel side loading
- LVDT displacement measurements
- POCO Graphite hardware for inert environment testing of ceramic composites
- IN625 hardware for metallic testing in air
- Sapphire viewing windows

Evaluation / Characterization

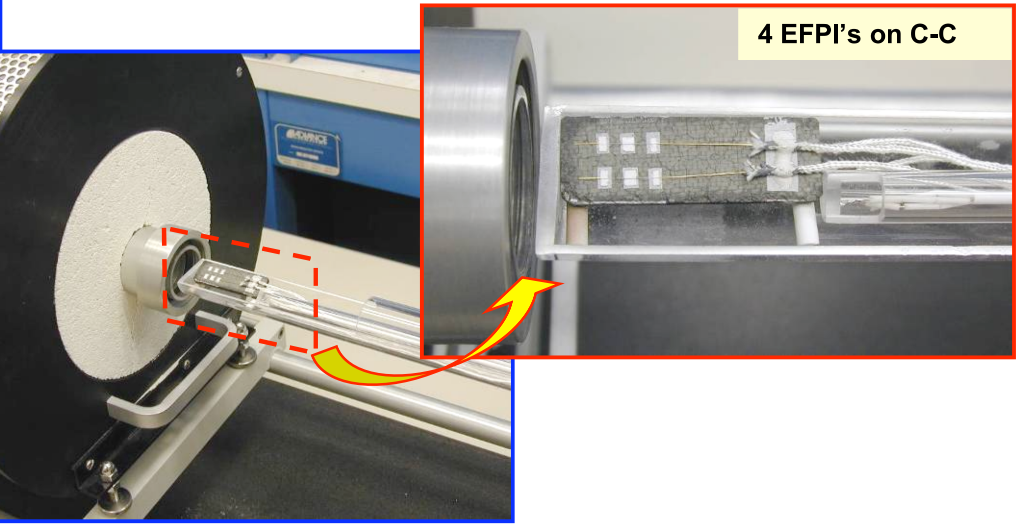
Dilatometer Testing

Modified Dilatometer System

Sensor Characterization

Air or inert (3000°F max)

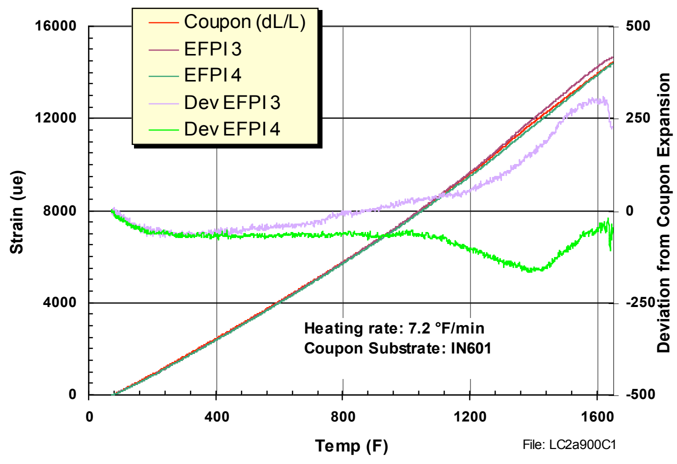
- Evaluate bond integrity
- Generate ξapp correction curves
- Evaluate sensitivity and accuracy
- Evaluate sensor-to-sensor scatter, repeatability, hysteresis, and drift

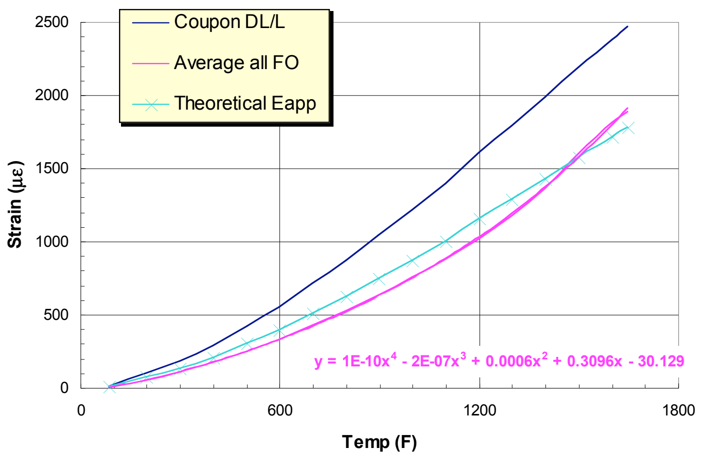


4 EFPI's on C-C

Evaluation / Characterization

EFPI Apparent Strain


Inconel Substrate


CMC Substrate

ξ_{app} Correction: The removal of inherent sensor traits and substrate expansion from indicated strain to acquire true applied strains or thermal stresses

$$\xi_{true} = \xi_{indicated} - \xi_{app}, \text{ where } \xi_{app} = (\alpha_{sub} - \alpha_{fiber}) * \Delta T$$

- Inconel (LH chart): Expansion ratio between IN and Si so large no sensor correction *required* (output primarily substrate expansion, CTE * ΔT)
- CMC (RH chart): Small CTE ratio between C-SiC and Si requires a correction for the growth in fiber (lessening cavity gap) verses the expansion of the substrate
- Graphs demonstrate how well actual ξapp curves followed theoretical

Future Fiber Optic Testing

- Test single-mode silica EFPI's in combined thermal / mechanical load fixture on C-C and C-SiC substrates
- Develop Sapphire strain sensor (multi-mode)
  - Keep precise parallel gap faces aligned throughout process
    - Develop precision transfer method (i.e. temporary alignment fixture)
  - Test in laboratory thermal / mechanical loads fixture to > 2500°F
- Test and evaluate high-temperature fiber Bragg Gratings for use as strain and temperature sensors
- Attach and evaluate high-temperature heat flux gage
- Evaluate weldable (shim) EFPI strain sensor on Inconel