10.3 High-Temperature Instrumentation

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February 28, 2008

Outline

- Background
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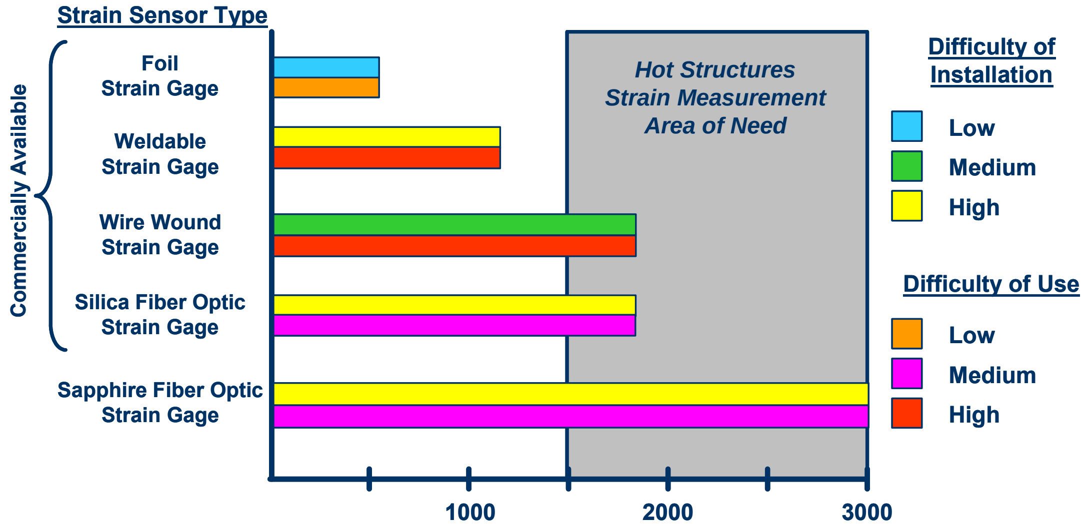
- Application and Sensor
  - Static
  - Dynamic
- Attachment Techniques
  - Thermal Spray / Cement Applications
  - Strain Sensors
  - Thermocouples
- Evaluation / Characterization Testing
- Future Testing

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

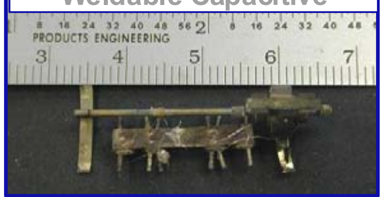
1960-1970 | **1980-1990** | **2000-Present**

1960-1970

Flame-Sprayed Resistive

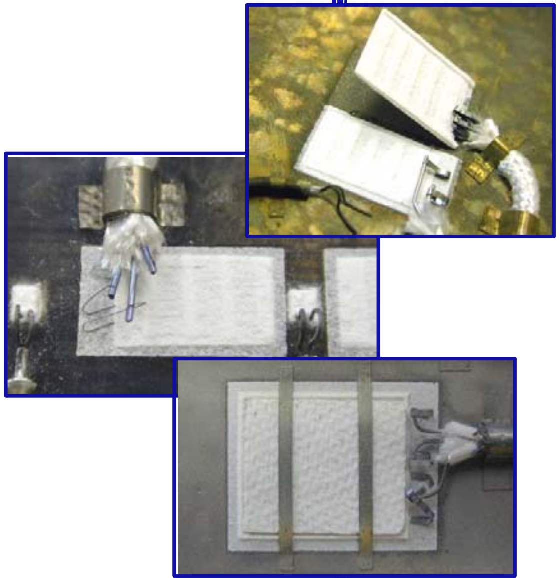
Weldable Resistive

Weldable Capacitive



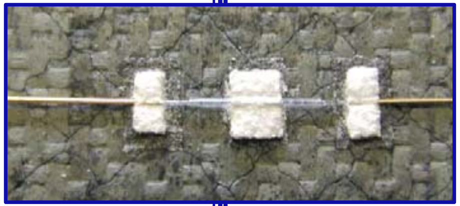
Large temperature-related measurement uncertainties

1980-1990



Improved temperature-compensation using flame-sprayed resistive gages

2000-Present

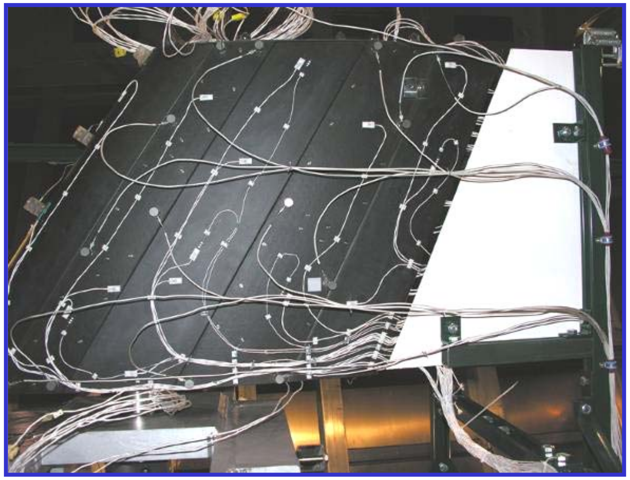


Improved measurement accuracy applying Silica and Sapphire EFPI Technology

Objective

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

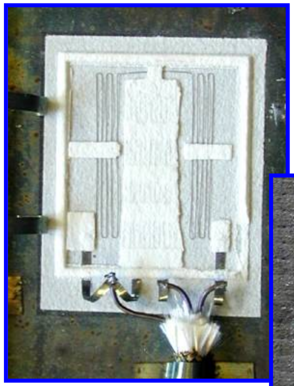
- Select sensor most suited to acquire needed information
- Develop sensor attachment techniques for structural material
- Validate strain and temperature measurements

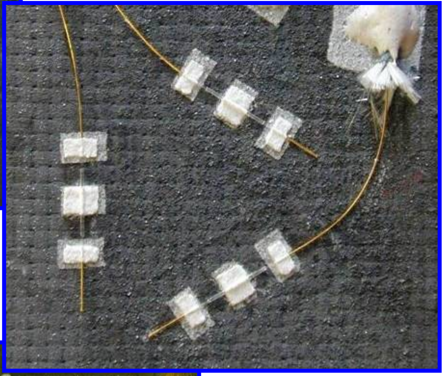


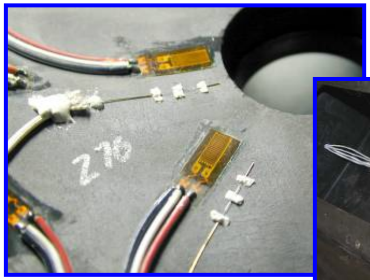
Application and Sensor

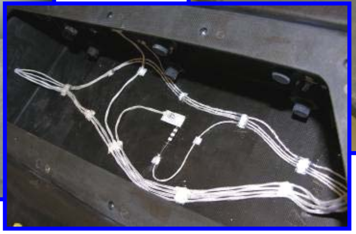
Select sensor most suited to acquire needed information

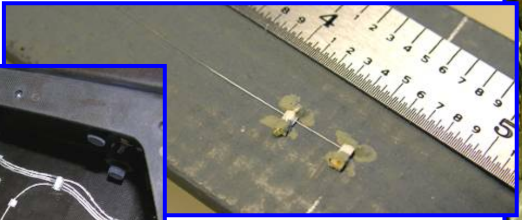
- Measurement required
- Substrate material
- Maximum test temperature
- Heating rate
- Static and / or dynamic environment

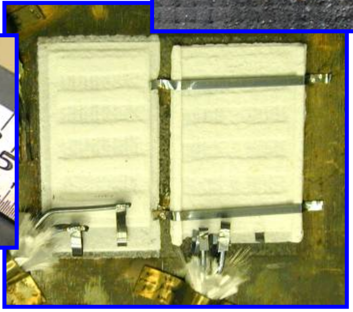








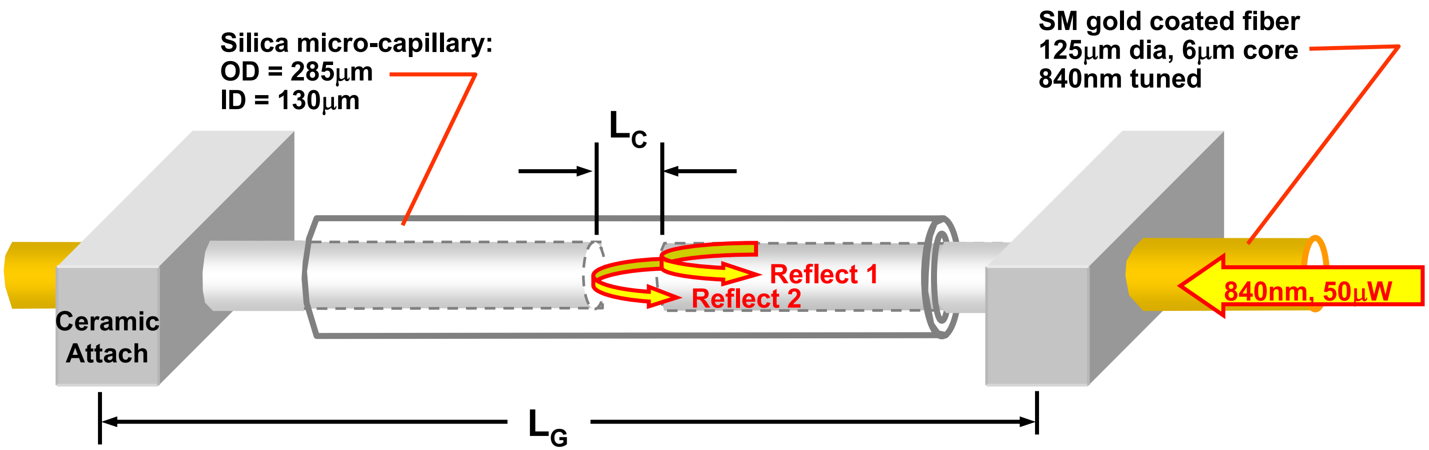




Application and Sensor

Static Strain Measurements

Extrinsic Fabry-Perot Interferometer (EFPI)



- Cavity Length (L_C): Distance (microns) separating the two reflecting fiber surfaces
- Gage Length (L_G): Sensitivity, distance (millimeters) separating the two points that attach the optical fiber to the substrate

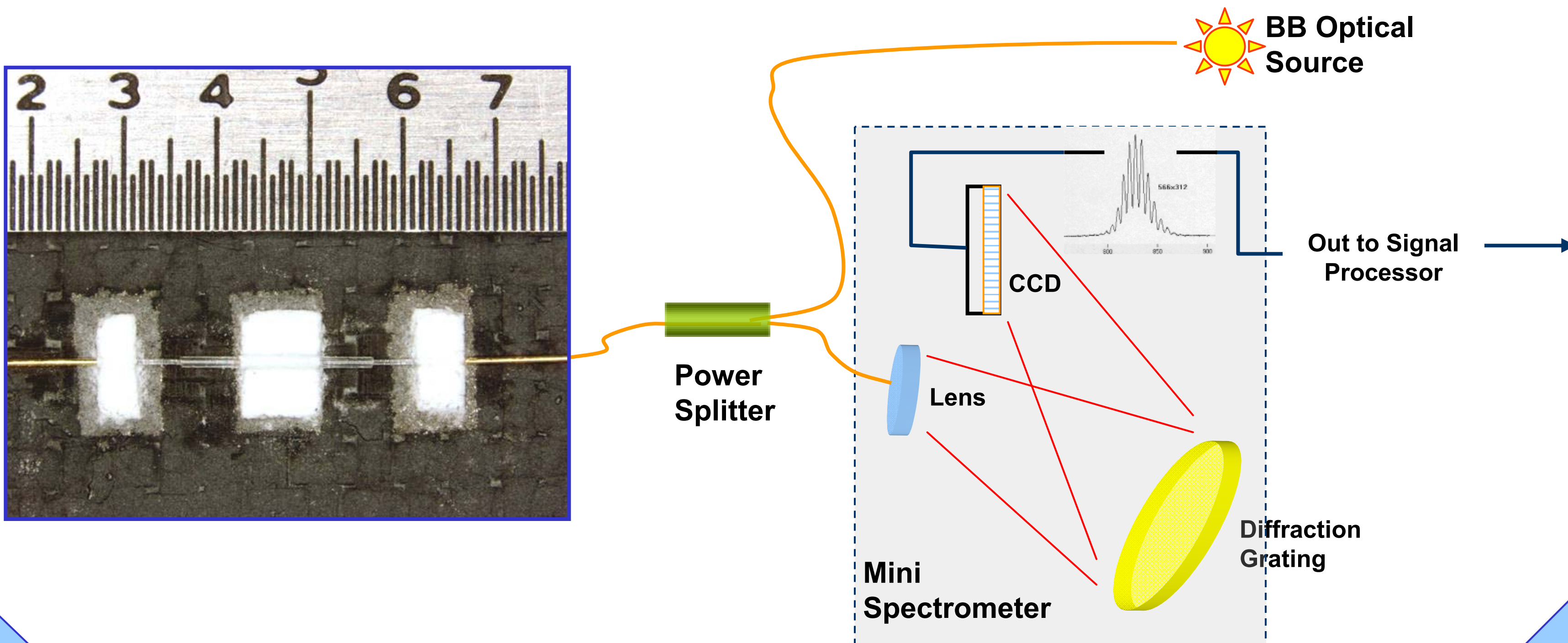
Strain = $\Delta L_C / L_{G\,(initial)}$

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

Application and Sensor

Static Strain Measurements

Single Mode Interferometer Signal Conditioning



Application and Sensor

Dynamic Strain Measurements

Electrical Resistive Strain Gage (SG)

Quarter-Bridge Strain Gage
Typical Sensor Traits

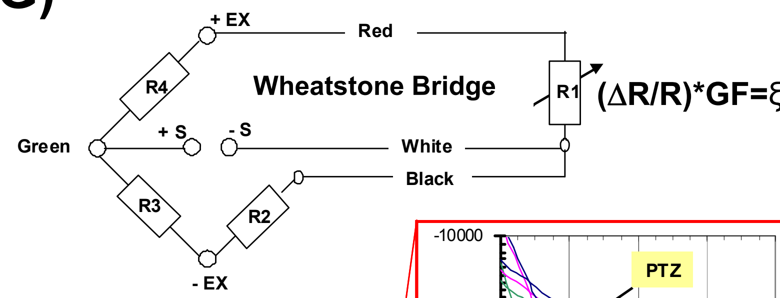
Pro's

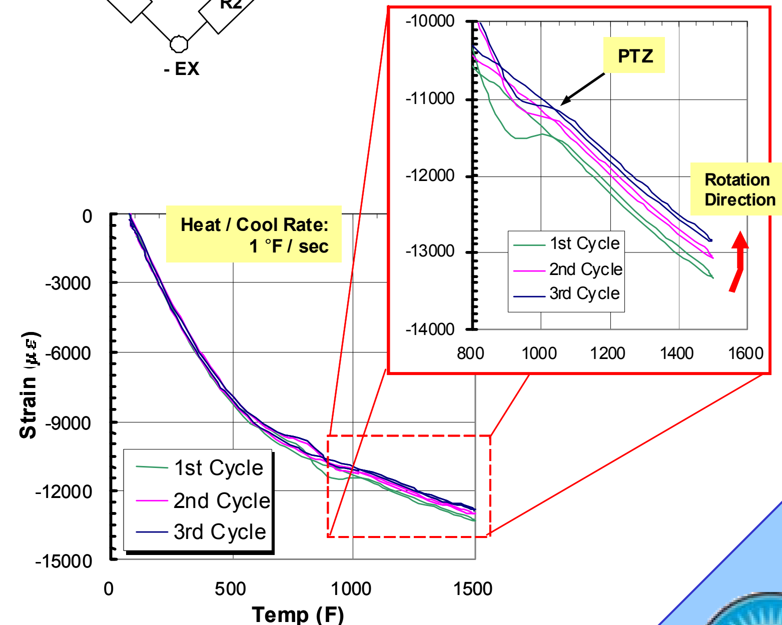
- Sturdy / rugged thermal sprayed installation and spot-welded leadwire stakedown
- Available high sample rate DAS, usually AC coupled to negate large ξapp

Con's

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

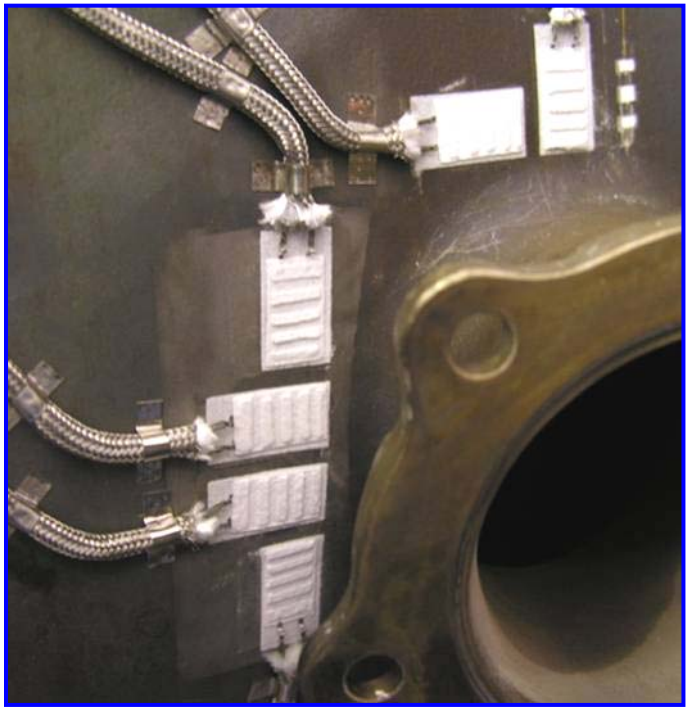
$$\xi_{app} = [TCR_{gage} / GF_{set} + (\alpha_{sub} - \alpha_{gage})] * (\Delta T)$$





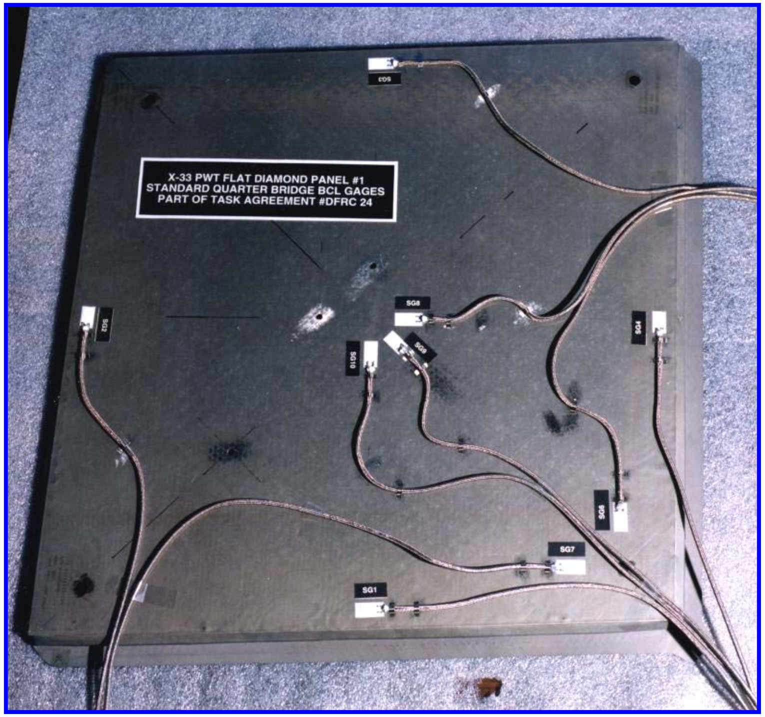
Application and Sensor

Dynamic Strain Measurement Examples



C-17 Engine Testing

- Test temperatures above 1100°F
- Engine intentionally unbalanced creating large peak-to-peak vibrations



X-33 Sonic Fatigue Testing

- Dynamic loads as high as -158db
- Test temperatures above 1500°F
- High transient heating rates producing large thermal stresses

Attachment Techniques

Develop sensor attachment techniques for structural material

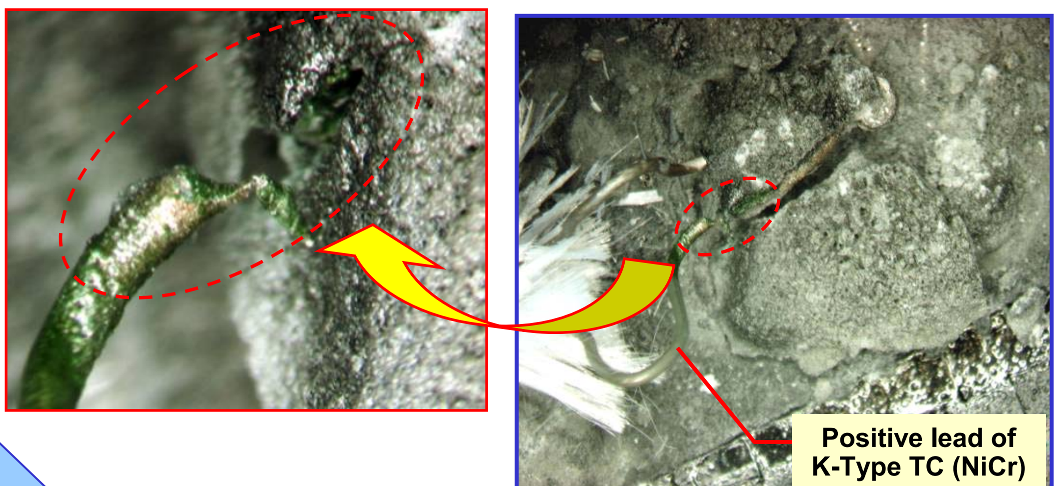
- Derive surface prep and optimal plasma spray parameters for applicable substrate
  - powder type, power level, traverse rate, and spraying distance
- Optimize / select cement that best fits application
- Improve methods of handling and protecting fragile sensors during harsh installation processes

Attachment Techniques

Thermal Spray vs Cement

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

- 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)

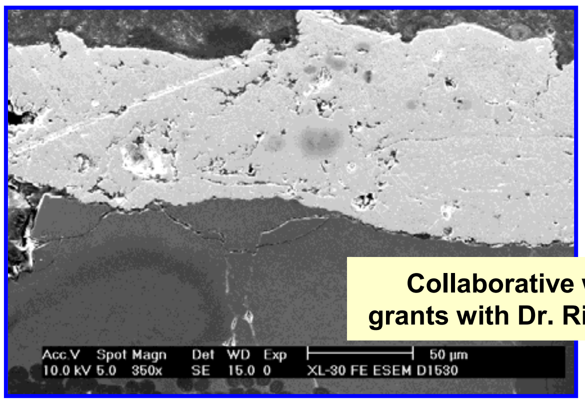
Post-Test: One cycle to 2550°F

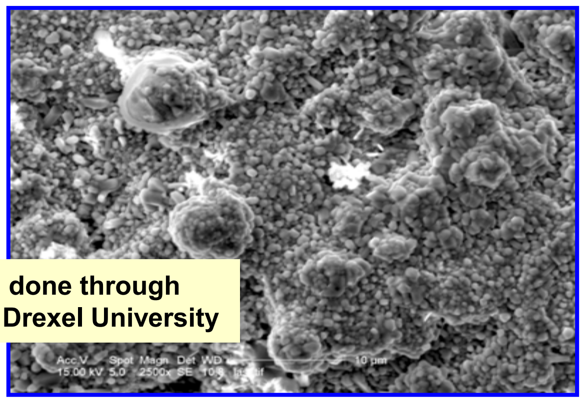
Attachment Techniques

Thermal Spray Processes

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

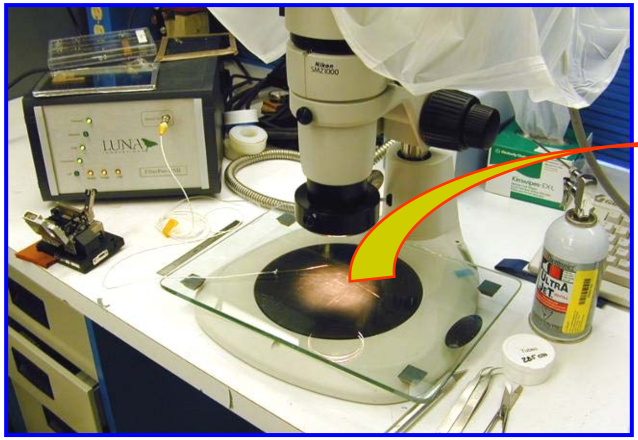
Thermal Spray Equipment

Thermal Spray Room

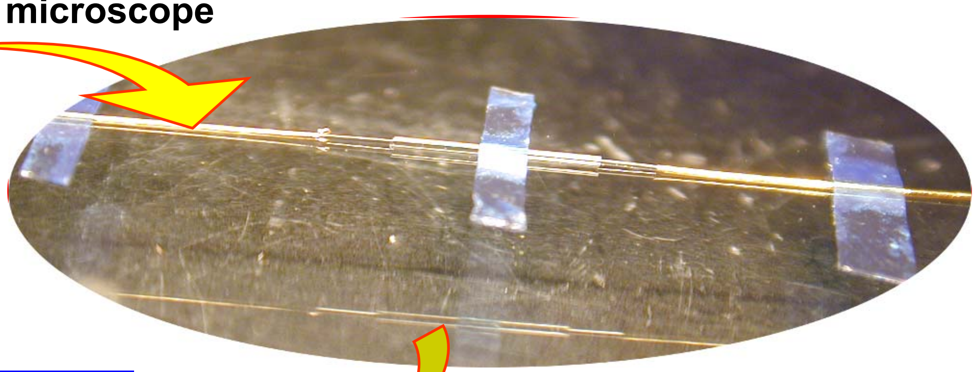
- 80KW Plasma System
- Rokide Flame-Spray System
- Powder Spray System
- Grit-Blast Cabinet
- Micro-Blast System
- Water Curtain Spray Booth

Attachment Techniques

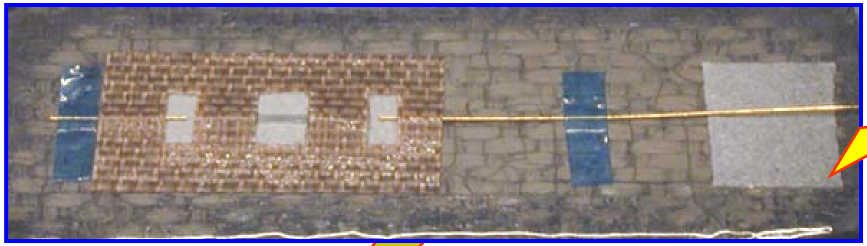
Fiber Optic EFPI Installation



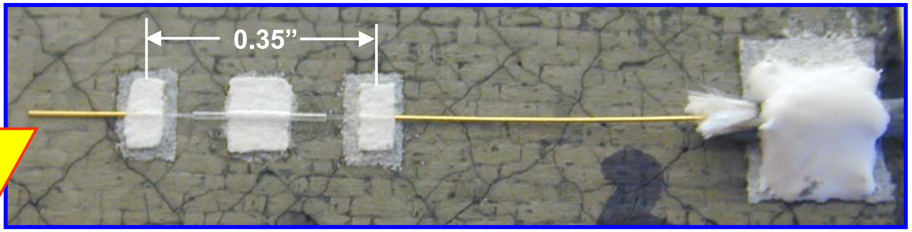
Fabricate sensor under microscope



Transfer to thermal sprayed base coat using carrier tape

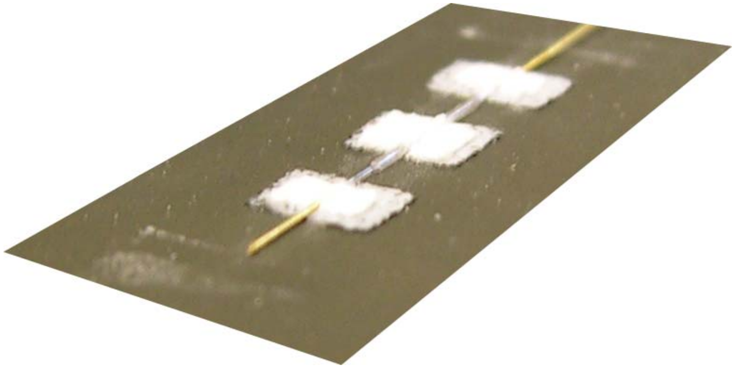


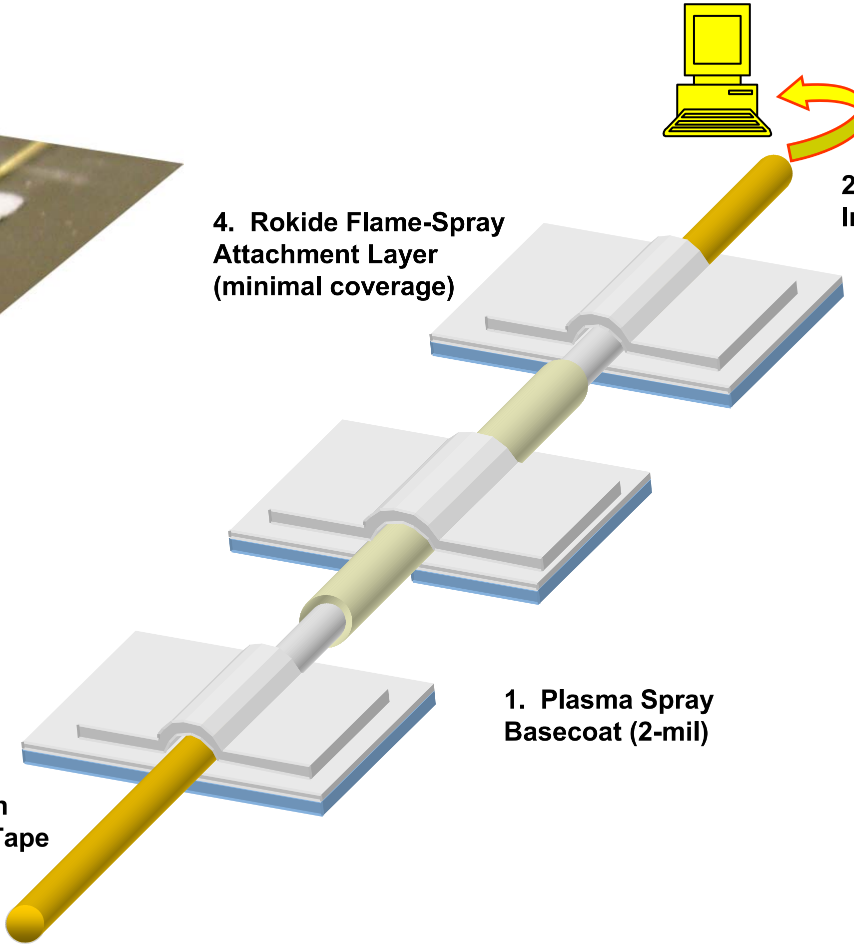
Flame-spray sensor attachment



Attachment Techniques

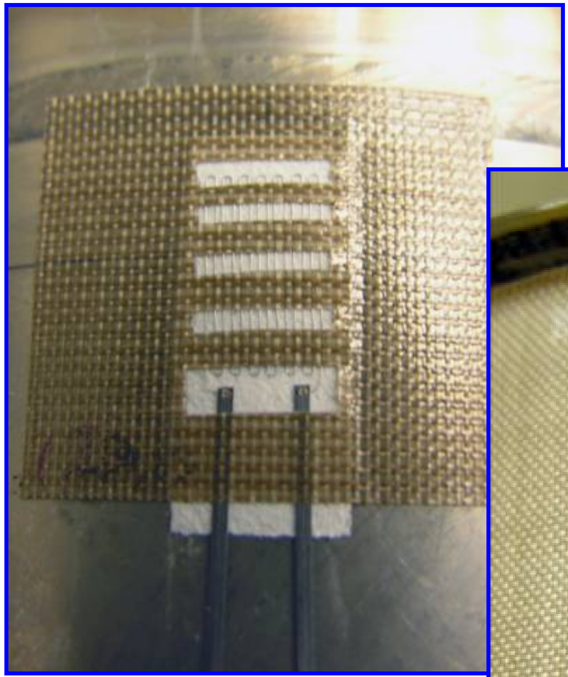
Fiber Optic EFPI Installation





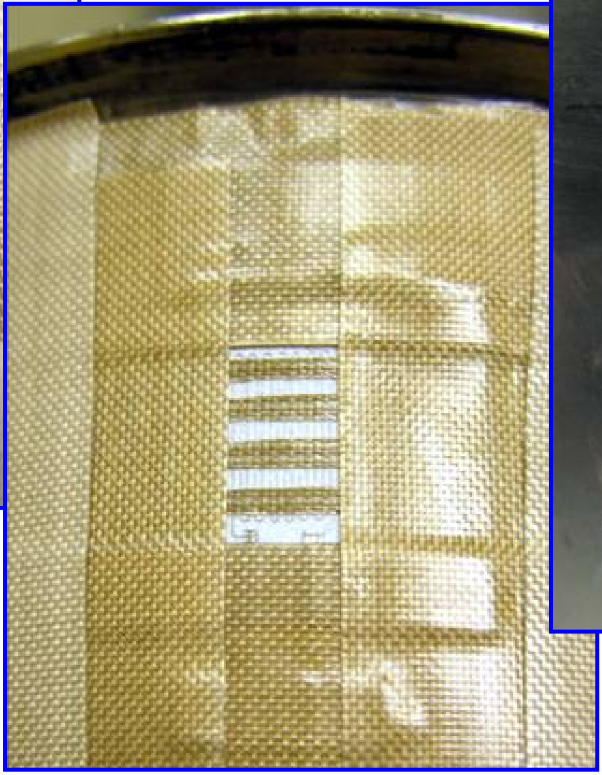
Attachment Techniques

Resistive Wire Strain Gage Installation



Place SG on thermal sprayed basecoats via carrier tape

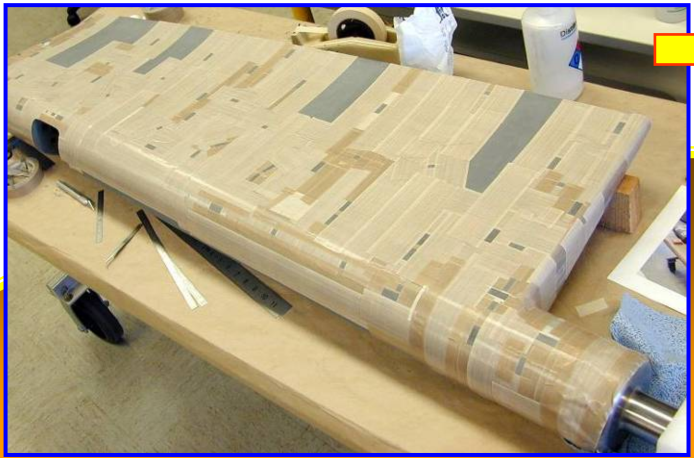
Apply flame-sprayed tack and cover coats

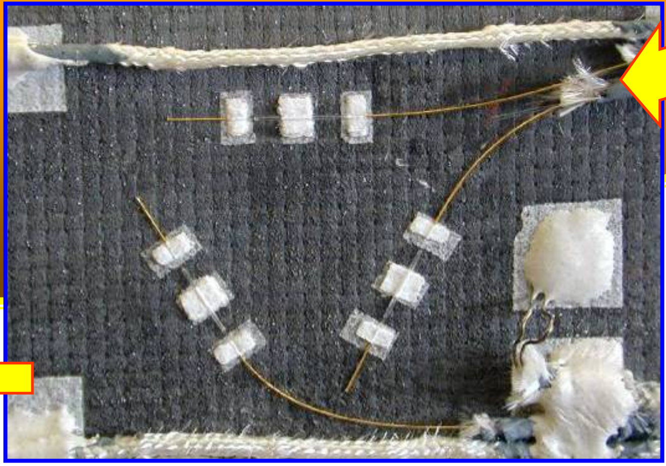


Spot weld three-conductor leadwire

Attachment Techniques

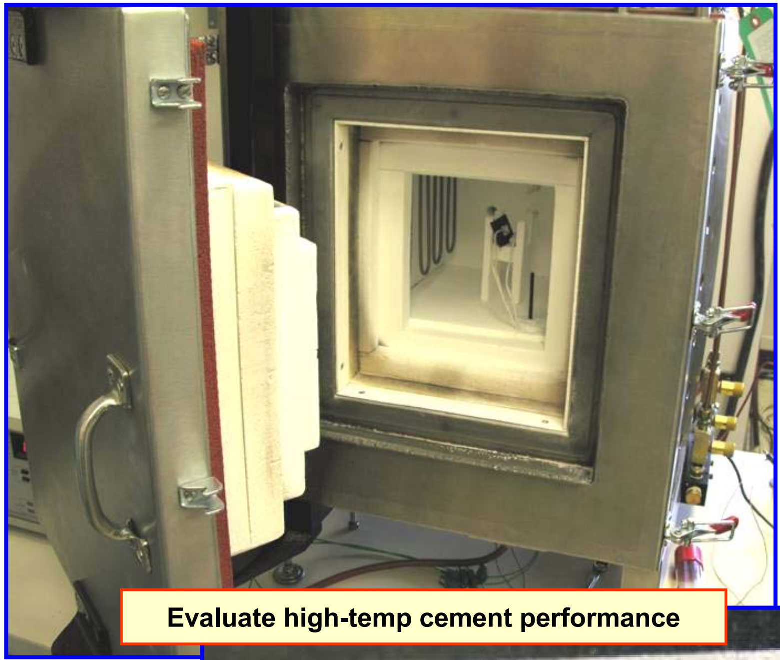
Large-Scale Structures



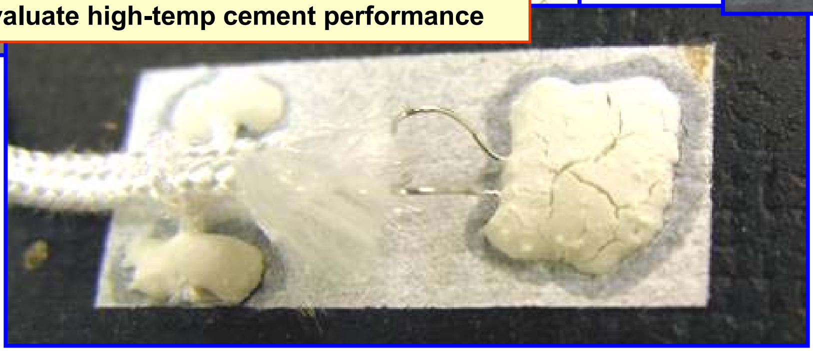


Attachment Techniques

Thermocouple Junction



Evaluate high-temp cement performance



Rapid-Heat Furnace

- Air or inert (2600°F max)
- 8-in^3 inner furnace with Molydisilicide elements

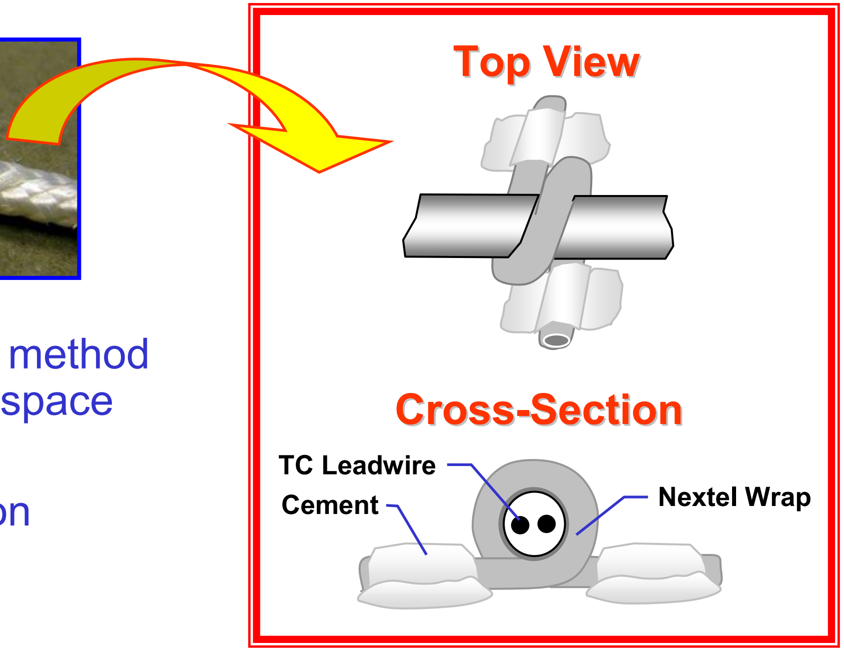
Thermal spray attachments must be as thin as possible to reduce sheering due to expansion differentials

Attachment Techniques

Thermocouple Leadwire

Improved Leadwire Stakedown

- Thermal sprayed base coats
- All Coverguard removed, only S-13 cement was used for TC attachment
- No cement applied directly on overbraid



- Leadwires staked with tie-down method developed during National Aerospace Plane program
- Reshaped service loops to lay on basecoat surface

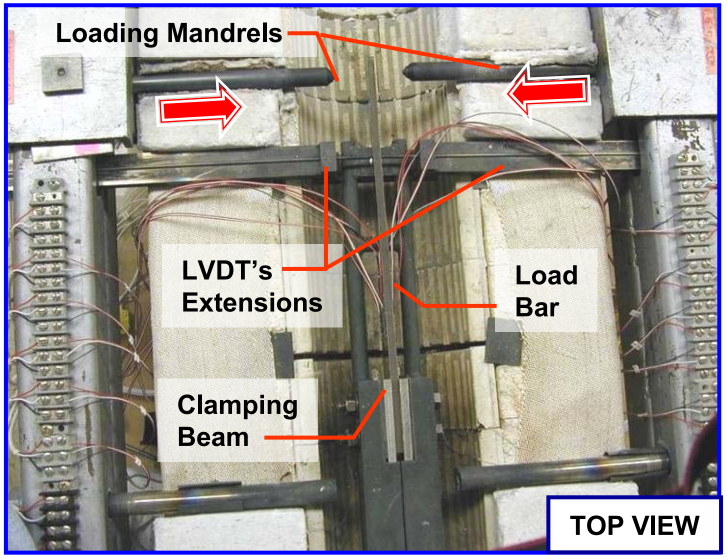
Evaluation / Characterization

Validate strain and temperature measurements

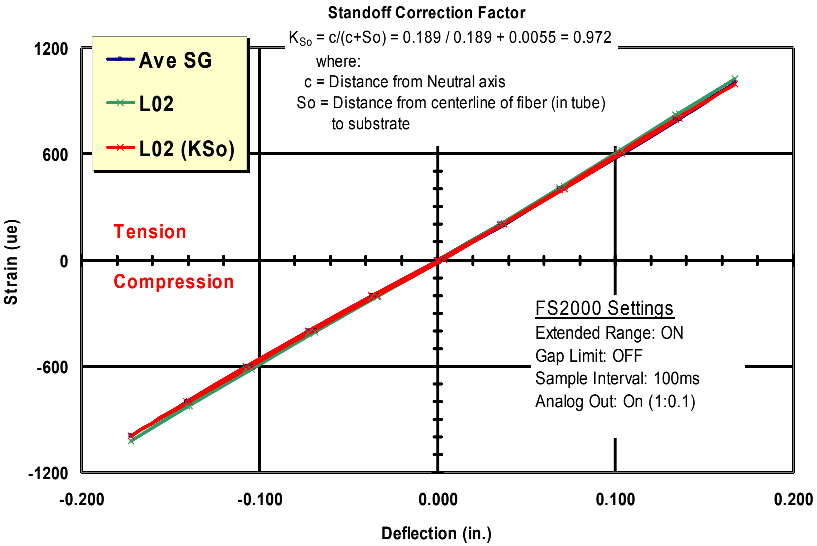
- Base-line / characterize high-temperature strain sensors on Inconel specimens
  - Known material spec's isolate substrate from inherent sensor traits prior to testing on more complex composites
- Evaluate / characterize sensitivity (GF) of strain sensors on ceramic composite substrates using laboratory combined thermal / mechanical load fixture
- Generate apparent strain curves for corrections
- Test and verify TC measurements in laboratory furnace under fast transient and steady-state conditions

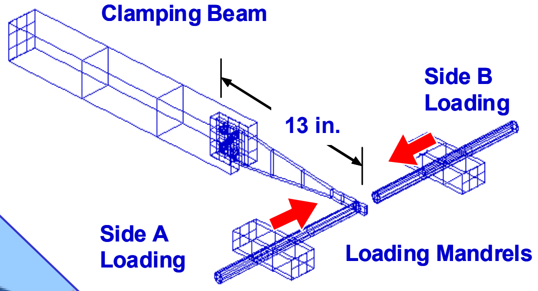
Evaluation / Characterization

Combined Thermal / Mechanical Loading (Obsolete)



EFPI Combined Loading on IN625



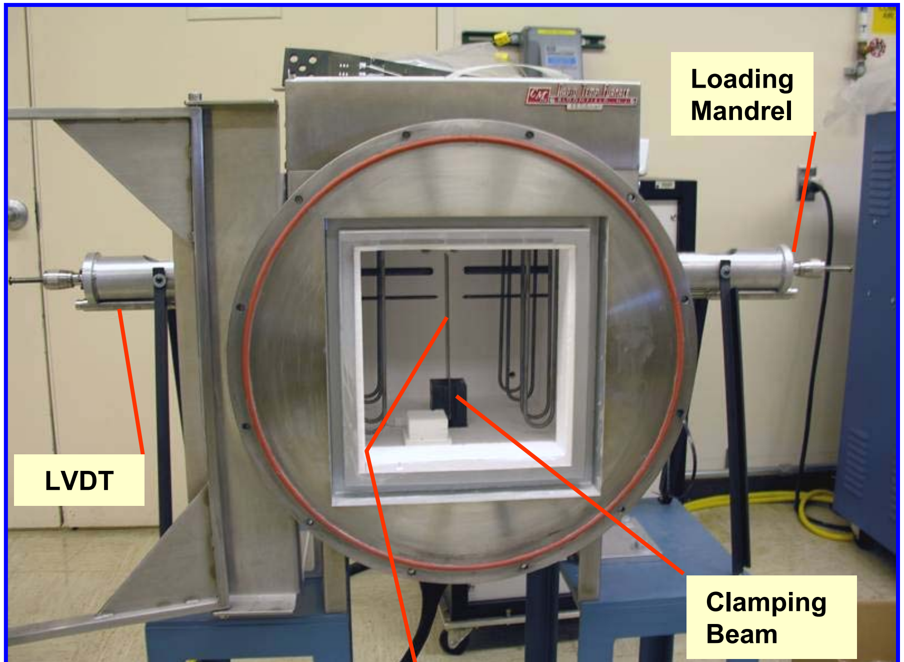


Thermal / Mechanical Cantilever Beam Testing of EFPI's

- 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

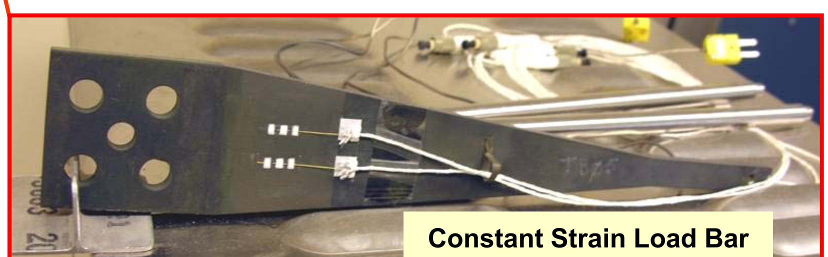
Evaluation / Characterization

Combined Thermal / Mechanical Loading (Current)



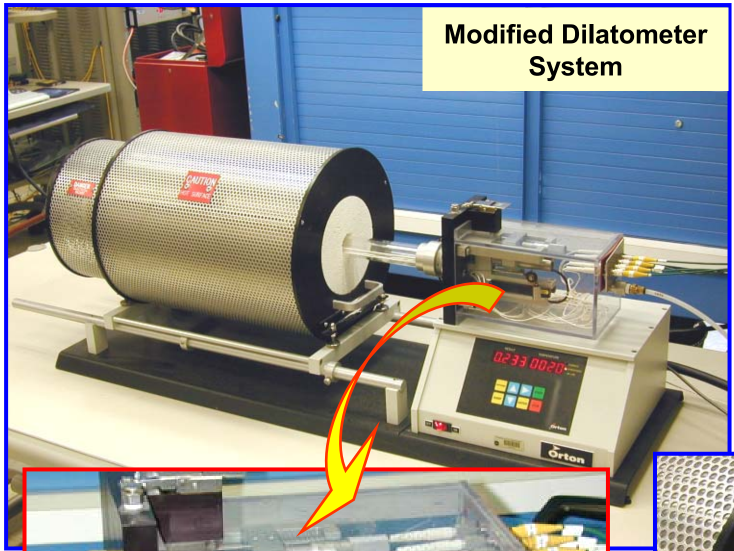
Furnace / cantilever beam loading system for sensitivity testing

- 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

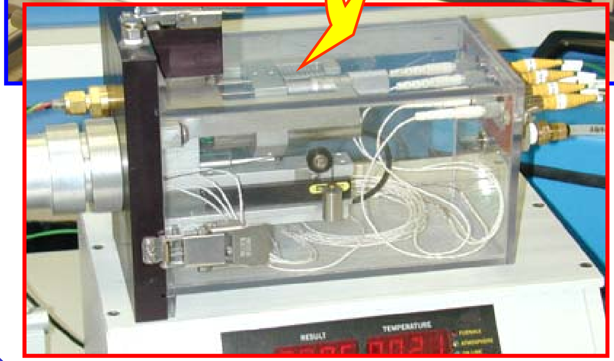


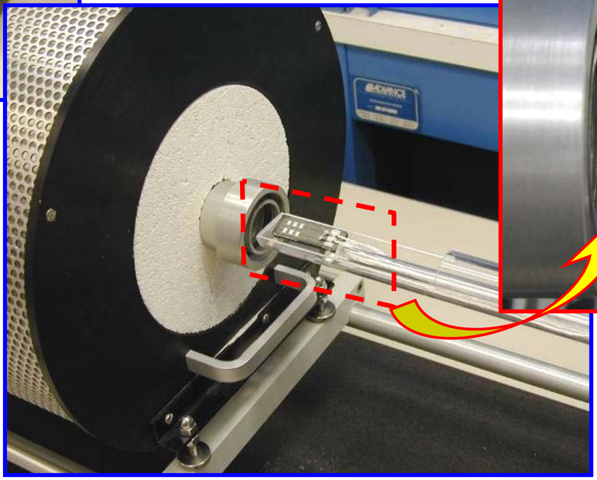
Evaluation / Characterization

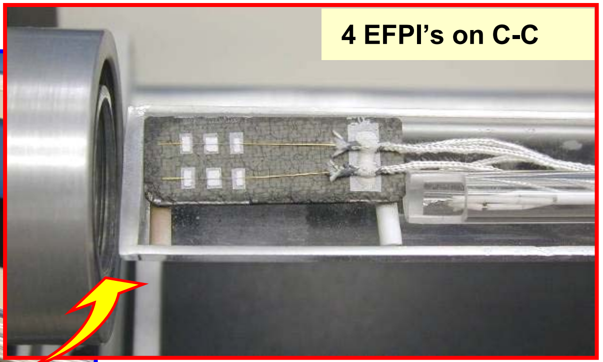
Dilatometer Testing



Modified Dilatometer System







4 EFPI's on C-C

Sensor Characterization

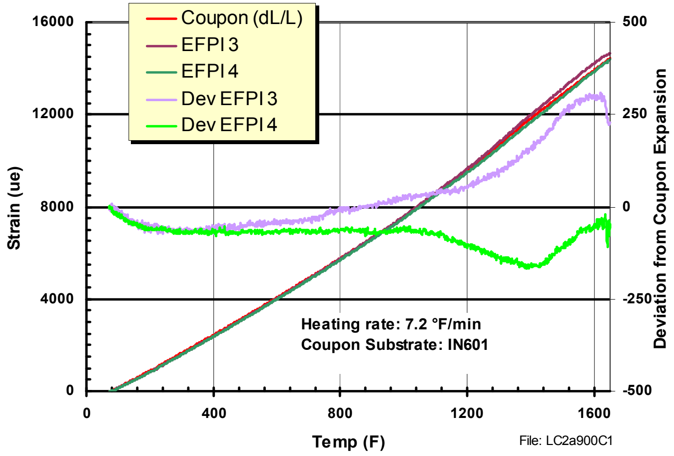
Air or inert (3000°F max)

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

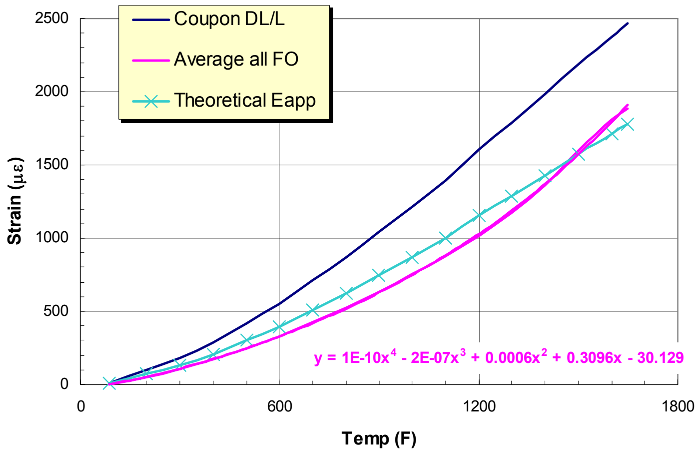
Evaluation / Characterization

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

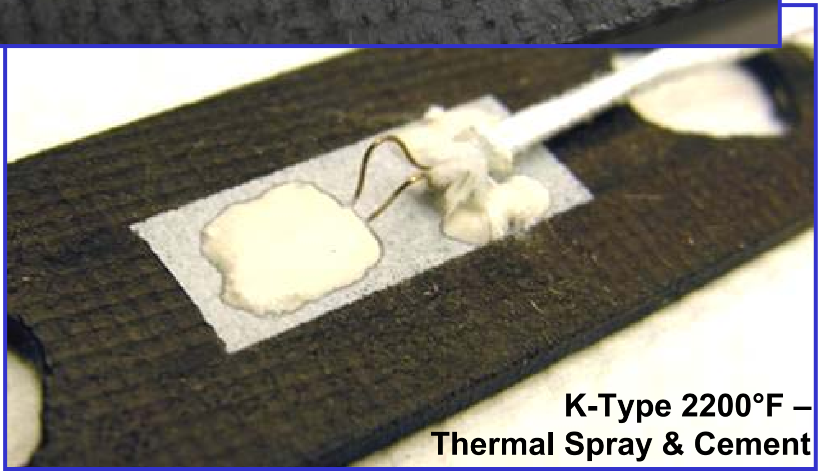
$$\xi_{true} = \xi_{indicated} - \xi_{app}, \text{ where } \xi_{app} = (\alpha_{sub} - \alpha_{fiber}) * \Delta T$$

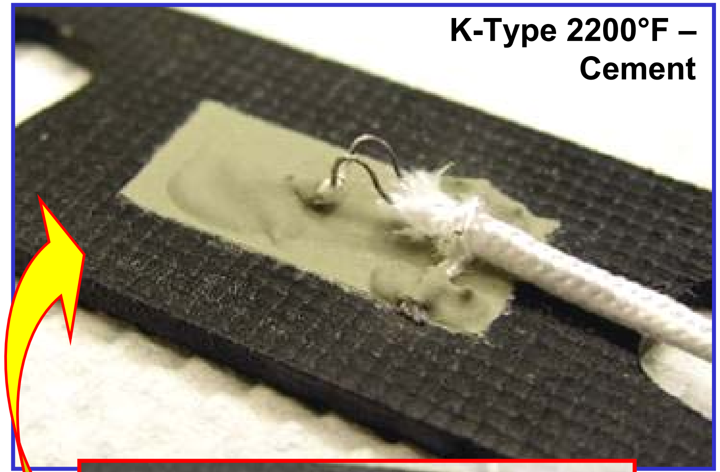
- Inconel (LH chart): Expansion ratio between IN and Si so large no sensor correction *required* (output primarily substrate expansion, CTE * ΔT)
- CMC (RH chart): Small CTE ratio between C-SiC and Si requires a correction for the growth in fiber (lessening cavity gap) verses the expansion of the substrate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

Evaluation / Characterization

Current Ceramic Composite Temperature Measurements

Pt is flattened to reduce Rokide flame-spray thickness





TC is isolated from high-strength (but corrosive) SiC cement by a benign (phosphate based) cement

Future 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
- Develop accelerometer attachment method for high-temp GVT
- Attach and evaluate high-temperature heat flux gage
- Evaluate weldable (shim) EFPI strain sensor on Inconel
- Continue to improve reliable / rugged TC attachments to ceramic composites, including flight application