10.3 High-Temperature Instrumentation

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Outline

• Background
• Objective
• 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
- Flame-Sprayed Resistive
  - Large temperature-related measurement uncertainties

1980-1990
- Weldable Resistive
- Weldable Capacitive
- Improved temperature-compensation using flame-sprayed resistive gages

2000-Present
- Improved measurement accuracy applying Silica and Sapphire EFPI Technology
- NASP X-33
- X-37
- CEV
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 = \( \frac{\Delta L_C}{L_G (\text{initial})} \)

Apparent Strain (\( \xi_{\text{app}} \)) = \((\alpha_{\text{sub}} - \alpha_{\text{fiber}})\Delta T\)
Application and Sensor
Static Strain Measurements

Single Mode Interferometer Signal Conditioning

BB Optical Source

Power Splitter

Out to Signal Processor

CCD

Lens

Diffraction Grating

Mini Spectrometer

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**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 $\xi_{\text{app}}$

**Con’s**

- Large magnitude $\xi_{\text{app}}$ primarily due to wire TCR, slope rotates cycle-to-cycle
- Sensitivity (GF): Function of temperature

$$\xi_{\text{app}} = \left[ \frac{\text{TCR}_{\text{gage}}}{\text{GF}_{\text{set}}} + (\alpha_{\text{sub}} - \alpha_{\text{gage}}) \right] \times (\Delta T)$$

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<table>
<thead>
<tr>
<th>Temp (F)</th>
<th>Strain (µε)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>500</td>
<td>-3000</td>
</tr>
<tr>
<td>1000</td>
<td>-6000</td>
</tr>
<tr>
<td>1500</td>
<td>-9000</td>
</tr>
</tbody>
</table>

*1st Cycle*  
*2nd Cycle*  
*3rd Cycle*  

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![Wheatstone Bridge Diagram](image)

Heat / Cool Rate: 1 °F/sec

PTZ

Rotation Direction

1st Cycle  
2nd Cycle  
3rd Cycle  

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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

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 ($\text{Al}_2\text{O}_3$)
- 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

Rokide flame-sprayed sensor attachment

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

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

0.35"
Attachment Techniques
Fiber Optic EFPI Installation

1. Plasma Spray Basecoat (2-mil)
2. Rokide Flame-Spray Intermediate Layer (1-mil)
3. Set EFPI Sensor in Place Using Carrier Tape
4. Rokide Flame-Spray Attachment Layer (minimal coverage)
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

Rapid-Heat Furnace
- Air or inert (2600°F max)
- 8-in³ inner furnace with Molydisilicide elements

Evaluate high-temp cement performance

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

Past Method

Top View

Cross-Section

TC Leadwire
Cement

Nextel Wrap
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)

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-in³ 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

Sensor Characterization
Air or inert (3000°F max)
- Evaluate bond integrity
- Generate $\xi_{\text{app}}$ correction curves
- Evaluate sensitivity and accuracy
- Evaluate sensor-to-sensor scatter, repeatability, hysteresis, and drift

Modified Dilatometer System

4 EFPI's on C-C
**Evaluation / Characterization**

**EFPI Apparent Strain**

**Inconel Substrate**

- Coupon (dL/L)
- EFPI 3
- EFPI 4
- Dev EFPI 3
- Dev EFPI 4

Heating rate: 7.2 °F/min
Coupon Substrate: IN601

![Graph showing strain vs temperature for Inconel Substrate](image)

**CMC Substrate**

- Coupon DL/L
- Average all FO
- Theoretical E$_{\text{app}}$

$y = 1E-10x^4 + 2E-07x^3 + 0.0006x^2 + 0.3096x - 30.129$

![Graph showing strain vs temperature for CMC Substrate](image)

**ξ$_{\text{app}}$ Correction:** The removal of inherent sensor traits and substrate expansion from indicated strain to acquire true applied strains or thermal stresses

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

- Inconel (LH chart): Expansion ratio between IN and Si so large no sensor correction required (output primarily substrate expansion, CTE $\times \Delta T$)
- 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 ξ$_{\text{app}}$ curves followed theoretical
Evaluation / Characterization

Current Ceramic Composite Temperature Measurements

Pt is flattened to reduce Rokide flame-spray thickness

S-Type 2500°F - Thermal Spray

K-Type 2200°F – Thermal Spray & Cement

K-Type 2200°F – Cement

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