10.3 High-Temperature Instrumentation

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Outline

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

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

2000-Present
- Improved measurement accuracy applying Silica and Sapphire EFPI Technology

Large temperature-related measurement uncertainties

Hypersonic Educational Initiative
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 ($\xi_{app}$): = ($\alpha_{sub} - \alpha_{fiber}$) $\Delta T$
Application and Sensor
Static Strain Measurements

Single Mode Interferometer Signal Conditioning

BB Optical Source
Power Splitter
Out to Signal Processor

Lens
CCD
Mini Spectrometer
Diffraction Grating
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 $\xi_{app}$

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

$$\xi_{app} = \left[ \frac{TCR_{gage}}{GF_{set}} + (\alpha_{sub} - \alpha_{gage}) \right] \times (\Delta T)$$
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

Positive lead of K-Type TC (NiCr)
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

1. Fabricate sensor under microscope
2. Transfer to thermal sprayed base coat using carrier tape
3. 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
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)

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 $\xi_{app}$ 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

### CMC Substrate

- **Coupon DL/L**
- **Average all FO**
- **Theoretical E_{app}**

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

\[ ξ_{true} = ξ_{indicated} - ξ_{app}, \text{ where } ξ_{app} = (α_{Sub} - α_{fiber}) \times ΔT \]

- **Inconel (LH chart):** Expansion ratio between IN and Si so large no sensor correction required (output primarily substrate expansion, CTE \( \times ΔT \))
- **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 ξ_{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