High-Temperature Strain Sensing for Aerospace Applications

Anthony (Nino) Piazza, Dr. Lance W. Richards, Larry D. Hudson
NASA Dryden Flight Research Center
Summer WRSGC in Bethlehem, PA
August 18-20, 2008

Cleared for public release
Outline

- Background
- Objective
- Sensors
- Attachment Techniques
- Laboratory Evaluation / Characterization
- Large-Scale Structures
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
Objective
Measurements Lab

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

• Develop sensor attachment techniques for relevant structural materials at the small test specimen level
  – Apply methods to large scale hot-structures test articles
• Perform laboratory tests to characterize sensor and generate corrections to apply to indicated strains
Sensors
Dynamic Measurements (Max Op 1850°F)

High-Temp Quarter-Bridge Strain Gage

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

Apparent Strain = $[\frac{\text{TCR}_{\text{gage}}}{\text{GF}_{\text{set}}} + (\alpha_{\text{sub}} - \alpha_{\text{gage}})] \times (\Delta T)$
Sensors
Static Measurement (Max Op 1850°F)

Extrinsic Fabry-Perot Interferometer (EFPI)
Commercially Available

Strain = \( \frac{\delta L_C}{L_G \text{ (initial)}} \), where sensitivity = \( L_G \)

Apparent Strain (\( \xi_{\text{app}} \)) = (\( \alpha_{\text{sub}} \times \alpha_{\text{fiber}} \) *) \( \Delta T \)
Sensors
Static Measurement

Single Mode EFPI Signal Conditioning
Sensors

Static Measurement (Max Op 600°F)

SM Polyimide Coated Fiber
125μm dia, 9μm core, 1550nm

Unstrained

Tensile Load

Reflected λ

Strain (με)
(δλ / λ) x 0.725

Diode Tunable Laser

BBR

2 x 1 Coupler

IFTT

FFT

Freq / Dist

Unstrained SM Polyimide Coated Fiber
125μm dia, 9μm core, 1550nm
Attachment Techniques
Applications Above 600°F

Develop sensor attachment techniques for relevant structural materials

• Derive surface prep and optimal plasma spray parameters for applicable substrate
  – i.e., powder media / type, power level, traverse rate, feed 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

- 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

Tests indicate increased EFPI gage-to-gage scatter on first cycle

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 (Al₂O₃)
- CMC Substrates (inert testing): High melting-point ductile transitional metals (i.e. Ta, TiO₂, & 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
Attachment Techniques

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

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

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
Applications Below 600°F

Two applications of MB610 sufficiently coat fiber (Cured @ 270°F)

Bonded FBG’s
Type-K TC
Refrasil Overbraid

Polyimide coated EFPI bonded with mixture of GA-61 and MB610
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 of indicated strains on relevant ceramic composite hot-structures
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
**Correction: Removal of inherent sensor traits and substrate expansion from indicated strain to acquire true strains or thermal stresses**

\[
\xi_{\text{true}} = \xi_{\text{indicated}} - \xi_{\text{app}}, \quad \text{where} \ \xi_{\text{app}} = (\alpha_{\text{sub}} - \alpha_{\text{fiber}}) \times \Delta T
\]

- **Inconel (LH chart):** Large expansion differential between IN601 and Si
  - output primarily substrate expansion, CTE * \(\Delta T\)
- **CMC (RH chart):** Small expansion ratio between C-SiC and Si
  - requires correction for fiber expansion (lessening cavity gap)
- Graphs demonstrate how well actual \(\xi_{\text{app}}\) curves followed theoretical
Evaluation / Characterization
FBG Apparent Strain

Theoretical Thermal Out = (α_fiber + ξ / Pe) * ΔT

where:
Thermal Optic Effect (ξ) = 3.78 με/F
Strain Optic Constant (Pe) = 0.725
Large Scale Structures
Ceramic Composite Control Surfaces

- C/C Control Surface
  - March, 2003
- C/SiC Bodyflap
  - Nov, 2003
- X-37 C/C Flaperon
  - August, 2004
- X-37 C/SiC Flaperon
  - May, 2004
- X-37 C/C Flaperon Qual Unit
  - August, 2005

Temperature Ranges:
- 2000°F
- 2100°F
- 2400°F
- 2300°F
- 2500°F
- 2100°F

Dryden Flight Research Center

NASA
Large Scale Structures
Metallic Dynamic Environment

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
Large Scale Structures
Fiber Optic Wing Shape Sensing

NASA Dryden Predator B (Ikhana)

ξapp coupon tested from -60°F to 150°F