High Temperature Strain Gages for SOFC Application

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Sponsor: SECA Program
Overview of NETL SECA Support

- Independent Testing of SECA Prototype Systems
- Model Development and Application
- Interconnect Development (coatings)
- Sensor Development
Sensor Development Review

- Technical Issues
- R&D Objective
- Approach
- Results
- Applicability to SOFC Commercialization
- Activities for next 12 months
Technical Issues / Challenges

- Cell mechanical failure occurs frequently but is little understood
  - Sudden event upon application of a load > critical strength (thermally or mechanically induced)
  - Can occur after numerous hours at a SCCG loading

- There are few tools available for the engineer to employ
  - ‘Integral’ strain measurements; Luna Innovations, Inc. (optical fiber; > 800 deg. C)
  - Optical profilometry; Solarius Development, Inc. (optical access)
  - Acoustic emission for catastrophic failure detection

- What is happening ‘inside the box’?
  - Stack compression/creep?
  - Cell strain prior to failure?
  - Are FEA models working?
R&D Objective

*Investigate/extend high temperature strain gage sensors to SOFC applications*

- NASA (and others) have supported the development of high temperature strain sensors for in-situ turbine mechanical study
- Apply to prototype SOFC cells and subcomponents to assess feasibility as a new tool for engineering analysis
  - test in oxidizing & reducing environments—prove capability
  - measure fuel cell strain during start-up, shut-down, load changes, and fuel and oxidant concentration gradients
Approach
High Temperature Strain Sensors

- Standards exist for resistive and capacitive gages
- Prototype evaluation: gage + calibration device + hardware + instrumentation for system behavior checkout and qualifying installation procedures.
- Issues: good sensitivity (high gage factor), zero drift, sensitivity drift, repeatability, hysteresis, thermal response

Gage factor:

\[
K = \frac{((R - R_{\text{ref}})/R_{\text{ref}}) / (L - L_{\text{ref}})/L_{\text{ref}}}{(\Delta R/R_{\text{ref}})/\varepsilon}
\]

\[K \sim 1.0 \text{ to } 20.0\]
Approach (cont.)

High Temperature Strain Sensors

- **Resistive** → suited for dynamic or short term static meas.
  - Gage Factor; $K \sim 2-6$ for most metals (Fraden, 1993)
  - PdCr; $K \sim 2$
  - oxidation effects (not used for long tests)
  - 800 deg. C max

- **Capacitive** → suited for long term tests (creep)
  - not affected by temperature, oxidation, phase change
Approach (cont.)

High Temperature Strain Sensors

- Piezo-resistive Semiconductors ➔ suited for dynamic measurement
  - Gage Factor; $K \approx 10$ @ 800 deg. C
  - indium-tin oxide (ITO); n-type ceramic
  - proven good thermal stability
  - oxidation resistance
  - good electrical response
  - used to study high cycle fatigue in jet engines (URI) up to 1500 deg. C (18-million cycle lifetime)
Thin Film Strain Sensors For SOFC

- **Benefits**
  - non-intrusive
  - small footprints
  - little thermal mass
  - sensitive for detecting small fluctuations associated with transient operation
Thin Film Strain Sensors For SOFC

*Pd-Cr/Indium-Tin Oxide*

- **Fabrication:**
  - passivation / electrical isolation
  - patterning of the thin film leads using masks
  - patterning of the active strain sensor elements using photolithography
  - deposition of the thin film leads and bond pads as well as the active strain material using rf sputtering
  - lead wire attachment
Experimental & Analysis Approach

*Strain Gage CTR*

- Initial bi-axial tests worked
- 3-point measurements gave improved resolution
- ANSYS used to predict strain

![Experimental setup](image)

- **1µm res.**
- **YSZ substrate with strain gage on bottom**
- **Macor**
- **alumina pushrod**
- **alumina tube**
11/09/04 PdCr gage
(zero reference method for deflection)

Thin-film Pt coated alumina sphere

Continuity Test
Specimens Studied

- **PdCr**
  - 8YSZ wafer (191 µm thick)
    - simplicity
    - ease of characterization
  - button cell

- **Indium-Tin-Oxide**
  - 8YSZ wafer (280 µm thick)
  - button cell

- Monoaxial design (see photo)
- Non-Temperature Compensated

Principle Strain Direction

PdCr strain gage applied to SOFC anode
PdCr Results

Thermal Response
Gage Resistance (vs. T)
Stability (in Air)
Strain Response
Gage Factor
## Pd-Cr Resistance

*(8YSZ Wafer; Non-Temperature Compensated)*

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Computed resistance (ohms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>800</td>
<td>92.1</td>
</tr>
<tr>
<td>600</td>
<td>106</td>
</tr>
<tr>
<td>400</td>
<td>103</td>
</tr>
<tr>
<td>200</td>
<td>94.0</td>
</tr>
<tr>
<td>RT</td>
<td>84.9</td>
</tr>
</tbody>
</table>

![Graph showing current vs. voltage relationship with temperature points at 800°C, 600°C, 400°C, and 200°C.](image)

![Inset graph showing Pd-Cr 800°C soak with time (14:00 to 15:12) and voltage (0.00 to 0.50 V).](image)
PdCr RT Strain Response
*(8YSZ Wafer; Non-Temperature Compensated)*

Voltage (V)

(displacements in µm)

Time (hh:mm)

10:15 10:20 10:25 10:30 10:35
PdCr 50 °C Strain Response
(8YSZ Wafer; Non-Temperature Compensated)

Voltage (V)

(displacements in µm)

Time (hh:mm)
PdCr 550 °C Strain Response
(8YSZ Wafer; Non-Temperature Compensated)
Pd-Cr Strain Response

(8YSZ Wafer; Non-Temperature Compensated)

- Good S/N Ratio at T<200 °C
- Gage factor is slightly increased at higher temperatures
PdCr Fracture Signal (750 °C)
(8YSZ Wafer; Non-Temperature Compensated)
PdCr Sensor on 1-mm Anode Supported Cell

Signal quality at RT

Cathode

Displacements (µm):
25 50 75 100 50

Time (hh:mm)
13:45 13:50 13:55 14:00 14:05 14:10

Voltage (V)
0.15566 0.15568 0.15570 0.15572 0.15574 0.15576 0.15578

13:45 13:50 13:55 14:00 14:05 14:10
- Calculated gage factor for PdCr sensor
  - K=0.78 at RT
  - K=0.93 at 550 °C
ITO Results

Thermal Response
Stability in Air
Strain Response
ITO Thermal Response

1/23-24/05 ITO ramps

Voltage(V) @ 0.5 mA

Time (hh:mm)

23:00 1:24 3:48 6:12 8:36 11:00

5-hour ramp from RT to 850°C

477°C

850°C

650°C

20°
ITO Stability

- ITO at 800 °C for one week with resistance measurements taken periodically

ITO strain gage @ 800 °C

Avg R = 75.8 ohms
ITO 650 °C Strain Response
(8YSZ Wafer; Non-Temperature Compensated)

(displacements in µm)

Voltage (V)

Time (hh:mm)

K = 2.56
Summary

- ITO strain gage has far better S/N ratio over PdCr
- Strain signal sufficient for detecting strain in SOFC materials
- Gage factors lower than typically cited
  - PdCr ~ 0.93
  - ITO ~ 2.5
Application to SECA

- High temperature strain gages may be of use in development of SECA cell and stack technology
  - Diagnostic during stack assembly (stack compression)
  - Diagnostic for ensuring creep effects are not relieving/removing desired compressive load for sealing
  - Diagnostic for stack state of stress
  - Diagnostic for on-cell state of stress
  - Experimentally validate models (e.g., GTech)

...and thereby improve our design capabilities through better modeling/prediction of mechanical performance
FY05-06 Project Tasks
(focus on ITO)

• Task 1 – YSZ Substrates
  • Confirm ITO sensor response (gage factor) at 200, 400, 600
    and 800 deg. C.
  • Determine stability in reducing atmosphere
  • Characterize temperature-compensated sensor

• Task 2 – Apply Sensor to Button Cell
  • Evaluate in-situ response during cell operation

• Task 3 – Model Experimental Conditions
  • Apply models to experimental cases
  • Determine ability of model to follow strain (mechanically or
    thermally induced)

• Task 4 – Journal Publications and Presentations
proposed 8YSZ strain beam

strain gage centered on strain beam

approximately 1.1 dia 8YSZ disk pressed, sintered & lapped, 2 sides scored & removed with cut edges ground to width (supplied by MSRI)