Progress on luminescence coatings for temperature mapping on turbine engines

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Progress on luminescence coatings for temperature mapping on turbine engines

Thermal Barrier Coatings V, 24-29th June 2018; Irsee, Germany

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4. Summary
Need for sensing in Thermal Barrier Coatings

- Failure mechanisms are complex – related to composition, production parameters and operating conditions
- Substantial safety margins employed
- Quantitative degradation assessment enables more accurate life prediction → ‘prime-reliance’

<table>
<thead>
<tr>
<th>Operating condition</th>
<th>Mechanism</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard</td>
<td>Growth of TGO</td>
<td>Grey failure</td>
</tr>
<tr>
<td>High temperature</td>
<td>Sintering</td>
<td>White failure</td>
</tr>
<tr>
<td></td>
<td>Phase degradation</td>
<td></td>
</tr>
<tr>
<td>Contaminated intake</td>
<td>Corrosion</td>
<td>White failure</td>
</tr>
<tr>
<td></td>
<td>Erosion</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CMAS</td>
<td></td>
</tr>
</tbody>
</table>

Accurate temperature measurement
Quantitative degradation assessment

Sensing degradation for future TBC systems
Luminescence sensing

- Add small amounts of lanthanide or transition metal dopants (few %) to make material luminescent
- Dopant ions act as atomic levels sensors of surrounding environment
- Enable multiple sensing capabilities

Multiple sensing capabilities

Temperature measurement (real time)
(Choy et al. 1998)
(Gentleman et al. 2004)

Temperature measurement (off-line)
(Feist et al. 2008)

Erosion / Spallation
(Amano et al. 1987)

Ageing & corrosion detection
(Srivastava et al. 2001)
(Feist et al. 2001)
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## Temperature measurement options - online

<table>
<thead>
<tr>
<th>Technique</th>
<th>Benefits</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermocouples</td>
<td>Well understood</td>
<td>Point measurements</td>
</tr>
<tr>
<td></td>
<td>Large temperature range</td>
<td>Wiring difficulties</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Intrusive</td>
</tr>
<tr>
<td>Pyrometry / IR camera</td>
<td>Suitable for moving objects</td>
<td>Emissivity changes</td>
</tr>
<tr>
<td></td>
<td>Non-contact</td>
<td>Stray light</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Transparency of coatings</td>
</tr>
</tbody>
</table>

New technique required to overcome current limitations
Phosphor thermometry

- After excitation, the phosphorescence decays exponentially
- Lifetime decay is dependent on material properties and the temperature
- Technique not affected by emissivity changes or stray light
- Optical access required during operation

Technique for temperature measurements during operation

\[ I = I_0 \exp \left( -\frac{t}{\tau} \right) \]
Demonstration in a RR Viper engine

- Coatings applied by industrial vendor
- Optical ports installed
- Operated over a range of conditions

Range of application environments in dedicated test vehicle

- Combustor - noisy
- NGVs - hot
- Blades - fast
Temperature measurements on NGVs

• Temperature measurements track engine operating conditions
• Much lower noise compared to gas stream thermocouple
• Recorded rapid transients (sampling rate ~8Hz)

First ever temperature detection using sensor coatings on an operating engine

NGV measurement repeatability

Two independent runs conducted with pyrometer and sensor coating measurements

Note:
The pyrometer observes at 1µm wavelength. This means that it can pick up reflections from the combustion flame very well and hence always indicates higher temperatures than expected. E.g. under full load conditions the temperature indicated by the pyrometer exceed the material capabilities of the Viper engine. This is obviously not possible. However, the temperature measured using the phosphorescence sensor coating remains below the critical 900°C, which is the highest permitted temperature for the Viper.


Sensor coating measurement repeatability is comparable to a commercial pyrometer
Burner rig tests

- Lab based rig allowed further testing in more controlled environment
- Substrate: 30 mm circular disc (Ni Alloy)
- Coating: YSZ:Eu/Dy (100 µm thick)
- Temperature control using gas flow
- Compare measurements to thermocouple and long-wavelength pyrometer

Results - Emissivity correction

- Cooling air off – ‘isothermal’ condition
- Compare measurements to thermocouple and pyrometer
- Temperature measured by sensor coating similar to thermocouple
  - ~10°C higher than thermocouple – insulation effect
- Emissivity of coating found to be 0.93 through independent test
- Very good agreement with pyrometer after emissivity correction
  - Uncorrected pyrometer underestimated temperature by 30-40°C

Phosphorescence can be used to calibrate the emissivity

Penetration depth

- YSZ material is transparent in visible wavelength range
- Excitation (and emission) light penetrates through coating
- Thermal gradient causes ambiguity in measurements
  - $T_{\text{gradient}} \sim 1^\circ \text{C/\mu m}$
  - Coating thickness $\sim 100 \mu\text{m}$

Where do we actually measure using a sensor coating?

Results – Penetration depth

- Rig operated with cooling air on
- Temperature of substrate and coating surface incrementally increased
  - Constant gradient \( \sim 100^\circ C \ (0.7 \pm 0.04^\circ C/\mu m) \)
- Sensor coating measurement inside the coating
  - Equivalent depth: \( 79 \pm 11.7 \ \mu m \) (considering linear temperature distribution across the coating)
- Temperature difference from surface approximately constant
- Measurement close to bond coat interface
- Further testing showing the equivalent depth increasing with higher thermal gradient

Sensor coating measurement close to the bond coat interface (typically critical temperature)

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4. **Summary**
Temperature measurement options – off-line

- Phosphor thermometry shown to have great potential
- Optical access required during operation – practically challenging
- ‘Off-line’ techniques used widely in industry

<table>
<thead>
<tr>
<th>Technique</th>
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<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microscopy / metallography</td>
<td>Long practised</td>
<td>Destructive</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Point measurement</td>
</tr>
<tr>
<td>Thermal crystals</td>
<td>High precision</td>
<td>Intrusive</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Labourious</td>
</tr>
<tr>
<td>Templugs</td>
<td>High durability</td>
<td>Point measurement</td>
</tr>
<tr>
<td>Thermochromic paints</td>
<td>Surface coverage</td>
<td>Toxicity (REACH)</td>
</tr>
<tr>
<td></td>
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<td>Durability</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Interpretation</td>
</tr>
</tbody>
</table>

New technique required to overcome current limitations
Thermal History Coating & Paint

How it works

- Paint (or coating) applied on component
- Component is operated at high temperatures (150°C - 1400°C) e.g. in engine test
- Once it has cooled down, SCS’s instrumentation is used to deliver **past maximum exposure temperatures**
- Full surface coverage achieved by measuring points across surface

**SCS develops Thermal History technology**
Thermal History Coatings & Paint theory

- Base of oxide ceramic
- Doped to make the material luminescent
- Material applied in the **amorphous** state
- Gradually **crystallises** with temperature - **permanently**
- Luminescence changes depending on the structure
- We measure the decay time \(\tau\) of the emitted intensity

\[
I = I_0 \exp\left(-\frac{t}{\tau}\right)
\]

Luminescent measurements are linked to past maximum exposure temperature
Sensor Application

• The powder can be applied as a paint or as a robust coating

Paint – easy to apply
• Sensor powder is mixed with a binder and applied through air spraying
• Application cost and time is lower
• Demonstrated for temperatures < 900 °C

Robust Coating – long-term applications
• Sensor powder applied through industrial atmospheric plasma spray (APS) process
• Can withstand longer exposure time of several hours
• Engine tested for 4500 hours
• Temperature aim ranging up to 1500 °C
Typical calibration

- Samples of same material as component applied with paint or coating
- Engine data analysed to determine time at temperature
- Samples heat treated in furnace for same duration as test

Continuous change in measurement parameter gives continuous temperature data
THC&P measurement

- Automated or manual measurement acquisition
- In-situ measurements possible
- Spot size 0.5mm
- One turbine blade of ~300 points in ~2.5 hours
Data visualisation

- Temperature data can be represented on 3D coordinates
- Facilitates comparison to simulation data

4D representation of data
**Thermal History Paint** – fire facing side

- THP measured using automated instrumentation
- Total 3240 measurement points
- Data normalised to max. T of thermocouple

**Full surface coverage**

Contour plot using Matlab
IGT Combustor panel - Detail

- Results used to quantify local and global variations
- Circular line of radius 76mm

THP provides high resolution temperature data

Global variations
- Higher T region 180-270°
- Variation: 15% of max. T

Local variations
- Rapid oscillations
- Variation: 31% of max. T

Thermal History Coatings – durability testing

- Sensor material mixed with standard YSZ and applied as a top coat
- Durability testing on burner rig at Jülich, Germany
- Compared to standard YSZ reference samples

Coating cross-section

Research Centre Jülich, R Vassen

Thermal gradient test
- Surface temperature ~ 1350°C
- Bondcoat temperature ~ 1130°C
- Substrate temperature ~ 1080°C

Sensor coatings equivalent or better compared to standard coatings
THC application – long term test

• THC applied on to existing thermal barrier coating
• Operated in Didcot power station for **4,500 hours**
• Coating less damaged compared to standard reference
• Post operation luminescence measurements indicate temperature profile over surface

Luminescence map indicates temperature profile after long term test
Current developments

• SCS offer service providing temperature data to end-users

• Thermal History Coatings
  – UK government supported project with OEM end-users
  – Target temperature range 500-1500°C
  – Silicate material compatible with EBC systems
  – Testing planned on TBC and CMC samples

• Thermal History Paint
  – UK government supported project
  – Extend temperature range to 1200°C
  – Testing planned on TBC samples

Enable high temperature measurements that are not possible with existing techniques
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**Summary**

- Luminescent materials enable multi-sensing capabilities in TBCs
- Progress has been made towards industrial adoption – particularly with THC&P

**Temperature measurement on-line**
- First demonstration in an operating engine
- Precise and repeatable measurements
- Accuracy demonstrated on burner rig
- Emissivity correction for pyrometers

**Thermal History Coatings & Paint**
- Demonstrated in many industrial applications
- Paint or coating available
- Instrumentation developed
- Automation of measurements enables high resolution temperature information

**New and unique measurement capability for future TBC applications**
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