Temperature Measurements of Thermal Barrier Coating Surfaces Using a Cr-Doped GdAlO$_3$ Thermographic Phosphor

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Background

- Discovery* of exceptional high temperature retention of ultra-bright luminescence by Cr-doped GdAlO$_3$ with orthorhombic perovskite crystal structure: Cr-doped gadolinium aluminum perovskite (Cr:GAP).
- Enables luminescence-based temperature measurements in highly radiant environments to 1250°C.

Objectives

- Implement the ultra-bright luminescence temperature sensing capability of Cr:GAP to:
  - Overcome the usually intensity-starved nature of the severely restricted solid angle of light detection associated with engine probes.
  - Enable surface temperature mapping using luminescence lifetime imaging by simply broadening the excitation laser beam to cover the region of interest.
    - Not previously practical because expansion of laser beam reduces S/N to unacceptable levels.

*J.I. Eldridge & M.D. Chambers
Approach

• Demonstrate successful spot temperature measurements using engine probe with restricted light collection.
  – Successfully demonstrated temperature measurements from Cr:GAP coated Honeywell stator vane doublet in afterburner flame of AEDC J85-GE-5 turbojet test engine.

• Demonstrate 2D temperature mapping of thermal gradients on TBC-coated surfaces under conditions ranging from well-controlled laboratory conditions to approaching turbine engine environment.
  – Coated button specimens in NASA GRC high heat flux laser for well-controlled thermal gradients.
  – Coated stator vane doublet in NASA GRC Mach 0.3 Burner Rig.
  – Coated stator vane in AEDC J85 afterburner flame.
Demonstrating Temperature Measurement Capability

Time-Averaged Luminescence Emission from Cr(0.2%):GAP Puck Temperature Dependence

532 nm excitation

Intensity (arb. units)

Wavelength (nm)

bandpass

20C
90C
284C
385C
484C
587C
686C
780C
880C
977C
Cr:GAP-Coated Specimens
EB-PVD at Penn State

- Buttons for furnace and laser heating tests
- Honeywell Stator Vane Doublet for Burner Rig and Afterburner Tests*

*Courtesy of Harvey Niska, Honeywell

![Diagram of Cr:GAP-Coated Specimens]

- Cr:GAP
- EB-PVD
- YSZ
- NiPtAl (Chromalloy)
- Rene N5
- 25 µm
- 200 µm

- Cr:GAP
- EB-PVD
- YSZ
- NiPtAl (Howmet)
- Vane
- 25 µm
- 200 µm
Coatings for 2D Temperature Mapping
Luminescence Decay Curves from 25 µm Thick EB-PVD Cr:GAP Coating

Fit to $I = I_1 e^{-t/\tau_1} + I_2 e^{-t/\tau_2}$

Superb signal-to-noise from thin 25 µm thick coating confirms retention of ultra-bright luminescence at high temperatures.
Demonstrating Temperature Measurement Capability

Calibration of Decay Time vs. Temperature for GAP:Cr Coating

Two distinct regions
200ºC<T<750ºC: less temperature sensitive
T>750ºC: more temperature sensitive

Fit to \( \tau = \frac{\tau_{2E}^R}{1 + 3e^{-\Delta E/kT}} \)
Surface Temperature Mapping Configuration

Control room

Test Bay

AEDC J85 Afterburner or NASA Burner Rig

or

NASA High Heat Flux CO₂ Laser

Pyrometer readout

Shutter activation

Data acquisition computer

Laser power supply

Laser synch

Power supply

Shutter control

Nd:YAG pulsed 532nm laser

593nm CL 40nm FWHM bandpass

PI-MAX4 ICCD

Vane or button

expander

shutter

gigE cable
Mapping Thermal Gradients Produced by High-Heat-Flux Laser

- High power CO$_2$ laser high-heat-flux rig

- CO$_2$ laser heating

- Illumination of Specimen by Expanded Laser Beam

- Nd:YAG pulsed 532nm laser

- Fly-eye integrating lens

- Laser beam/integrating lens 300 rpm

- Pyrometers

- PI-MAX4 ICCD

- Specimen

- Thermocouple
2D Temperature Maps of Thermal Test Pattern

- Step 1: Collect sequence of time-gated images at different delay times after laser pulse.
- Step 2: Remove thermal radiation background from each image in sequence.
- Step 3: Fit luminescence decay curve at each pixel to produce decay time map.

Individual Pixel Decays

\[ \tau = 2.0 \, \mu s \quad (1076^\circ C) \]
\[ \tau = 4.0 \, \mu s \quad (1024^\circ C) \]

Decay Time Map

Temperature Map

- Step 4: Use calibration data to convert decay time map to temperature map.

Temperature Line Scan

Fly-eye integrating lens

3.8 cm diam
Thermal test pattern demonstrates excellent temperature sensitivity/spatial resolution

- Sensitive to $\Delta T$ of 5°C over distance of 0.5 mm
- Insensitive to surface emissivity & reflected radiation!
2D Temperature Mapping of Honeywell Stator Vane in NASA GRC Mach 0.3 Burner Rig Flame

Burner/vane orientation

Cr:GAP coated vane with cooling air supply tubing

ICCD, laser, & pyrometer pointed at vane
Surface Temperature Mapping of Honeywell Stator Vane in NASA GRC Mach 0.3 Burner Rig Flame

Surface temperature maps

Min flow

High flow

Good temperature measurements despite rust stain!
Would not be possible with pyrometer!

Increase air flow through cooling holes

Before burner rig test

After burner rig test
J85-GE-5 Engine Test at UTSI

Engine Aft View

Overhead View of Vane in Afterburner Flame

Afterburner Flame at Night
Surface Temperature Mapping of Honeywell Stator Vane in AEDC J85 Afterburner Flame

First gate image

Decay Time Map

Surface Temperature Map

PLA (throttle) = 99°

Evidence of air film cooling

PLA (throttle) = 101°
Summary

- Ultra-bright high-temperature luminescence of Cr:GAP enables practical temperature mapping of TBC-coated surfaces by luminescence lifetime imaging.
  - Advantages over pyrometry/thermal imaging
    - Emissivity-independent
    - Insensitive to reflected radiation
  - Disadvantages over pyrometry/thermal imaging
    - Requires Cr:GAP coating
    - Applicable to steady-state conditions only (at this time)
  - Impressive temperature sensitivity/spatial resolution.
    - $\Delta T$ of 5°C over sub-millimeter distances
  - Demonstrated over conditions ranging from well-controlled laboratory conditions to burner rig and engine afterburner environments.

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