Development of YAG:Dy Thermographic Phosphor Coatings for Turbine Engine Applications

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AFRL Versatile Affordable Advanced Turbine Engines (VAATE) Project
Gas Turbine Engine Sensor and Instrumentation Development
Project 1: TBC Health & Component Temperatures of Turbine Blades & Vanes

NASA GRC High-Heat-Flux Laser Facility
• Proof-of-concept with easy optical access, no radiative background, no probe heating issues.
Demonstrated to 1360°C.

Williams International Combustor Burner Rig
• Address probe/TP survivability & ability to “see” through flame.
Demonstrated to >1400°C.

AEDC J85-GE-5
• Probe/translate through afterburner flame.
• Opportunity to test excitation/collection integrated probe.

Goal: Demonstrate thermographic phosphor (TP) based temperature measurements to 1300°C on TP/TBC-coated HPT stator on Honeywell TECH7000 demonstrator engine.
Basis for Selection of YAG:Dy

- Advantages of YAG:Dy (at least in powder form produced at high temperature)
  1. Excellent temperature sensitivity from 1100°C to 1700°C.
  2. Higher upper temperature limit than other thermographic phosphors.
  3. Short-wavelength emission at 456 nm reduces interference from background thermal radiation.
  4. Nearly single exponential decay for simple, robust decay time determination.

But, will YAG:Dy coatings exhibit these desirable attributes because temperatures of coating processing restricted to much lower temperatures (<1200°C) than powder processing?
Coating Deposition Methods Investigated

• **Binder-Based Paint Application**
  1. Mixture of YAG:Dy powder and ZAP binder (ZYP Coatings, Oak Ridge, TN)
  2. Air-brush or paint brush application.
  3. Fire to produce coating consisting of YAG:Dy powder particles in AlPO$_4$ matrix.
     - Simple, fast, & inexpensive.
     - Incorporates fully crystallized phosphor powder.

• **Electron-Beam Physical Vapor Deposition (EB-PVD)**
  - E-beam evaporation of YAG:Dy ingot at Penn State.
  - Most compatible for in-line industrial thermal barrier coating (TBC) deposition.
  - Excellent thickness control.
  - Desirable microstructure.

• **Solution Precursor Plasma-Spray (SPPS)**
  - Injection of atomized solution into plasma jet.
  - Low-cost alternative to EB-PVD and conventional plasma-spray.
  - Easily tailorable composition.
Binder-Based Paint Application
ZAP YAG:Dy
ZAP YAG:Dy on Plasma-Sprayed YSZ

Coating consists of YAG:Dy powder particles in aluminum phosphate matrix.
Effect of Heat Treatment on ZAP YAG:Dy

Time-Averaged Luminescence Emission
Excitation at 355 nm

4F9/2 → 6H15/2

4F9/2 → 6H13/2

4F9/2 → 6H11/2

Dy3+ energy levels

ZAP YAG:Dy coating exhibits desired YAG:Dy emission spectrum.
Effect of Heat Treatment on ZAP YAG:Dy

Time-Averaged Luminescence Emission
Excitation at 355 nm

Both slurry coating and ZAP YAG:Dy coating exhibit desired YAG:Dy emission spectra.
Time-Resolved Luminescence
15°C

ZAP YAG:Dy no heat treatment

ZAP YAG:Dy emission spectrum + decay appear identical to that of YAG:Dy powder standard. Very promising.

YAG:Dy Powder Standard
Time-Resolved Luminescence with Logarithmic Intensity Scale
15°C

ZAP YAG:Dy
no heat treatment

YAG:Dy powder standard

ZAP YAG:Dy
No Heat Treatment
Luminescence Decay Curves at 15°C
Compared to YAG:Dy Standard

- Nearly single exponential decay.
- Uniform decay rate over full wavelength range.
Effect of Heat Treatment on ZAP YAG:Dy

Time-Averaged Luminescence Emission
Excitation at 355 nm

Proposed reaction: $\text{Y}_3\text{Al}_5\text{O}_{12} + 3\text{AlPO}_4 \rightarrow 3\text{YPO}_4 + \alpha\text{-Al}_2\text{O}_3$

YAG: Dy
YPO$_4$: Dy

Intensity (arb. units)

Wavelength nm
Effect of Heat Treatment on ZAP YAG:Dy

Time-Averaged Luminescence Emission
Excitation at 355 nm

Proposed reaction: $\text{Y}_3\text{Al}_5\text{O}_{12} + 3\text{AlPO}_4 \rightarrow 3\text{YPO}_4 + \alpha-\text{Al}_2\text{O}_3$

YAG binder
Time-Resolved Luminescence
15°C

After 24hr @1163°C, ZAP YAG:Dy emission spectrum is completely different and exhibits faster decay than YAG:Dy powder standard. Not so promising.
Time-Resolved Luminescence with Logarithmic Intensity Scale 15°C

ZAP YAG:Dy 24hr @1163°C

Luminescence Decay Curves at 15°C Compared to YAG:Dy Standard

- Steeper decay than YAG:Dy standard.
- Spectra contain mixture of YPO4:Dy & unreacted YAG:Dy. Peak at 496nm mostly from unreacted YAG:Dy.
- ZAP coating unsuitable for high temperature measurements for any significant duration.
EB-PVD YAG:Dy
Multi-Ingot EB-PVD Chamber at Penn State

- Guns
- Crucibles + Ingots
- Oxygen Supply Path
- Thermocouple
- Airfoil
- Ion Source
- Graphite heating plate
- Ingots (Trans-Tech):
  - Undoped 7YSZ
  - YAG:Dy
Effect of Heat Treatment on EB-PVD YAG:Dy

Time-Averaged Luminescence Emission
Excitation at 355 nm

amorphous YAG:Dy

Peak positions & ratios indicate amorphous phase is not precursor to YAG.
Effect of Heat Treatment on EB-PVD YAG:Dy

YAP:Dy
YAM = Y₄Al₂O₉
YAP = YAIO₃
YAG:Dy
YAG = Y₃Al₅O₁₂

α-Al₂O₃:Cr
α-Al₂O₃:Cr
θ-Al₂O₃:Cr

Amorphous → YAP + α-Al₂O₃ + θ-Al₂O₃ → YAP + α-Al₂O₃ (no YAG)
Effect of Heat Treatment on EB-PVD YAG:Dy

Time-Averaged Luminescence Emission
Excitation at 355 nm

Intensities (arb. units)

Wavelength nm

Amorphous → YAP + $\alpha$-Al$_2$O$_3$ + $\theta$-Al$_2$O$_3$ → YAP + $\alpha$-Al$_2$O$_3$ (no YAG)

YAG is difficult to achieve due to non-congruent evaporation from ingot.
Effect of Heat Treatment on Decay Curves for EB-PVD YAG:Dy

- YAP:Dy displays less single exponential decay & exhibits thermal quenching at substantially lower temperatures than the desired YAG:Dy coating.
- YAP:Dy not a suitable replacement for YAG:Dy for performing temperature measurements at 1300°C.
- Producing YAG:Dy coatings by EB-PVD is challenging. Will require optimized multiple ingot evaporation.
SPPS YAG:Dy
SPPS at U. of Connecticut

Diagram showing the process of SPPS with labels for Tungsten cathode, Atomizing nozzle, Gas, Copper anode, Pump, YSZ Liquid feedstock, SPPS YAG:Dy, EB-PVD YSZ, YAG:Dy, and YSZ.
Effect of Heat Treatment on SPPS YAG:Dy

Time-Averaged Luminescence Emission
Excitation at 355 nm

$^{4}F_{9/2} \rightarrow {6}H_{15/2}$

$^{4}F_{9/2} \rightarrow {6}H_{13/2}$

$^{4}F_{9/2} \rightarrow {6}H_{11/2}$

SPPS YAG:Dy coating exhibits desired YAG:Dy emission spectrum.
Effect of Heat Treatment on SPPS YAG:Dy

Time-Averaged Luminescence Emission
Excitation at 355 nm

SPPS YAG:Dy survives high temperature exposures!
Effect of Heat Treatment on SPPS YAG:Dy

Time-Averaged Luminescence Emission
Excitation at 355 nm

SPPS YAG:Dy resistant to change with high temperature exposure. Very promising.
After fast initial decay, SPPS YAG:Dy before & after heat treatment exhibit emission spectrum + decay identical to that of YAG:Dy powder standard. Very promising.

Heat treatment reduces minor YAM & YAP content.
SPPS YAG:Dy 3hr laser Ts=1300°C

Time-Resolved Luminescence with Logarithmic Intensity Scale
15°C

SPPS YAG:Dy
3hr laser Ts = 1300°C
Luminescence Decay Curves at 15°C
Compared to YAG:Dy Standard

- Except for initial fast decay, similar to YAG:Dy standard.
- Uniform decay rate over full wavelength range.
Heat Treatments Improve High Temperature Luminescence Intensity for SPPS YAG:Dy

3 hr @1000°C
94% decrease

24 hr @1163°C
90% decrease

3 hr high heat flux laser Ts=1300°C
68% decrease

YAG:Dy Powder Standard
49% decrease

SPPS YAG:Dy coatings benefit from heat treatments or engine run-in.
Faster Decay from YAM:Dy & YAP:Dy Content SPPS YAG:Dy, no heat treatment

Comparison of Time-Gated Luminescence Emission at Short & Long Delays after Laser Excitation

Minor YAM & YAP have disproportionate effect on early stages of decay. YAM:Dy & YAP:Dy decay faster than YAG:Dy. Heat treatments should reduce YAM & YAP content.
SPPS YAG:Dy Selected for Near-Term Engine-Testing

SPPS YAG:Dy after 3 hr high heat flux laser $T_s=1300^\circ C$

Effect of Exposure to Williams International Combustor Burner Flame $T=1150^\circ C$

- SPPS YAG:Dy is suitably robust & stable at turbine engine temperatures.
- Heat treatment or engine run-in is recommended prior to temperature calibration.
  - Reduces loss of high temperature luminescence intensity.
  - Produces more nearly single exponential decay.
Summary

• **ZAP Binder-Based Paint Application**
  – Great for fast, inexpensive demonstration of feasibility.
  – Unsuitable for high temperature measurements >1000°C for any duration due to severe reaction between binder & YAG.

• **EB-PVD**
  – YAG:Dy coating difficult to achieve.
  – Simple oxides are better candidates for EB-PVD because incongruent evaporation from ingot is not an issue.
  – May still be best choice for large scale in-line industrial adoption where optimization effort could be justified.

• **SPPS**
  – Suitable for stable high temperature measurements.
  – Selected for engine measurements.
  – Heat treatment or engine run-in recommended.

Summary

• Dongming Zhu – High heat flux laser testing
• Joy Buehler – Metallography
• Rick Rogers – X-ray diffraction