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

J.I. Eldridge
NASA Glenn Research Center
Cleveland, OH

T.P. Jenkins
Metrolaser, Inc.
Irvine, CA

S.W. Allison
Oak Ridge National Laboratory
Oak Ridge, TN

D. E. Wolfe
Penn State University
University Park, PA

E. H. Jordan
University of Connecticut
Storrs, CT

58th International Instrumentation Symposium
San Diego, CA
June 5-8, 2012
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° 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 AlPO₄ 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

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

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

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

**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

YAG:Dy Powder Standard

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

$\alpha$-Al$_2$O$_3$:Cr

no heat treat
24hr @1163°C
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

ZAP YAG:Dy 24hr @1163°C

YAG:Dy Powder Standard

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
- Thermocouple
- Airfoil
- Ion Source
- Ingots (Trans-Tech):
  - Undoped 7YSZ
  - YAG:Dy
- Crucibles + Ingots
- Oxygen Supply Path
- Graphite heating plate

YAG:Dy
YSZ

6.07 μm

600x
Effect of Heat Treatment on EB-PVD YAG:Dy

Time-Averaged Luminescence Emission
Excitation at 355 nm

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 = YAlO₃
YAG: Dy
YAG = Y₃Al₅O₁₂

α-Al₂O₃: Cr
θ-Al₂O₃: Cr

24hr @1163°C
2hr laser Ts = 1300°C
YAG: Dy slurry coating

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

Intensity (arb. units)

Wavelength nm

Amorphous → YAP + α-Al₂O₃ + θ-Al₂O₃ → YAP + α-Al₂O₃ (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

Luminescence Decay at Room Temperature

Luminescence Decay at 1075°C

- 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 at U. of Connecticut

[Diagram showing a tungsten cathode, gas, copper anode, atomizing nozzle, and YSZ liquid feedstock]

-SPPS YAG:Dy
-EB-PVD YSZ
-YAG:Dy
-YSZ
Effect of Heat Treatment on SPPS YAG:Dy

Time-Averaged Luminescence Emission
Excitation at 355 nm

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

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

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

Intensity (arb. units)

Wavelength nm

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.
Time-Resolved Luminescence 15°C

SPPS YAG:Dy no heat treatment

SPPS YAG:Dy 3hr laser Ts=1300°C

YAG:Dy Powder Standard

XRD SPPS no heat treat

XRD SPPS 3 hr laser

*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

Intensity (V)

Time (sec)

24 hr @1163°C

90% decrease

Intensity (V)

Time (sec)

3 hr high heat flux laser Ts=1300°C

68% decrease

Intensity (V)

Time (sec)

YAG:Dy Powder Standard

49% decrease

Intensity (V)

Time (sec)

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

Wavelength nm

Intensity (arb. units)

Peak at 496 nm less affected.

Minor YAM & YAP have disproportionately 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