

Temperature Mapping Above and Below Thermal Barrier Coatings Using Phosphor Thermometry

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Summary

Luminescence lifetime imaging was obtained from thin Er-doped yttria-stabilized zirconia (YSZ:Er) layers integrated into either the top or bottom of thermal barrier coatings (TBCs) to produce temperature maps from either the TBC surface or from the TBC/substrate interface. Temperature mapping was combined with luminescence intensity-based delamination monitoring to quantitatively assess the degradation of thermal protection associated with localized TBC delamination. Temperature mapping of either the TBC surface or TBC/substrate interface during air film cooling was also performed to evaluate the effectiveness of air film cooling both at the TBC surface as well as the cooling effectiveness at the TBC/substrate interface.

Introduction

While most optical temperature measurement techniques are restricted to near-surface analysis, phosphor thermometry applied to translucent materials provides an opportunity to achieve depth-selective temperature measurements by restricting the presence of the luminescing dopant to the depth range of interest. The primary objective of this work is to apply the unique depth-selective measurement advantage of phosphor thermometry to obtain temperature maps from the TBC/substrate interface as well as from the TBC surface under conditions where significant heat fluxes are present. In one application, bottom-of-the-TBC temperature mapping is combined with simultaneous luminescence-based delamination monitoring to quantitatively evaluate thermal protection degradation at the TBC/substrate interface associated with mechanically induced TBC delamination. In a second application, temperature mapping at the top and bottom of the TBC is performed to evaluate the effectiveness of air film cooling, not only at the surface of the TBC where cooling effectiveness is usually measured, but also at the TBC/substrate interface (where cooling effectiveness is more important).

Methods

TBCs with integrated YSZ:Er layers were deposited by electron-beam physical vapor deposition (EB-PVD) by sequential evaporation from an undoped YSZ ingot and an Er-doped YSZ ingot ($\text{Zr}_{0.913}\text{Y}_{0.079}\text{Er}_{0.008}\text{O}_{1.9565}$). For TBC-coated button specimens with the YSZ:Er layer on the top, deposition of 125 μm of undoped YSZ onto the 25.4 mm diameter bond-coated superalloy button was followed by deposition of 12 μm of YSZ:Er. The layer order was reversed for specimens with the YSZ:Er layer at the bottom of the TBC. For the TBC-coated plates (76.2 mm x 177.8 mm x 6.35 mm) used for air film cooling studies, the undoped YSZ layers were 200 μm thick and the YSZ:Er layers were 15 μm thick.

Temperature maps were obtained from luminescence lifetime imaging. A 20 Hz 517 nm excitation beam provided by a wavelength tuneable optical parametric oscillator OPO was directed at the specimen after passing through either a 10x (for button specimens) or 15x (for plate specimens) beam expander. The 517 nm excitation takes advantage of the high oscillator strength hypersensitive $^4\text{I}_{15/2} \rightarrow ^2\text{H}_{11/2}$ Er^{3+} transition to achieve efficient population of the $^2\text{H}_{11/2}$ and $^4\text{S}_{3/2}$ radiating levels. Images of the $^4\text{S}_{3/2} + ^2\text{H}_{11/2} \rightarrow ^4\text{I}_{15/2}$ emission were acquired using an intensified charge-coupled device (ICCD) camera with a bandpass filter centered at 542 nm positioned between the lens and detector and a 514 nm notch filter in front of the lens to block scattered excitation light. Image stacks were acquired that consisted of a sequence of background-corrected images (typically 64), all with the same exposure time, but with an incrementally increasing delay time after the laser pulse. The ICCD was limited to collecting one exposure per excitation pulse; therefore, temperature mapping was only suited to steady state thermal conditions. Image processing was developed to convert the image stacks into temperature maps. For a 64-frame image stack with incrementing gate delay time, the image processing software constructs a 64-point decay curve for each pixel stack. A least squares nonlinear regression method was applied to fit a single exponential to the decay curve associated with each pixel stack. Intensity threshold crossings at 60% and 5% of the initial intensity (first frame) were selected to be the start and end of the fitting window range, respectively. Only pixels with a minimum of four frames with pixel intensity within the fitting window range were considered valid candidates for fitting. A luminescence lifetime map was then produced using the decay time determined at each pixel stack. Calibration luminescence lifetime measurements were obtained by collecting luminescence lifetime maps from specimens in a furnace with optical access, with temperatures verified by a contacting thermocouple. A relationship between decay time and temperature was established by fitting the calibration data to a multiphonon emission model that includes a transition temperature from high to low effective phonon energy [1].

Combined bottom-of-the-TBC temperature mapping and luminescence-based delamination monitoring were performed in a high heat flux laser facility where specimens were subjected to a heat flux by a combination of

high-power CO₂ laser surface heating and backside forced air cooling. Luminescence lifetime imaging was acquired from specimens with the YSZ:Er luminescent layer incorporated at the bottom of the TBC. Localized TBC/substrate delaminations were produced by a controlled scratch by a hemispherical diamond indenter.

Temperature maps obtained during air film cooling were performed in a Mach 0.3 burner rig facility. Temperature mapping was obtained in the vicinity of three 3.2 mm diameter cooling holes drilled 9.5 mm apart at an angle of 30° from glancing, and the test plate was oriented at an angle of 37° to the unducted hot gas flow exiting the burner. Temperature maps were obtained from test plates with the YSZ:Er layer incorporated at the top of the TBC or incorporated at the bottom of the TBC. TBC surface temperature maps were compared with thermal images obtained simultaneously with a long wavelength (9-11 μm) infrared thermal imager.

Results

High spatial resolution luminescence lifetime-based temperature mapping from the bottom of the TBC was performed simultaneously with luminescence intensity-based TBC delamination monitoring. The same 517 nm excitation and 542 nm emission used for temperature mapping was used for delamination detection. High temperature detection of a scratch-induced delamination employed gated detection during the initial 200 ns following the excitation pulse. The gated detection successfully suppressed collection of the thermal background and produced high resolution delineation of the delaminated region surrounding the scratch by the reflectance-enhanced [2] higher emission intensity in the delaminated region. The temperature map from the bottom of the TBC (Fig. 1) reveals the thermal effect of the delamination in the presence of a heat flux produced by the CO₂ laser. A hot spot associated with the delamination is observed where the bottom of the TBC is about 100 °C hotter in the delaminated region than the surrounding area.

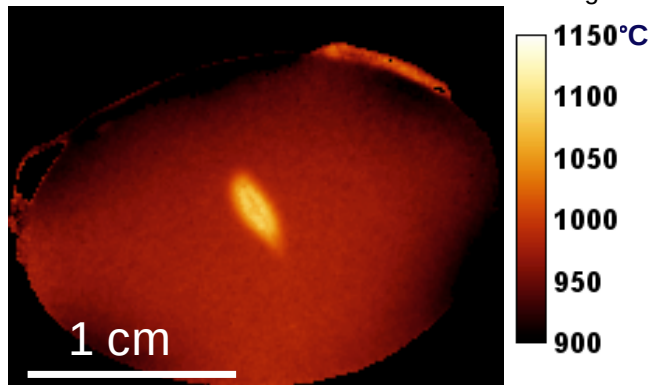


Figure 1 Luminescence lifetime-based temperature map from bottom of TBC in region of scratch-induced delamination.

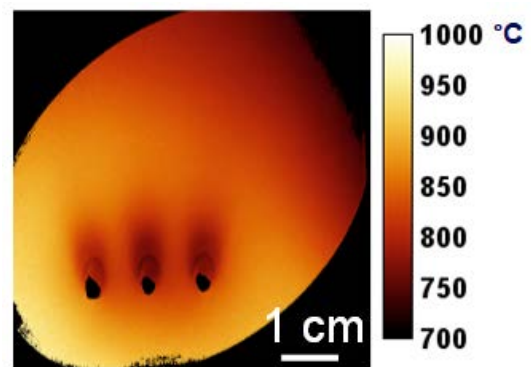


Figure 2 Luminescence lifetime-based TBC surface temperature map in the vicinity of cooling air jets

The effectiveness of air film cooling was studied by obtaining temperature maps either from the TBC surface or from the TBC/substrate interface under different conditions of hot gas temperature and cooling air flow during burner rig testing. Fig. 2 shows an example of the effects of cooling air jets exiting the cooling holes on the TBC surface temperature. The areas under the cooling jets are approximately 120 °C cooler than the surrounding area. The spatial extent of the air film cooling was observed to increase with cooling flow until the point where the air jets lift from the surface with an associated loss of surface cooling effectiveness. Temperature mapping obtained by long wavelength infrared thermal imaging was found to be in good agreement with temperature maps obtained by luminescence lifetime. Luminescence lifetime-based temperature maps from the TBC/substrate interface showed reduced effectiveness of air film cooling at the bottom of the TBC, important information that cannot be obtained by infrared thermal imaging.

Conclusions

Phosphor thermometry offers a unique opportunity not possible by other measurement methods to obtain temperature measurements/maps from selected depths of translucent materials. This feature is particularly valuable for studying the performance of TBCs because the temperature at the TBC/substrate is usually of more interest than the surface temperature. Luminescence lifetime-based temperature mapping was demonstrated to be capable of obtaining high spatial resolution temperature maps from either the TBC surface or at the TBC/substrate interface, at least under steady-state temperature conditions.

References

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