Configurations for Temperature Sensing of Thermal Barrier Coatings

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Abstract: Thermal barrier coatings (TBCs) are used to protect turbine components from the extremely hot gas flow, which may be near or above the component material's melting point. More accurate temperature measurements enable more accurate lifetime prediction, which in turn increases safety and efficiency. In-situ monitoring of in-service turbine components is ideal; a promising method is the luminescence decay of doped coatings stimulated by a pulsed laser. There are various configurations of candidate phosphors and host materials, but it is crucial to find the optimum combination to ensure both sensing and integrity needs are met. In this work, an algorithm is being developed to select combinations of dopant and host TBC material with optimal combined properties. The algorithm's objective function maximizes luminescence properties of a given configuration, while a penalty function is implemented to account for any reduction in thermo-mechanical properties. The expected output is a ranked selection of doped configurations. The algorithm will be flexible and allow different optimization requirements. A custom-made luminescence lifetime decay measurement system is being developed for coating measurements.

Keywords: TBC, Luminescence, Temperature Sensing, Finite Element Analysis, Optimization.

INTRODUCTION

Thermal barrier coatings (TBCs) protect the metallic components in turbine engines and are key to achieving higher gas temperatures [1-3]. Higher operational temperatures in turbines increase overall energy efficiency, which could then ultimately lower emissions [4-7]. Efficiency is critical to the growing power generation and aviation industries. Currently, TBCs are not being used to their highest potential because of uncertainty in temperature measurements. Because the major mechanisms determining life are thermally activated, uncertainty in temperature measurements of in-service conditions contributes significantly to lifetime uncertainty [8].

Advanced monitoring techniques that ensure the integrity and durability of the TBC are paramount to the structural integrity of the turbine blades. Optical methods are non-invasive and can potentially capture data under limited access to the hot-section of turbines. One such optical method is luminescence decay of TBCs doped with phosphorescent materials. This work will analyze the properties of some promising doped configurations and develop predictive methods for optimal configuration selection. The final objective is a selected configuration capable of temperature measurements with improved accuracy and reduced uncertainty. The selection process outlined in this paper accounts for the relevant parameters that influence luminescent efficiency of the material. The effect of the dopant on the overall mechanical and thermal properties of the TBC will also be considered. A finite element analysis will be conducted on some of the more optimal configurations found in previous research as part of the algorithm.

METHODOLOGY

The study focuses on the development of a multi-objective optimization algorithm to select the best configuration for a TBC system for phosphor thermometry, based on the luminescent, thermal, and mechanical properties of the material combinations. The algorithm consists of an objective function, to determine the best configurations in terms of luminescence properties, and a penalty function, to consider mechanical and thermal properties, as presented in Figure 1.

The objective function will optimize a parameter called Luminescence Efficiency, which considers both intensity of the radiation and sensitivity of luminescence decay to temperature. These parameters depend on many variables, including material properties, such as quantum efficiency of the dopant, and configuration properties, such as the topology of the coating (thickness, porosity and location of the doped layer). The doped coating must meet the industry requirements for thermal and mechanical properties of TBCs; the penalty function accounts for this.

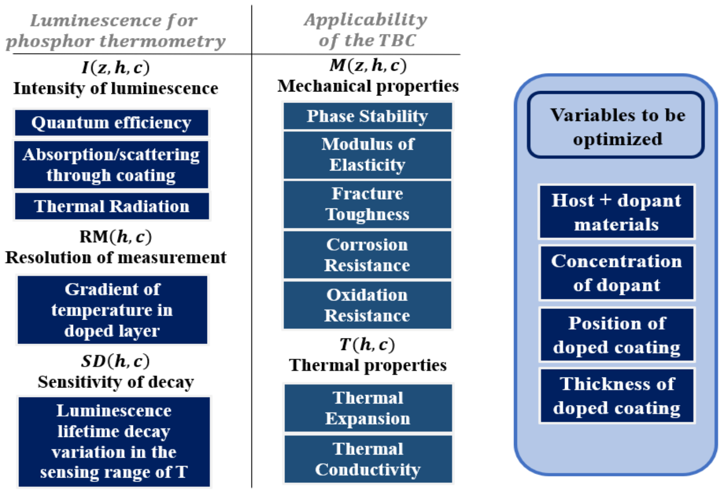

Figure 1: Schematic of the input parameters for the doped TBC material selection algorithm

The variables are supplied to the algorithm by sub-functions. Initially, these variables are supplied from the literature. Algorithms are being developed to generate values for these variables from first principles derivations or from finite element analysis.

The second part of this work is about improving of luminescence decay measurements through the calibration of the instrumentation. The luminescence decay measurements will be validated against concurrent, benchmarked methods, including pyrometry, infrared thermography and thermocouples on existing laboratory-replicated environments.

RESULTS

Material Selection

The definition of the optimal "sensor" configuration through modeling is in development and uses algorithms to combine basic multi-physics laws. The range of operating temperatures in turbine systems is 800 to 1200˚C [9]. The thermal radiation emitted by the material may mask the luminescence and must be considered. Blackbody radiation at 1200˚C has been modeled and plotted in Figure 2, along with two equally intense peaks from dopants of different characteristic wavelength. Dysprosium (Dy) and Europium (Eu) have strong emission peaks at 585 nm [8] and 615 nm [10], respectively. Selecting dopants with a smaller emission wavelength (typically shorter than 600 nm [11]) limits this masking effect.

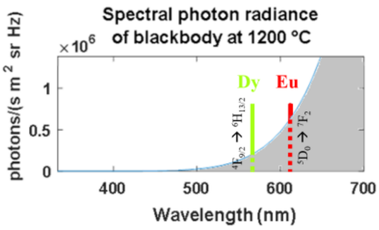

Figure 2: Quantity of photons emitted by the thermal radiation per unit area per unit time at 1200˚C with arbitrarily equally intense luminescence from both typical Dy and Eu dopant emission wavelengths

Methods to predict some of the mechanical properties that determine the behavior and the capabilities of the TBC are being developed. Thermal properties are crucial to the performance of thermal barrier coatings, and are affected by the configuration. The Maxwell-Garnett and Turner models for thermal conductivity and thermal expansion with respect to the concentration of embedded dopant are respectively used as initial models, both of which assume dilute concentrations and well-dispersed spherical dopant particles in the host [12-15]. A computational code has been successful in delivering linear relationships for a chosen selection of rare earth elements. Ongoing work will translate these analytical predictions to more complex and accurate sets of finite element models to accurately predict high temperature properties of the doped TBC material configurations.

Sample Manufacturing

The thermal barrier coating system is typically made of a ceramic top coat and a metallic bond coat adhered to a superalloy substrate. A well-known configuration for luminescence measurements uses an IN738 substrate, NiCoCrAlY bond coat, a plasma spayed YSZ layer, and finally a very thin layer of YAG:Dy; this configuration is shown with the typical targeted thickness values and deposition techniques in Figure 3. From the onset of the coating process, a thin thermally grown oxide (TGO) develops between the bond coat and the ceramic top coat, creating stresses that lead to degradation and spallation of the TBC. The YAG:Dy layer contains the dopant for temperature sensing on the surface, and improves oxidation resistance [16]. This well-known configuration will be used for calibration.

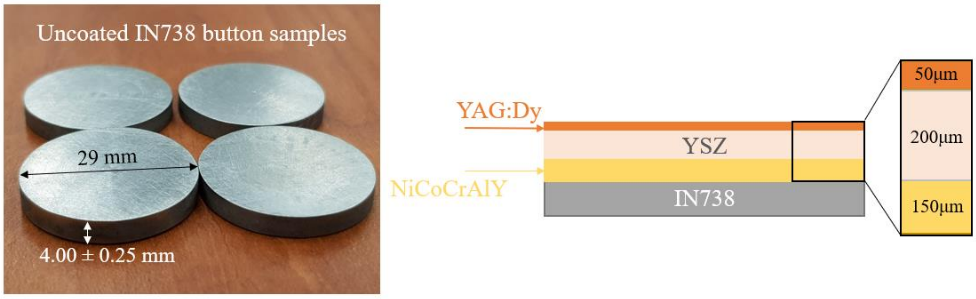

Figure 3: Dimension of the uncoated IN738 button samples and thickness of the coating of the calibration samples

Luminescence Lifetime Decay Instrumentation

An infrared (IR) chamber heater manufactured by Precision Controls of Research INC., which delivers 8 kW of power via 4 quartz lamps focused on the center line by reflecting mirrors will be used to heat the TBC samples. The heater can heat to 1300 ˚C and has a 10-mm diameter viewing hole for optical access, as shown in Figure 4. Low-power pulsed lasers of 532 and 355 nm wavelengths will excite the dopant, and the dopant’s emission will be collected through 4 photomultipliers tubes (PMTs). A schematic of the instrumentation under development is shown in Figure 4. It will enable laboratory-scale simulation of industrial design requirements with high resolution and signal to noise ratio.

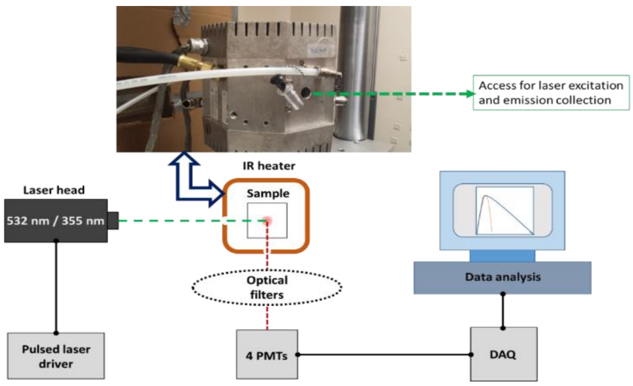

Figure 4: Schematic of the luminescence lifetime decay instrumentation system with infrared (IR) heating furnace

CONCLUSION

The algorithm under development will select doped TBC configurations that exhibit superior luminescence properties without compromising the thermo-mechanical properties of the TBC. Luminescence instrumentation will be calibrated with a configuration known in the literature, then used to evaluate the performance of configurations selected by the algorithm.

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