DEVELOPMENT OF NONDESTRUCTIVE EVALUATION METHODS FOR THERMAL BARRIER COATINGS

J. G. Sun
Argonne National Laboratory, Nuclear Engineering Division
9700 S. Cass Ave., Argonne, IL 60439

E-mail: sun@anl.gov; Telephone (630)252-5169; FAX (630)252-2785

An invited summary for inclusion in the Proceedings of the
22nd Annual Conference on Fossil Energy Materials

July 8-10, 2008
Pittsburgh, PA

Work supported by the US Department of Energy, Office of Fossil Energy, Advanced Research and Technology Development/Materials Program.

DEVELOPMENT OF NONDESTRUCTIVE EVALUATION METHODS FOR THERMAL BARRIER COATINGS

J. G. Sun
Argonne National Laboratory, Nuclear Engineering Division
9700 S. Cass Ave., Argonne, IL 60439
E-mail: sun@anl.gov; Telephone (630)252-5169; FAX (630)252-2785

ABSTRACT

Nondestructive evaluation (NDE) methods are being developed at Argonne National Laboratory for thermal barrier coatings (TBCs) applied to components in the hot-gas path of advanced high-efficiency and low-emission gas turbines, including syn-gas fired turbines. As TBCs become "prime reliant," it becomes important to know their conditions nondestructively to assure the reliability of these components. For these applications, quantitative NDE methods to determine the physical and geometrical TBC parameters are essential. This work is focused on developing several quantitative NDE methods for direct measurement and imaging of TBC thickness and thermal conductivity. These NDE methods can be used to assess the reliability of new coating processes, identify defective components that could cause unscheduled outages, monitor degradation rates during engine service, and provide data for reaching rational decisions on replace/repair/re-use of components.

INTRODUCTION

Thermal barrier coatings (TBCs), applied by two deposition methods, electron beam–physical vapor deposition (EB-PVD) and air plasma spraying (APS), allow for metallic components to be utilized at higher temperatures in the hot-gas path of gas turbines, including syn-gas fired turbines.[1-3] As TBCs become "prime reliant" to the performance and reliability of the engine components such as vanes, blades, and combustor liners, it becomes important to know their condition nondestructively after coating application and at scheduled or unscheduled outages. For these applications, quantitative nondestructive evaluation (NDE) methods to determine the physical and geometrical TBC parameters are essential. Although various NDE methods have been reported in the literature, most are not capable to deriving quantitative data and/or providing property distributions (images) over the entire surface of TBC-coated components.

Work at Argonne National Laboratory (ANL) is underway to develop quantitative NDE methods for TBCs. TBC failure normally starts from initiation of small cracks at the TBC/bond coat interface. These cracks then grow and link together to form delaminations which eventually cause TBC spallation. Two TBC parameters, thickness and thermal conductivity, are important in TBC degradation process because they determine the thermal gradient that affects stress distribution in crack development. Recent effort at ANL was directed to develop optical[4-5] and thermal-imaging[6-8] methods to measure TBC thickness and thermal conductivity. An optical coherence tomography method[5] has been used for 3D imaging of TBC cross sections. Direct measurement of TBC thickness and its distribution is achieved when the refractive index of the TBC material is accounted for. However, optical methods are effective only for relatively thin TBCs because of limited optical penetration depth. On the other hand, thermal-imaging methods are applicable for both thin and thick TBCs. Two thermal imaging methods are being developed at ANL: multilayer thermal modeling[6-7] and thermal tomography[8]. The multilayer-modeling method may determine the thickness distribution of the TBC layer over an entire component surface, and the thermal tomography method can image the TBC depth distributions. In addition, both thermal methods can determine thermal conductivity that may be used to assess TBC degradation condition. This paper presents the technical developments carried out for and experimental results obtained from these three NDE methods to illustrate their capability for quantitative measurement of TBC parameters.

OPTICAL COHERENCE TOMOGRAPHY (OCT)

OCT is a 3D method originally developed for imaging biological materials.[9] It is based on the Michelson interferometer between a reference and a detection beam to differentiate the reflection from different depths of a translucent material. The block diagram of the OCT system at ANL is shown in Fig. 1. Light from an optical source is split into two paths, a sample path and a reference path. Light in the reference path is reflected from a fixed-plane mirror, whereas light in the sample path is reflected from surface and subsurface features of a ceramic sample. The reflected light from the sample path will only be detected if it travels a distance that closely matches the distance traveled by the light in the reference path. Thus, by scanning the sample, data can be obtained in a plane perpendicular or parallel to the sample surface. For an OCT system, typical spatial resolution is ~10 µm when a low-coherence diode laser is used.

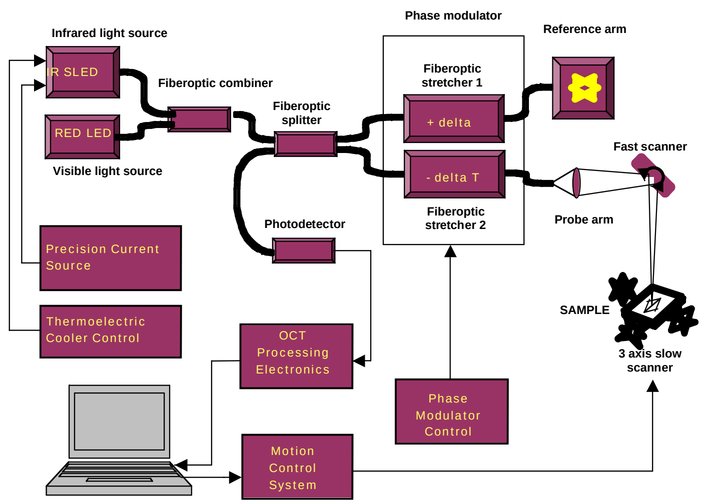
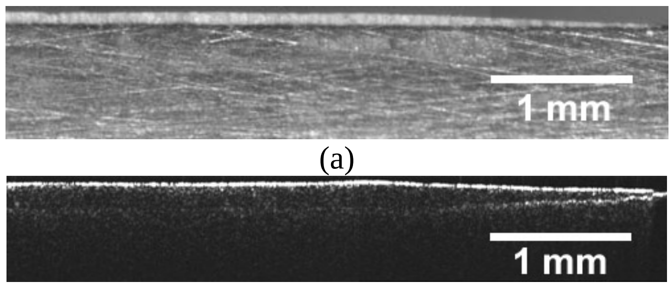


Fig. 1.   Block diagram of basic elements in OCT system.

The ANL OCT system was evaluated by scanning the cross sections of an EBPVD TBC sample. The cross-sectional scan images allow for a direct measurement of TBC thickness uniformity which is an important parameter because temperature drop across the coating is dependent upon the thickness (and the thermal conductivity). Figure 2a shows a micrograph of the cross section of the TBC specimen, which was cut perpendicularly and also polished horizontally with an angle to the TBC surface. The TBC thickness is ~20 µm at the right side and varies between 80-100 µm towards the left side of the image. The OCT cross-sectional scan image along the cut edge is shown in Fig. 2b, in which the top and bottom surfaces of the TBC layer are detected. Because the scanned cross section is very close to the edge, and the TBC thickness is generally uniform in the plane direction perpendicular to the edge, the TBC thickness determined from the OCT scan image in Fig. 2b should be the same as that determined from the micrograph in Fig. 2a. In Fig. 2b, the scanned depth is call the optical depth, which equals to the physical depth multiplied by the refraction index of the material. By direct comparison of optical depth determined from Fig. 2b and the physical depth from Fig. 2a, the refraction index of the ceramic TBC coating can be derived. The measured refection index from the Fig. 2 images is 2.04, which is in general agreement with reported values of typical TBC materials.[10] In addition, the OCT image in Fig. 2b reveals many scattering sources within the TBC coating. Higher scattering is usually an indication of porosity or cracks; this method may therefore be used to detect flaws or damages within the TBC layer.



(b)

Fig. 2. (a) Photomicrograph and (b) scanned cross-sectional OCT image of the edge of a TBC sample.

THERMAL IMAGING METHODS

In a three-layer TBC system consisting of a ceramic topcoat, a bond coat, and a metallic substrate, a large disparity in thermal conductivity exists between the topcoat and the substrate and, when the topcoat is delaminated with air filling the gap, between the topcoat and the air. For TBC system characterization, pulsed (or flash) thermal imaging is effective because it involves with detection of thermal signature that is dependent upon the thermal properties of the test specimen. Figure 3 shows a schematic diagram of a one-sided pulsed-thermal-imaging setup. After a pulsed thermal energy is applied onto the sample surface, the temperature decay on the surface is continuously monitored by an infrared camera. The premise is that the heat transfer from the surface (or surface temperature/time response) is affected by internal material structures and properties. Therefore, by developing appropriate data processing methods, pertinent TBC parameters may be derived from the pulsed thermal-imaging data.

Thermal imaging data are sensitivity to several important TBC parameters, including the thickness, thermal conductivity and heat capacity (the product of density and specific heat) of the top ceramic TBC layer. However, because the TBC layer is optically translucent, optical properties will also affect thermal imaging data. To avoid the optical translucency issue and the requirement to determine optical properties which are normally not important for TBC performance, TBCs were usually coated by a thin (graphite-based) black paint when conducting thermal imaging tests. Two data processing methods have been developed to determine TBC parameters, a multilayer thermal modeling method and a thermal tomography method. The multilayer modeling method may be used to determine TBC thickness, conductivity, and optical absorptance,[6,7] and the thermal tomography method may image the 3D distribution of TBC thermal properties.

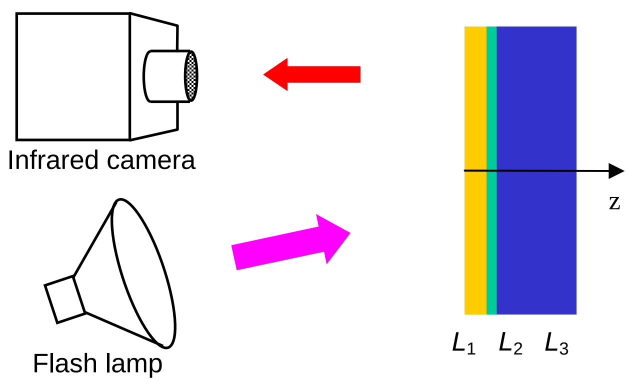
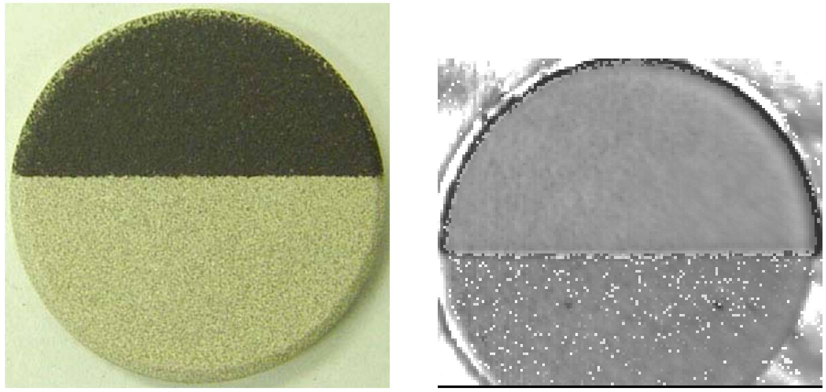


Fig. 3. Schematic of pulsed thermal imaging of a 3-layer material system.

Multilayer Thermal Modeling Method

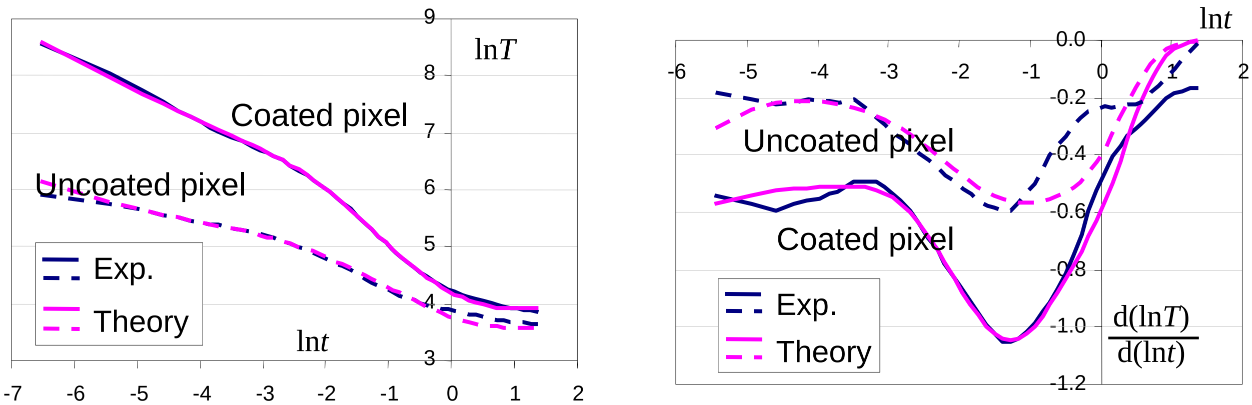
In the multilayer modeling method, a TBC is modeled by a multilayer material system and the 1D heat-transfer equation governing the pulsed thermal-imaging process is solved by numerical simulation. The numerical formulation may also incorporate finite heat absorption depth effect due to the TBC translucency. The numerical solutions (of surface temperature decay) are then fitted with the experimental data at each pixel by least-square minimization to determine unknown parameters in the multilayer material system. Multiple parameters in one or several layers can be determined simultaneously. Among the three parameters when the TBC is coated by a black paint, the TBC thickness, thermal conductivity and heat capacity, it was identified that only two parameters can be independently determined from pulsed thermal imaging.[11] The multilayer modeling method can therefore be configured to calculate one or two of the three parameters by setting the remaining ones at constant. This data fitting process is automated for all pixels within the thermal images and the final results are presented as images of the predicted TBC parameters.[6]

When TBC thermal properties are given, the multilayer modeling method can determine the TBC thickness distribution. Figure 4a is a photograph of an as-processed APS TBC specimen (sample curtsey of Dr. A. Kulkarni, Siemens Power Generation, Inc.). It consists of a nickel-based substrate and a 0.3-mm-thick TBC layer. The upper half of the TBC surface was coated with a black paint. The predicted TBC thickness distribution is shown in Fig. 4b. It is seen that the thickness of the coated region is uniform with an average thickness of 3.04 mm, which is consistent with that from the processing. However, the predicted TBC thickness in the uncoated region is not uniform or accurate, because of the lack of an appropriate optical model in the current method. To further verify the prediction accuracy, Fig. 5 compares the experimental data and fitted theoretical data for a pixel in the coated region and a pixel in the uncoated region. Although the fitted temperature data are reasonably well for both cases (Fig. 5a), the fitting accuracy is more evident in the temperature slope data in Fig. 5b: the theoretical results fit well with experimental data in almost the entire time domain for the pixel in coated surface while the fitting is poor for the pixel in uncoated region. Improvement of the optical model will be carried out in future development.



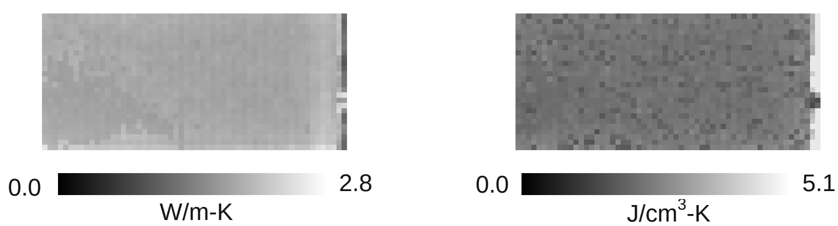
(a) (b)

Fig. 4. (a) Photograph and (b) predicted TBC thickness image of a TBC specimen.



(a) (b)

Fig. 5. (a) Measured and (b) predicted surface-temperature-slope data for TBCs of different thicknesses.



(a) (b)

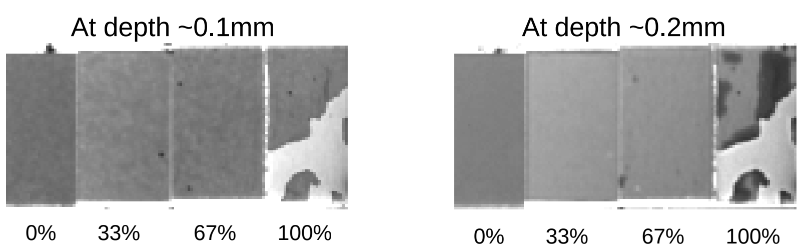
Fig. 6. Predicted TBC (a) conductivity and (b) heat capacity images of a TBC specimen.

Multilayer modeling method can also be used to predict TBC thermal properties, conductivity and heat capacity, once the TBC thickness is know. This can be demonstrated using an as-processed EBPVD TBC specimen (sample curtsey of Mr. A. Luz, Imperial College London). The surface area of this sample is 10 mm x 15 mm and the TBC coating thickness is 0.2 mm. The TBC surface was also coated with a black paint. The predicted TBC conductivity and heat capacity distributions are shown in Fig. 6. It is seen that the predicted thermal conductivity is uniform. The heat capacity is also generally uniform, but with some variations;

the reason for such variations was not investigated at present. The predicted average TBC conductivity is 1.8 W/m-K, which is at the higher end of typical EBPVD TBCs, and the predicted average TBC heat capacity is 2.2 J/cm^3-K which is at the average of typical EBPVD TBCs. These results indicate that the multilayer modeling method can be used to predict TBC parameters, although the predicted conductivity value is probably slightly higher, possibly due to nonlinear temperature response of the infrared camera that was used to measured raw thermal images. This effect will be further examined.

Thermal Tomography

The thermal tomography method developed at ANL can be used to construct 3D images of material's thermal effusivity in an entire TBC specimen volume. Because thermal effusivity is an intrinsic material thermal property, it equals to the square root of the product of conductivity and heat capacity, thermal tomography data can be used to evaluate the properties of TBCs as well as to detect damages/flaws in the TBC system. It has been evaluated for detecting small cracks at the TBC/bond coat interface which would lead to delaminations and eventual spallation (or failure) of the coating. By detecting the small cracks early in the TBC degradation process, this NDE technology may be used to monitor and predict TBC life. Figure 7 shows two plane thermal effusivity images for a set of four 0.2-mm-thick EBPVD TBC samples at conditions: as-processed (0% life) and thermally cycled to 33%, 67%, and 100% (failure) of life (sample curtsey of Mr. A. Luz, Imperial College London). In Fig. 7a, the thermal effusivity image at mid TBC thickness, the TBC appears to be uniform with little damage, although a few damaged spots showing with lower grayscale is seen in thermally cycled samples. The large area with brighter grayscale in the 100%-life sample is the region where TBC has spalled. In Fig. 7b, the thermal effusivity image at the depth of TBC/bond-coat interface, the samples at 0% and 33% of life show no damage; the sample at 67% of life has couple larger black spots of sizes 0.3-1mm and many smaller darker spots, which are likely cracks at the interface; the sample at 100% life contains many large TBC delaminations (black regions) around an away from the TBC-spalled area. These NDE results will be further corroborated with destructive evaluation data.



(a) (b)

Fig. 7. Plane thermal effusivity images at (a) 0.1 mm and (b) 0.2 mm depth constructed by thermal tomography method for four 0.2-mm-thick EBPVD TBC samples thermally cycled at various TBC lifetime (0 – 100%).

CONCLUSION

Quantitative NDE methods are being developed to determine the physical and geometrical parameters of a TBC material system, including the TBC thickness and thermal conductivity. These TBC parameters are representative of the TBC quality, so they can be used to evaluate as-processed TBCs and monitor TBC degradation. For relatively thin TBCs, an optical coherence tomography method has been successfully used for 3D imaging of TBC cross sections to determine TBC thickness and TBC refractive index. For both thin and thick TBCs, two thermal-imaging methods are being developed: multilayer thermal modeling and thermal tomography. The multilayer-modeling method has been used to determine the thickness and thermal conductivity distributions of the TBC layer over an entire component surface. Current models may have predicted a slightly higher thermal conductivity, which will be investigated and corrected in future development. The thermal tomography method was used to image 3D thermal effusivity distributions in thermally-cycled TBC samples. The method was shown to be able to detecting small cracks at TBC/bond-coat interface caused by thermal cycling well before its intended lifetime. Based on the combined measurement data for both TBC thermal property and damage (cracking) condition, these NDE methods may be used to monitor TBC degradation and to predict TBC life.

REFERENCES

1. North Atlantic Treaty Organization, "Thermal Barrier Coatings," Advisory Group for Aerospace Research and Development Report, AGARD-R-823, Neuilly-Sur-Seine, France, April 1998.
2. US National Research Council, National Materials Advisory Board, "Coatings for High Temperature Structural Materials," National Academy Press, Washington, DC, 1996.
3. US National Aeronautics and Space Administration, "Thermal Barrier Coating Workshop," NASA Conference Publication 3312, 1995.
4. W.A. Ellingson, S. Naday, R. Visher, and C. Deemer, "Development of Nondestructive Evaluation Technology for High Temperature Ceramic Coatings," Proc. 19th Annual Conference on Fossil Energy Materials, Knoxville, TN, May 11-13, 2005.
5. W.A. Ellingson, S. Naday, R. Visher, R. Lipanovich, L. Gast and C. Deemer, "Development of Nondestructive Evaluation Technology for Ceramic Coatings," Proc. 20th Annual Conference on Fossil Energy Materials, Knoxville, TN, June 12-14, 2006.
6. J.G. Sun, "Method for Analyzing Multi-Layer Materials from One-Sided Pulsed Thermal Imaging," Argonne National Laboratory Invention Report, US patent pending, 2006.
7. J.G. Sun, "Thermal Imaging Characterization of Thermal Barrier Coatings," in *Ceramic Eng. Sci. Proc.*, eds. J. Salem and D. Zhu, Vol.28, no. 3, pp. 53-60, 2007.
8. J.G. Sun, "Method for Thermal Tomography of Thermal Effusivity from Pulsed Thermal Imaging," U.S. Patent No. 7,365,330, issued April 29, 2008.
9. B.E. Bouma and G.J. Tearney, Handbook of Optical Coherence Tomography, Marcel Dekker, New York (2002).
10. L. Li and D.R. Clark, "Effect of CMAS Infiltration on Radiation Transport Through an EB-PVD Thermal Barrier Coating," Int. J. Appl. Ceram. Technol., Vol. 5, pp. 278-288, 2008.
11. J.G. Sun, "Thermal Imaging Analysis of Thermal Barrier Coatings," paper to be presented at the 35th Annual Review of Progress in Quantitative Nondestructive Evaluation, Chicago, IL, July 20-25, 2008.