DEVELOPMENT OF NONDESTRUCTIVE EVALUATION METHODS FOR CERAMIC COATINGS

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ABSTRACT

Nondestructive evaluation (NDE) methods are being developed for ceramic 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. The objectives of the NDE development are to assess TBC condition for quality control as well as to monitor TBC degradation and predict TBC life during service. For these applications, NDE development at Argonne National Laboratory (ANL) is focused on quantitative methods including laser backscatter, mid-IR reflectance (MIRR) and thermal imaging. Both laser backscatter and MIRR are optical methods and have been attempted for TBC health monitoring. They were developed and evaluated under this study using thermal-cycled TBC samples. For thermal imaging, the multilayer-analysis method developed at ANL has been demonstrated for accurate determination of TBC thermal properties; it therefore may also be used for TBC health monitoring because TBC properties change with life. To ensure measurement accuracy at all conditions, secondary factors such as flash duration, surface roughness, and carbon coating were analyzed based on analytical and numerical calculations. This paper describes these recent developments and experimental results.

INTRODUCTION

Ceramic thermal barrier coatings (TBCs) are extensively used on hot gas-path components in advanced high-efficiency and low-emission gas turbines, including syn-gas fired turbines.[1-2] In this application, a thermally insulating ceramic topcoat (the TBC) is bonded to a thin oxidation-resistant metal coating (the bond coat) on a metal substrate. TBC coated components can therefore be operated at higher temperatures, with improved performance and extended lifetime. TBCs are usually applied by electron beam–physical vapor deposition (EB-PVD) and air plasma spraying (APS). As TBCs become "prime reliant," it becomes important to know their conditions nondestructively to assure the reliability of these components. NDE methods can be used to assess the quality of new coatings, 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.

Work at Argonne National Laboratory (ANL) is underway to develop advanced 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. Although qualitative NDE methods can detect large-scale flaws/damages,[3] quantitative methods are necessary to determine crack progression during the entire TBC life cycle. Therefore, for TBC health monitoring, NDE development at ANL is focused on quantitative methods including laser backscatter, mid-IR (infrared) reflectance (MIRR), and thermal imaging. Laser backscatter is an optical scanning method developed at ANL for detection of subsurface flaws in ceramic materials.[4-5] MIRR is an optical imaging method developed at NASA for TBC health monitoring.[6] To evaluate this method, a new MIRR experimental system was developed at ANL. Both optical methods explore the increased light scattering/reflection from the progressive crack development during the TBC life. In this study, they were evaluated for TBC health monitoring based on experimental results from two sets of TBC samples that were thermal cycled to various percentages of life.

The change of thermal conductivity with TBC life has been studied by many authors.[7-9] In early exposure times, TBC undergoes a sintering process, resulting in a denser material and an increased conductivity. As exposure time increases, the initiation and growth of microcracks causes a gradual reduction of TBC conductivity. When delamination occurs in the later stage of the TBC life, a significant conductivity decrease can be observed in the delaminated regions. This characteristic change in TBC conductivity with TBC life can be used to monitor TBC degradation condition and predict TBC life. Such approach for TBC health monitoring has not been attempted because of the lack of a NDE method that can accurately measure TBC conductivity. The multilayer analysis method developed at ANL, which is a NDE method and has been demonstrated for accurate TBC conductivity measurement, may therefore be used for TBC health monitoring.[10] This application however requires the measurement accuracy to be maintained at all conditions. To achieve this, secondary factors that affect the measurement accuracy, including flash duration, surface roughness, and carbon coating, were examined in this study. The effects were analyzed based on analytical and numerical calculations.

OPTICAL NDE METHODS FOR TBC HEALTH MONITORING

Laser Backscatter Method

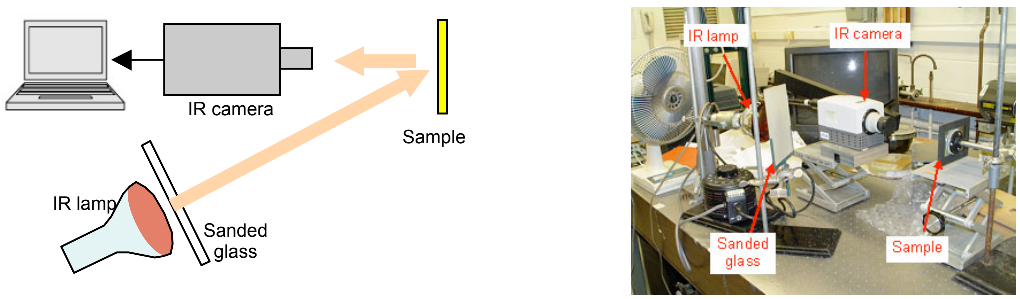
The laser backscatter method is based on the cross-polarization detection of the scattered light from the subsurface of a translucent material.[4] When a polarized laser beam is incident on a translucent material such as a TBC, the total backscattered light consists of surface reflection and subsurface backscatter. However, the surface reflection typically has no change in its polarization state while the subsurface scatter has a significant change. This method therefore selectively measures only the subsurface backscatter from cracks and interfaces, while filtering out the surface reflection. This method has been investigated for NDE of TBCs, specifically for health monitoring during isothermal heat-treatment testing.[5]

Mid-IR Reflectance (MIRR) Method

MIRR is an optical imaging method developed by Dr. Eldridge of NASA for TBC health monitoring.[6] Because optical penetration for TBCs is at maximum in mid-infrared wavelengths (3-5 μm), MIRR has higher sensitivity to detect TBC cracking near the TBC/substrate interface. Therefore, changes in MIRR measurements may be used to monitor the progression of TBC cracking and delamination.

In MIRR, a steady-state infrared light source is used to illuminate the TBC surface and the total reflection, including those from the TBC surface, TBC volume, and cracks near TBC/substrate interface, is imaged by an infrared camera. In the NASA system, a SiC IR emitter coupled with an off-axis parabolic mirror is used to provide collimated illumination to the TBC samples, and imaging is performed at the wavelength of 4 μm with a narrow-band filter.[6] A different system was built at ANL, as shown in Fig. 1. The ANL system utilizes a standard IR heating lamp (operated at a low voltage) coupled with a sanded-glass plate to provide smooth illumination, and imaging is taken in the entire wavelength band (3-5 µm) of the IR camera. The wide-band imaging allows a weak IR illumination to be used, which reduces sample heating and is more convenient in on-line inspection application.

Image processing is necessary to produce a true MIRR image. The processing steps include the subtraction of background reflection (the un-illuminated image), flat-field correction (for uneven illumination), and calibration of reflectance intensity (using a standard sample). These steps were implemented in a software used to process the MIRR data.



(a) (b)

Fig. 1. (a) Schematic and (b) photograph of MIRR system setup at ANL.

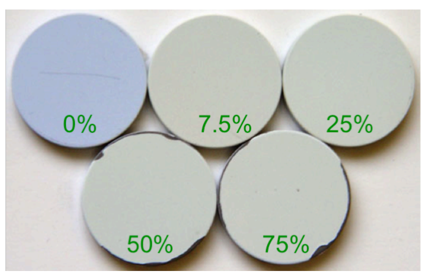


Fig. 2. Photograph of 5 thermal-cycled EB-PVD TBC samples (% life is indicated).

TBC Samples

Two sets of thermal-cycled TBC samples were obtained from Dr. Eldridge of NASA and used to evaluate the laser backscatter and MIRR methods. All TBC samples have a dimension of 1-inch diameter. One set consists of 5 EB-PVD TBC samples cycled up to 75% life (100% life corresponds to failure), and the other consists of 3 APS TBC samples to 45% life. Figure 2 show a photograph of the EB-PVD samples. It is noted that some small spallations exist at the edge of the 50% and 75% TBC samples, which were probably induced by handling.

Experimental Results from Laser Backscatter and MIRR

Figure 3a shows the scan images of the 5 EB-PVD TBC samples using the laser backscatter method. The scatter intensity is generally uniform on each TBC surface, although surface markings (contaminations) caused reduction in local intensity. The intensity is stronger around the edges of spalled TBC areas, which indicates the detection of TBC delaminations around the edges. In Fig. 4a the average scatter intensity is plotted as a function of TBC life for both sets of TBC samples; the intensity data seem not sensitive within the life range of these

TBCs. However, in previous studies[5] it was found that the backscatter intensity increases significantly near the end of TBC life. Therefore, further study is necessary to evaluate TBCs in later stage of their life.

Figure 3b shows the MIRR image of the 5 EB-PVD TBC samples. MIRR also detected the surface markings (contaminations) and small delaminations around TBC spalled areas. In addition, the reflectance value increases with TBC life, as shown in Fig. 4b. The reflectance is sensitive to even the very early stages of TBC cracking progression. The reflectance value however is different for each type of TBC (APS and EB-PVD) and TBC thickness,[6] which is a factor to be considered when using this method.

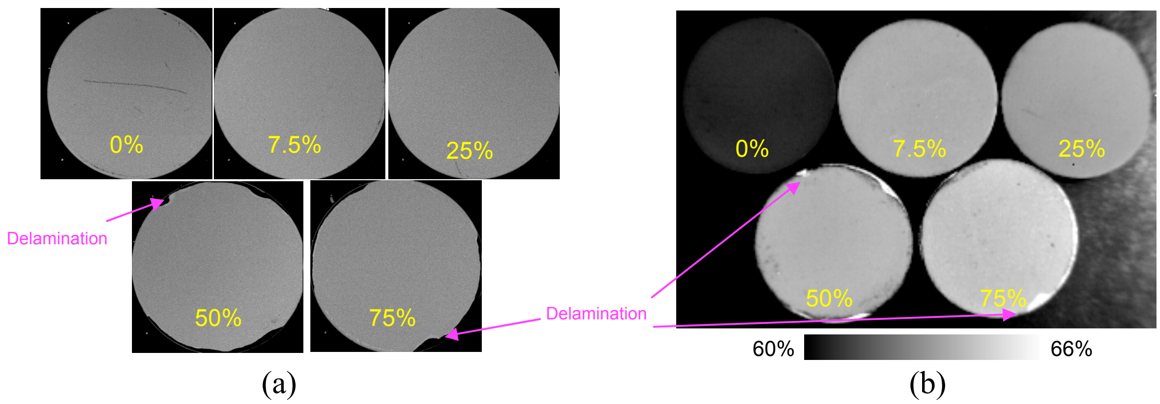


Fig. 3. (a) Laser backscatter scan images and (b) MIRR image of 5 EB-PVD TBC samples.

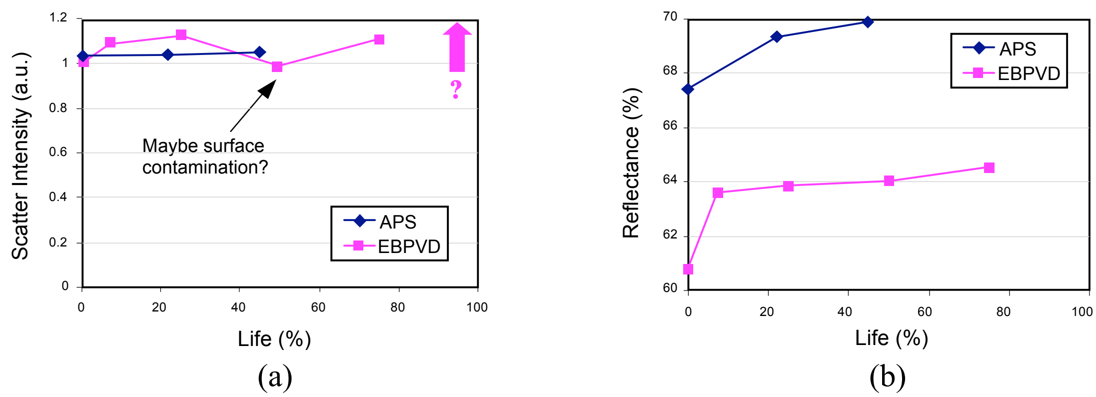


Fig. 4. (a) Laser backscatter intensity and (b) MIRR reflectance as function of TBC life for EB-PVD and APS TBC samples.

MEASUREMENT ACCURACY FOR MULTILAYER ANALYSIS METHOD

TBC thermal properties, especially the thermal conductivity, may also be used for TBC health monitoring because they undergo characteristic changes during a TBC service life.[10] This approach of TBC health monitoring has not been attempted before because of the lack of an accurate NDE method to measure TBC properties. The development of the multilayer analysis method makes it possible to use this approach, as long as measurement accuracy can be maintained at all conditions. Although the measurement accuracy has been demonstrated in laboratory tests of standard TBC samples,[11] several secondary factors related to the experimental system or sample conditions may affect the accuracy. The effects of these factors are discussed and analyzed below.

Factors Affecting Measurement Accuracy

In multilayer thermal analysis method,[11] measured temperature transient data on heated surface are used to determine TBC thermal properties: the thermal conductivity k and heat capacity ρc (where ρ is density and c is specific heat). Therefore, the primary factor affecting TBC thermal property measurement is the accuracy of measured surface temperature, which is obtained by an IR camera. To achieve temperature measurement accuracy, the IR camera was carefully calibrated, and a reference sample was used in all tests to account for small variations in camera response and TBC surface conditions.

The multilayer analysis method[11] calculates the TBC properties based on a theoretical solution derived from an ideal condition, i.e., the flash heat is deposited on sample surface (no depth penetration) instantaneously (zero flash duration) and there is no heat loss from all sample surfaces. Many factors may alter the experimental condition, and they can also be difficult to be quantified and incorporated in the theoretical model. As a result, robust data-processing procedure is needed to eliminate/reduce the effects of these factors to measurement accuracy.

Three important secondary factors are examined below. They include flash duration, surface roughness, and carbon coating. To facilitate the analyses, postulated material properties for a two-layer TBC system are assumed and listed in Table 1, where L is layer thickness.

Table 1. Postulated material properties for TBC material systems used in this study.

Materials	L (mm)	k (W/m-K)	ρc (J/m^3-K)
TBC	0.2	2	$3.016*10^6$
Substrate	1.0	8	$3.237*10^6$
Carbon coat		0.5	$2*10^6$

Flash Duration Effect

The flash duration of flash lamps is typically in the range of 1-5ms.[12] Figure 5a shows the flash duration effect on the temperature slope data. It is seen that this effect is more significant in early times with larger flash durations. If the flash duration for a data set is unknown and a theoretical model with an arbitrary value, say 1.8ms, is used to analyze (fit) the data, it is obvious that the predicted results are not accurate if the entire curve is used. However, if only part of the curve around the main peak is used in the analysis, e.g., within the range of 10ms to 1s, the results can be improved. A partial curve fitting is therefore used in this and the following analyses. Figure 5b shows the predicted TBC conductivity and heat capacity when a fixed value of flash duration of 1.8ms is used to analyze the data obtained with different flash durations. The maximum prediction error for conductivity is <1.5% and for heat capacity is <4%. This accuracy is considered good.

Carbon Layer Effect

The carbon paint layer applied on TBC surface for thermal imaging test may have different thermal properties and thicknesses. Figure 6a shows the effect of carbon layers of various thicknesses to the temperature slope curve, based on theoretically generated data with the properties listed in Table 1. Because the thickness of the carbon layer on real samples is usually unknown, it is normally not accounted for in the data analysis. Figure 6b shows the predicted TBC conductivity and heat capacity for TBCs with carbon layers up to 10μm thick (5% of the TBC thickness). The maximum prediction error for conductivity is <4% and for heat capacity is <1%. This accuracy is also considered good.

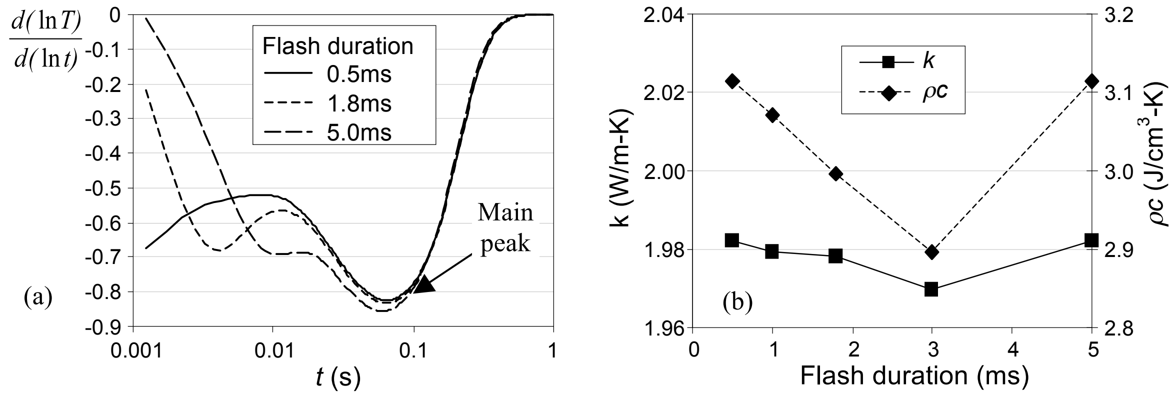


Fig. 5. Flash duration effect on (a) temperature slope data and (b) predicted TBC properties.

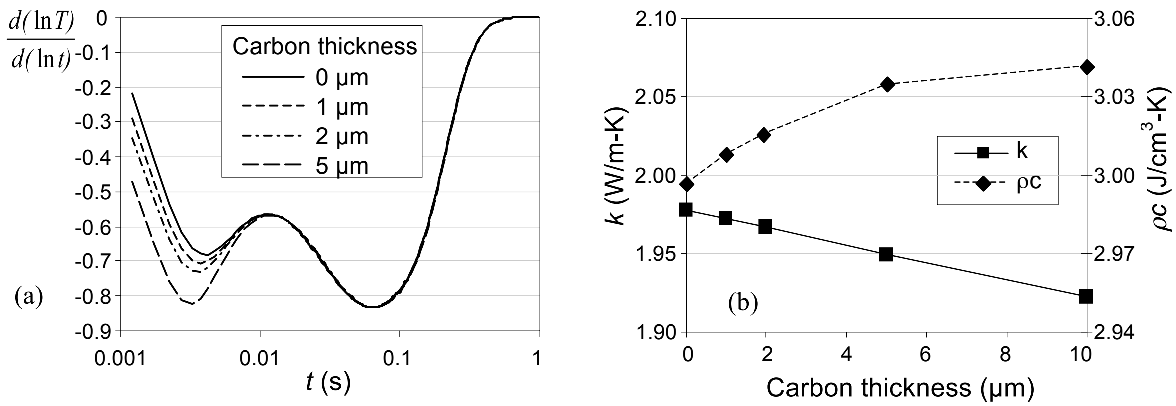


Fig. 6. Carbon layer effect on (a) temperature slope data and (b) predicted TBC properties.

Surface Roughness Effect

The surface roughness effect is analyzed based on 2D numerical simulation data for TBC samples with various surface roughness levels. The simulations were performed using the COMMIX computer code,[13] which is a three-dimensional, transient, finite-difference-based code developed and validated for computational heat transfer and fluid flow. The cross-sectional geometry of the TBC sample is illustrated in Fig. 7. Because the roughness is assumed to be periodic and simplified as steps, only the shaded area is used in the simulation. Figure 8a shows the surface temperature slope curves at the peak and valley positions on the TBC surface with a roughness of 10μm and a periodic length of 160μm (flash duration is 0). The surface roughness effect appears mostly in the early times. Although the predicted TBC property values at these positions can be quite different, the averaged values are very close to the real material values, as shown in Fig. 8b for TBCs with roughness of 10 and 20μm and various periodic lengths. The maximum prediction error for conductivity and for heat capacity is typically <1%. This accuracy is very good.

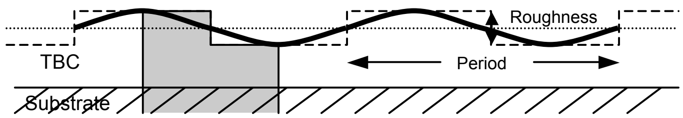


Fig. 7. Cross-sectional geometry of a TBC material with surface roughness.

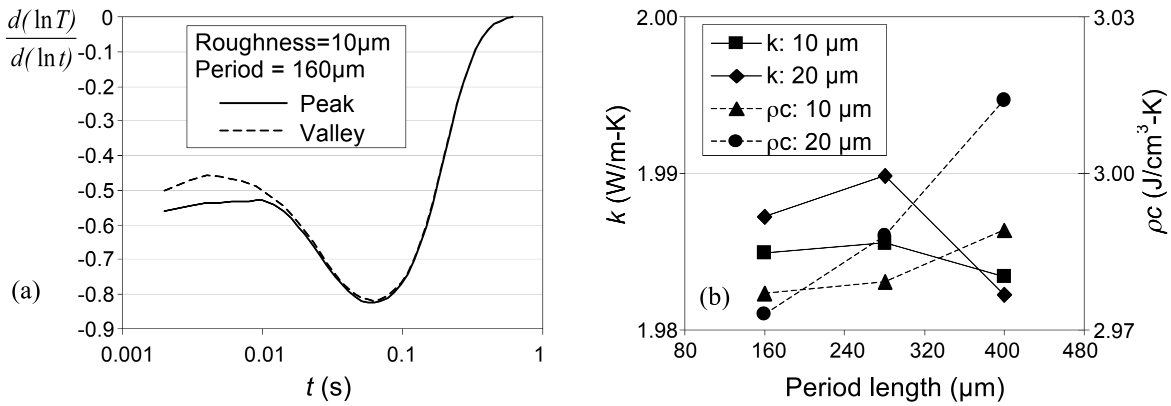


Fig. 8. Surface roughness effect on (a) temperature slope data and (b) predicted TBC properties.

CONCLUSION

Quantitative NDE methods based on optical and thermal imaging are being developed for TBC health monitoring and life prediction. Two optical methods, the laser backscatter developed at ANL and mid-IR reflectance (MIRR) developed at NASA, were investigated for these applications. To use MIRR, a new MIRR system was developed at ANL. These optical methods were evaluated using two sets of TBC samples that were thermal-cycled to various percentages of life. Experimental results showed that both methods may detect delaminations below the thin TBC layers. The MIRR reflectance was found to increase monotonically with TBC life, while the laser backscatter intensity was not very sensitive to the range of TBC lifes investigated in this study (although it was found in other studies to increase near the end of TBC life). On the other hand, TBC health monitoring may also be achieved based on the change of TBC thermal conductivity with TBC service life. This approach can be apply to a wider variety of TBCs (e.g., thicker coatings) but has not been attempted because of the lack of a NDE method to accurately measure TBC properties. The multilayer thermal analysis method developed at ANL can be used for this purpose if its measurement accuracy is maintained at all conditions. Therefore, secondary factors that affect measurement accuracy were analyzed; they include the flash duration, carbon-layer thickness, and surface roughness. It was identified that these factors all affect the temperature data in the early time period. By proper selection of the data segment used in the analysis, without directly modeling of these factors, the error of predicted TBC thermal properties in all cases is <4%. Although further improvement in measurement accuracy may be achieved, these results demonstrate that the multilayer-analysis method is robust and accurate for TBCs condition monitoring.

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