DEVELOPMENT OF NDE METHODS FOR CERAMIC COATINGS

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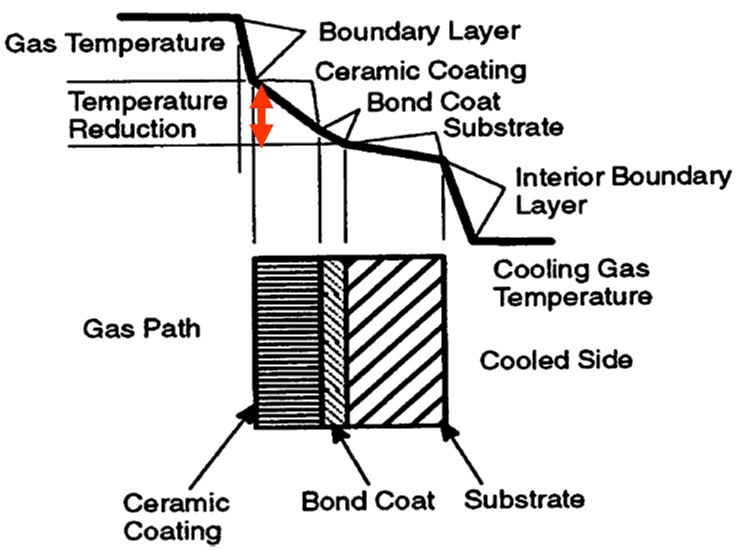
Outline

- Background on TBC degradation and NDE
- Objectives of this project
- NDE developments for TBC systems
  - Method development/validation
  - NDE for industrial components
- NDE for TBC life prediction
- Summary
- Planned future efforts

Background

- Thermal barrier coatings (TBCs) are required for high-temperature metallic components in advanced gas turbines to be operated at higher efficiency and low emission
  – TBCs may reduce metal surface temperature by >100ºC
- TBCs have become "prime reliant" material → their condition monitoring and lifetime prediction by NDE is important

Temperature drop schematics



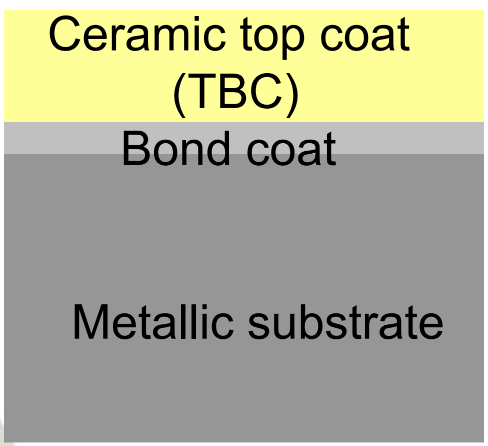
From Feuerstein et al, 2008

Uncoated and TBC-coated blades

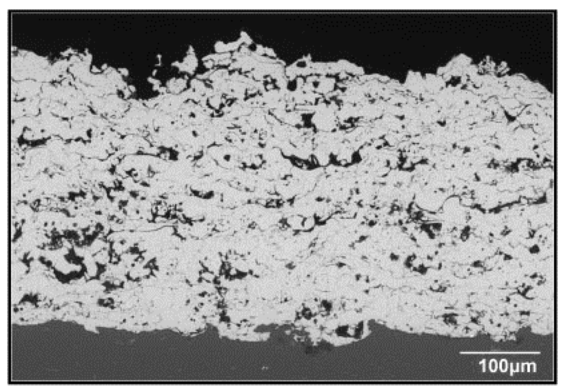
TBC Materials and Structures

- Standard TBC material is 7-8wt% yttria stabilized zirconia (7-8YSZ)
  - Multi-ceramic-layer TBCs are being developed
- TBC is usually applied by air plasma spraying (APS) or electron-beam – physical vapor deposition (EB-PVD)
  - Both thermal conductivity and thickness are important TBC parameters
- Because TBC is applied on component surface, its inspect over entire surface (by imaging NDE methods) is necessary

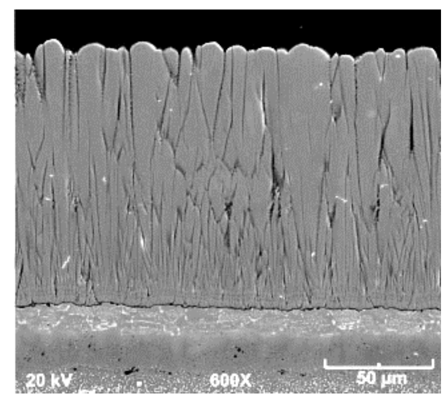
Schematic of TBC system



APS TBC

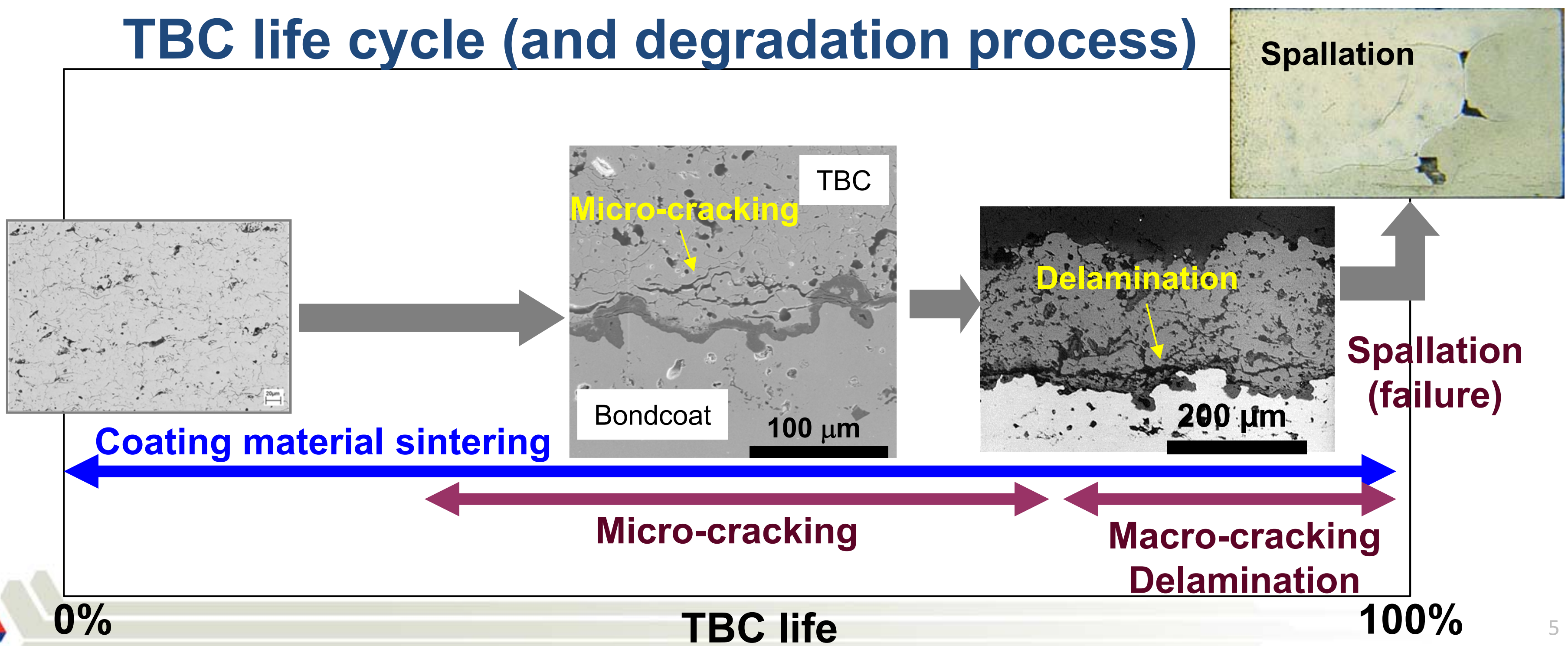


EB-PVD TBC



TBC Property/Structural Change in Life

- Two characteristic changes:
  - (1) TBC contineously sinters with conductivity increase
  - (2) Cracks and delaminations develop near interface
- Quantitative NDEs are required to detect both changes for life prediction
  - To measure material property changes
  - To determine property – structure relationship (for entire TBC life)



NDE Applications for TBCs

- Many NDE technologies have been studied/used for TBCs: thermal imaging, optical (reflection/scatter, emission, spectroscopy, etc), electrochemical, electromagnetic, ultrasonic, x-ray, etc
  - Most are not quantitative
  - Most are not suitable for field application
- NDE for TBC health monitoring and life prediction:
  - A practical NDE method/model has not been established
- NDE for detection of coating flaws (eg, delaminations, FOD):
  - Many NDE methods can detect large flaws; those flaws usually appear near end of TBC life so their detection is of less value
  - Small and deep flaws are difficult to detect but more important
- NDE for quality control of fabricated TBC components:
  - Only single-point thickness measurement is used by manufacturer
  - Current NDE methods are not suitable for TBC property/quality measurement especially for entire TBC-coated component surface

Objectives of This Project

- Develop and evaluate advanced NDE methods for (1) TBC life prediction and (2) high-resolution detection of coating flaws
  - (1) For life prediction (quantitative NDE):
    - thermal multilayer analysis (MLA) method
  - (2) For high-resolution flaw detection
    - thermal tomography (TT) method
- Develop NDE methods for functional materials (gas-separation membrane, fuel cell, etc)
  - Synchrotron x-ray CT, thermal tomography

Recent NDE Developments

- Continued development of two thermal imaging methods
  - Thermal multilayer analysis (MLA) for TBC life prediction
    - Validation of MLA measurement accuracy for TBCs
    - Surface treatment (black paint) material evaluation
    - Development of theoretical models for (1) translucent TBCs and (2) double-layer TBCs
    - Evaluation for testing industrial components
  - Thermal tomography method (3D TT imaging)
    - Continued development of new algorithm for high-resolution imaging
- Continued evaluation of thermal imaging NDE methods for TBC life prediction
  - Collaborations with Siemens and Stony Brook Univ.

Presentation Topics

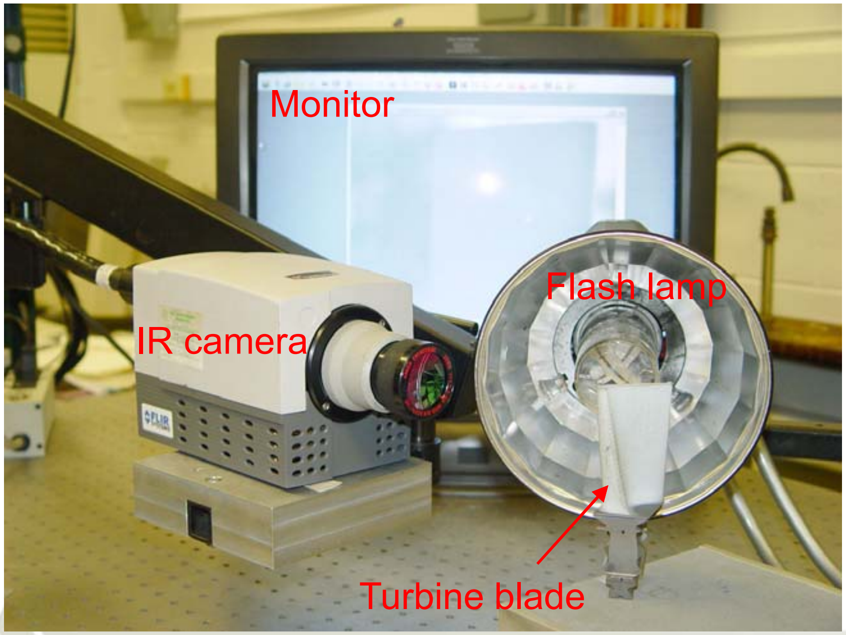
- Development and application of multilayer analysis MLA method
  - Validation of MLA measurement accuracy
  - Effect of surface paint on TBC property measurement
  - Theoretical development for translucent TBCs
  - Theoretical development for double-layer TBCs
  - Application for a turbine blade

- NDE for TBC life prediction

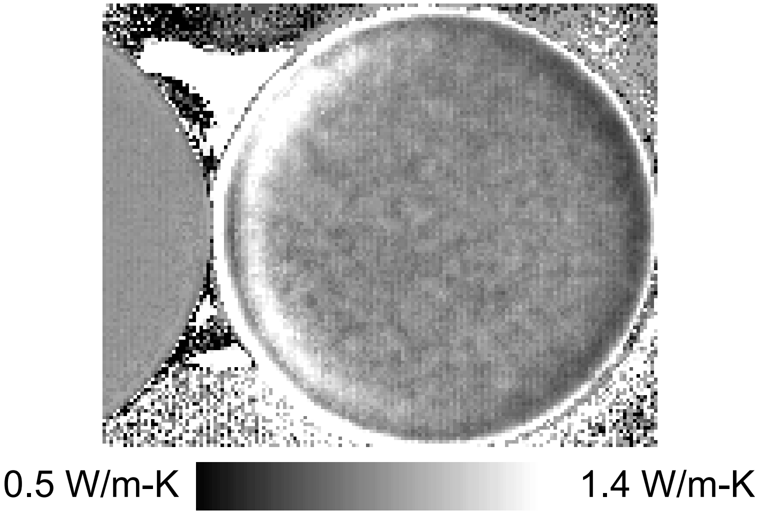
Thermal Imaging Multilayer Analysis (MLA) Method

- MLA method developed at ANL can measure TBC thermal properties:
  - Two TBC properties: thermal conductivity and heat capacity (or thickness)
  - The only method suitable for field applications (and fully automated)
  - The only method for imaging entire component surface
  - Paper accepted by JHT

One-sided experimental setup

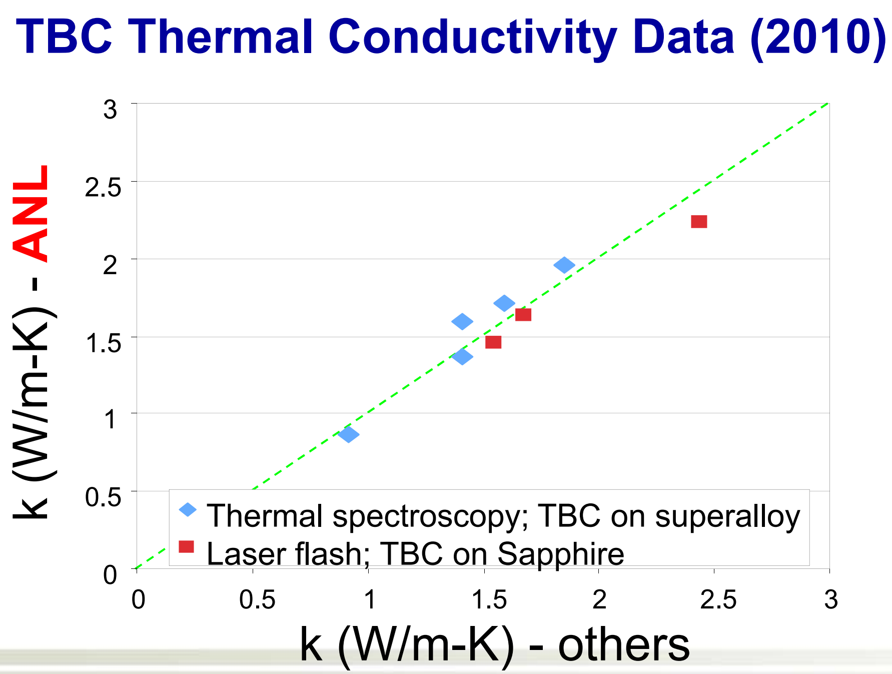


Thermal conductivity imaging



MLA Measurement Accuracy

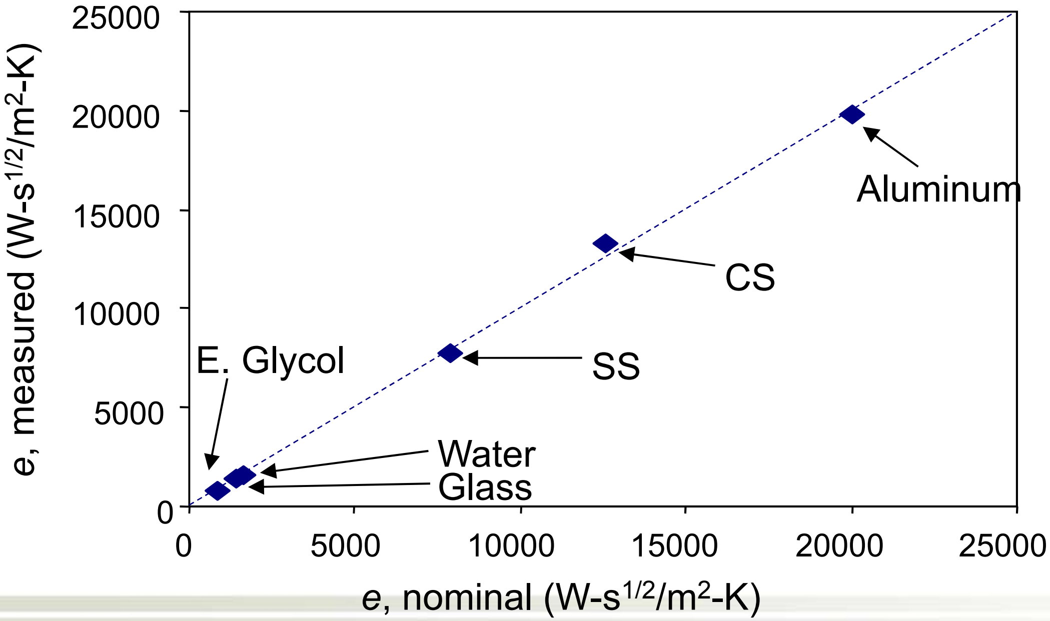
- MLA measurement results were demonstrated to be consistent with other measurement methods
- However, all other methods don't have adequate accuracy (5% or poorer) and there is no TBC "standard"
- What is absolute accuracy for MLA?
  – A long-standing problem for MLA and all other NDE methods



MLA Absolute Accuracy - Demonstrated

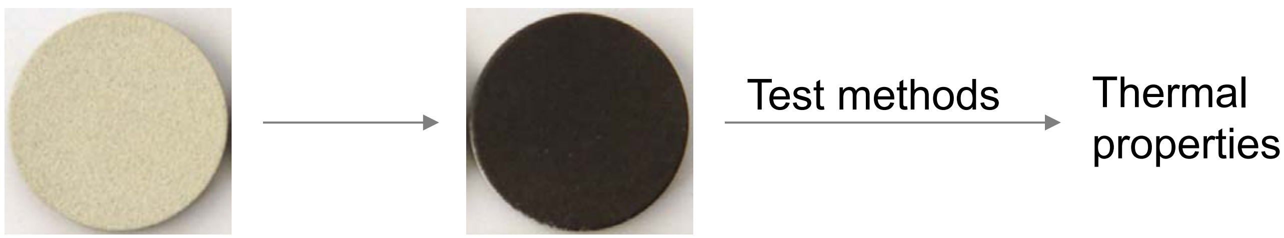
- MLA accuracy was demonstrated from thermal effusivity $e=(k\rho c)^{1/2}$ measurements for various standard bulk materials
- A tape was bonded on bulk material to form a two-layer system
  - Measured bulk material effusivity e is within 2% of nominal value
  - This is best demonstrated accuracy among all methods
    - Suitable for TBC life prediction because TBC property change is small (10%)

Predicted and nominal thermal effusivity e values for various standard materials



Effect of TBC Surface Treatment

- Current thermal-imaging model is for opaque coatings (eg, metallic)
- TBC is translucent, needs surface treatment to make it opaque
  - Common method: apply a thin graphite-based paint on TBC surface (which can be easily burn off at a low temperature)

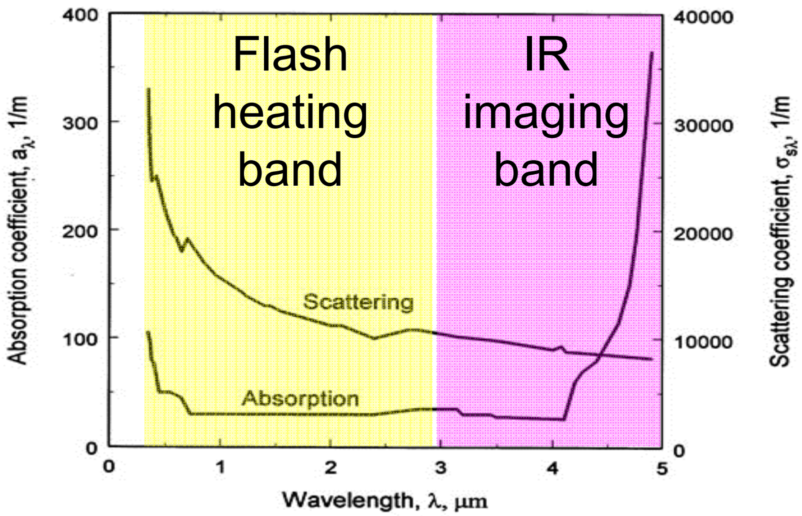


- In collaboration with Dr. Cernuschi and Dr. Bison of Italy, effect of surface treatment on TBC property measurement was evaluated
  - Three different graphite paints
  - Three type TBCs: APS, EB-PVD, PS-PVD
  - Graphite layer did not affect measured TBC thermal diffusivity
  - A paper was submitted to a journal

Thermal Imaging for Translucent TBCs

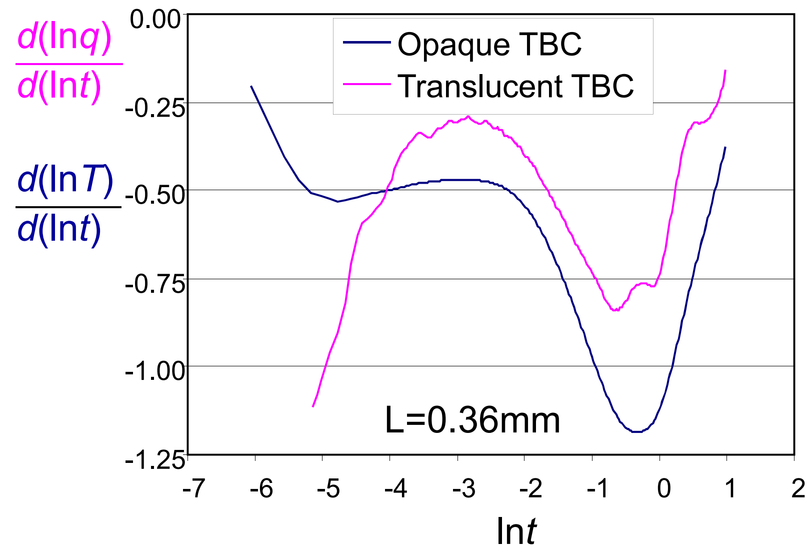
- A method for translucent TBC property measurement is needed
  - Because it is usually not desirable to paint a TBC part black
- Difficulty: large optical property changes over thermal imaging wavelength bands
- No theoretical model for flash thermal imaging at present
  - Exp. data for “opaque” and translucent TBC are significantly different

TBC optical properties



From: Wahiduzzaman & Morel, ORNL Report, 1992

Thermal imaging data for “opaque” and translucent TBC



Theoretical Modeling for Translucent TBCs

- Theoretical model for translucent TBCs include both conductive and radiative heat transfer within the coating layer

$$\rho c \frac{\partial T(z,t)}{\partial t} = k \frac{\partial^2 T(z,t)}{\partial z^2} - \frac{\partial q_r(z,t)}{\partial z}$$

Stored energy | Conduction | Radiation

  - Radiative transport is modeled by a two-flux formulation:

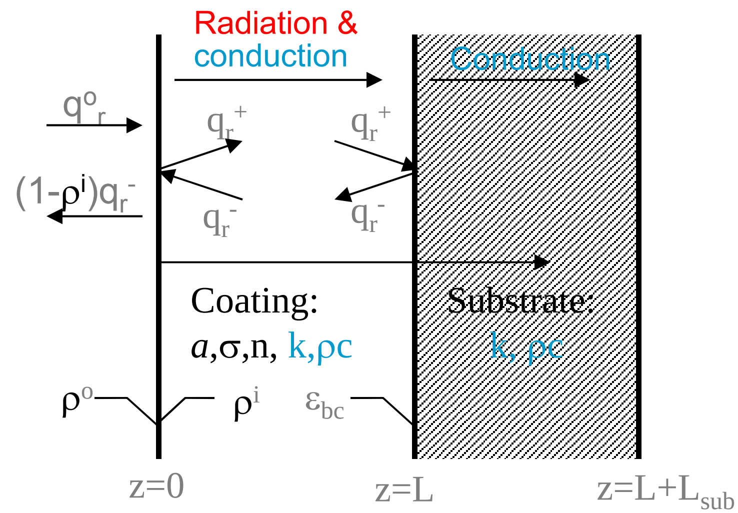
$$q_r = \int_0^\infty q_{r\lambda} d\lambda = \int_0^\infty (q_{r\lambda}^+ - q_{r\lambda}^-) d\lambda$$

  - IR camera reading:

$$E(t) = N(1-\rho^i)\int_3^5 [q_{r\lambda}^-(0,t) - q_{r\lambda}^-(0,0)] d\lambda$$

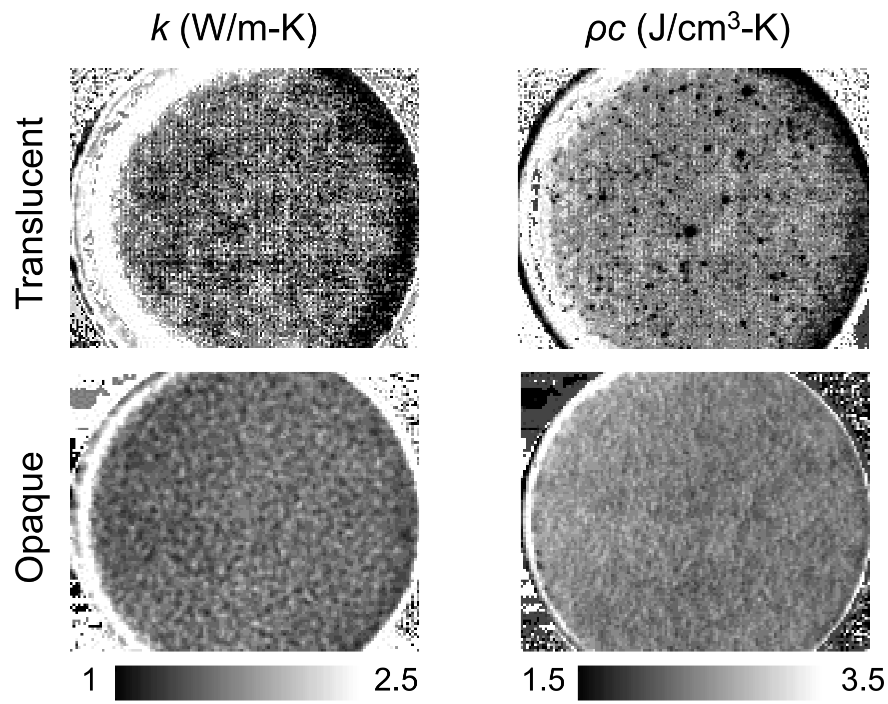
- A complete solution was derived

Heat transfer in translucent TBC



Preliminary Results for A Translucent TBC

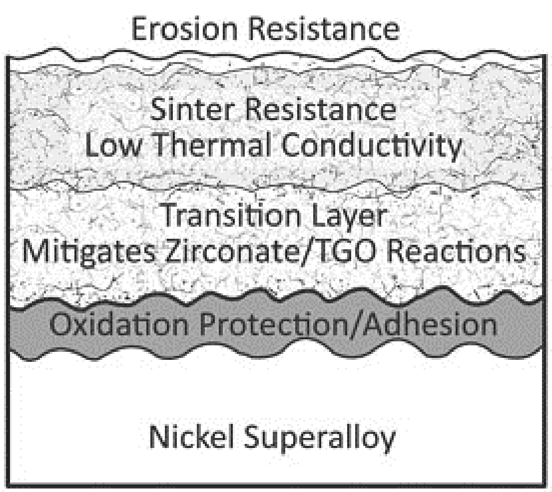
Predicted thermal conductivity k and heat capacity ρc images for a TBC sample at translucent and "opaque" conditions

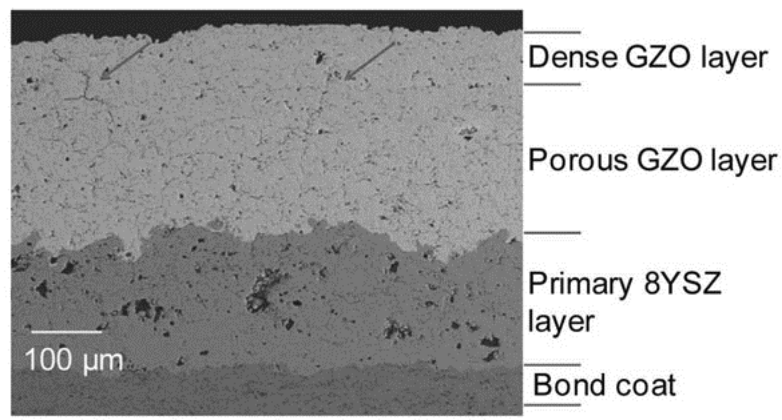


- Predicted properties for translucent TBC are consistent with those of "opaque" TBC (for the same TBC sample)
- A paper is being prepared

Multilayer (>=2) TBCs

- Multilayer TBCs are being developed to extend functionality (eg, erosion) or higher-temperature capabilities of current TBCs
- A collaboration has been established with Dr. Sampath at Stony Brook Univ. for NDE study of multilayer TBCs
  - Dr. Sampath's group is developing multilayer TBCs under a DOE FE project





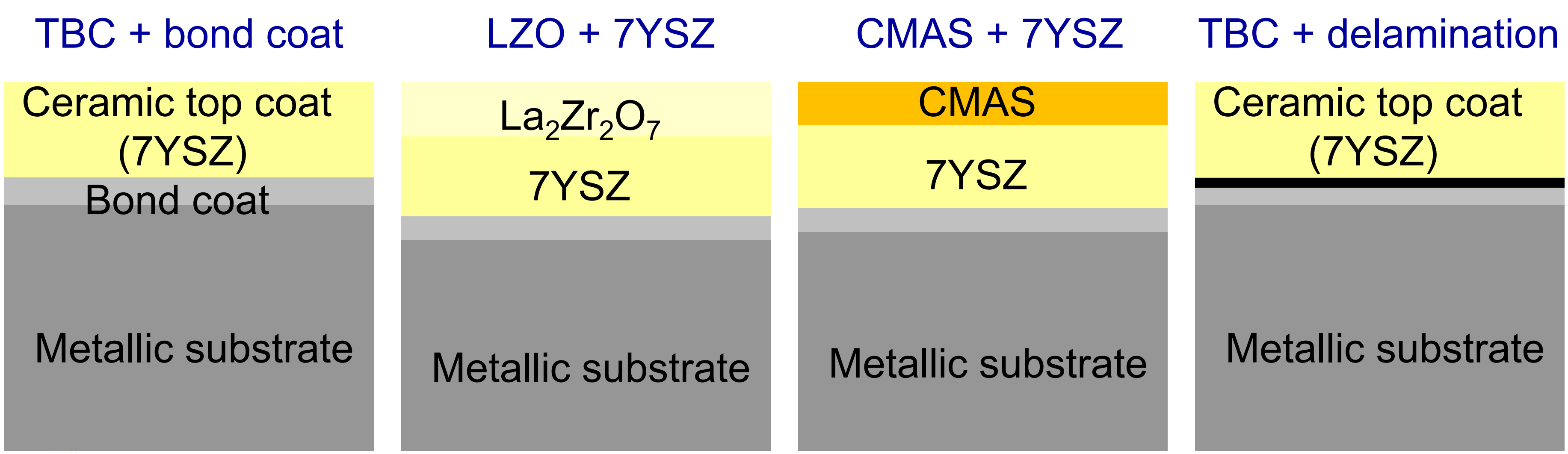
YSZ: 8wt% Yttria stabilized zirconia
GZO: $Gd_2Zr_2O_7$

From: Dwivedi, Viswanathan, and Sampath (2013)

Thermal Imaging for Double-Layer TBCs

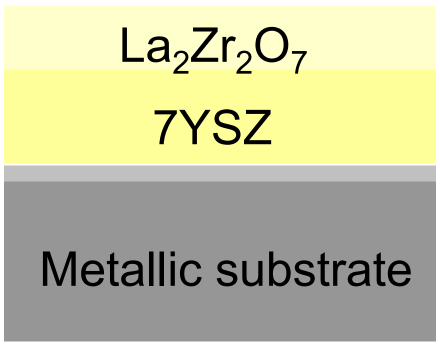
- Many double-layer TBCs or coatings are of interests
- Initial effort was on measuring 2-layer-averaged TBC property
- Current effort is on measuring coating properties for each layer
  - MLA method was extended to 2-layer coating systems
  - Preliminary tests were conducted – data need verification

Four types of double-layer coating configurations

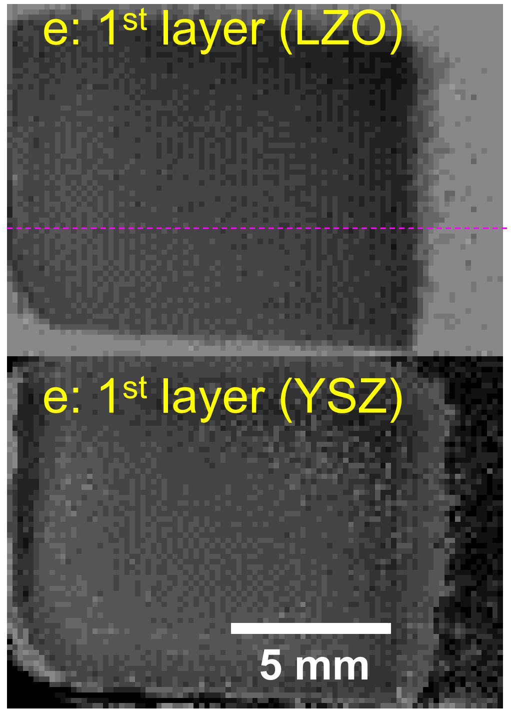


Prediction of Double-Layer TBC Properties

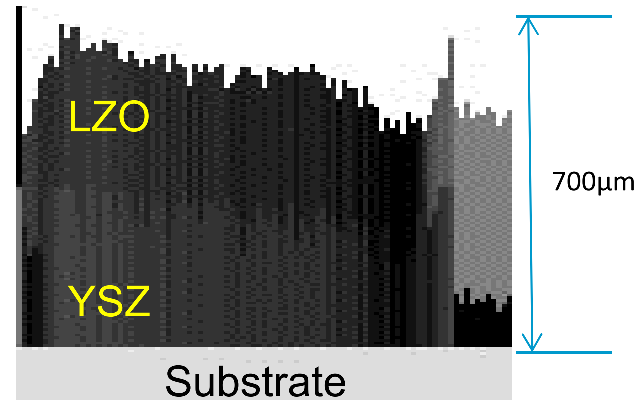
Double-layer TBC



Predicted layer effusivity

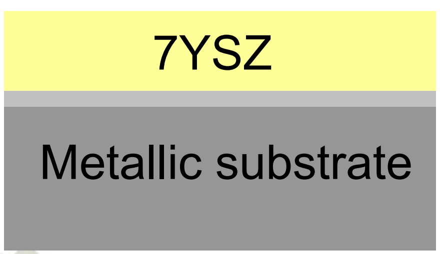


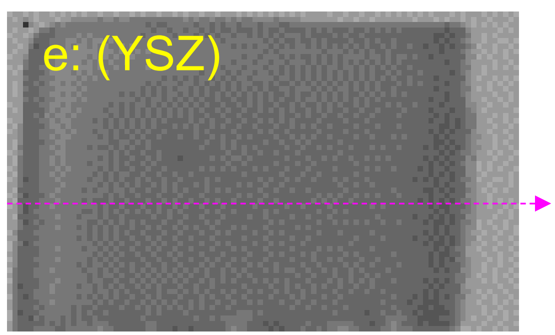
Predicted thickness profiles

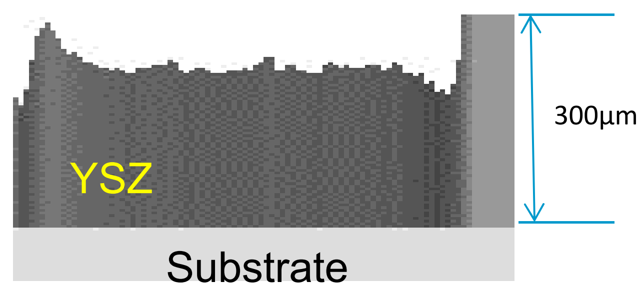


Thermal effusivity of YSZ in double-layer TBC is much lower that that in single-layer TBC?

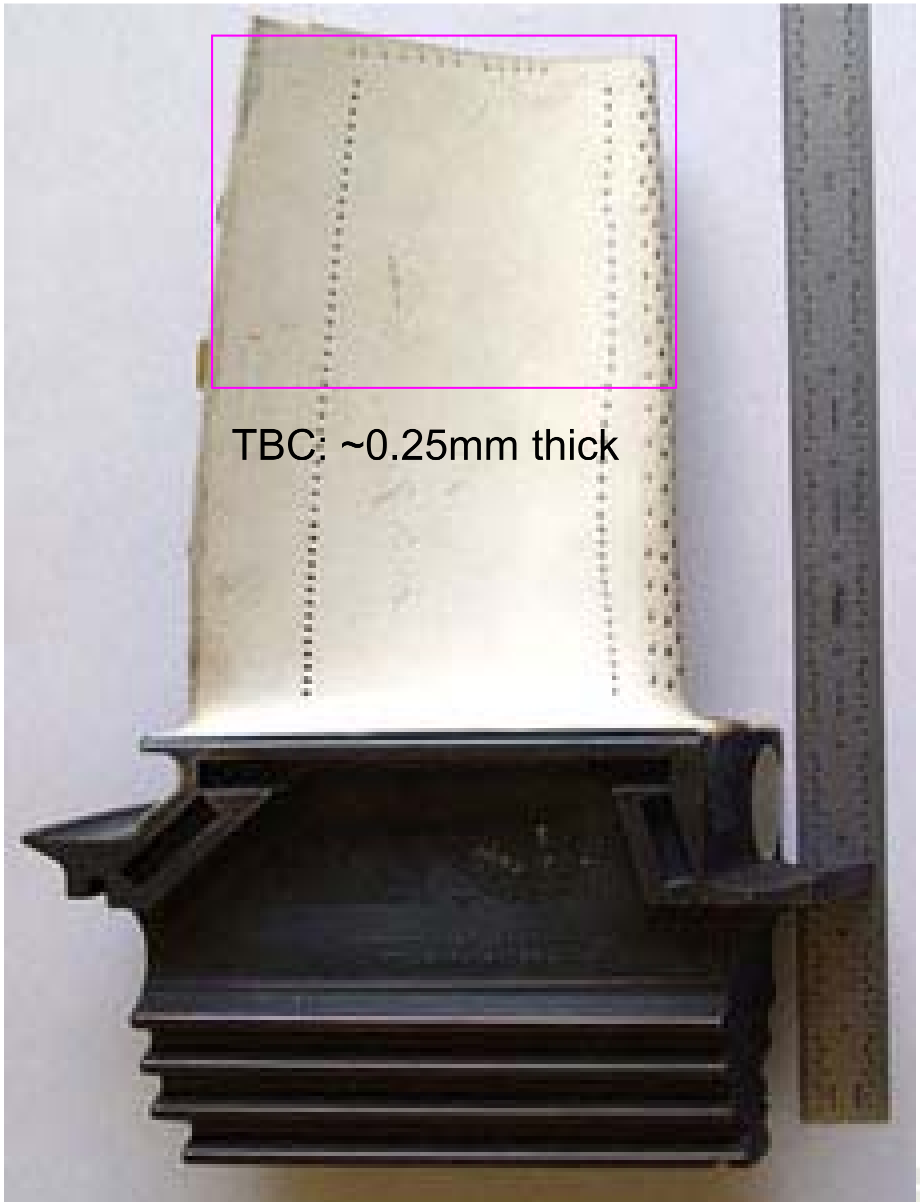
Single-layer TBC



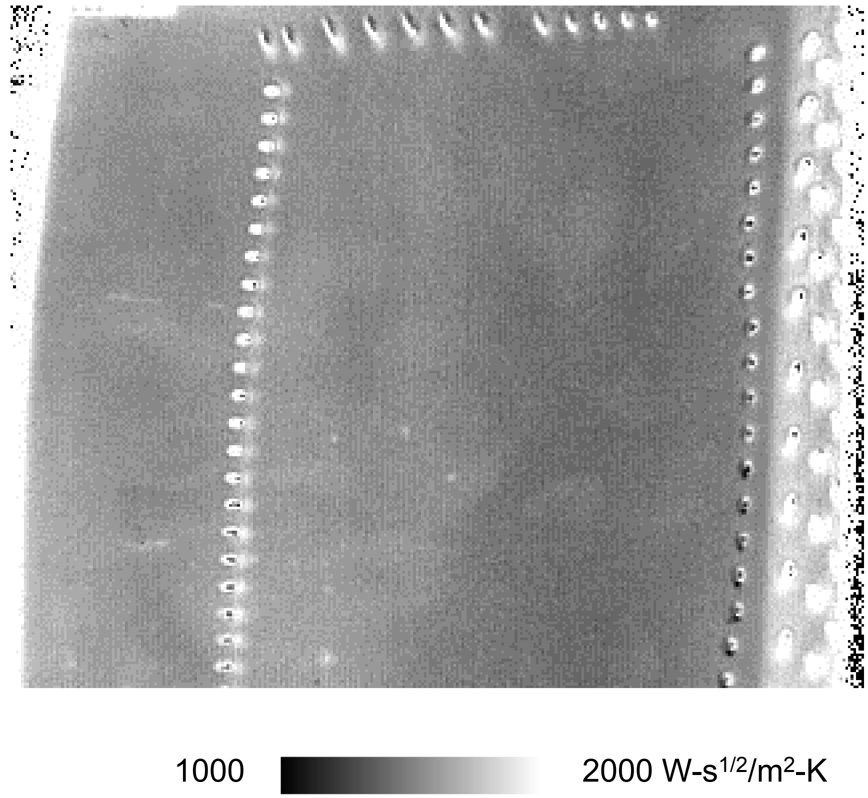




TBC Property Measurement for a Turbine Blade

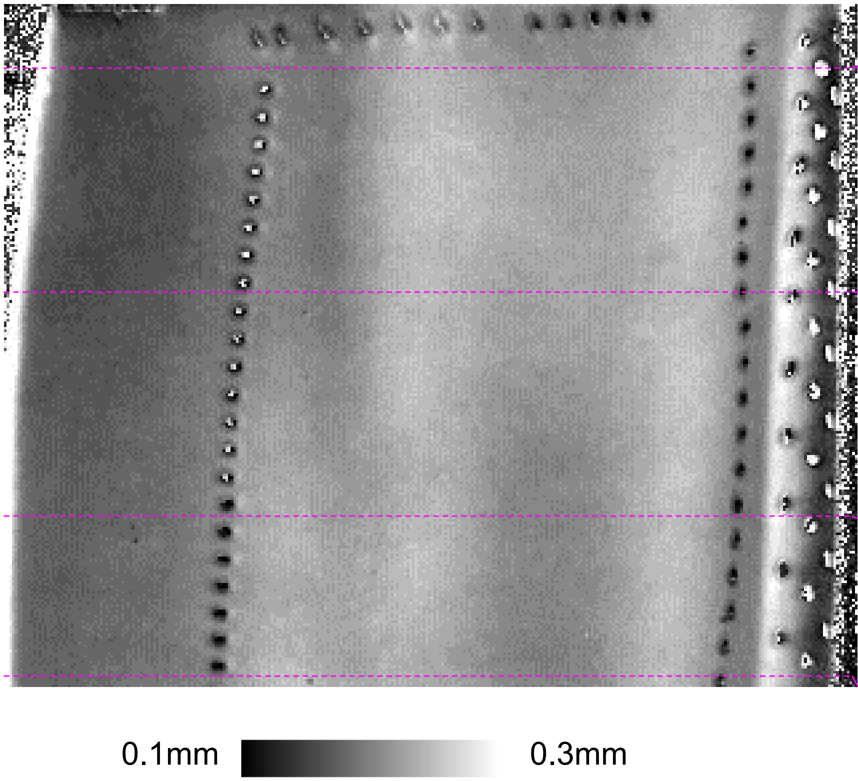


Thermal effusivity image

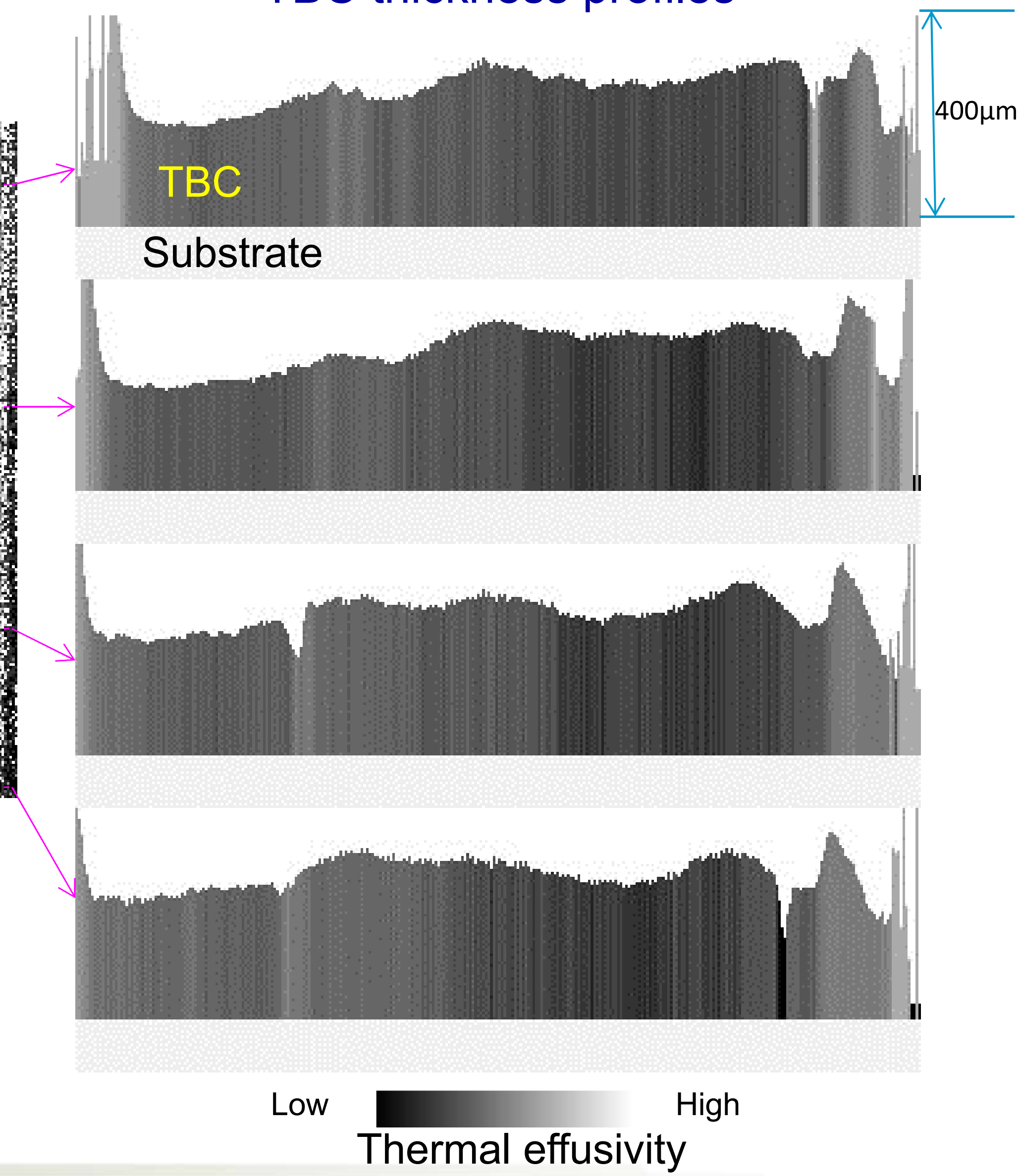


TBC Thickness Predictions

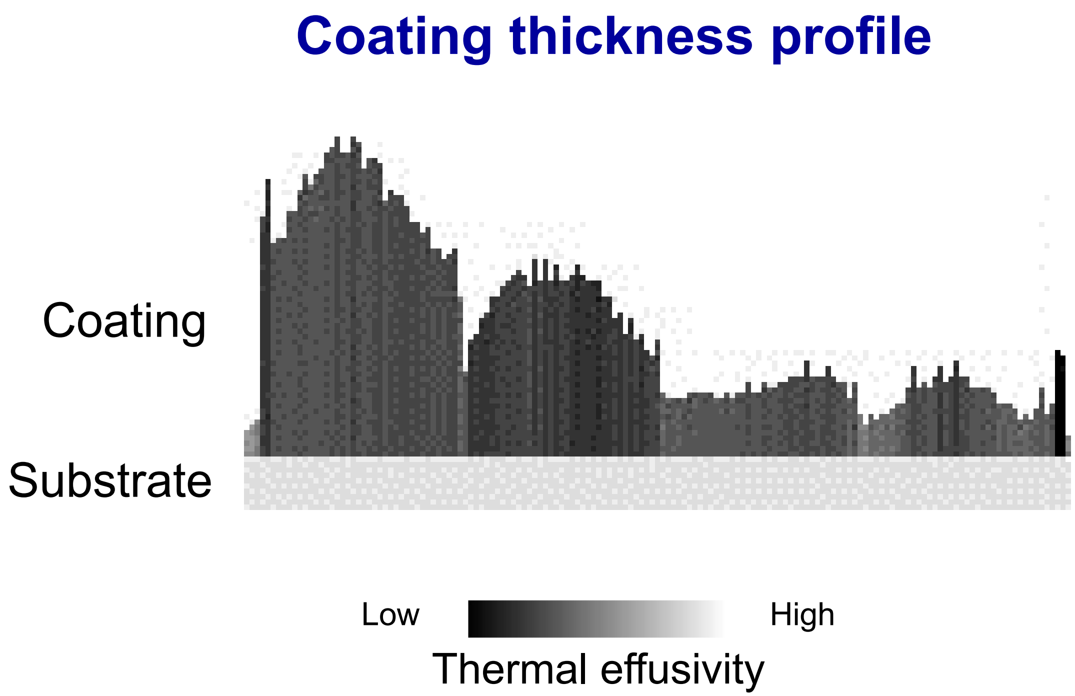
Thickness image



TBC thickness profiles



Metallic coating property/thickness prediction



Presentation Topics

- Development and application of multilayer analysis MLA method
  - Validation of MLA measurement accuracy
  - Effect of surface paint on TBC property measurement
  - Theoretical development for translucent TBCs
  - Theoretical development for double-layer TBCs
  - Application for a turbine blade

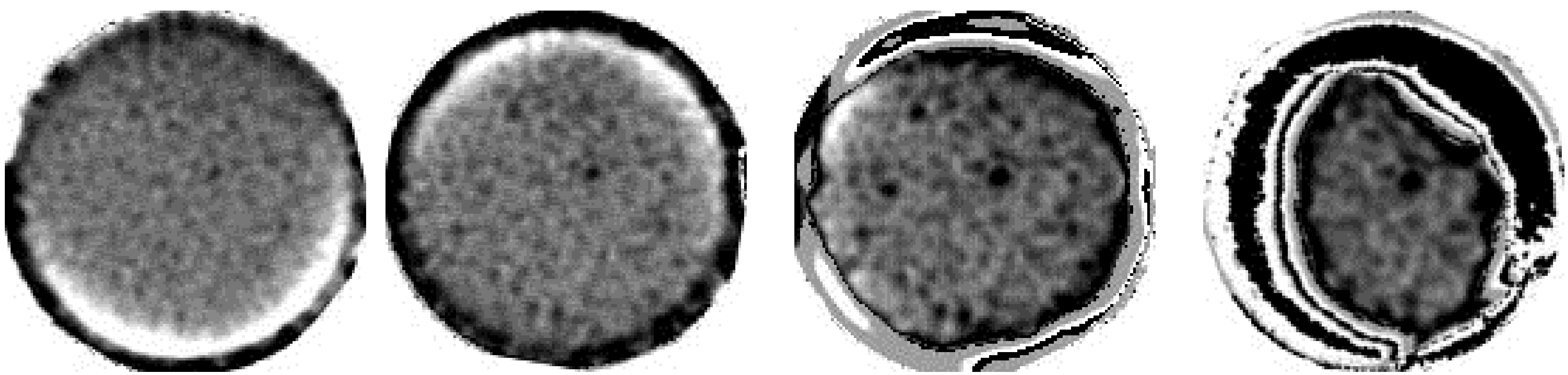
- NDE for TBC life prediction
  - Crack/delamination progression

Tests for APS TBC Sample (SB Univ.)

120hr 216hr 384hr 484hr

Exposed at 1100ºC

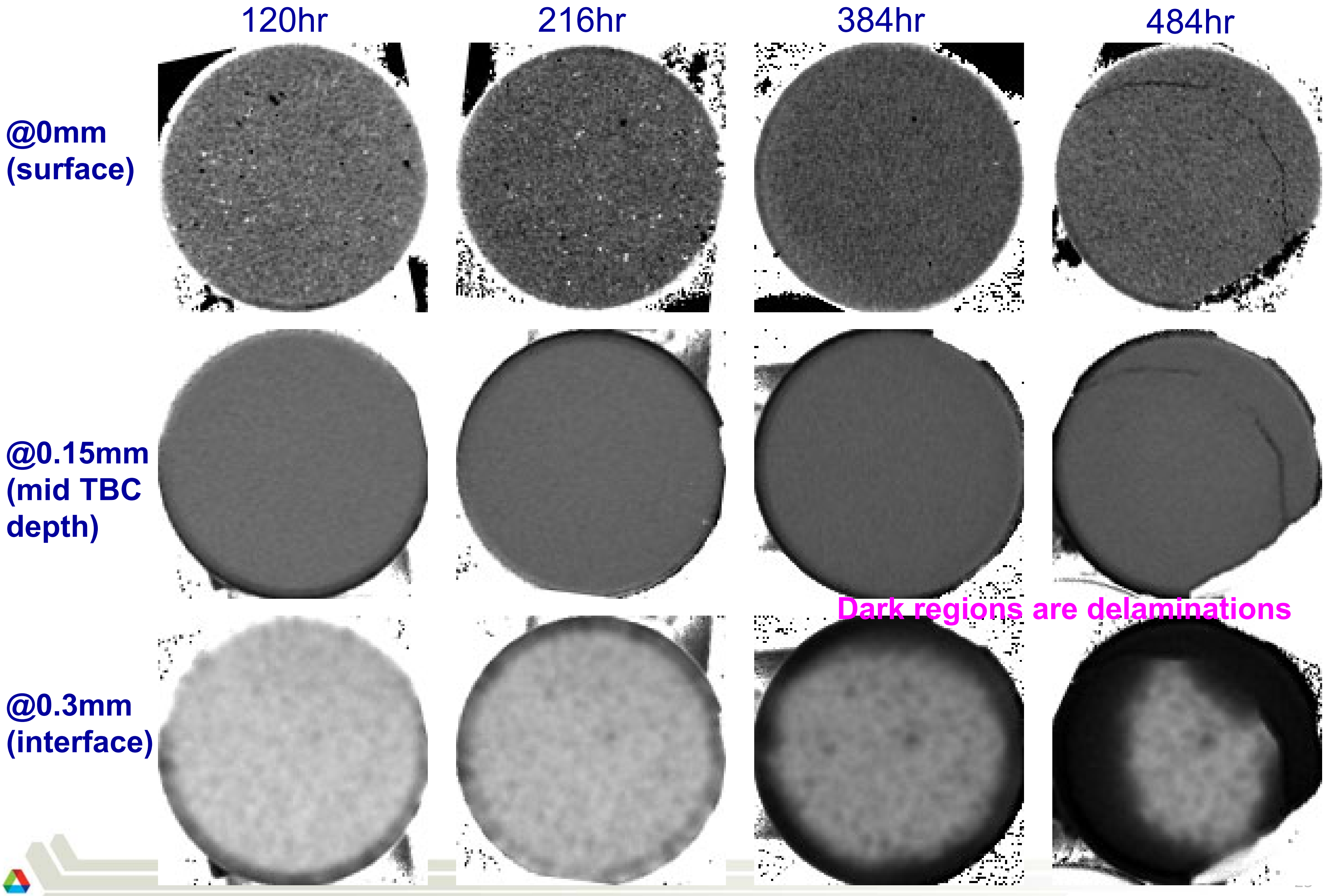
Measured thermal conductivity images



0.6W/m-K 1.2W/m-K

Delamination (low conductivity dark regions) development at edge and internal

Thermal Tomography Images



Summary

- Thermal imaging multilayer analysis (MLA) method development:
  - Absolute accuracy of 2% was demonstrated – MLA is ready for TBC studies
  - Developments for translucent and double-layer TBCs are successful
  - Successfully applied for testing of industrial components

- NDE for TBC life prediction:
  - Thermal tomography is successful for detect delamination growth

Planned Future Efforts

- Continued evaluation of NDEs for TBC lifetime prediction
  - Collaborations with Siemens and Stony Brook Univ.
- Thermal NDE method development for complex TBC systems:
  - For complex coatings: translucency, multilayer
  - Evaluation of measurement accuracy for TBC thermal conductivity, thickness, density/porosity
  - Improving crack/delamination resolution
- Tech transfer to industry