DEVELOPMENT OF NDE METHODS FOR CERAMIC COATINGS

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Outline

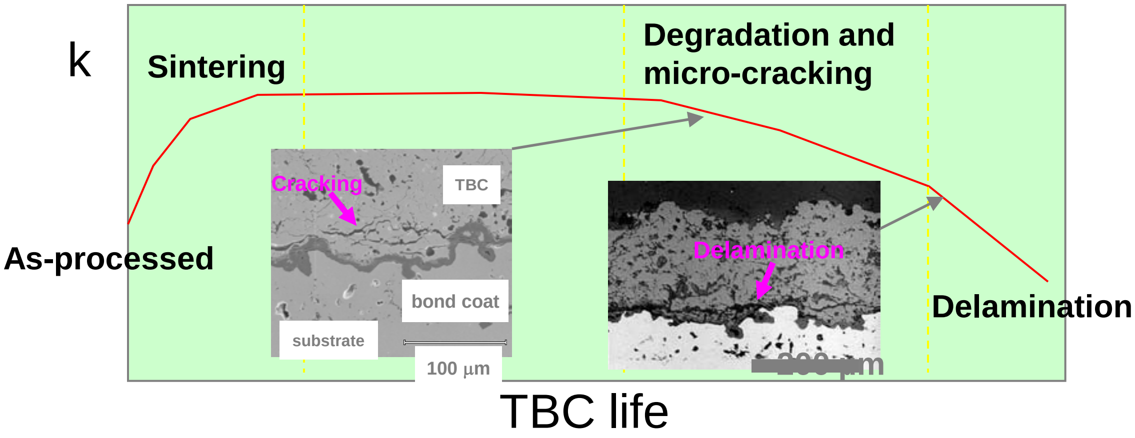
- Background
- Objectives
- Development of (2) thermal imaging methods for TBCs and other coatings
  - Theories
  - Performance
  - Results
- Summary
- Planned future efforts

Background

- Advance turbine systems with higher efficiency and low emission operate at high inlet temperatures that require the use of thermal barrier coatings (TBCs) on metallic engine components
- TBCs become "prime reliant" material – evaluation of their quality/condition and prediction of their life by NDE is important
- Current NDE methods are not suitable for quantitative TBC evaluation
  - Optical methods have some success (e.g., stress sensing), but only suitable for thin or EB-PVD TBCs that are semi-transparent, and susceptible to coating contaminations (in dirty fuels)
    - Development in optical NDE methods has dominated in last decade
  - Other methods (ultrasonic, eddy current, traditional thermal, etc) are not quantitative and generally with no or poor spatial resolution
  - Current methods are mostly used to detect large defects such as delaminations
- Quantitative NDE methods are required for TBC characterization
  - Accurate measurement of TBC properties
  - High-resolution detection of crack initiation and propagation
  - Applicable to more complex TBCs (duel-layer) or with property gradient

Quantitative Approach for TBC Life Prediction

- Based on NDE measurement of TBC conductivity k
  - TBC conductivity is the most important thermophysical parameter
    - Measured for all coatings
    - Used in component design
  - TBC conductivity evolution has characteristic features (many studies)
    - As-processed TBC: baseline conductivity
    - → TBC sintering: conductivity increase
    - → TBC degradation (internal cracking): conductivity decrease
    - → TBC delamination: significant conductivity drop
    - → TBC spallation (failure)
- This approach requires **<u>accurate</u>** measurement of TBC conductivity!



Objectives

- Development of advanced NDE methods for coatings
  - Multilayer thermal modeling method for quantitative measurement of TBC thermal properties including conductivity and heat capacity
    - For ceramic as well as metallic coatings with various thickness
  - Thermal tomography method for high-resolution imaging of internal structures and detection of small cracks and delaminations
    - For ceramic as well as metallic coatings with various thickness
  - Optical methods: laser backscatter, mid-IR reflectance, OCT, confocal
    - For thin APS TBCs and EB-PVD TBCs

- Development of NDE methods for functional materials
  - Synchrotron x-ray microCT for microstructural imaging of membranes
  - Thermal tomography for imaging component internal structure

Milestones

- Evaluation of NDE technologies for TBCs (12-15-09)
  - Optical methods, mid-IR back reflection, OCT, and laser backscatter, are most suitable for thin APS TBCs (<200-300μm) and EB-PVD TBCs
    - Confocal microscopy does not work well due to refractive index mismatch
  - Effort was focused on development of thermal imaging methods that are applicable to all TBCs (also metallic coatings)

- Evaluation of thermal and x-ray imaging for functional materials such as membranes (6-15-10)
  - Development of thermal tomography method

- Thermal imaging NDE tests to assess potential for prediction of TBC degradation and lifetime (9-30-10)
  - Some samples were obtained and will be tested

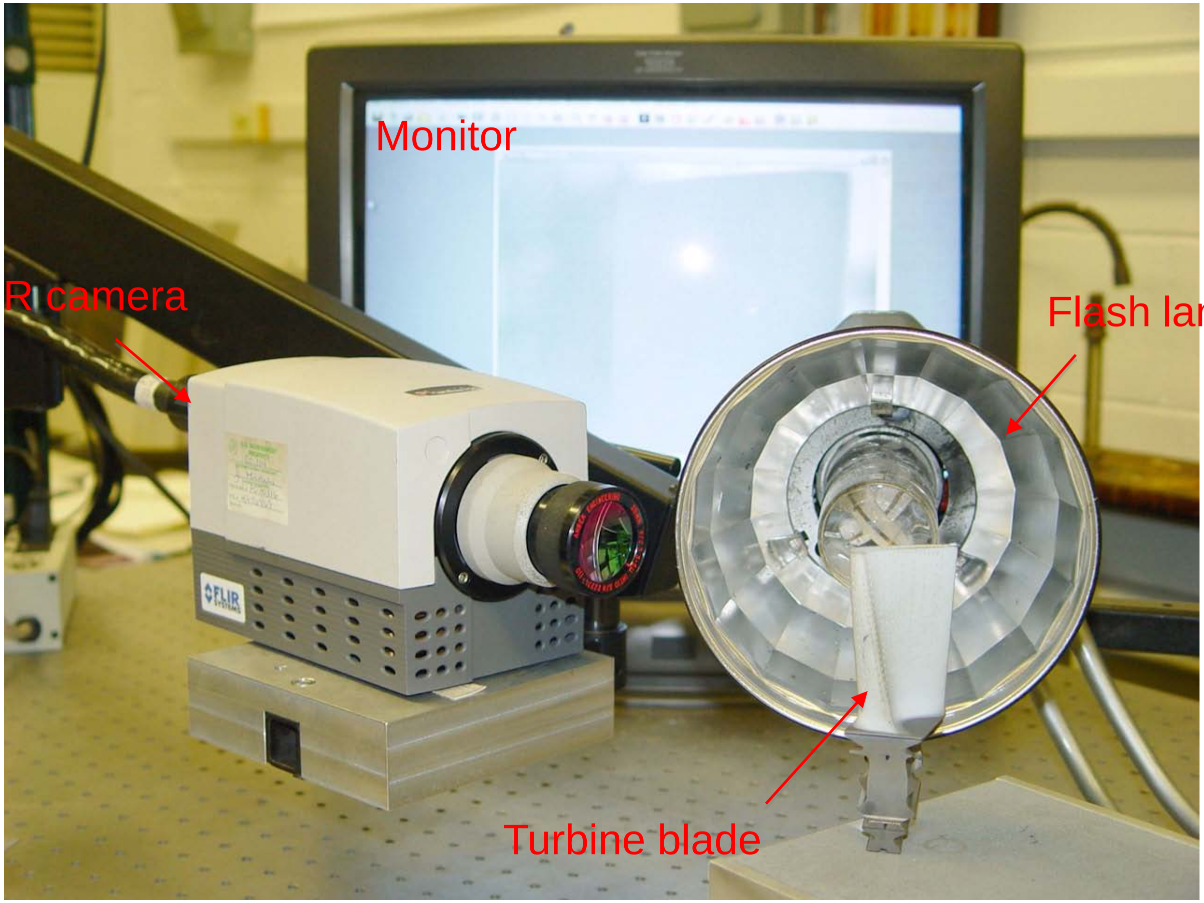
NDE Development for TBCs

- NDE development at ANL is focused on thermal imaging methods
  - For quantitative TBC analysis (e.g., thermal properties, flaw size/depth)
  - Applicable to all TBCs and other coatings (e.g., metallic coatings)

- (1) Multilayer thermal modeling method (2D imaging):
  - TBC thermal conductivity and thickness distribution
    - **Accuracy** is most important!
    - TBC conductivity is measured mostly by laser flash method which is a two-sided thermal method and not suitable for NDE of real component
  - TBC cracking and delamination

- (2) Thermal tomography method:
  - 3D imaging of TBC structure and property distribution
  - Determination of TBC thickness and damage size/depth

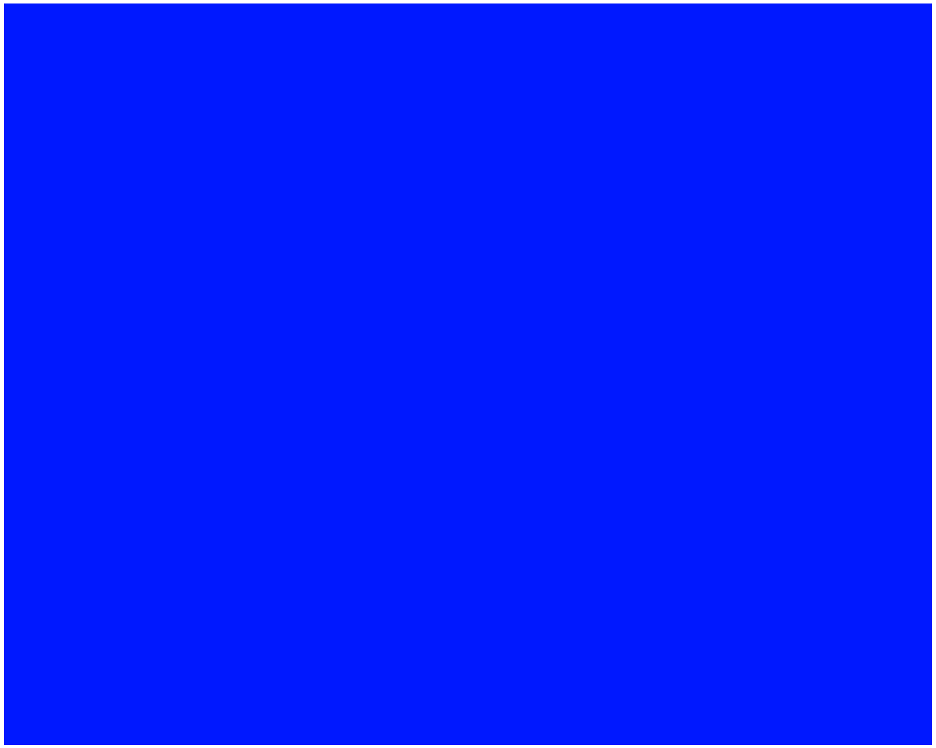
One-Sided Flash Thermal Imaging Setup for Testing TBC-Coated Turbine Blade



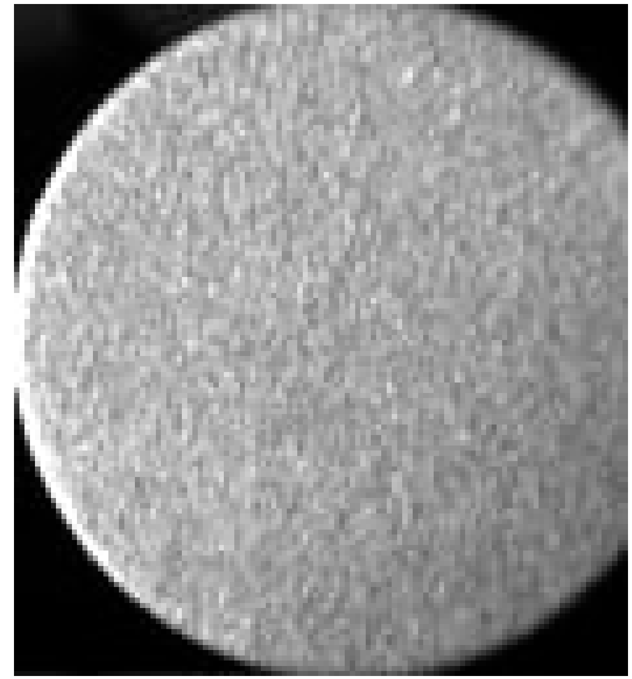
- Image entire surface (100% inspection)
- Fast (a few seconds for testing, up to a few minutes for data processing)
- Data processing is completely automated (no operator adjustment)

Typical Raw Thermal Imaging Data

Flash lamp
at left side



A typical image

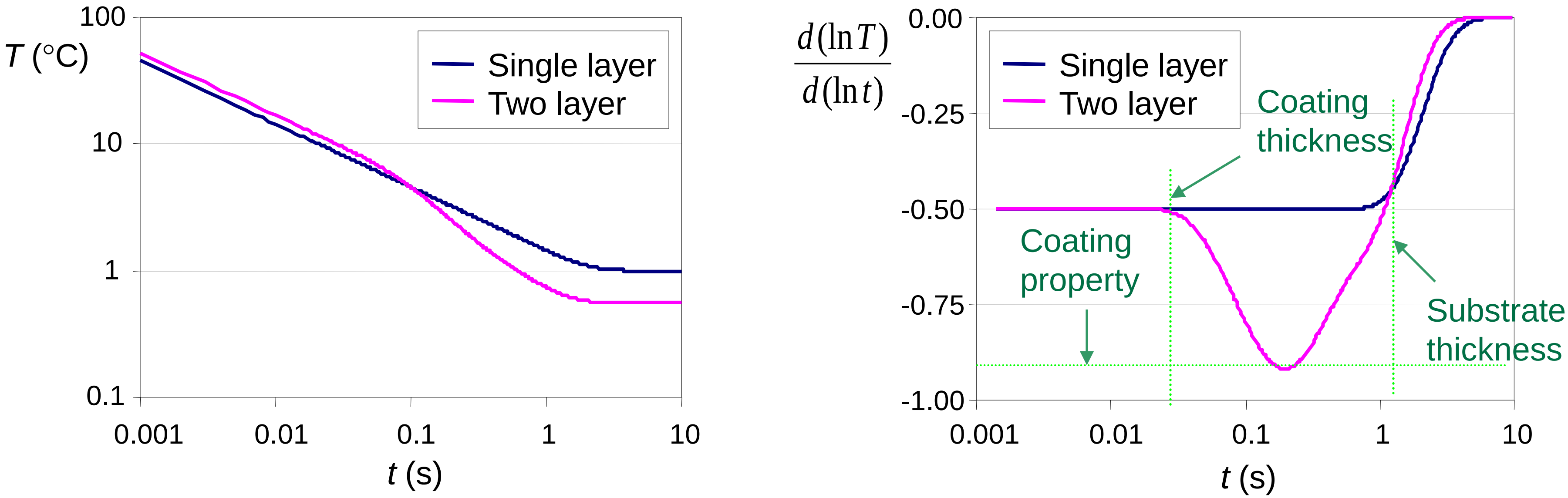


Low temperature  High temperature

- Total time period is ~0.1 s
- APS TBC of 1” diameter

Characteristics of Thermal Imaging Data (1- and 2-layer materials)

Typical surface temperature and its slope at a single pixel

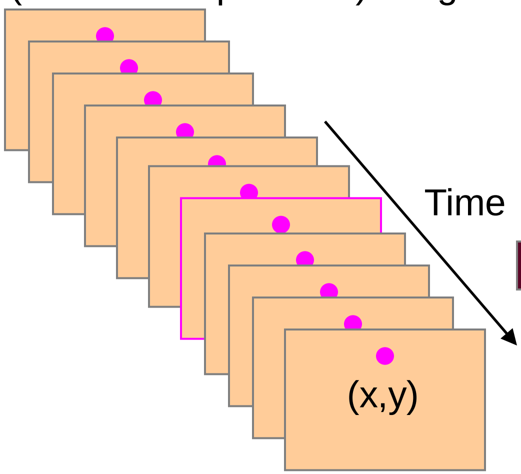


- Thermal imaging data, i.e., surface temperature and its slope at each surface pixel, are significantly different for 1- and 2-layer materials
- Same data can be used to:
  - Predict thermal properties of coating (and substrate thickness)
  - Construct 3D (tomography) images of the material system

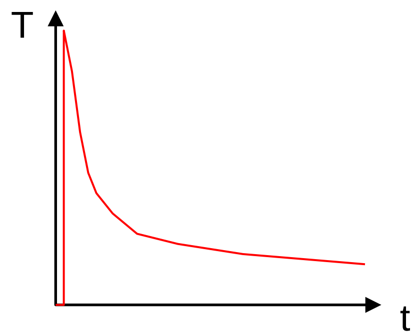
Multilayer Thermal Modeling Method

Measured data T(x,y,t):

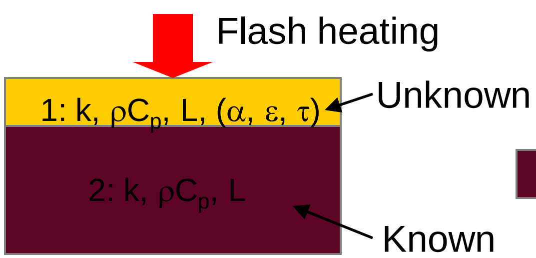
Time series of 2D thermal (surface temperature) images



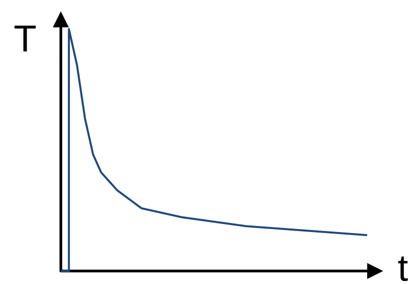
Surface temperature variation at pixel (x,y)



Multilayer TBC model



Numerical solution of surface temperature variation



- Fitting numerical result with exp. data to derive correct TBC parameters:

  Coating 1:
  k, (ρC_p,) L, (α, ε, τ)

  Substrate 2:
  fixed properties

- Repeat this process for every pixel

Prediction for TBC Thermal Properties

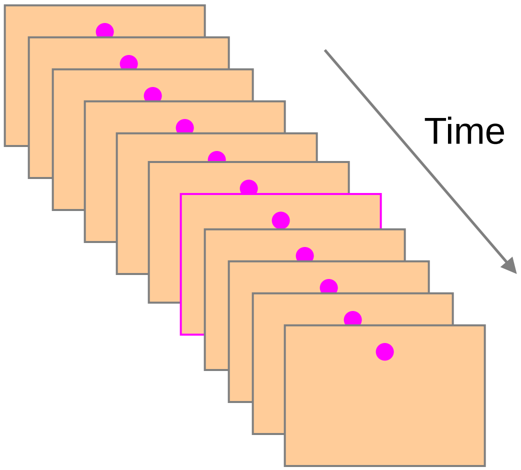
- Multilayer thermal modeling can determine two coating parameters:
  - Thermal effusivity: $e = (\rho C_p k)^{1/2}$
  - Parameter: $\eta = L/\alpha^{1/2}$ where α is thermal diffusivity

- TBC thermal properties are determined when thickness L is know:
  - Thermal conductivity: $k = Le/\eta$
  - Heat capacity: $\rho C_p = e\eta/L$

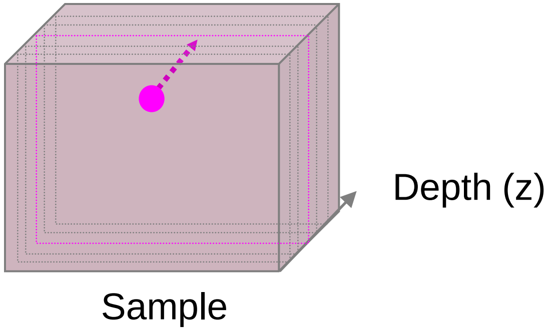
- Significant advantage: k and ρC_p are determined together
  - Note: laser flash can only determine parameter η
  - Measurement of coating density ρ and specific heat C_p is not trivial!

Thermal Tomography Method

Measured data T(x,y,t):
Time series of thermal (surface temperature) images



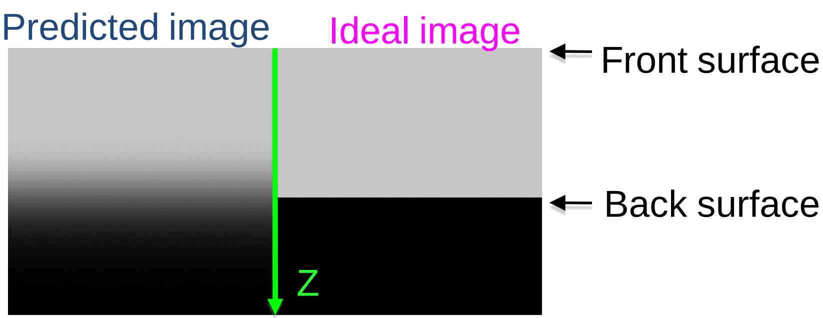
Tomography results e(x,y,z):
3D spatial distribution of a material property within the sample

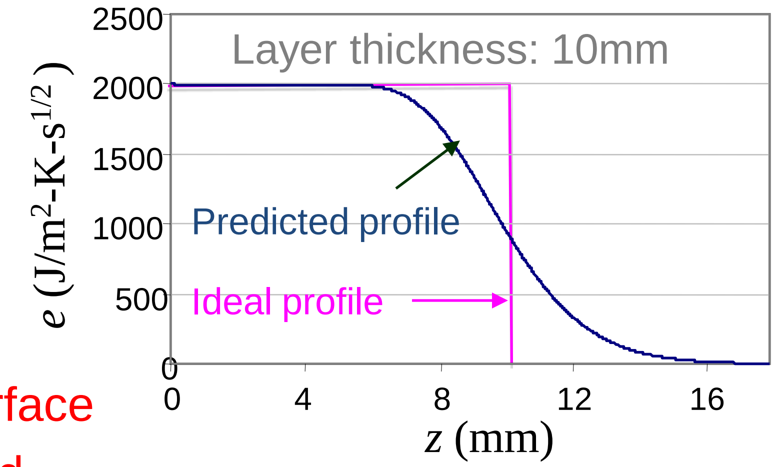


- Thermal effusivity tomography:
  - Convert measured thermal-imaging data T(x,y,t) into 3D material thermal-effusivity distribution e(x,y,z) [$e = (\rho C_p k)^{1/2}$]
  - e(x,y,z) can be sliced in any planes (similar to x-ray CT slices)
  - Thermal effusivity is significantly different between coating, substrate, and flaws
  - **Does not require prior knowledge of sample property for analysis**

Performance of Thermal Tomography Method

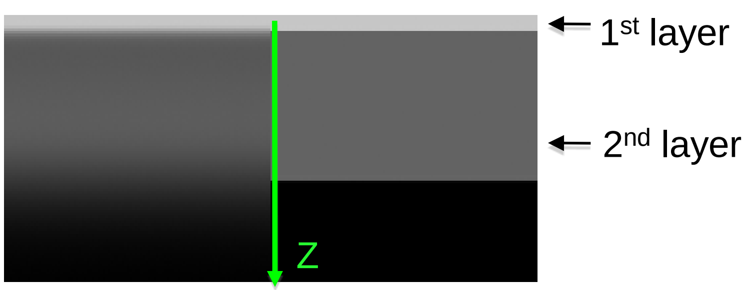
Single-layer material; effusivity profiles along depth (cross-section)

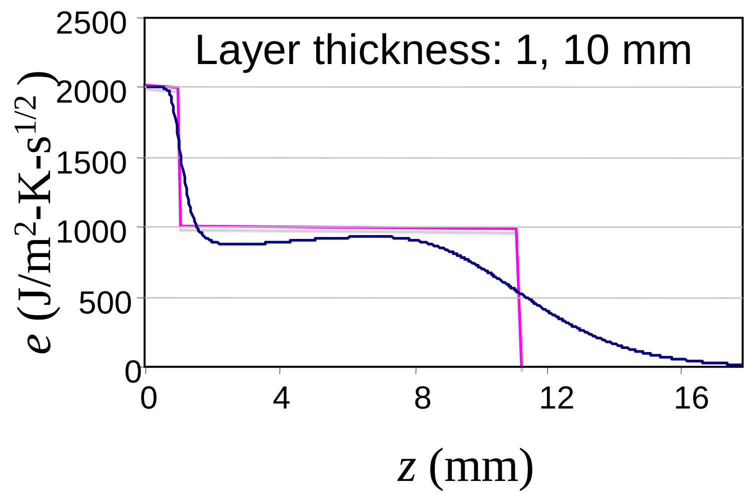




- Some resolution degradation at back surface
- Total effusivity conservation is maintained

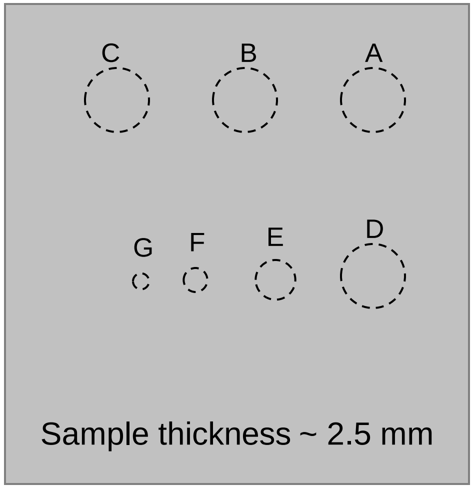
Two-layer material:





Thermal Tomography Imaging of a CMC Plate

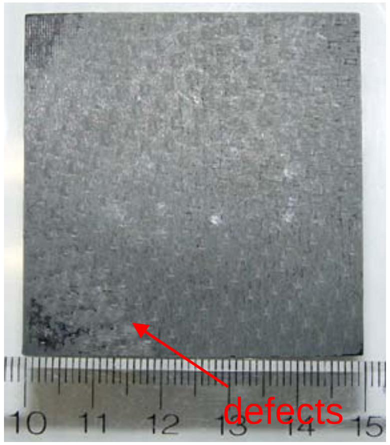
Sample diagram



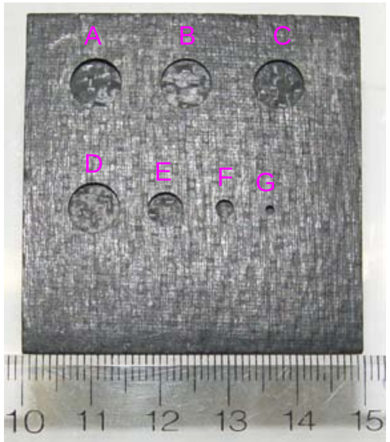
Hole	Diameter (mm)	Depth (mm)
A	7.5	0.25
B	7.5	1.12
C	7.5	0.97
D	7.5	0.87
E	5.0	0.78
F	2.5	0.85
G	1.0	0.85

Depth is measured from front surface to the bottom surface of the machined holes from back surface

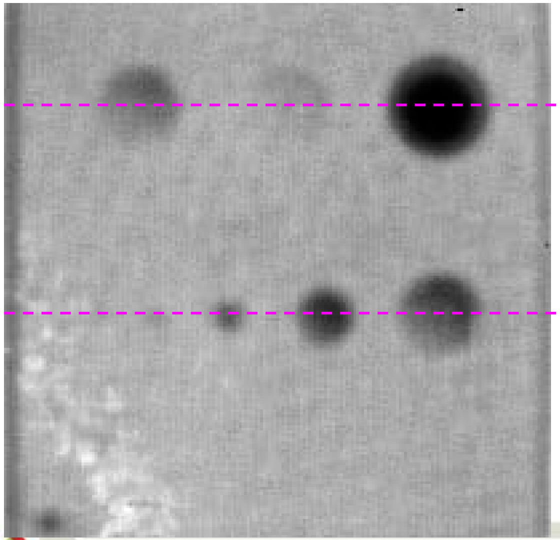
Front surface



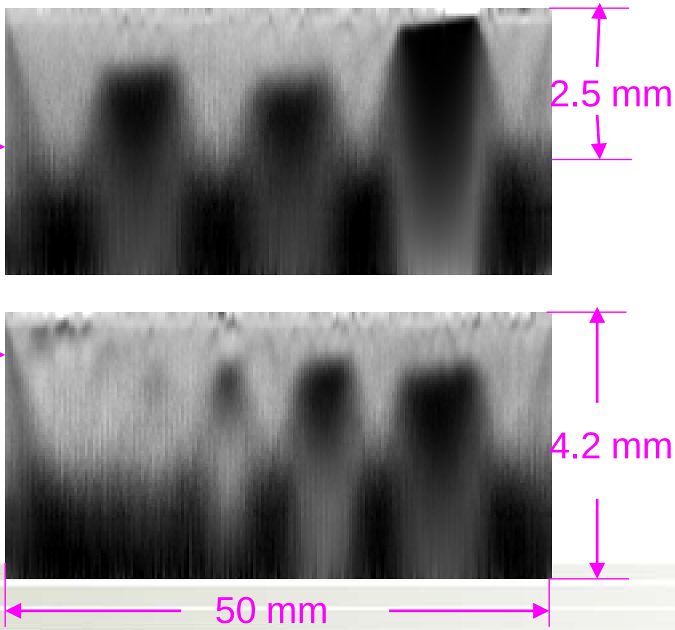
Back surface



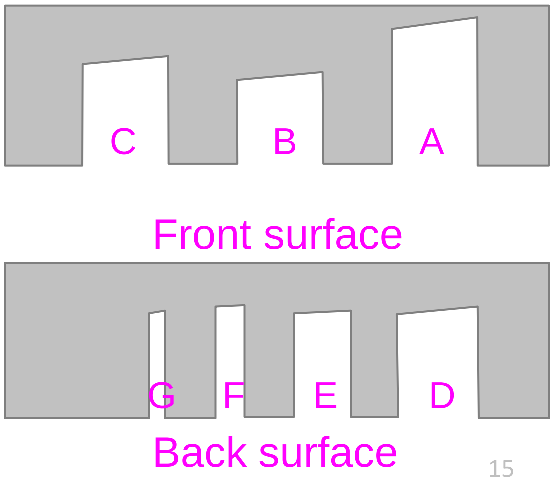
Plane image at 0.86 mm depth



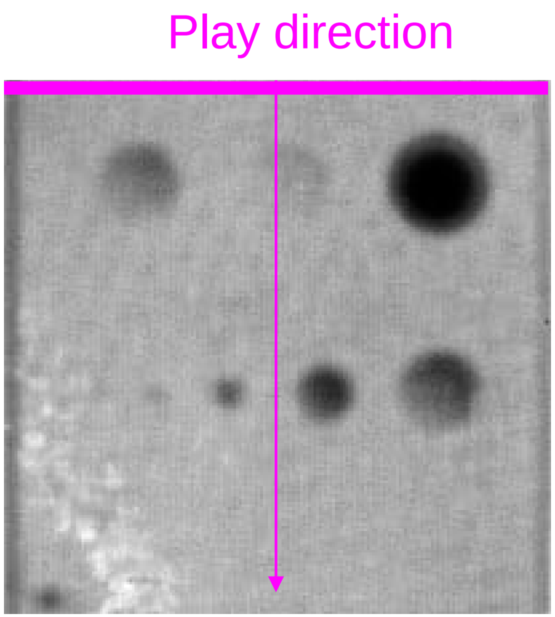
Cross-Sectional Images

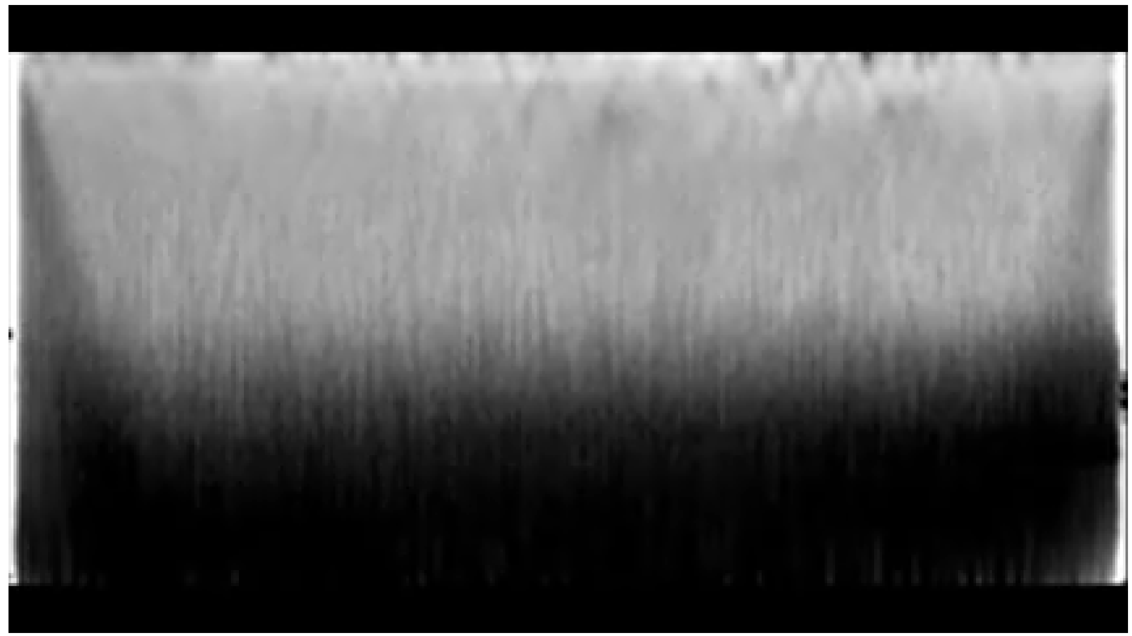


Sample Cross Sections (not in scale)



Cross-Sectional Video of Entire Plate





- Many small defects (with low/”high” effusivity) in effusivity images
- High spatial resolution; but it decreases with depth

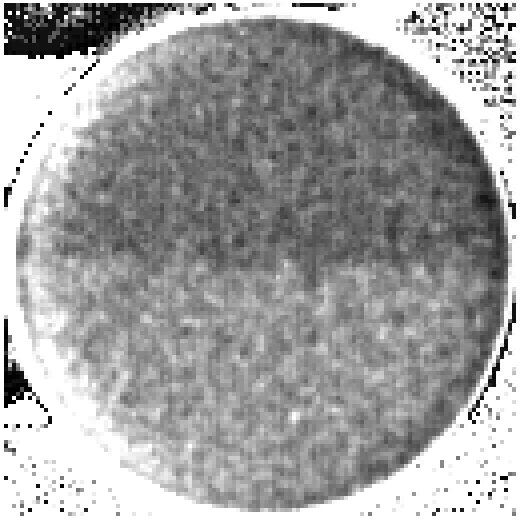
Recent Thermal Imaging NDE Development for TBCs

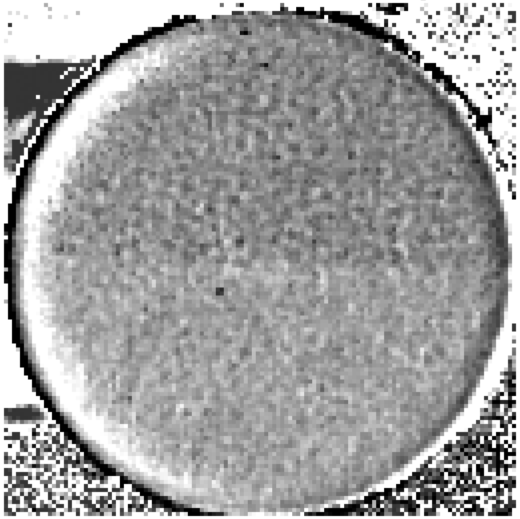
- 2D multilayer thermal modeling method
  - Two issues identified last year were resolved:
    - (1) use of black paint on thin coatings (<300μm thickness)
    - (2) prediction accuracy was improved by use of a reference
  - Calibration tests were conducted for a set of EB-PVD TBCs and still underway for both APS and EBPVD TBCs

- 3D Thermal tomography method
  - Analysis of TBCs, alumina and metallic coatings (thin and thick)
  - Data-processing software was further improved
  - A new theory with improved depth-resolution was developed (a U.S. patent is being filed)

Paint Assessment Result (0.15mm APS TBC)

Thermal conductivity k | **Heat capacity ρC_p**





0.5 W/m-K — 1.2 W/m-K

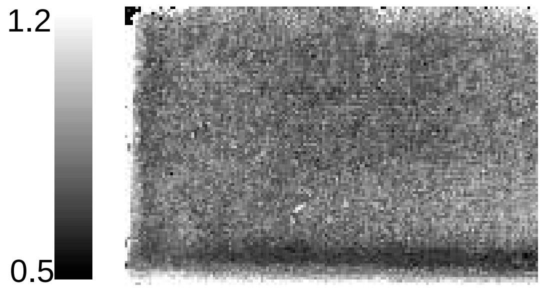
2 J/cm³-K — 4 J/cm³-K

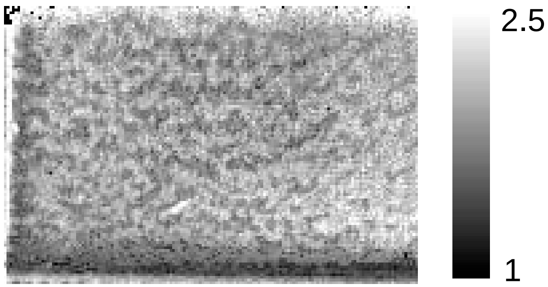
- Average thermal properties:
  - Paint #1: k = 0.925 W/m-K, ρC_p = 3.272J/cm^3-K
  - Paint #2: k = 0.803 W/m-K, ρC_p = 3.057J/cm^3-K
- Paint #2 produces better thermal property data
  - Data difference between the paints is ~10%!
  - This only affects thin coatings (<300µm thick)

Multilayer Modeling Predicted TBC Properties

TBC conductivity k (W/m-K) TBC heat capacity ρC_p (J/cm^3-K)

Average k = 0.93 W/m-K (1.0±0.2 typical)



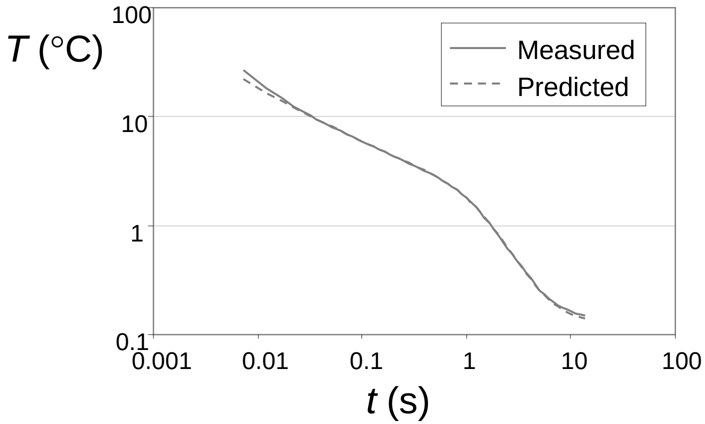


Average ρC_p = 2.19 J/cm^3-K (2.0 typical)

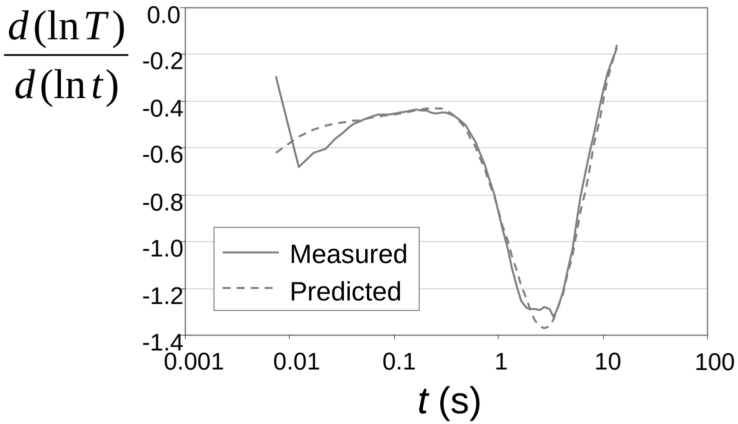
- APS TBC thickness = 0.86 mm, substrate thickness = 9.5 mm
- Sample curtsey of Dr. Y. Tan of Stony Brook Univ.

Typical fitting data at each pixel

Temperature vs. time



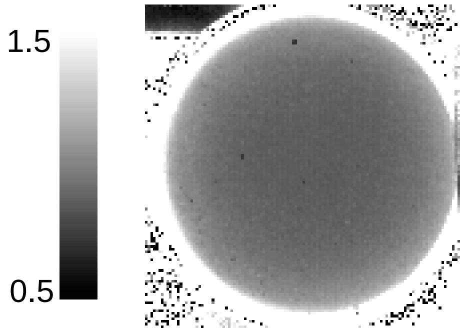
Temperature slope vs. time



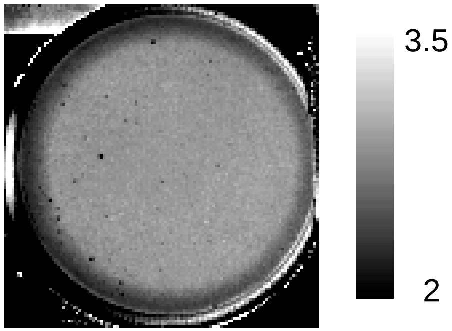
Predicted Thermal Properties for Thin EB-PVD TBC

TBC conductivity k (W/m-K)

Average k = 0.87 W/m-K



TBC heat capacity ρC_p (J/cm^3-K)

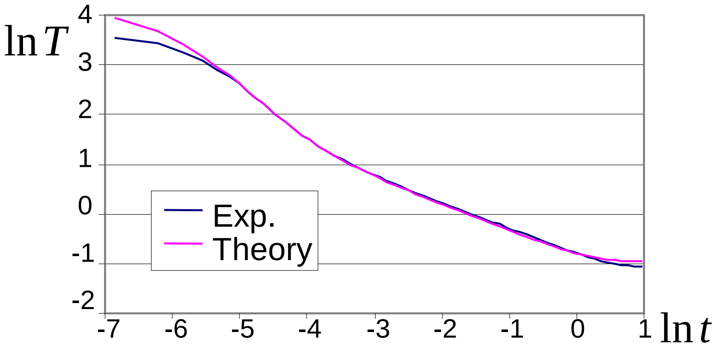


Average ρC_p = 2.90 J/cm^3-K

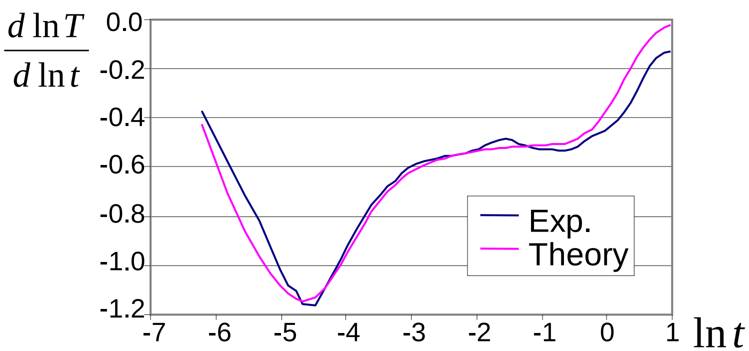
- TBC coating thickness L = 50µm, substrate thickness = 3.1 mm
- Sample curtsey of Dr. A.M. Limarga and Dr. D. Clark of Harvard Univ.

Typical fitting data at each pixel

Temperature vs. time



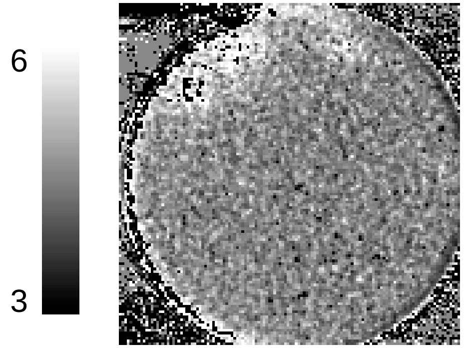
Temperature slope vs. time

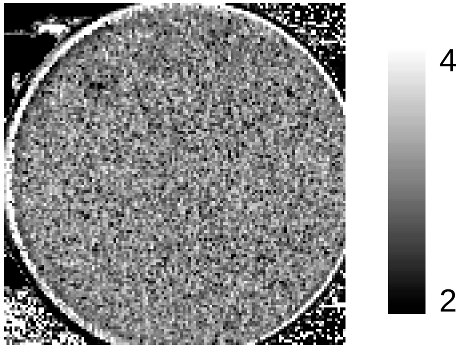


Predicted thermal properties for thin metallic bond coat on Rene80 substrate

BC conductivity k (W/m-K) **BC heat capacity ρC_p (J/cm^3-K)**

Average k = 4.51 W/m-K



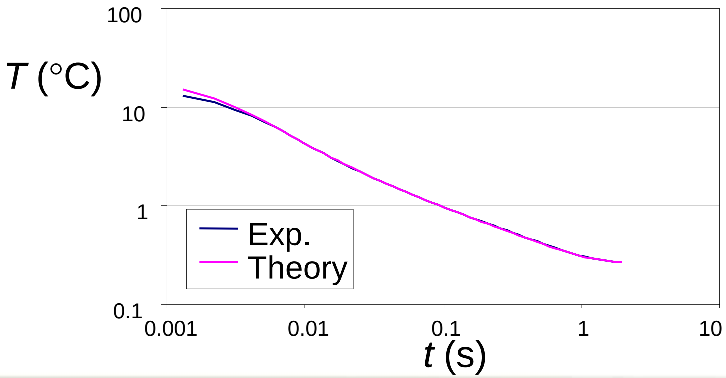


Average ρC_p = 3.03 J/cm^3-K

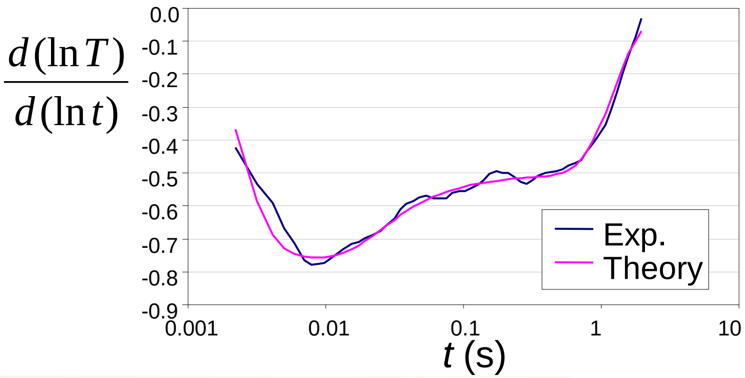
- Bond coat thickness ~125µm; image noise due to surface roughness
- Sample curtsey of Dr. A. Kulkarni of Siemens

Typical fitting data at each pixel

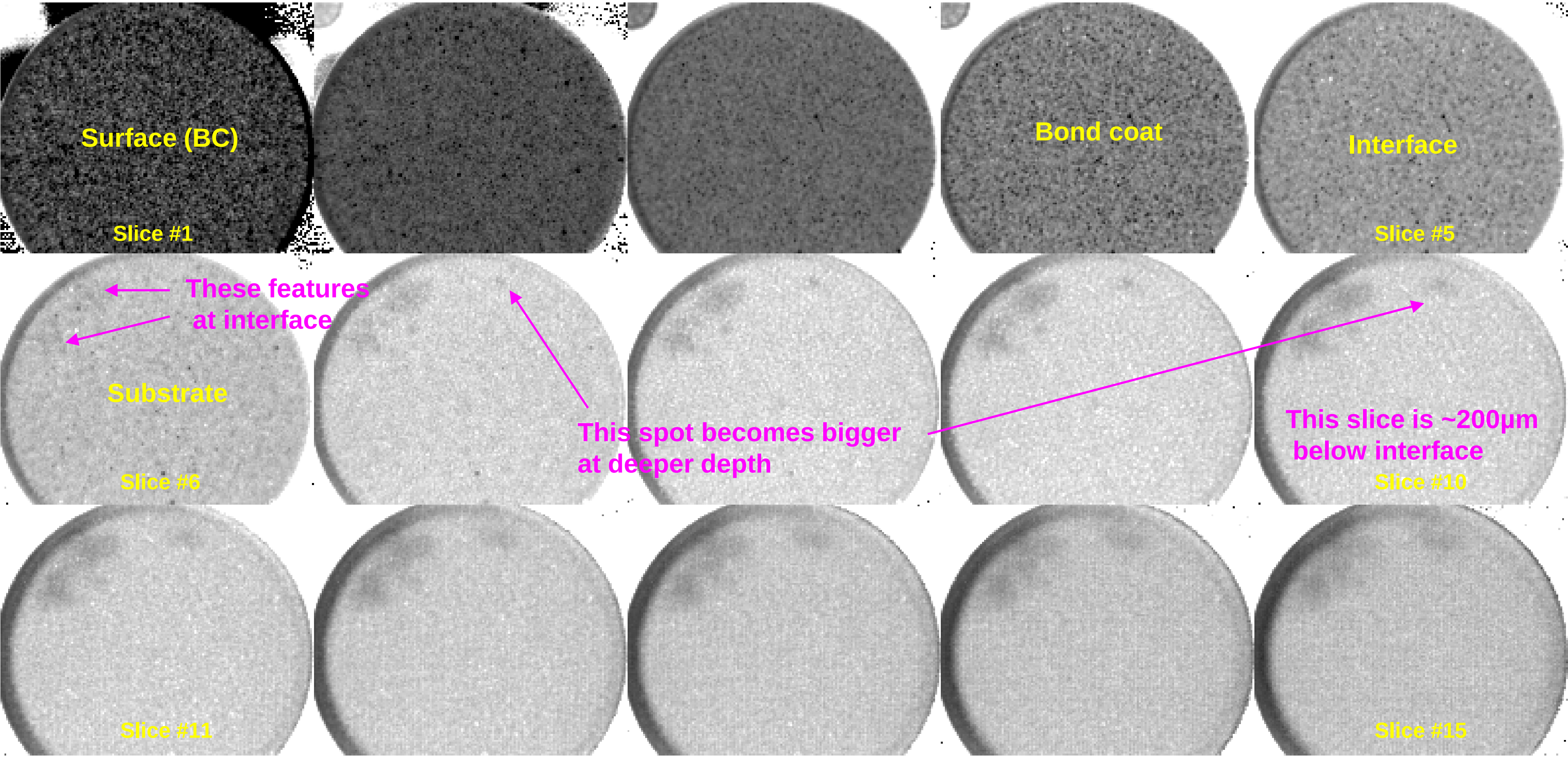
Temperature vs. time



Temperature slope vs. time



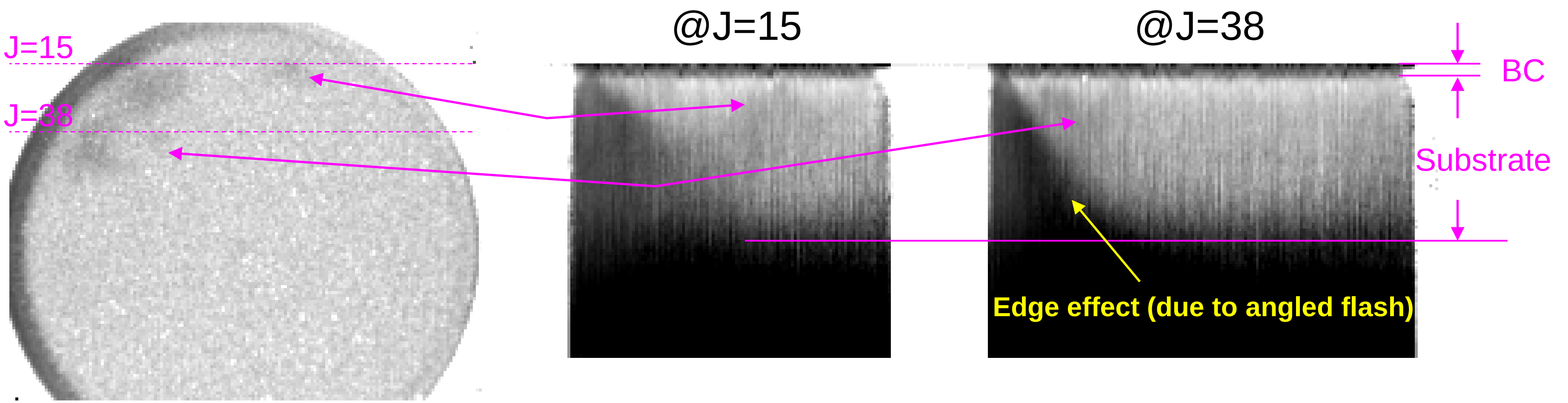
Thermal tomography plane slice images of thin metallic bond coat on Rene80 substrate



- Each bond coat slice ~28µm thick; each substrate slice ~55µm thick

Thermal tomography cross-section slice images of thin metallic bond coat on Rene80 substrate

Location of cross-sections

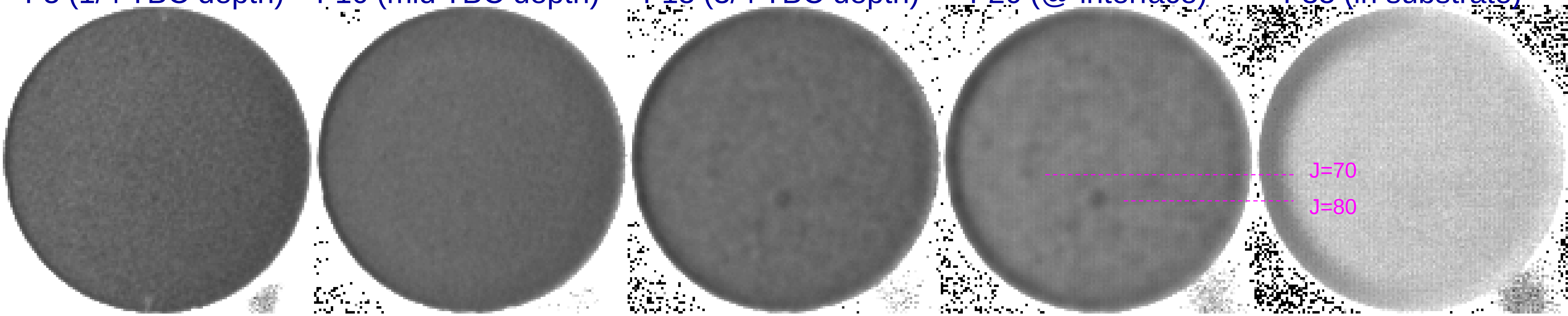


- Bond coat thickness is assumed at 125µm with total of 4.5 slices, so each slice thickness is 28µm
- Substrate thickness is assumed 3.1mm with total of 56.5 slices, so each substrate slice is 55µm thick

Thermal tomography images of a 1”-dia. TBC sample (APS TBC, 14mil thick)

Plane slice images

F5 (1/4 TBC depth) F10 (mid TBC depth) F15 (3/4 TBC depth) F20 (@ interface) F35 (in substrate)

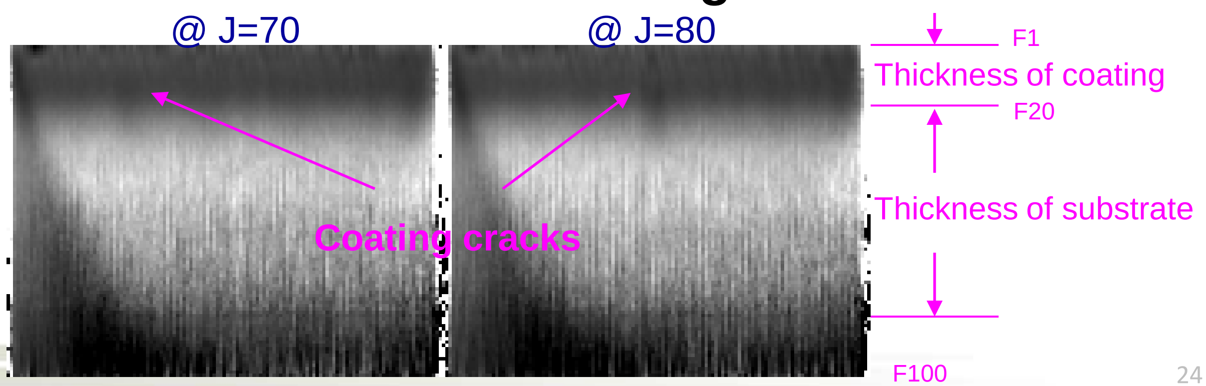


- Each coating slice is ~18µm thick, each substrate slice is ~43µm (scaled by diffusivity)
- Many small cracks (<1mm in size) were detected within TBC (@ half TBC thickness)
- Sample curtsey of Dr. D. Zhu of NASA – NASA is now conducting destructive verification!

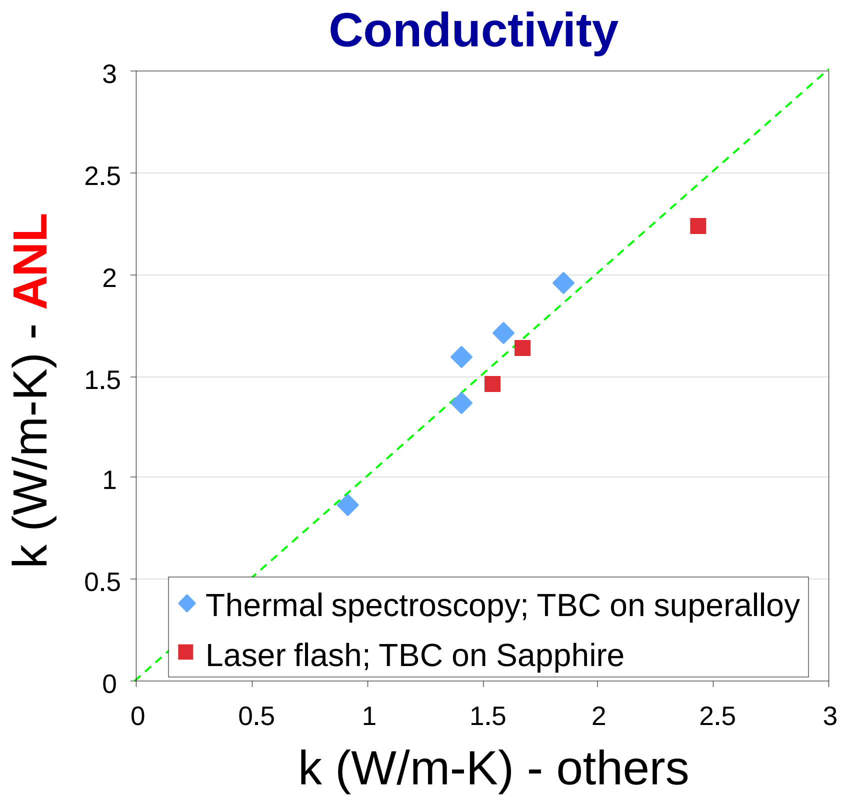
Thermal gradient test:
- 10-30min cycles
- surface @ 1500°C
- interface @1220°C

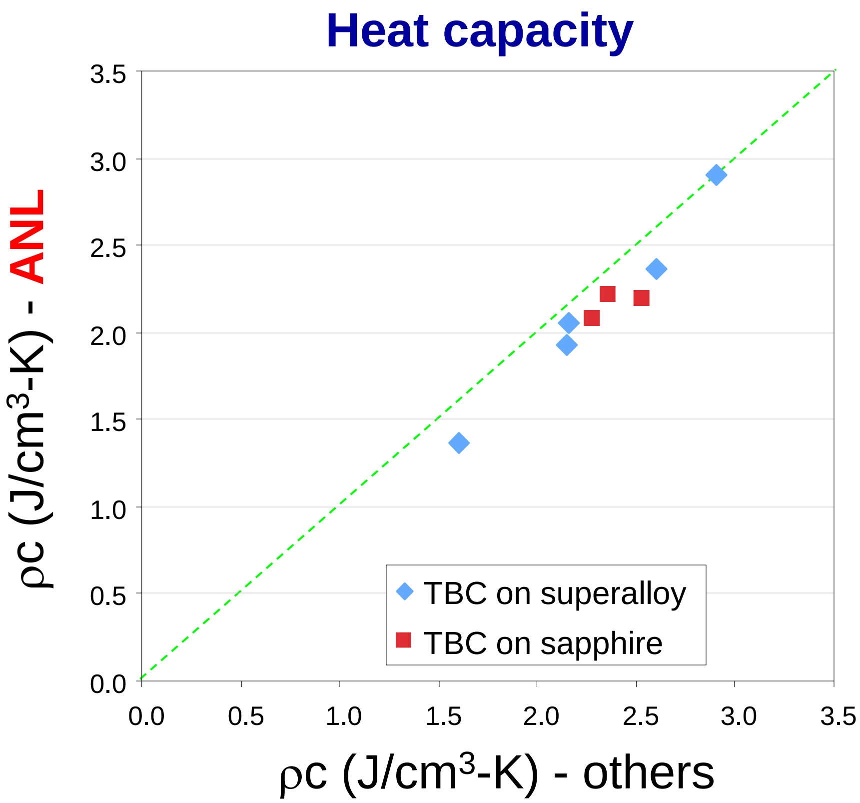
(micro-delaminations)

Cross-section slice images



Comparison of measured TBC thermal properties from thermal imaging at ANL and other methods





- All EB-PVD TBCs, thickness from 50 to 175 µm
- Accuracy typically within 10%!
- Samples from Dr. A.M. Limarga and Dr. D. Clark of Harvard Univ.

Accuracy for TBC Property Predictions

- Current measurement data are repeatable and accurate
  - Repeatability is typically <2%
  - Measured data are <10% compared with those by other methods (for EB-PVD TBCs)

- Measurement accuracy could be affected by
  - Secondary effects such as surface roughness, flash duration, black paint, system setup, etc;
  - Note: data from other methods may not be accurate (e.g., accuracy of laser flash method is normally considered within 10%)

Summary

- Multilayer modeling method was developed for quantitative measurement and imaging of TBC thermal properties
  - Predicted thermal properties are repeatable and accurate
    - Repeatability is typically <2%
    - Measured data are <10% compared with those by other methods (for EB-PVD TBCs)
    - Measured data for metallic coatings were also accurate (data not shown here)
    - Additional calibration with APS TBCs are planned
  - "All" thermal properties of a coating are measured in one test
    - Laser flash, e.g., needs to measure coating density and heat capacity, both measurements are not trivial
  - Capable to predict evolution of TBC conductivity for entire TBC life cycle
    - TBC samples are required (some obtained)
- Thermal tomography method was improved for 3D structural imaging
  - Destructive verification for detected small-cracks is being conducted (NASA)
  - A new theory with improved depth resolution was developed
- Collaborations were established with industry and academia for technology development and potential technology transfer
  - Siemens, Praxair, Rolls Royce, SUNY, NASA, UCSB, etc

Planned Future Efforts

- Development of thermal modeling method
  - Continue calibration of predicted TBC properties
    - For APS TBCs as well as EB-PVD TBCs
    - Apply to wider TBC parameter range: thin/thick, graded/layered, etc
  - Investigate secondary effects that affect prediction accuracy
    - Surface roughness, heat loss, flash duration, black paint, system setup, etc
  - Develop method to determine thermal properties of dual-layer coatings and coating conductivity gradient with depth (due to thermal exposure)
  - Develop models to account for coating transparency (so as-sprayed coating can be directly imaged)
- Development of thermal tomography method
  - Correlate NDE data with destructive examination results
  - Implement and validate the new high-resolution algorithm for data processing
- Validation of NDE model for TBC lifetime prediction
  - In collaboration with partners, perform TBC life-cycle tests and correlate NDE data with TBC life
- Correlation between different NDE methods
  - Work with collaborators who are developing other methods