DEVELOPMENT OF NONDESTRUCTIVE EVALUATION METHODS FOR THERMAL BARRIER COATINGS

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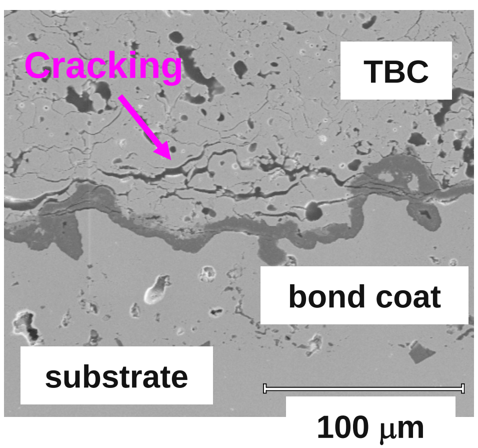
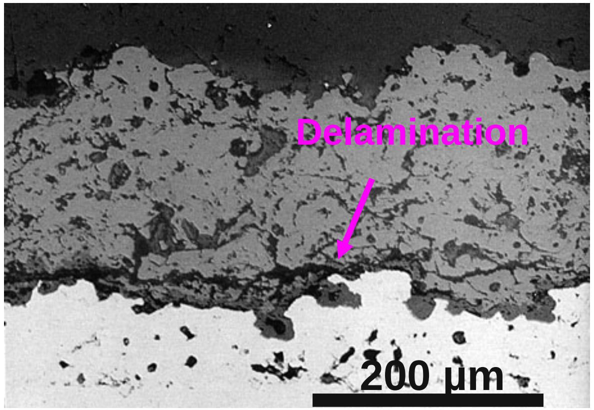
Outline

- Background
- NDE technologies and typical results
  - Optical methods
    - *TBC thickness*
  - Thermal imaging methods
    - *TBC thickness and thermal property*
- Summary
- Planned future efforts

Background

- Thermal barrier coatings (TBCs) are “prime reliant” material for turbine engine components – evaluation of their conditions by NDE is important
- NDEs may be used to:
  - Assess TBC process reliability and product quality (specs, defects, etc)
    - *Current TBC processing relies on robust process conditions*
  - Monitor TBC degradation and predict TBC lifetime
    - *TBC degradation mechanism: crack initiation near TBC/bond coat interface → TBC delamination → TBC spallation (failure)*





Top coat spallation (failure)

Background - continued

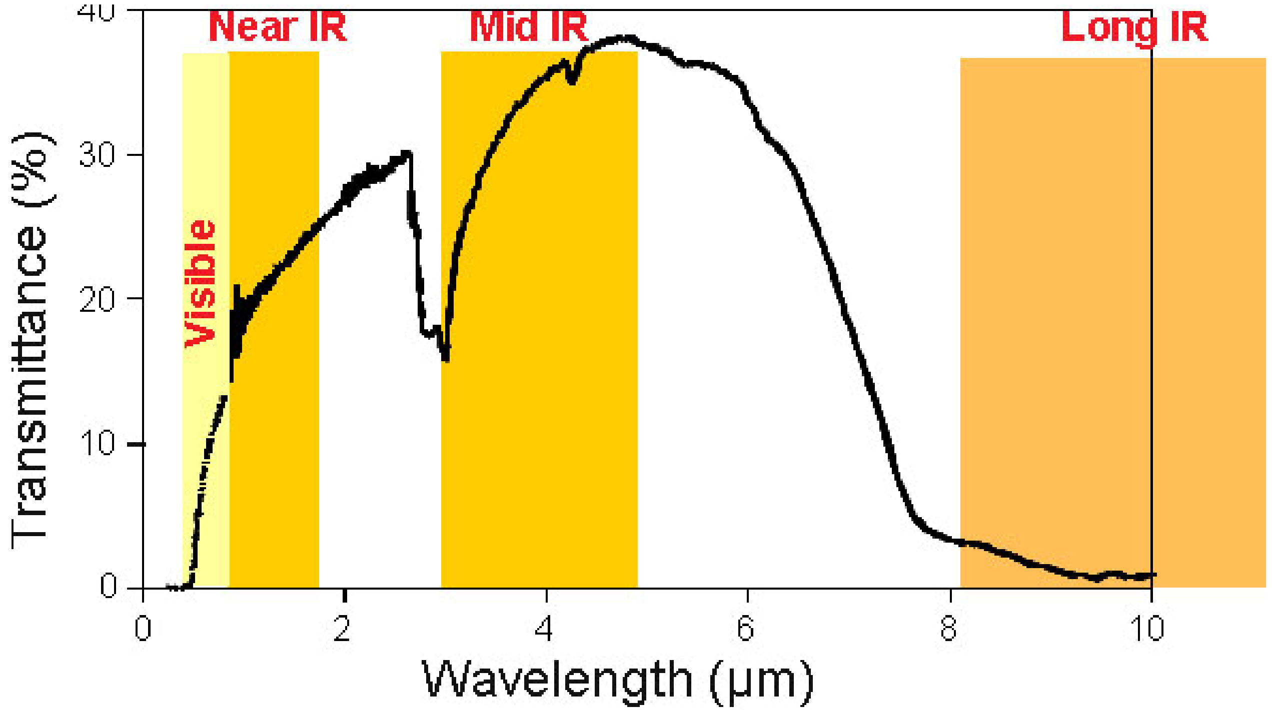
- Current NDE methods are not suitable for quantitative TBC evaluation
  - Optical methods; eddy current; impedance spectroscopy; thermal spectroscopy; thermal imaging, etc
    - *qualitative, semi-empirical, point detection-not suitable for full field imaging*
- NDE development at ANL is focused on quantitative methods that can be used for fundamental TBC property/condition studies and for field monitoring/prediction of TBC degradation and lifetime
  - Quantitative determination of TBC thickness and thermal conductivity which are two of the most important parameters for TBC quality and degradation
    - *They determine the substrate surface temperature*
- NDE methods developed under this project - 2D and 3D imaging technologies:
  - Optical methods: for TBC thickness and degradation/delamination
    - *For EB-PVD and thin APS TBCs (without surface contamination)*
  - Thermal imaging methods: for TBC thickness and conductivity (degradation/delamination)
    - *Not limited by TBC thickness and surface contamination*
    - *Can be applied to other coating and multilayer systems*

NDE Technologies for TBCs

- Optical methods
  - 3D optical coherence tomography (OCT)
    - *TBC thickness*
    - *3D TBC microstructure (and cracking)*
  - 2D laser backscatter
    - *TBC degradation (cracking and delamination)*
- Thermal imaging methods
  - 2D thermal multilayer modeling:
    - *TBC thickness and conductivity distribution*
    - *TBC cracking and delamination*
  - 3D Thermal tomography:
    - *TBC thickness & thermal property distribution in 3D*
    - *3D TBC structure (e.g., crack depth and size distribution within TBC layer)*

Typical Optical Transmission Property of TBC

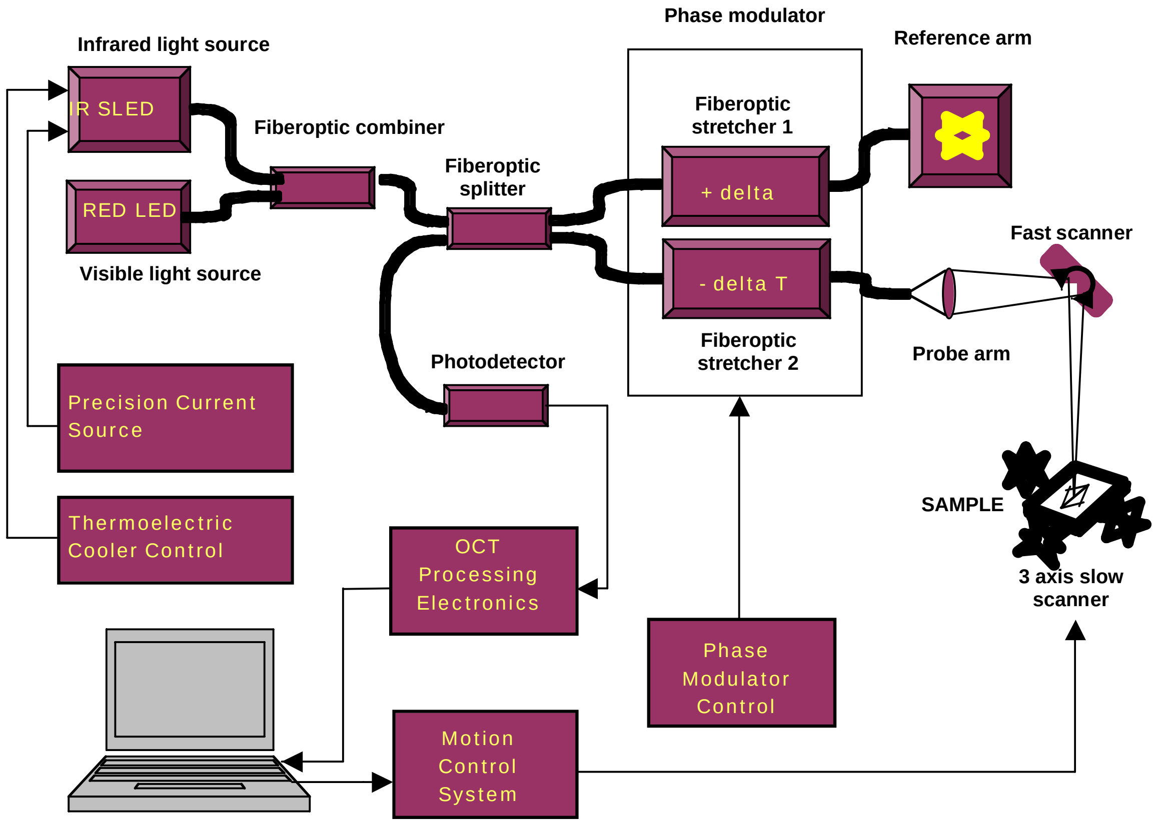
Hemispherical Transmittance of a 172-micron-thick TBC (APS-8YSZ)



From J.I. Eldridge, C.M. Spuckler, J.A. Nesbitt, and K.W. Street, “Health Monitoring of thermal barrier coatings by mid-infrared reflectance,” presented in 2003 Cocoa Beach Conference

- Optical methods can detect TBC condition up to TBC/bond coat interface
- Deeper penetration when using infrared light
- This optical translucency is a problem for thermal imaging methods

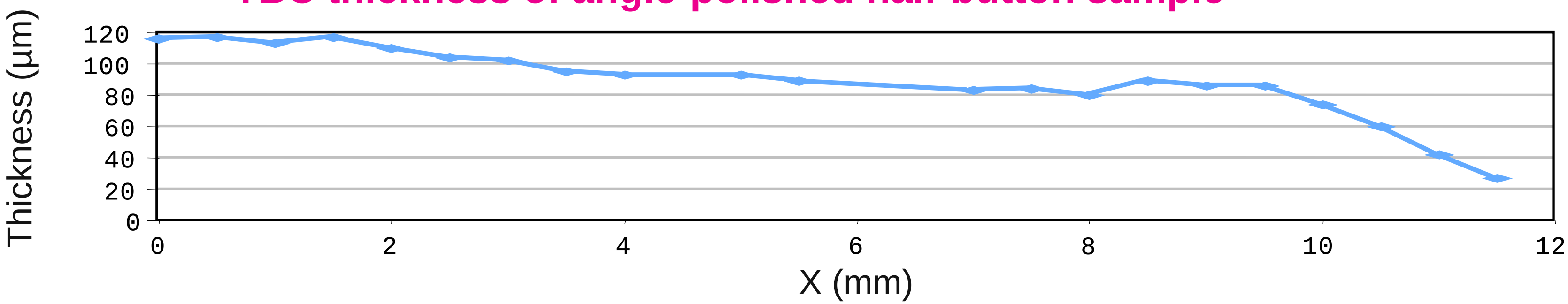
Schematic of ANL's OCT System



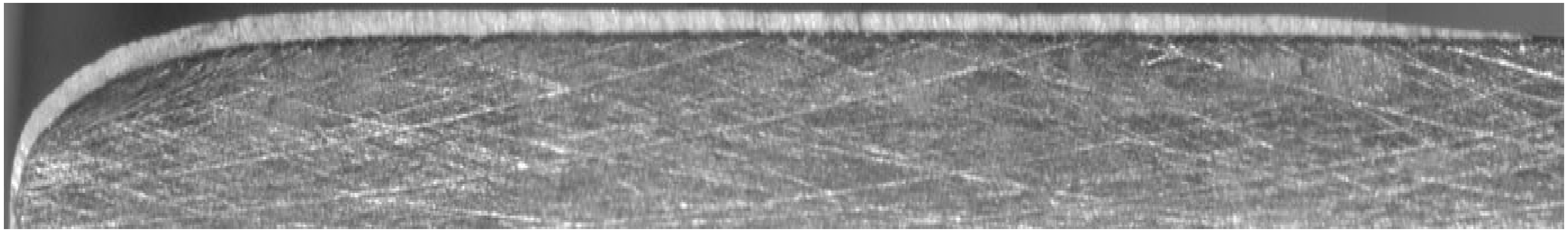
- Interference for depth resolution; laser spot scanning for lateral resolution
- 3D imaging with typical resolution ~10µm in all dimensions
- Near IR light source, relatively deeper penetration depth
- Well developed method

OCT result for an angle-polished EB-PVD TBC

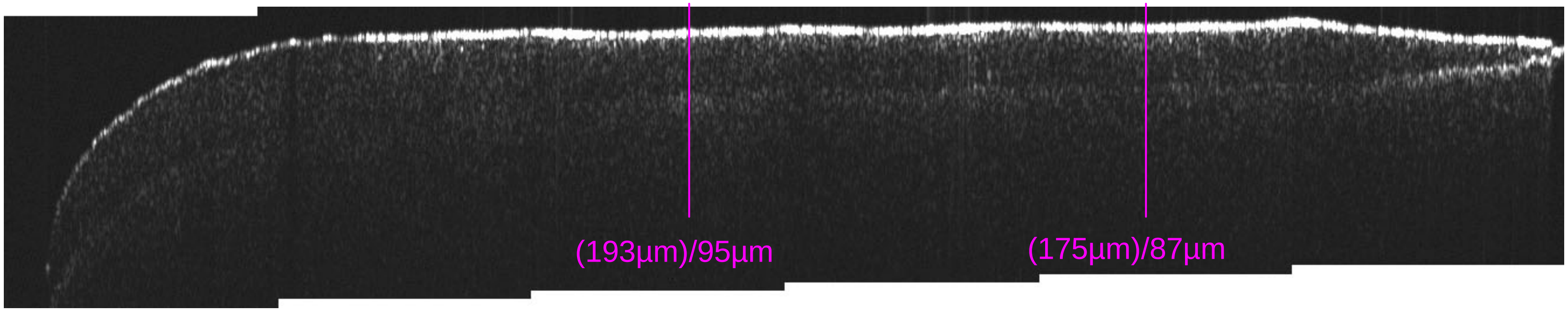
TBC thickness of angle-polished half-button sample



Photomicrograph of TBC sample edge (Aspect ratio: 1:2)



OCT Image near TBC sample edge (TBC refraction index = 2.04)

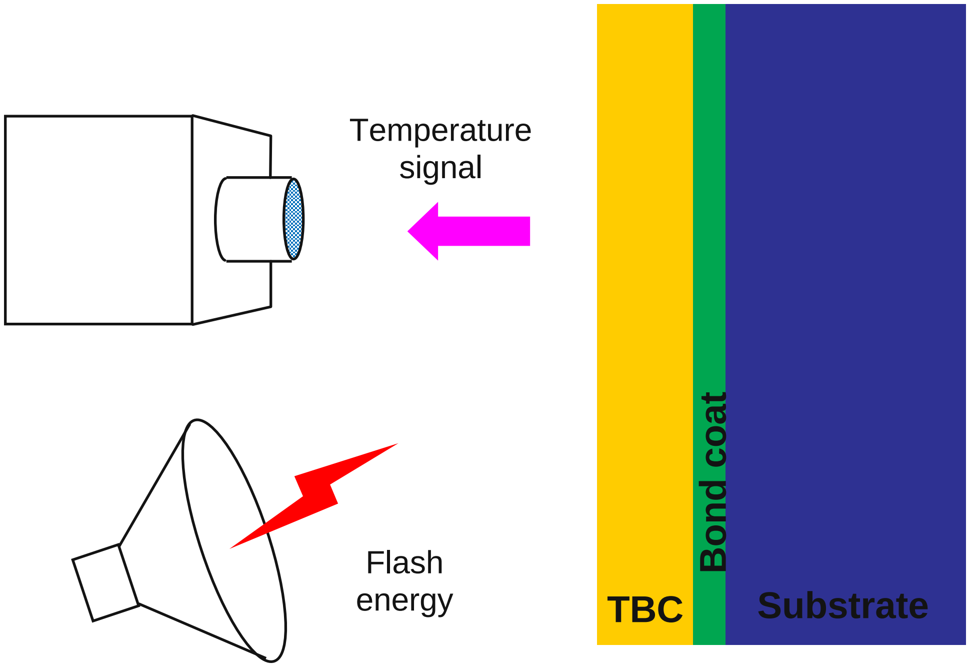


- May detect cracks within TBC

NDE Technologies for TBCs

- Optical methods
  - 3D optical coherence tomography (OCT)
    - *TBC thickness*
    - *3D TBC microstructure (and cracking)*
  - 2D laser backscatter
    - *TBC degradation (cracking and delamination)*
- Thermal imaging methods
  - 2D thermal multilayer modeling:
    - *TBC thickness and conductivity distribution*
    - *TBC cracking and delamination*
  - 3D Thermal tomography:
    - *TBC thickness & thermal property distribution in 3D*
    - *3D TBC structure (e.g., crack depth and size distribution within TBC layer)*

Thermal Imaging Methods – Based on 1-Sided Flash Setup



Thermal conductivity:

TBC: k~1 W/m/°C

Bond coat: (similar as substrate)

Substrate: k~10 W/m/°C

Air: k=0.024 W/m/°C
(fills cracks when they exist)

- High detection sensitivity due to large disparity of thermal properties at each layer
- Imaging method, fast (few to few tens seconds) for 100% surface inspection
- New 2D and 3D methods are developed at Argonne National Laboratory

TBC Parameters Measurable by Flash Thermal Imaging

- Transient heat transfer equation (1D):

$$\rho C_p \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial z^2}$$

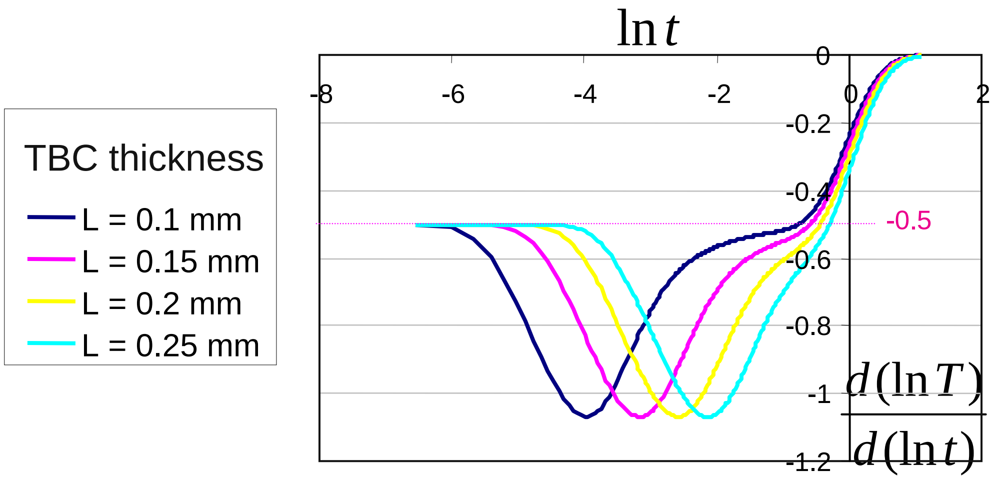
- Parameters in the equation:
  - TBC material properties: ρC_p – heat capacity; k – thermal conductivity
  - Length scale: TBC thickness (L)
  - Temperature scale: based on experimental maximum-minimum
  - Time: measured in experimental data

- Therefore, three parameters are relevant in transient thermal test: ρC_p, k, and L. Can they be independently determined from flash thermal imaging test?

- Note: ρC_p and k can be converted to another two thermal parameters:
  - Thermal difusivity $\alpha = k/\rho C_p$
  - Thermal effusivity $e = (k\rho C_p)^{1/2}$
  - Any two of these four parameters are independent

Analysis of thermal imaging response to TBC parameters -- TBC thickness L

- Plot of surface temperature decay slope vs. time in log-log scale
  - Simulated data for pulse thermal imaging of TBC specimens
    - *TBC: L = varies, k = 1.5 W/m-K, ρC_p = 2.5 J/cm^3-K*
    - *Substrate: L = 3mm, k = 11, ρC_p = 3.5*



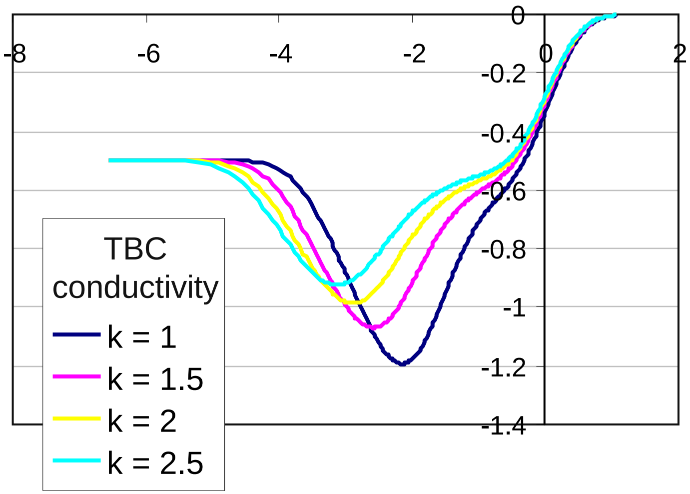
- TBC thickness determines the time when slope deviates from initial value of -0.5

Analysis of thermal imaging response to TBC parameters -- TBC conductivity k and heat capacity ρC_p

Variation in TBC conductivity:

TBC: L = 0.2mm, k = varies, ρC_p = 2.5 J/cm³-K

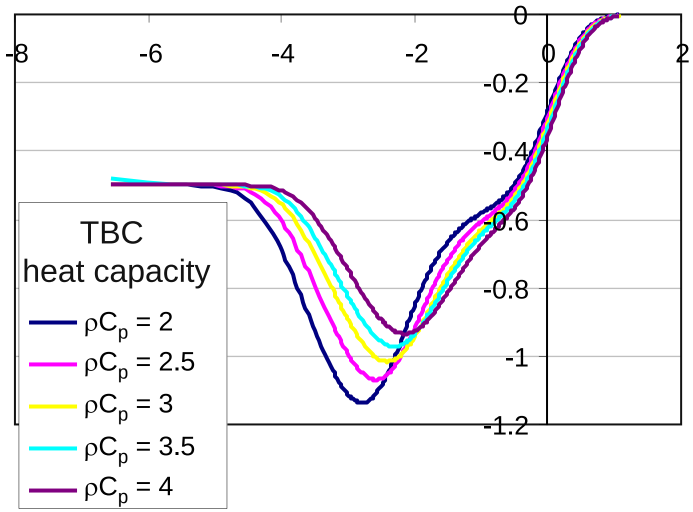
Substrate: L = 3mm, k = 11, ρC_p = 3.5



Variation in TBC heat capacity:

TBC: L = 0.2mm, k = 1.5 W/m-K, ρC_p = varies

Substrate: L = 3mm, k = 11, ρC_p = 3.5



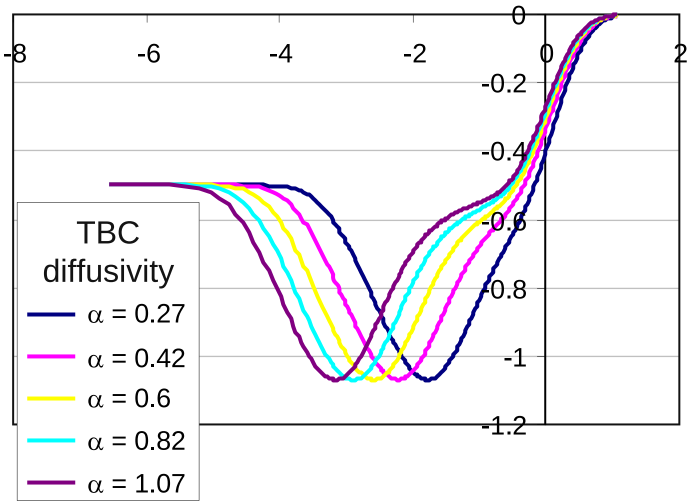
- Response of thermal imaging data to TBC conductivity & heat capacity is not distinct and separable

Analysis of thermal imaging response to TBC parameters
-- TBC diffusivity α and effusivity e

Variation in TBC diffusivity α:

TBC: L=0.2mm, α = varies, e = 3.75 $J/m^3\text{-}K\text{-}s^{1/2}$

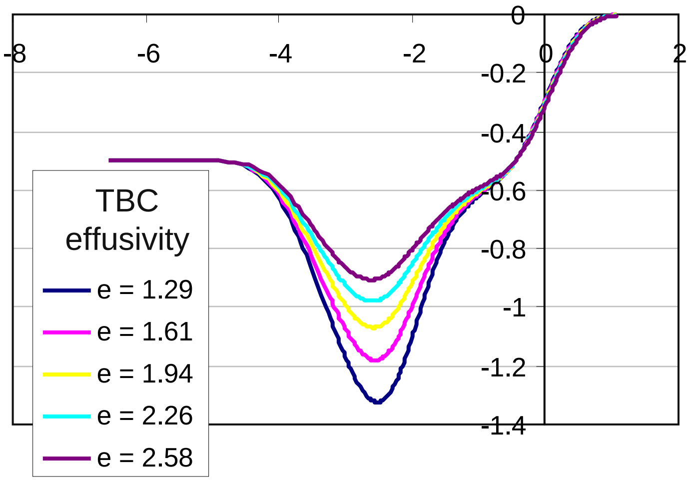
Substrate: L = 3mm, k=11, ρC_p=3.5



Variation in TBC effusivity e:

TBC: L=0.2mm, α = 0.6 mm^2/s, e = varies

Substrate: L = 3mm, k=11, ρC_p=3.5



- Response of thermal imaging data to TBC diffusivity α is similar to TBC thickness! In fact, $\alpha t/L^2$ is a nondimensional parameter, and α and L cannot be individually determined in thermal imaging test for single-layer specimen
- TBC effusivity e affects only the maximum slope value, i.e, independent of L or α

Thermal Imaging Measurement for TBC parameters

- Among two TBC thermal properties and the TBC thickness, total of three parameters, only two can be determined independently by flash thermal imaging

- Thermal imaging (multilayer-modeling method) can determine/image:
  - (a) TBC thickness L with known TBC thermal properties k and ρC_p
  - (b) TBC thermal properties k and ρC_p with known TBC thickness L
  - (c) TBC conductivity k and thickness L with know TBC heat capacity ρC_p
    - *Work for this development is underway*

- Thermal imaging (tomography method) can image:
  - TBC effusivity e distribution (3D) as a function of depth (related to TBC diffusivity α)

NDE Technologies for TBCs

- Optical methods
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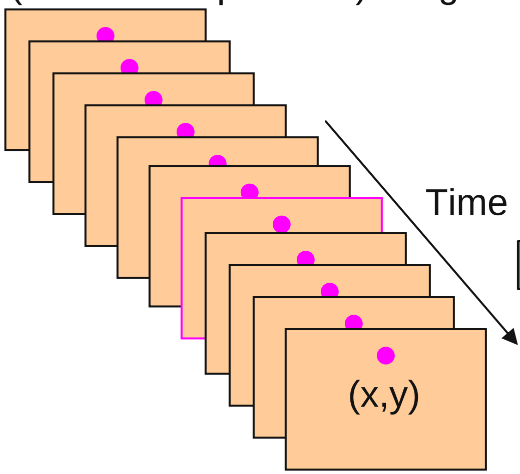
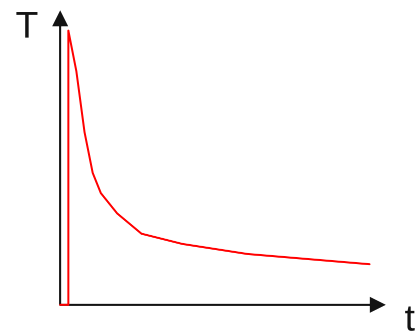
2D Thermal Multilayer Modeling for TBC Systems

Measured data T(x,y,t):

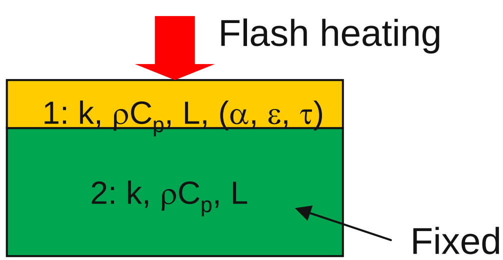
Time series of 2D thermal (surface temperature) images



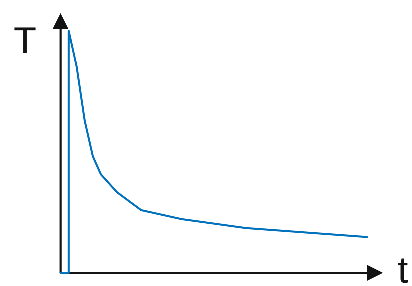
Surface temperature variation at pixel (x,y)



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

Analytical Thermal Imaging Model for Multilayer Materials

- Numerical solution of governing heat transfer equation for multilayer TBC materials
  - Crank-Nicolson scheme - 2nd order in both time and space
  - with finite flash duration, finite absorption depth, finite imaging depth

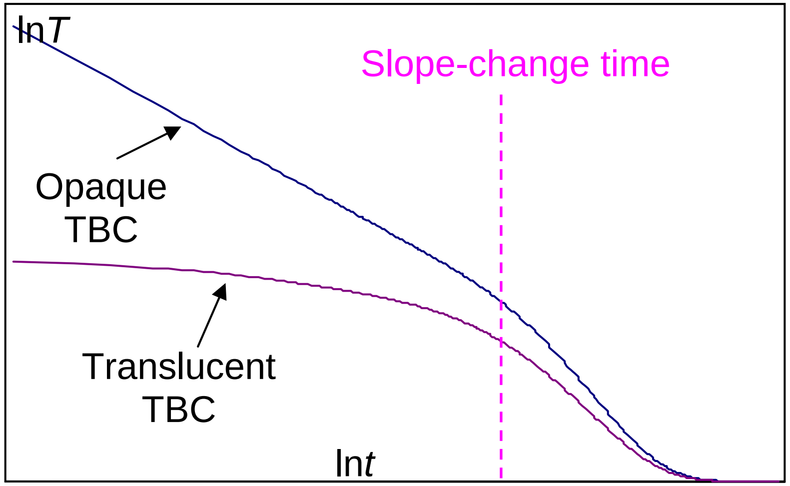
- Automated procedure for prediction of TBC parameters
  - At each pixel, measured surface temperature is fitted with numerical solutions to obtain a least-square fit which determines correct TBC parameters: thermal conductivity, thickness, and absorption coefficient
  - Process all pixels to determine distributions of the parameters

- For multilayer materials, parameters in each layer include:
  - thermal conductivity k,
  - heat capacity ρC_p,
  - layer thickness L,
  - and for translucent materials, the "absorption coefficient"

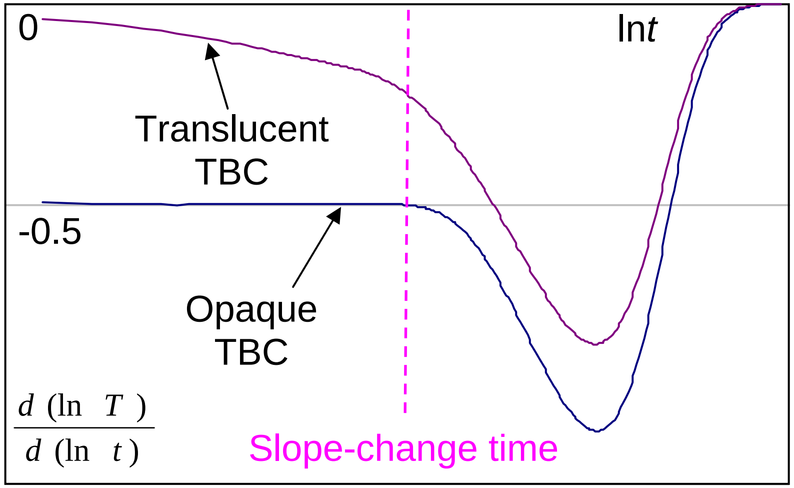
- This method can be used for any multilayer materials with any number of parameters

Translucent (natural) and opaque (black-coated) TBCs

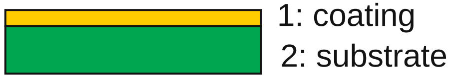
Temperature vs. time



Temperature slope vs. time



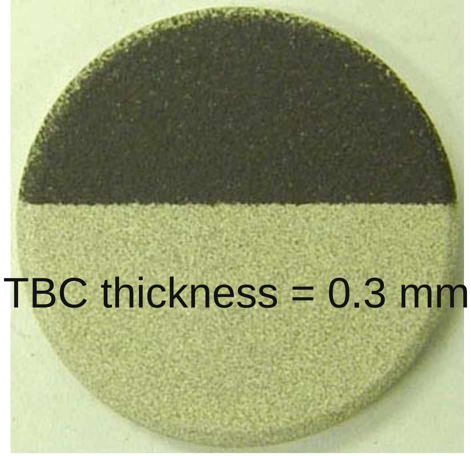
Two-layer TBC



- TBC thickness is related to the slope-change time
- TBC translucency is related to initial slope

TBC Thickness Distribution by Multilayer Modeling Method

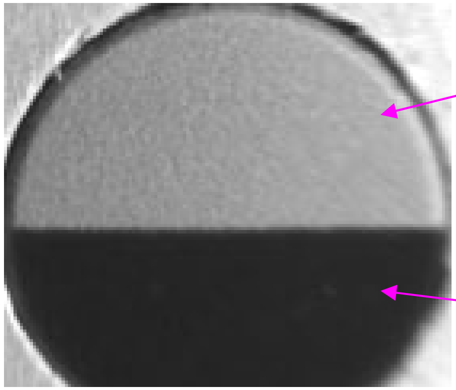
1”-dia TBC sample partially coated with a black paint



TBC thickness = 0.3 mm

Sample curtsey of Dr. A. Kulkarni, Siemens

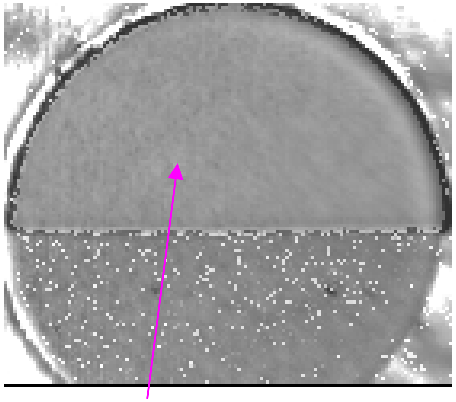
Typical thermal image after flash



Coated region has high temperature

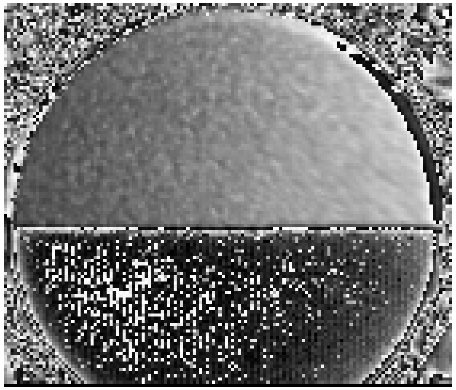
Uncoated region has low temperature

Predicted thickness map



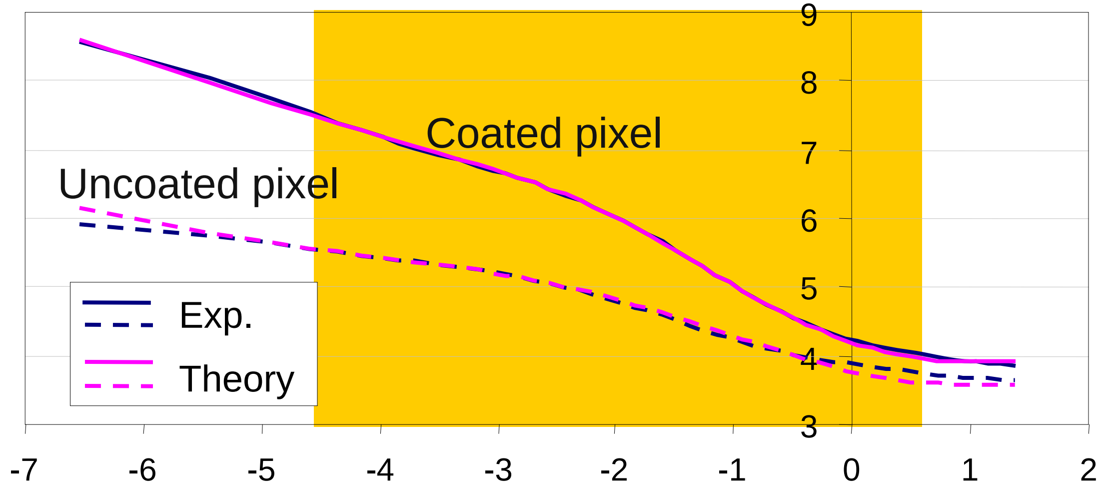
Average thickness = 0.302 mm

Predicted optical attenuation coefficient map

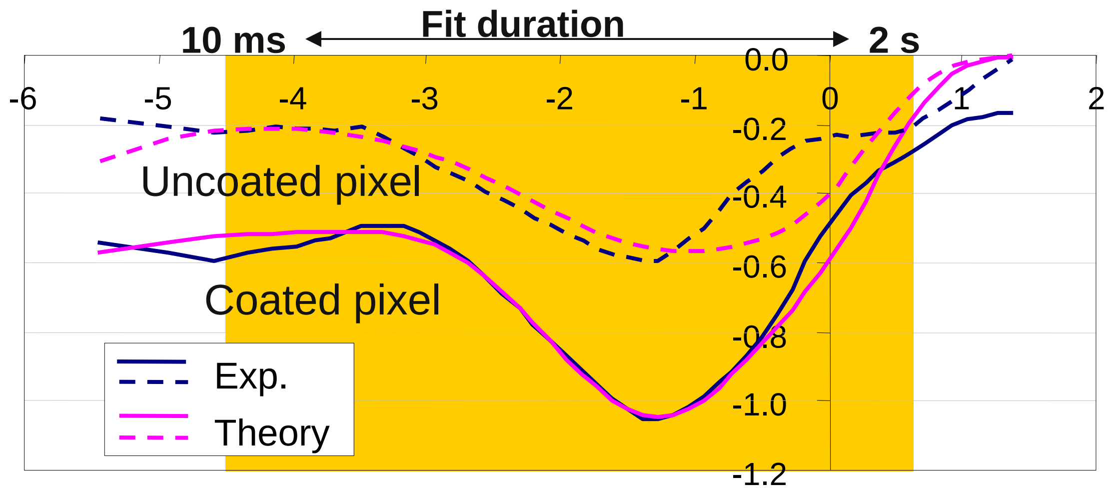


Typical Fitting Results

Temperature vs. time (log-log scale)



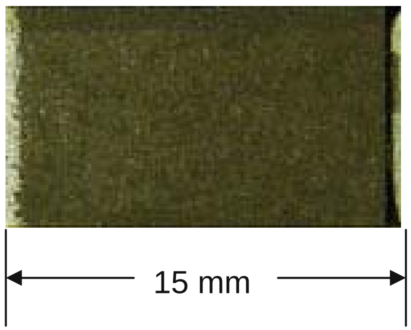
Temperature slope vs. time (linear-log scale)



- Poor fit in uncoated pixel due to inadequate optical transmission model

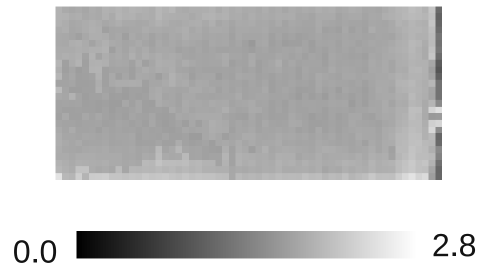
Multilayer thermal modeling for TBC thermal properties

EBPVD TBC sample

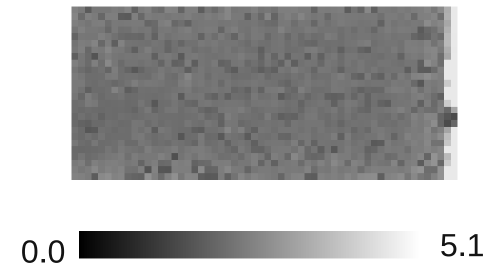


- As-processed TBC, 0.2 mm thick
- TBC was coated by a black paint

TBC conductivity k (W/m-K)



TBC heat capacity ρC_p (J/cm^3-K)



Sample curtsey of Mr. A. Luz, Imperial College London

- Average TBC conductivity: 1.8 W/m-K (high?)
- Average TBC heat capacity: 2.2 J/cm^3-K

- TBC thickness L = 0.2mm is fixed in the analysis
- Substrate (Inconel superalloy) property is fixed

Multilayer thermal modeling method summary

- Current software is robust to predict TBC thickness and TBC thermal properties (not combination of thickness + conductivity)
  - Among two thermal properties and a thickness (total 3 parameters), only two parameters can be determined by thermal imaging methods

- For thermal property prediction, current results are probably ~10% higher, likely due to nonlinear temperature response of the infrared camera
  - This will be examined and corrected
  - Prediction accuracy of <5% is expected (similar accuracy as laser-flash method when testing stand-alone TBC specimens)

- Additional developments:
  - Improve accuracy for predicting both TBC thickness and conductivity
  - Improve optical models used for thermal imaging of natural TBCs (w/o black coat)
  - Evaluate prediction accuracy for thin and thick TBCs
  - Account for interface resistance (due to cracks)

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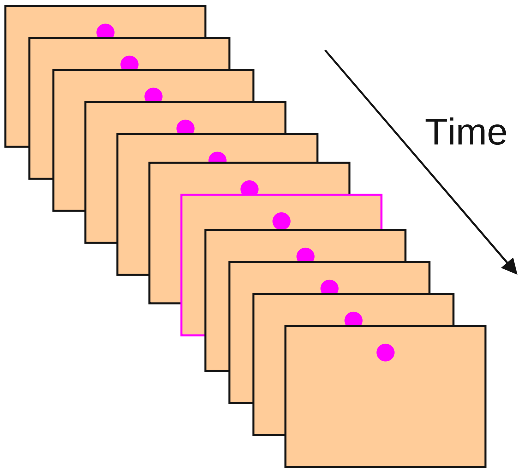
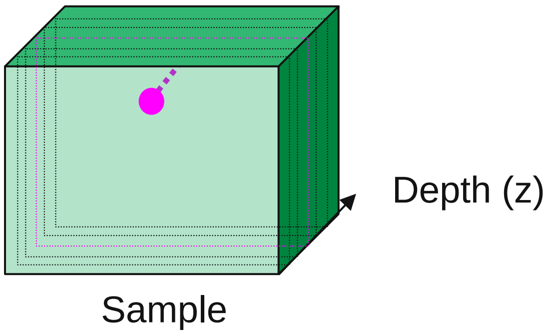
3D Thermal Tomography Method

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



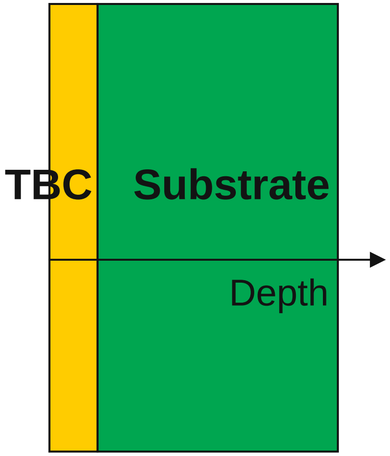
- Thermal effusivity tomography technology:
  - Convert measured thermal-imaging data T(x,y,t) into 3D material thermal-effusivity distribution e(x,y,z) [$e = (\rho C_p k)^{1/2}$]
  - e(x,y,z) can be sliced in any planes (similar to x-ray CT slices)
- A new technology, US patent 7,365,330 issued in April, 2008

Thermal Tomography Result for a Simulated TBC System

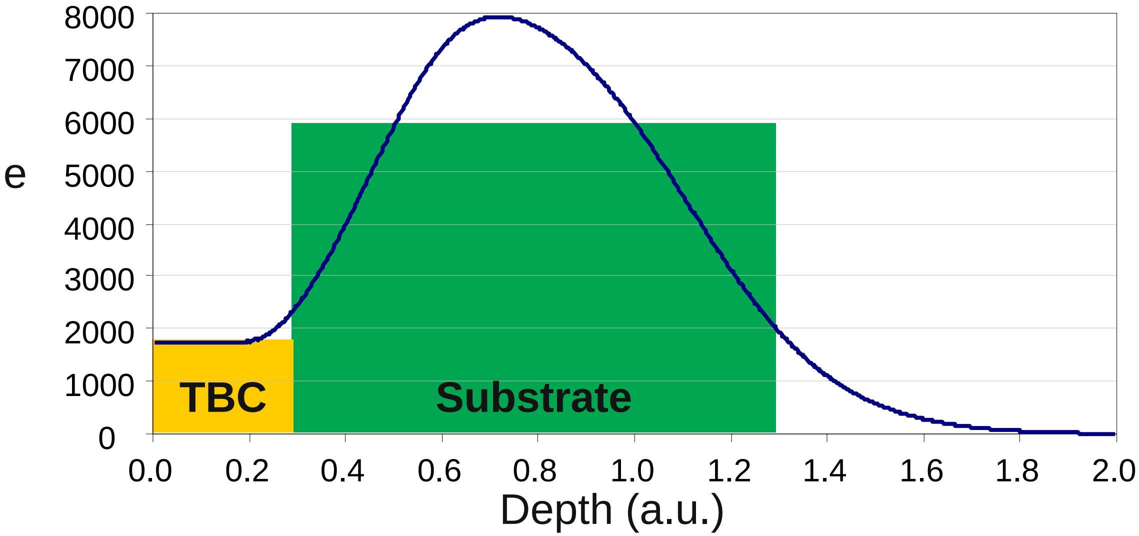
Material properties for a simulated TBC system

	L(mm)	k(W/m-K)	ρC_p(J/cm^3-K)	e(J/m^2-K-s$^{1/2}$)	α(mm^2/s)
TBC	0.3	1	3	1732	0.33
Substrate	3	10	3.5	5916	2.86

Two-layer opaque TBC



Predicted effusivity distribution along depth

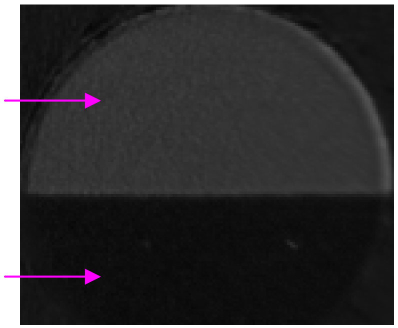


- Thermal diffusion reduces resolution in substrate
- Methods to improve resolution are being investigated

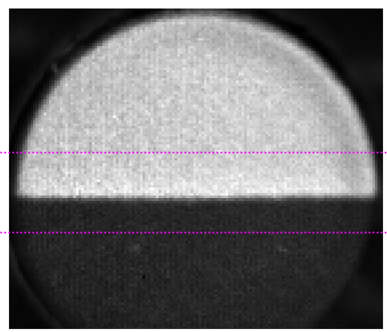
Thermal tomography imaging for as-processed APS TBC

Thermal Effusivity Plane images

At depth around half TBC thickness

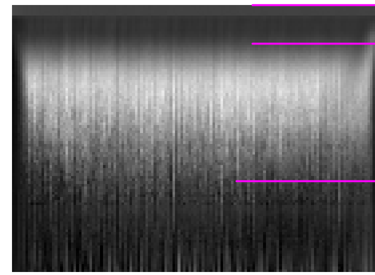


At depth around half substrate thickness

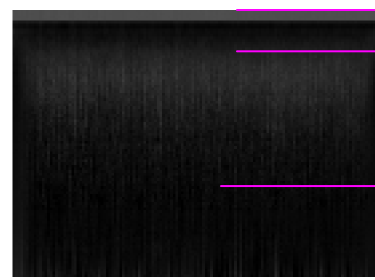


Thermal Effusivity Cross-Sectional Images

In coated region



In uncoated region



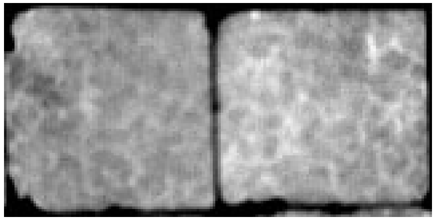
- TBC translucency affects derived thermal effusivity values for TBC
- Depth resolution for TBC: 22.5 µm/pixel; for substrate: 62.4 µm/pixel

Thermal tomography results for a thick TBC

TBC thickness = 2 mm
Substrate thickness = 4 mm

Sample courtesy
of Dr. Derek Allen
Alstom, England

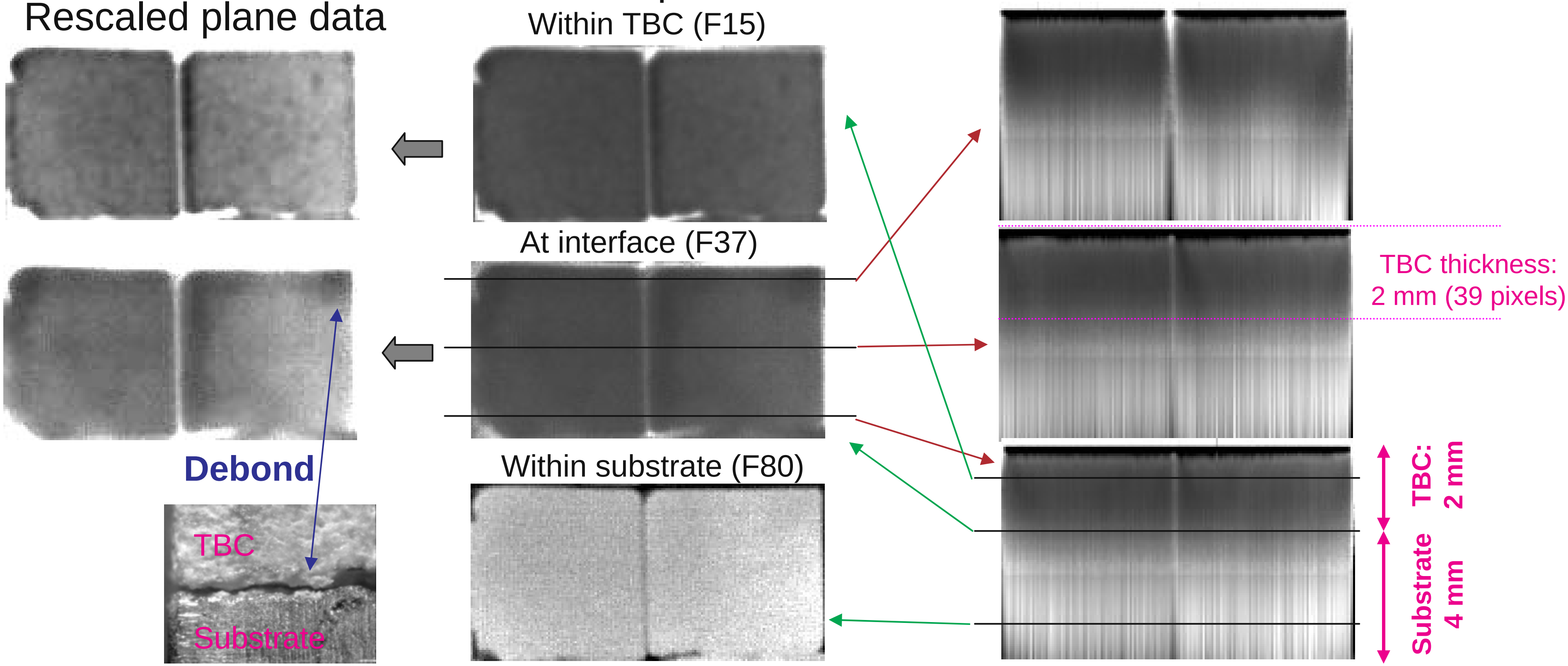
Typical raw thermal image (t=0.024s)



Rescaled plane data

Processed plane data

Processed cross-section data



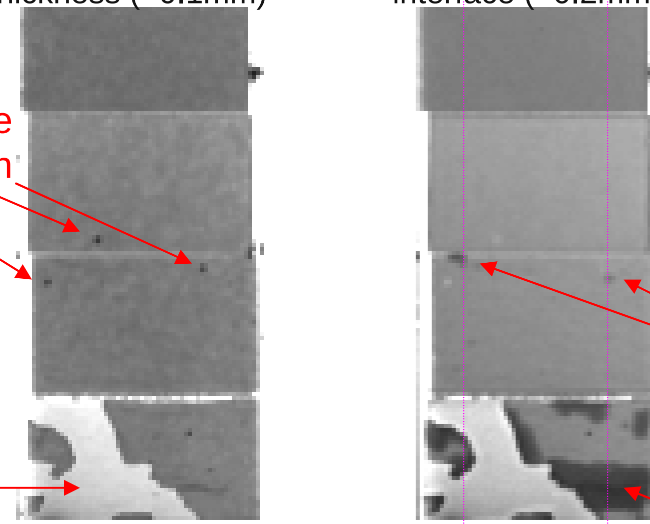
- TBC diffusivity $\alpha = 0.4\ mm^2/s$; Depth resolution = 51 µm/pixel

Thermal tomography imaging for thermal-cycled TBCs

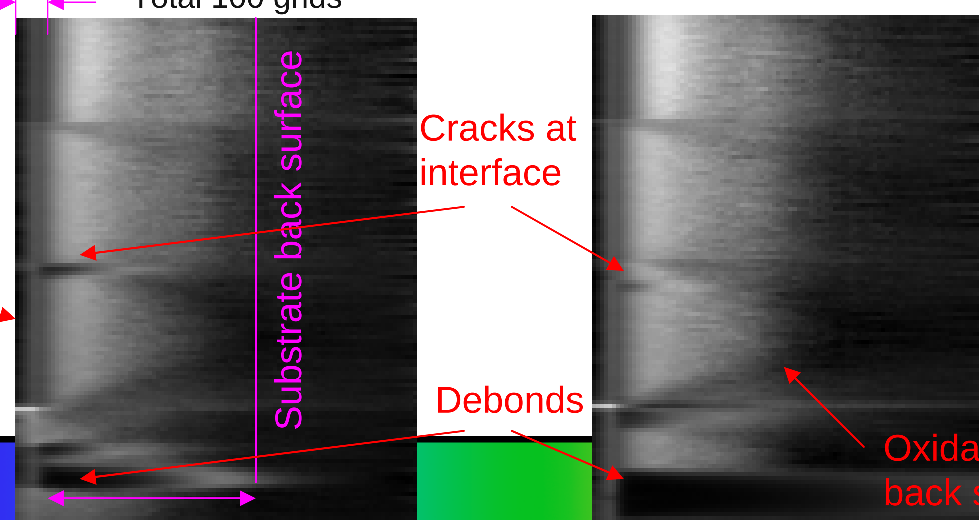
4 EBPVD TBC samples

- TBC thickness is 0.2 mm
- TBC was coated by a black paint

Two plane images



Two cross-sectional images



Thermal tomography method summary

- Thermal tomography is robust for 3D imaging of TBC systems – direction determination of TBC parameters: thickness and thermal properties
  - US patent 7,365,330 issued in April, 2008
  - Software is being copyrighted
  - Considerable interests for this technology from industry

- Additional developments
  - Correct flash duration effect which affects imaging of thin TBCs
  - Evaluate/correlate TBCs with various microstructure (layered) and defects
  - Improve spatial resolution in depth direction
  - Improve spatial resolution in lateral direction

Summary

- 2D and 3D NDE methods were developed for quantitative imaging of TBC parameters – thickness and thermal property; preliminary results were obtained
  - (1) OCT method
    - *3D imaging of coating microstructure (needs refractive index for depth scale)*
    - *Max. detection depth depends on light wavelength and TBC microstructure*
  - (2) Thermal multilayer modeling method
    - *2D imaging of TBC thickness and/or TBC thermal property*
    - *Current model valid for opaque TBCs (and thick translucent TBCs)*
  - (3) Thermal tomography method
    - *3D imaging subsurface coating thermal property (effusivity)*
    - *Direct visual identification of TBC thickness*

- These NDE methods can be used to monitor TBC degradation/delamination and to predict TBC lifetime

- Thermal methods are capable for fast imaging of large complex components

Planned Future Efforts

- Further developments of these NDE methods
  - Issues and correction approaches for each method were identified
  - Prediction accuracy of within 5% is targeted
  - Capable to image various TBC structures: thin/thick, graded/layered, opaque/translucent
- Validation of NDE methods for TBC degradation monitoring
  - Comparison with destructive examination results
  - Verification of data accuracy
  - Correlation of TBC parameter change to degradation “level”
- Correlation of NDE data between all methods