DEVELOPMENT OF NDE METHODS FOR CERAMIC COATINGS

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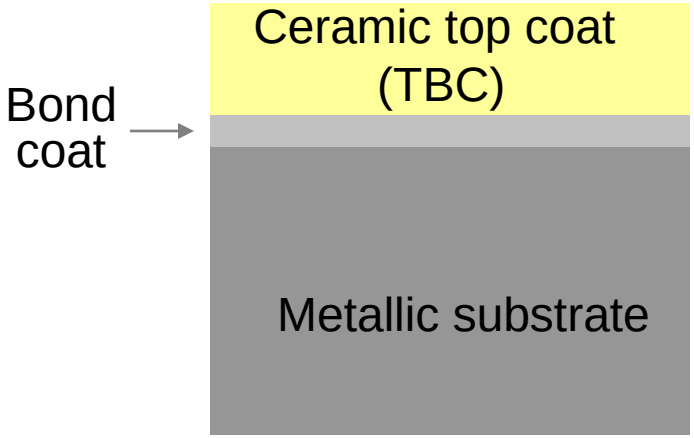
Outline

- Background on TBC degradation and NDE
- Objectives of this project
- NDE for TBC life prediction
  - Optical and thermal imaging methods
- NDE developments for TBC systems
  - Thermal imaging NDE for a turbine blade
  - TBC translucency modeling
  - Thermal imaging for multilayer TBCs
- Summary
- Planned future efforts

Background

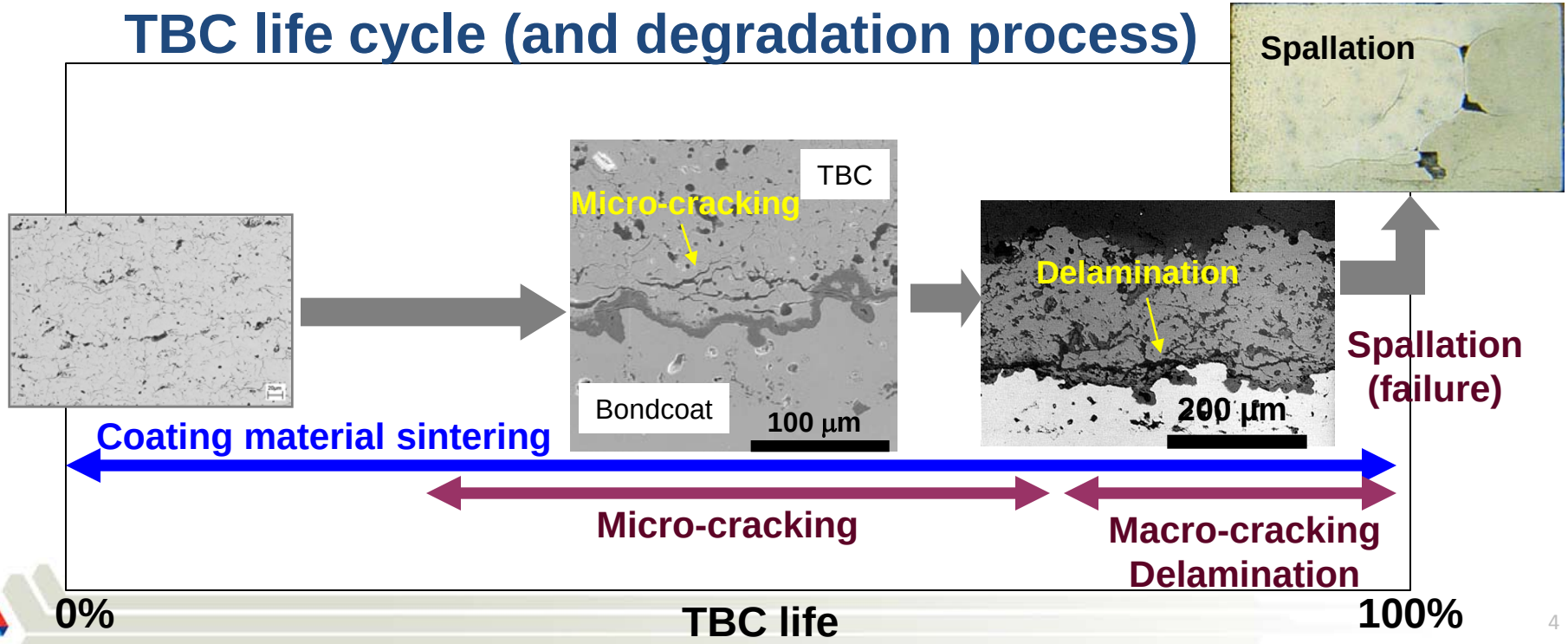
- Thermal barrier coatings (TBCs) are required for high-temperature metallic components in advance turbine systems to be operated with higher efficiency and low emission
- TBCs have become “prime reliant” material → their condition monitoring and lifetime prediction by NDE is important
- Entire TBC surface should be inspected (by imaging NDE methods) because TBC damage can be highly localized



TBC Structural Damage in Lifetime

- Two characteristics of TBC degradation/failure:
  - (1) Ceramic top coat continuously sinters with minimal structure damage
  - (2) Cracks and delaminations develop and expand near interface
- Quantitative NDEs are required to detect both changes for life prediction
  - Use material properties: mechanical (+stress/strain), thermal, electrical, etc
  - Structure – property (function) relationship?
  - A “failure structure”?

TBC life cycle (and degradation process)



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 NDE technologies are not suitable for field application
- NDE for TBC health monitoring and life prediction:
  - A practical NDE method/model has not been well established
    - Spectroscopy methods are not suitable for real component field application
    - Optical methods have some success for thin coatings in lab tests
    - Thermal imaging methods were not very quantitative
- 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):
    - Optical mid-IR reflectance
    - thermal multilayer analysis (– also for complex TBC systems)
  - (2) For high-resolution flaw detection
    - thermal tomography
- Develop NDE methods for functional materials (gas-separation membrane, fuel cell, etc)
  - Synchrotron x-ray CT, thermal tomography

Recent NDE Developments

- Continued evaluation of optical (mid-IR reflectance) and thermal imaging NDE methods for TBC life prediction
  - Collaborations with Siemens and Stony Brook Univ.

- Continued development of two thermal imaging methods
  - Thermal multilayer analysis for TBC life prediction
    - Continued calibration for TBC property measurement accuracy
    - Evaluation for testing turbine components
    - Development of theoretical models for translucent TBCs and for multilayer TBCs
  - Thermal tomography method (3D imaging)
    - Continued development of new algorithm for high-resolution imaging

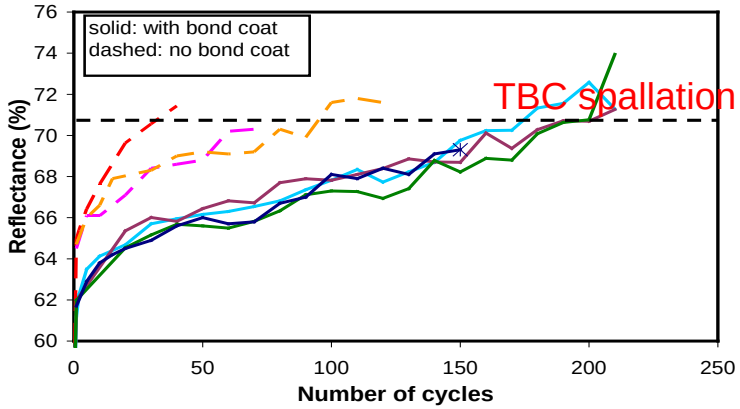
Presentation Topics

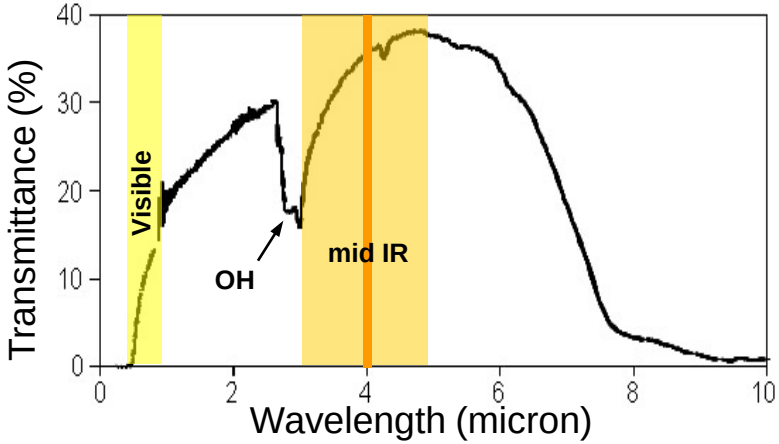
- NDE for TBC life prediction
  - Optical mid-IR reflectance (MIRR) method
  - Thermal imaging multilayer analysis method – TBC property measurement
  - TBC life prediction model and experimental evaluation
- Development and application of multilayer analysis method
  - Application for a turbine blade
  - Theoretical development for translucent TBCs
  - Theoretical development for multilayer TBCs

Mid-IR Reflectance for TBC Life Prediction

- Technology developed by Dr. Eldridge of NASA

Reflectance vs. TBC life

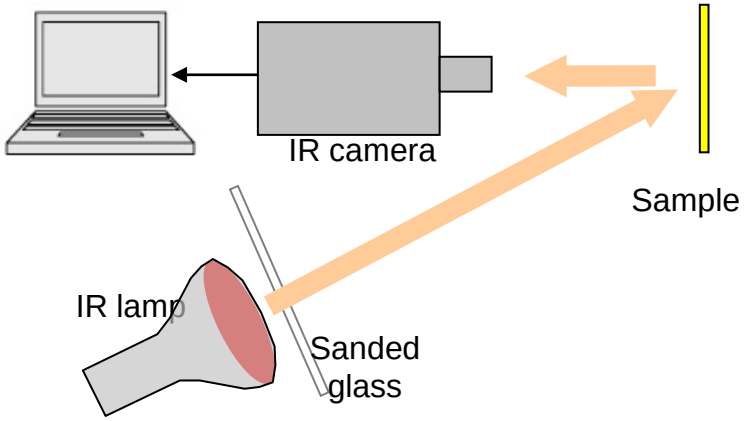




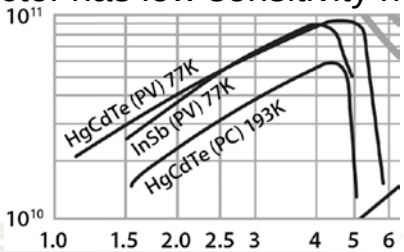
J.I. Eldridge, et al., 2003 Cocoa Beach Conference

- Mid-IR reflectance system at ANL
  - Use entire 3-5µm wavelength (narrow band @4µm in NASA system)
  - Use weaker IR source (low thermal heating)
  - Effect of OH absorption band is small

Schematic of ANL system



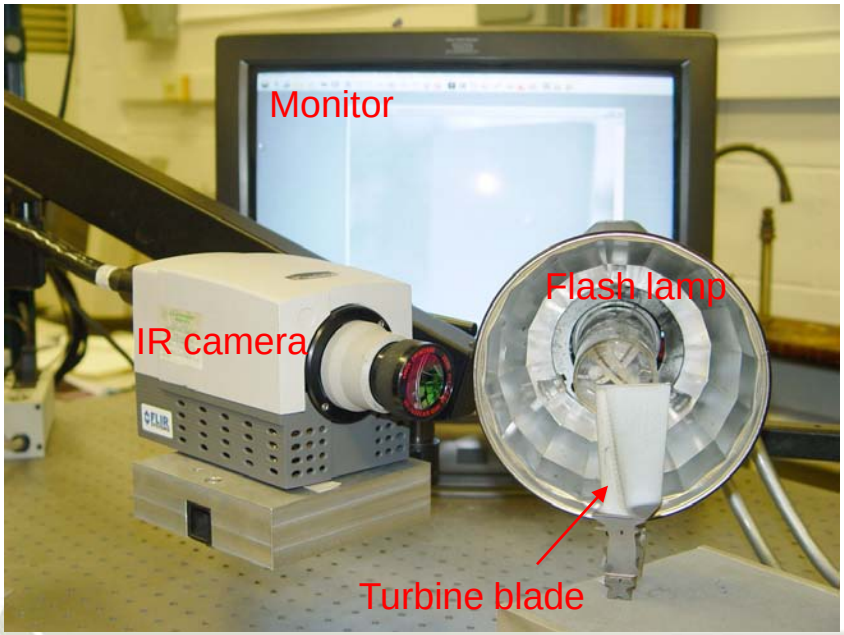
IR detector has low sensitivity near OH line



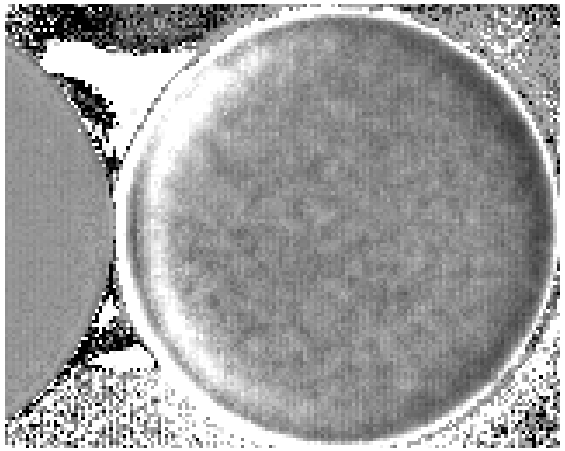
Thermal Imaging Method for TBC Life Prediction

- Multilayer analysis method developed at ANL can accurately measure TBC thermal properties:
  - Two TBC properties: thermal conductivity and heat capacity (or thickness)
  - Measurement accuracy is typically <3% (likely best among all methods)
  - The only method suitable for field applications (and fully automated)
  - The only method for imaging entire component surface

One-sided experimental setup

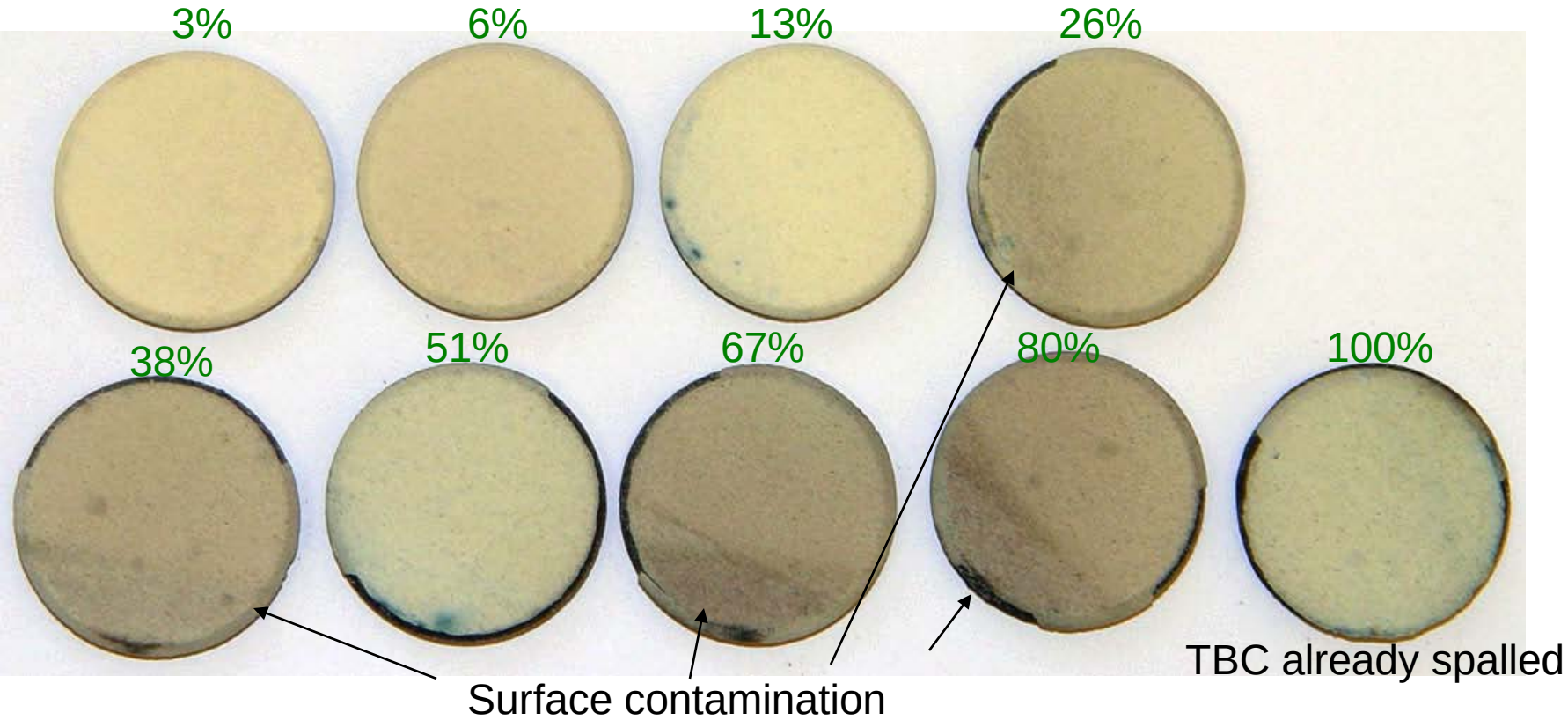


Thermal conductivity imaging



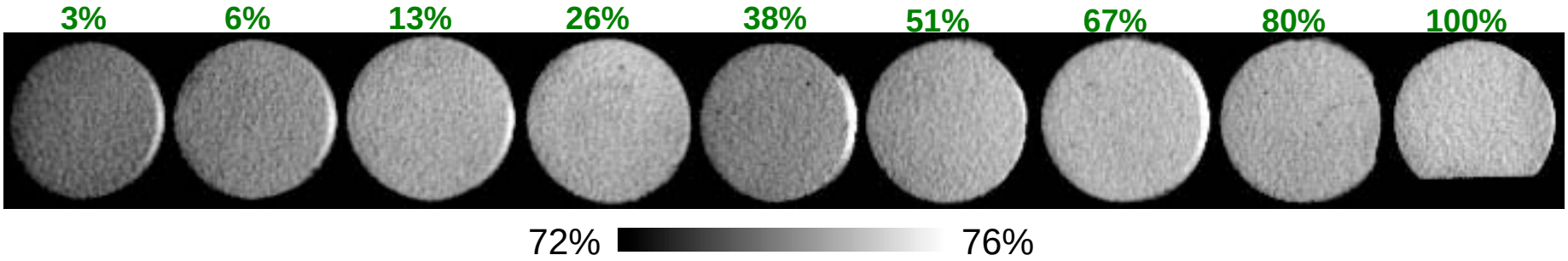
0.5 W/m-K 1.4 W/m-K

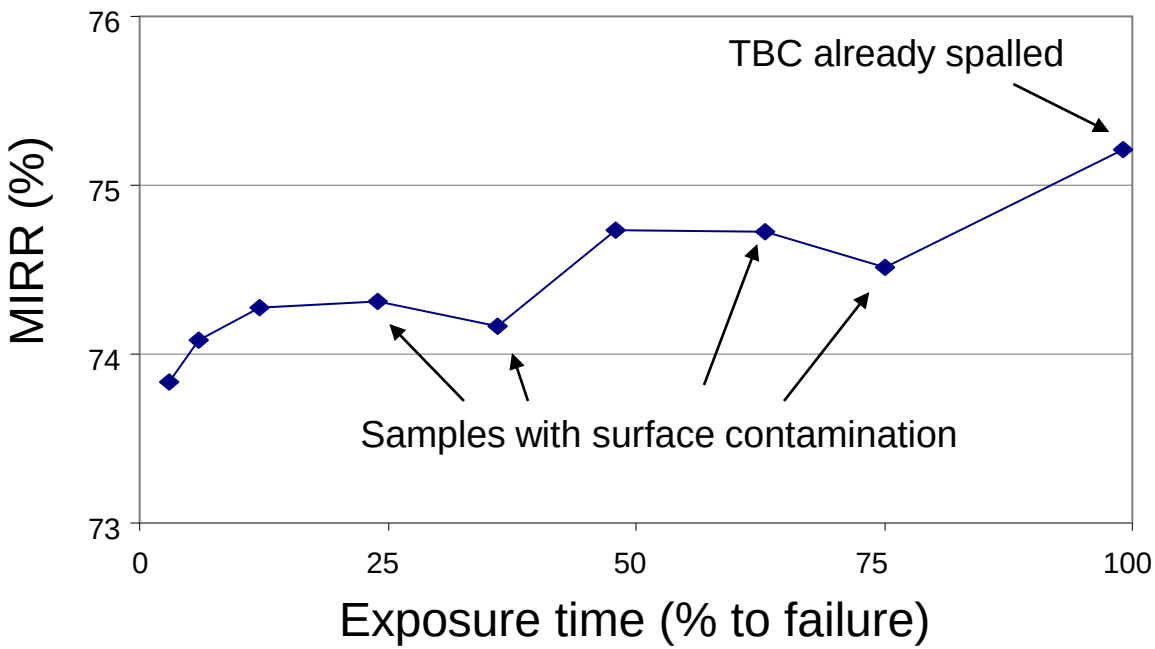
APS TBC Samples from Siemens



- Samples were thermal cycled to various % of life
- Sample courtesy of Dr. Kulkarni

Mid-IR Reflectance Data

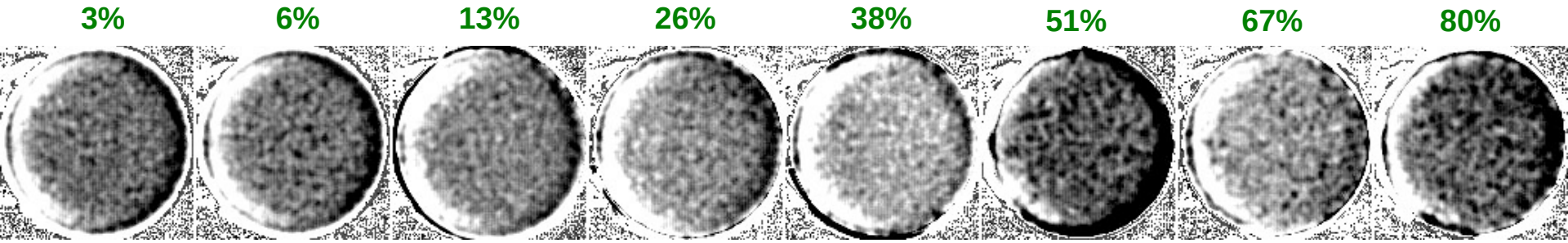




- **Mid-IR reflectance correlates well with TBC life**
- **Small-range ~1% variation – requires accurate measurement**
- **Data affected by surface contaminations**

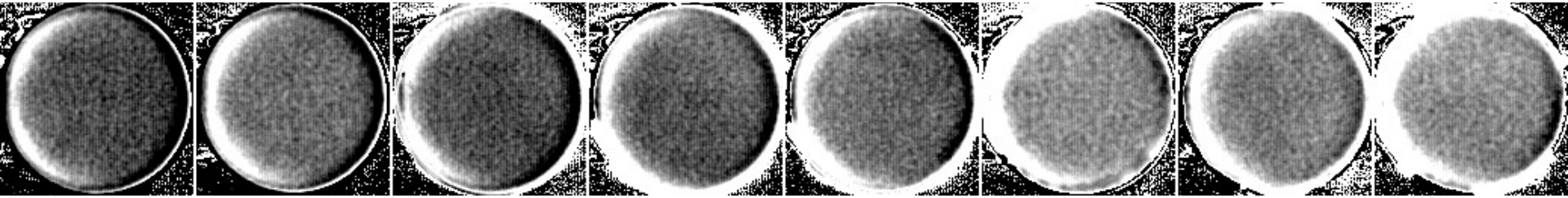
Thermal Imaging Data

Thermal conductivity (k) images



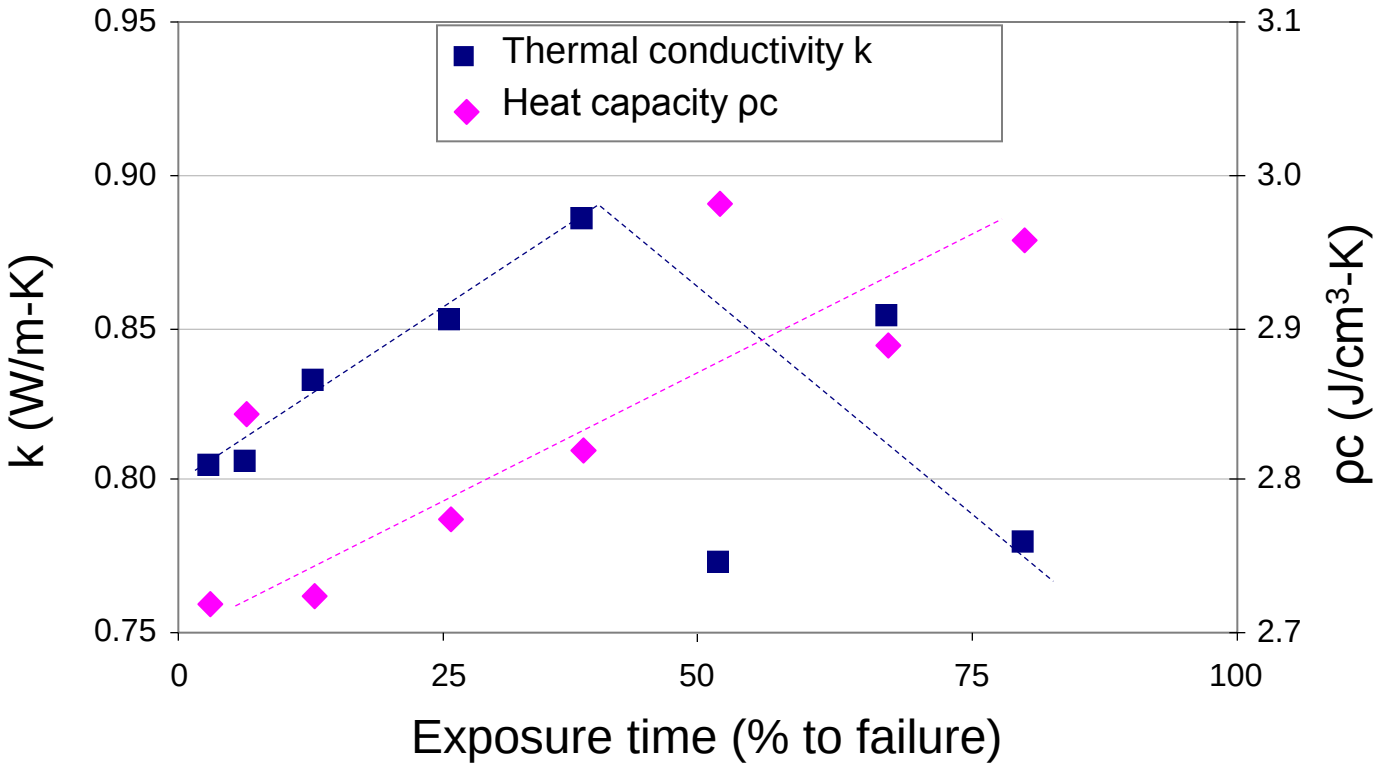
0.7 W/m-K — 1 W/m-K

Heat capacity (ρc) images



2.5 J/cm^3-K — 3.5 J/cm^3-K

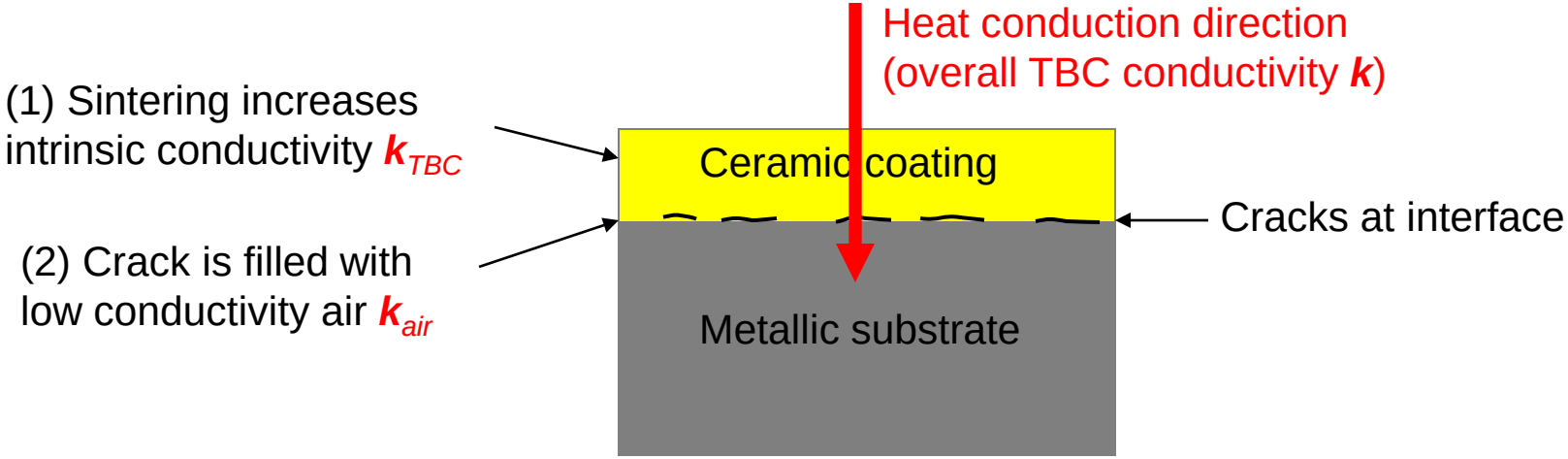
Thermal Imaging Data – cont.



- Conductivity k increases till ~40% life and then decreases (~10% change)
- Heat capacity ρc increases continuously with time (~10% change)
- Noises are likely due to TBC thickness error (assumed 0.3mm for all)

Modeling TBC Conductivity Change with Life

- Overall TBC thermal conductivity ***k*** is affected by two factors:
  - (1) Intrinsic TBC material conductivity $\boldsymbol{k_{TBC}}$ increases due to sintering
  - (2) Interface cracking/delamination is filled by air of low conductivity $\boldsymbol{k_{air}}$ that reduces overall TBC conductivity (the measured value)
- A TBC conductivity-life model should account for both factors



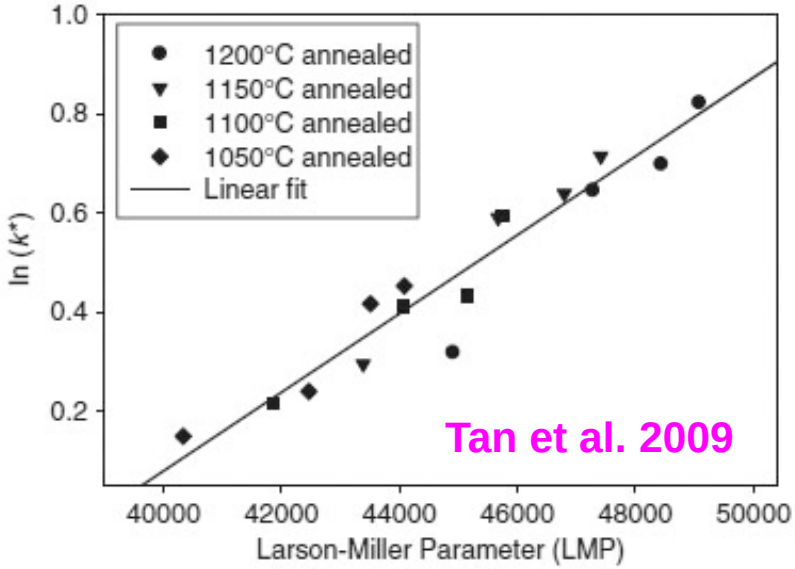
Intrinsic Coating Conductivity due to Sintering

- Intrinsic coating conductivity change due to sintering (annealing) is commonly correlated with LMP (Larson-Miller parameter):

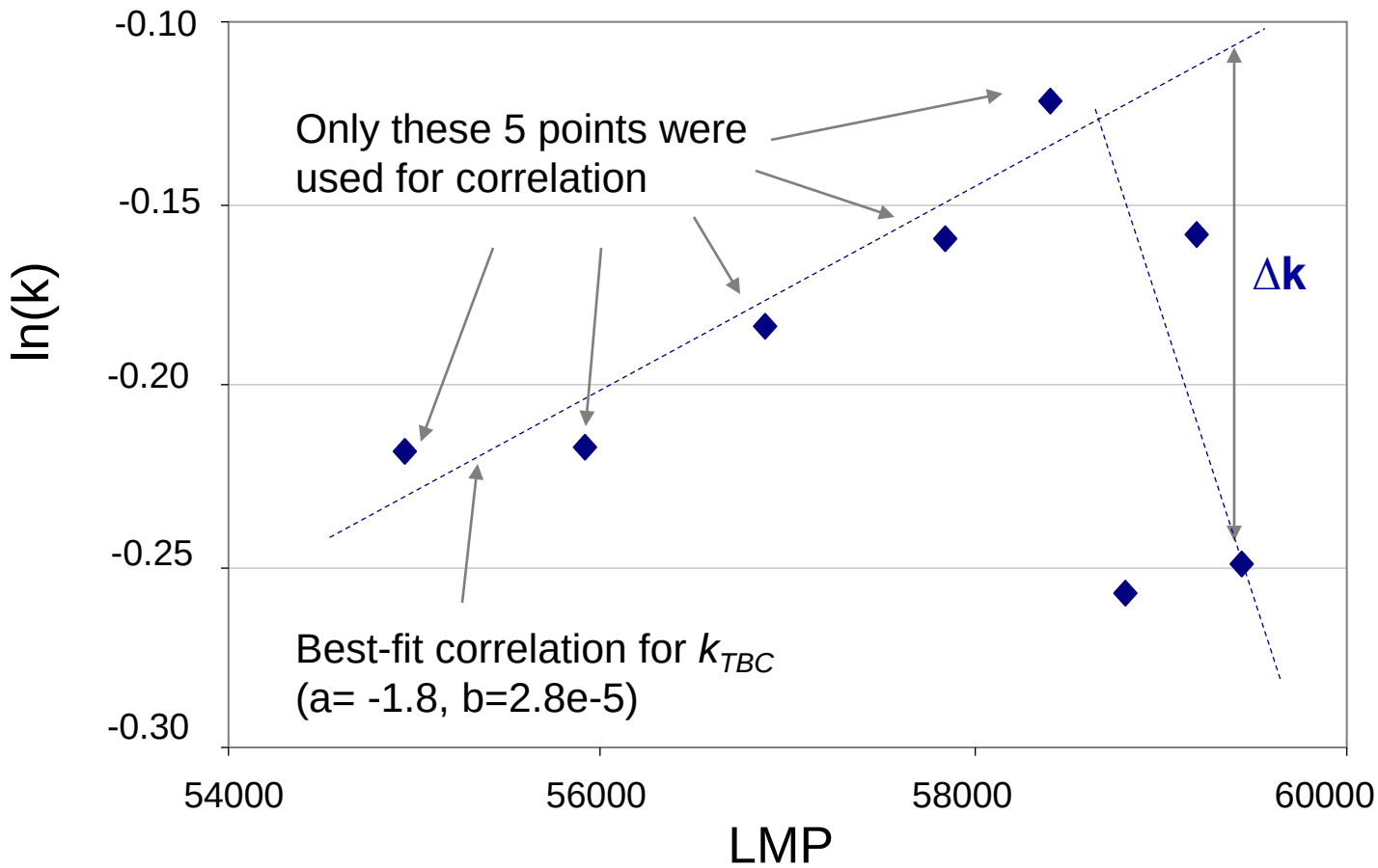
$$\ln(k/k_0) = a + b*\mathrm{LMP},$$

$$\mathrm{LMP} = T*(\ln t + C),$$

k = conductivity (W/m-K),
k_0 = initial conductivity (at t=0),
T = temperature (K),
t = time (s),
a,b,C = fitting constants



Correlation of TBC Conductivity with LMP



- Now the question: what value for TBC failure?

Estimation of Delamination Gap Thickness

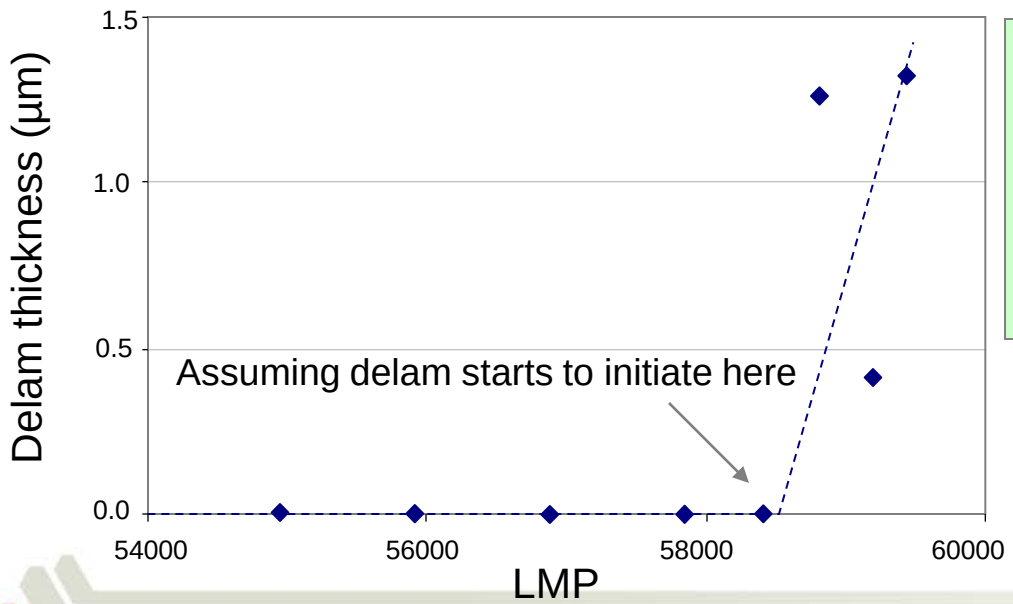
- Average delamination gap thickness L_{air} is estimated from:

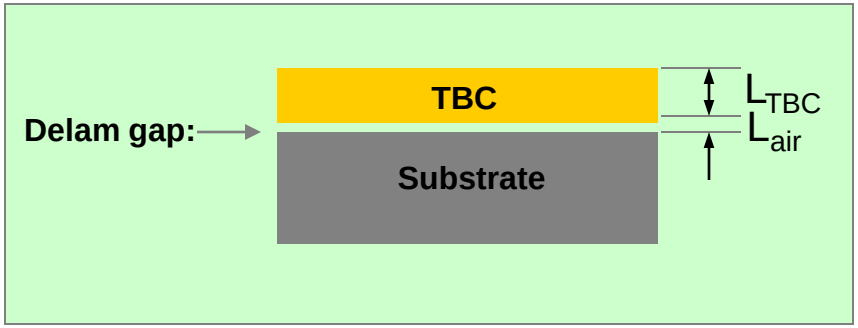
$$\frac{L}{k} = \frac{L_{TBC}}{k_{TBC}} + \frac{L_{air}}{k_{air}}$$

where $L = L_{TBC}+L_{air}$, k, k_{air} and k_{TBC} are all known

- Cernuschi et al. (2010) used this equation to estimate fraction of cracked interface (assumed L_{air} = 2 µm)

Estimated delam gap thickness vs. LMP





- **Data seems to suggest TBC fails at L_{air} ~ 2µm**

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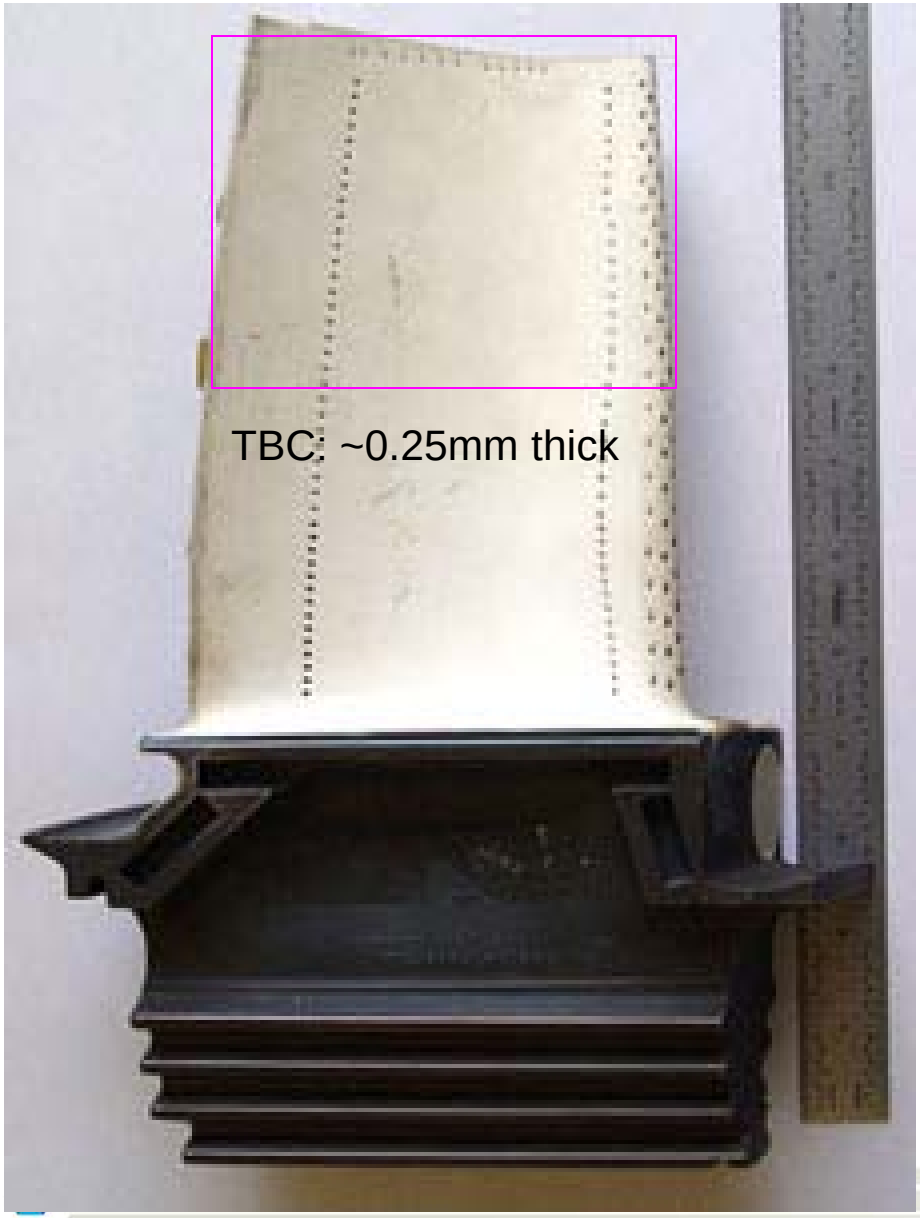
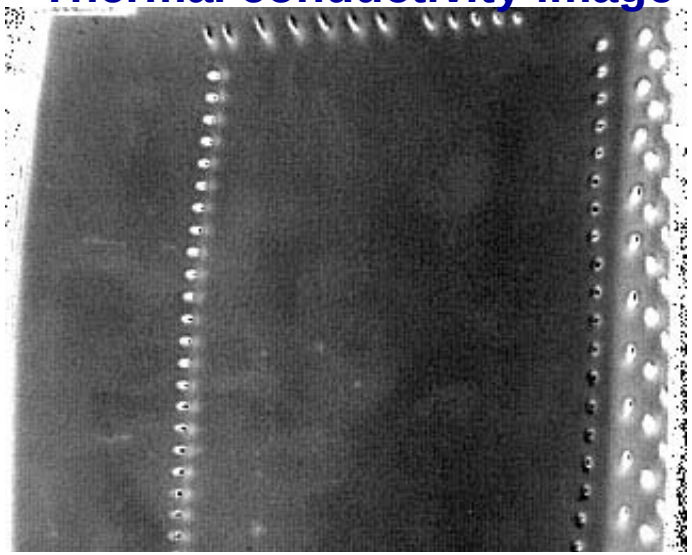
  - Application for a turbine blade
  - Theoretical development for translucent TBCs
  - Theoretical development for multilayer TBCs

TBC Property Measurement for a Turbine Blade

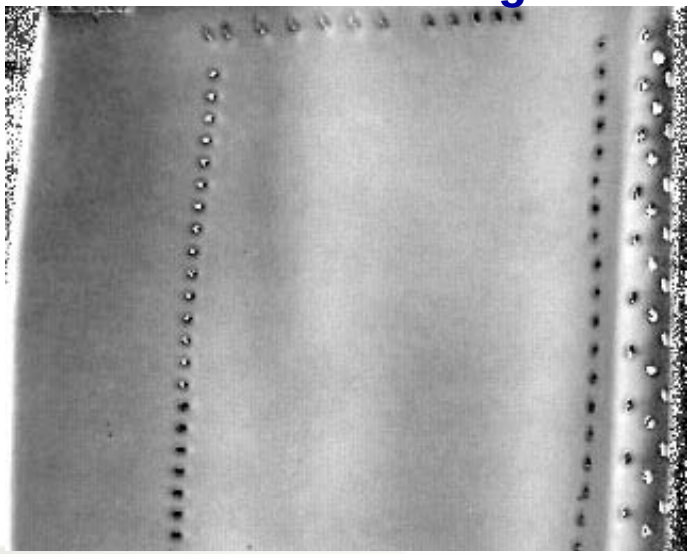


Thermal conductivity image



0.7 W/m-K 2 W/m-K

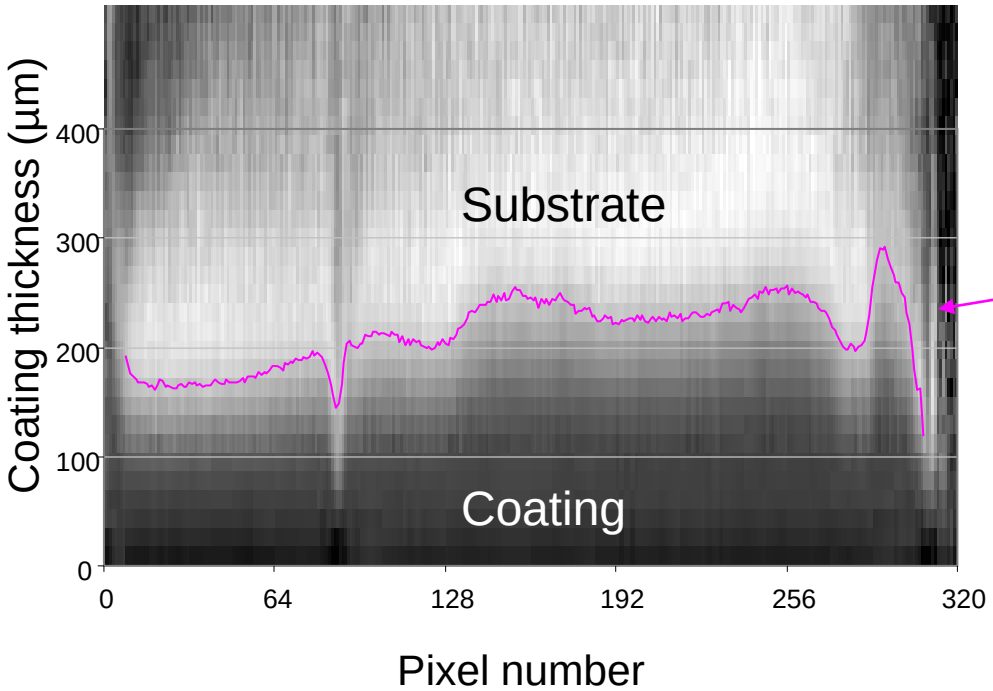
Thickness image



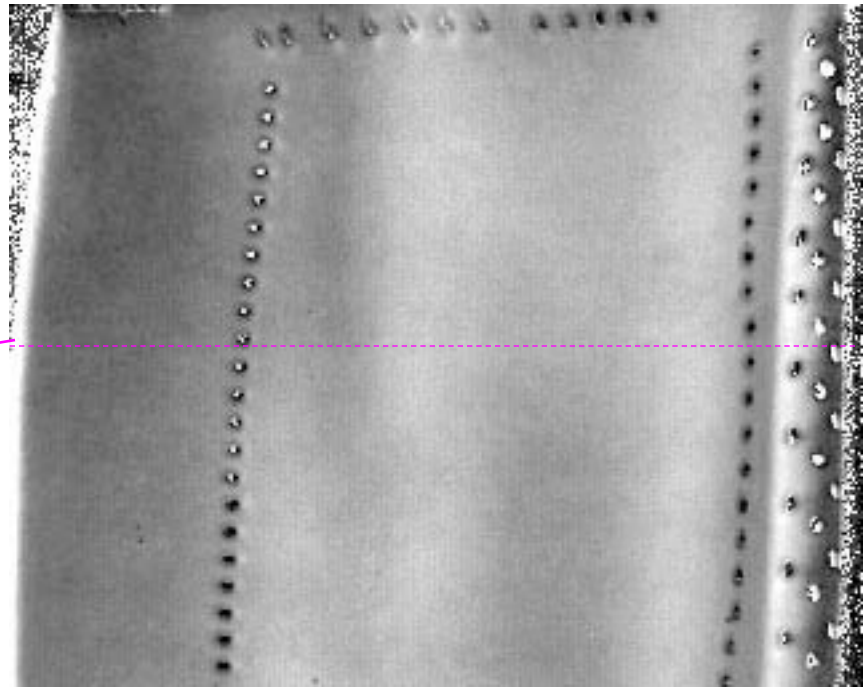
0.1mm 0.3mm

Comparison of TBC Thickness Predictions

Thickness profile superimposed on thermal tomography image



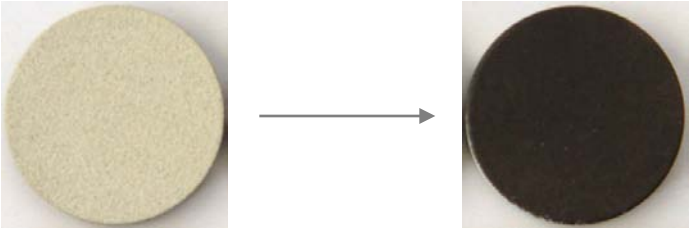
Thickness image – location of profile



Good pixel-by-pixel agreement in predicted coating thickness profiles by two methods!

TBC Translucency (Natural TBCs)

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



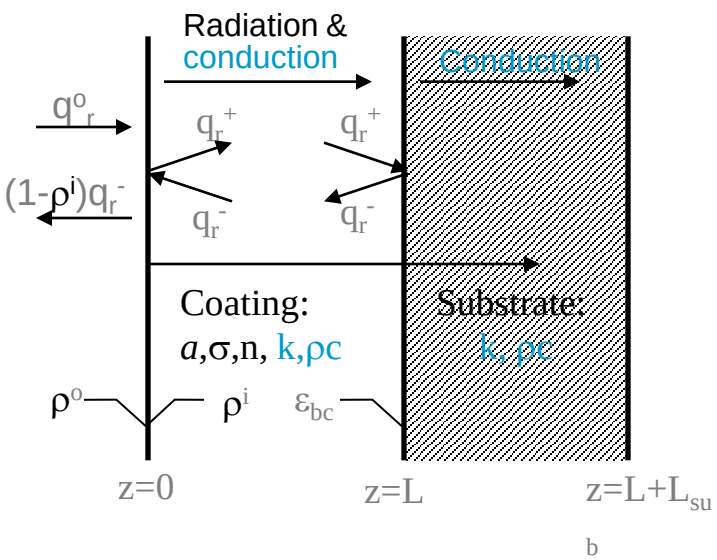
Test methods → Thermal properties

  - Essentially all TBC thermal properties are measured this way
  - However, the graphite coat is not desirable to be used on real components, and it also increases testing cost (extra processes)
- A thermal imaging method for thermal property measurement of translucent TBCs is needed
- Note: TBC translucency is not an issue for flaw detection by thermal imaging methods

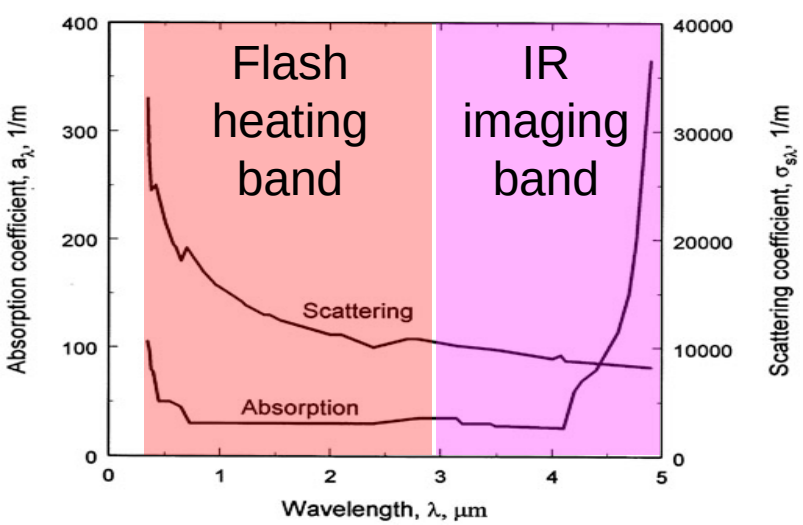
Thermal Imaging Issues for Translucent TBCs

- Both conduction and radiation heat transfer within coating system
  - Radiation models are usually not very precise and difficult to solve
  - There is no theoretical model for flash thermal imaging at present
- TBC optical properties are very complex
  - Large change over a wide wavelength band
  - Very little data

Heat transfer in translucent TBC



TBC optical properties



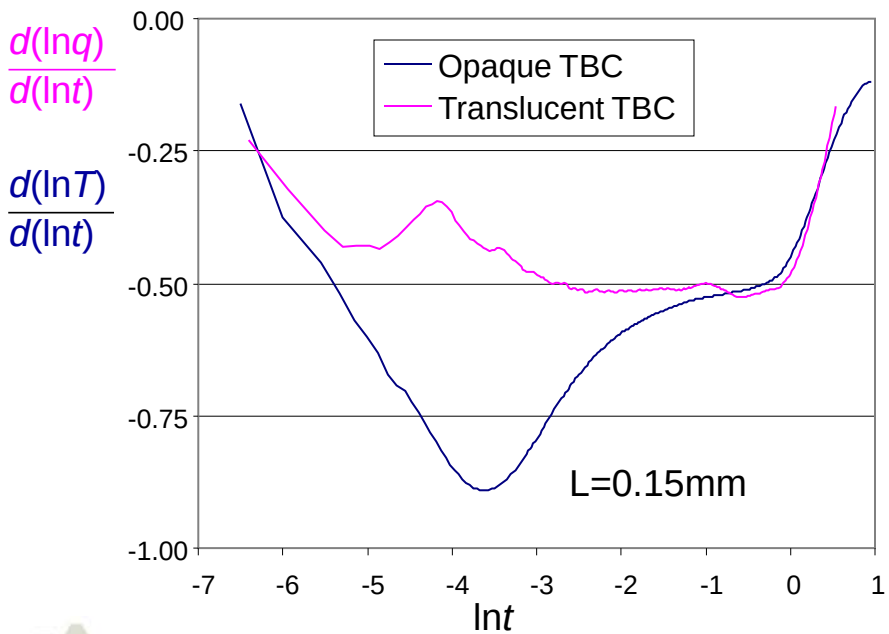
From: Wahiduzzaman & Morel, ORNL Report, 1992

Theoretical Modeling for Translucent TBCs

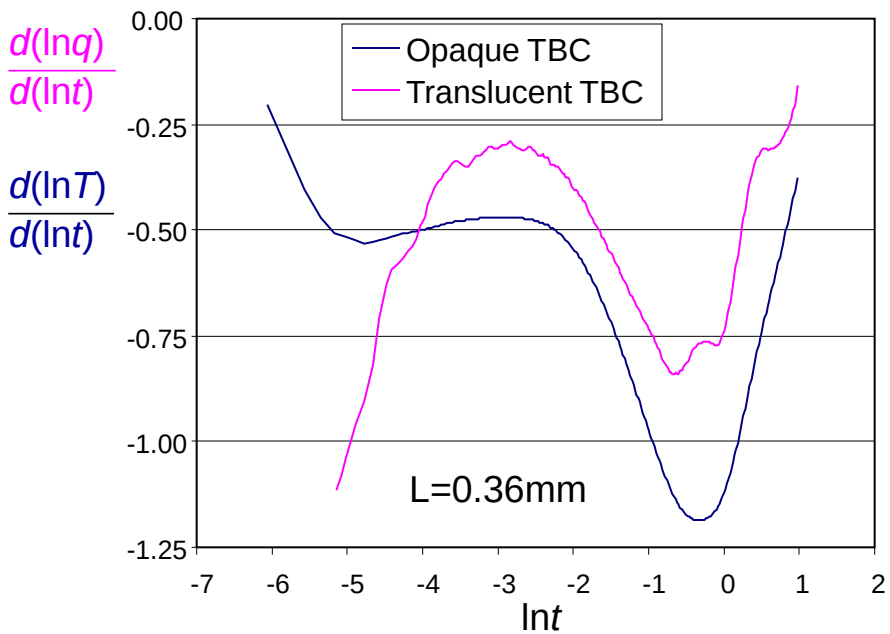
- Thermal imaging data for “opaque” and translucent TBCs are significantly different
- Theoretical model for translucent TBCs is being developed
  - Preliminary study showed that translucent TBCs can be modeled to reproduce the observed experimental data

Thermal imaging data for “opaque” and translucent TBCs

EBPVD TBC

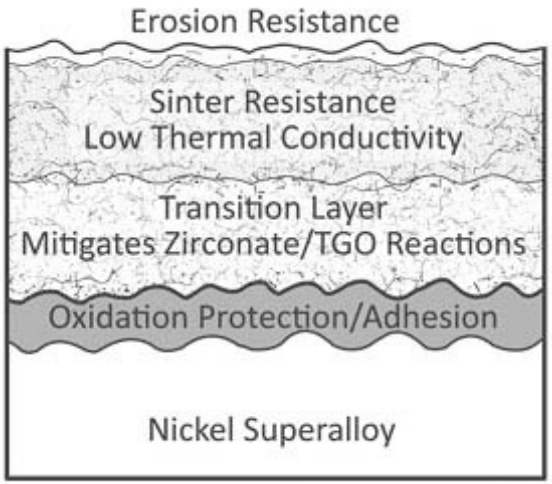


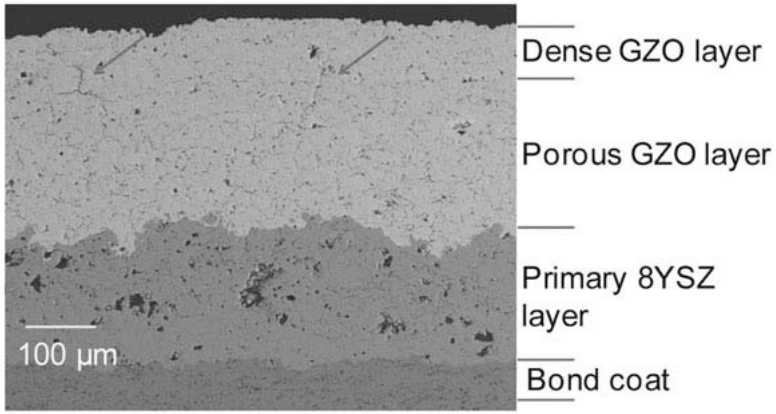
APS TBC



NDE Development for Multilayer 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
- Initial focus will be on measuring TBC property and its change with life
  - Current method can measure average TBC properties
  - Model development is planned to measure properties for individual layers





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

From: Dwivedi, Viswanathan, and Sampath (2013)

Summary

- NDE methods were evaluated for TBC life prediction:
  - Mid-IR reflectance: MIRR value increases ~1% during life (from this study)
    - Small change requires very accurate measurement so can be difficult
    - Data are affected by surface contaminations and require scaling (by a reference)
  - Thermal imaging: conductivity changes ~10% during life
    - Onset of TBC damage (crack development) can be determined
    - A complete NDE model for TBC life prediction was developed →NDE data alone may predict TBC life (with known exposure history)

- Thermal imaging multilayer analysis method development:
  - Successfully applied for imaging of a 3D turbine blade
  - Theoretical development for translucent TBCs is underway
  - Theoretical development and application for multilayer TBCs is planned

Planned Future Efforts

- Continued evaluation of NDEs for TBC lifetime prediction
  - More samples with different thermal exposure conditions
- Development of thermal multilayer analysis method:
  - For complex coatings: translucency, multilayer
  - Continued evaluation of measurement accuracy due to secondary effects, test condition variation, engine component geometry, etc
- Development of thermal tomography method
  - Correlate NDE data with destructive examination results
  - Develop new high-resolution algorithm for data processing