DEVELOPMENT OF NONDESTRUCTIVE EVALUATION (NDE) METHODS FOR STRUCTURAL AND FUNCTIONAL MATERIALS

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Outline

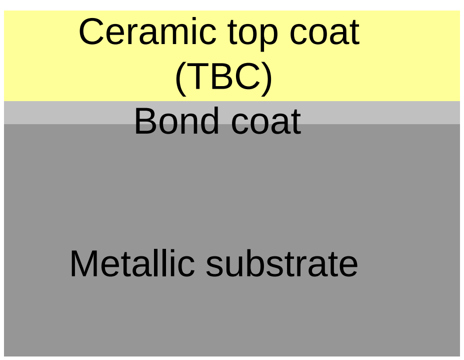
- Current effort of this project is focused on NDE for thermal barrier coatings (TBCs)

- Background for TBC and NDE
- Objectives of this project
- Recent NDE developments
- Summary
- Planned future efforts

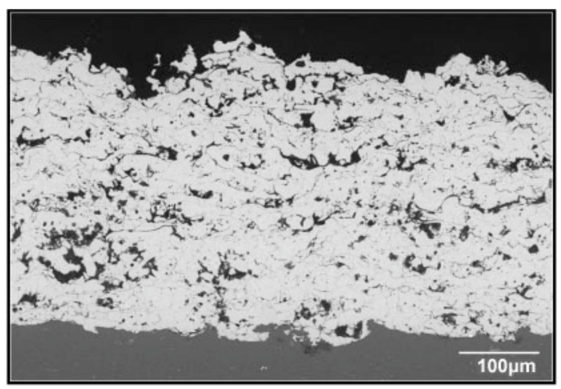
Background – TBC Material and Structure

- Thermal barrier coatings (TBCs) are commonly used to insulate high-temperature metallic components in advanced gas turbines to achieve higher efficiency and low emission operations
  - TBCs may reduce metal surface temperature by >100ºC
- Standard TBC material is 7-8wt% yttria stabilized zirconia (7-8YSZ)
- TBC is usually processed by air plasma spraying (APS) or electron beam – physical vapor deposition (EB-PVD)
  - TBCs have low thermal conductivity and can be single or multiple layers

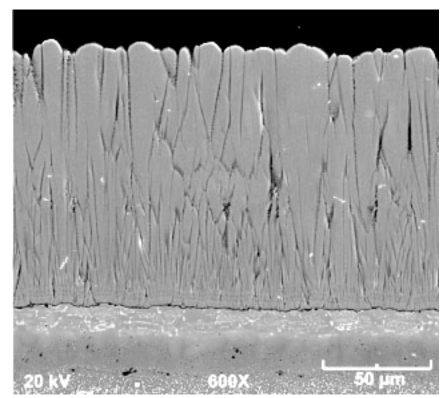
Schematic of TBC system



APS TBC



EB-PVD TBC



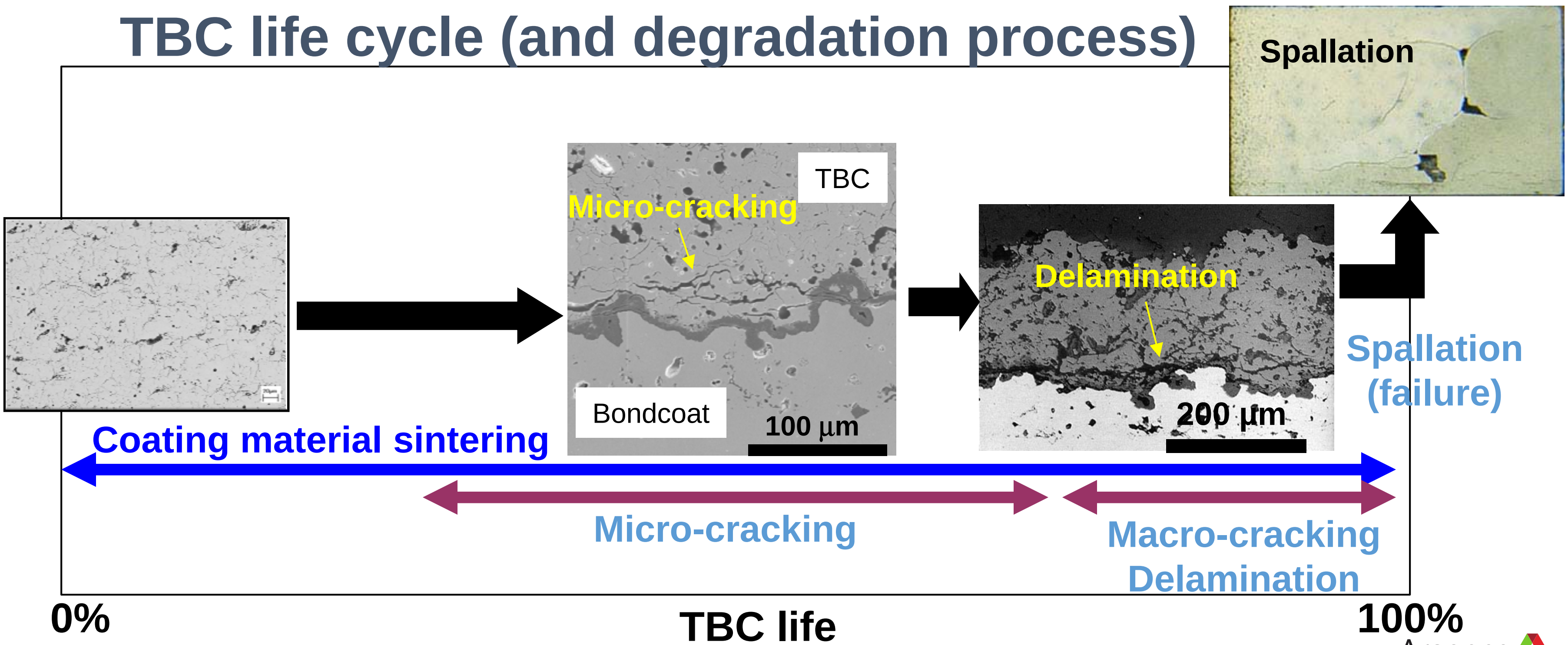
Background – TBCs on Engine Components

- TBCs have become "prime reliant" material → their condition monitoring and life prediction is needed (by NDE)
- Because TBC is applied on entire component surface, entire surface inspection is necessary (by imaging NDE)

Uncoated and TBC-coated turbine blades

Background – TBC Degradation with Life

- TBC property/structure degrades during its lifetime:
  - (1) TBC continuously sinters with conductivity increase
  - (2) Interface cracks develop and lead to delaminations near end life
- These characteristics have been explored by NDEs



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Background – NDE Development for TBCs

- Many NDE technologies were evaluated for TBCs in last few decades → generally not very successful
- Current TBC analysis still relies on destructive methods
- Pulsed thermal imaging (PTI) with advanced data processing algorithms (MLA and TT) developed under this project has emerged as a promising NDE for entire TBC lifetime evaluation:
  - Inspection of fabricated TBC components (thickness, conductivity)
  - TBC health monitoring and life prediction during service
  - Detection of TBC flaws/damages (cracks, delaminations)

Objectives of This Project

- Develop and demonstrate advanced thermal imaging NDE technologies for coatings:
  - For coating quality inspection
    - Coating property measurement: multilayer analysis (PTI-MLA) method
    - Coating defect detection: thermal tomography (PTI-TT) method
  - For TBC life prediction
    - Modeling degradation of TBC property (measured by PTI-MLA) with life
- Develop NDE methods for functional materials (gas-separation membrane, fuel cell, etc)
  - Synchrotron x-ray CT, thermal tomography

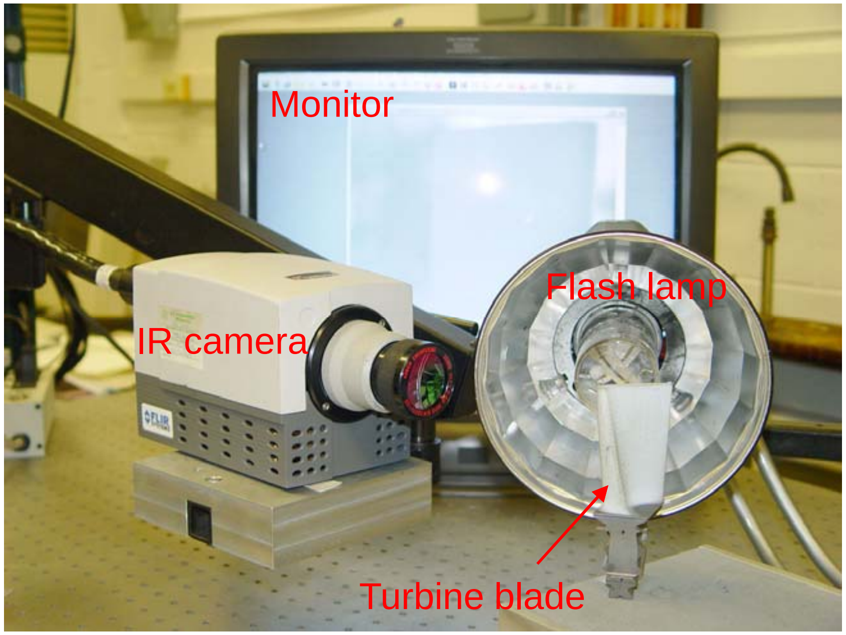
Recent NDE Developments

- Development/validation of PTI-MLA NDE method
  - For complex TBC systems
- Evaluation of low-cost IR camera for industrial applications.

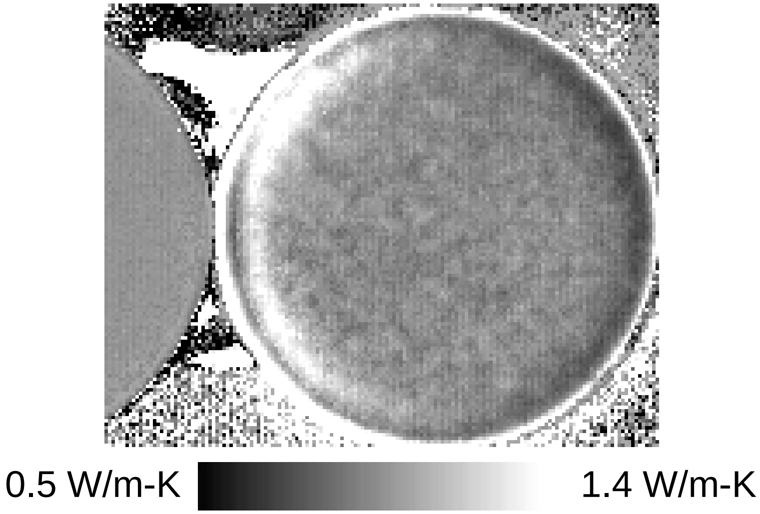
Pulsed Thermal Imaging – Multilayer Analysis (PTI-MLA)

- PTI-MLA consists of a pulsed thermal imaging (PTI) experimental system and a multilayer analysis (MLA) data-processing code
  - MLA development is the focus of this project
- PTI-MLA images two coating properties over entire coating surface
  - thermal conductivity and heat capacity (or thickness)

PTI experimental setup

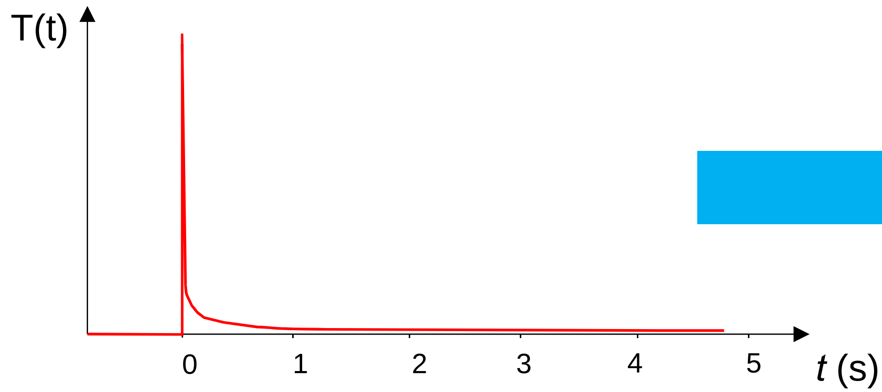


Thermal conductivity imaging

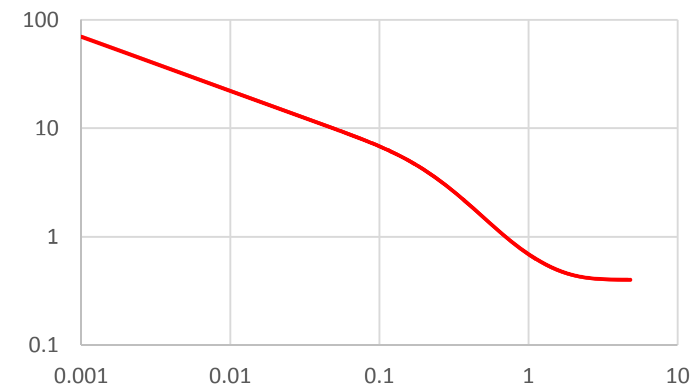


PTI-MLA: Characteristics of Experimental Data

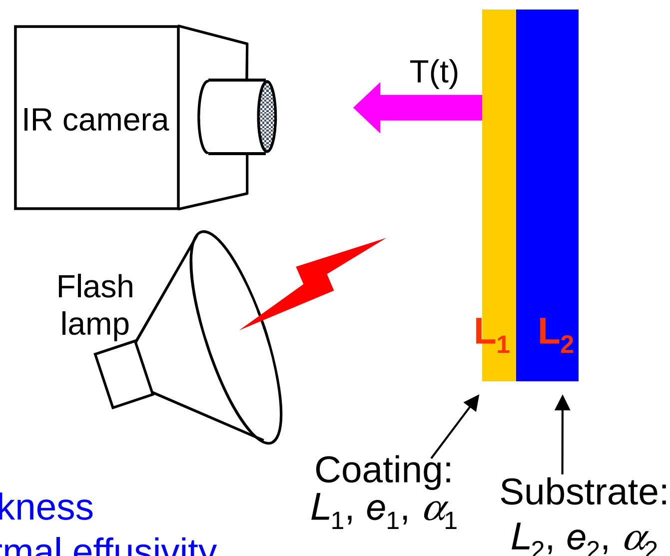
Temperature profile for a single pixel



Temperature profile T(t)

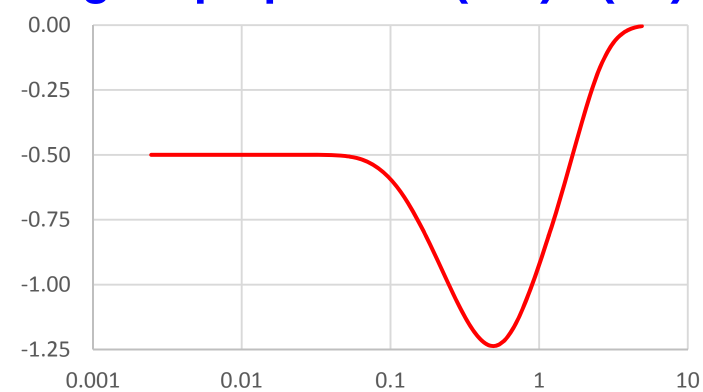


Test setup



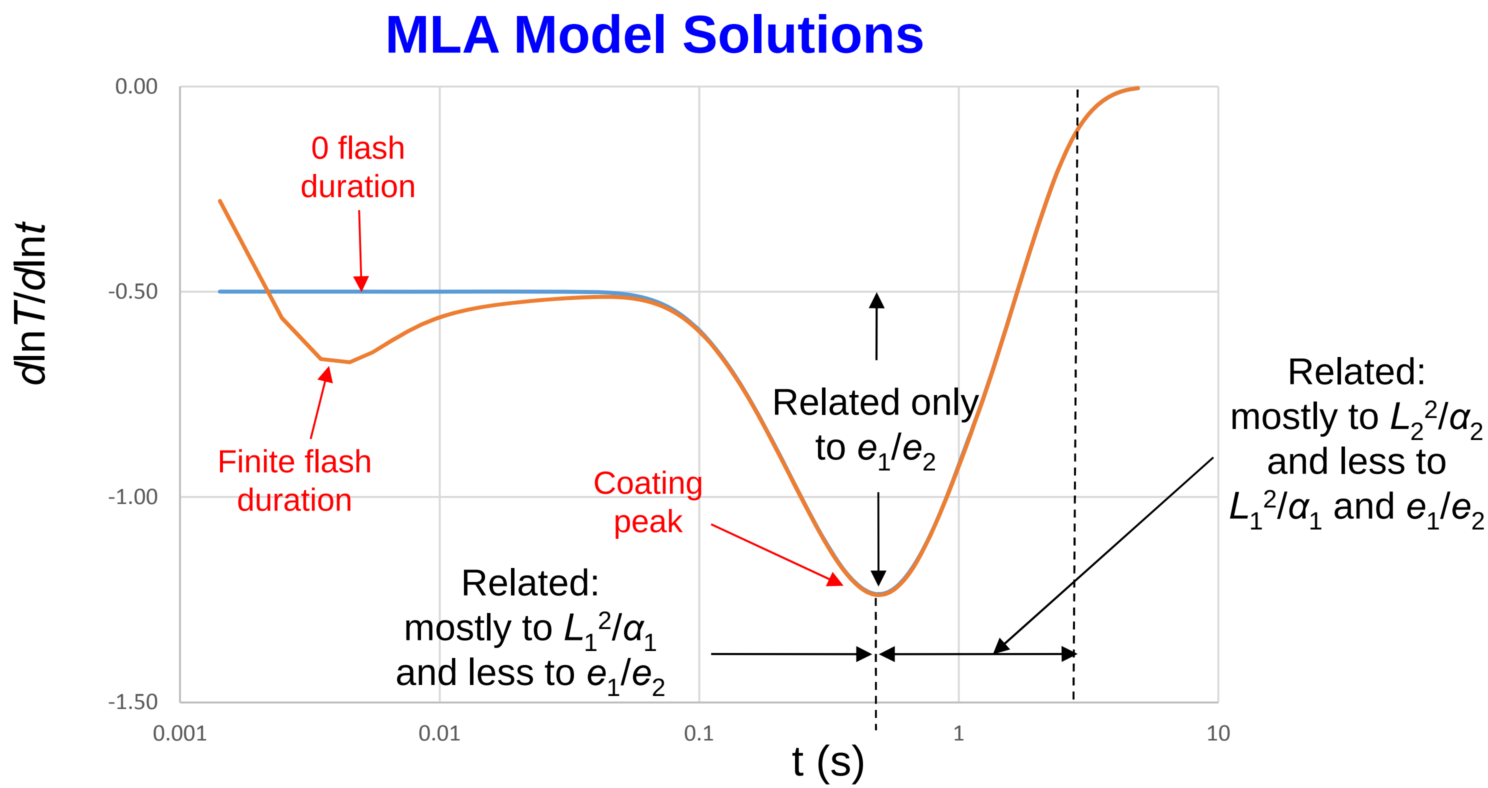
L – thickness
e – thermal effusivity
α – thermal diffusivity

Log slope profile $d(\ln T)/d(\ln t)$



Slope $d(\ln T)/d(\ln t)$ is dimensionless and very easy to view the effects of coating parameters, so is used in all analysis

PTI-MLA: Principle for Coating Property Measurement

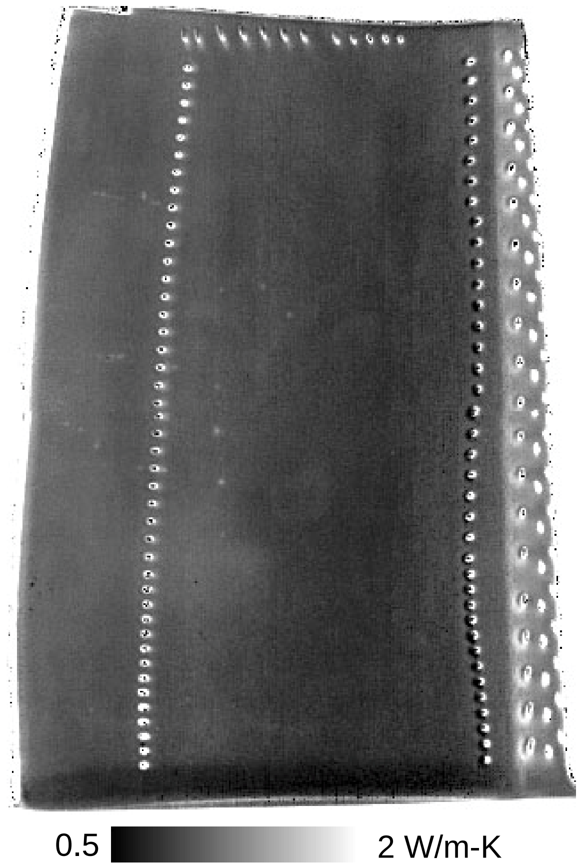


- MLA method: solve governing equation for layered materials and then fit the solution with experimental data
- MLA determines 3 parameters: e_1/e_2, L_1^2/α_1, and L_2^2/α_2 (substrate properties e_2 & α_2 are known)
  - MLA is not sensitive to flash duration and early data deviation

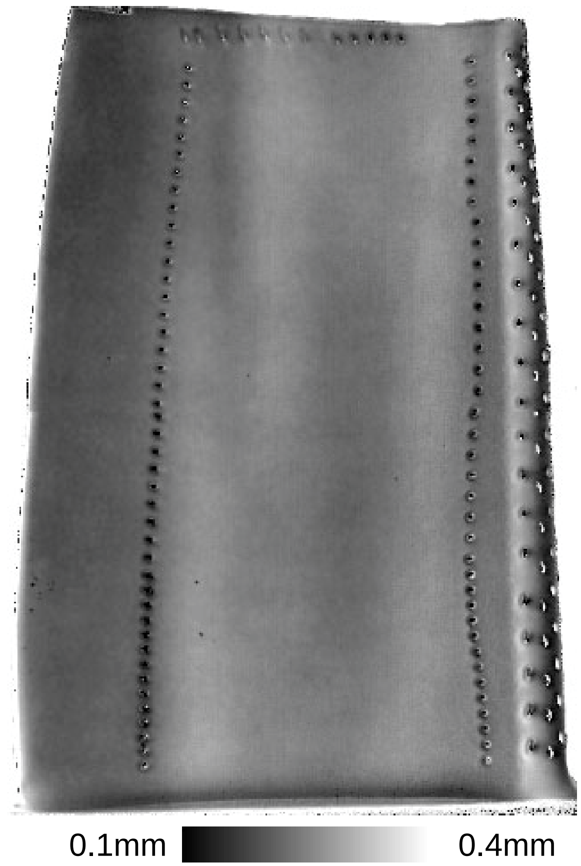
Typical PTI-MLA Results for TBC on Turbine Blade

A TBC-coated gas-turbine blade

TBC thermal conductivity image



TBC thickness image



Entire test and data-processing time for such results can be obtained within a few minutes

Summary of PTI-MLA Capabilities

- It measures two coating parameters per pixel: e_1 and L_1^2/α_1
  - Coatings have three parameters: e_1, α_1, and L_1
    - It determines k_1 and $\rho_1 c_1$ when thickness L_1 is known
    - Or it determines k_1 and L_1 when heat capacity $\rho_1 c_1$ is known
- It automatically processes all pixels to construct entire images
  - No operator action in data processing, little in test
- Absolute measurement error could be <2%:
- PTI-MLA was awarded a 2015 R&D100 Award Finalist

Extending MLA for Complex Coating Systems

- Multilayer (3 layer)
  - Effect of bondcoat (TBC-bondcoat-substrate)
  - Double-layer TBC (TBC1-TBC2-substrate)
- Thin substrate thickness

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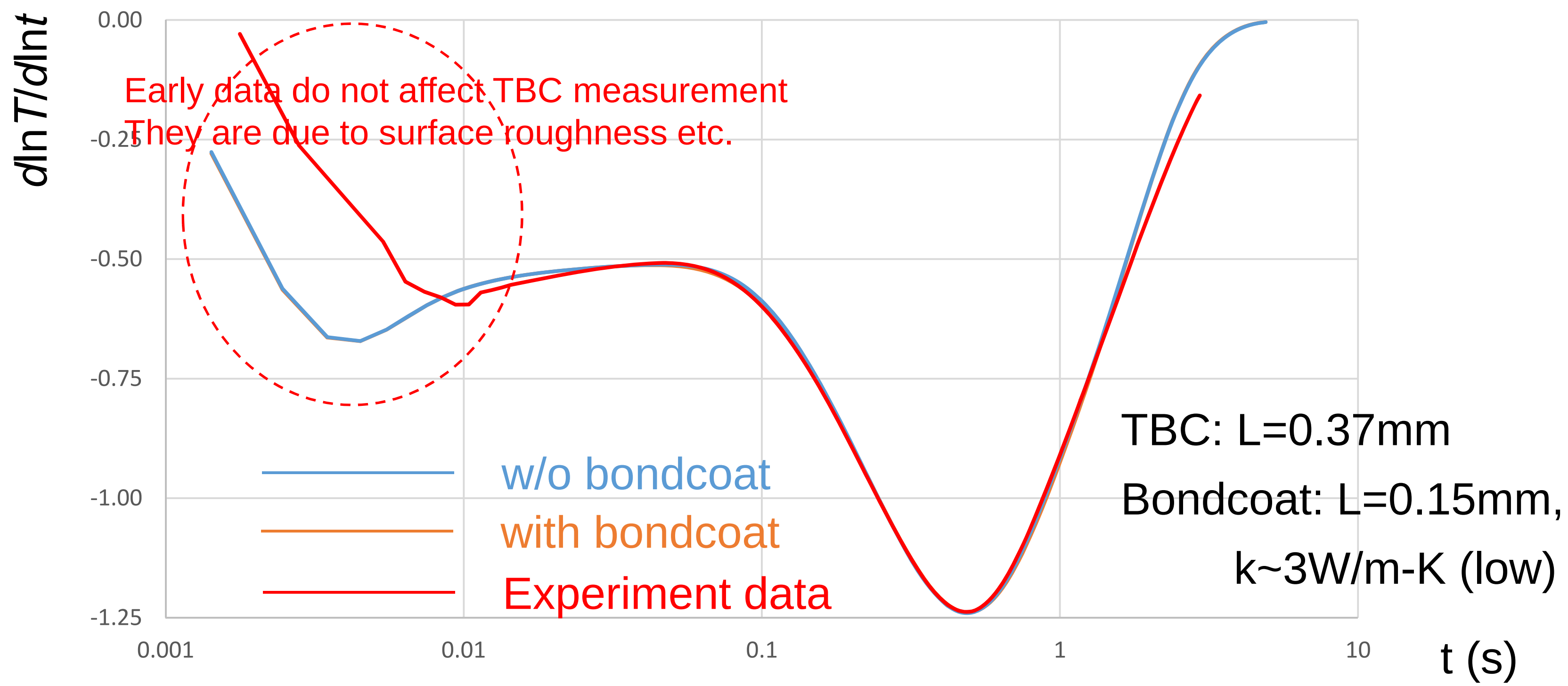
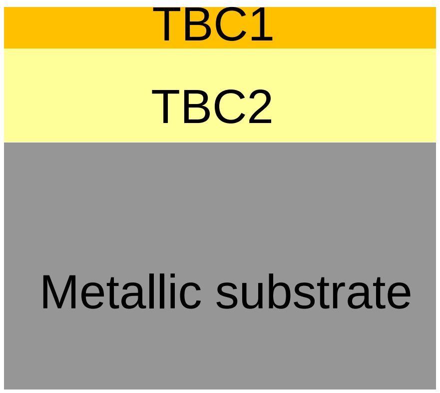
Bondcoat effect to measured TBC properties



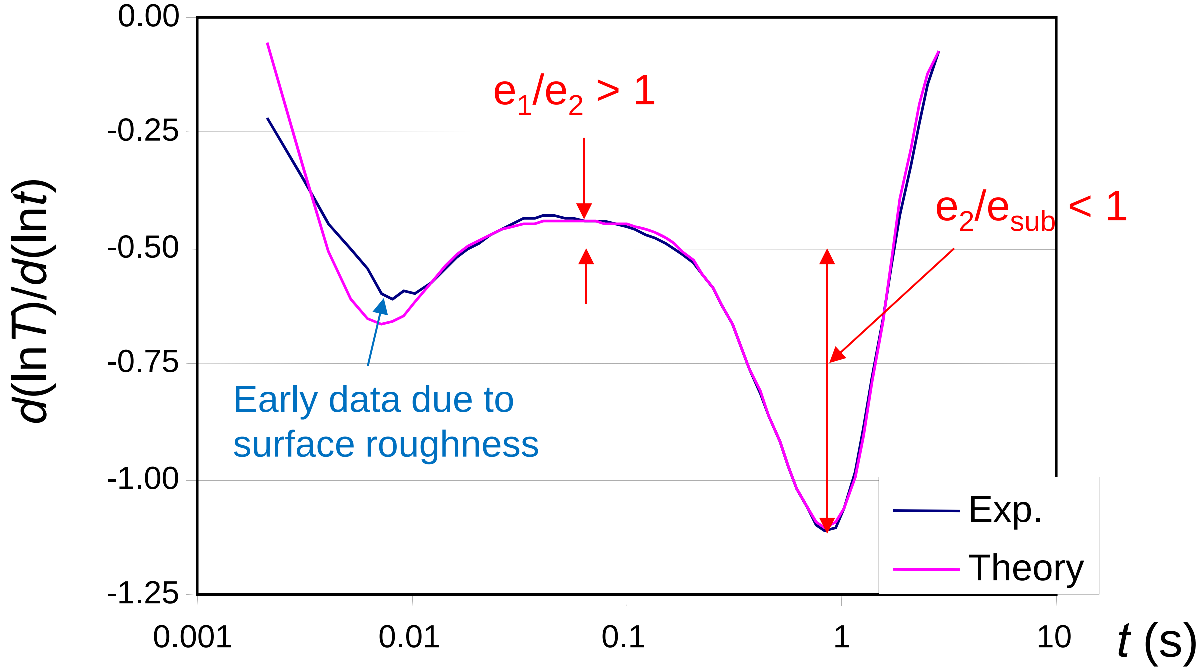
- TBC properties determined from 3-layer model (TBC-bondcoat-substrate):
  - k = 0.78W/m-K, ρc=2.00J/cm³-K, with L=0.37mm
- TBC properties determined from 2-layer model (TBC-substrate):
  - k = 0.73W/m-k, ρc=2.22J/cm³-K, with L=0.37mm
- Difference for k is 6% and for ρc is 10% (for such analysis the bondcoat property has to be known)

PTI-MLA for 2-layer TBC (TBC1-TBC2-substrate)

2-layer TBC



A typical fitting data for a pixel

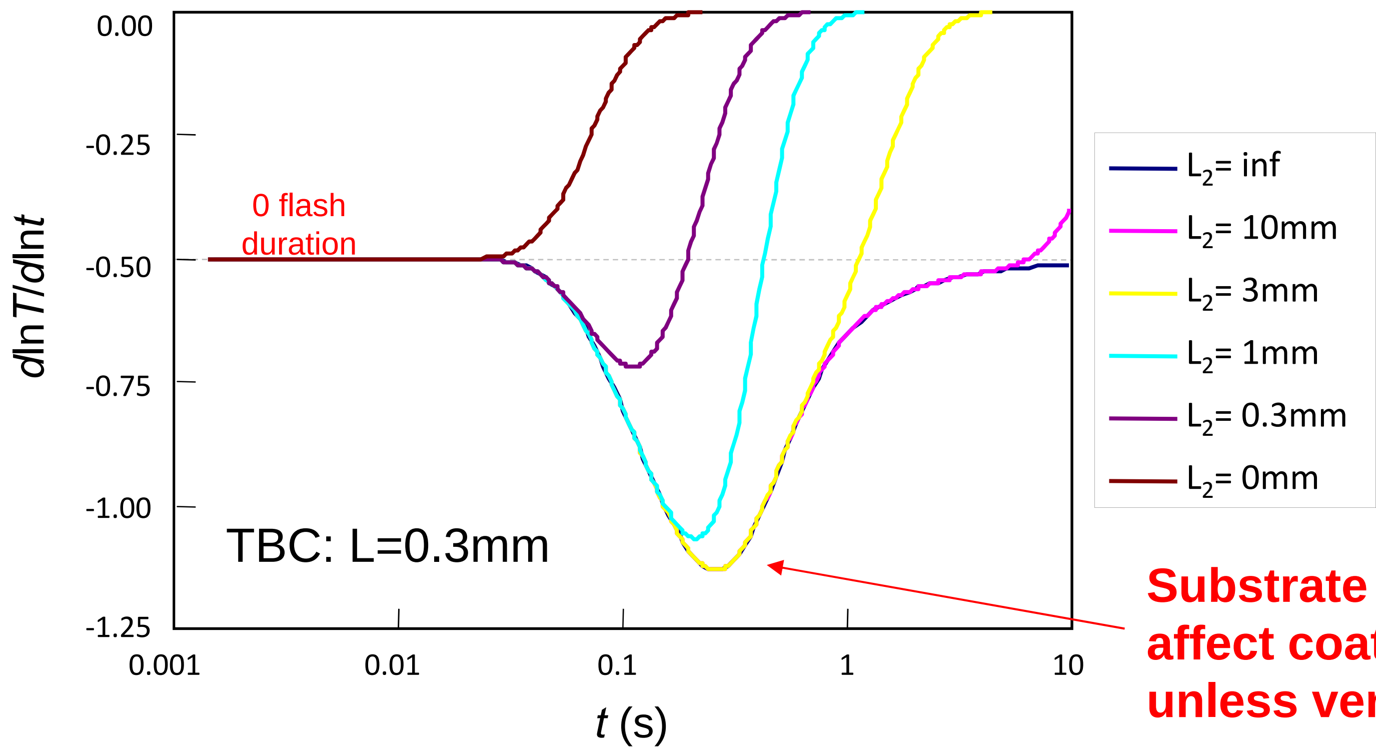


- Measured properties for each TBC layer (L_1/L_2=0.2):
  - k_1/k_2=1.27, $\rho c_1/\rho c_2$=1.26 (only ratios are listed here)

Effect of Finite Substrate Thickness

- Many engine components have varied and thin metallic substrate walls; failure to account for thin substrate may cause significant error
- Substrate thickness is also measured by PTI-MLA
  - This is the only NDE method with such capability

Effect of substrate thickness to thermal imaging data



Substrate does not affect coating peak unless very thin

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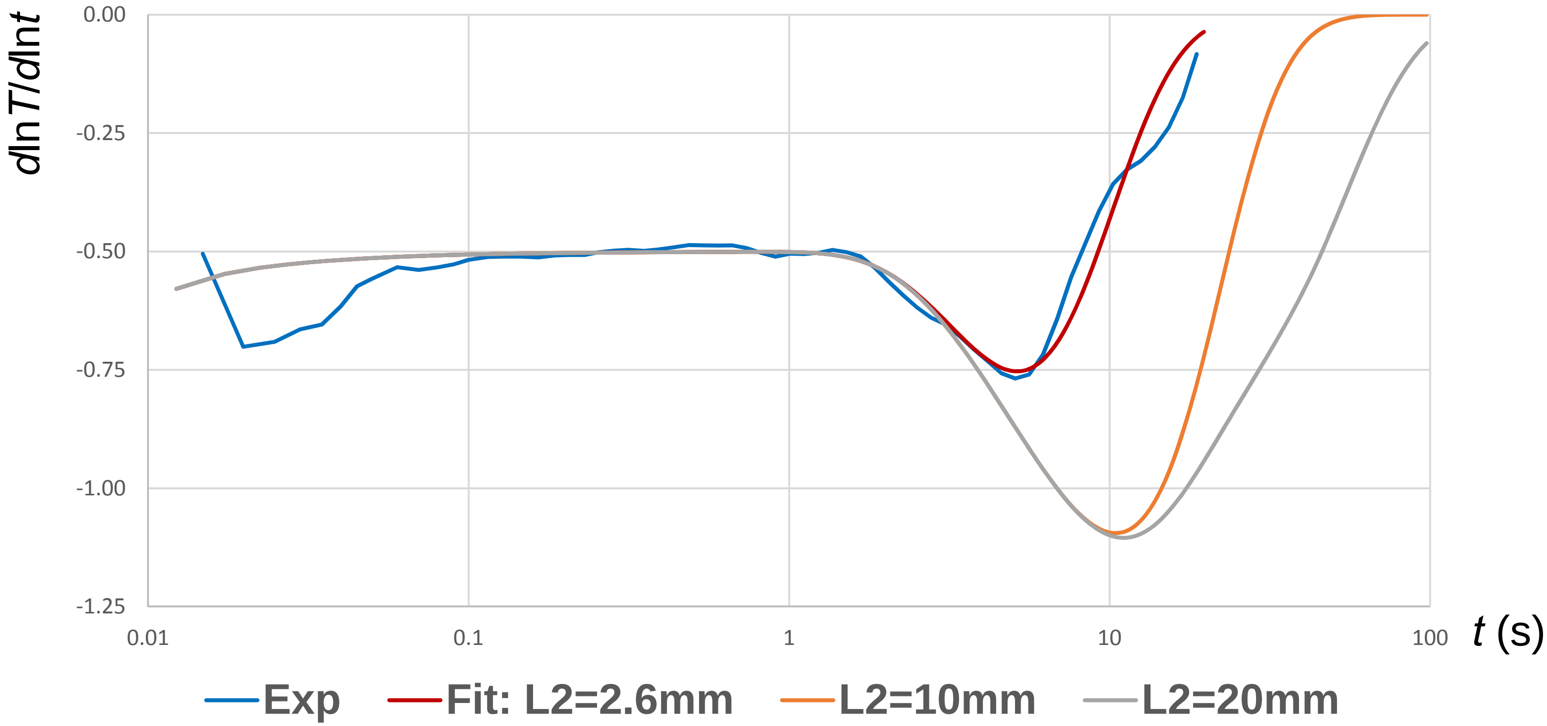
PTI-MLA Measures Substrate Thickness at each pixel



- MLA correctly determined TBC and substrate thickness of 2mm and 2.6mm
- Note: Experimental data are noisy due to thick TBC and low flash energy

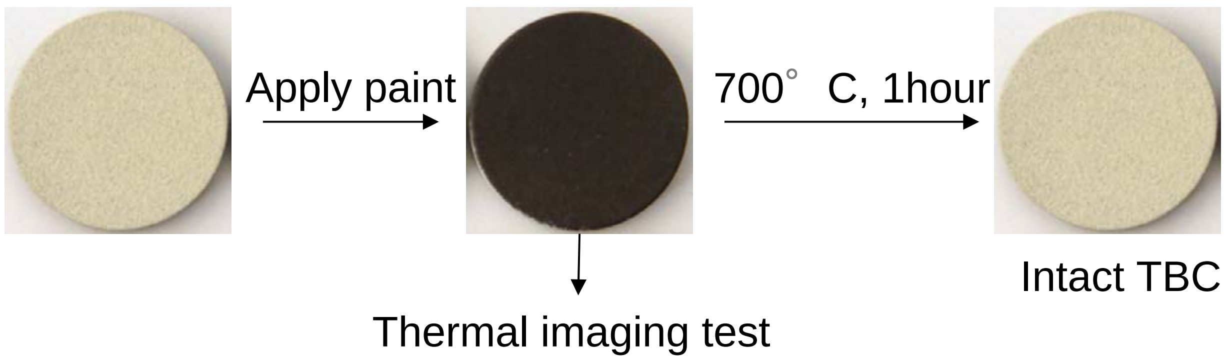
PTI-MLA for Industrial Applications

- Current MLA model may handle essentially all complex TBC systems in real engine components

- Two factors limit PTI-MLA for industrial applications:
  - TBC translucency requires surface treatment
  - High-cost and large size of high-end IR cameras
- Is there a simple solution?

TBC Surface Treatment for Thermal Imaging

- Current PTI-MLA 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



- However, TBC is naturally opaque at long IR wavelengths >7μm, so paint is not needed if we use a LWIR camera (sensitive in 7-14μm)
  - Although TBC is still translucent in flash heating wavelength band

IR Cameras for PTI System

State-of-the-art IR camera: SC4000
(Cooled, MWIR, 320x256, high speed)

Low-cost IR camera: A35
(RT, LWIR, 320x256, 60Hz)

- Cost of a PTI system comes mainly from the IR camera
- Small, cheap (0.1X), RT, LWIR cameras are widely available
  - It addresses both TBC translucency and cost issues
- An A35 camera was evaluated for TBC property measurements

Evaluation of a FLIR A35 IR camera

- Various TBC samples were tested using SC4000 and A35
  - TBC thickness range was >0.25mm
  - Some TBCs were unpainted and later painted black
    - Note: SC4000 can only measure TBCs with black paint

- Results from A35 were compared with those from SC4000 which were considered to be “exact”
  - Compared parameters: TBC thickness and thermal conductivity

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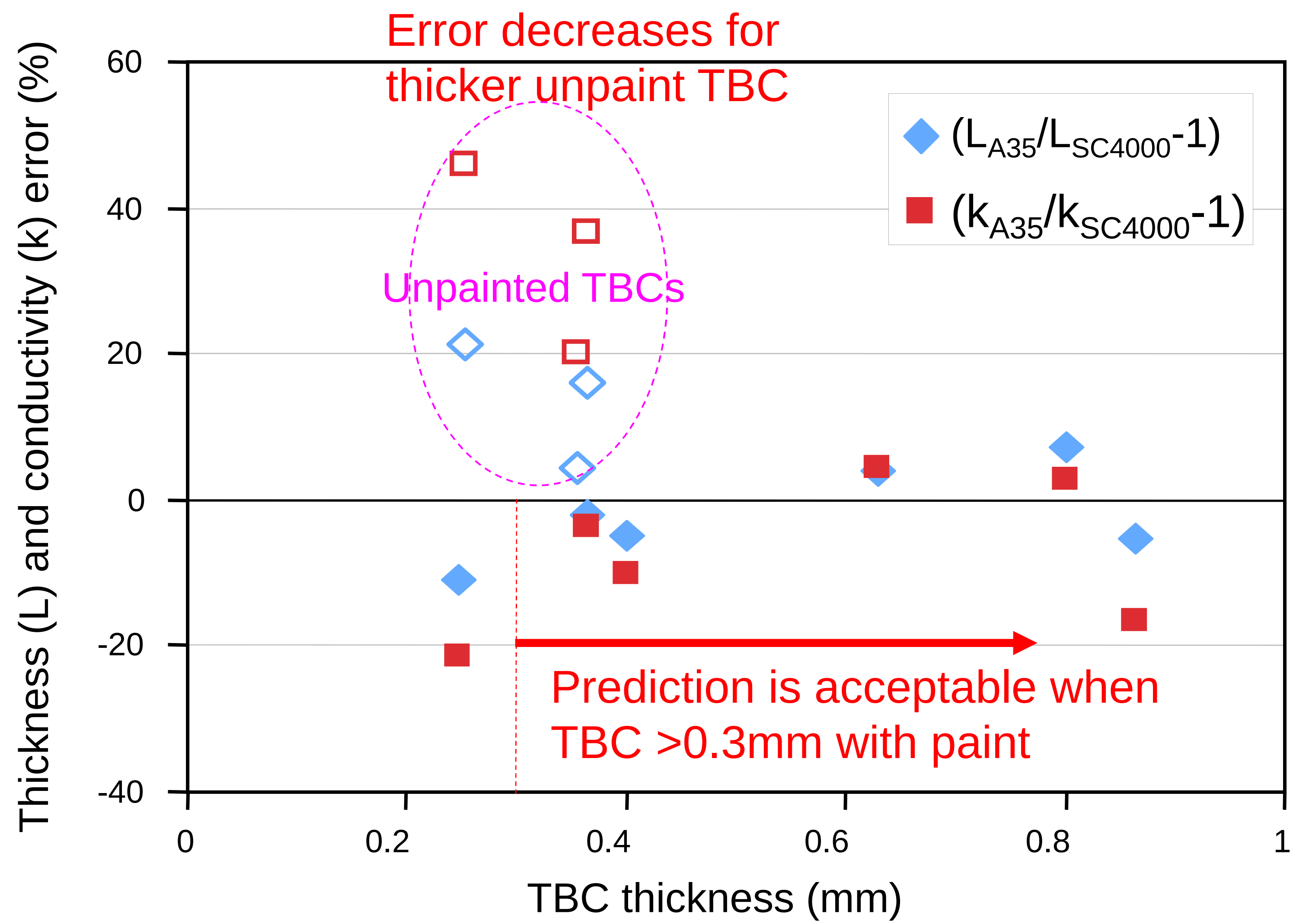
TBC measurement error by A35 camera



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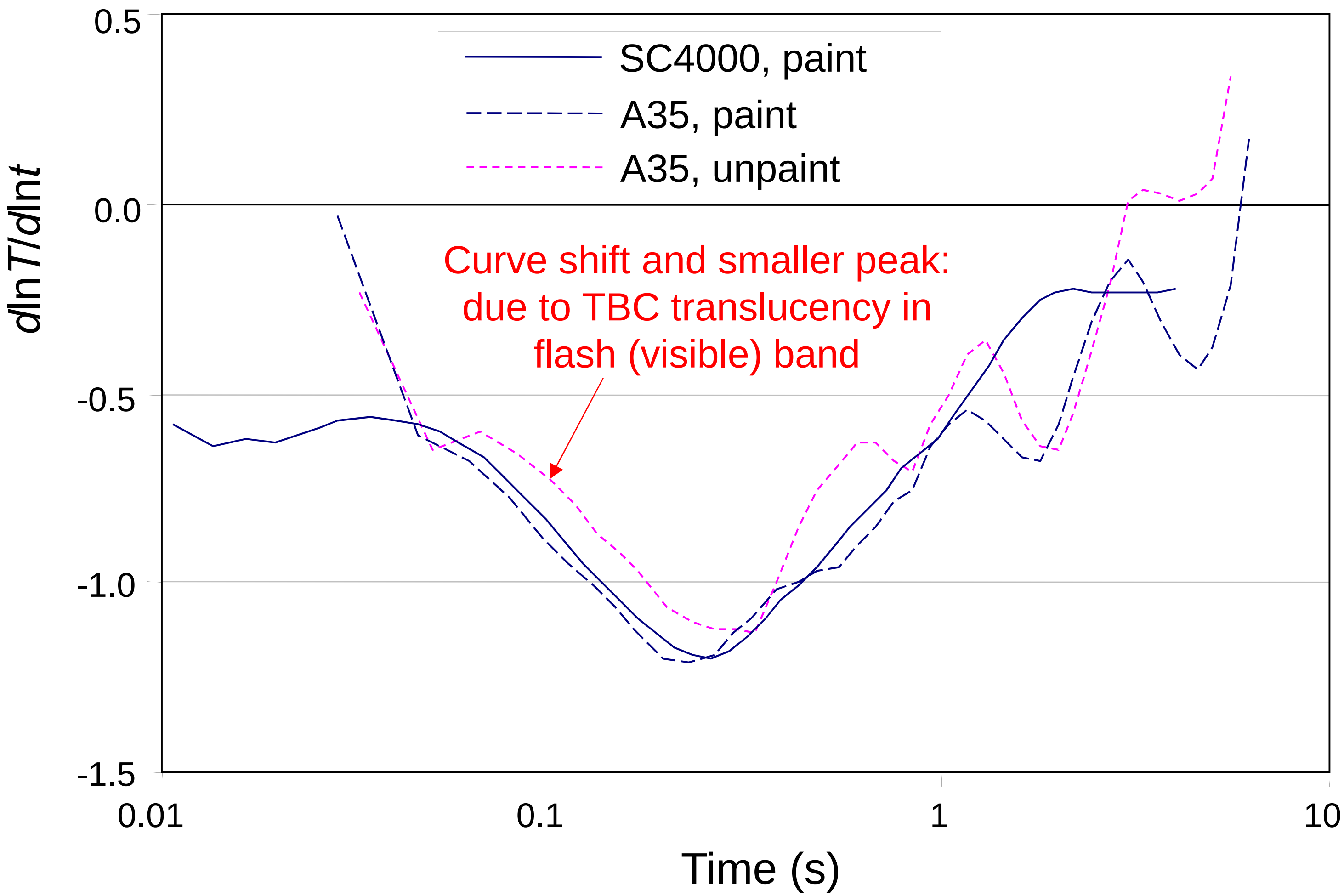
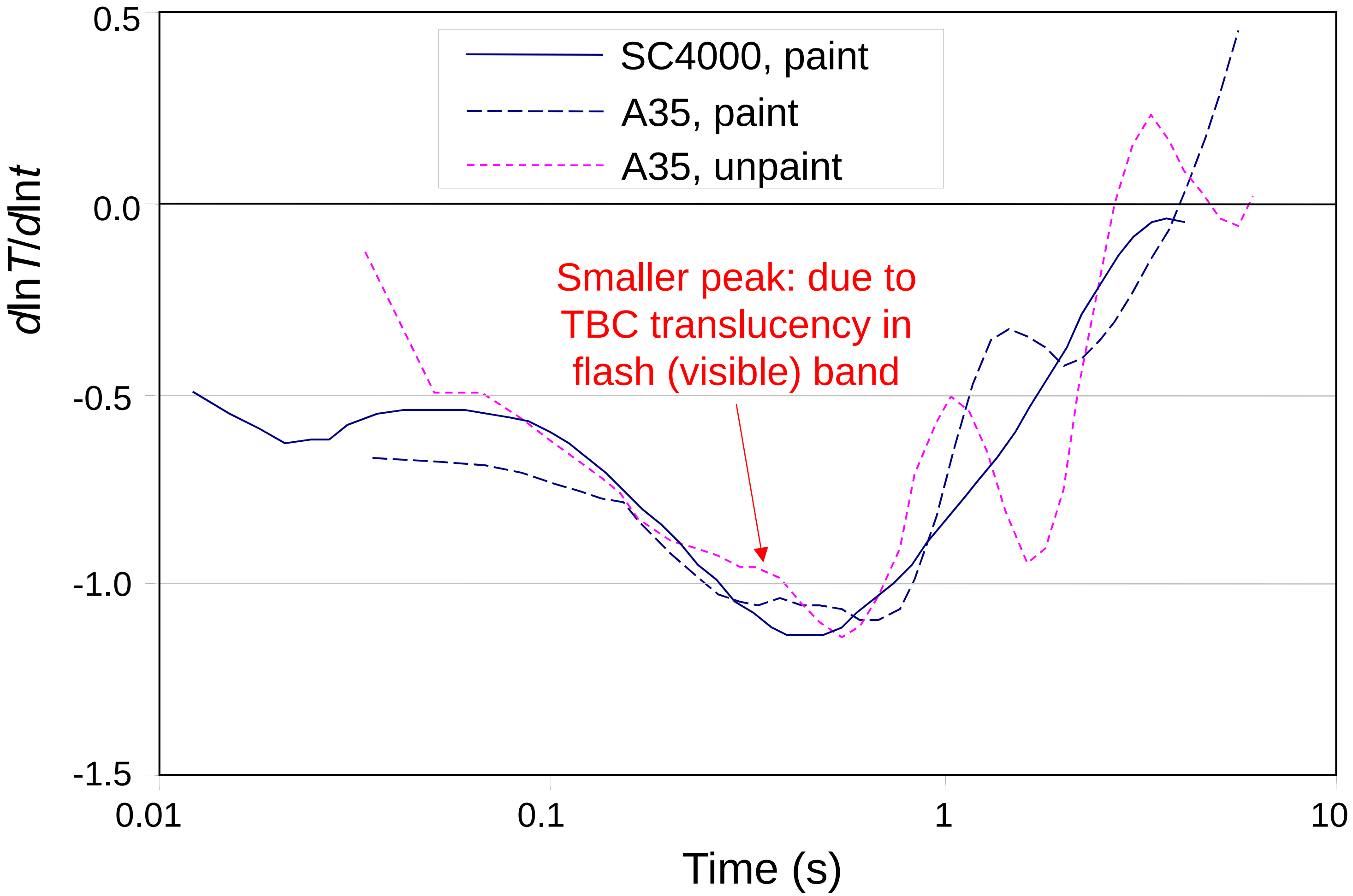
Comparison of pixel data for 0.25mm-thick TBC



Note: experimental curves have been smoothed by the code

Comparison of pixel data for 0.36mm-thick TBC



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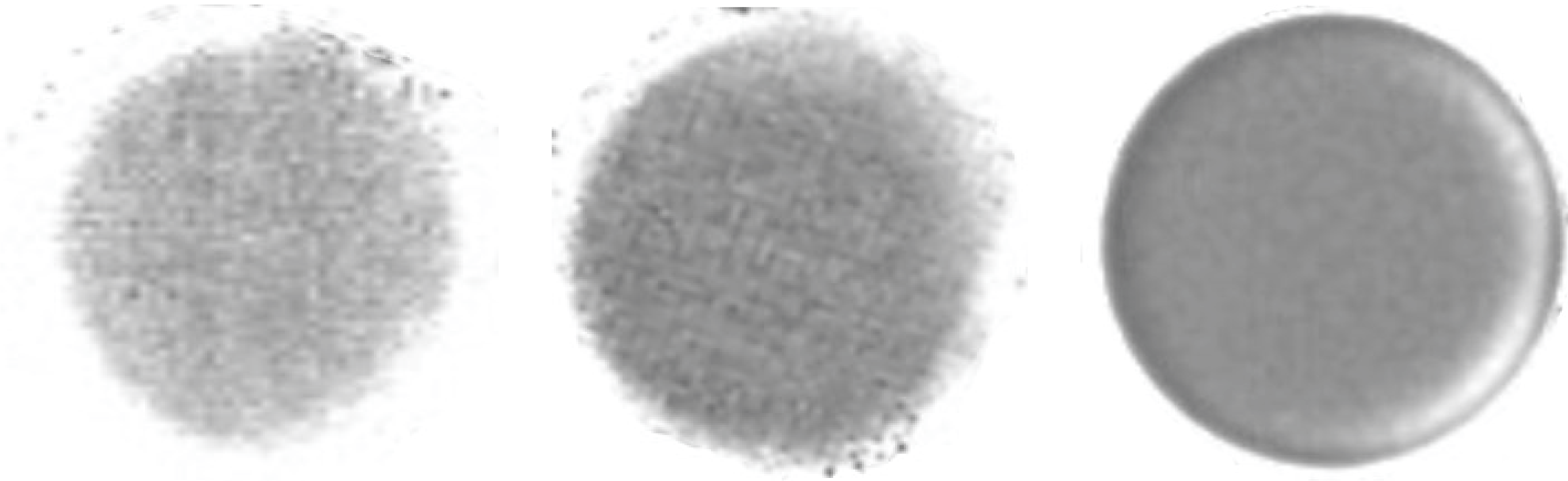
Measured conductivity images for 0.36mm TBC

A35, unpainted TBC | A35, painted TBC | SC4000, painted TBC



0 ▬ 2 W/m-K

- Comparison for TBC thickness images are better
- Development of a optical model for flash heating band is needed when using low-cost IR cameras for testing thinner TBCs

Summary

- Pulsed thermal imaging multilayer analysis (PTI-MLA) developed:
  - Fully automated to process entire images of TBC properties
  - Absolute prediction error of <2% is possible
  - Capable to analyze (all) complex TBC systems for real engine parts
    - Multilayers
    - Variable substrate thickness
  - An 2015 R&D100 Award Finalist

- PTI-MLA was evaluated for using low-cost IR camera:
  - Benefits: low cost, no paint, small camera for easy field application
  - With paint, acceptable performance for TBCs >0.3mm thickness
  - Without paint, an optical model for flash band needs to be developed for thin TBCs (<0.5mm ?)

Planned Future Efforts

- Continued development of TBC life prediction models
- Thermal NDE method developments:
  - Modeling of flash heat absorption by translucent TBCs
  - Development of effective display method for NDE data
  - Investigation for field applications of PTI-MLA
  - Thermal imaging application for additive manufacturing
- Tech transfer to industry