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

J.G. Sun
Argonne National Laboratory, Argonne, IL, USA

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Outline

- Objective of this project
- NDE for thermal barrier coatings (TBCs)
- NDE for additive manufactured (AM) samples
- Summary
- Planned FY2017 effort

Objectives of This Project

- Develop and demonstrate advanced NDE methods for structural and functional materials
  - Current development is focused on thermal imaging NDE methods

Recent NDE Developments

- NDE for thermal barrier coatings (TBCs)
  - Evaluation/modeling low-cost IR camera for industrial applications
  - NDE analysis for TBC life prediction
- NDE for additive manufactured (AM) samples
  - Evaluation 3D thermal diffusivity (for AM material isotropy)

TBC Background – Material and Structure

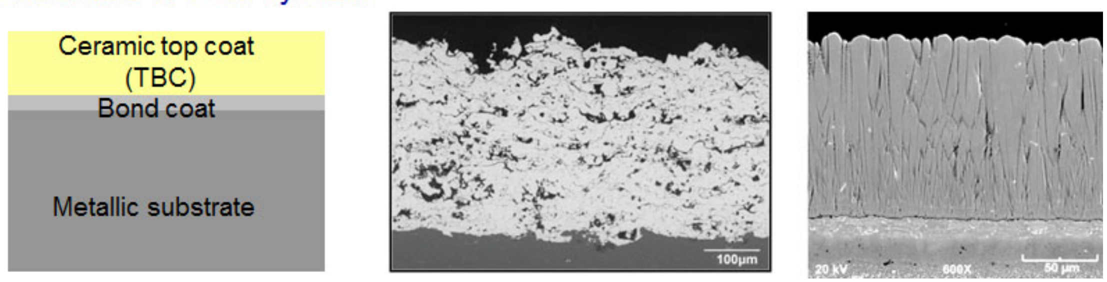
- Thermal barrier coatings (TBCs) are commonly used to insulate high-temperature metallic components in gas turbines
  - TBCs may reduce metal surface temperature by >100ºC
- TBCs are "prime reliant" material → nondestructive evaluation (NDE) is needed for their condition monitoring and life prediction
  - Need 100% coating surface inspection by imaging NDE

Uncoated and TBC-coated turbine blades

- TBC material: yttria stabilized zirconia (YSZ)
- TBC processing: air plasma spraying (APS) or electron beam–physical vapor deposition (EB-PVD)

TBC Background – NDE Development

- Many NDE technologies were evaluated for TBCs in last few decades → generally not very successful
- Current TBC analysis and quality control still relies on destructive methods



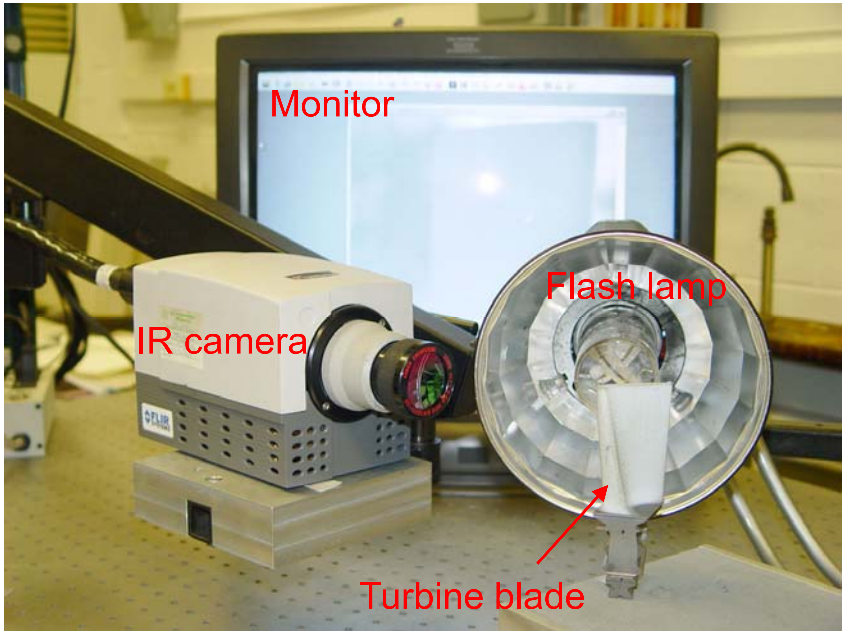
Schematic of TBC system | APS TBC | EB-PVD TBC

- This research has established Pulsed Thermal Imaging – Multilayer Analysis (PTI-MLA) as a promising NDE method for entire TBC lifetime evaluation

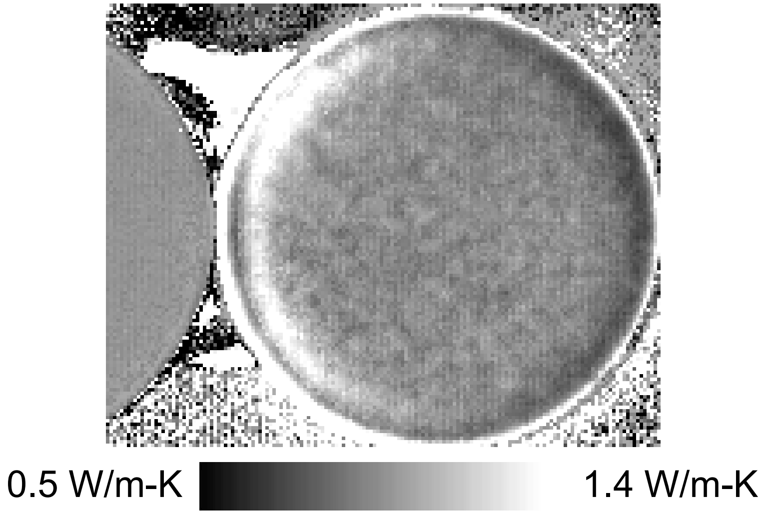
Pulsed Thermal Imaging – Multilayer Analysis (PTI-MLA)

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

PTI experimental setup

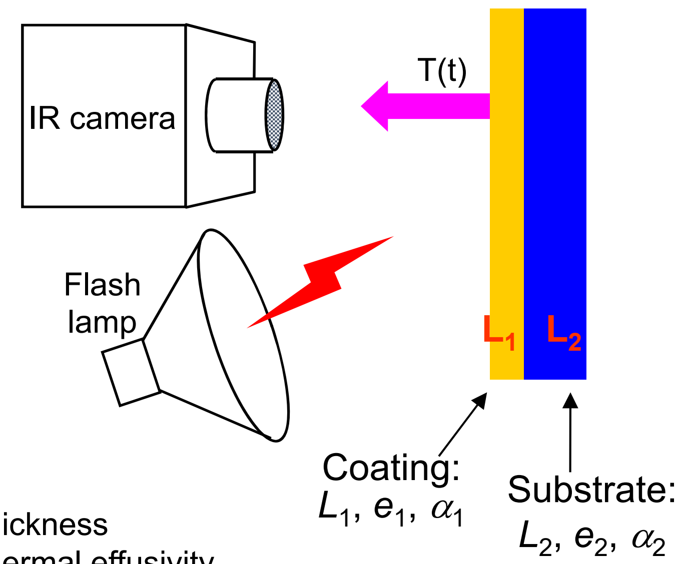


Thermal conductivity image



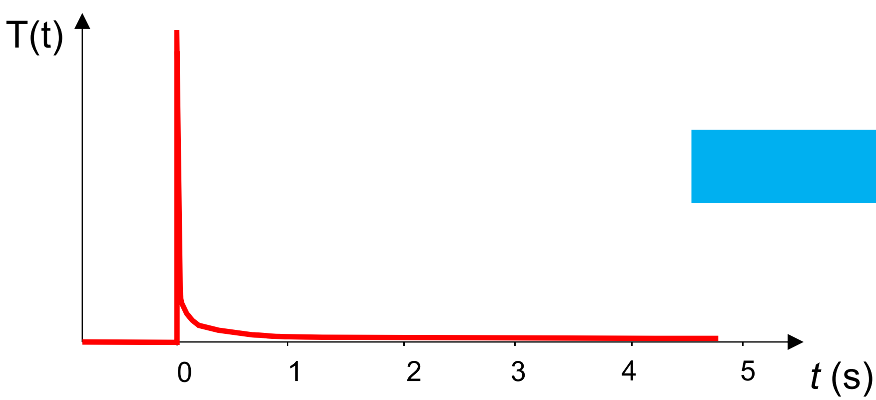
PTI-MLA: Principle for Coating Analysis

PTI system setup



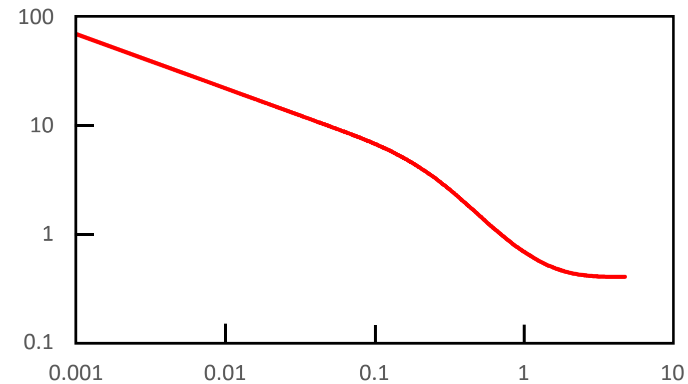
L – thickness
e – thermal effusivity
α – thermal diffusivity

Temperature profile *T*(*t*) at each pixel

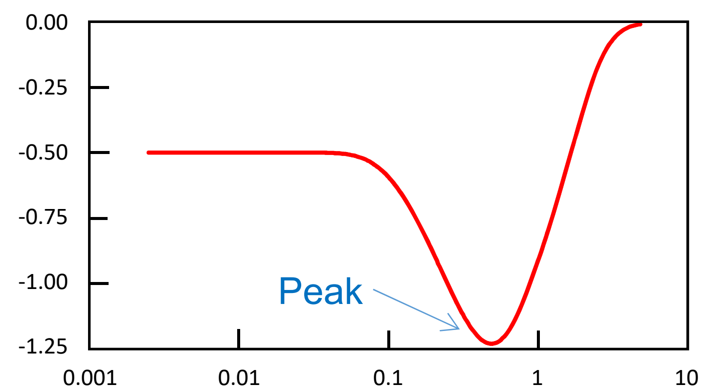


MLA analysis

Log temperature profile ln*T*(*t*)



Log slope profile *d*(ln*T*)/*d*(ln*t*)



Slope *d*(ln*T*)/*d*(ln*t*) peak time and magnitude determine two coating parameters (out of *L*, *e*, and *α*)

Summary of PTI-MLA Capabilities

- PTI-MLA may evaluate TBC material in its entire life cycle
  - Inspection of fabricated TBC components (for quality control)
  - TBC health monitoring and life prediction during service
  - Detection of TBC flaws/damages (for research and application)

- PTI-MLA is used in industrial applications
  - Inspection of engine components (collaborated with Dr. A. Kulkarni of Siemens Corp.)
  - Recent developments to address all remaining issues

PTI-MLA for Industrial Applications

- Two factors affect PTI-MLA NDE for industrial applications:
  - TBC translucency requires surface treatment (usually graphite paint)
  - High-cost and large size of high-end IR cameras
- Solution: use low-cost LWIR camera (bolometer)
  - TBC is naturally opaque at LWIR (7-13µm) (no paint required)
  - Bolometers are small and much cheaper (~10% of cooled IR camera)

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

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

Recent NDE Developments

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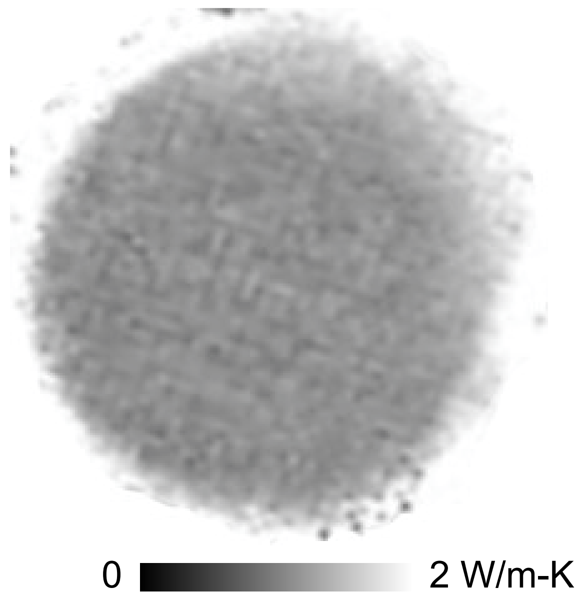
Evaluation of a FLIR A35 IR camera

- Various TBC samples were tested using SC4000 and A35

- A35 results were compared with SC4000 results (as “exact”)
  - Compared parameters: TBC thickness and thermal conductivity

Measured conductivity images for 0.36mm TBC

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



Error: +37% | **Error: - 4%** | **Assumed: exact**

- Comparison for TBC thickness are better (+16% and -2%)

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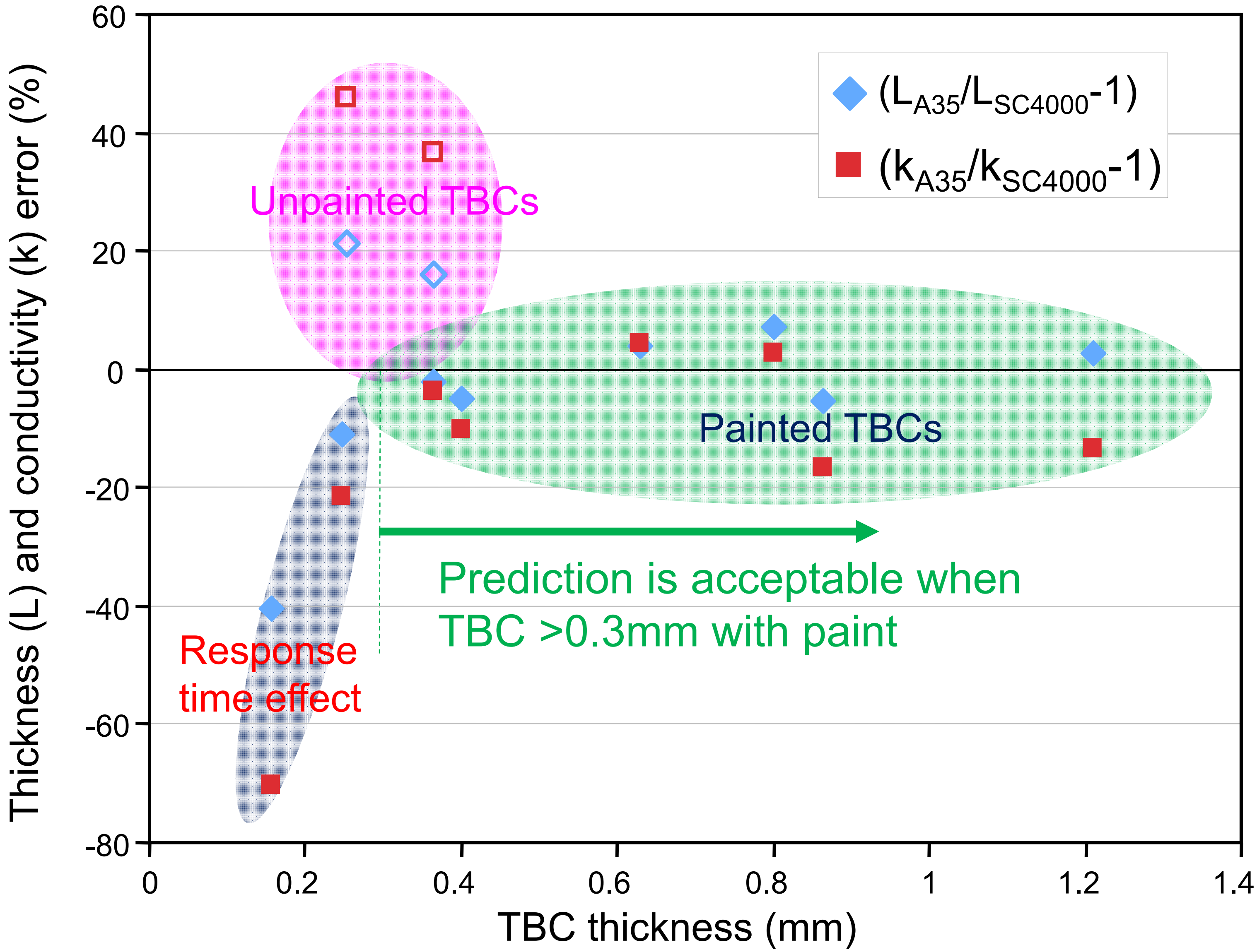
TBC measurement error by A35 camera



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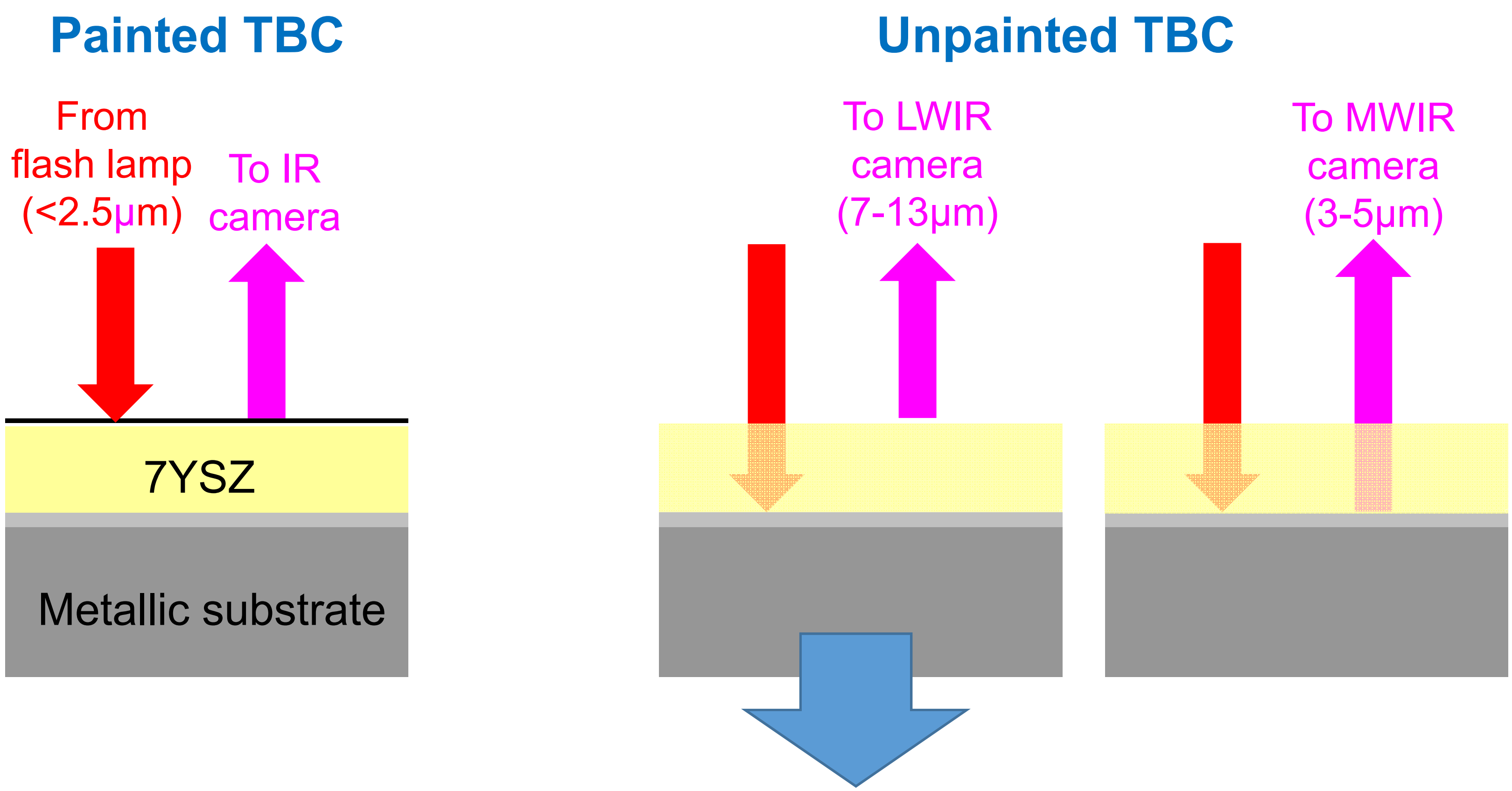
PTI-MLA Development for Bolometers

- Modeling flash heat absorption inside translucent TBCs
- Modeling bolometer response time

Modeling TBC Translucency for LWIR Camera



- A model was developed for flash heat absorption inside unpainted TBC
- No model is needed for LWIR emission (surface emission only)

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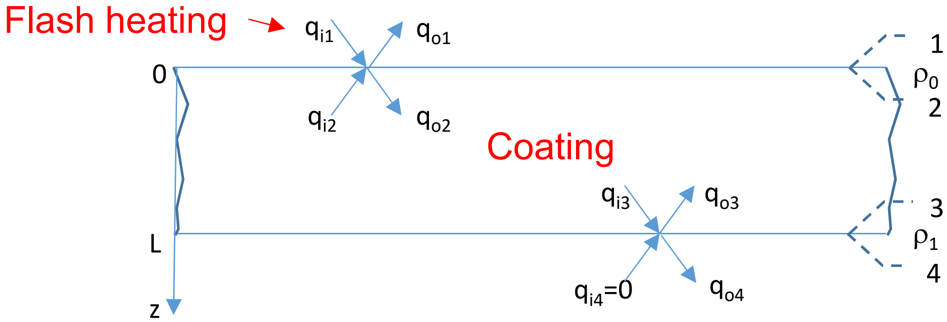
Optical Model for TBC Heat Absorption

Flash heating as a function of coating depth q(z):

$$q(z) = q_{i1}(1-\rho_0)\frac{e^{-\alpha z} - \rho_1 e^{-\alpha(2L-z)}}{1-\rho_0\rho_1 e^{-2\alpha L}}$$



α = optical attenuation coefficient
ρ_0 & ρ_1 = surface reflectivity
L = coating thickness

- This optical model was implemented in MLA code
  - α = 7 mm^{-1} was found to be appropriate for TBC button samples
  - α can be different for other TBCs

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Modeling Bolometer Response Time

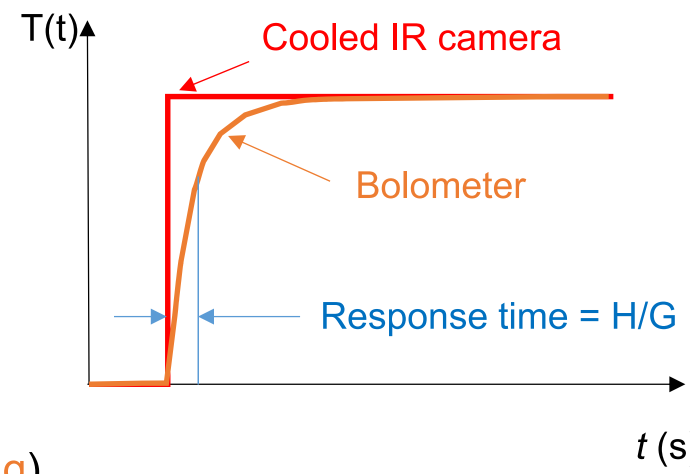
- In bolometer, pixel temperature change from absorbed incident thermal energy is used to sense radiation intensity

- This process is modeled by:

$$P(t) = G\Delta T + H\frac{d\Delta T}{dt}$$

P(t) = incident power,
G = thermal conductance of thermal link
H = pixel heat capacity
ΔT = relative pixel temperature (bolometer reading)

IR camera reading to abrupt incident radiation change



- When P(t) changes abruptly from 0 to a constant P at t=0, ΔT follows:

$$\Delta T = \frac{P}{G}\left(1 - e^{-\frac{G}{H}t}\right)$$

H/G = bolometer response time

- Response time for A35 is 12ms (← reason for poor NDE results for thin TBCs)
- Response time was implemented in MLA code

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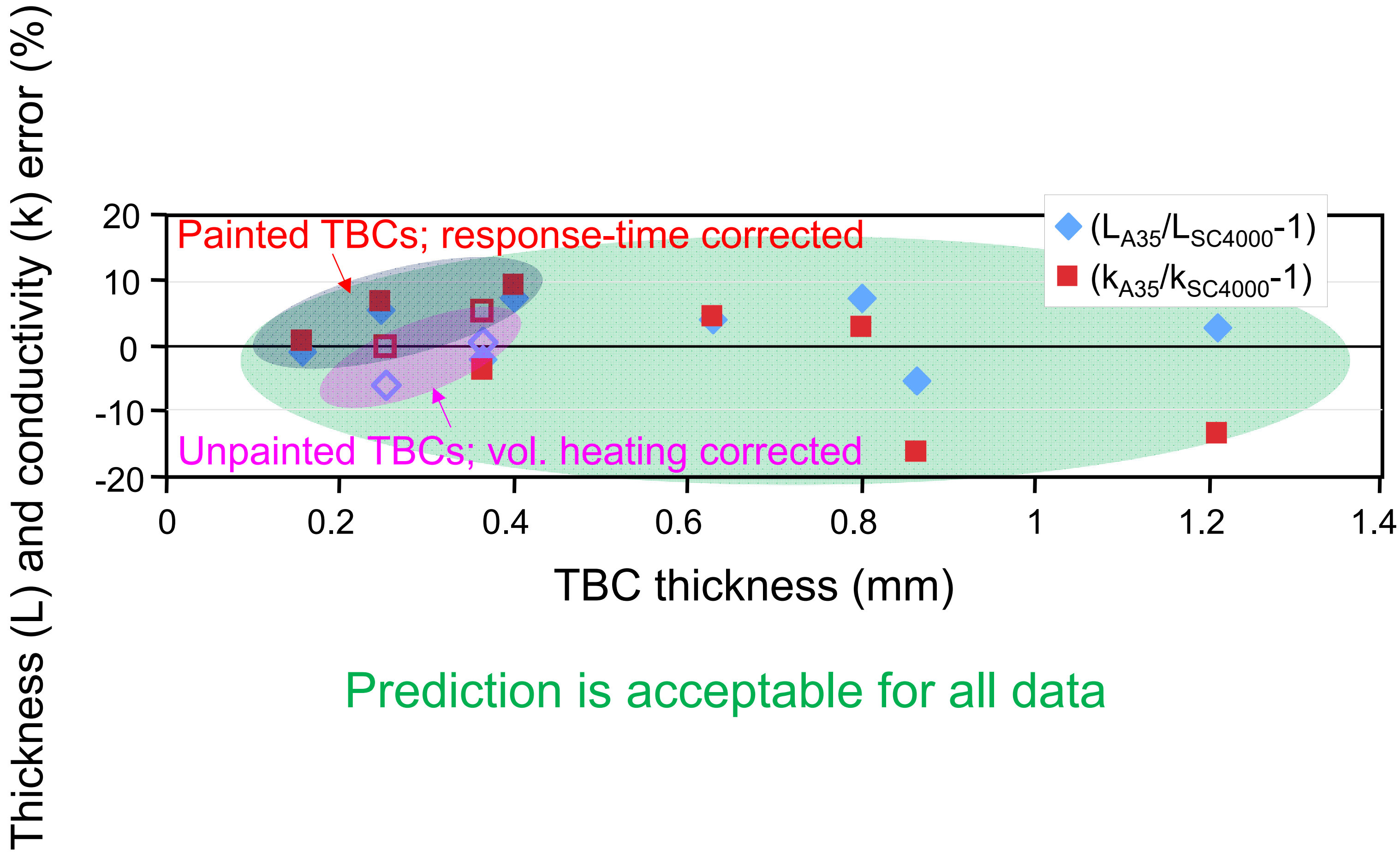
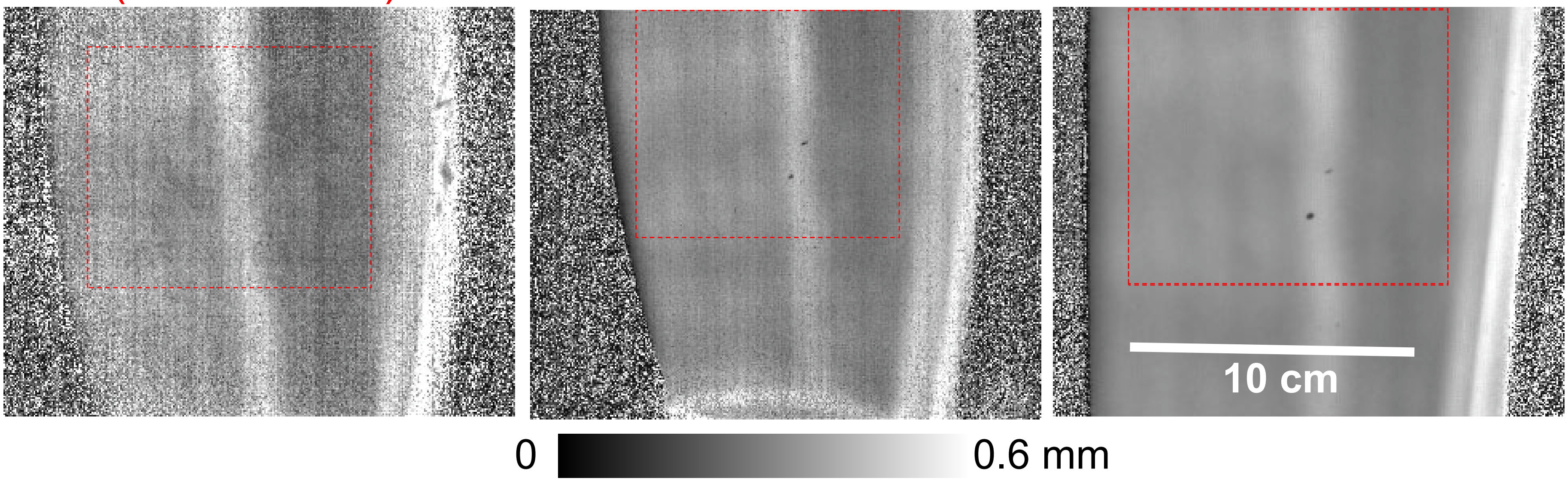
TBC measurement error by A35 camera
- with heat absorption and response time models



Prediction is acceptable for all data

Typical Measured TBC Thickness on Blade

A35, unpainted TBC (α = 3.9 mm^{-1}) | A35, painted TBC | SC4000, painted TBC



Error: - 7.2% | **Error: - 6.5%** | **Assumed: exact**

- Error for measured TBC conductivity is similar (+7.7% and +7.4%)
  - Note: errors of <10% are generally considered acceptable
- Errors in A35 results are mostly due to noise → higher flash heating will reduce them! (especially for unpainted and thicker TBCs)

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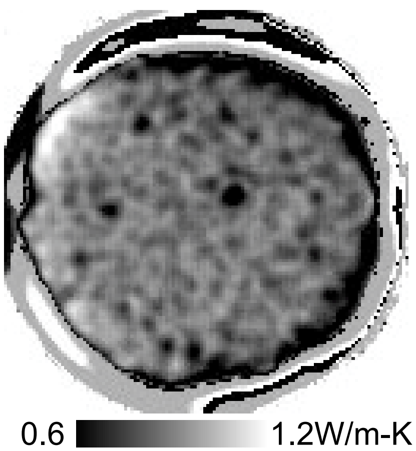
Thermal Imaging NDE for TBC Life Prediction

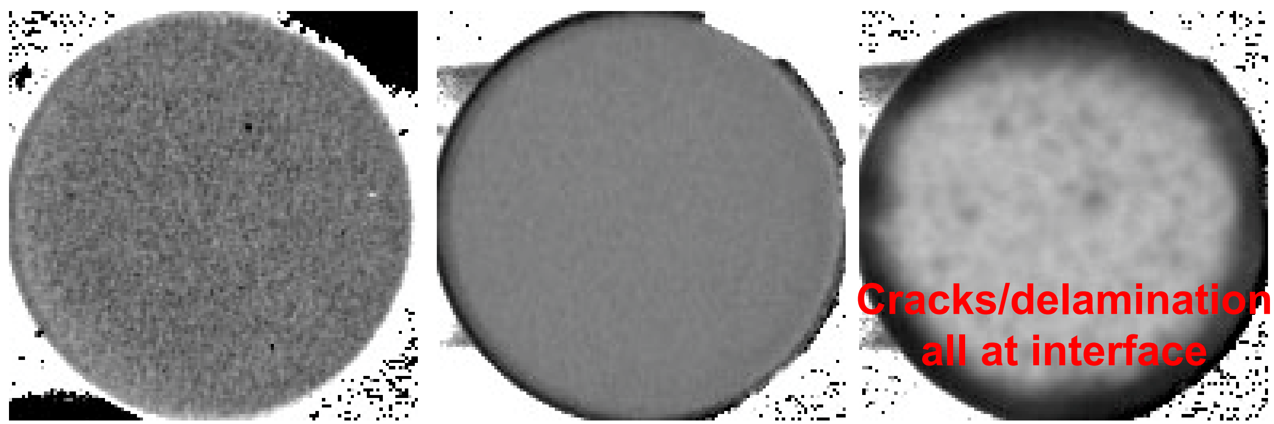
- TBC damage and life: TBC delamination/spallation from substrate
- NDE may examine detailed damage initiation and development
  - Collaborated with Prof. Sampath's group in Stony Brook University

Confirmation for cracks/delaminations in PTI-MLA data

PTI-MLA data



Thermal tomography depth-slice data

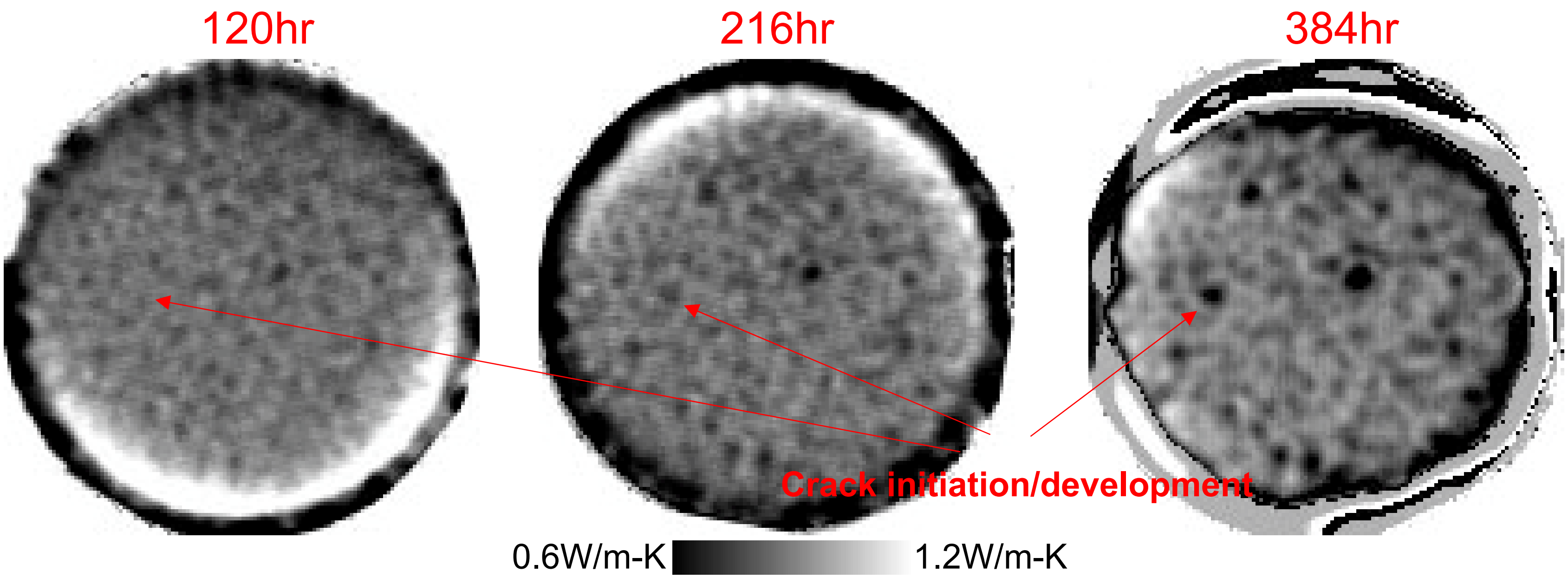


@0mm depth (surface) **@0.15mm depth** **@0.3mm depth (interface)**

Cracks/delaminations at interface in all images – correlated well

NDE for TBC Life Prediction

Thermal conductivity images for a thermal-cycled TBC (@1100° C)



- NDE data may detect crack initiation and propagation
  - crack initiation and size increase with time (thru image analysis)
  - crack gap expansion with time (thru conductivity value)

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Recent NDE Developments

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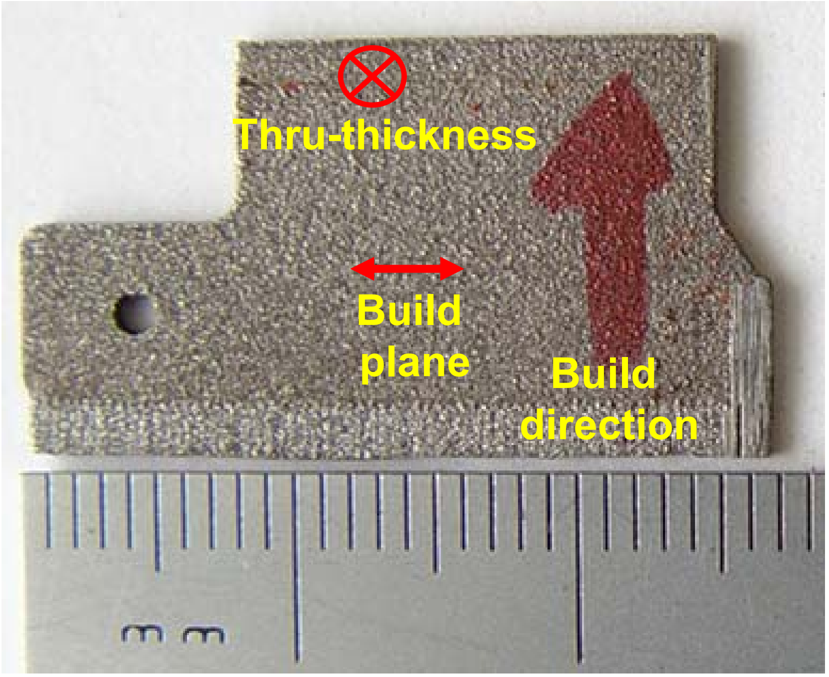
  - Evaluation 3D thermal diffusivity (for AM material isotropy)

NDE for Additive Manufacturing (AM)

- AM is an emerging technology expected to be widely adopted
- Selective laser melting (SLM) has been used to make engine parts
- NDE will be an issue in future AM routine production
  - No NDE has been established for:
    - on-line monitoring
    - quality inspection

- We examined isotropy of AM parts
  - by measuring thermal diffusivity in all three directions from same AM sample
- Collaborated with Dr. J. Zhang of Indiana University – Purdue University Indianapolis



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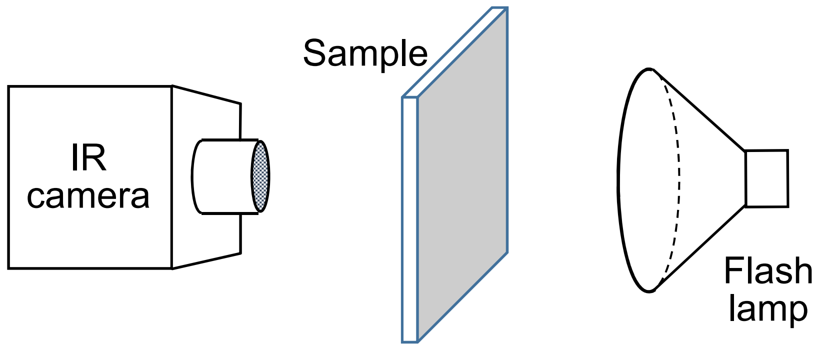
Thru-Thickness Thermal Diffusivity Measurement

Test system setup



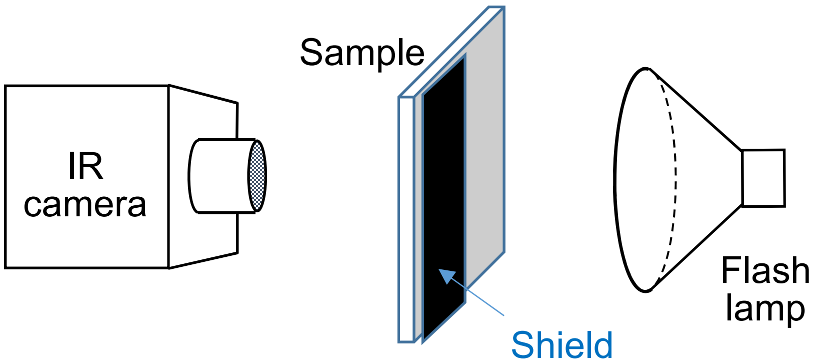
Thru-thickness diffusivity α_z is measured by fitting data with:

$$T_0(z = L, t) = \frac{Q}{\rho c L}\left[1 + 2\sum_{n=1}^{\infty}(-1)^n \exp\left(-\frac{n^2\pi^2\alpha_z t}{L^2}\right)\right]$$

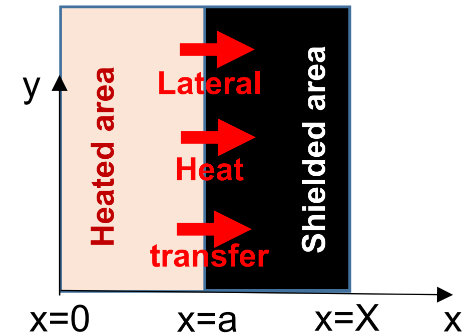
α_z measurement accuracy is typically within 2%

Lateral Thermal Diffusivity Measurement

Test system setup



Heat transfer field observed by IR camera



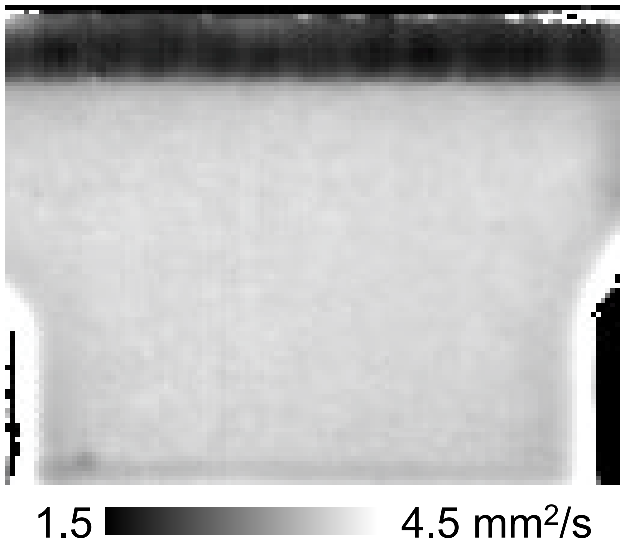
Lateral diffusivity α_x is measured at each y level from:

$$T(x, z = L, t) = \frac{a}{XL}\left[1 + 2\sum_{m=0}^{\infty}\frac{X}{m\pi a}\sin\frac{m\pi a}{X}\cos\frac{m\pi x}{X}\exp\left(-\frac{m^2\pi^2\alpha_x t}{X^2}\right)\right]\left[1 + 2\sum_{m=0}^{\infty}(-1)^n\exp\left(-\frac{m^2\pi^2\alpha_z t}{X^2}\right)\right]$$

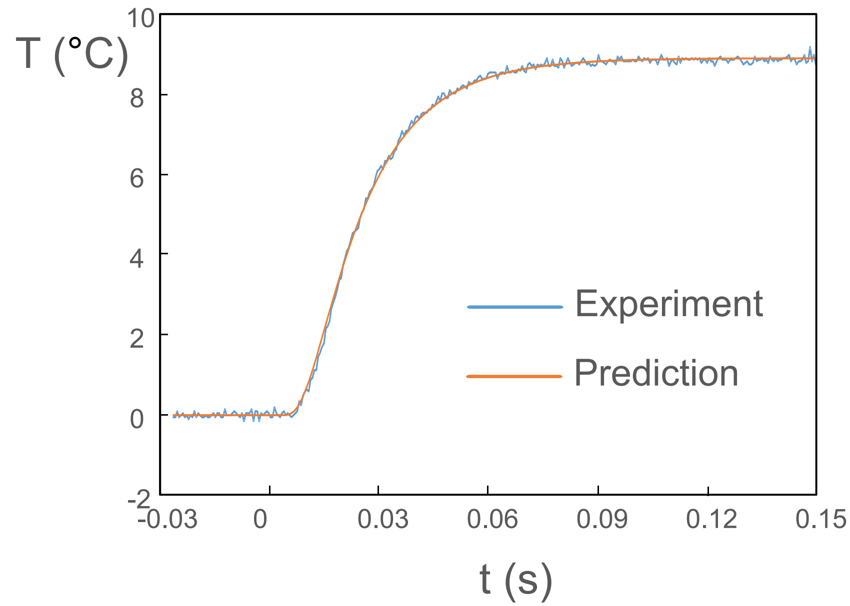
Measured α_x was validated to be within 3% of α_z for an isotropic steel sample

Thru-Thickness Measurement

Typical measured thru-thickness diffusivity image

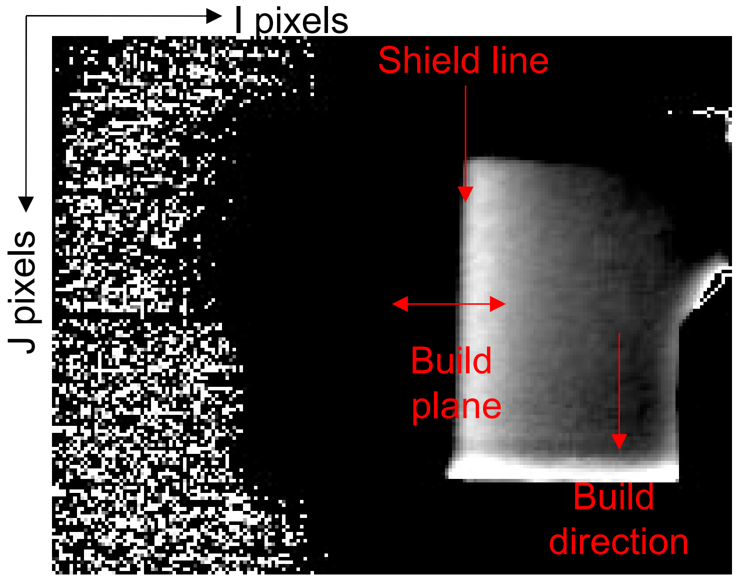


Typical fitting at a pixel

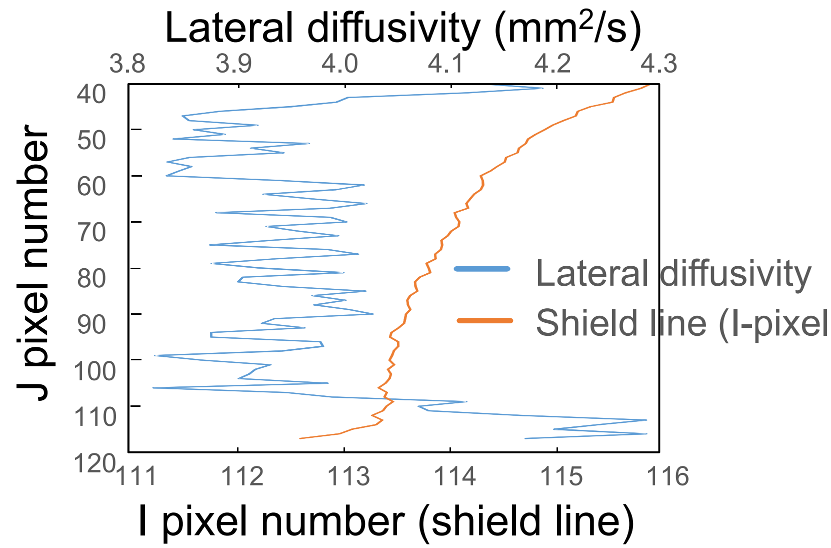


Measured mean a_z = 3.97±0.023 mm^2/s

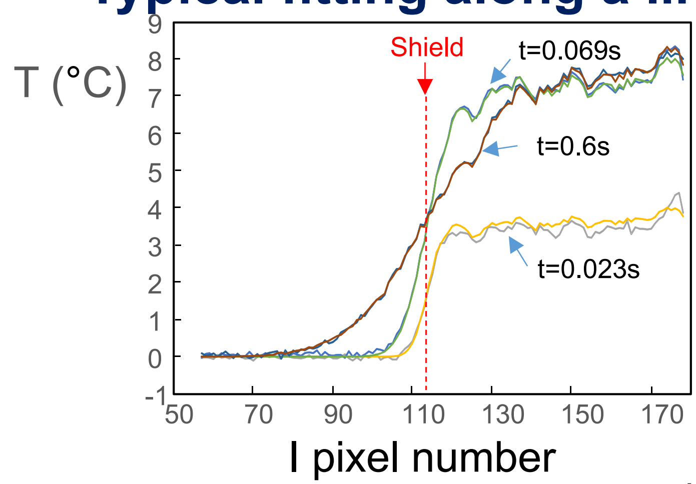
Lateral Measurement along Build Plane



Typical measured data



Typical fitting along a line



Measured thermal diffusivities:

Thru-thickness	3.97±0.023
Build plane direction	3.97
Build direction	4.00

→ AM sample is isotropic!

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Summary

- Thermal imaging NDE method was developed for TBCs
  - May evaluate entire TBC life cycle
- Low-cost NDE system was developed for industrial applications
- Thermal imaging NDE may determine AM material isotropy

Planned FY2017 Efforts

- Thermal imaging NDE method for TBCs:
  - Continue TBC life prediction analysis
  - Find simple approach to determine TBC translucency
  - Study substrate curvature on TBC property prediction
- Thermal imaging NDE for AM material quality
- Tech transfer