Development of Laser Fluorescence as a Non-Destructive Inspection Technique for Thermal Barrier Coatings

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Program Objectives

- **Develop an Understanding of the Evolution of the Stress in the Thermally Grown Oxide (TGO) and the Associated Failure Mechanisms for Thermally Cycled TBC Specimens.**

- **Demonstrate the Ability to Predict Life Remaining for Engine Tested Turbine Blades.**

- **Measure the TGO Stress in Turbine Components In and Out of the Engine.**

- **Develop and Implement a Portable NDI Instrument for ATS and Other Industrial Applications.**

Program Organization

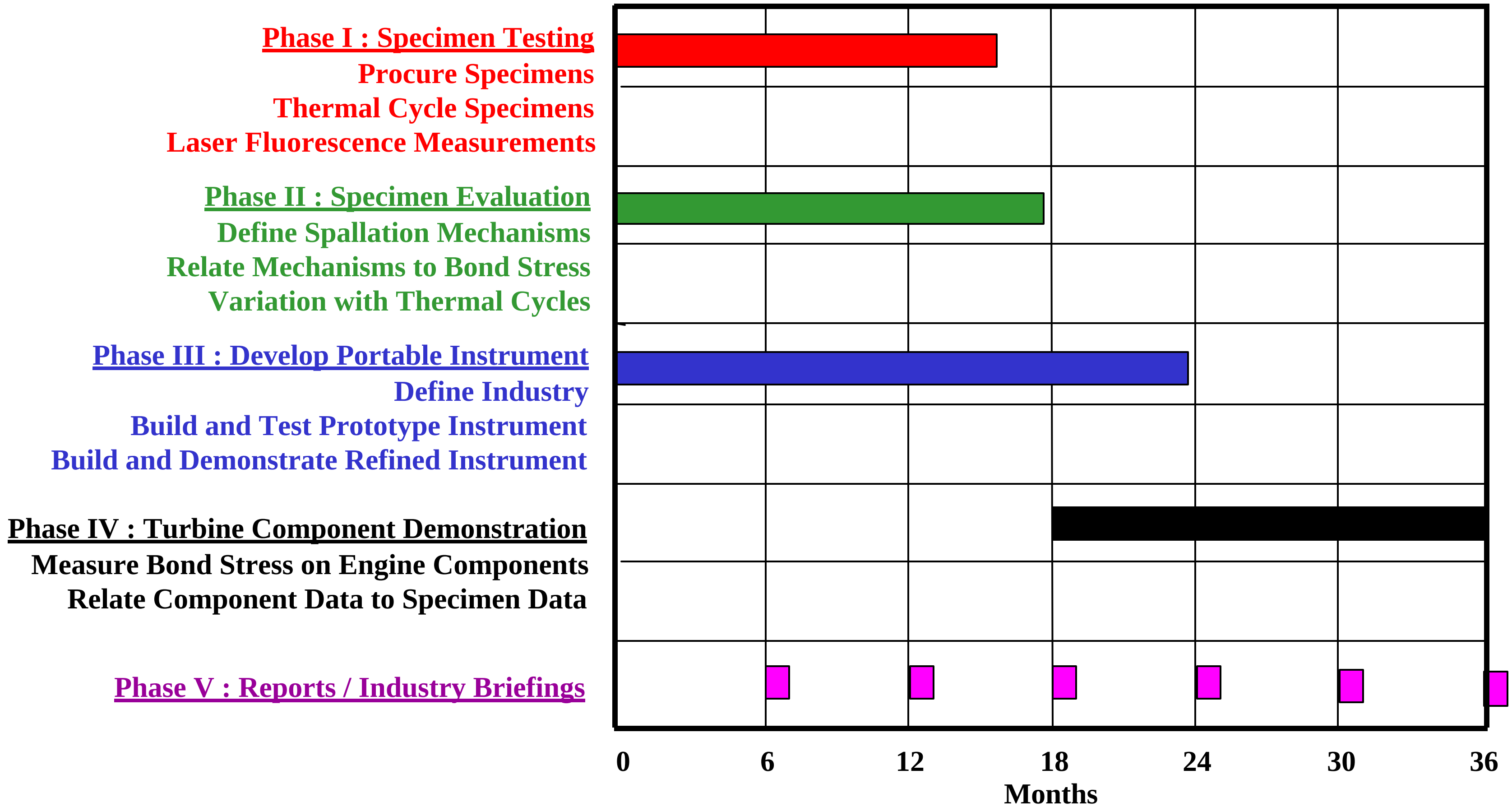
University of Connecticut
Eric Jordan
Maurice Gell

University of California-SB
David Clarke

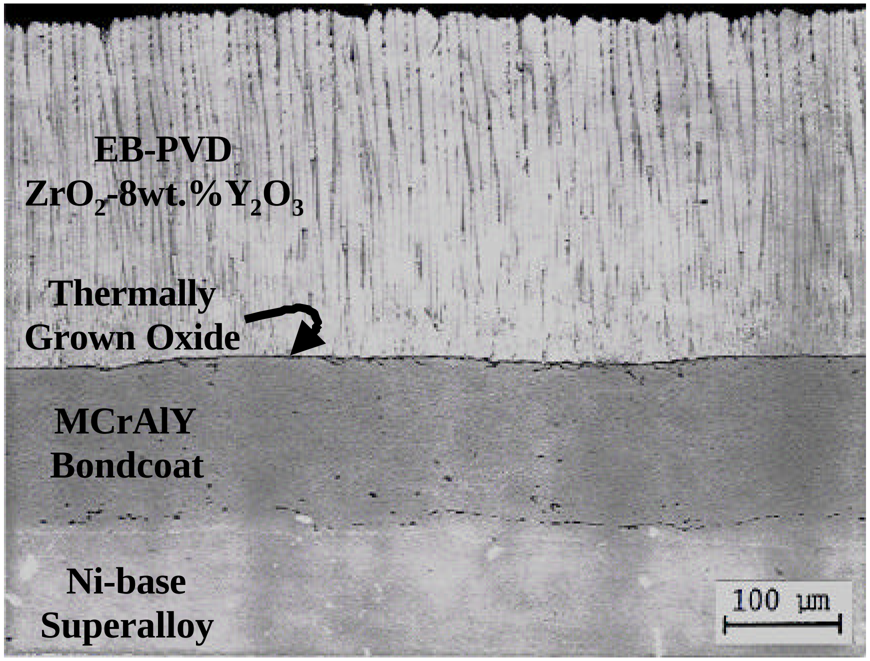
ATS Engine Developers and Coating Manufacturers
ABB
Allied Signal Engines
GE Power Systems
Howmet International
Pratt & Whitney
Rolls Royce -Allison
Siemens-Westinghouse
Solar Turbines

NDI Instrument Manufacturer
Renishaw Inc.

Program Schedule



Thermal Barrier Coatings

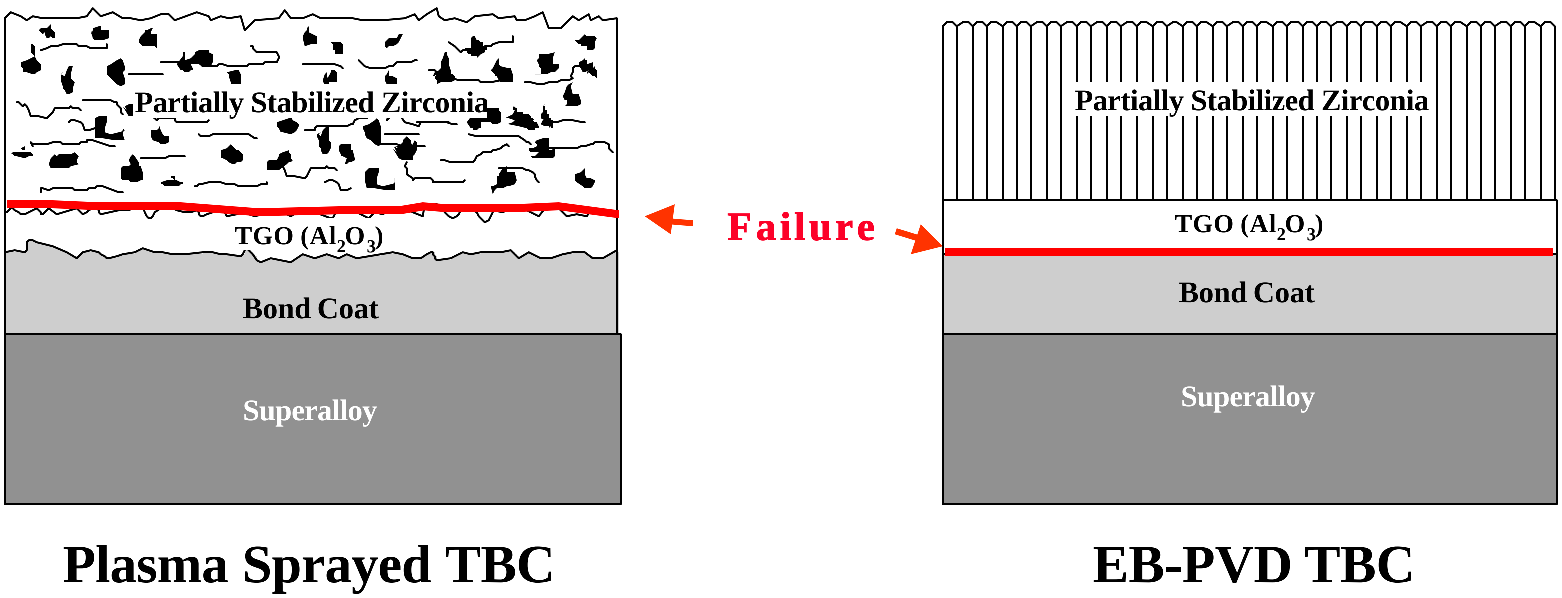


- Thermal/environmental protection of hot components in gas turbine engines.
- Increase in operating temperature
  Decrease in metal temperature
  Reduced air cooling.
- Improvement in performance, durability and efficiency of gas turbine engines.
- Requires an understanding of failure mechanisms and an assessment of life remaining / prediction.

Applications of Laser Fluorescence for Thermal Barrier Coatings

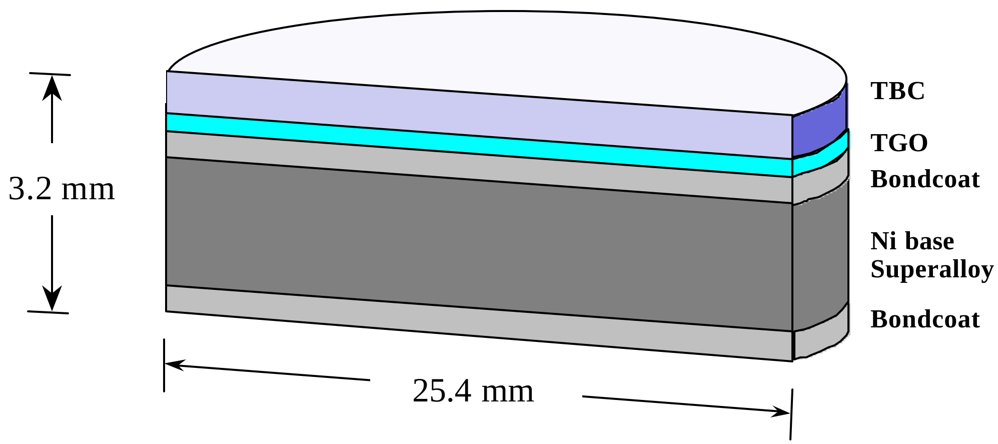
- Assessment of Life Remaining
- Input for Lifetime Prediction Methods
- Quality Control
- Coating Development

Microstructure and Spallation Failure Location of TBCs



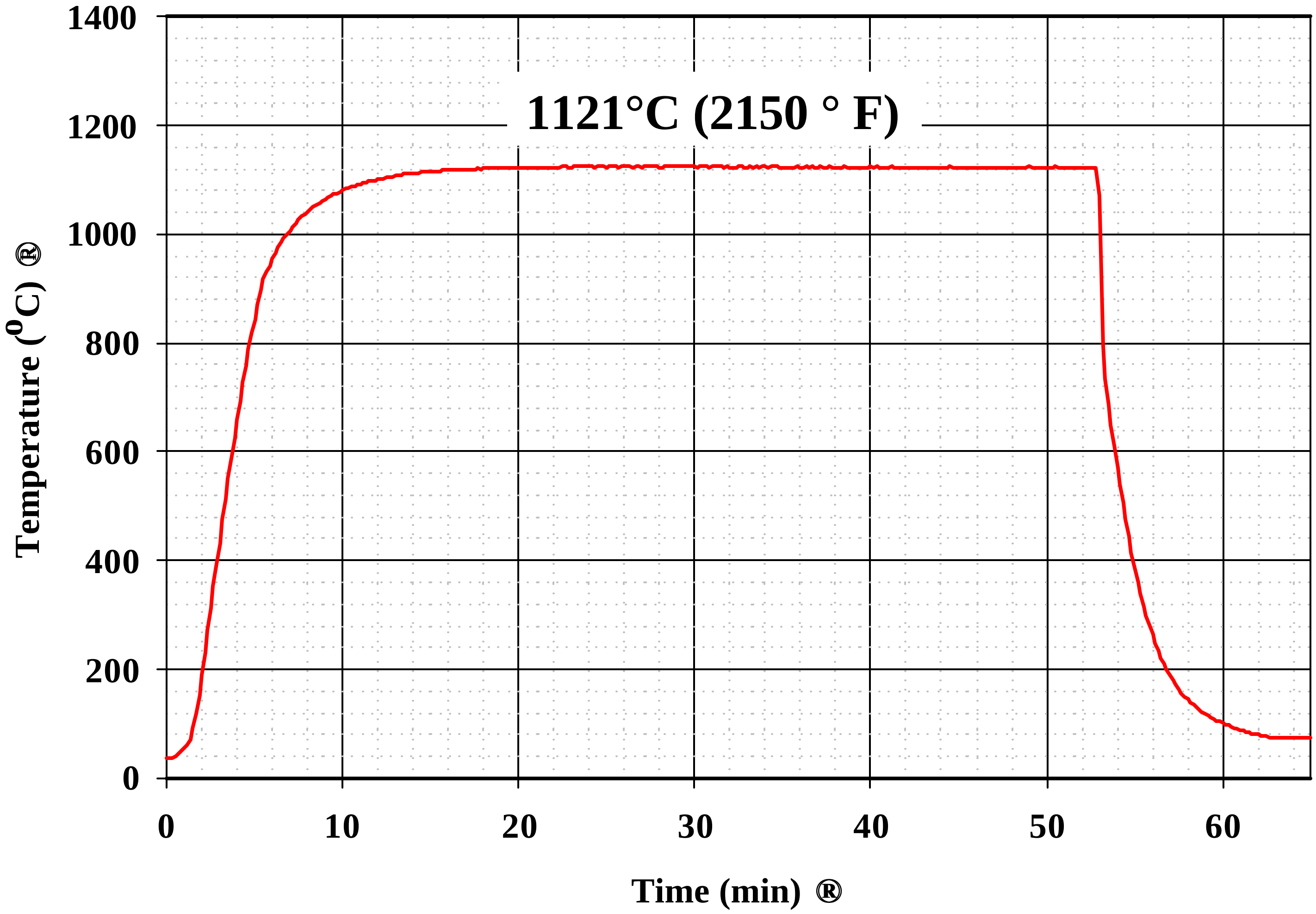
TBCs and Specimen Design

Type	Number of Specimens	Superalloy Substrate	Bondcoat*		Ceramic*	
			Type	Thickness (μm)	Type	Thickness (μm)
A	100	CMSX-4	(Ni,Pt)Al	65	EB-PVD	115
B	100	IN - 738	MCrAlY	100	EB-PVD	200
C	100	GTD-111	MCrAlY	120	APS	400

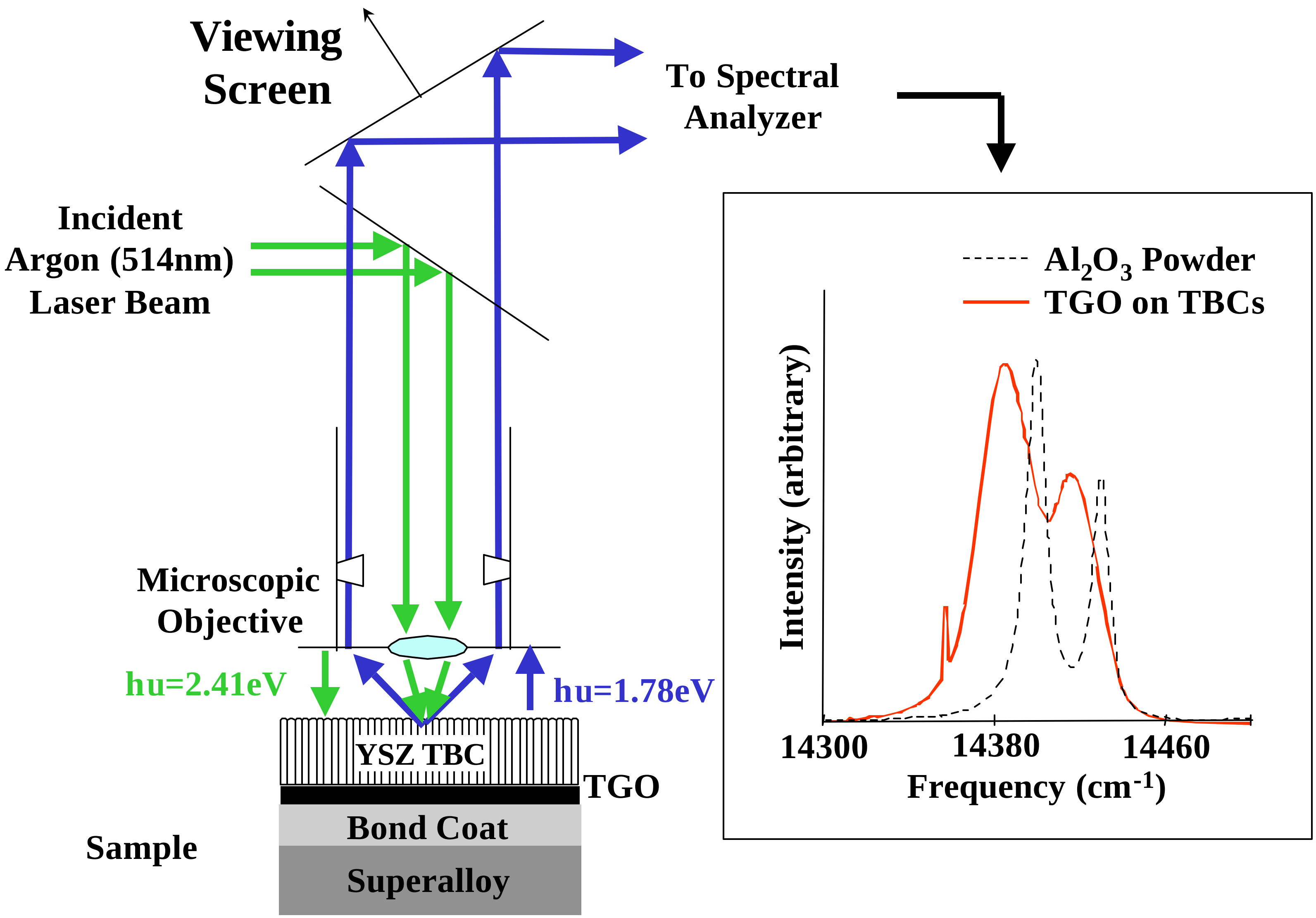


* TBCs are Production Coatings Supplied by ATS Engine Manufacturers

Furnace Thermal Cycle



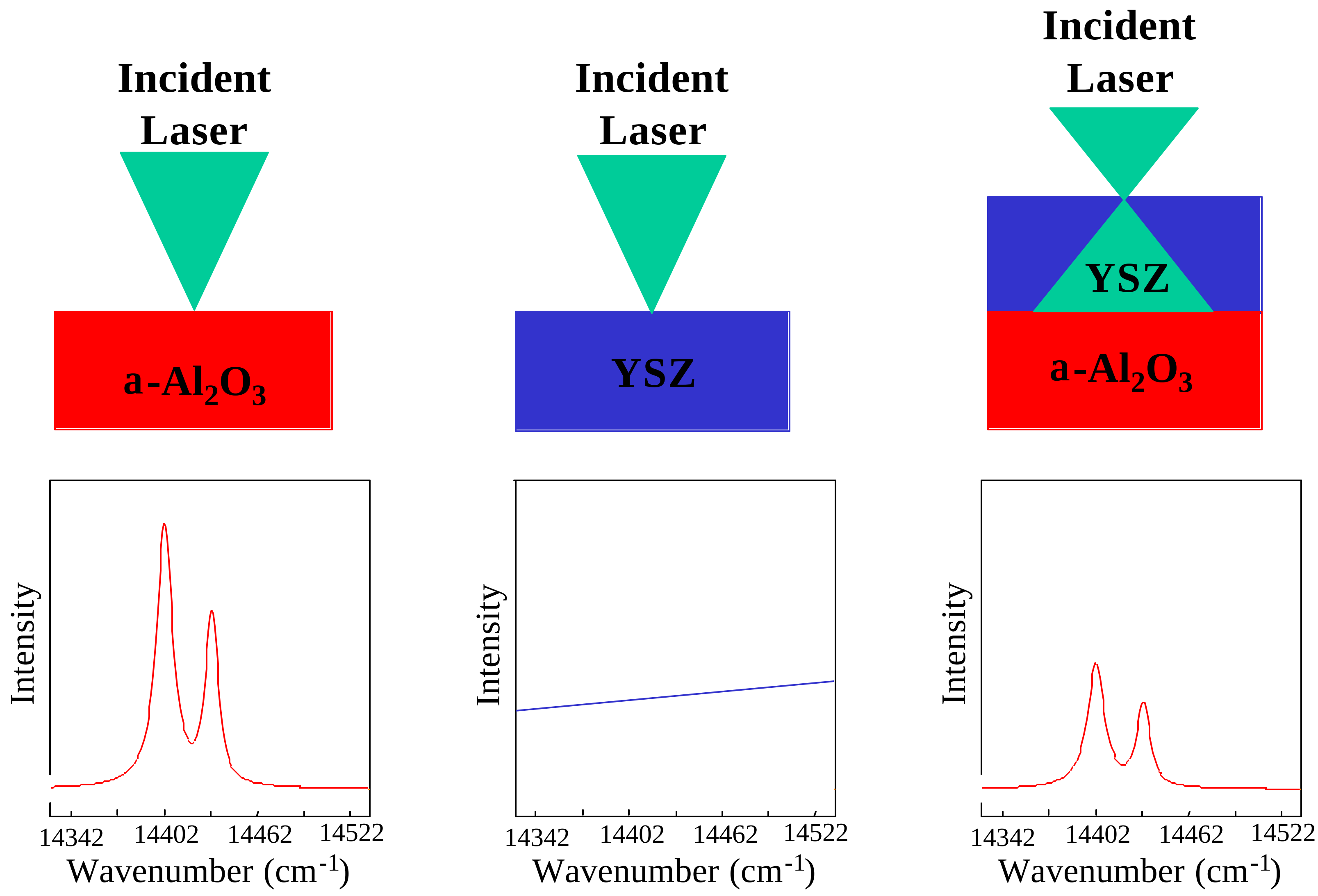
Laser Fluorescence Technique



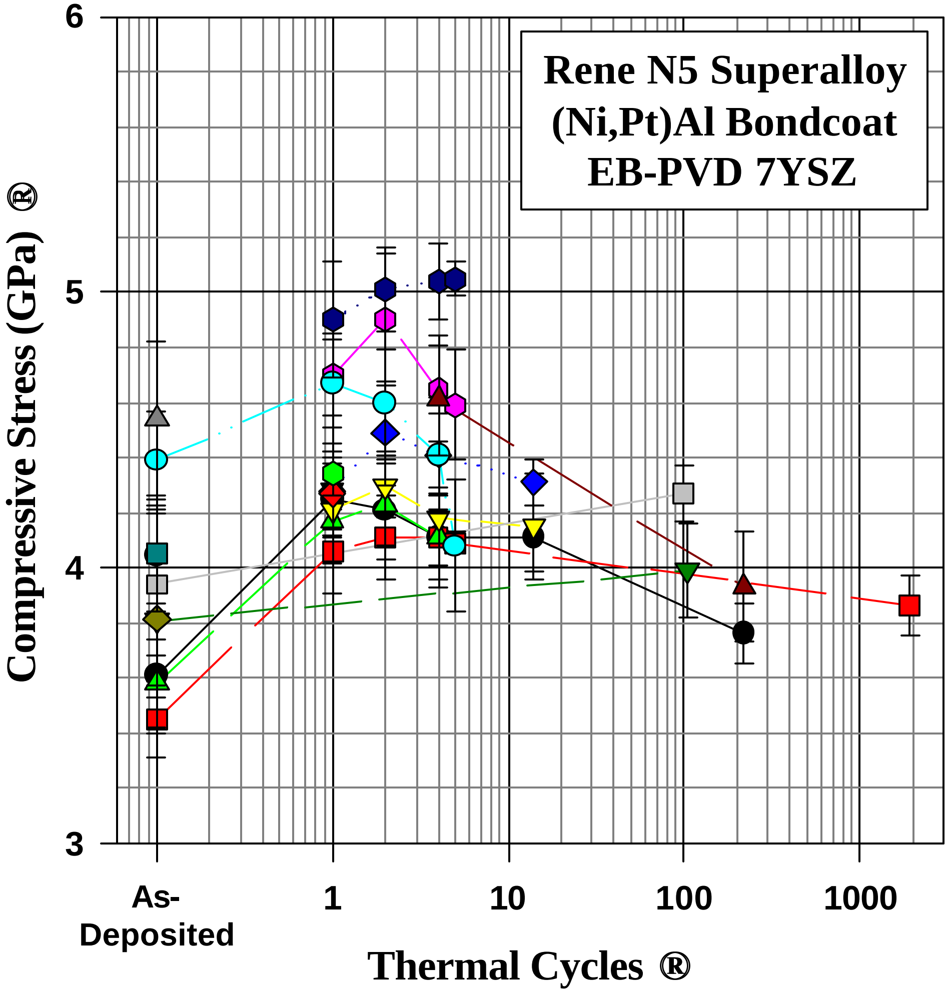
Requirements for Laser Fluorescence as a NDI Technique

- Accuracy
- Repeatability
- As-Coated TGO Stress Can Be Related to Physical Processes
- Changes in TGO Stress Can Be Related to Thermal Cyclic Processes and Damage Accumulation
- Ease of Operation
- Portable, Robust Instrument
- Field Applications

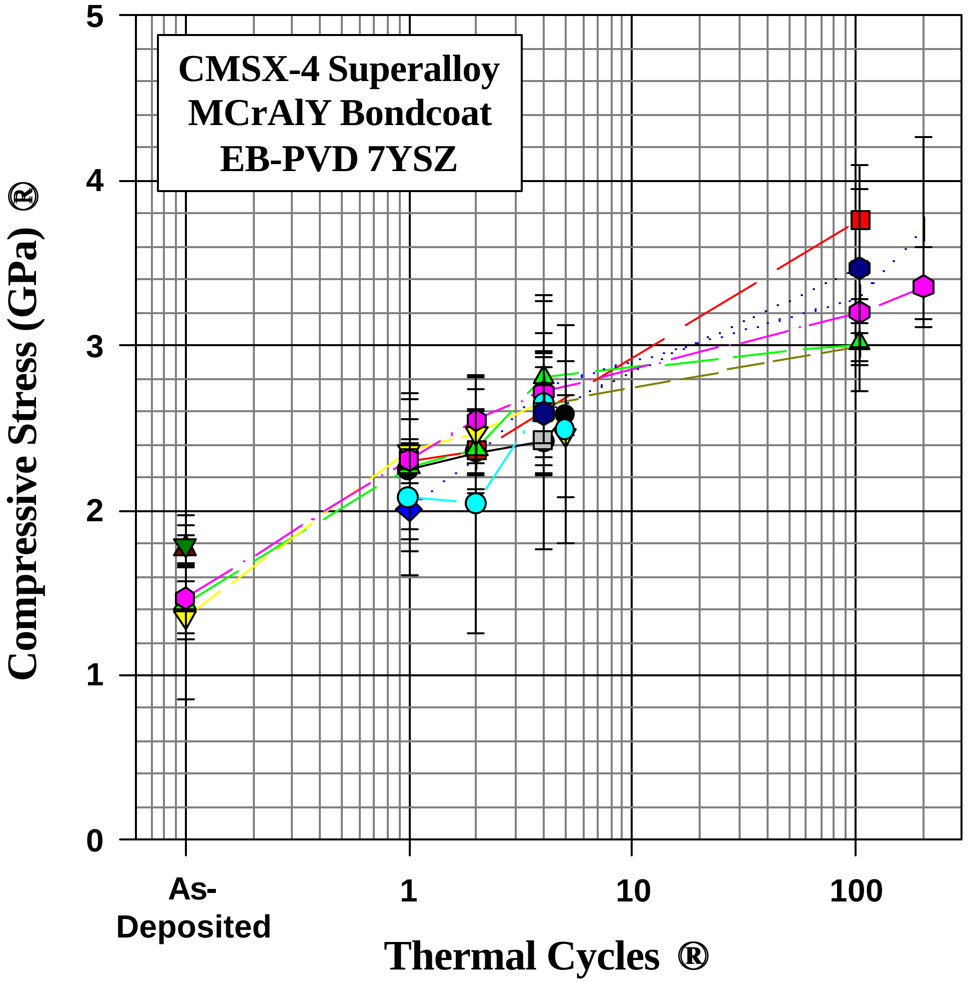
Laser Fluorescence Technique



Evolution of Compressive Stress in TGO with Thermal Cycling for TBCs

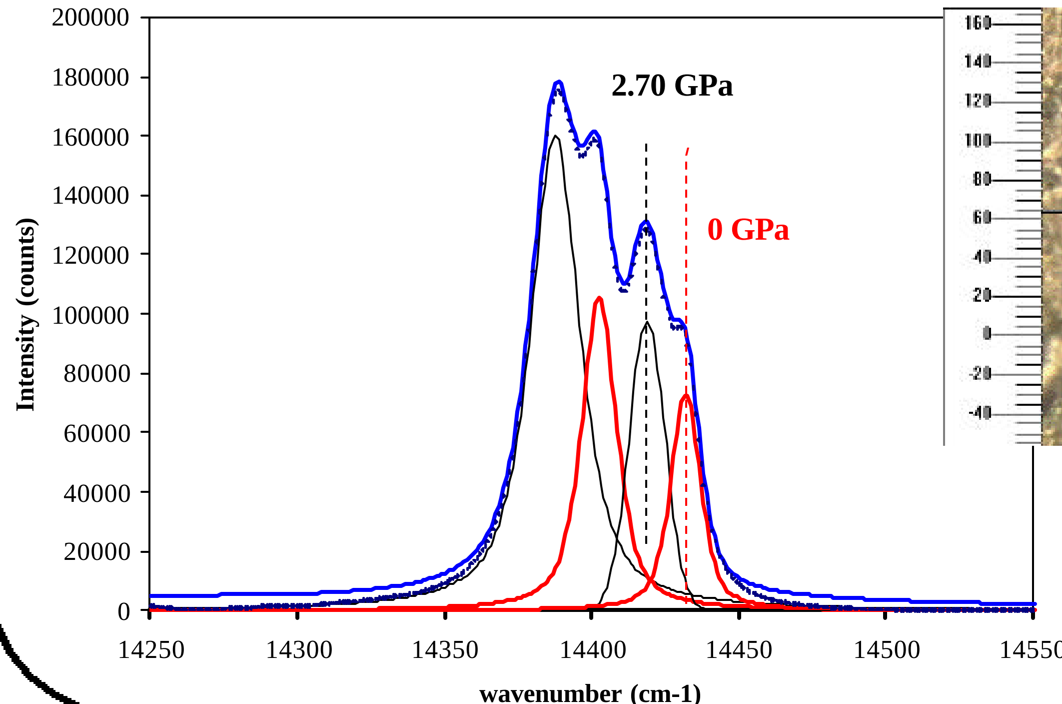


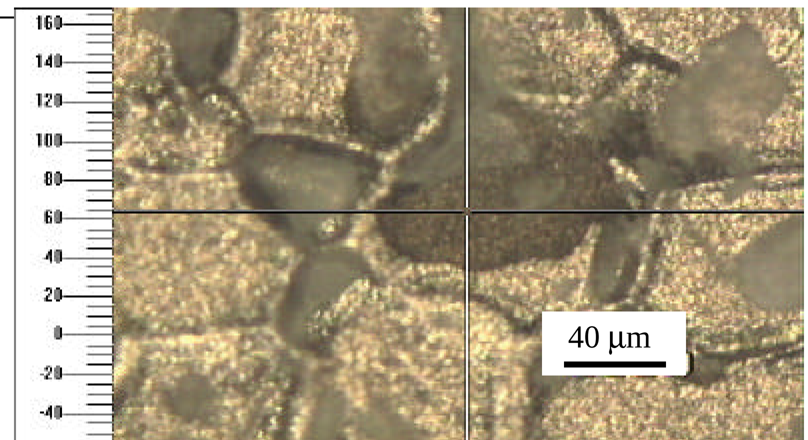
Evolution of Compressive Stress in TGO with Thermal Cycling for TBCs



Bimodal Stress State Observed by Laser Fluorescence Technique

- **Bimodal Stress State on TBC Spalled Surface**
  - **Stressed (2.7 GPa)**
  - **Stress-Free (0.0 GPa)**

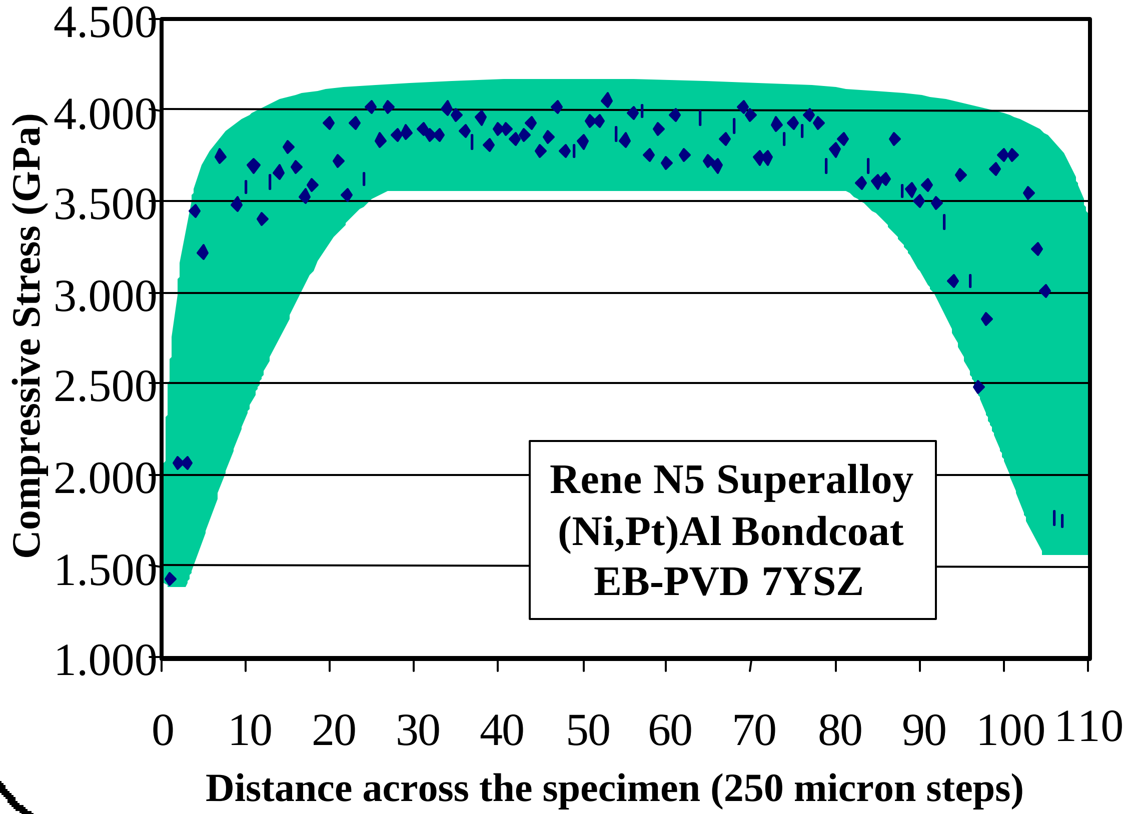


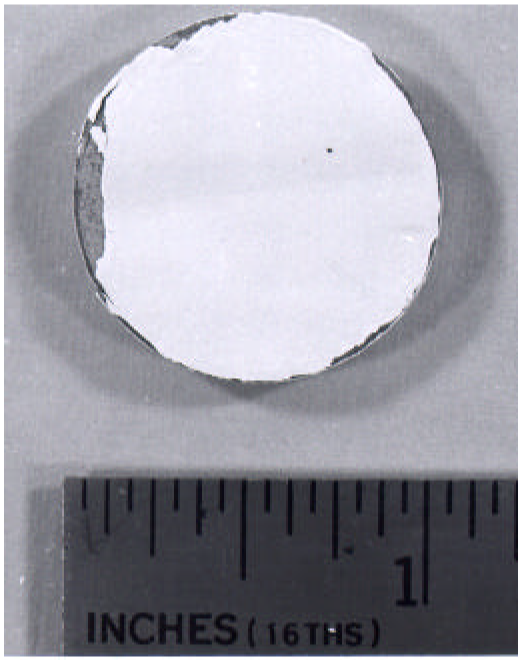


Rene N5 Superalloy
(Ni,Pt)Al Bondcoat
EB-PVD 7YSZ

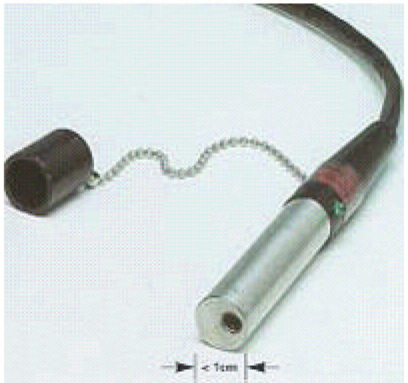
Relationship Between TGO Stress Measured by Laser Fluorescence Technique and Failure of TBCs

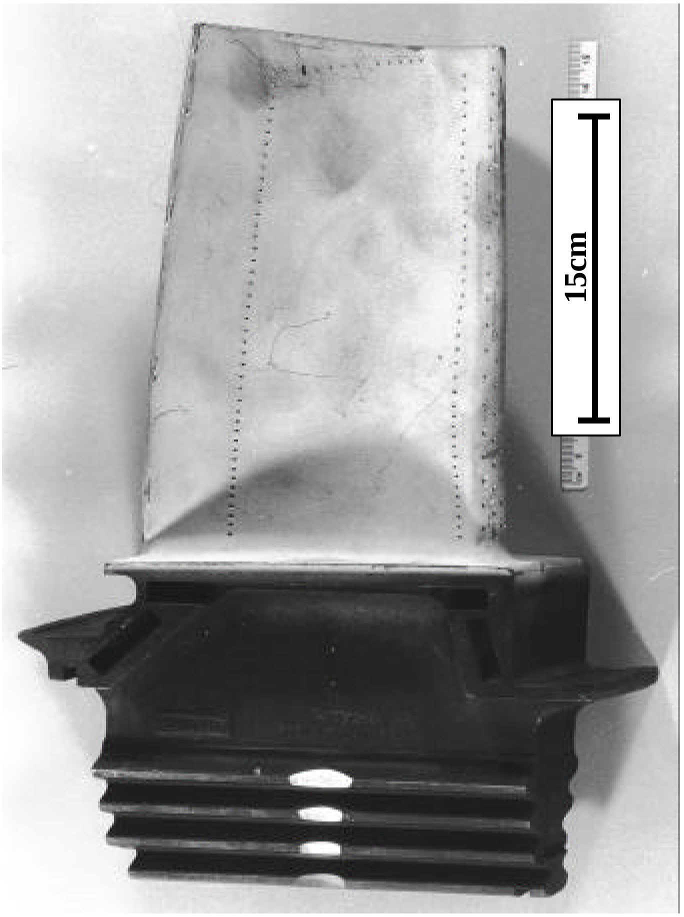
Specimen : AD56 After 1917 Cycles





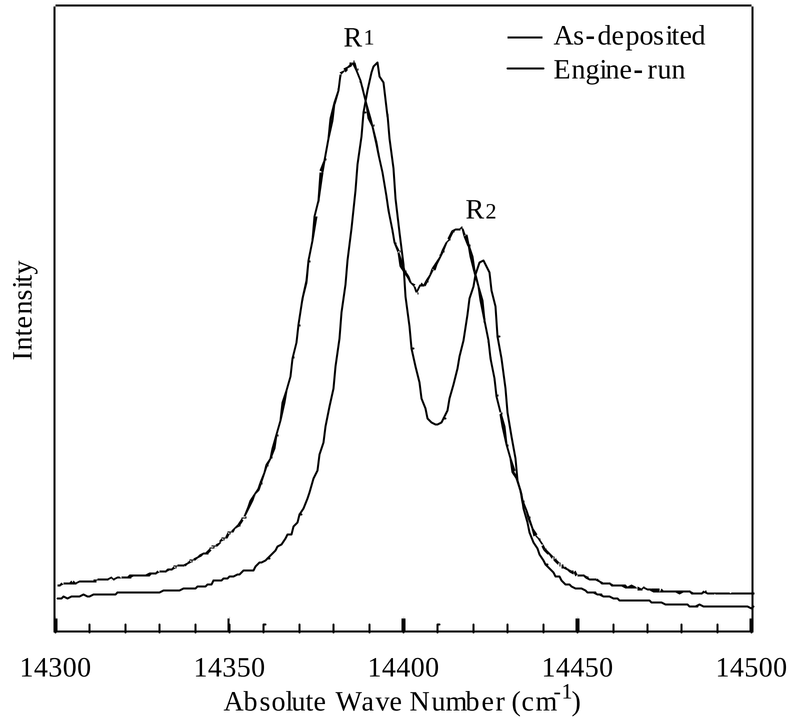
Portable Laser Fluorescence NDI Technique for TBCs Demonstrated





Application of Laser Fluorescence on Thermal Barrier Coated Turbine Blades

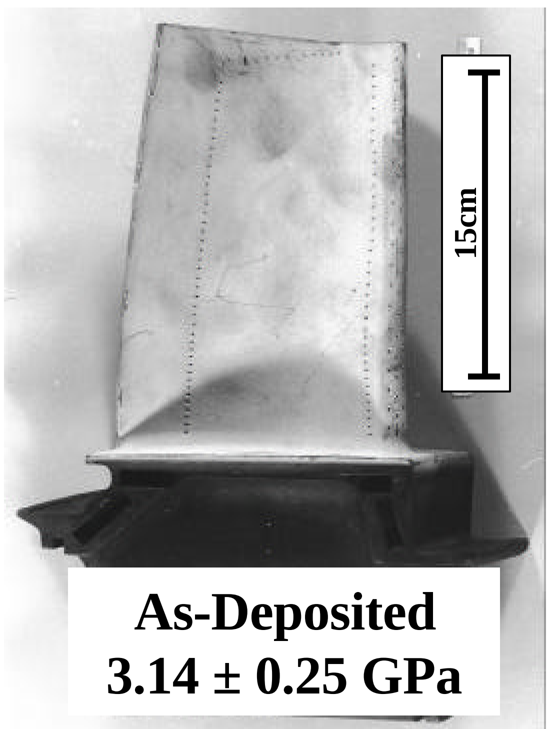
- **Residual Stress in TGO was Measured for 10 Random Spots on Pressure Surface, Suction Surface and Near Leading Edge for Thermal Barrier Coated Turbine Blades.**

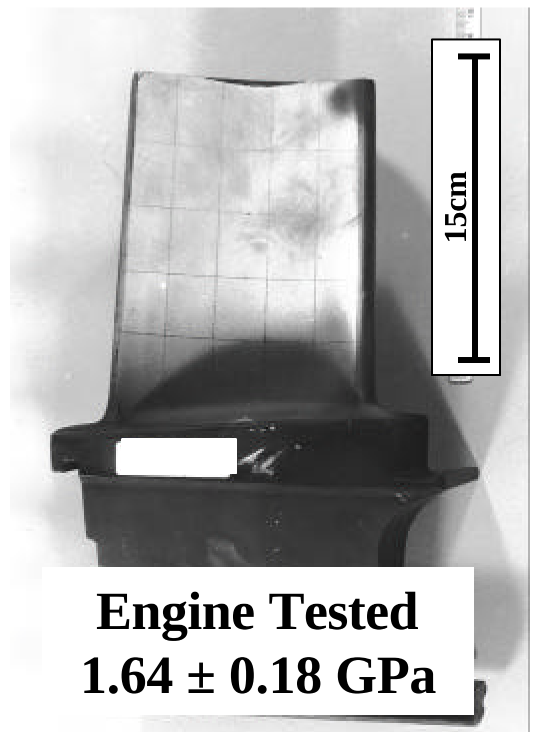


Typical Cr^{3+} Photo-luminescence Spectra Acquired from Thermal Barrier Coated (EB-PVD YSZ and MCrAlY Bondcoat) Turbine Blade Before and After the Engine-Run.

Laser Fluorescence of Thermal Barrier Coated Turbine Blade

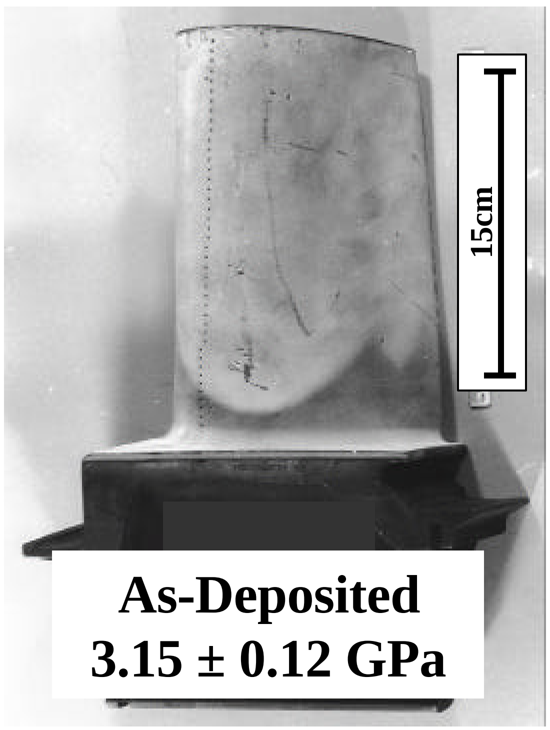
- **Compressive Residual Stress of Thermally Grown Oxide Measured for Pressure Surface of Thermal Barrier Coated Turbine Blades Before and After the Engine Test (27000 Hours).**



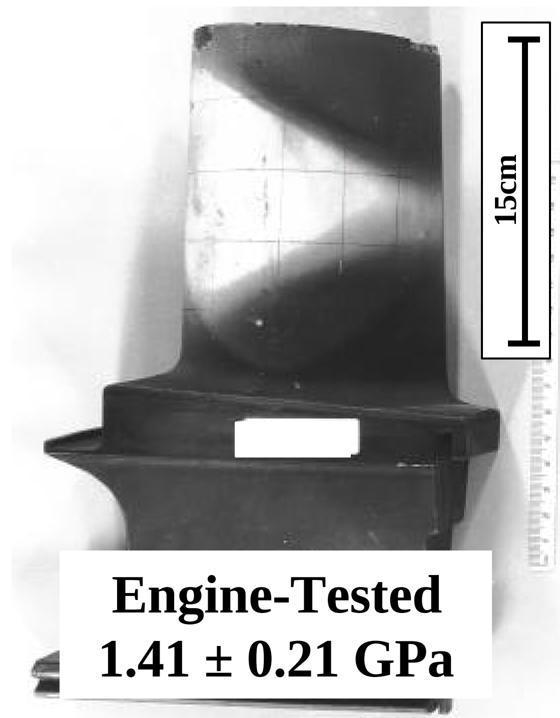


Application of Laser Fluorescence on Thermal Barrier Coated Turbine Blades

- **Compressive Residual Stress of Thermally Grown Oxide Measured for Suction Surface of Thermal Barrier Coated Turbine Blades Before and After the Engine Test (27000 Hours).**

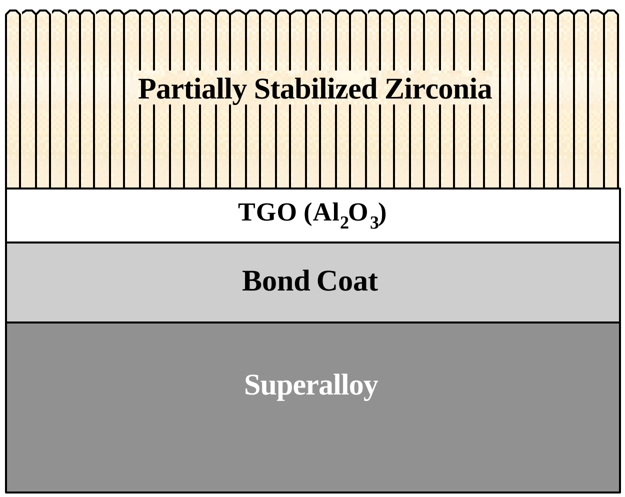


As-Deposited
3.15 ± 0.12 GPa



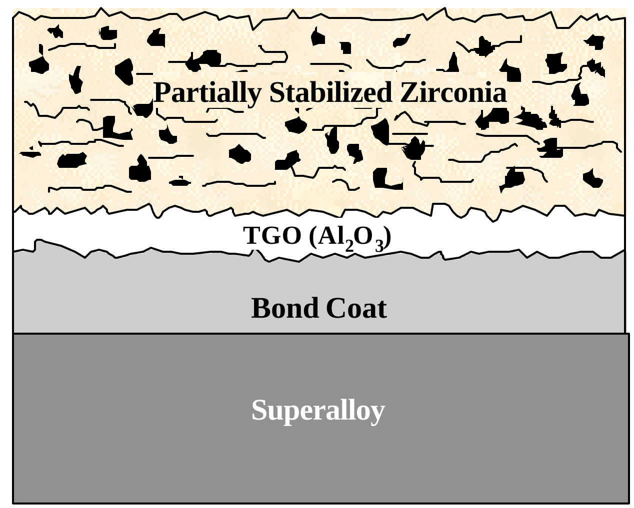
Engine-Tested
1.41 ± 0.21 GPa

Laser Fluorescence Technique for EB-PVD and Plasma Sprayed TBCs



EB-PVD TBC

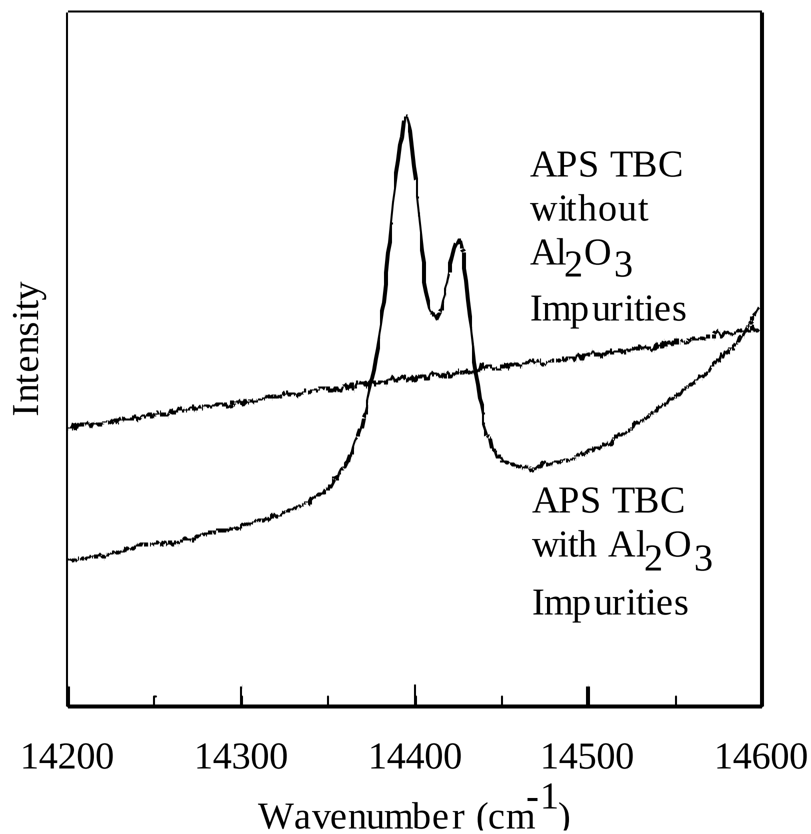
- Columns Act As Optical Wave Guide
- Stress Determination Through 300 mm-Thick TBC



Plasma Sprayed TBC

- Pores, Splat Boundaries and Cracks Scatter Photons
- Fluorescence May Occur from a-Al_2O_3 Impurities in 7YSZ
- Stress Determined Through £ 170 mm Thick TBC

Laser Fluorescence Spectroscopy on Plasma Sprayed TBCs

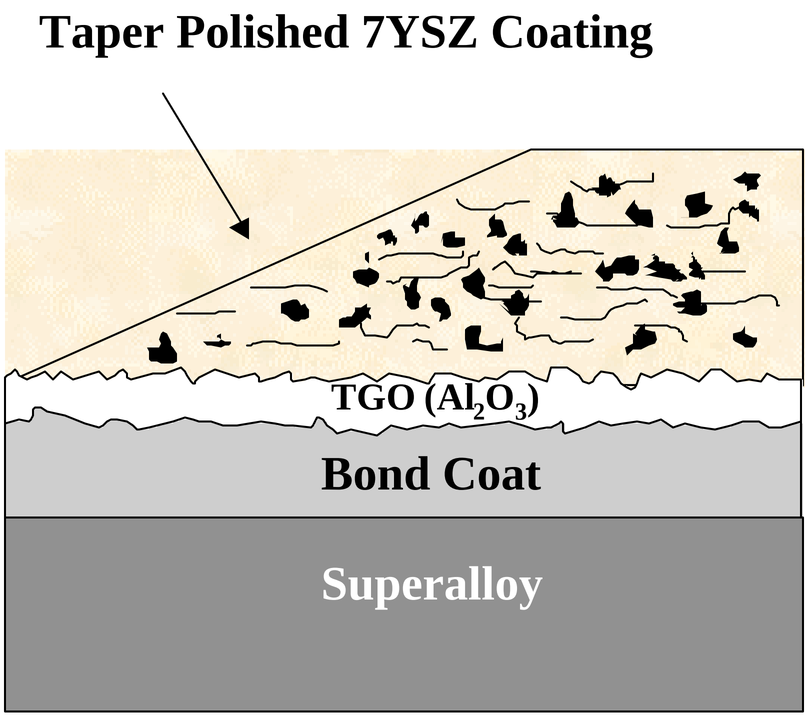


- **For Plasma Sprayed TBCs without Al_2O_3 Impurities, No Cr^{3+} Photoluminescence Signal from TGO was Observed.**

- **For Plasma Sprayed TBCs with Al_2O_3 Impurities, Cr^{3+} Photo-luminescence Signal Only from Al_2O_3 Impurities was Observed.**

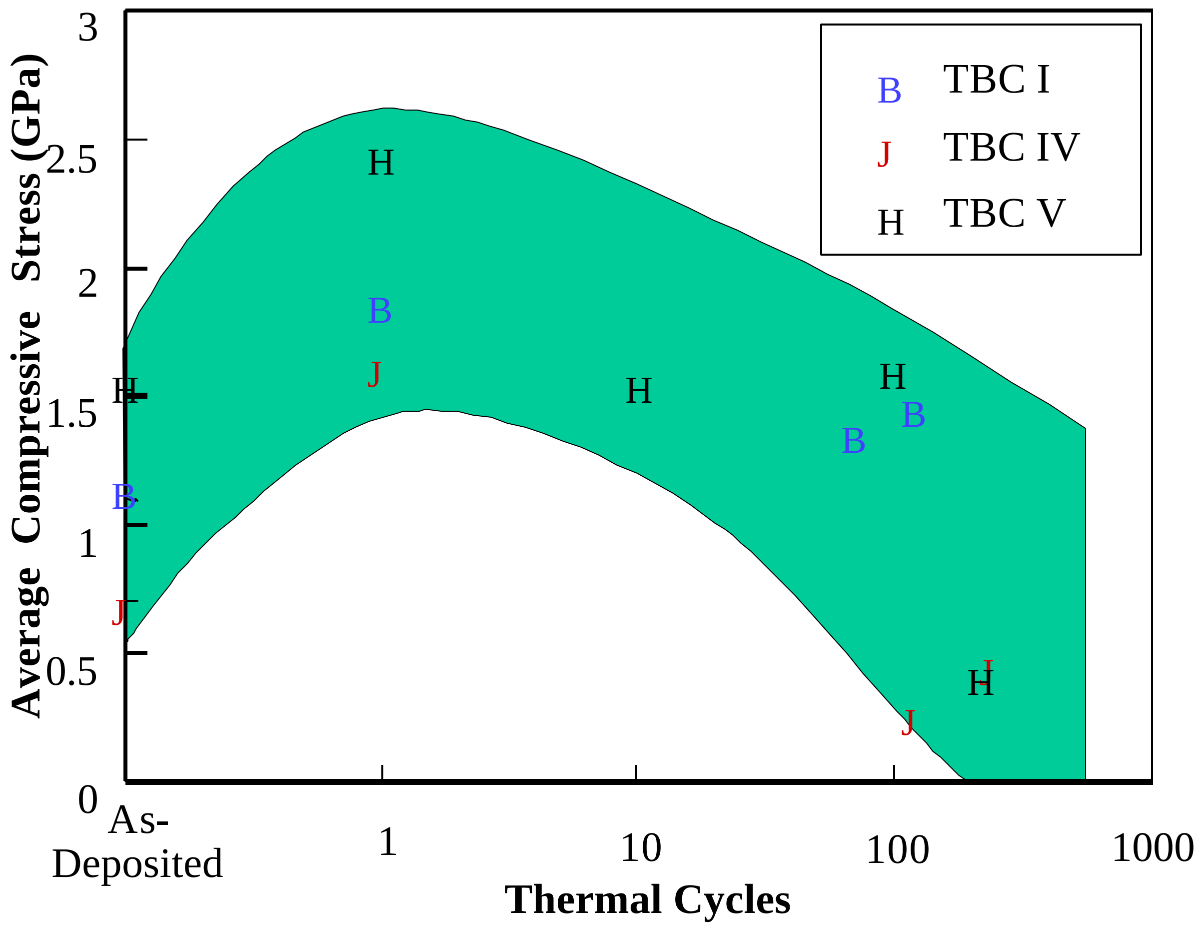
  - **Residual Stress of Al_2O_3 Impurities is Significantly Lower than That of Al_2O_3 in TGO.**

Laser Fluorescence Spectroscopy on Taper-Polished Plasma Sprayed TBCs



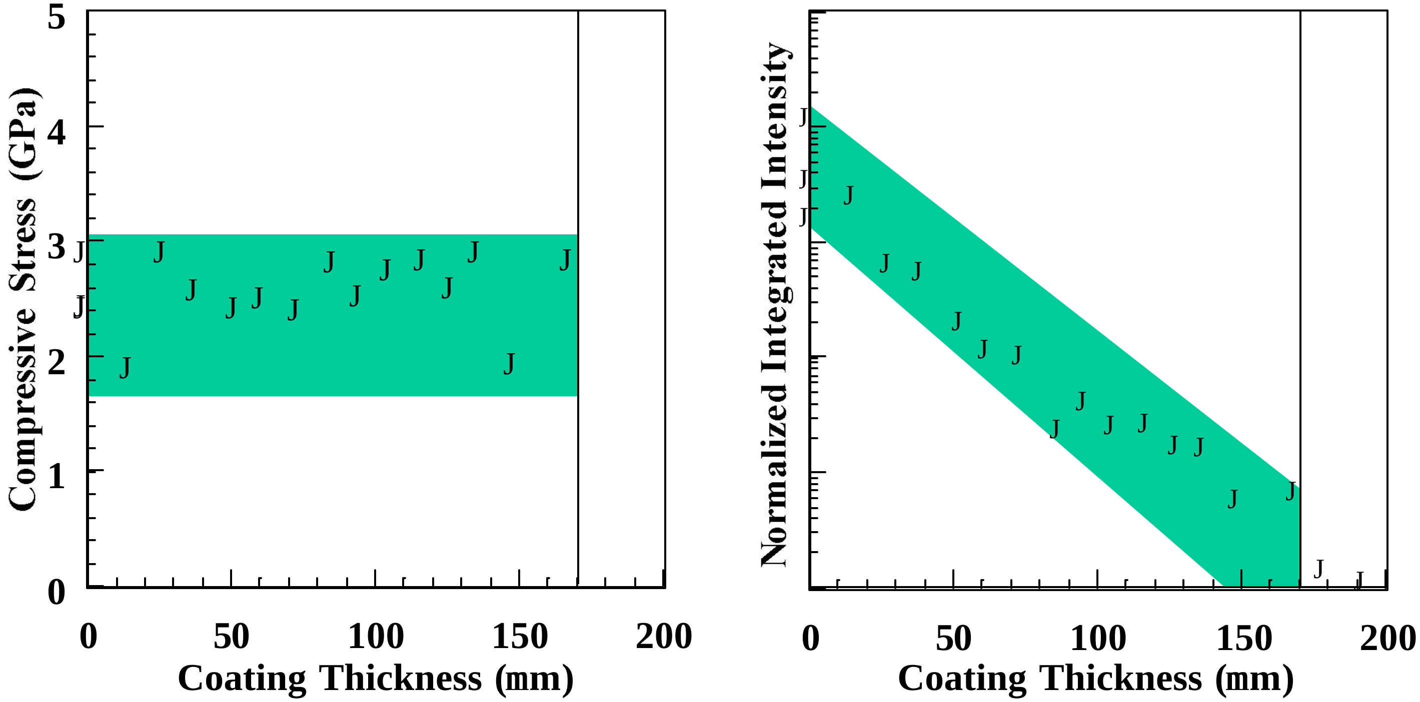
Selected Plasma Sprayed TBCs were Taper-Polished for Laser Fluorescence Measurement as a Function of Coating Thickness

Laser Fluorescence Spectroscopy on Taper-Polished Plasma Sprayed TBCs



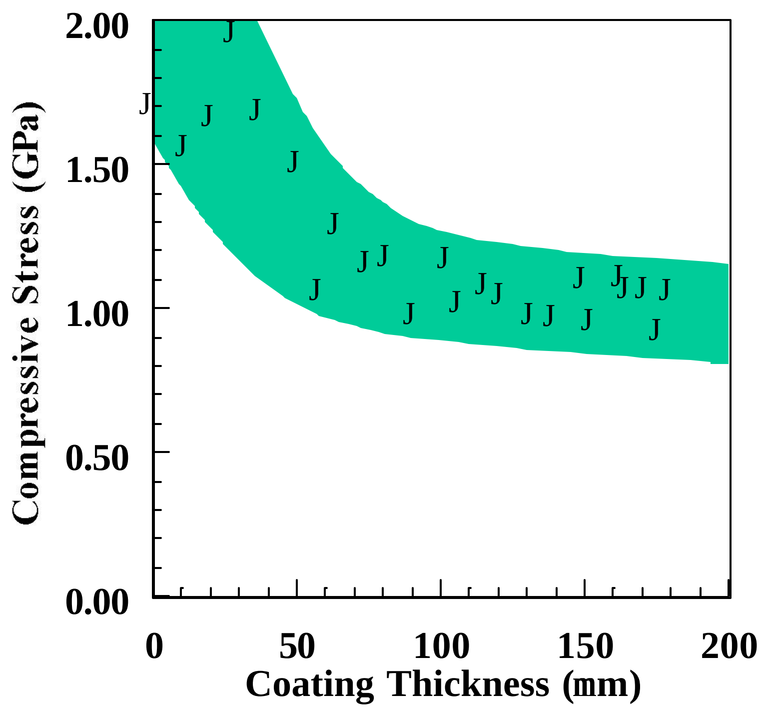
Laser Fluorescence Spectroscopy on Taper-Polished Plasma Sprayed TBCs

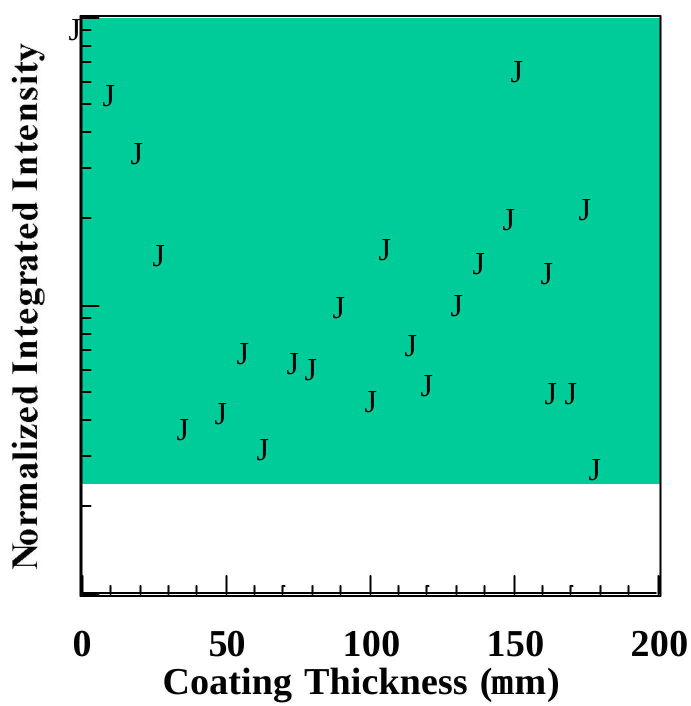
No a-Al_2O_3 Impurities in 7YSZ : Intrinsic Factors Influencing Laser Fluorescence Technique on Plasma Sprayed TBCs.



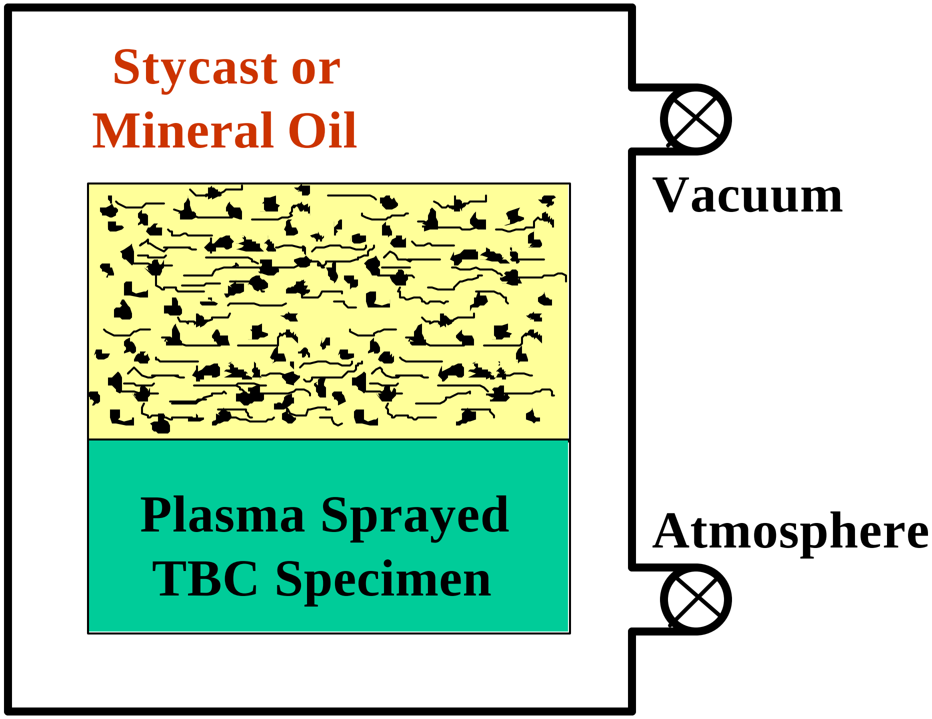
Laser Fluorescence Spectroscopy on Taper-Polished Plasma Sprayed TBCs

a-Al_2O_3 Impurities in 7YSZ: Extrinsic Factor Influencing Laser Fluorescence Technique on Plasma Sprayed TBCs.



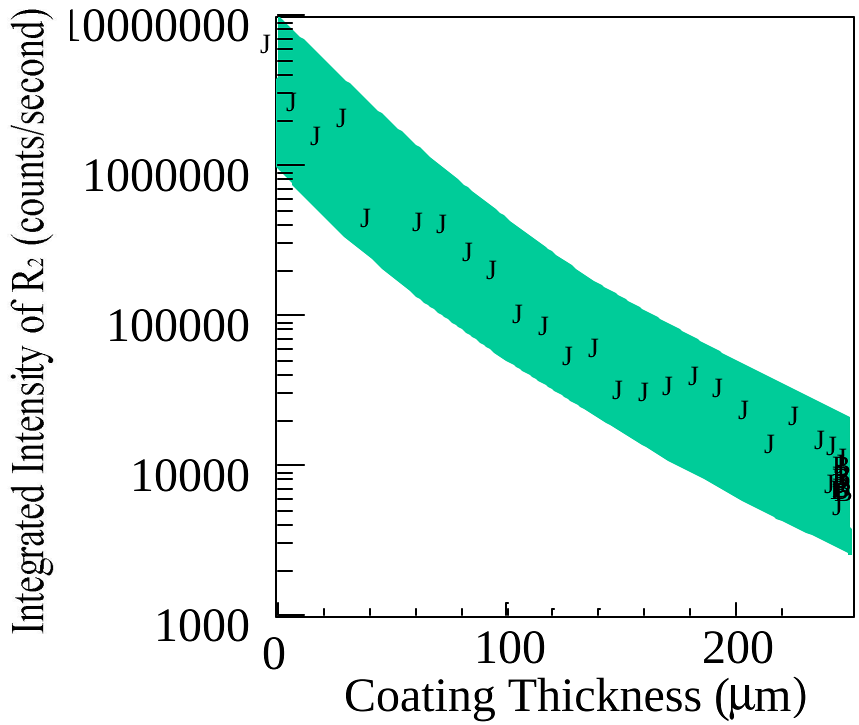


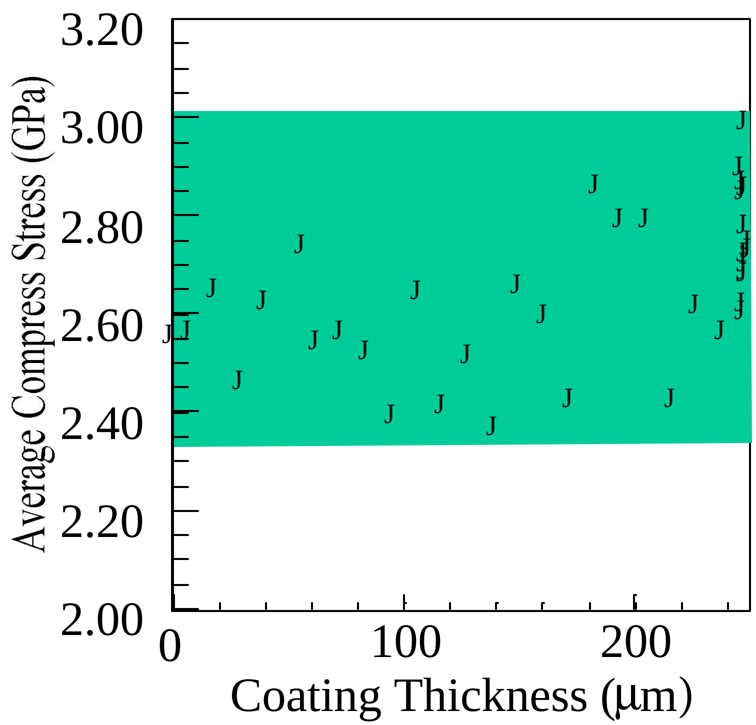
Development of Improved Laser Fluorescence Technique for Plasma Sprayed TBCs



Porosity and Splat Boundary of Plasma Sprayed YSZ Coatings are Vacuum Impregnated with Materials (such as Stycast or Mineral Oil) to Reduce the Mismatch of Refraction Index Compared to Air.

Development of Improved Laser Fluorescence Technique for Plasma Sprayed TBCs

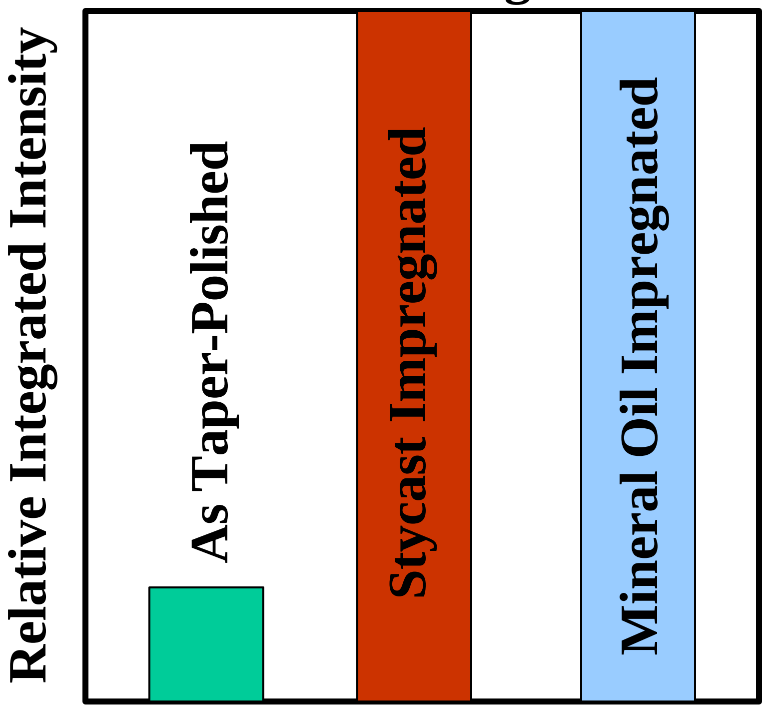




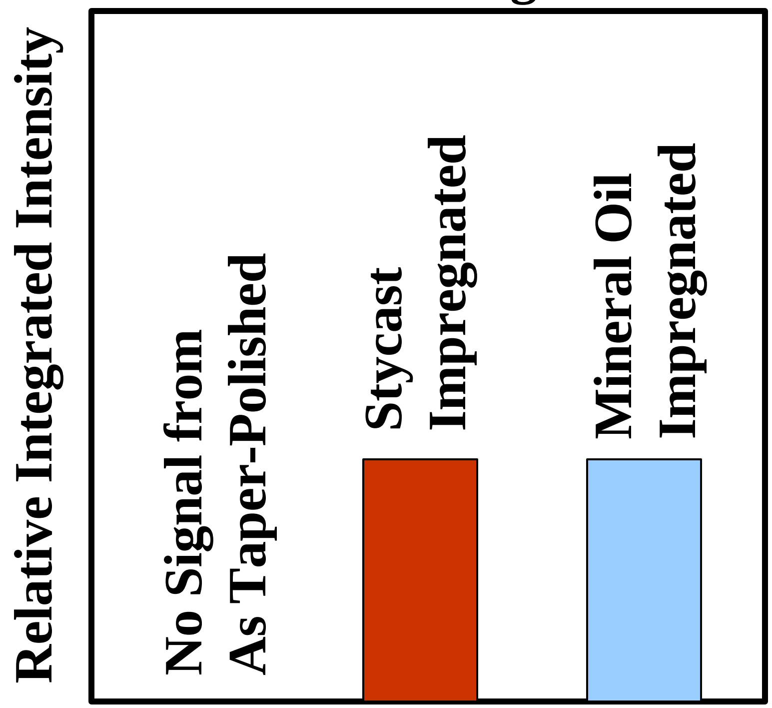
For Plasma Sprayed TBCs Impregnated with Stycast, Cr^{3+} Photo-luminescence was Observed Through Full-Thickness of the YSZ Coating (250 ㎜) with Consistent TGO Stress (2~3 GPa).

Development of Improved Laser Fluorescence Technique for Plasma Sprayed TBCs

150 mm-Thick Plasma Sprayed YSZ Coatings



250 mm-Thick Plasma Sprayed YSZ Coatings



Summary and Conclusions

- Potential Demonstrated for Laser Fluorescence of TBCs As Technique for :
  - Non-Destructive Inspection
  - Quality Control
  - Coating Development

- Laser Fluorescence Demonstrated on Full-Thickness (300 mm) EB-PVD Specimens and Turbine Blades.

- Increased Scattering and Absorption of Incident Laser Beam Occur in Plasma Sprayed Coatings.

- Sources of Scattering are Pores, Splat Boundaries, Grain Boundaries and Cracks.

- Use of Solutions with High Refractive Index and Low Frequency Laser are Being Examined for Full-Thickness Plasma Sprayed TBCs.

Future Work

- **Laser Fluorescence Data Base Generation as a Function of Temperature, Hold Time and Life Fraction in Thermal Cycle Tests.**
- **Understanding for the Evolution of Cr^{3+} Photo-luminescence Spectrum as a Function of Cyclic Oxidation and Associated Spallation-Failure Mechanisms by Microstructural Analysis.**
- **Automation of Data Acquisition and Spectrum Analysis for Laser Fluorescence Technique in a Laboratory Environment.**
- **Modeling and Experimental Optimization of Materials Selection for Impregnation of Full-Thickness Plasma Sprayed TBCs.**
- **Detailed Examination of Thermal Barrier Coated Engine Parts with Respect to Temperature Profiles and Engine-Test History.**
- **Develop a Robust, Portable Laser Fluorescence Instrument with Guidance from ATS Engine Developers.**

Acknowledgements

- Advanced Gas Turbine Systems Research (AGTSR) Contract #99-01-SR073.
- Dr. Lawrence Golan, South Carolina Institute of Energy Studies.