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# Development and Testing of Ceramic Thermal Barrier Coatings

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Ceramic thermal barrier coatings will play an increasingly important role in future gas turbine engines because of their ability to effectively protect the engine components and further raise engine temperatures. Durability of the coating systems remains a critical issue with the ever-increasing temperature requirements. Thermal conductivity increase and coating degradation due to sintering and phase changes are known to be detrimental to coating performance. There is a need to characterize the coating behavior and temperature limits, in order to potentially take full advantage of the current coating capability, and also accurately assess the benefit gained from advanced coating development. In this study, thermal conductivity behavior and cyclic durability of plasma-sprayed $ZrO_2$-8wt%$Y_2O_3$ thermal barrier coatings were evaluated under laser heat-flux simulated high temperature, large thermal gradient and thermal cycling conditions. The coating degradation and failure processes were assessed by real-time monitoring of the coating thermal conductivity under the test conditions. The ceramic coating crack propagation driving forces and resulting failure modes will be discussed in light of high temperature mechanical fatigue and fracture testing results.

Full paper version
and advanced copy of this Poster
already approved by Diane Chapman

# Development and Thermal Fatigue Testing of Ceramic Thermal Barrier Coatings

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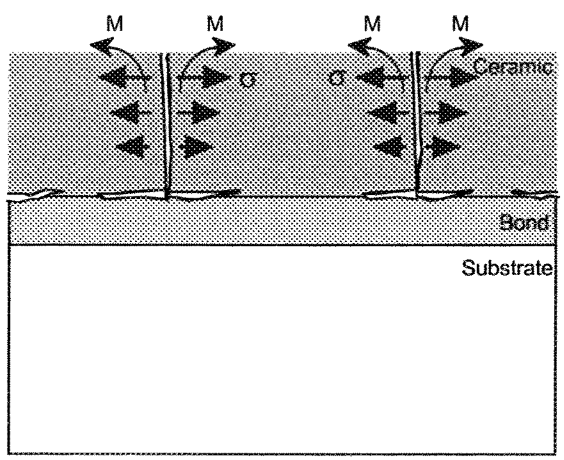
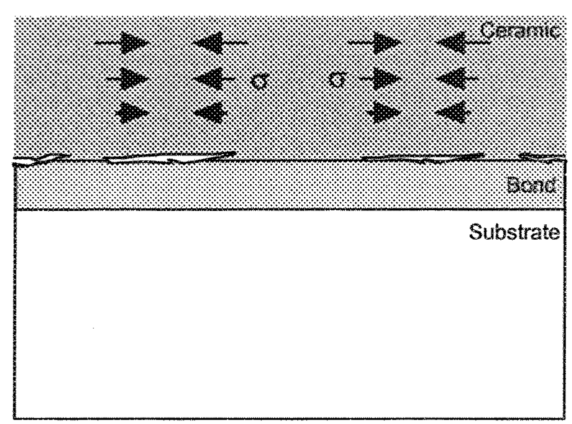
# Generalized Thermal Barrier Coating Failure Modes

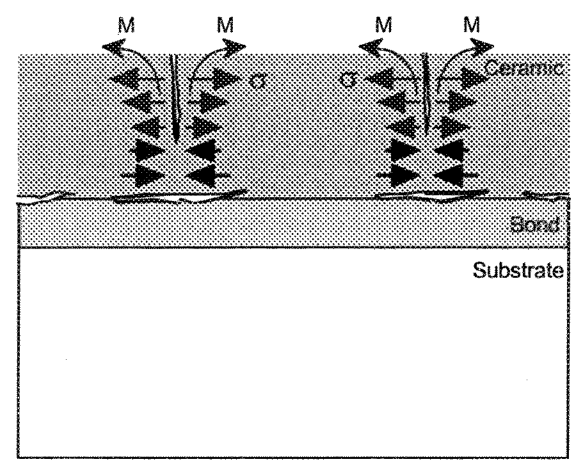
— Crack propagation is a critical issue especially under surface heat flux, thermal gradient cyclic loading




(a) High Heat Flux and Low Interface Temperature




(b) Low Heat Flux and High Interface Temperature




(c) Medium Heat Flux and Interface Temperature

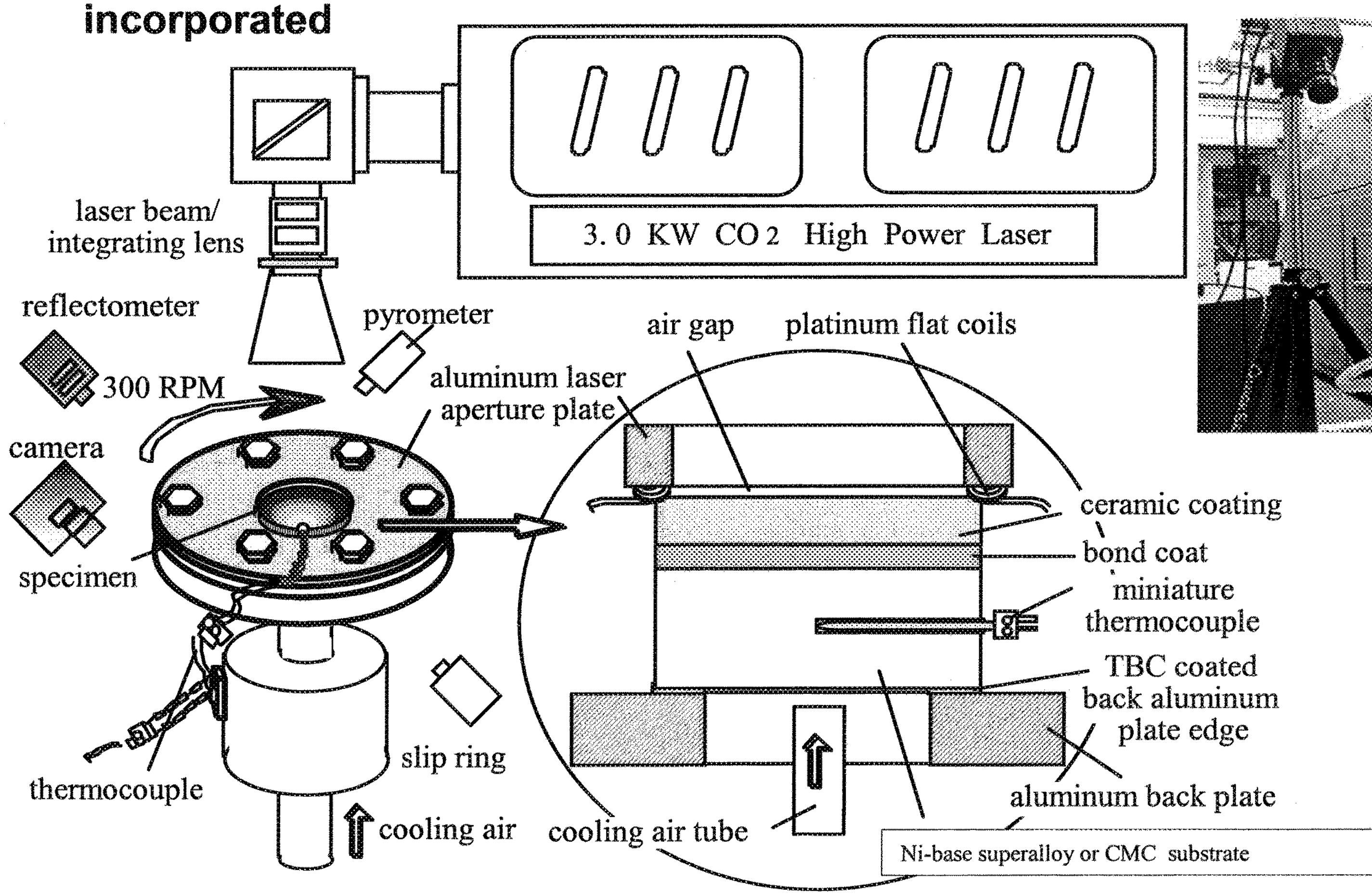
# Objectives

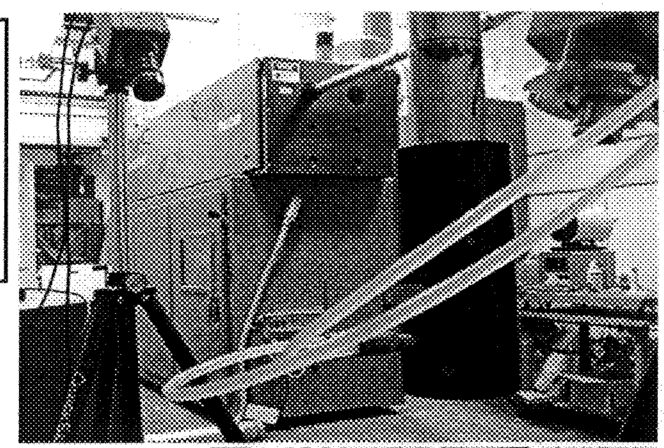
- Investigate the coating crack propagation under realistic high temperature and thermal gradient cyclic loading

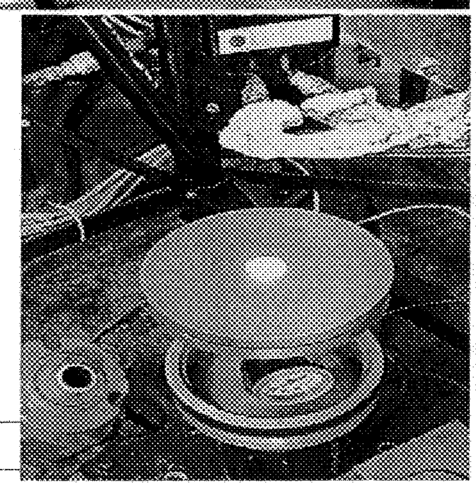
- Laser heat flux testing for advanced thermal barrier coatings development

# Laser Heat Flux Technique used for the Coating Real-time Crack Propagation Study

- A uniform laser (wavelength 10.6 μm) power distribution achieved using integrating lens combined with lens/specimen rotation
- The ceramic surface and substrate temperatures measured by 8 micron and two-color pyrometers and/or by an embedded miniature thermocouple
- Thermal conductivity measured at 5 second intervals in real time and thermal cycling incorporated

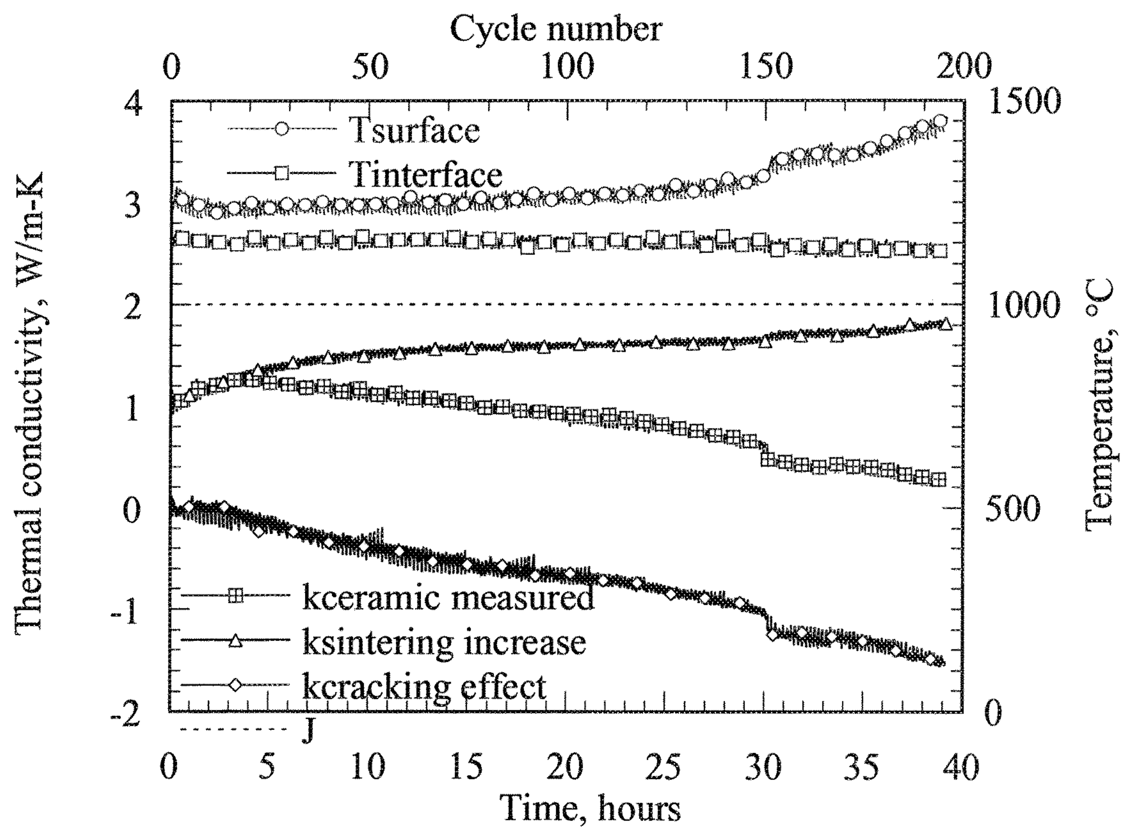




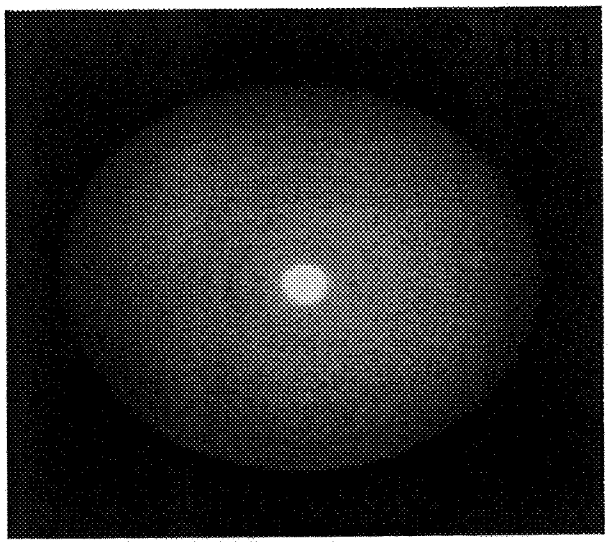
# Temperature Response and Thermal Conductivity Changes of $ZrO_2$-8wt%$Y_2O_3$ as a Function of Cycle Number

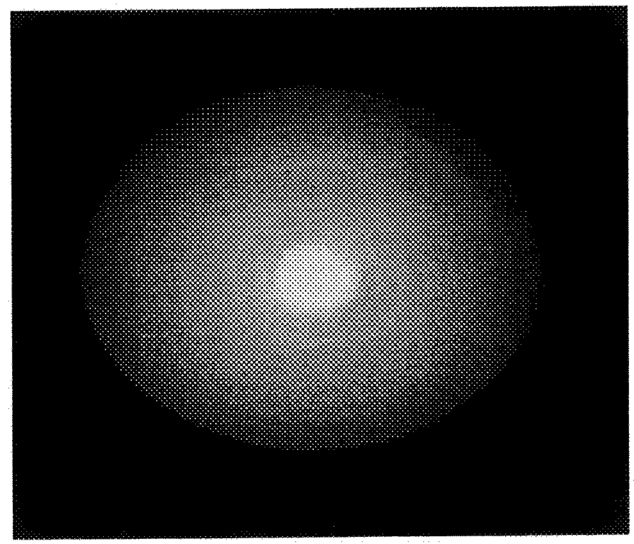
- Coating tested under 10 min heating and 2 min cooling laser thermal cycling condition
- Surface temperature increases and the metal backside temperature decreases as the delamination crack is initiated and propagated
- Coating conductivity initially increases due to coating sintering and then decreases due to crack propagation

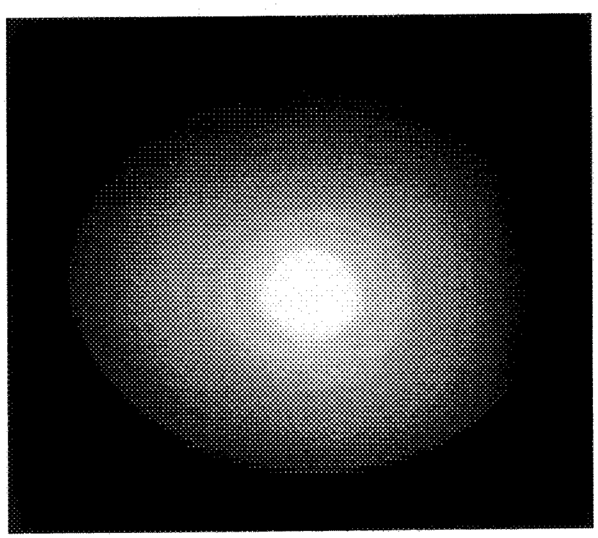


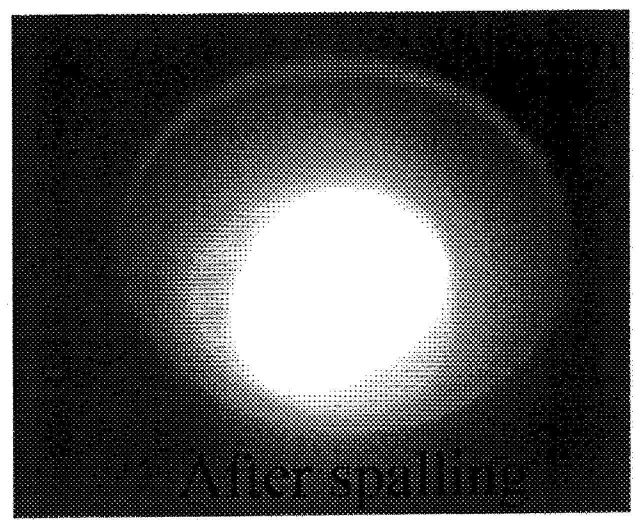
# Crack Propagation of $ZrO_2$-8wt%$Y_2O_3$ System

— 0.2 mm Thick TBC Specimen with a 2-mm hole in the Substrate





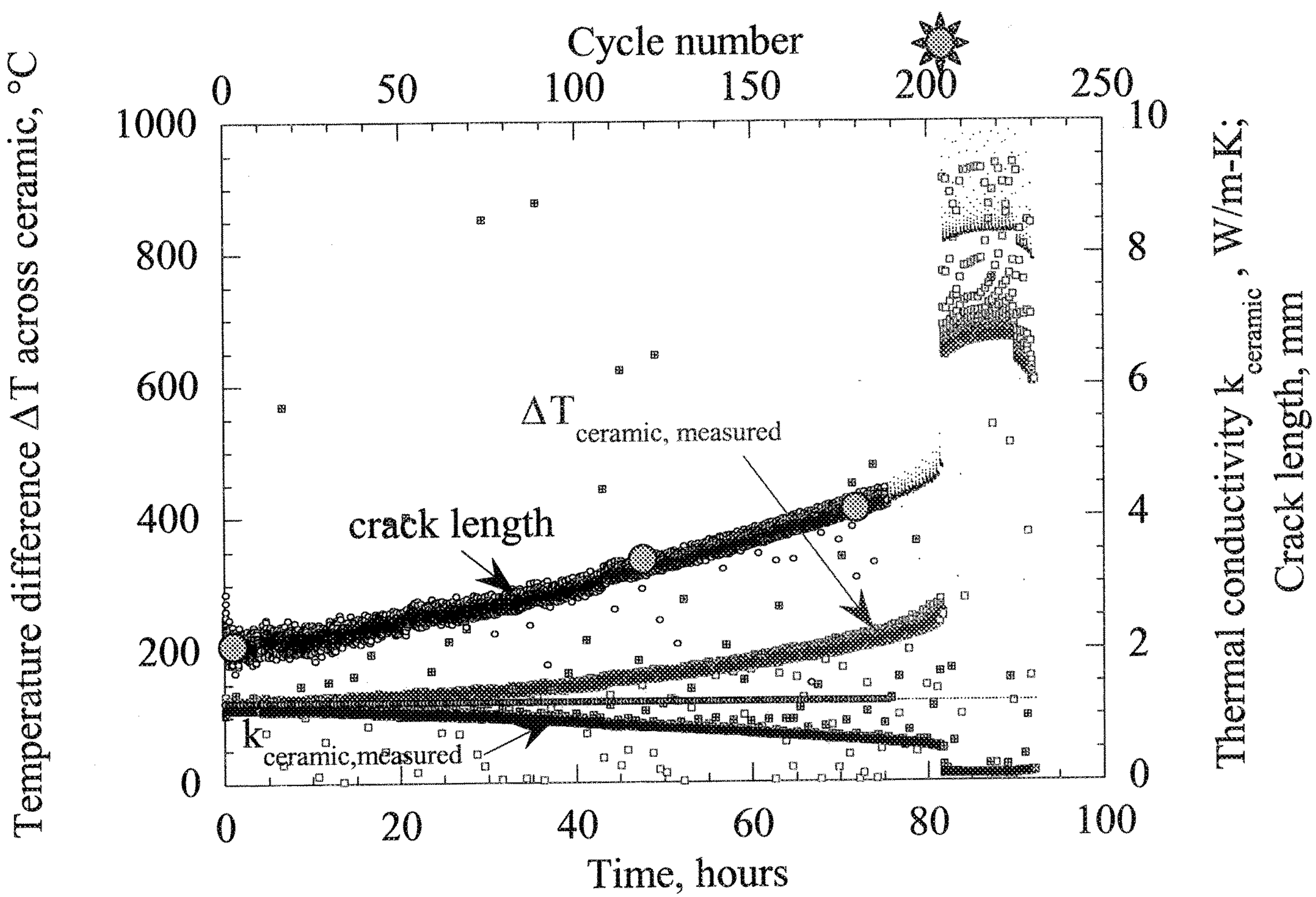




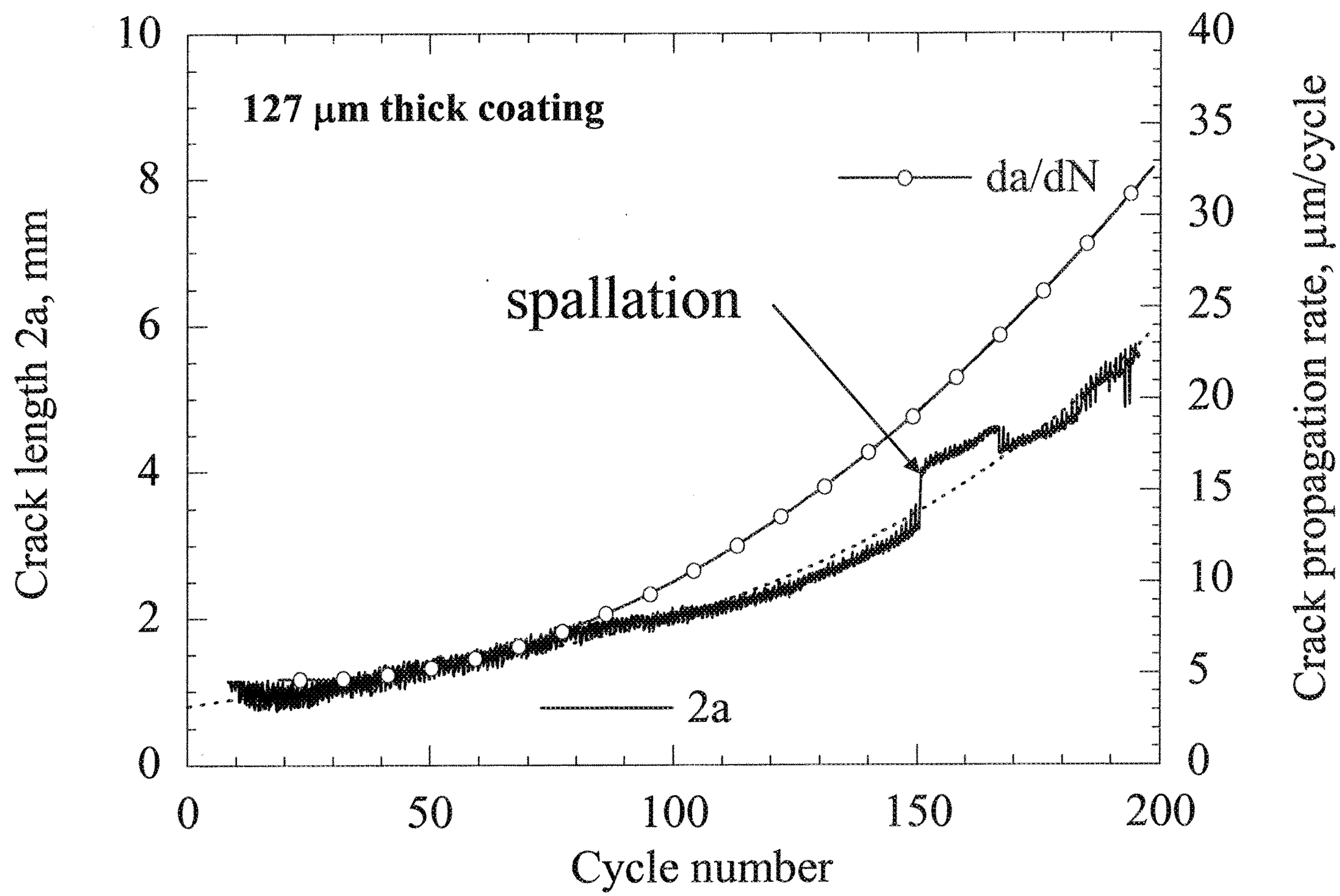
# The Laser Thermal Fatigue Test Results of A 0.2 mm Thick $ZrO_2$-8wt%$Y_2O_3$ with a 2 mm hole in the Substrate

— Specimen exposed to 20 min heating and 4 min cooling laser cycling

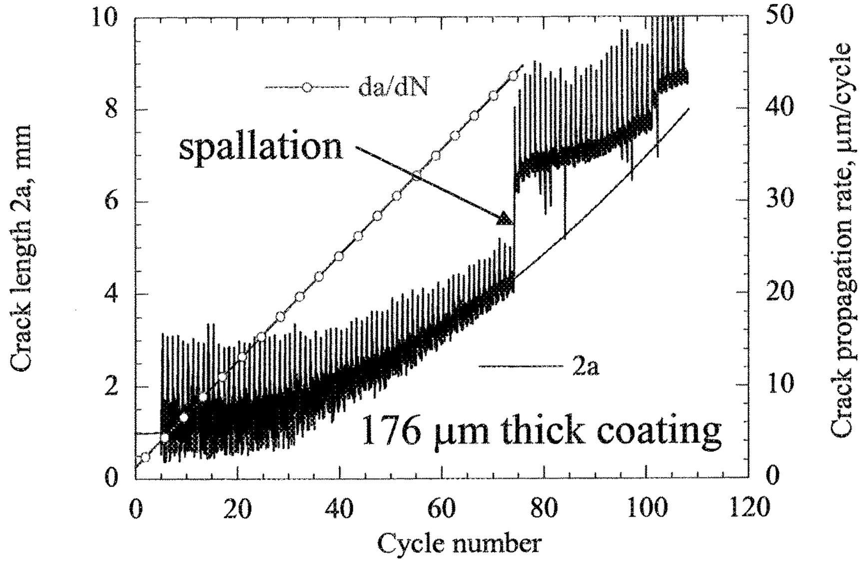
— A close relationship between the coating conductivity and delamination crack length demonstrated

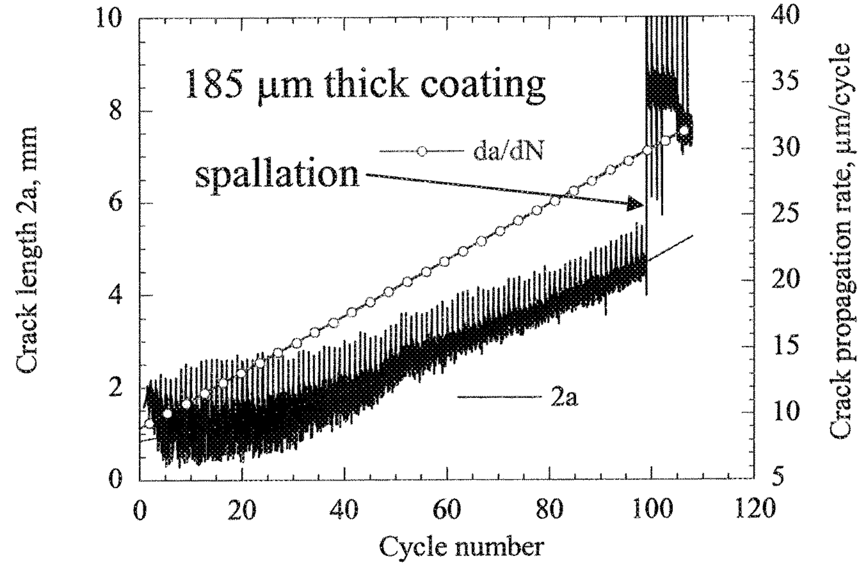


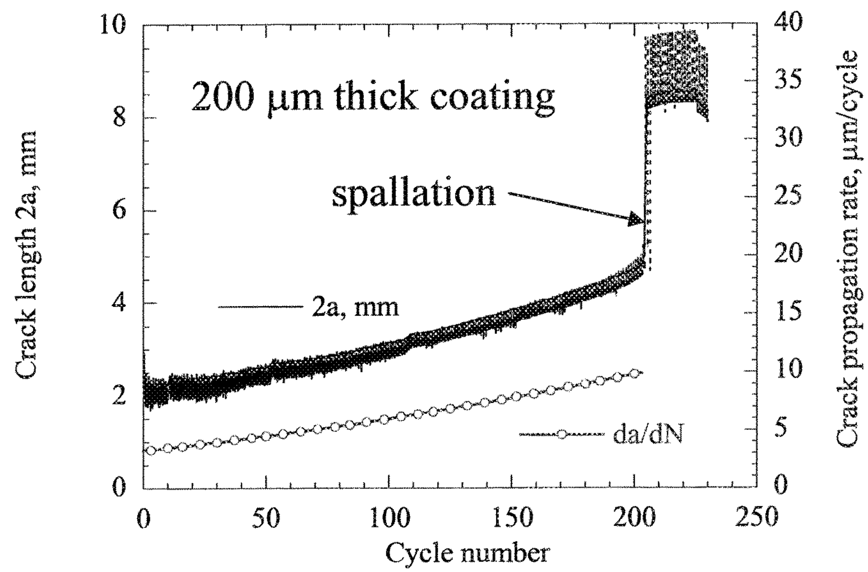
# Crack Length and the Crack Propagation Rates of $ZrO_2$-8wt%$Y_2O_3$ as a Function of Cycle Number



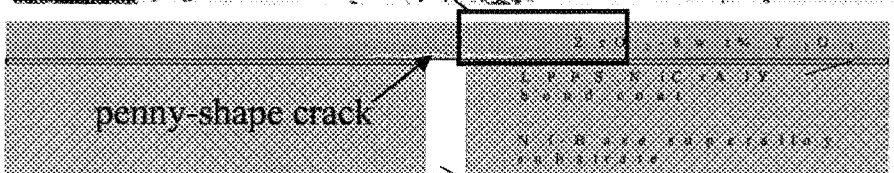
# Crack Length and the Crack Propagation Rates of $ZrO_2$-8wt%$Y_2O_3$ as a Function of Cycle Number



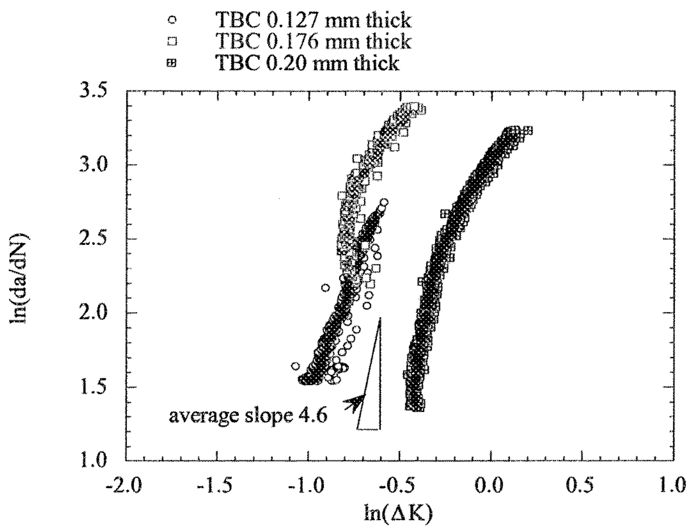



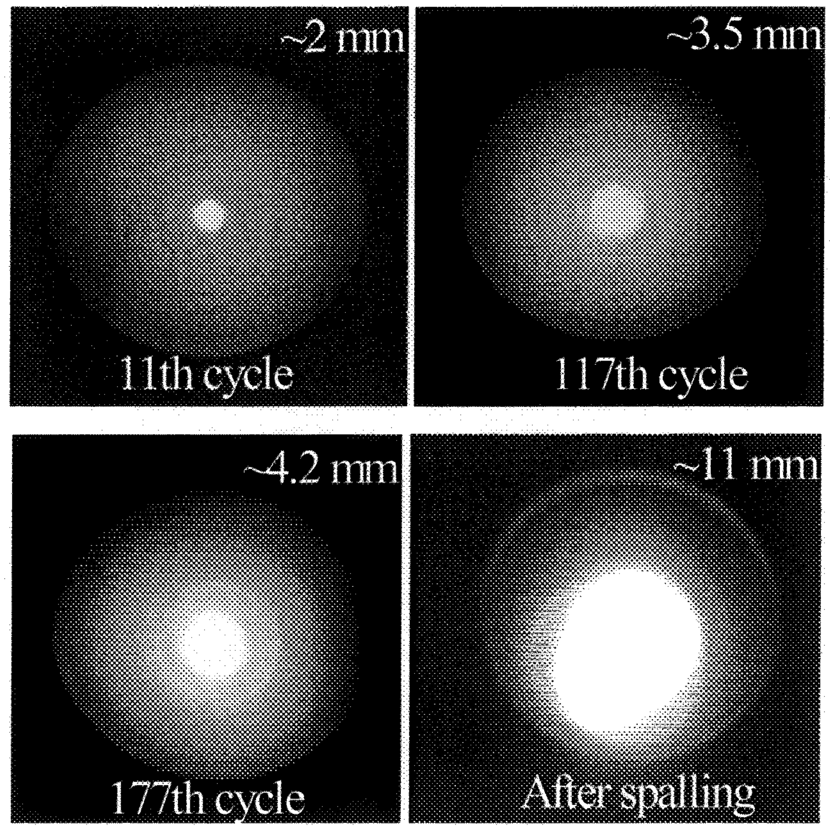
# The Relationship between Crack Propagation Rate and Laser Thermal Stress Associated Stress Intensity Factor Amplitude


A center penny-shape crack propagation




Crack propagation da/dN-stress intensity amplitude ΔK plot for life prediction

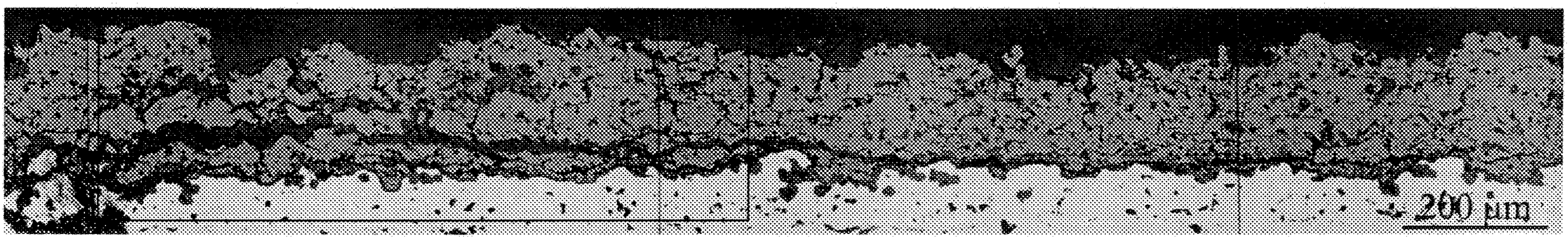


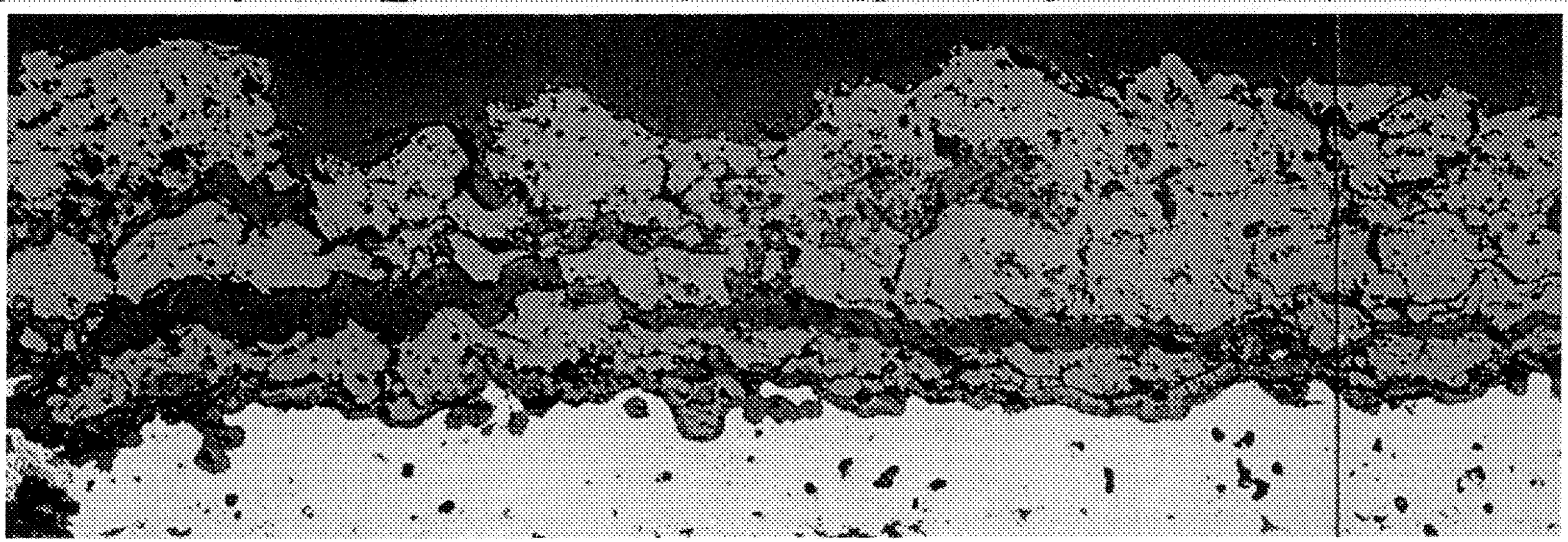
# Micrograph of Laser Thermal Fatigue Tested TBC Showing Coating Delamination Crack Propagation

— Severe fatigue damages are observed near the early crack propagation wake surfaces

— Strong coating asperity/debris interactions and coating multiple delaminations

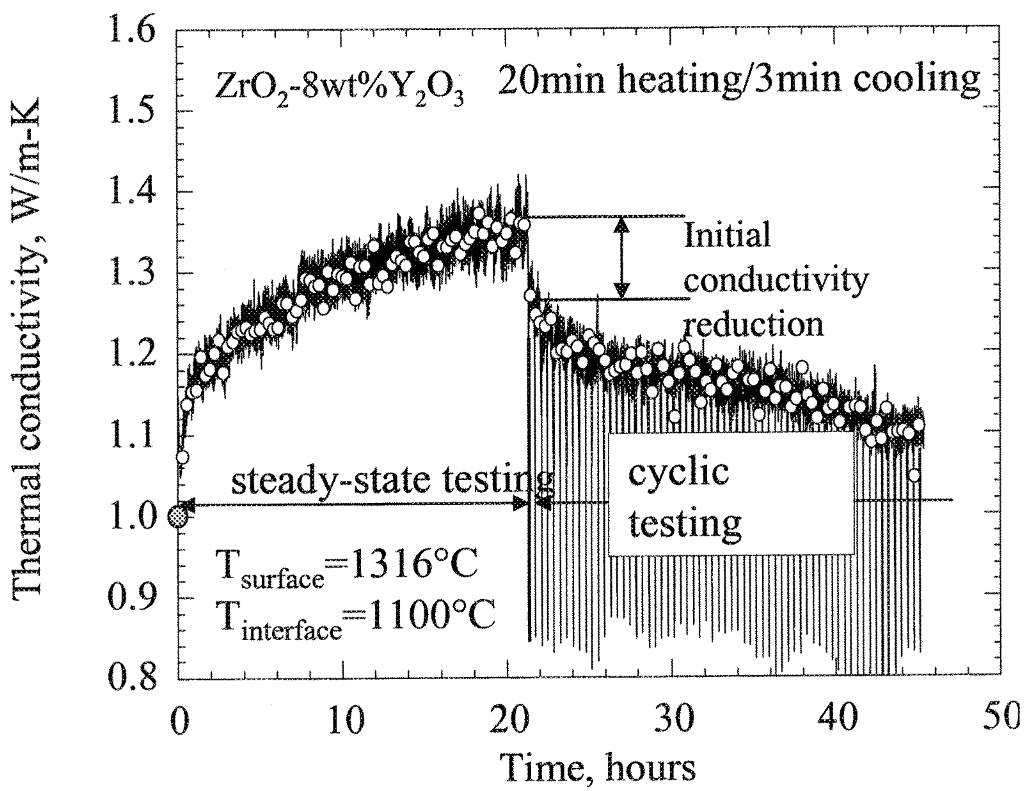
— The later crack paths show relatively smooth surfaces, which corresponds to the faster crack propagation regions under the increased crack propagation driving force

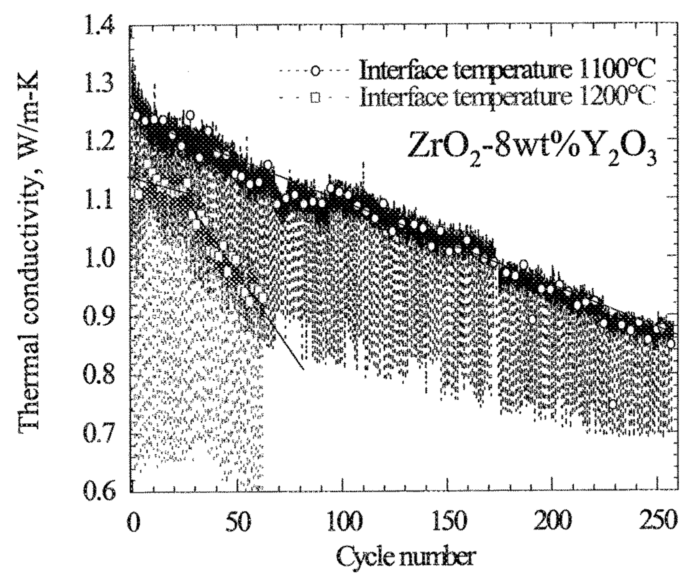


# Laser Heat Flux Steady-State and Cyclic Testing of $ZrO_2$-8wt%$Y_2O_3$ Thermal Barrier Coatings

- Thermal conductivity monitoring used for coating durability evaluation
- $ZrO_2$-8wt%$Y_2O_3$ coating cyclic durability demonstrated an issue at 1316°C



# Development of Advanced Defect Cluster Thermal Barrier Coatings

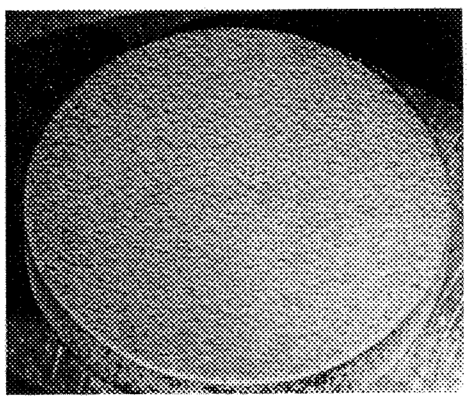
— Develop low conductivity and high stability thermal barrier coatings using oxide defect clustering approach

— Selected multi-component clustered oxide TBC systems investigated and reported - *NASA UEET low k coating systems*

$ZrO_2$-$Y_2O_3$-$Nd_2O_3$($Gd_2O_3$,$Sm_2O_3$)-$Yb_2O_3$($Sc_2O_3$) systems

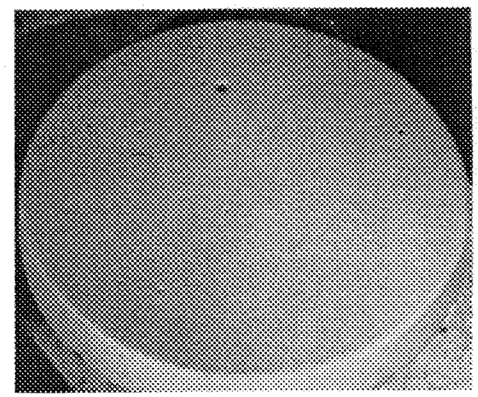
Primary stabilizer

Oxide cluster dopants with distinctive ionic sizes



**Plasma-sprayed coating specimen**

**EB-PVD coating Specimen**



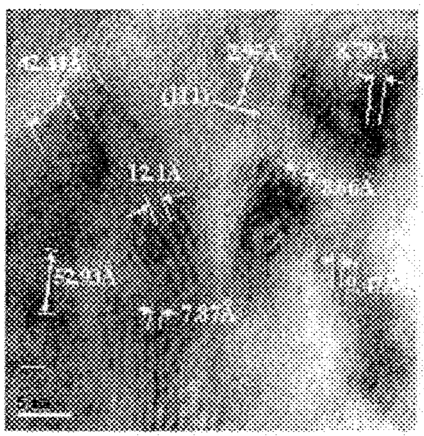
— Real-time monitoring and evaluation of the coating thermal conductivity and sintering

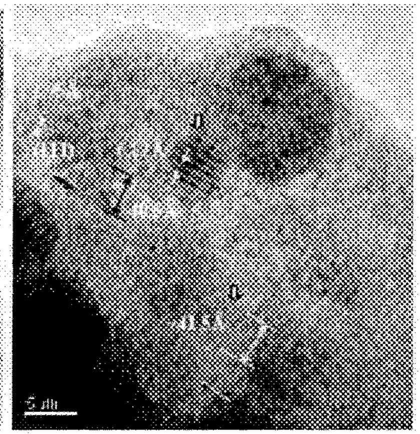
— Furnace cyclic oxidation test for initial coating durability assessment

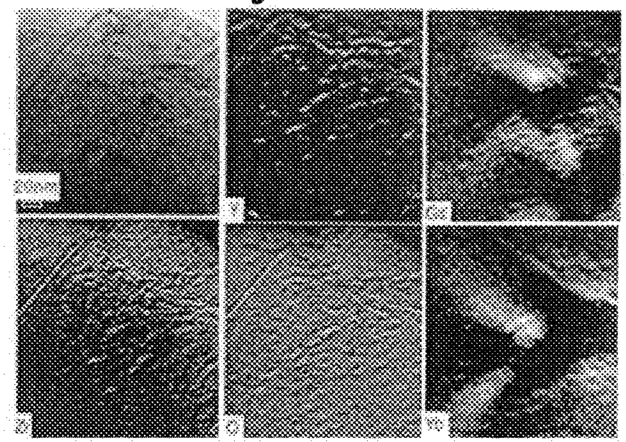
— Higher temperature heat-flux cyclic tests for temperature durability/capability test

# Defect Clusters Identified using High Resolution Transmission Electron Microscopy and EELS Analysis

— The 5 to 100 nm size defect clusters are believed to be responsible for the reduced thermal conductivity and improved stability



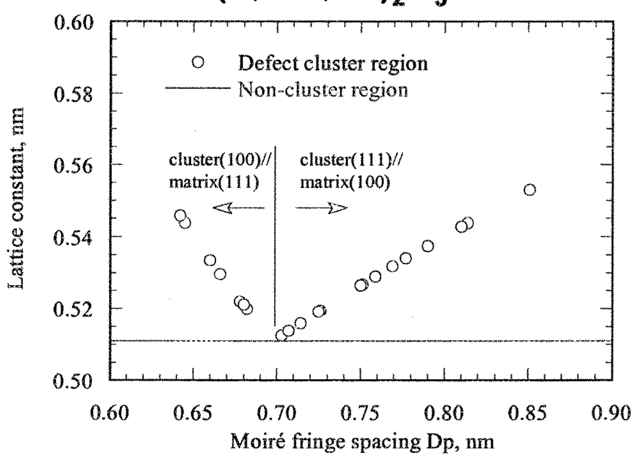


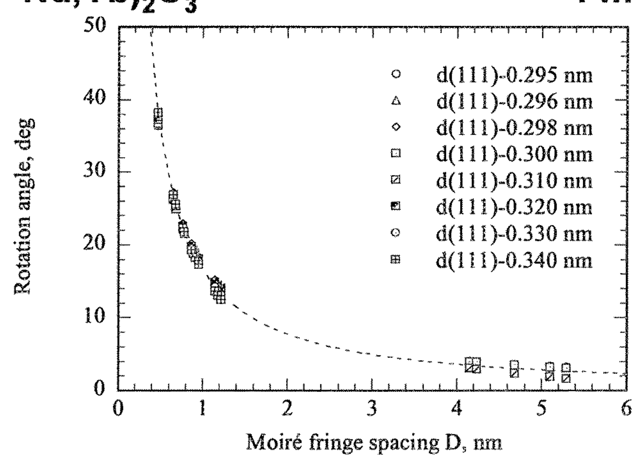


**Plasma-sprayed $ZrO_2$-13.5mol%(Y, Nd,Yb)$_2O_3$**

**EB-PVD $ZrO_2$-12mol%(Y, Nd,Yb)$_2O_3$**

**EELS elemental maps of EB-PVD $ZrO_2$-14mol%(Y, Gd,Yb)$_2O_3$**

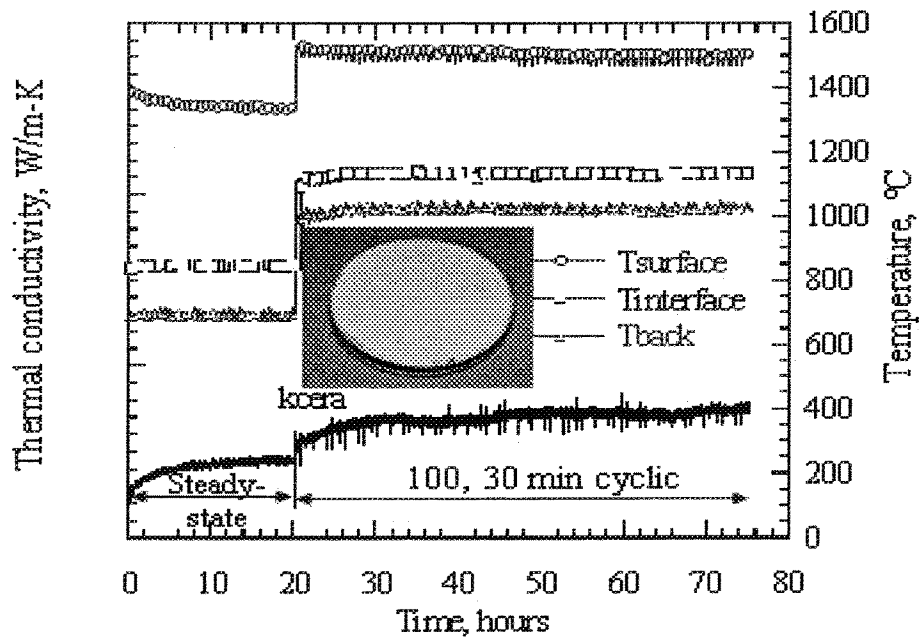



**Lattice constant and rotation angle of the defective and dopant segregated lattice characterized**

# Sintering and Cyclic Durability of Advanced TBCs

— The advanced defect cluster coatings demonstrated very high temperature cyclic durability



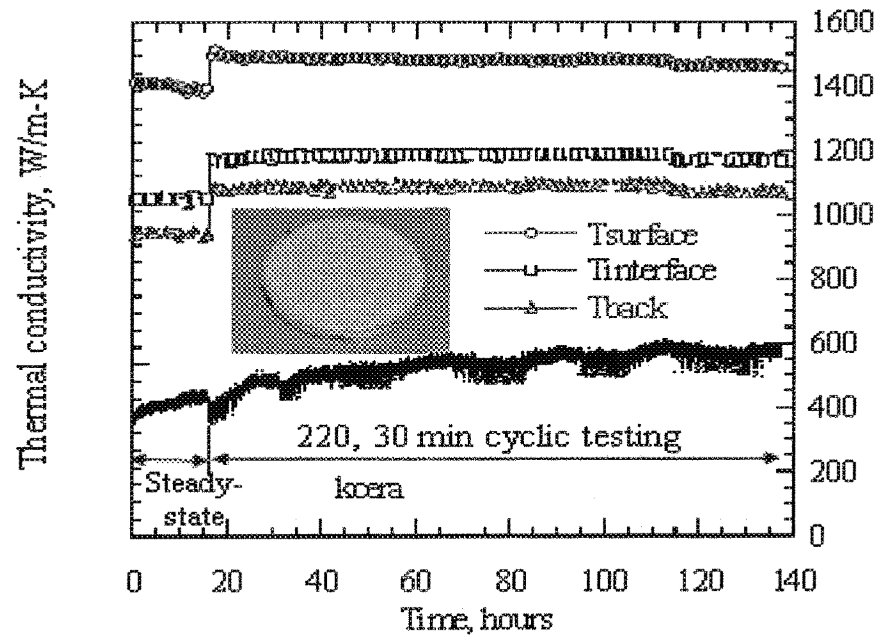

(a) The NASA t' low k coatings

– 20h Sintering:

$T_{surface}$=1360°C (2500°F), $T_{interface}$=850°C (1562°F)

– 100, 30 min cyclic testing:

$T_{surface}$ =1535°C (2795°F), $T_{interface}$ 1135°C (2075°F)




(b) NASA low k/advanced interlayer coating

– 20h Sintering:

$T_{surface}$=1400°C (2552°F), $T_{interface}$=1050°C (1922°F)

– 220, 30 min cyclic testing:

$T_{surface}$ =1510°C (2750°F), $T_{interface}$=1180°C (2156°F)

# Conclusions

- A laser thermal fatigue approach has been established to study the delamination crack propagation of thermal barrier coatings.

- Real-time monitoring of coating thermal conductivity demonstrated as an effective technique to assess coating performance under simulated engine conditions.

- For the $ZrO_2$-8wt%$Y_2O_3$ coating specimens tested, the initial average crack propagation rate was in the range of 3-8 μm/cycle. The crack propagation rates increased to 30-40 μm/cycle at the later stage of the tests. The accelerated crack growth is attributed to the increased driving force for the crack propagation under the laser heat flux cyclic test conditions.

- The multi-component advanced TBCs demonstrated significantly improved long-term high temperature stability and cyclic durability at very high temperatures required for advanced turbine airfoil and combustor applications.