Interface-Related Damage Evolution in Air-Plasma-Sprayed Thermal Barrier Coatings

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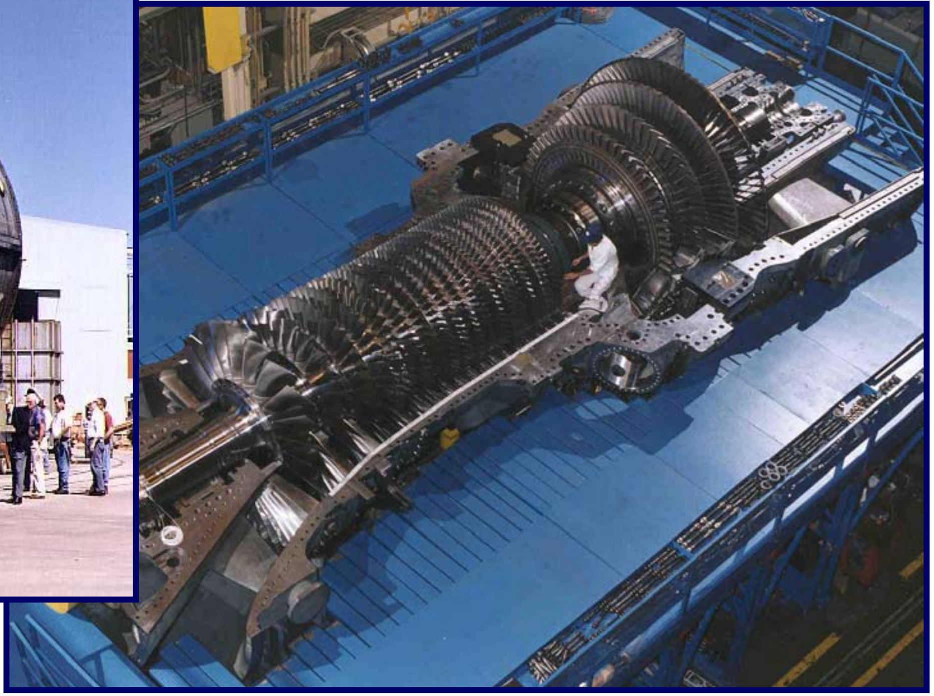
NIST
National Institute of Standards and Technology

GE's 9H Gas Turbine



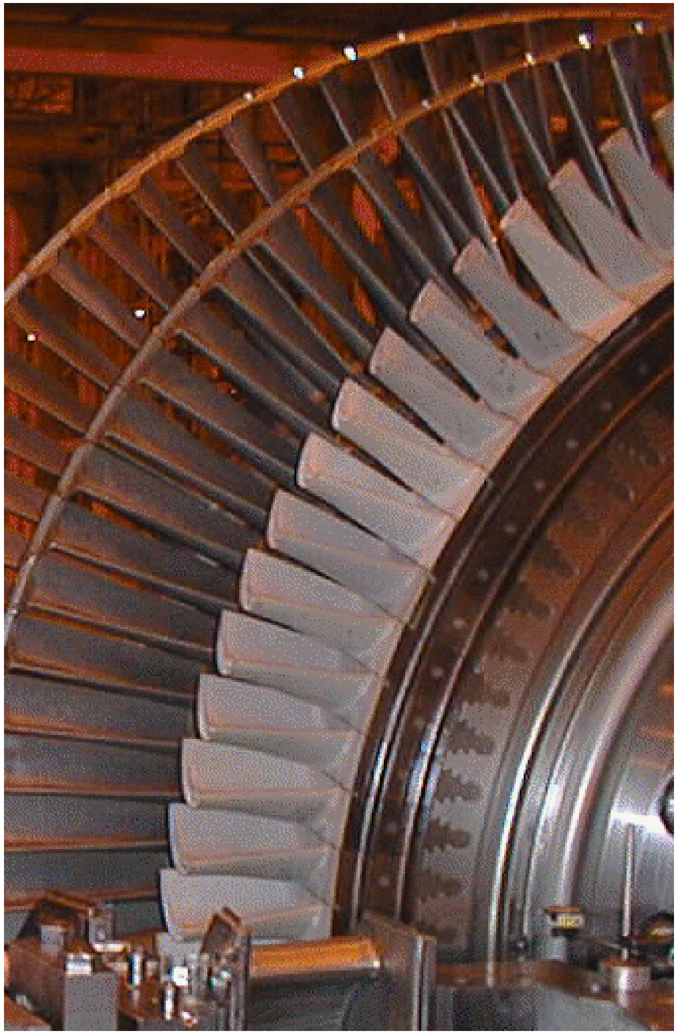
Combined-Cycle Performance

Net Output:	480 MW	Compressor	
Net Efficiency:	60%	Pressure Ratio:	23:1
Firing Temperature:	2600°F / 1430°C	Air Flow:	1510 lbs/sec

Thermal Barrier Coatings (TBC's) on Gas Turbine Buckets

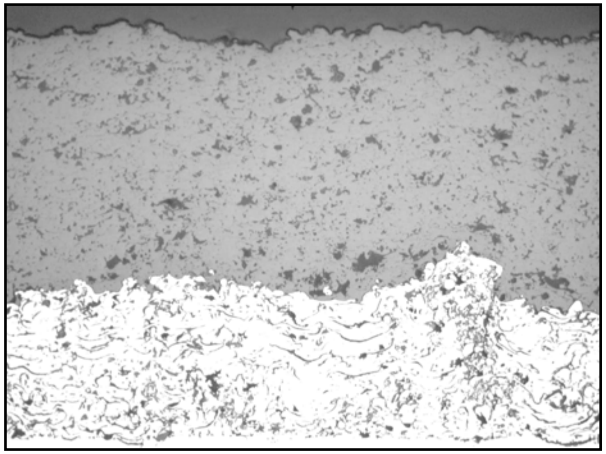
- **In production since 1997 on 7FA class**
  - coated multiple parts on H class in 1998
  - expanded to service market in 1999
- **Air Plasma-Spray (APS) process used for ZrO_2 top coat**
  - bulk temperature reduction (> 75°C) significantly increases creep life
- **Vacuum Plasma-Spray (VPS) or High Velocity Oxy-Fuel (HVOF) process used for MCrAlY bond coat**

  protection of substrate alloy from oxidation and hot corrosion

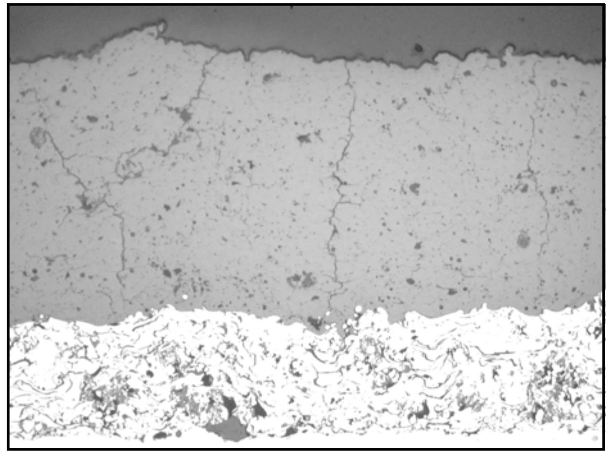


first stage of industrial gas turbine

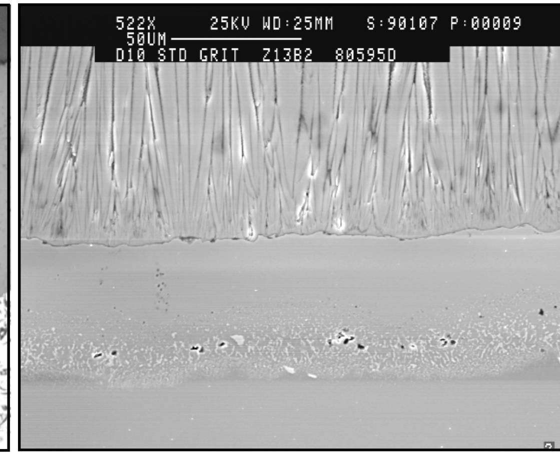
Types of Thermal Barrier Coatings and Deposition Processes



Conventional APS TBC



Advanced APS TBC



Air Plasma Sprayed TBC's

EB-PVD TBC's

Two-layer structure:

- ceramic top coat: $(ZrO_2 + Y_2O_3)$ thermal barrier
- metallic bond coat: MCrAlY oxidation protection

Two deposition processes:

air plasma spray (APS) & physical vapor deposition (PVD)

Industrial Needs for TBC Life Modeling

- Translate laboratory results to engine life models and life prediction
- Develop microstructural failure models to guide development of improved materials and processing techniques

"... microstructurally-based models are needed,"

"...can be qualitative or quantitative"

Micromechanical Damage Model

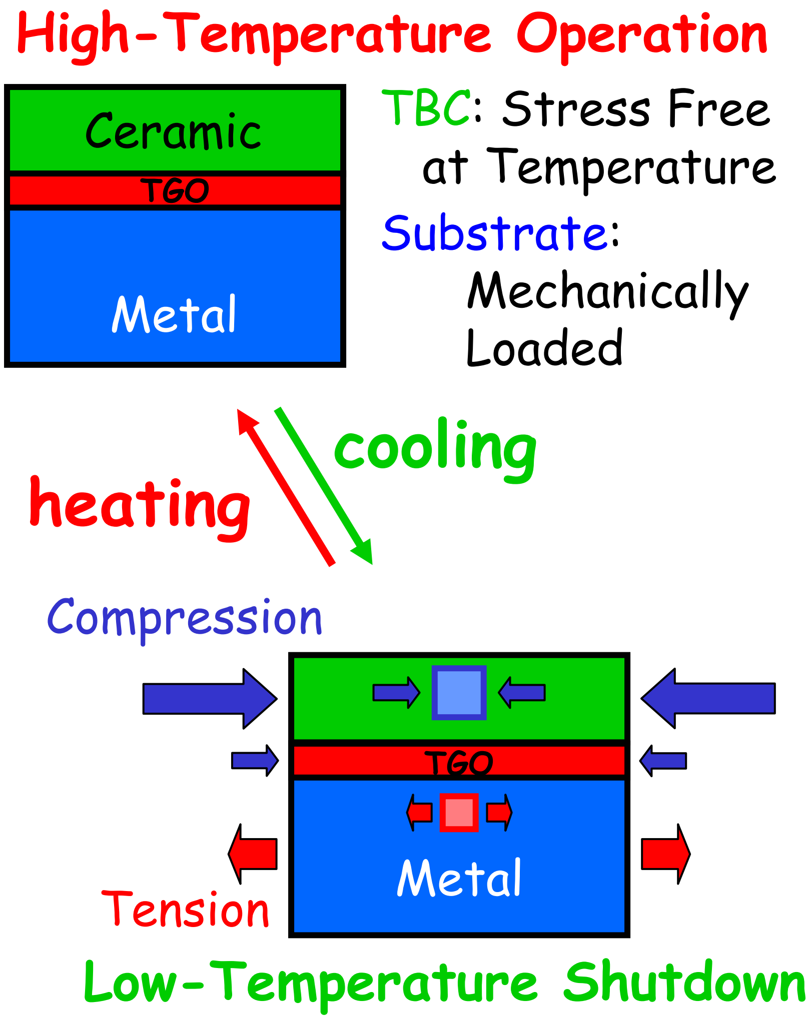
Freborg *et al.* proposed a failure scenario based on the stress reversal above asperities with TGO growth.

- G. C. Chang, W. Phucharoen & R. A. Miller, *"Behavior of thermal barrier coatings For advanced gas-turbine blades,"* Surface & Coatings Technology, **30** [1]: 13-28 (1987).
- A. M. Freborg, B. L. Ferguson, W. J. Brindley, G. J. Petrus, "Modeling oxidation induced stresses in thermal barrier coatings," Mat Sci Eng A-Struct **245** [2]: 182-190 (1998).
- C.-H. Hsueh & E. R. Fuller, Jr., *"Residual stresses in thermal barrier coatings: effects of interface asperity curvature/height and oxide thickness,"* Mat. Sci. Eng. A-Struct **283** [1-2]: 46-55 (2000).
- J. Rösler, M. Bäker & M. Volgmann, *"Stress state and failure mechanisms of thermal barrier coatings: role of creep in thermally grown oxide,"* Acta Mater., **49** [18]: 3659-3670 (2001).
- K. Sfar, J. Aktaa & D. Munz, *"Numerical investigation of residual stress fields and crack behavior in TBC systems,"* Mat. Sci. Eng. A-Struct **333** [1-2]: 351-360 (2002).

Spallation Failure Mechanism for Thermal Barrier Coating

Stresses in TBC-Substrate System:

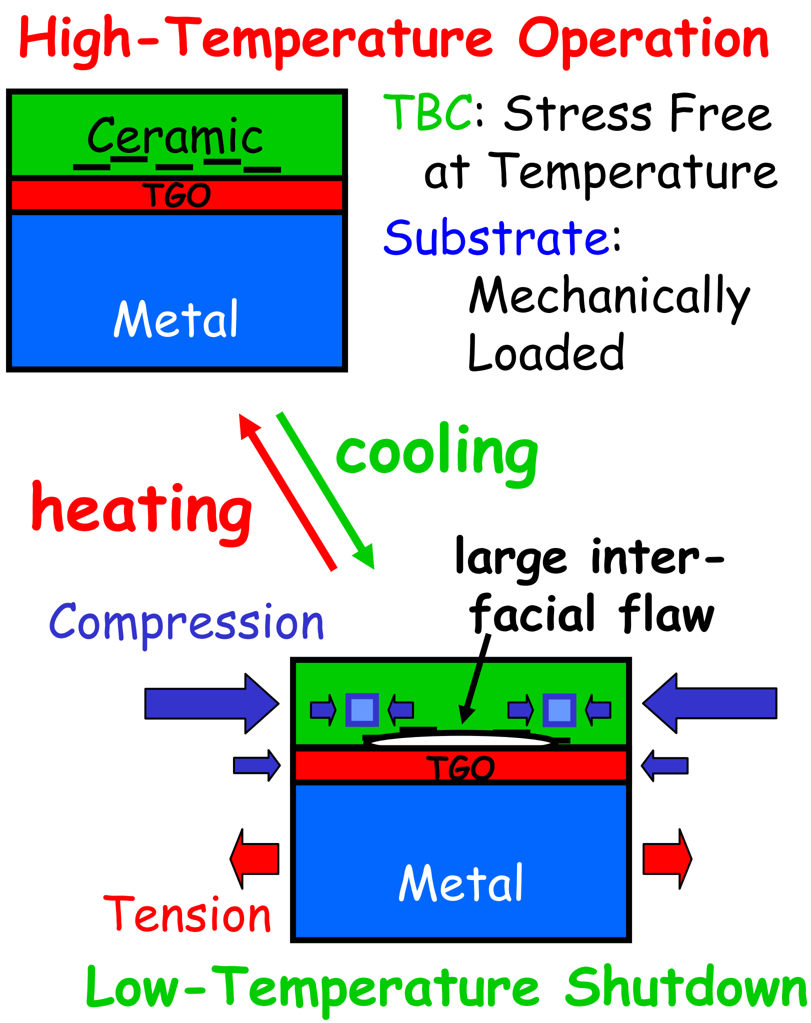
- Result from mechanical loading, thermal expansion mismatch, & TGO growth
- Stress relaxation time in TBC is short compared to engine operation time, but long compared to engine cool-down time



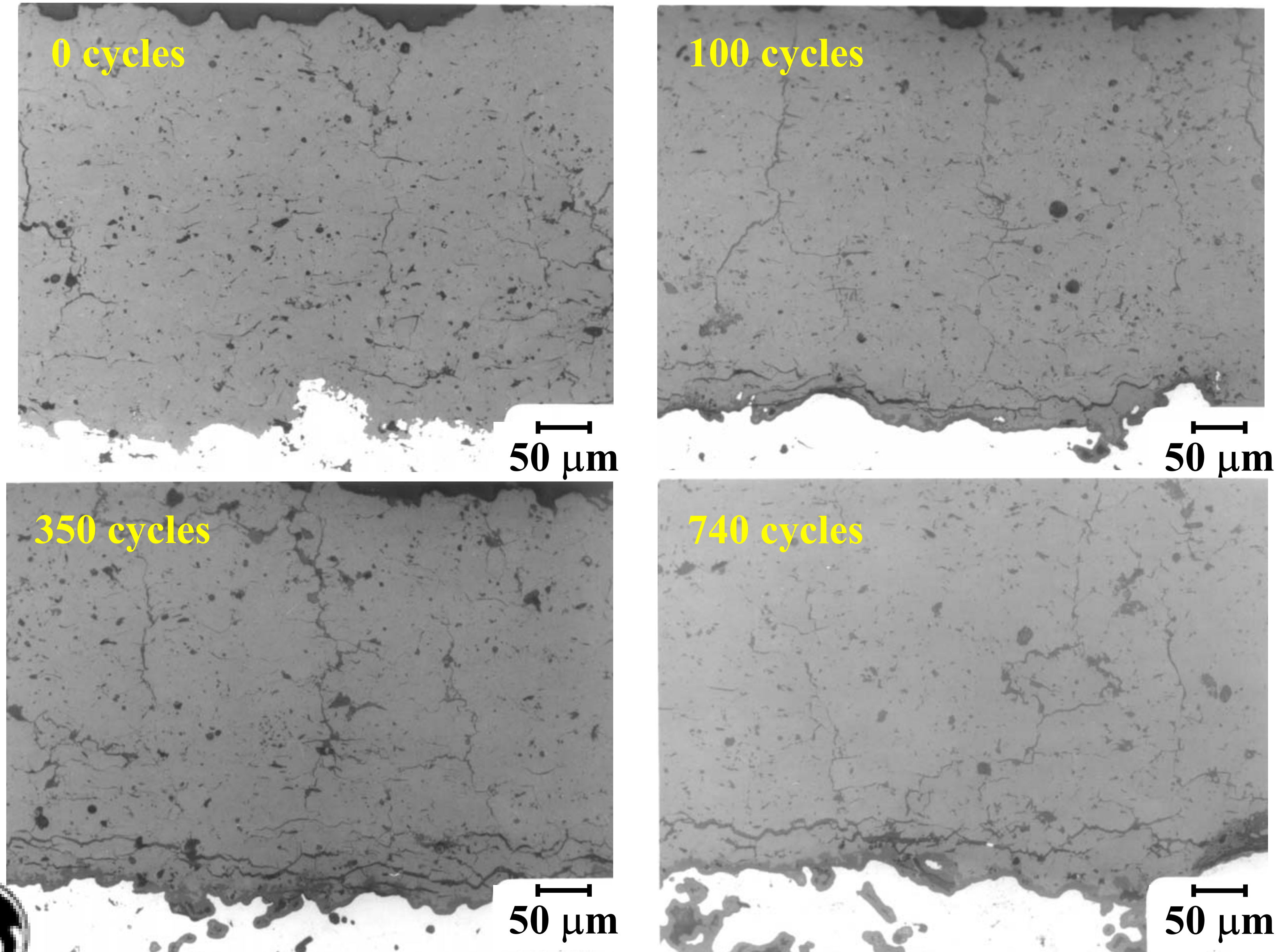
Spallation Failure Mechanism for Thermal Barrier Coating

***Coating Failure*: when pieces of the top coat spall**

- **Damage accumulates near metal-ceramic interface due to mechanical, thermal expansion, & TGO growth stresses**
- **When damage produces a critical-size crack, the top coat locally buckles and spalls, due to large in-plane stresses**



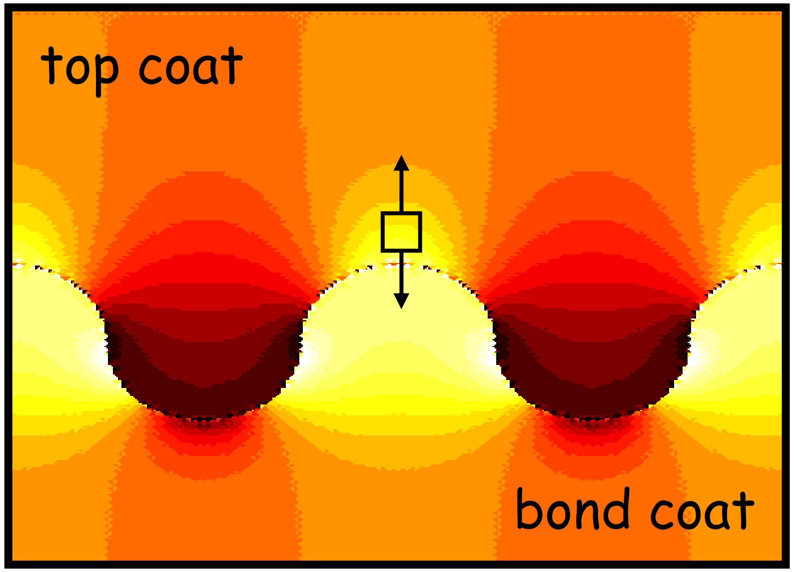
Air Plasma Spray TBC on HVOF CoNiCrAlY



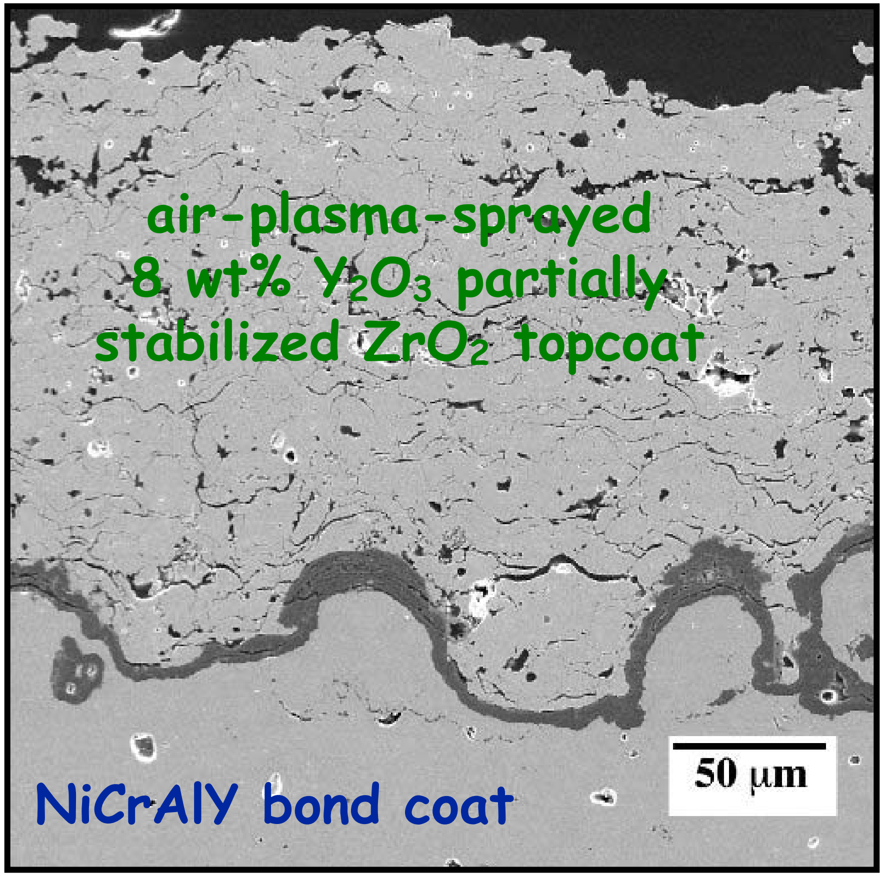
Courtesy of Jim Ruud, GE CR&D

Residual Stresses
Above Asperities on Cooling

Tensile Normal
Residual Stress

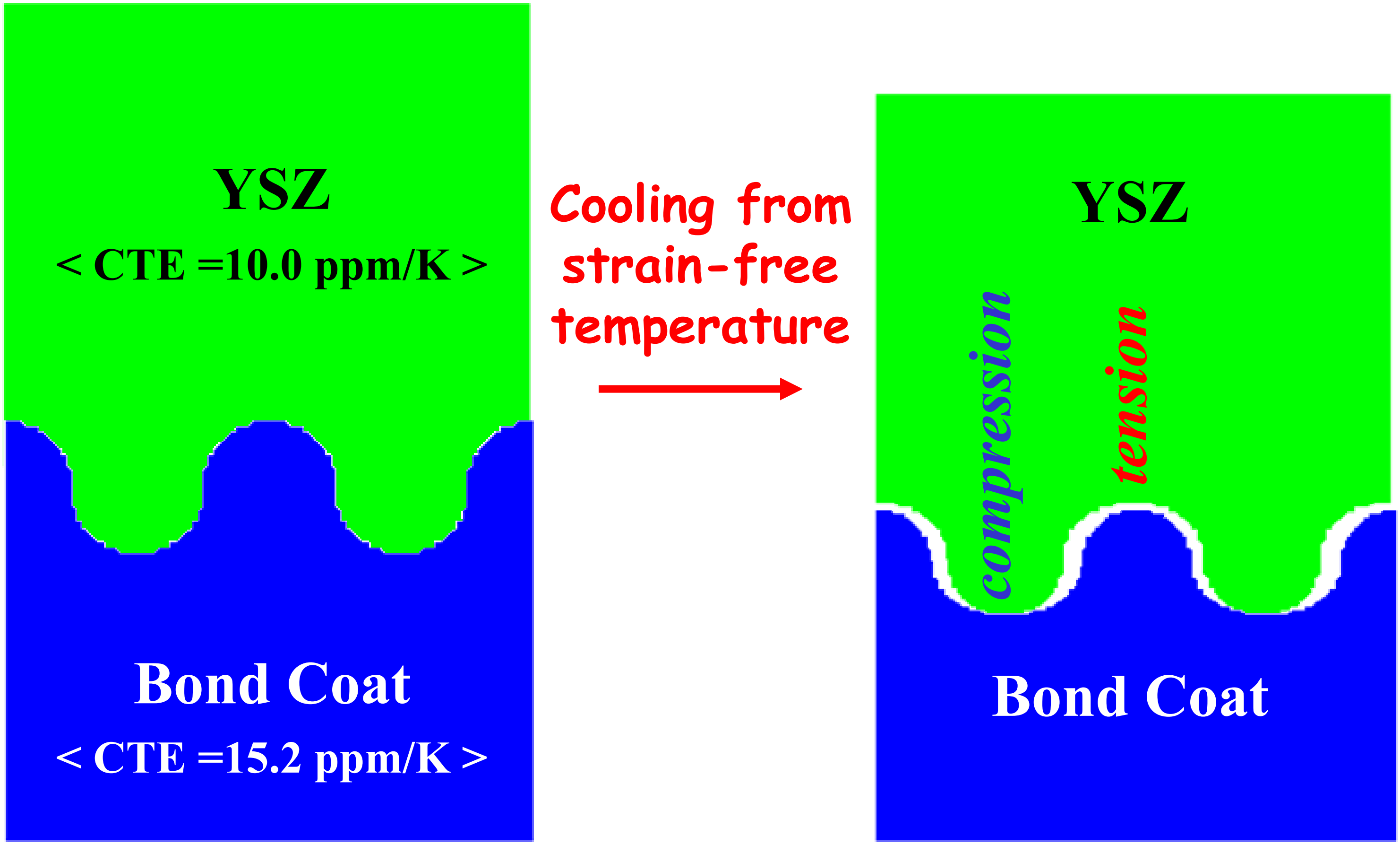


(Compressive In-Plane
Residual Stress)

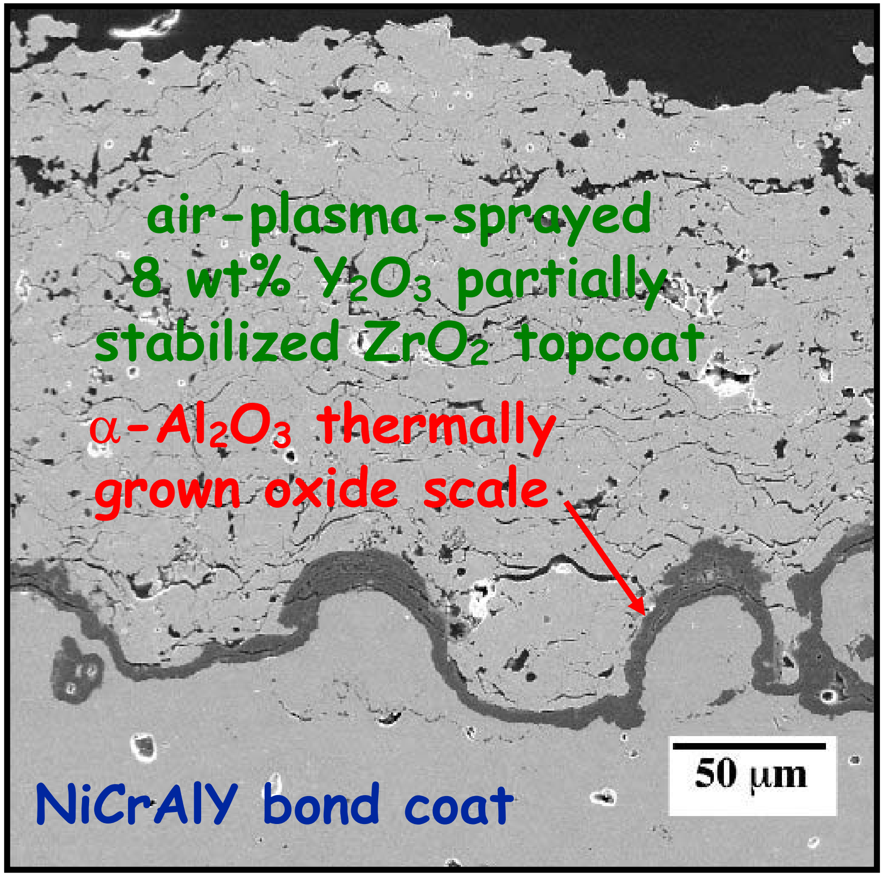


René N5 substrate (not shown)

Residual Stresses from Thermal Misfit Strains

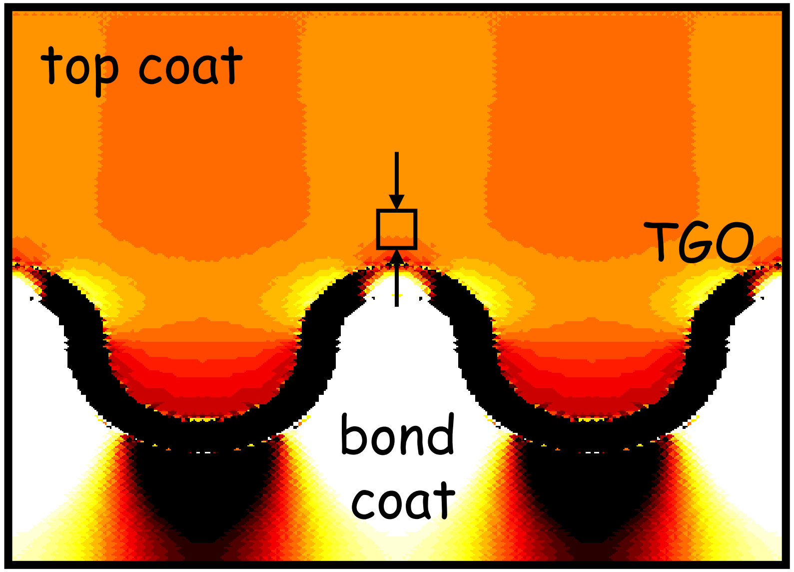


Stress Reversal with TGO Growth



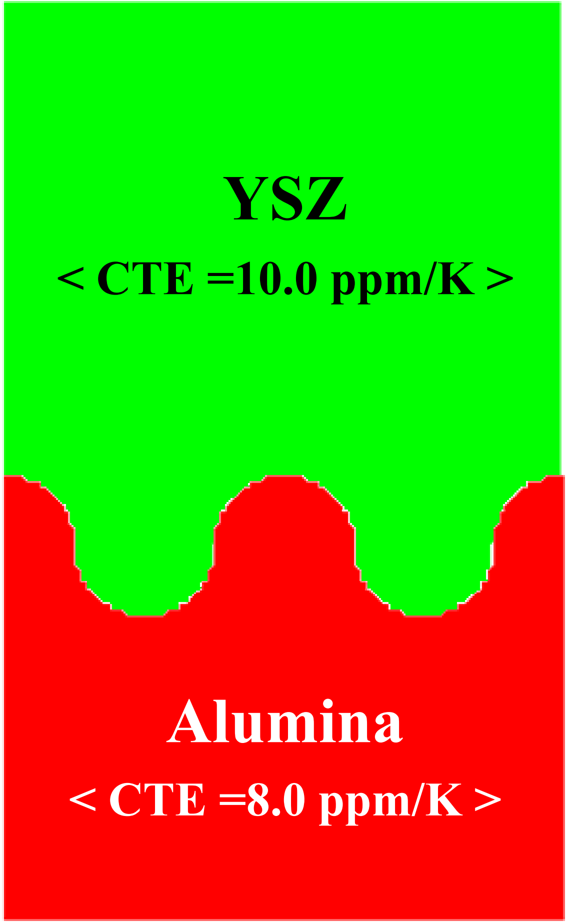
René N5 substrate (not shown)

Compressive Normal
Residual Stress

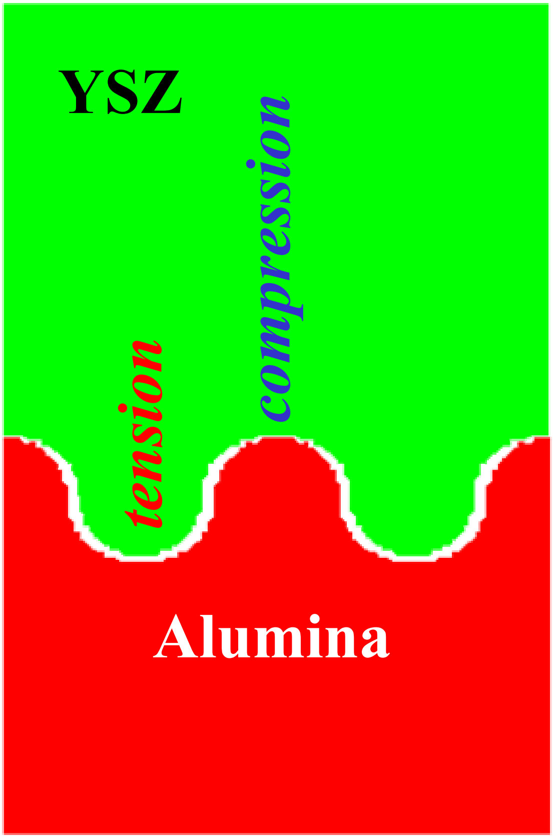


(Compressive In-Plane
Residual Stress)

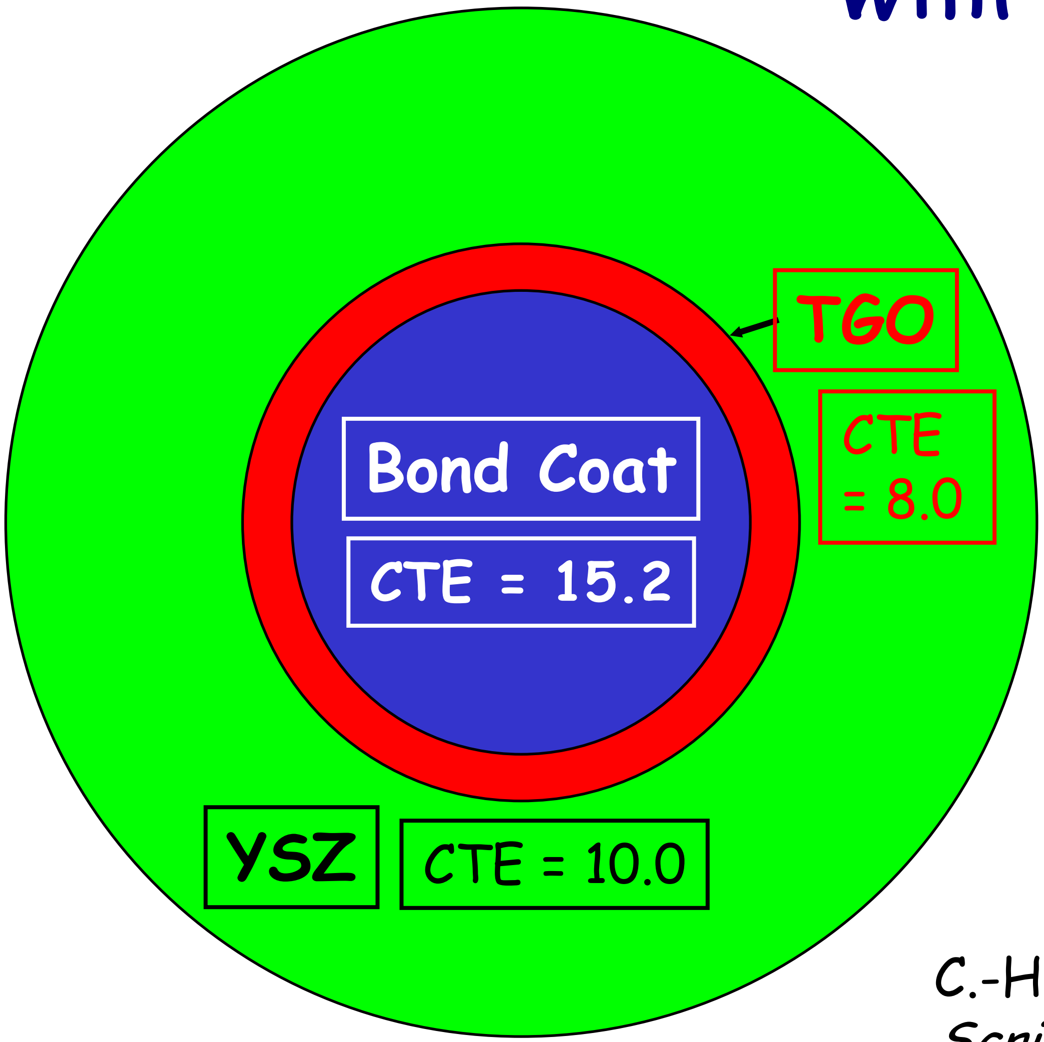
Residual Stresses from Thermal Misfit Strains



Cooling from strain-free temperature

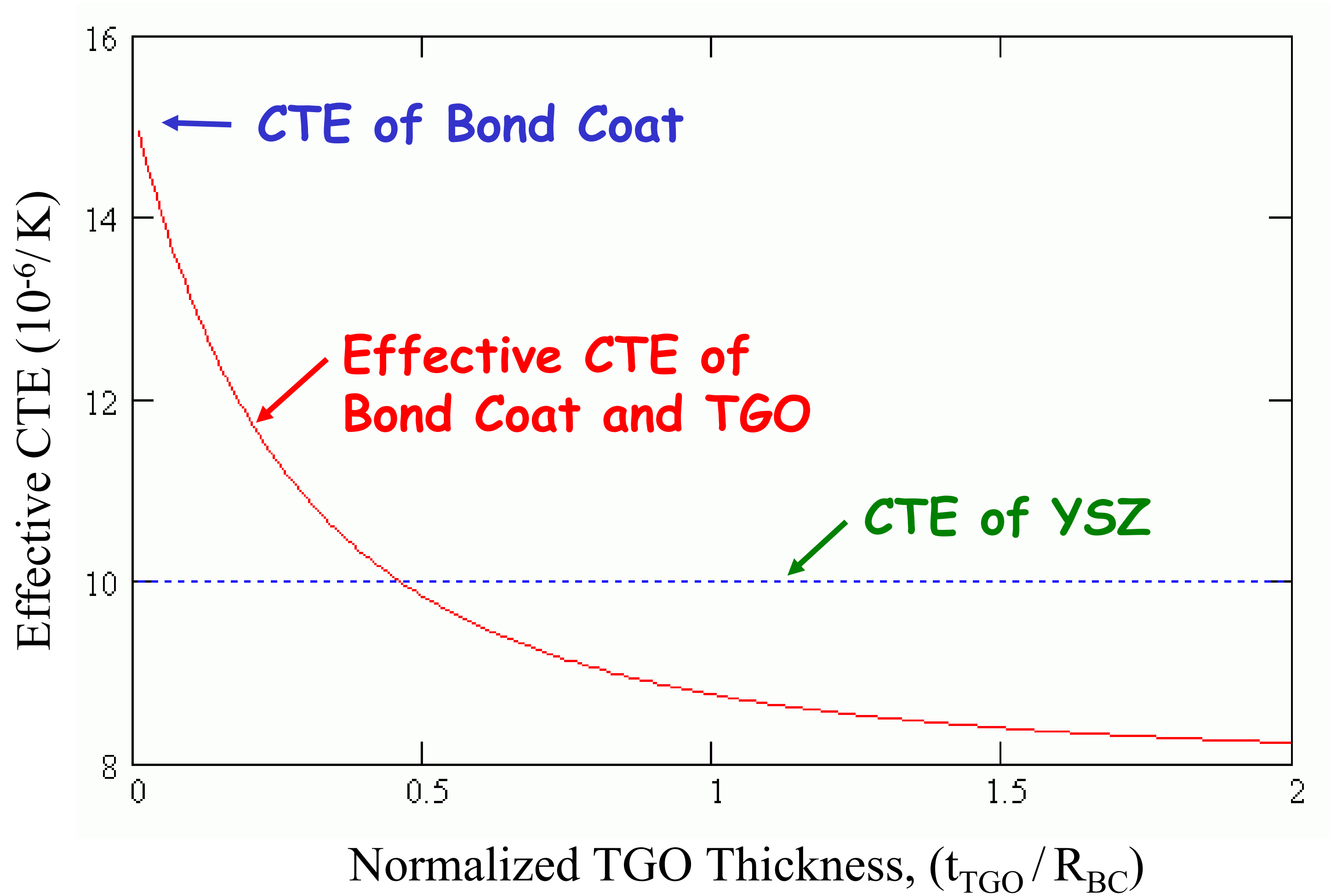


This Process Can Be Modeled With Three Concentric Spherical Shells

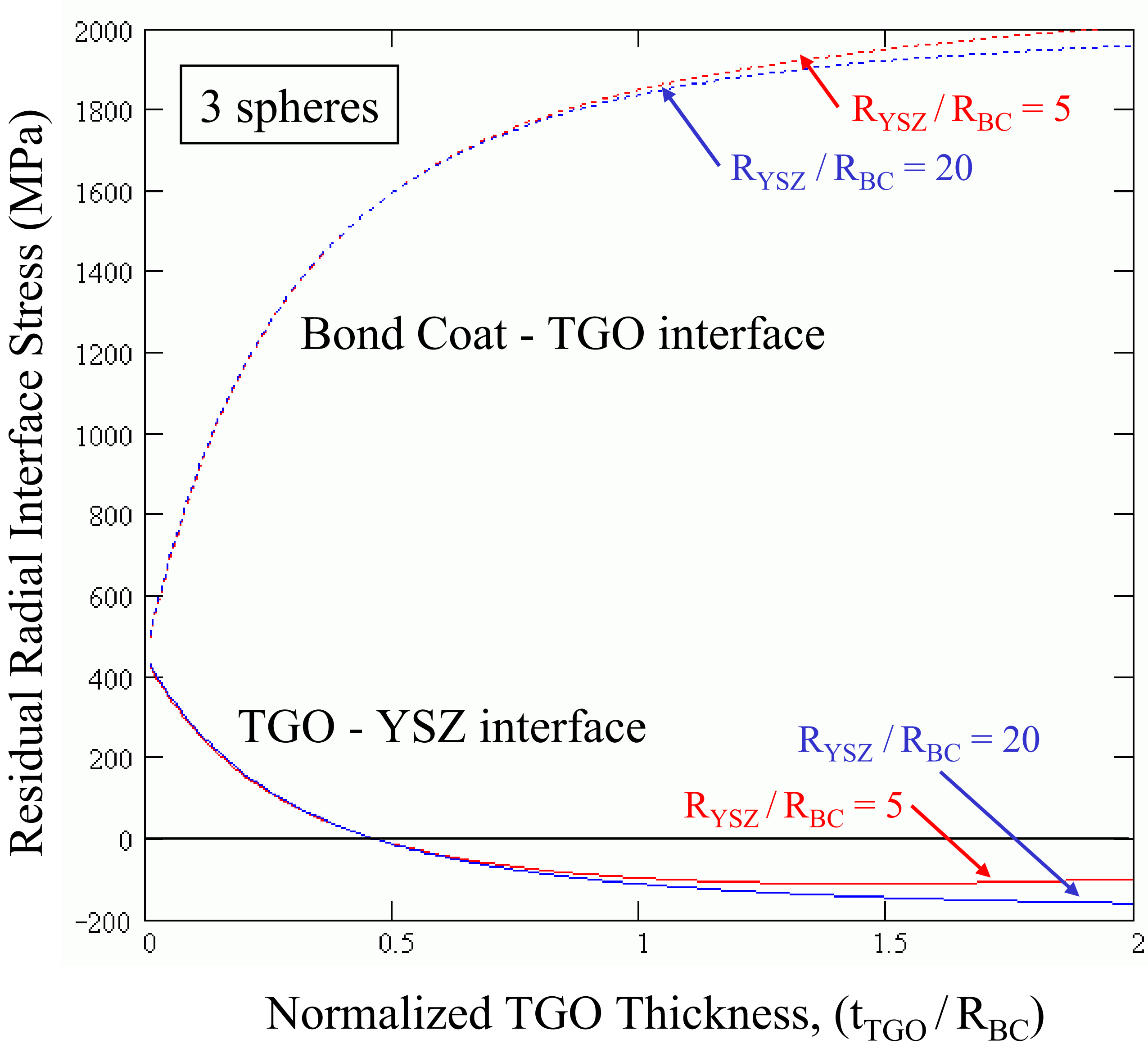


C.-H. Hsueh & E. R. Fuller, Jr., *Scripta Mater.*, **42** (2000) 781.

Effective CTE of the Inner Two Shells

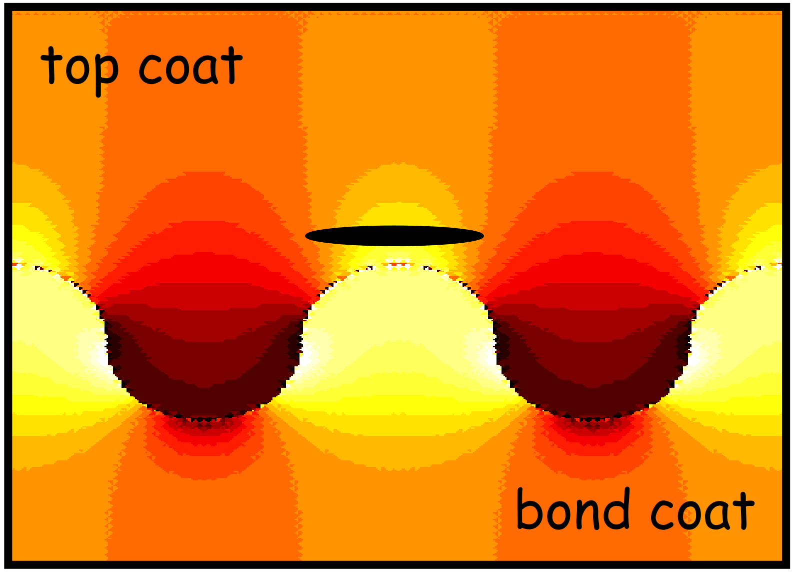


Residual Radial Interfacial Stress

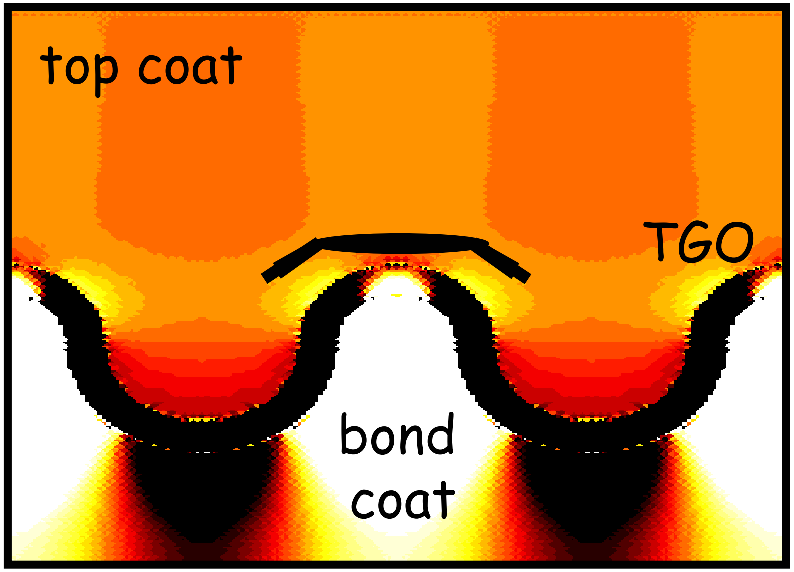


Failure Scenario based on Stress Reversal above Asperities with TGO Growth

Tensile Residual Stress



Compressive Residual Stress



A. M. Freborg, B. L. Ferguson, W. J. Brindley, G. J. Petrus, "Modeling oxidation induced stresses in thermal barrier coatings," Mat Sci Eng A-Struct 245 [2]: 182-190 (1998).

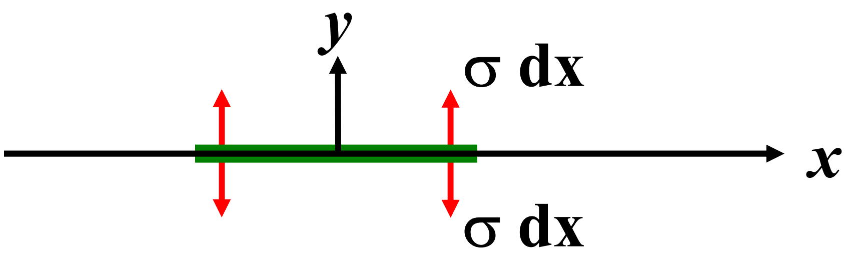
Fracture Mechanics Model

Determine crack stability from an appropriate set of fracture mechanics expressions:

$$K_I = \int_0^a \mathbf{G}\left(\frac{\mathbf{x}}{\mathbf{a}}\right)\sigma(x, y; t_{TGO}, \text{asperity geometry, etc.})\,dx$$

asperity tension

$t_{TGO} < t_{critical}$

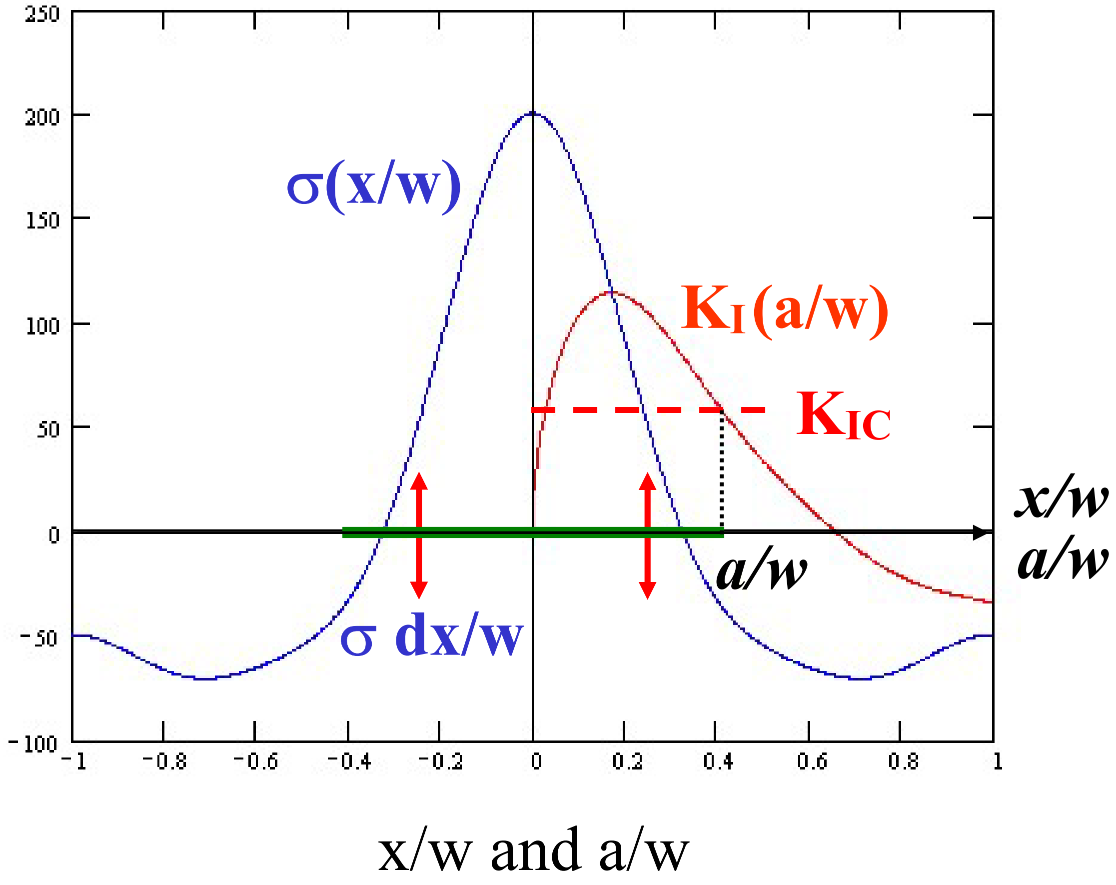


Griffith crack:

$$K_{Ia} = \sqrt{\pi a}\,\frac{2}{\pi}\int_0^1 \frac{1}{\sqrt{1-\zeta^2}}\,\sigma(\zeta a)\,d\zeta$$

$$\zeta = \frac{x}{a}$$

Crack Stability for Tensile Stresses



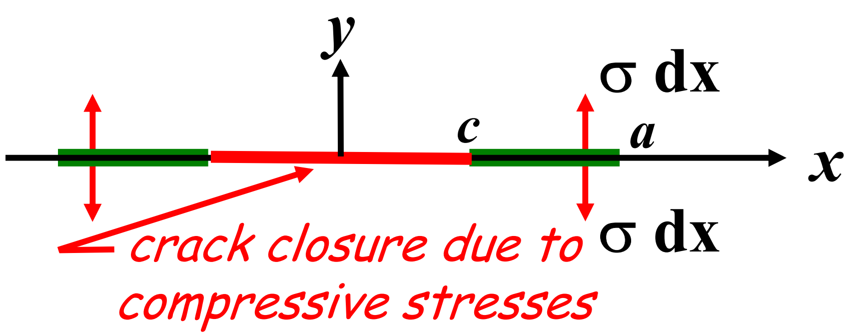
Fracture Mechanics Model

Determine crack stability from an appropriate set of fracture mechanics expressions:

$$K_I = \int_c^a \mathbf{G}\left(\frac{\mathbf{x}}{\mathbf{a}}, \frac{\mathbf{c}}{\mathbf{a}}\right) \sigma(x, y; t_{TGO}, \text{asperity geometry, etc.})\, dx$$

asperity compression

$t_{TGO} > t_{critical}$



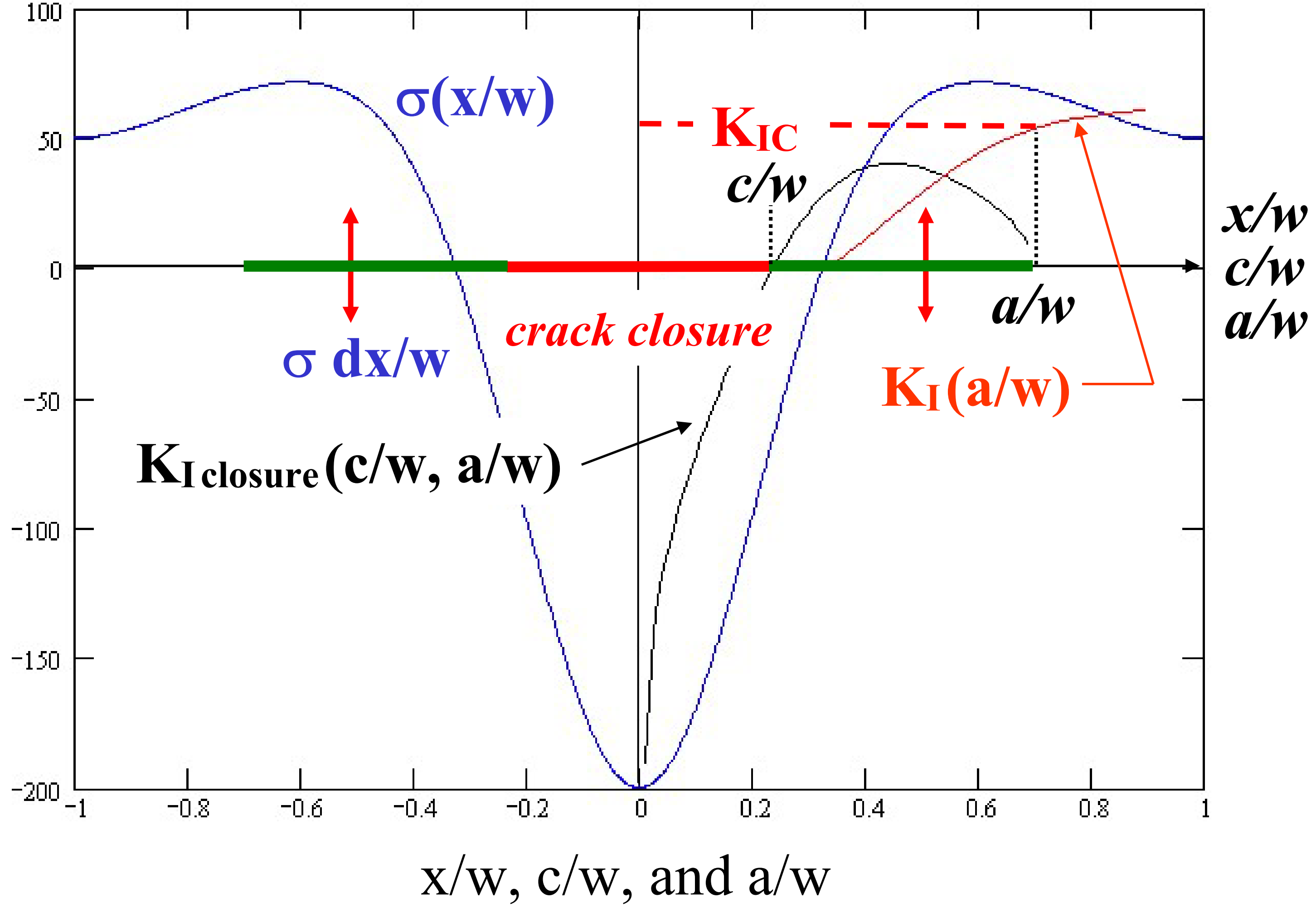
$$\zeta = \frac{x}{a}$$

$$K_{Ic} = \sqrt{\pi c}\, \frac{2}{\pi} \int_{\frac{c}{a}}^{1} G_c(\zeta, \tfrac{c}{a})\, \sigma(\zeta a)\, d\zeta$$

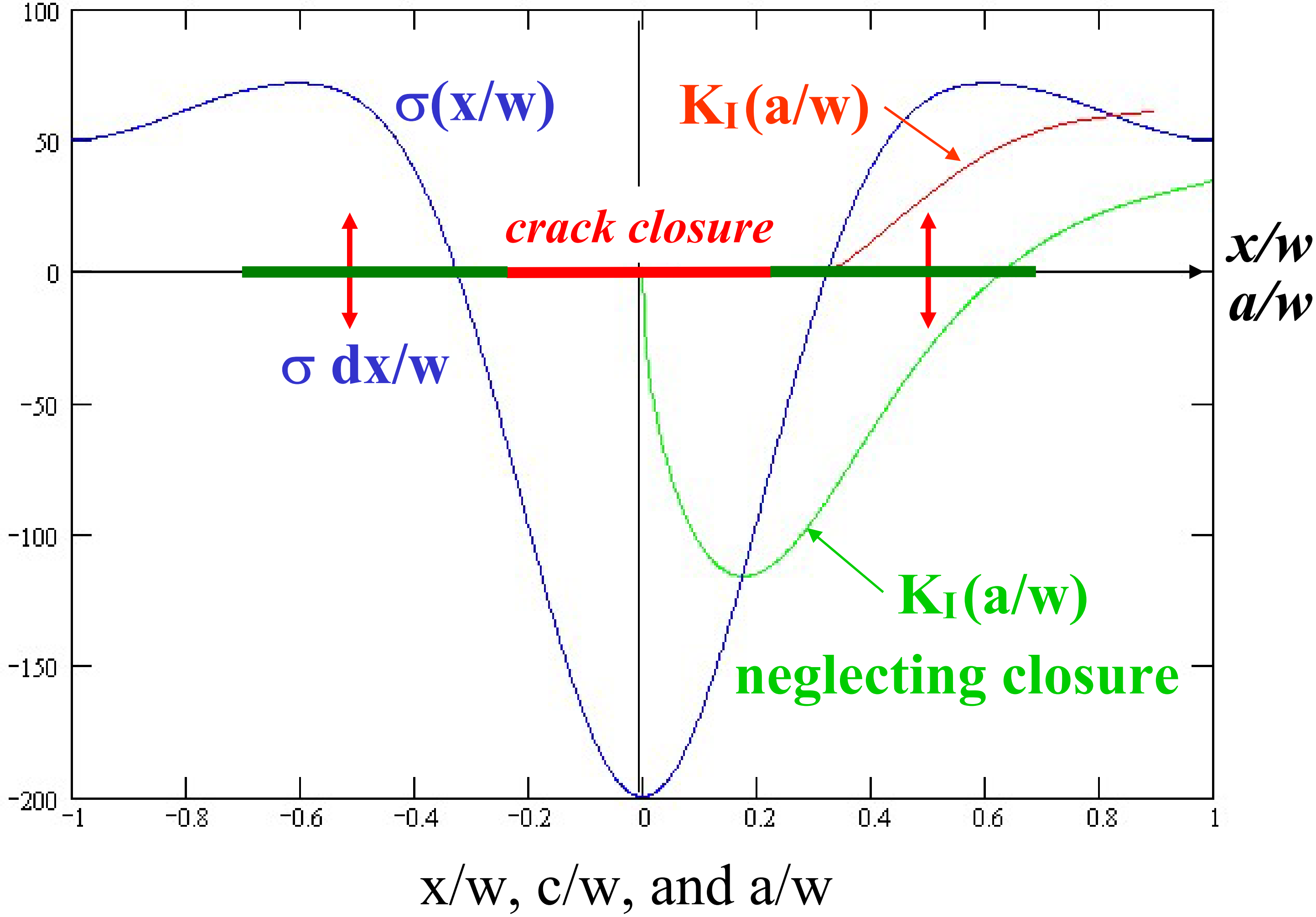
$$K_{Ia} = \sqrt{\pi c}\, \frac{2}{\pi} \int_{\frac{c}{a}}^{1} G_c(\zeta, \tfrac{c}{a})\, \sigma(\zeta a)\, d\zeta$$

Fazil Erdogan, *"On the stress distribution in plates with collinear cuts under arbitrary loads,"* in Proceedings of Fourth U.S. National Congress of Applied Mechanics, pp. 547-553 (1962).

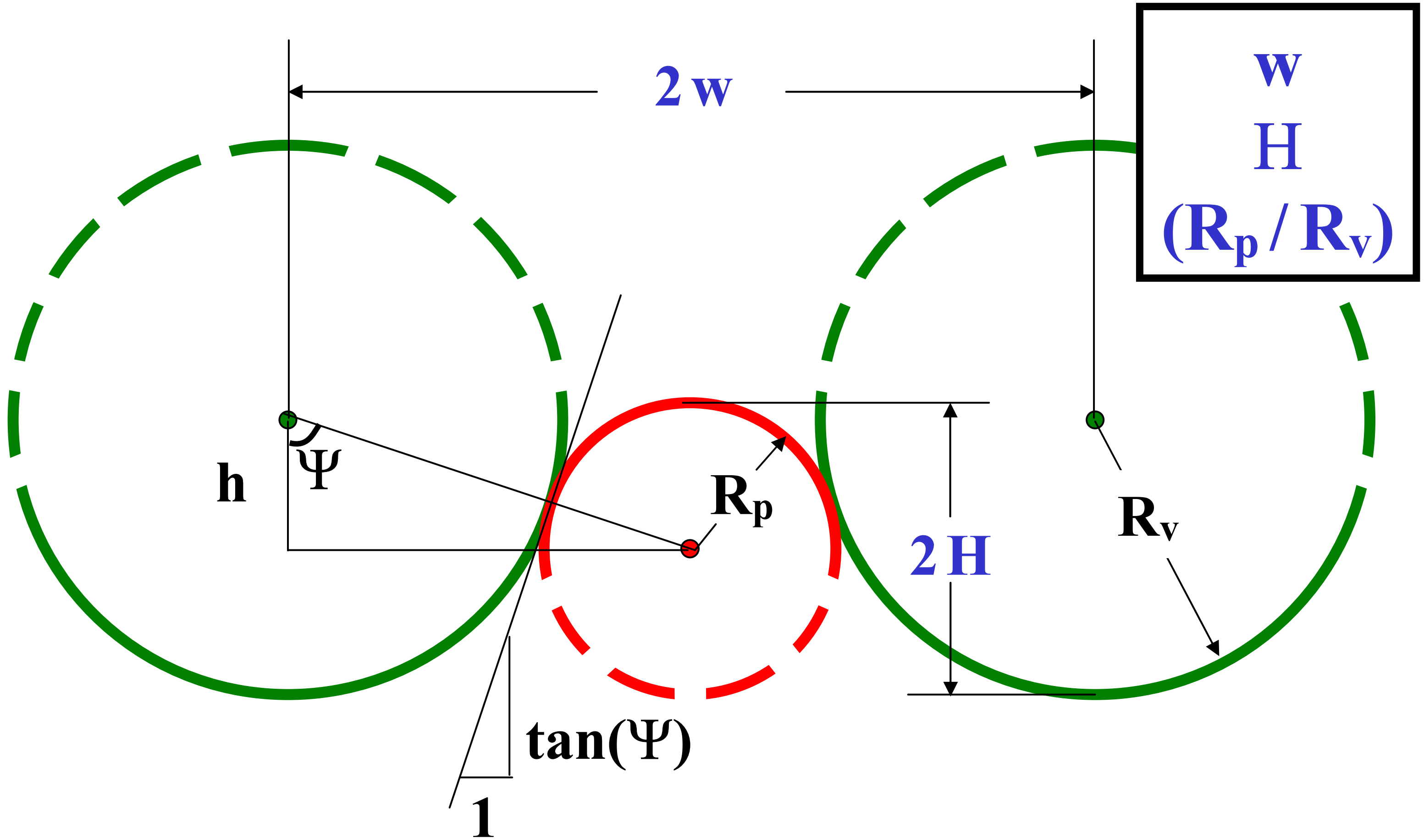
Crack Stability for Compressive Stresses



Crack Stability for Compressive Stresses

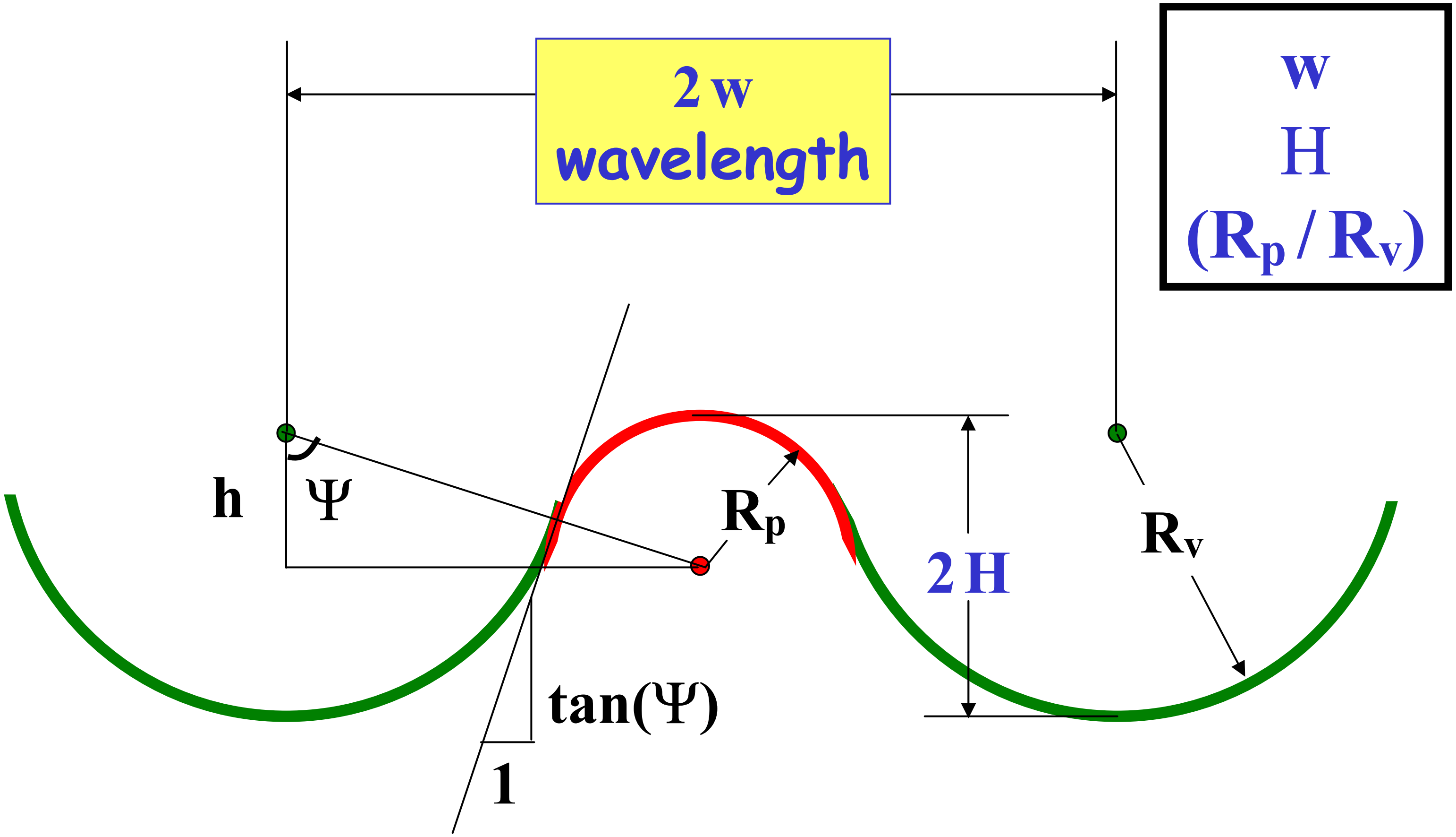


Three-Parameter Roughness Model



after D. R. Clarke and W. Pompe, "Critical Radius for Interface Separation of a Compressively Stressed Film from a Rough Surface," Acta mater., **47** [6], 1749-1756 (1999).

Three-Parameter Roughness Model



valley-to-peak curvature ratio: (R_p/R_v)

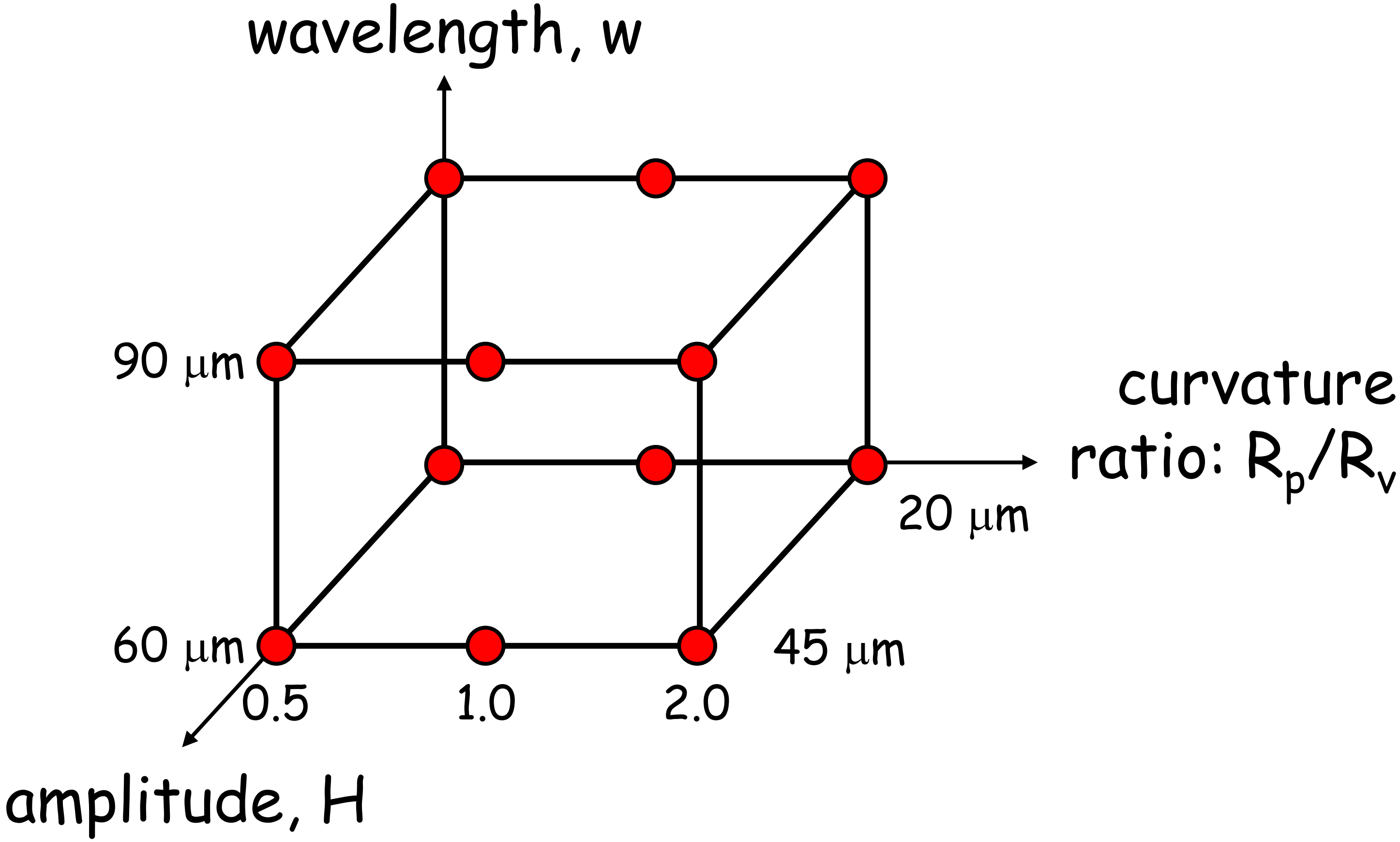
$$(R_p + R_v) = w / \sin(\Psi)$$

$$h = w \cot(\Psi)$$

peak-to-valley amplitude

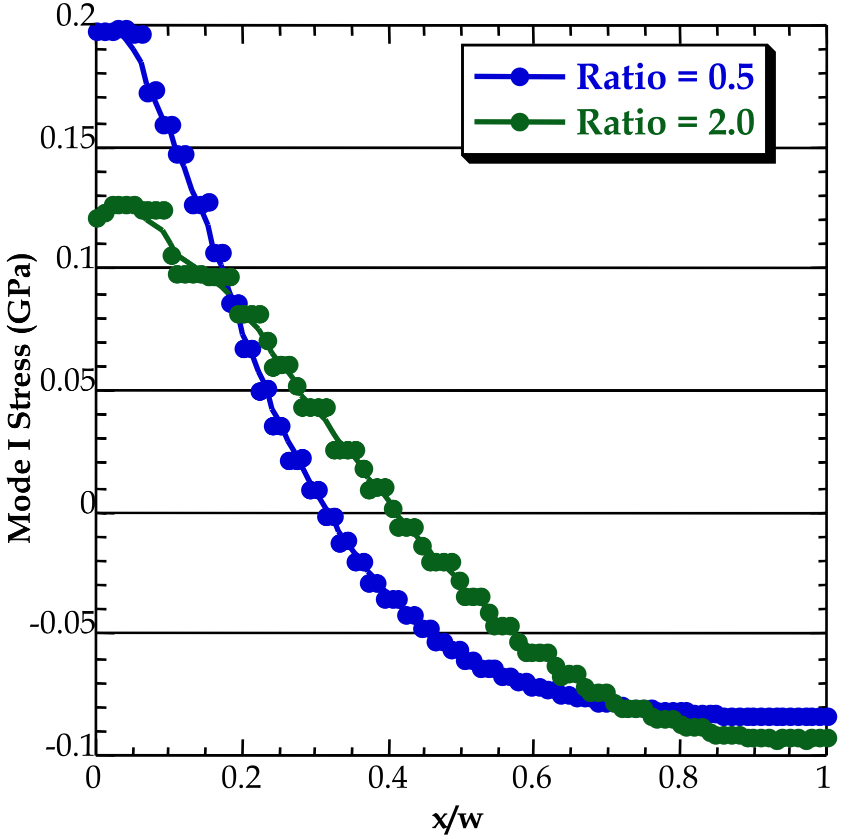
$$2H = w \tan(\Psi/2)$$

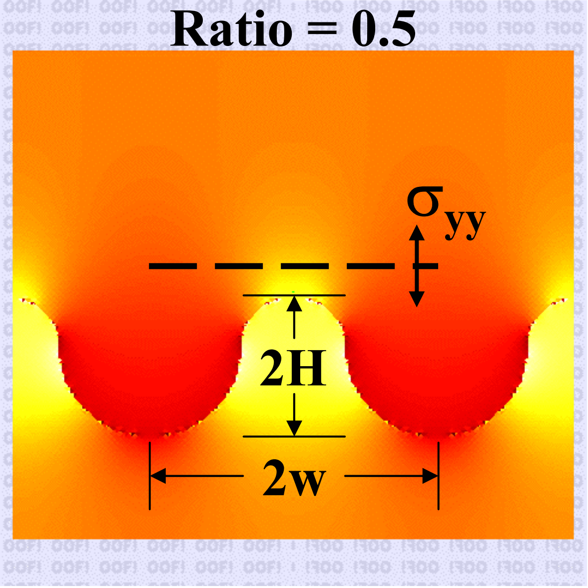
Factorial Experimental Design

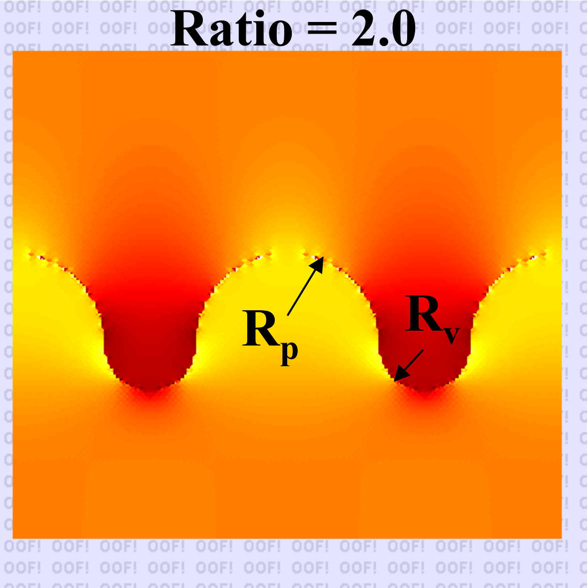


twelve (12) simulated interface microstructures

Residual Stress as a Function of Microstructure: R_p/R_v

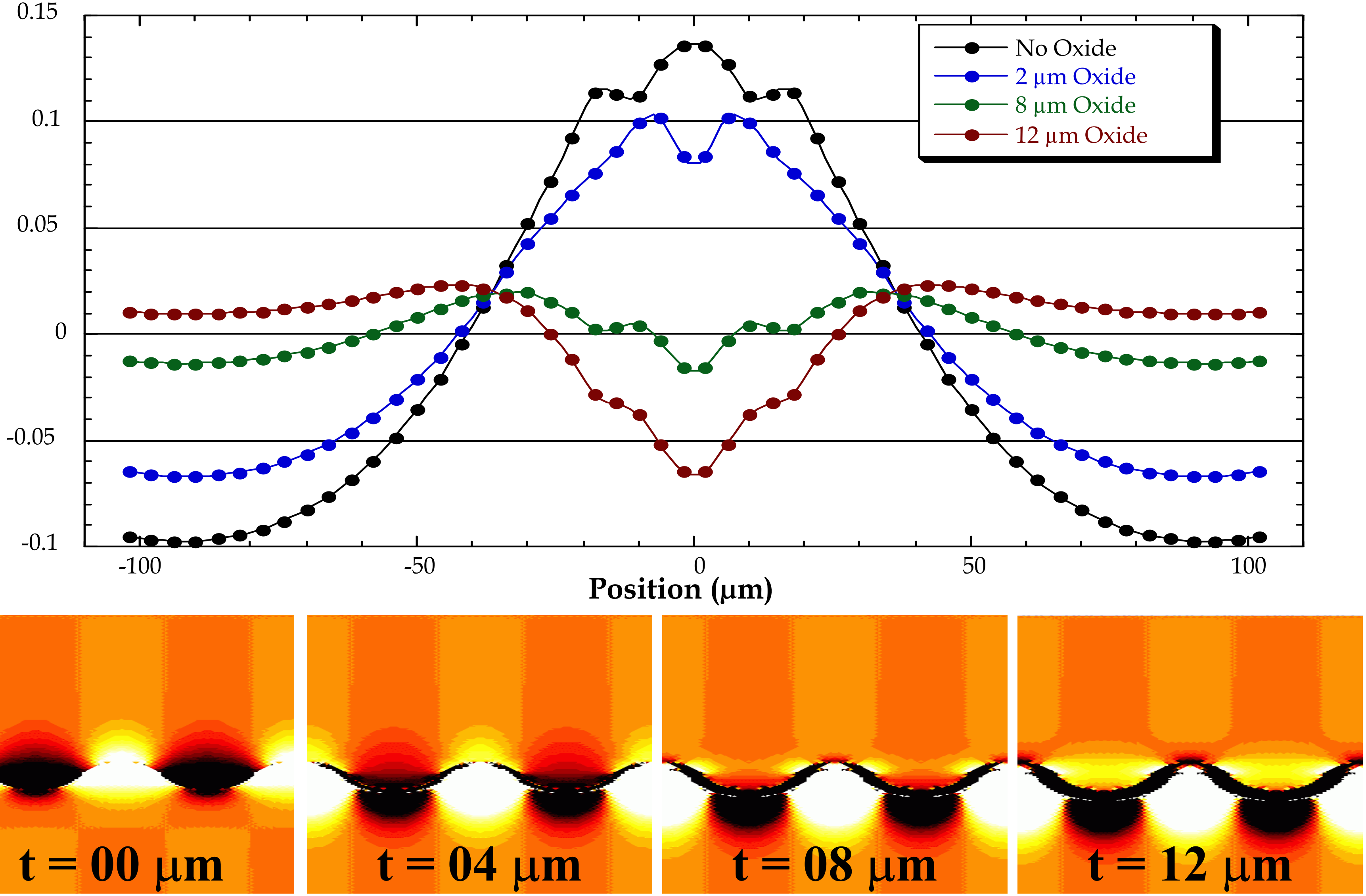




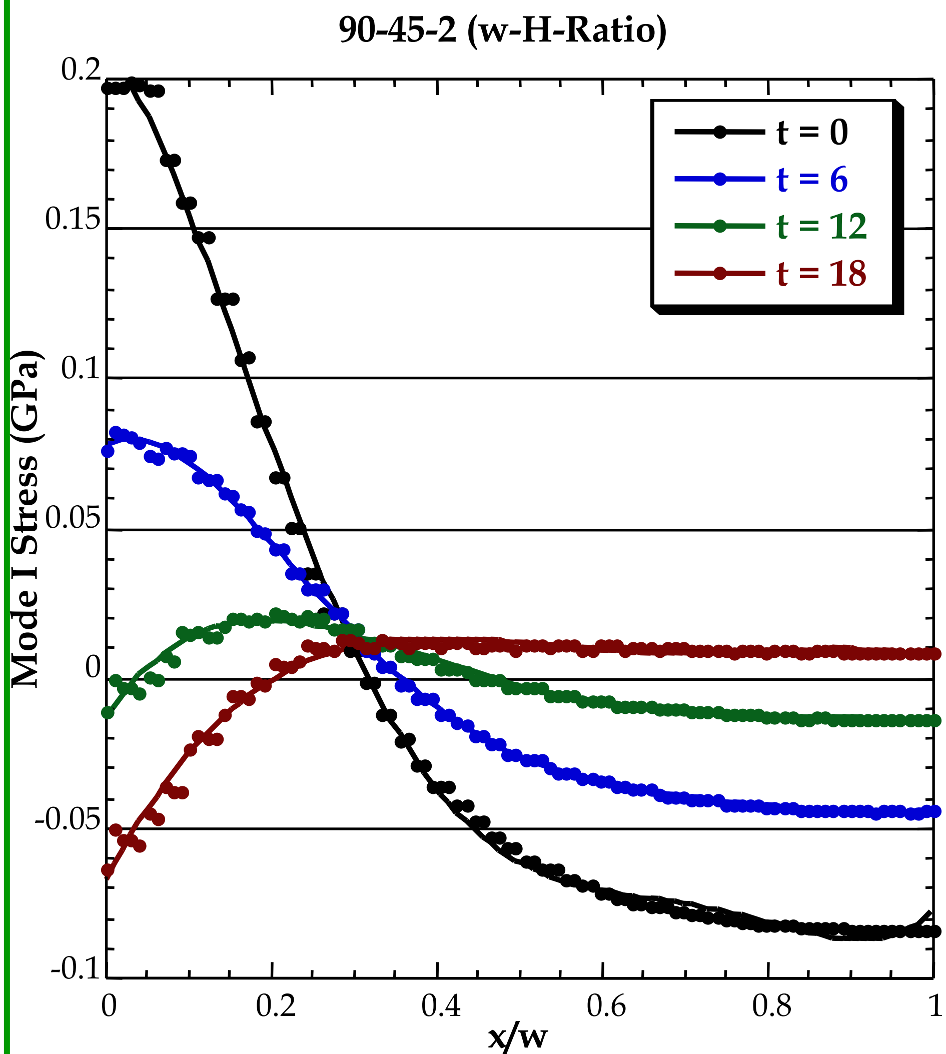


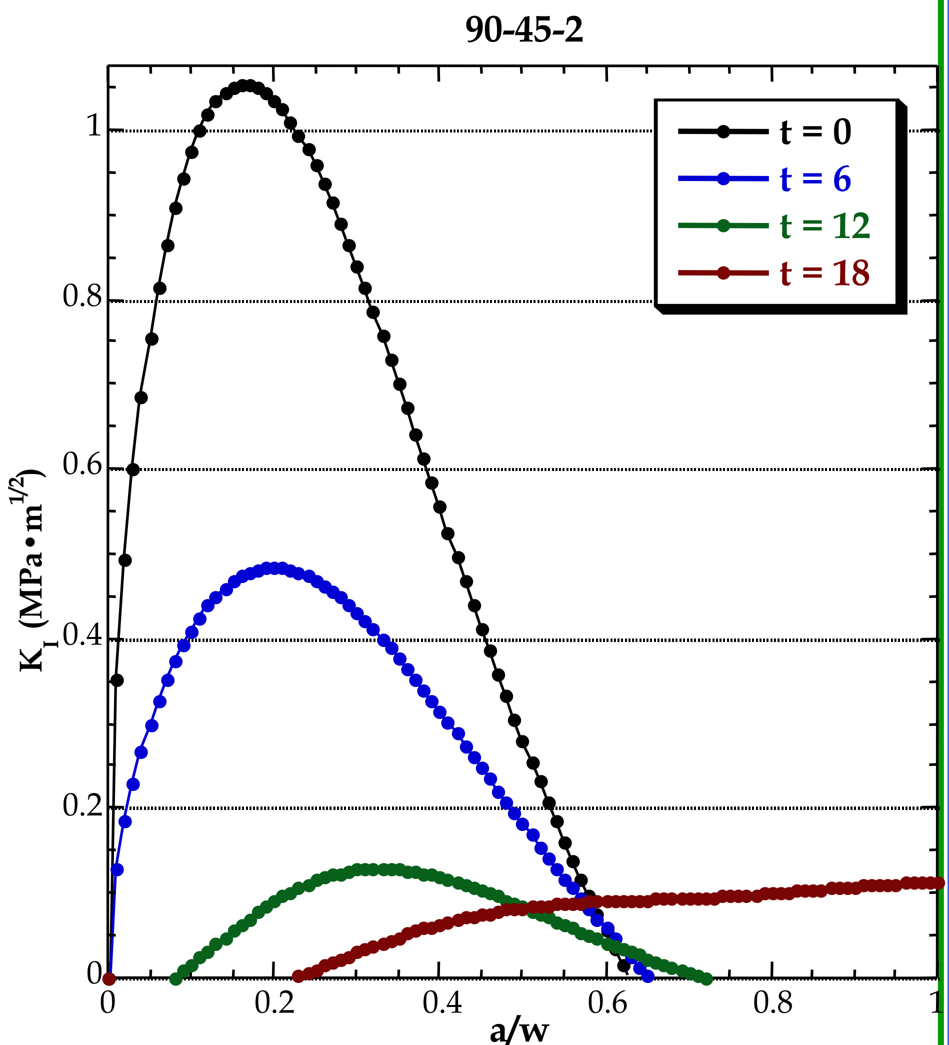
Only the roughness parameters H/w & R_p/R_v have a significant effect on the stress distribution

Residual Stress versus Oxide Thickness

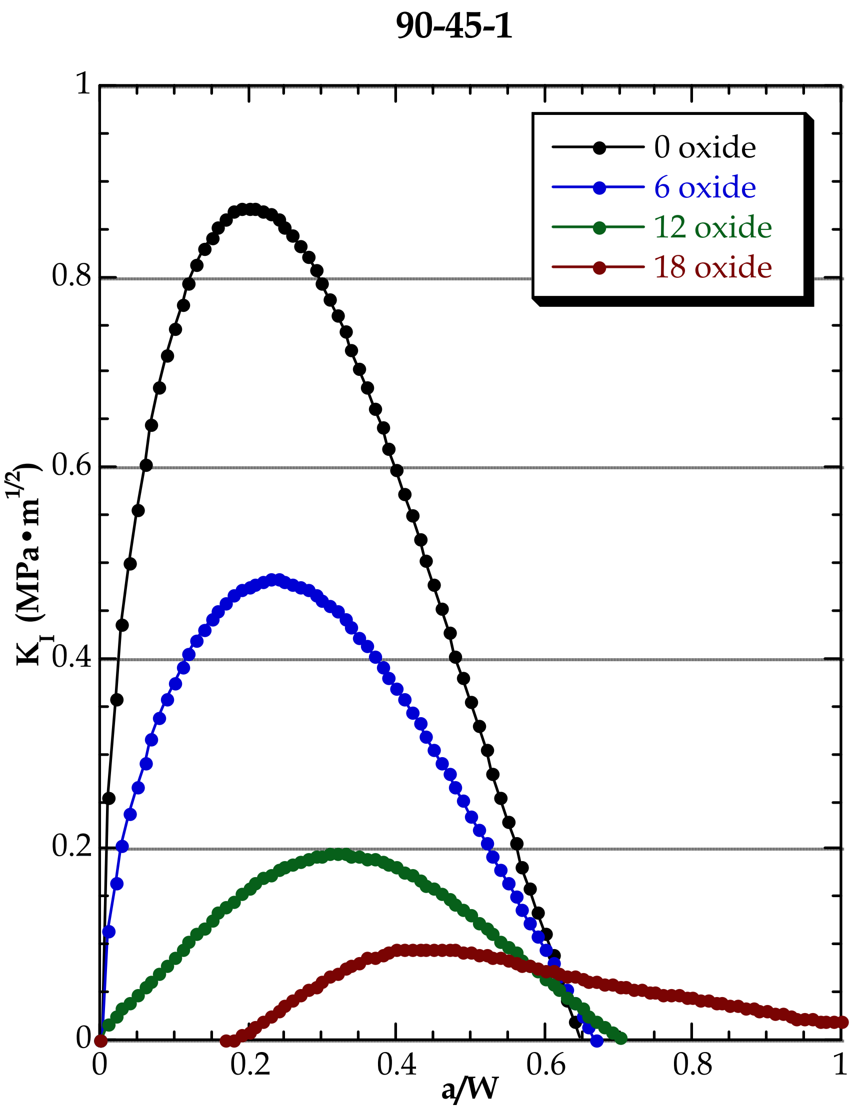


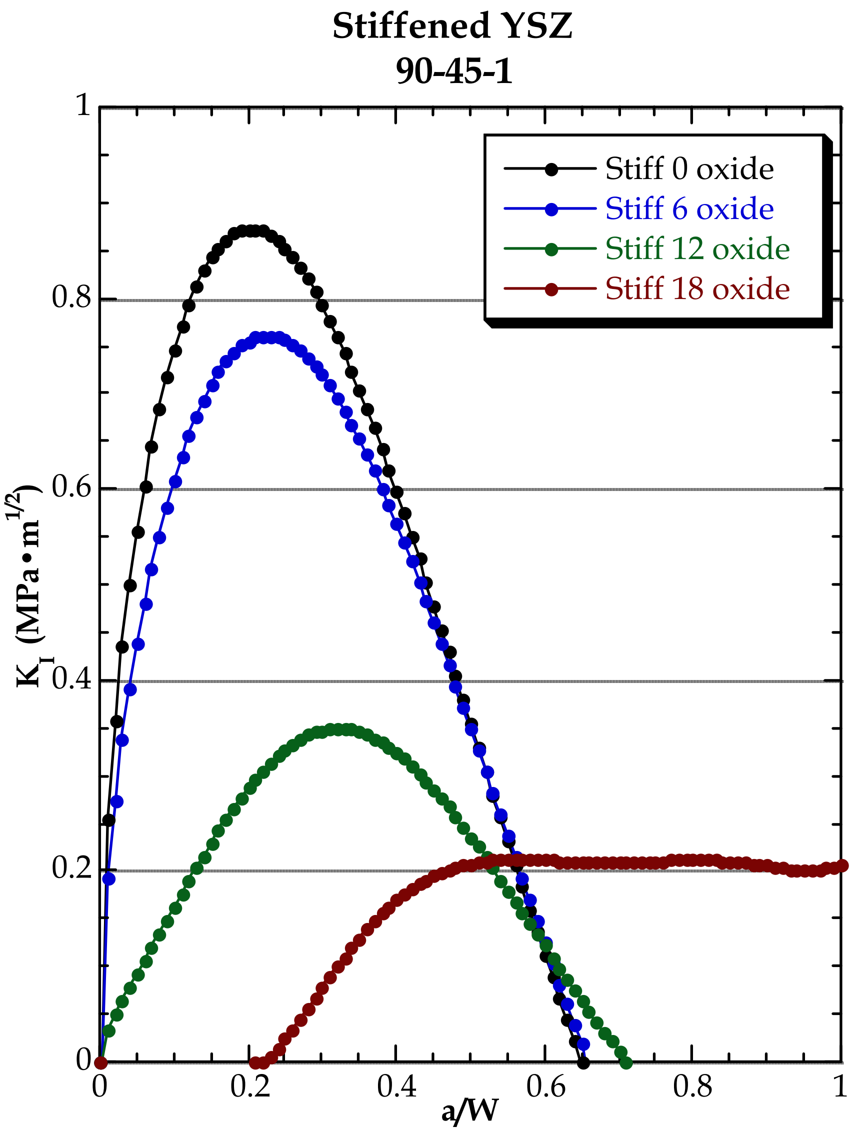
Fracture Mechanics Results



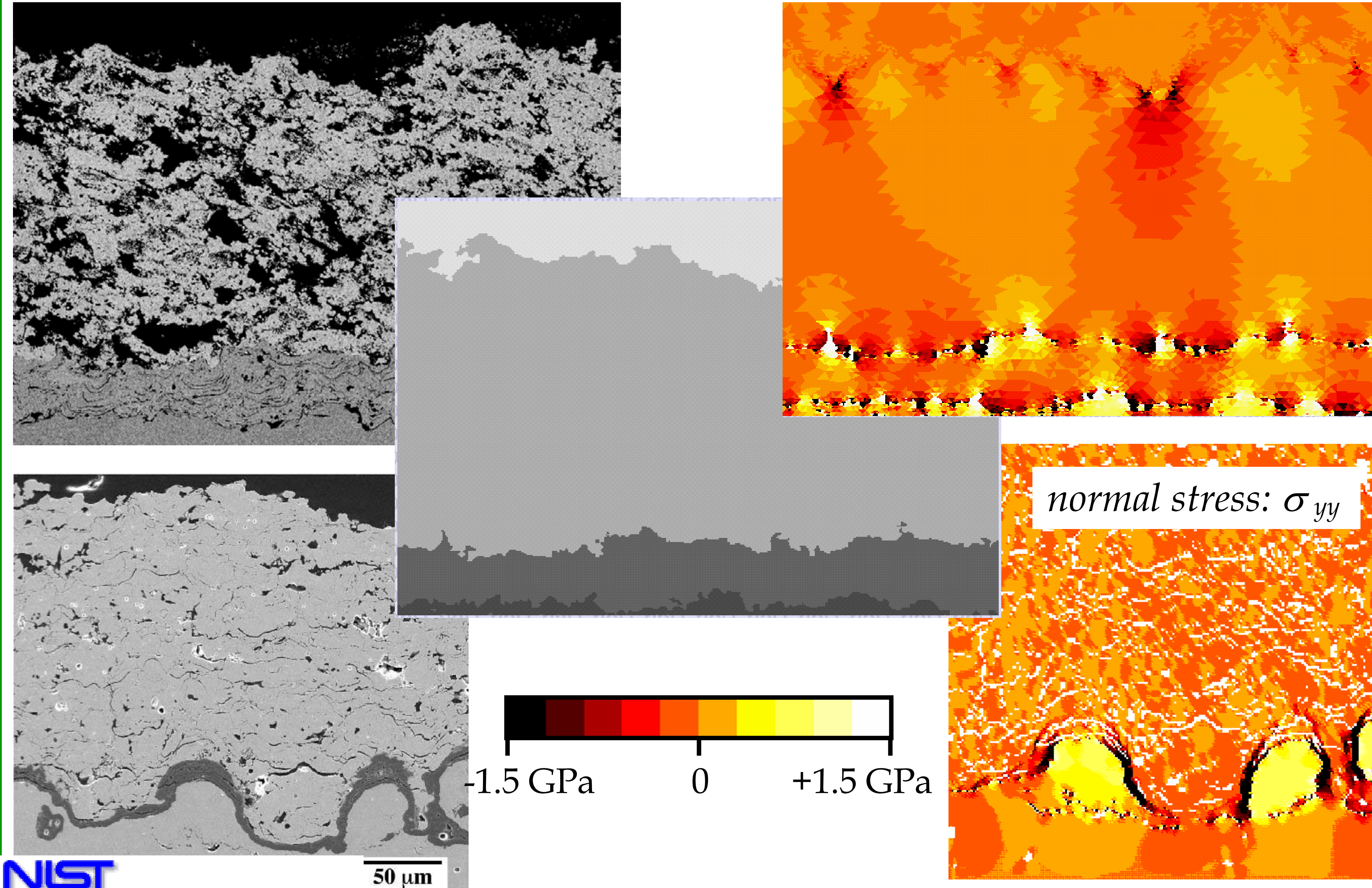


Influences of YSZ Microcrack Sintering





Modeling Real Microstructures



Interface-Related Damage Evolution in APS TBC's

SUMMARY:

- A damage evolution mechanism proposed by Freborg *et al.* was quantitatively analyzed with a *fracture mechanics weight function* approach
- *Reversal in residual stress distribution* above interface asperities drives damage evolution
- *Microstructural variables* studied with a three parameter roughness model:
    - Wavelength
    - Amplitude
    - Peak Sharpness
    - TGO Thickness

Interface-Related Damage Evolution in APS TBC's

SUMMARY:

- Crack closure enhances the crack-tip stress intensity factor
- However, calculated K_I-fields are still below the expected threshold for crack growth
- Top coat sintering enhances damage evolution
- Several other factors are under investigation, e.g., top coat sintering, TGO growth strain, bond coat creep, crack path

Abstract

INTERFACE-RELATED DAMAGE EVOLUTION IN AIR-PLASMA-SPRAYED THERMAL BARRIER COATINGS

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Spallation of air-plasma-sprayed (APS) thermal barrier coatings (TBC's) typically stems from the damage that accumulates near the metal-ceramic and ceramic-ceramic interfaces in these coatings. Damage evolution is driven by stresses perpendicular to the interface that result from rough interfaces in combination with thermal-expansion-anisotropy and oxide-growth strains. These stresses are incorporated into a fracture-mechanics weight-function formalism to quantify the driving forces for crack growth near the interface. Residual stresses as a function of interfacial structure are derived for both periodic and random structures, and are used to derive crack-driving, stress-intensity-factor fields as a function of the interfacial, thermally grown oxide (TGO) thickness, and other microstructural parameters. Residual stresses and associated stress intensity factors are presented for both model and real interfaces, attempting to identify critical microstructural features for predicting damage evolution, and hence, reliability of TBC's.