Overview of Factors Affecting Lifetime of TBCs in Land-Based GTs

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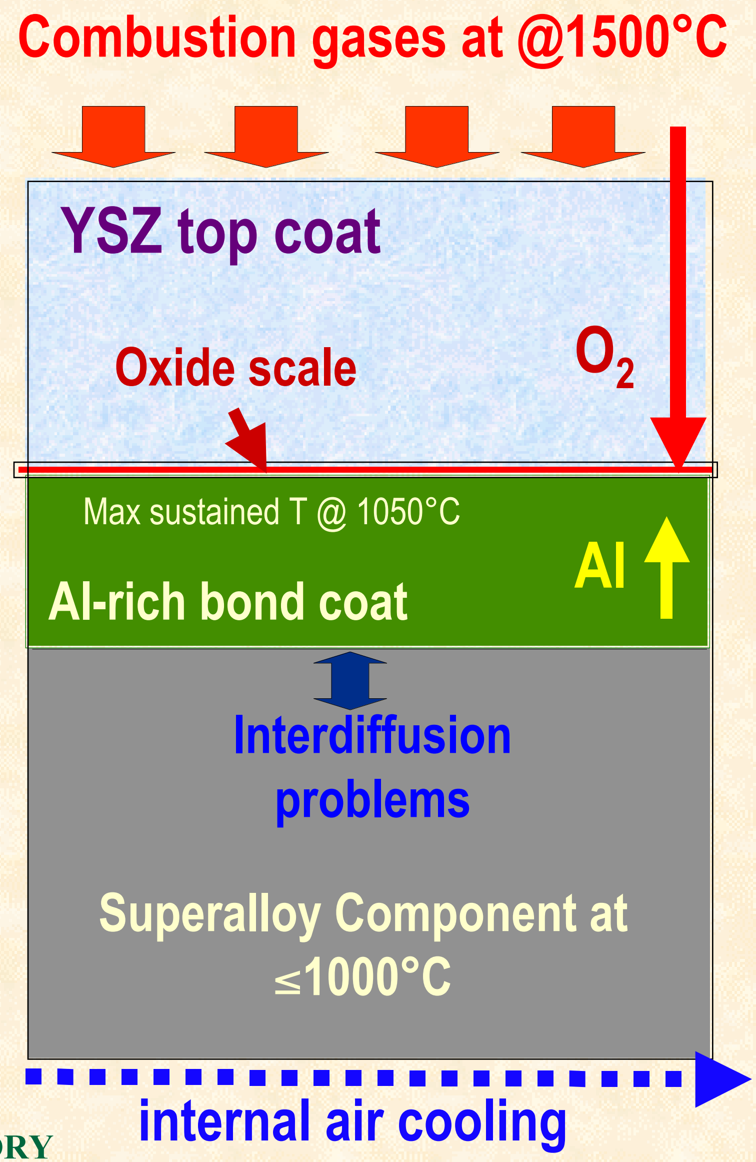
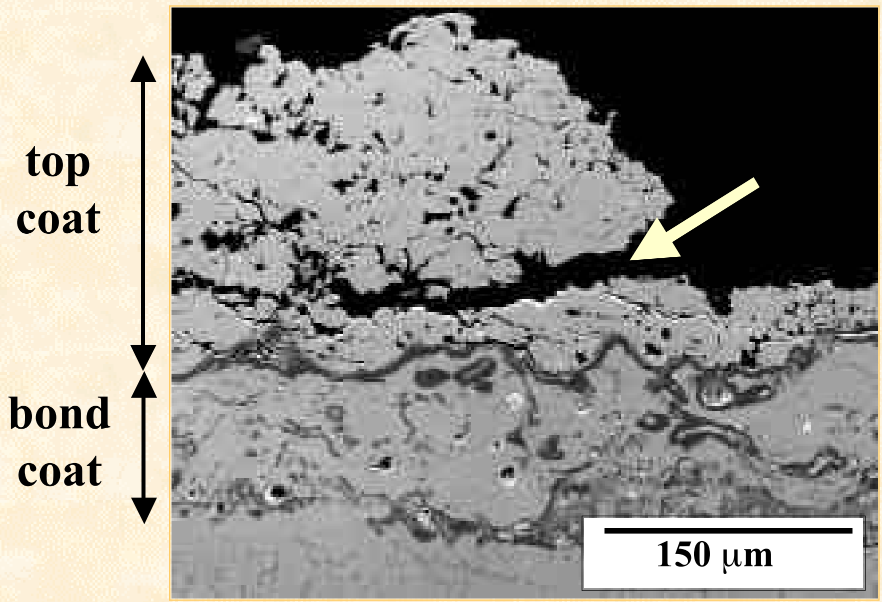
Outline

- Overview of the modes of degradation
- Discuss the major life-determining issues
  - experimental results
  - guidelines
- Condition monitoring
- Summary

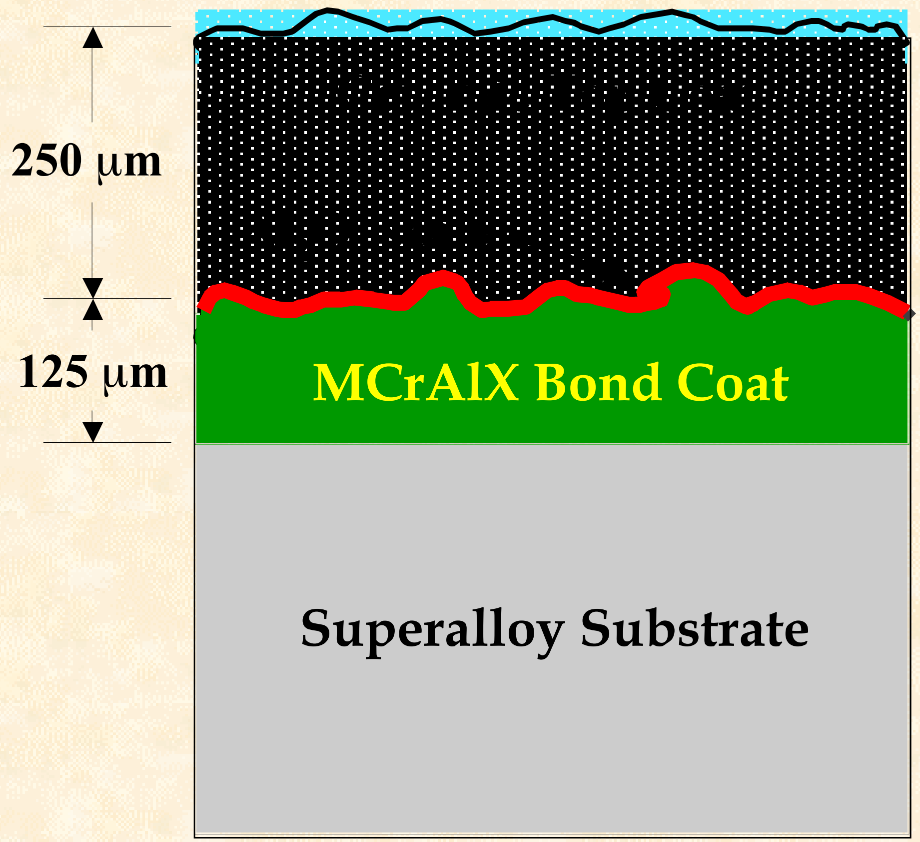
TBCs are complex systems



Plasma-Sprayed Thermal Barrier Coatings



Haynes, et al., 2000

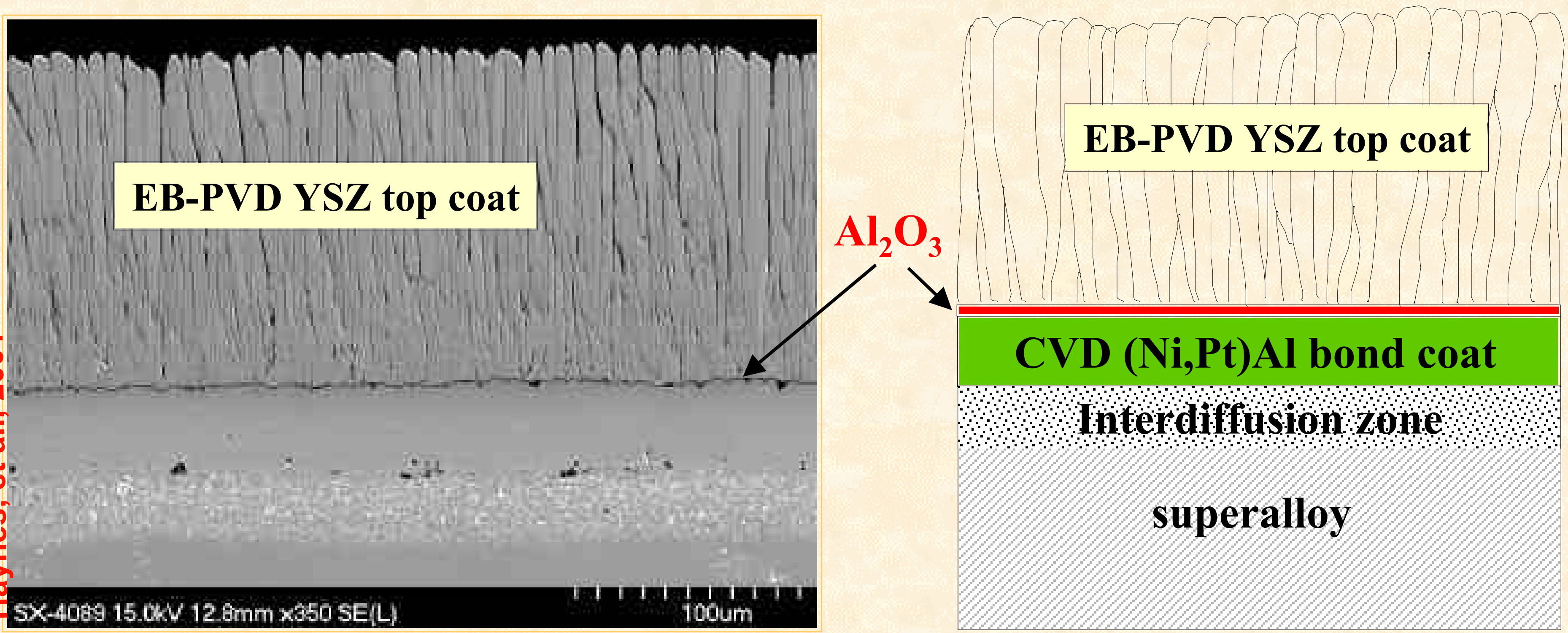


- Y_2O_3-ZrO_2 (YSZ) top coat
  - provides thermal insulation
- Metallic bond coat
  - provides oxidation resistance
  - facilitates YSZ adherence
- Interfacial Al_2O_3 scale

**M = Ni and/or Co, X = Y, Hf, or Si*

APS = air plasma-spray
VPS = vacuum plasma-spray

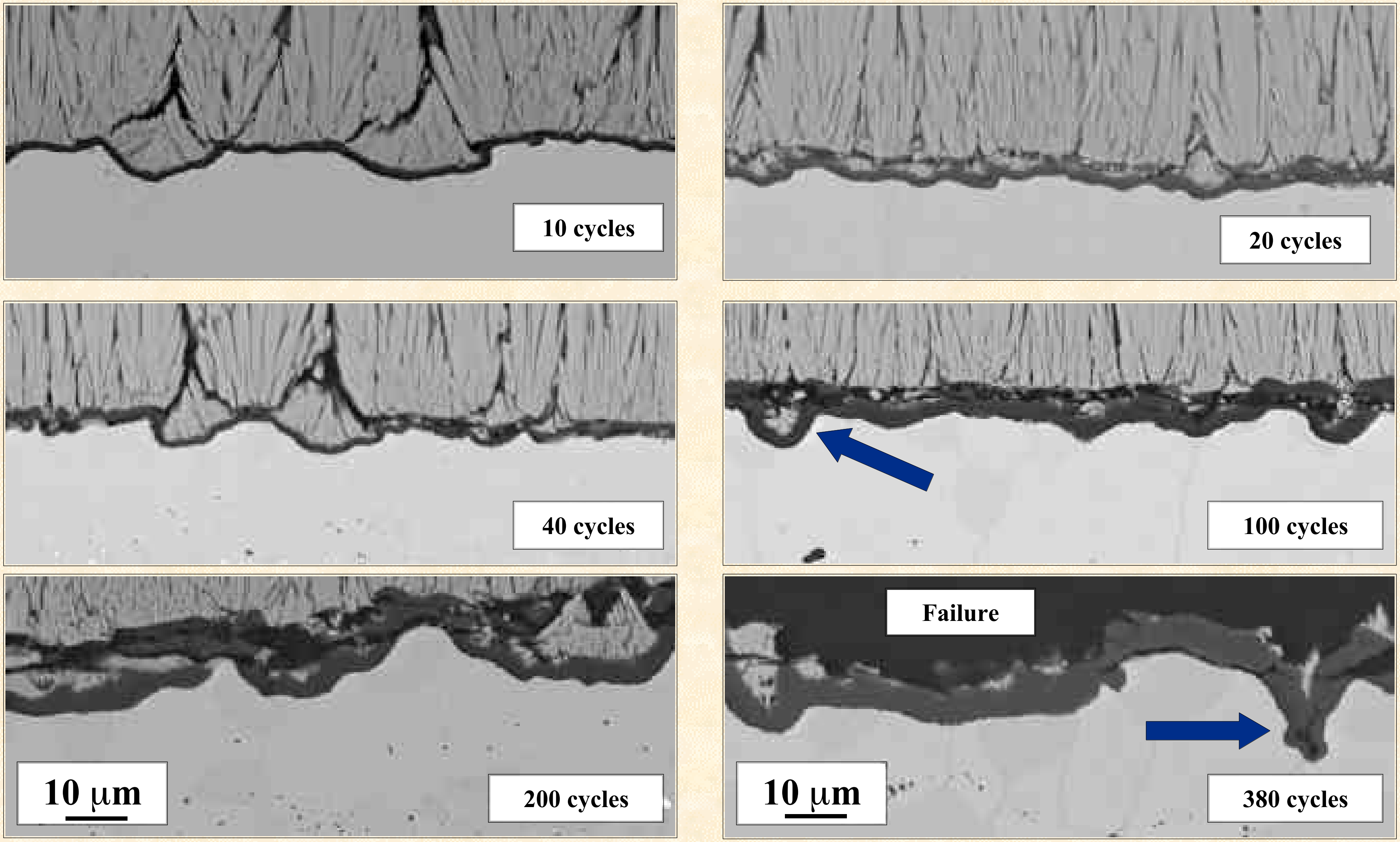
EB-PVD Thermal Barrier Coatings



Haynes, et al., 2001

- Strain-tolerant ceramic top coating deposited by electron beam-physical vapor deposition (EB-PVD)
- Metallic bond coating of single-phase (Ni,Pt)Al produced by Pt electro-plating + pack, or chemical vapor deposition (CVD) aluminizing

Lab. thermal cycling at 1135°C: interfacial roughness increased with time



Haynes et al., 2001

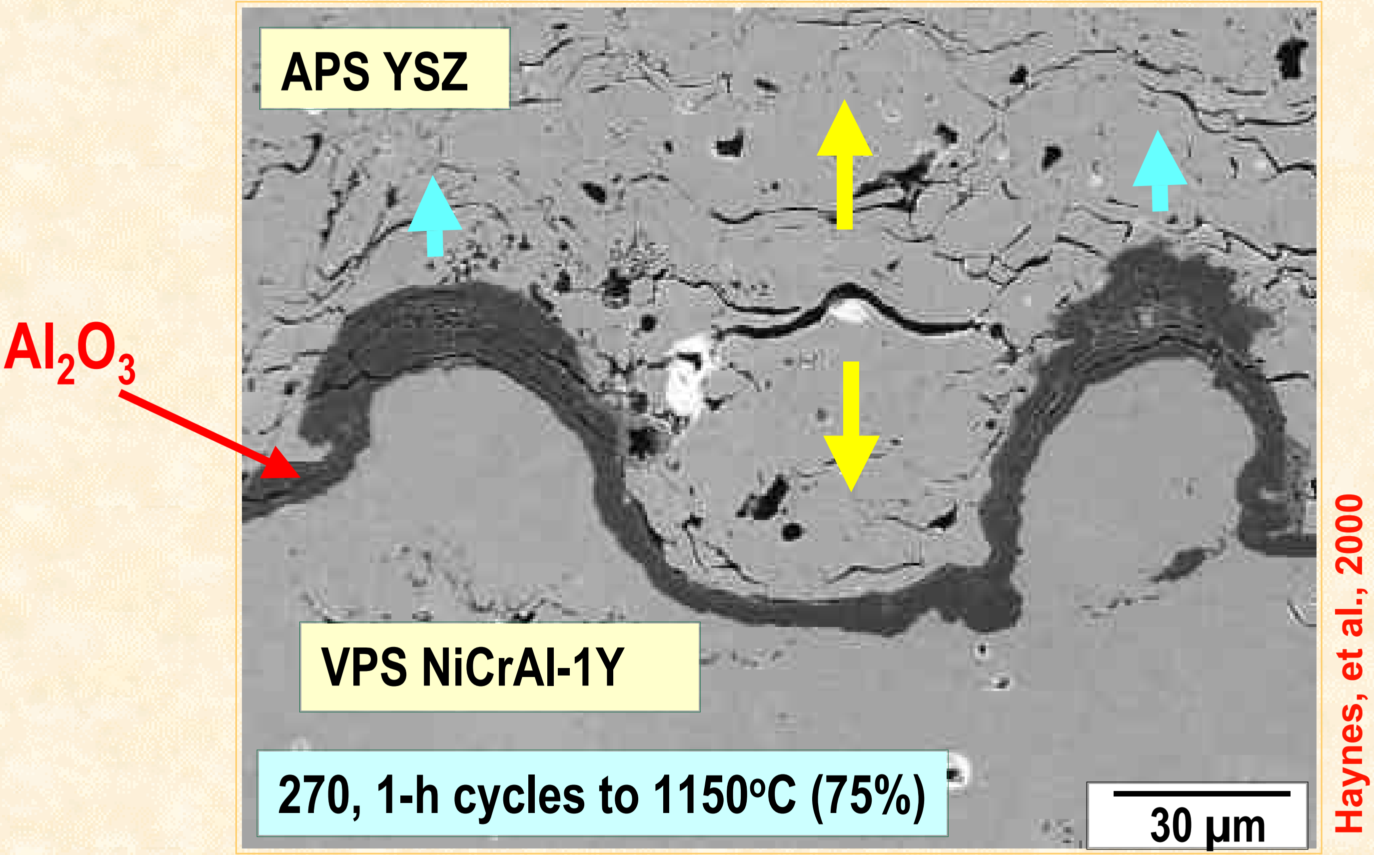
Major TBC Life-Determining Issues

- **TBC application:** ability to apply the specified coating
- **Operating temperature:** assurance of providing the design ΔT at design conditions
- **Cyclic operation:** effects on durability
- **Loss of ceramic:** especially erosion/FOD
- **Other duty cycle issues:** off-specification fuel
- **Lifetime modeling/monitoring:** assurance; early warning

Coating Application Issues

- **PS vs EB-PVD**
  - cost
  - size limitations
  - control of ceramic microstructure
- **Function of the bond coating**
  - MCrAlY or aluminide
  - effect of surface finish
  - BC ‘conditioning’ - aim to quickly establish an α-Al_2O_3 layer
- **Microstructure and thickness**
  - complexity of shape ±determines processing route
- **Cost**
  - low infant mortality

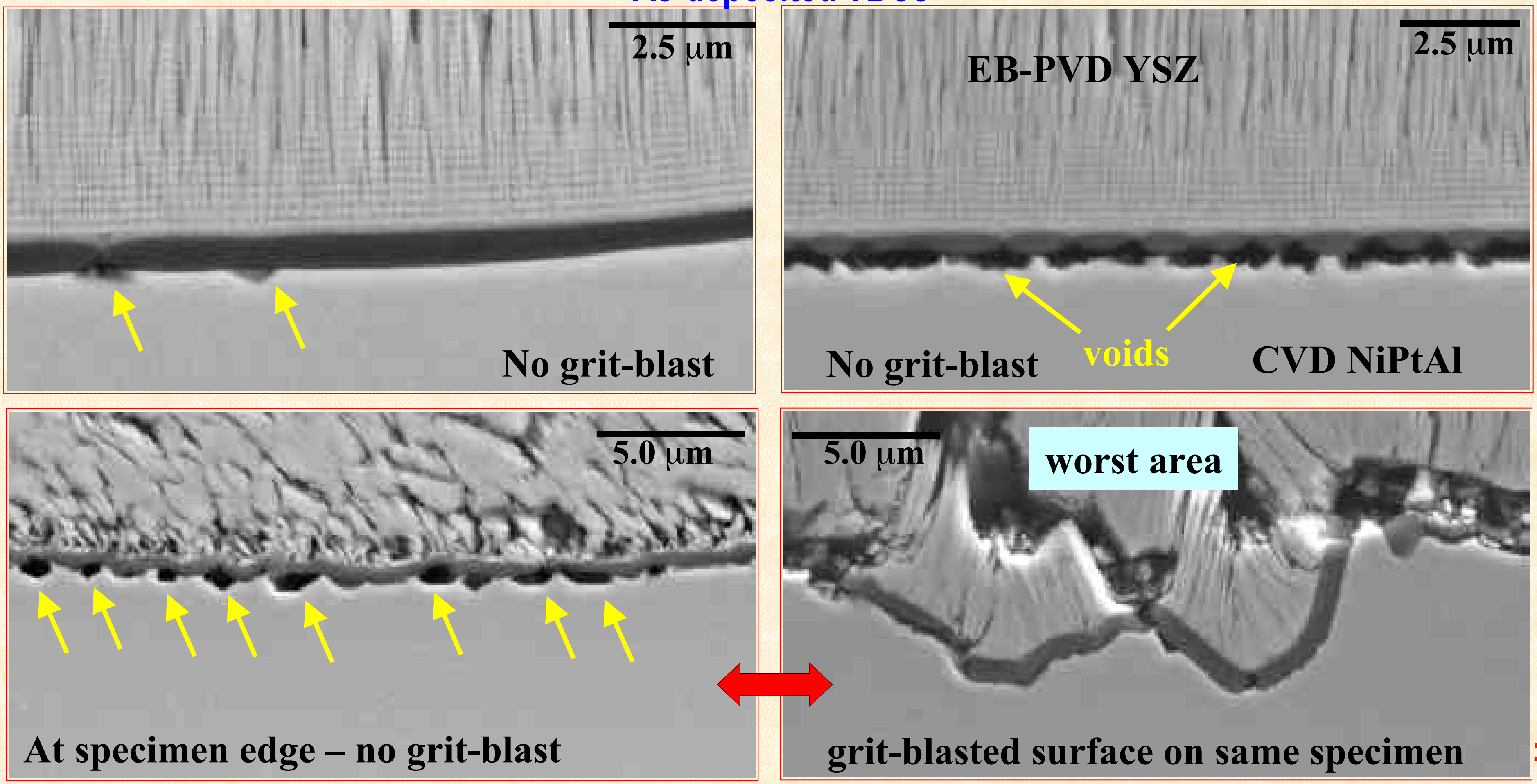
Rough BC surface is an intrinsic feature & problem of PS TBCs



- Evidence of localized oxidation-induced YSZ damage
- Localized Al_2O_3 scale damage very variable—not clear whether it was a factor in determining relative TBC lifetimes on the various MCrAlX bond coatings

Grit-blasting of CVD (Ni,Pt)Al has unexpected benefit for BC oxidation

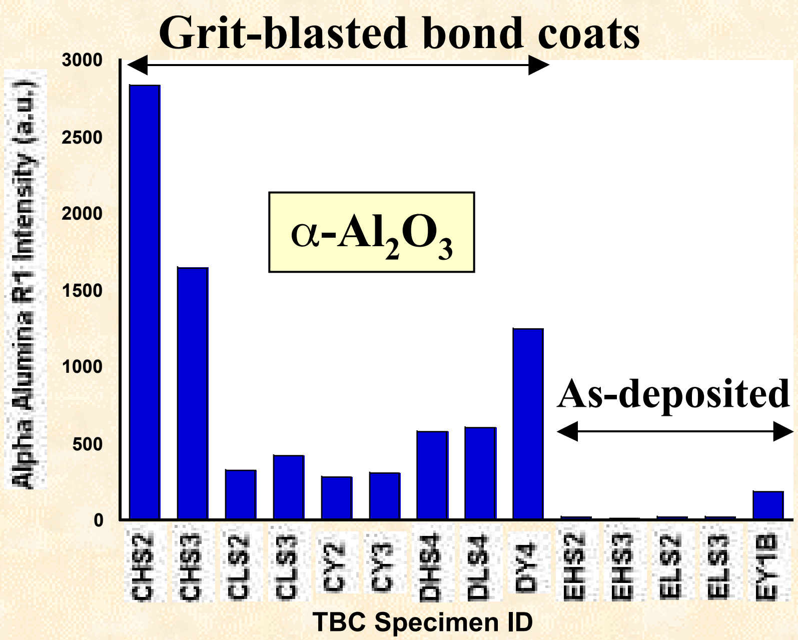
As-deposited TBCs

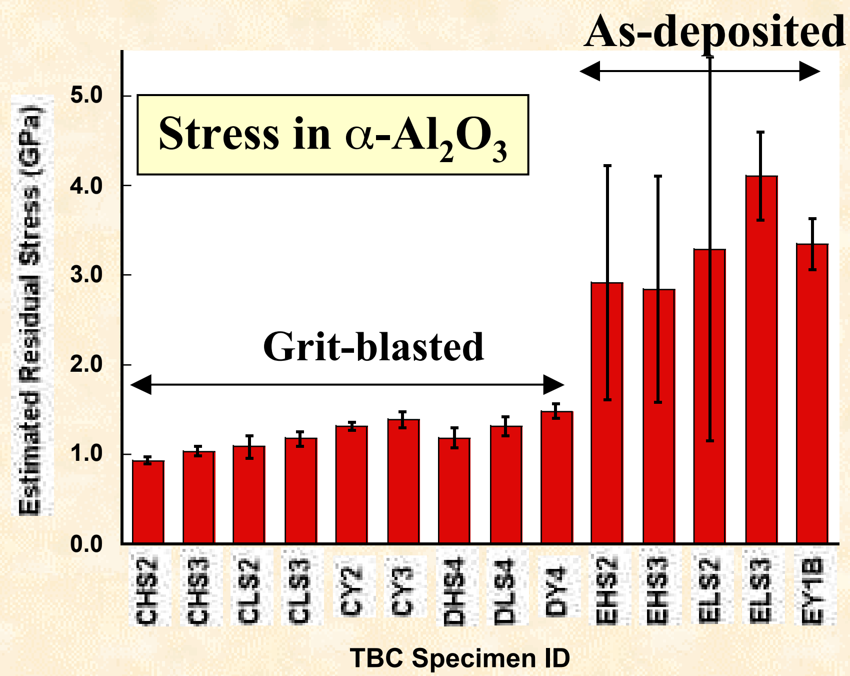


Haynes, et al., 2001

- All surfaces not grit-blasted contained voids at the metal-oxide interface
- Void density & scale thickness varied from grain to grain
- Grit-blasted surfaces contained no obvious voids at the metal-oxide interface

Bond coating surface finish influences first-formed oxide



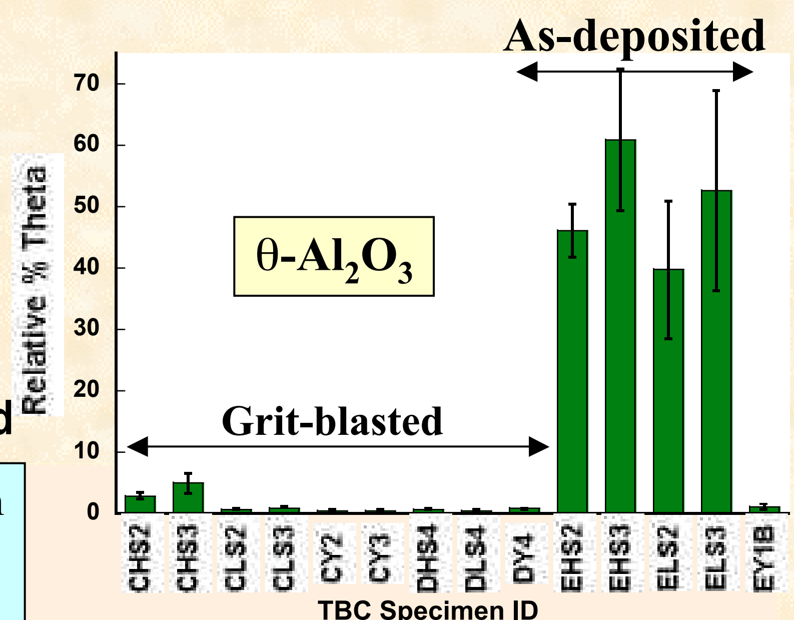


Laser fluorescence of as-deposited EB-PVD TBCs

- Laser fluorescence detectable through the YSZ.
- Grit-blasted surfaces formed more α-Al_2O_3.
- Average stress was lower on grit-blasted surfaces.
- All specimens contained detectable θ- Al_2O_3.
- Greater amounts of θ-Al_2O_3 formed on most as-deposited (Ni,Pt)Al surfaces.

Haynes et al., 2002

Dilor XY 800 Raman
5145 Å, 500 mw
10-12 μm spot size



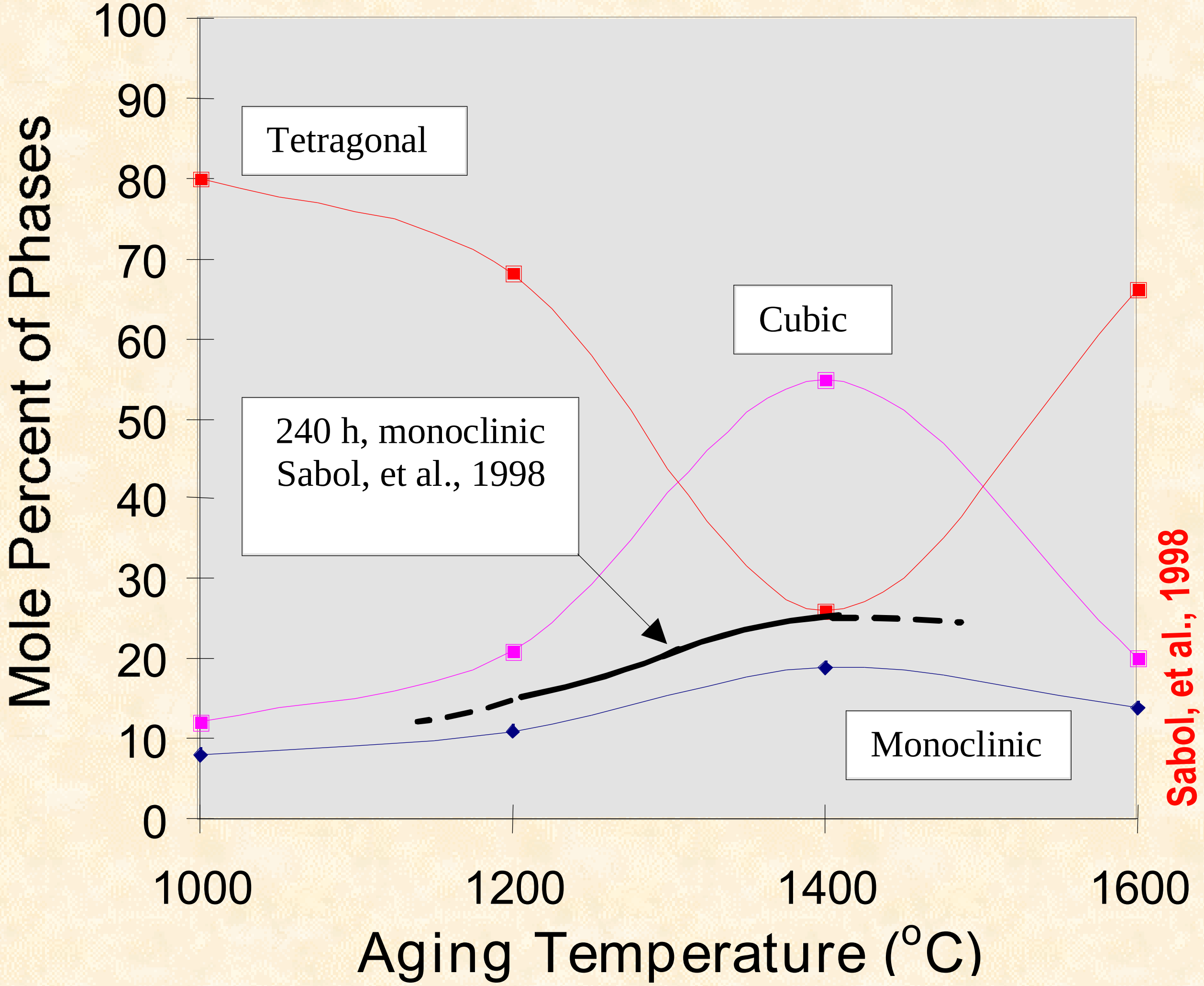
Operating Temperature Issues

Concerned with the effects of time at temperature:

- Effects on the ceramic layer
  - phase change of YSZ
  - sintering of ceramic surface
    - modification of microstructure
    - change in mode of failure
- BC oxide growth
  - some lifing models based on rate of oxide thickening
  - exhaustion of Al reservoir--formation of voluminous base metal oxides
- BC-superalloy interdiffusion
  - depletion of Al
  - BC phase change/effect on CTE
  - ingress of unwanted elements from superalloy

Effect of 100 hr Aging on Phase Stability of YSZ

(after Miller, et al., NASA, 1981)

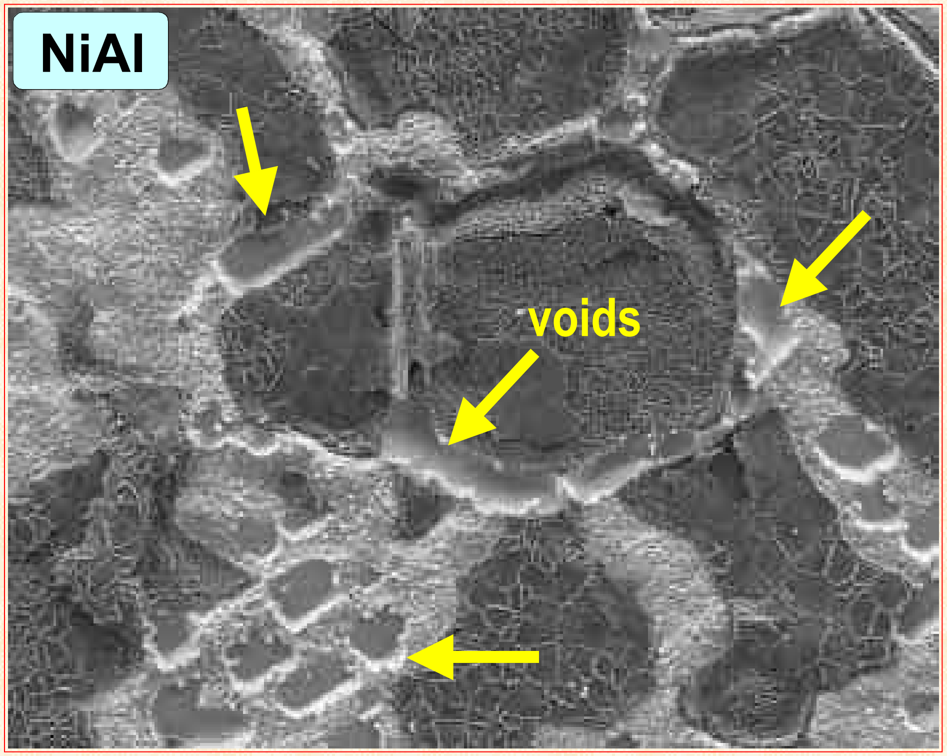


BC oxide thickness increases with t at T

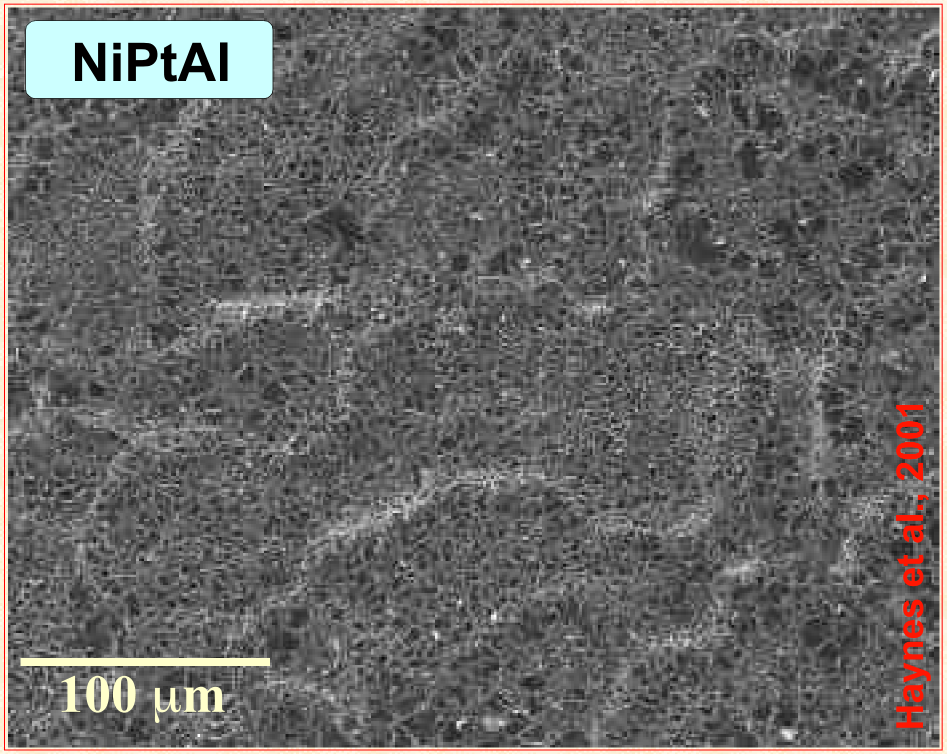
- Increasing oxide thickness equates to:
  - *increased stress generation*
    - increased tendency for scale spallation
  - *increased consumption of Al reservoir*
    - loss of β-phase in BC (lower-Al phases do not form the desired oxide)
    - approach to non-protective oxidation (voluminous scales)
    - with Pt addition, min. Al content for protective oxidation is reduced from ≈43 to ≈38 at%Al
- Oxide growth rate can be minimized by:
  - *forming α-Al_2O_3 as soon as possible (Pt effects)*
  - *controlled addition of a reactive element (Y, Hf, …)*
    - MCrAlYs
    - aluminides
- Resistance to scale spallation can be improved by:
  - *Pt additions*
  - *removal of alloy/BC tramp S to <<1 ppm*
  - *RE additions*

‘High’ superalloy S—increased interfacial void growth and scale spallation on CVD-NiAl; but no voids formed on CVD-NiPtAl

200-h isothermal @ 1150°C (substrate: Hi-S N5A, S = 3.6 ppmw)



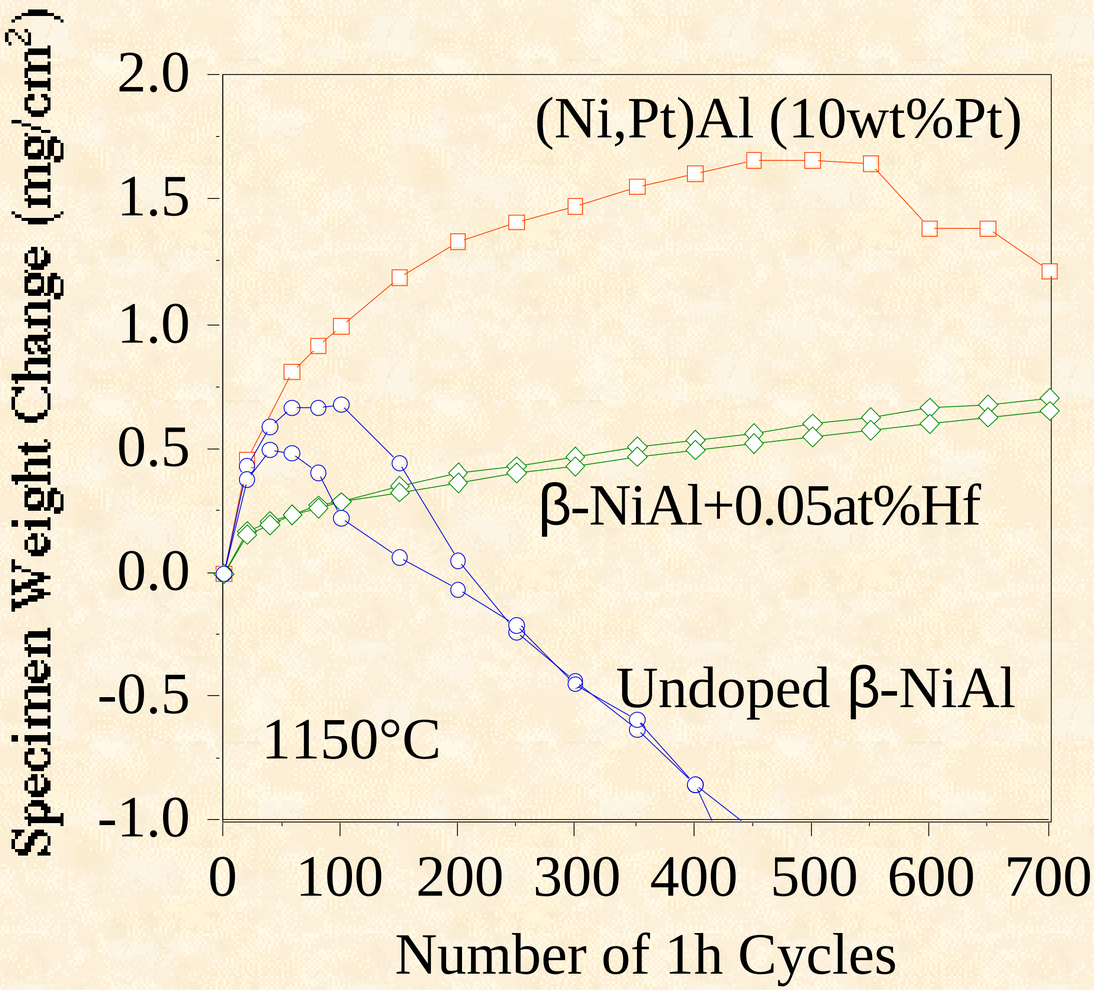
NiAl on High-S Rene N5



NiPtAl on High-S Rene N5

- Increased substrate S resulted in massive void formation & scale spallation on grain boundaries & grain surfaces of NiAl.
- Neither voids nor scale spallation were observed on NiPtAl despite the increased S impurities (and high C) of the Hi-S N5 substrate.

RE & Pt additions improve scale spallation lifetimes; RE additions are more potent



- *Undoped*:—rapid scale spallation
- *Pt*: improved resistance to spallation…for a time
- *RE-doping*:—lower scale growth rate + greatly improved spallation resistance

(Pint, et al., 1998)

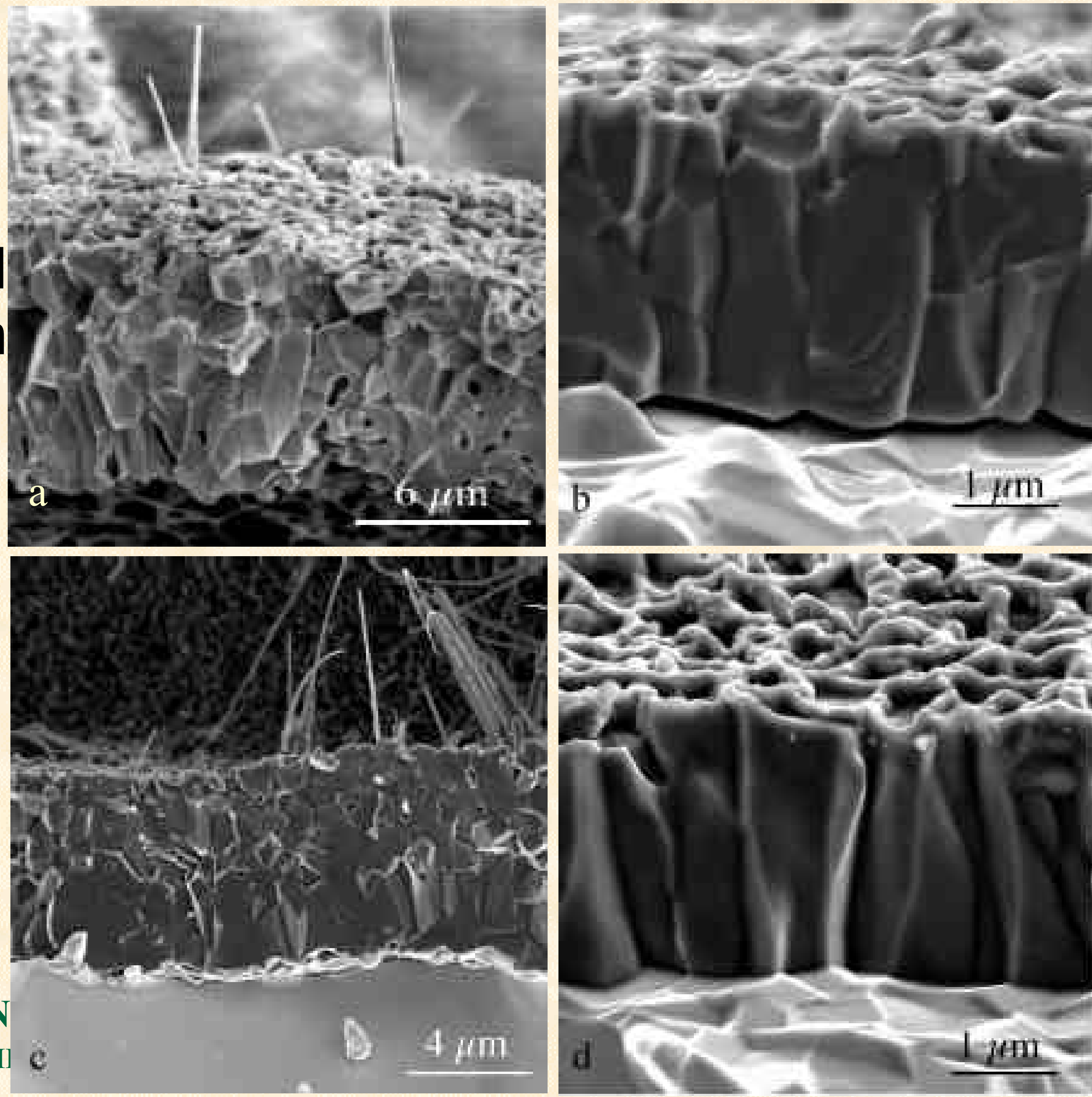
RE additions modify scale morphology and reduce growth rate; Pt does not (1200°C)

Undoped βNiAl, 200h

βNiAl+Hf, 100h

PtAl, 100h

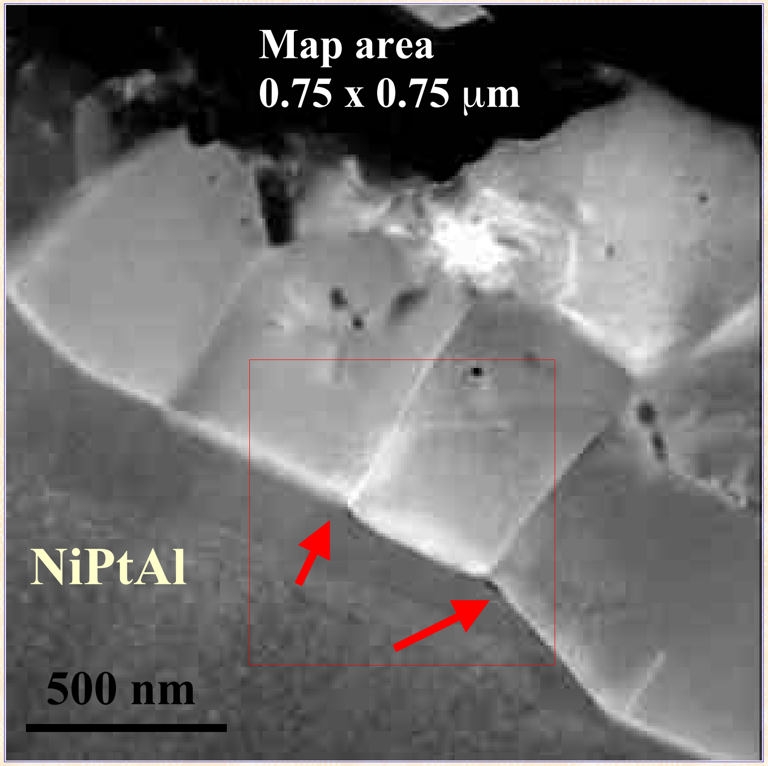
NiPtAl+Hf, 100h

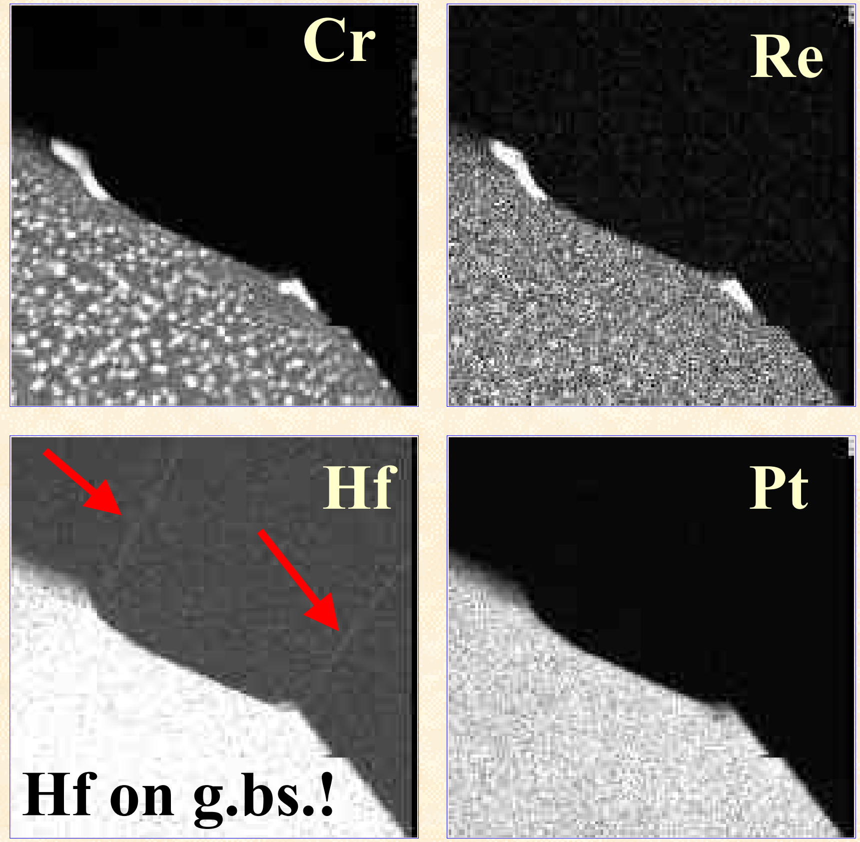


Pint et al., 1998

STEM/EDS Mapping of Alumina Scales on NiPtAl

100-h isothermal @ 1150°C (substrate S ~ 0.8 ppmw, C ~1000 ppmw)





More, et al., 2001

- Hf from the Rene N5 substrate was detected on the columnar oxide grain boundaries of NiPtAl, but not in the equiaxed outer grains.
- No Hf was detected on oxide grain boundaries on NiAl.
- Apparently, Hf diffused more rapidly through NiPtAl than NiAl.

BC-Superalloy Interdiffusion

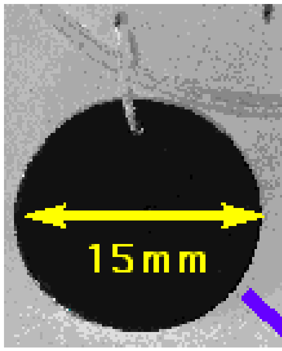
- **Concern over loss of Al reservoir**
  - minimum Al level for maintaining α-Al_2O_3
  - Pt beneficial

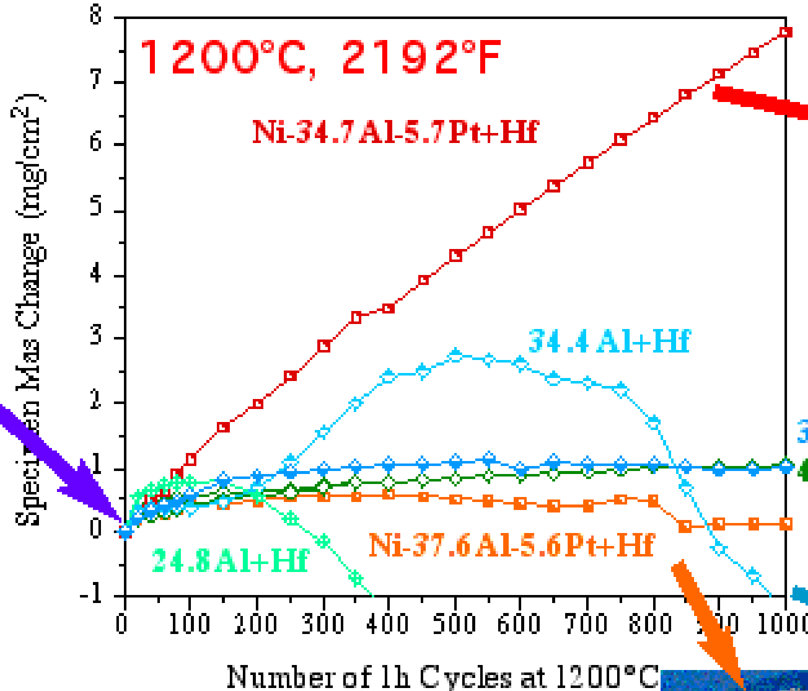
- **Ingress of other elements** is typically detrimental to the protective nature of the oxide scale
  - Ti, Cr, Re…
  - Hf: from good to bad

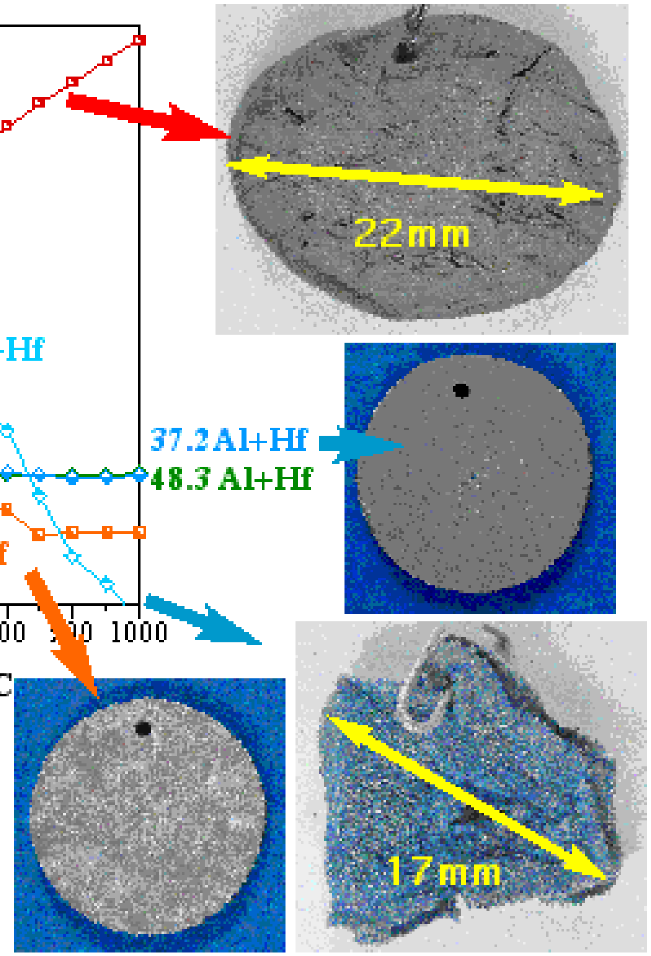
- **NiAl BC phase change**
  - critical range appears to be 35-37.5 at% Al
  - at RT: γ' + β; at 1100°C: one phase (β?)
  - effect on CTE

NiAl+Hf: Critical Effect of Al Content

cast alloys, oxidized 1000x1h cycles at 1200°C in O_2







Critical range: 35-37.5%

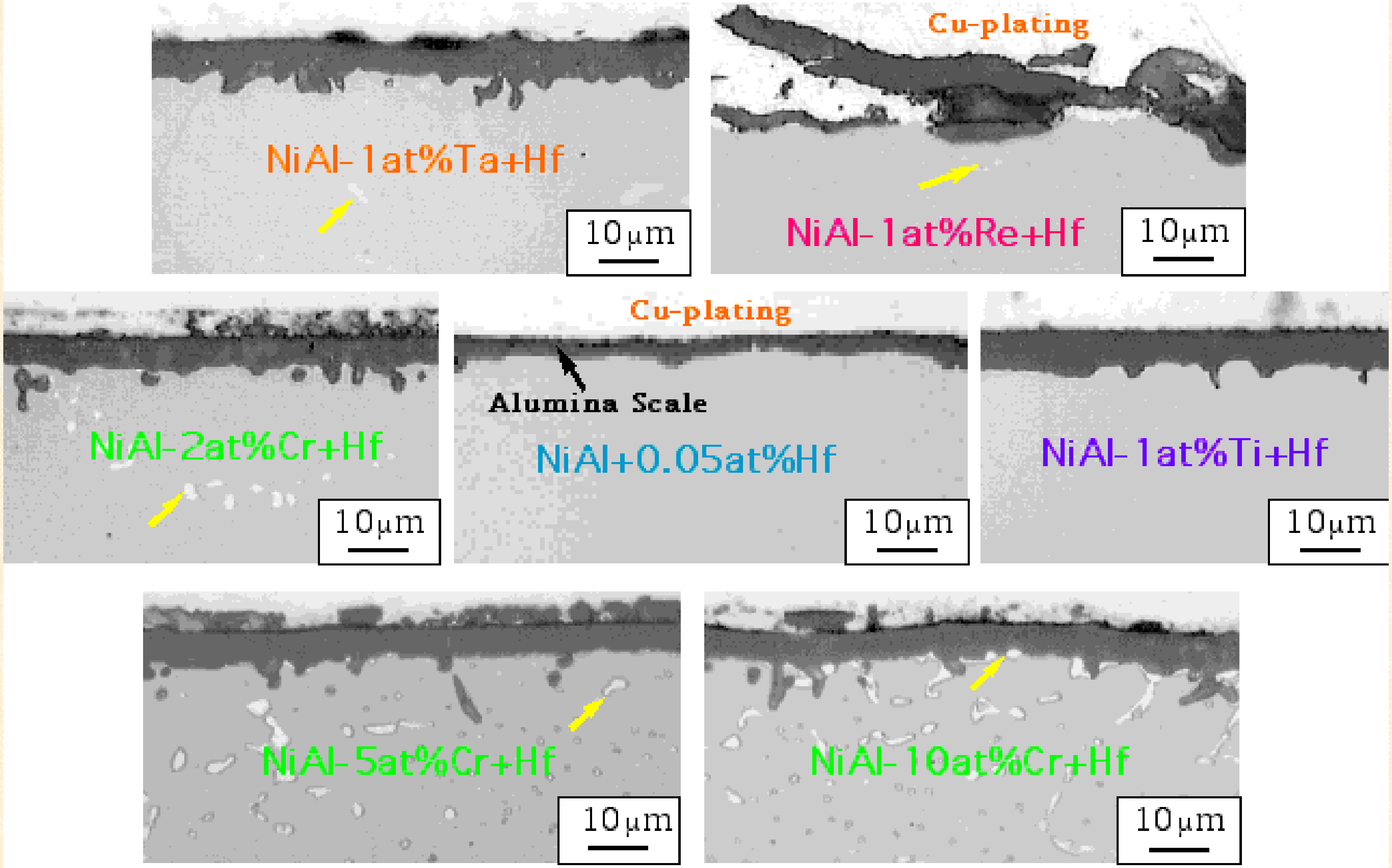
two phase vs. one phase?

Pint, et al., 2001

- Al contents < 37.5 at% have significant oxidation problems
- Macroscopic deformation occurs for low-Al two-phase alloys
- Addition of Pt does not stop deformation, or spallation (but no blue oxide)

Tramp elements are detrimental to NiAl+Hf

polished cross-sections after 1000x1h at 1150°C in O_2



Pint, et al., 2001

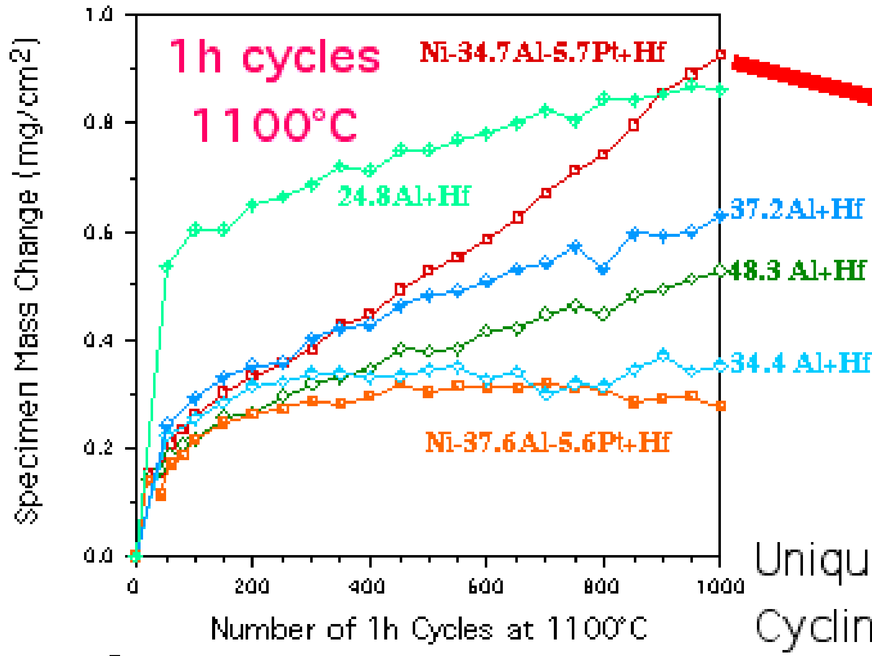
All additions accelerate scale growth rate compared to NiAl+Hf

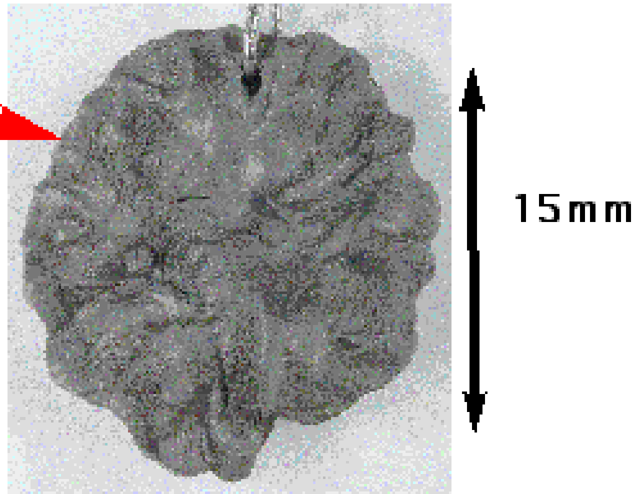
Problems with scale adhesion with Cr and Re -> precipitates

Cyclic Operation Issues

- Increased stress generation due to:
  - CTE mismatch YSZ - oxide scale - BC
  - BC - superalloy CTE mismatch
  - oxide growth
- Need to consider matching superalloy and BC CTEs
- Can't do much to modify the YSZ - oxide scale CTE mismatch
- Need to maximize adherence of oxide scale to BC
  - Pt,S,RE effects
- Are long or short cycles worse?
  - long cycles: more oxide growth between cycles, but increased opportunity for stress relief-localized rather than massive damage?
  - short cycles: more cycles/unit time

Deformation of BC: depends on T & cycle frequency

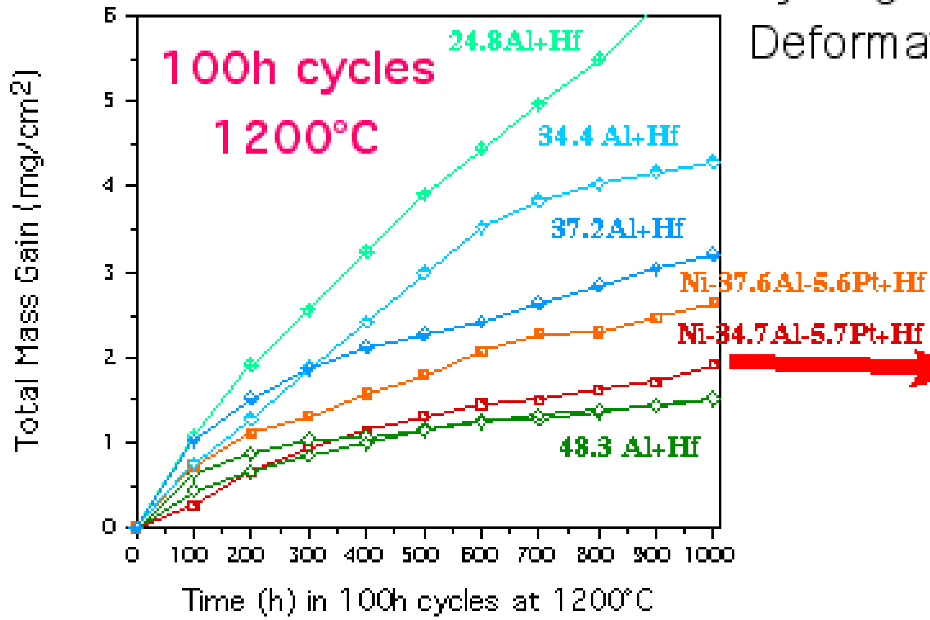


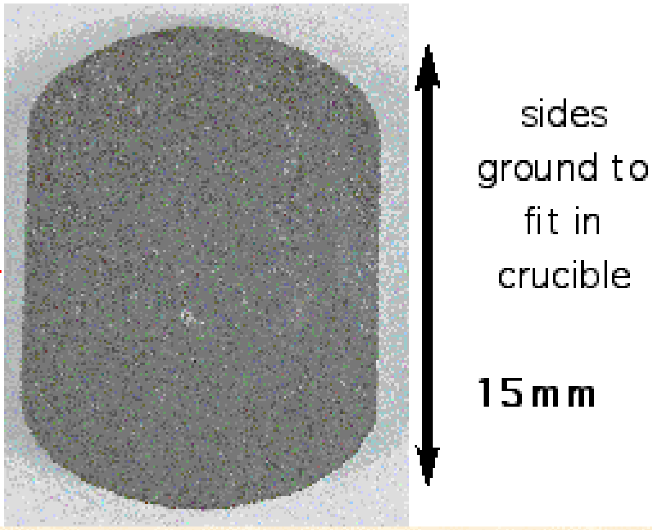


Unique behavior of Ni-34.7Al-5.7Pt+Hf

Cycling causes repeated phase change

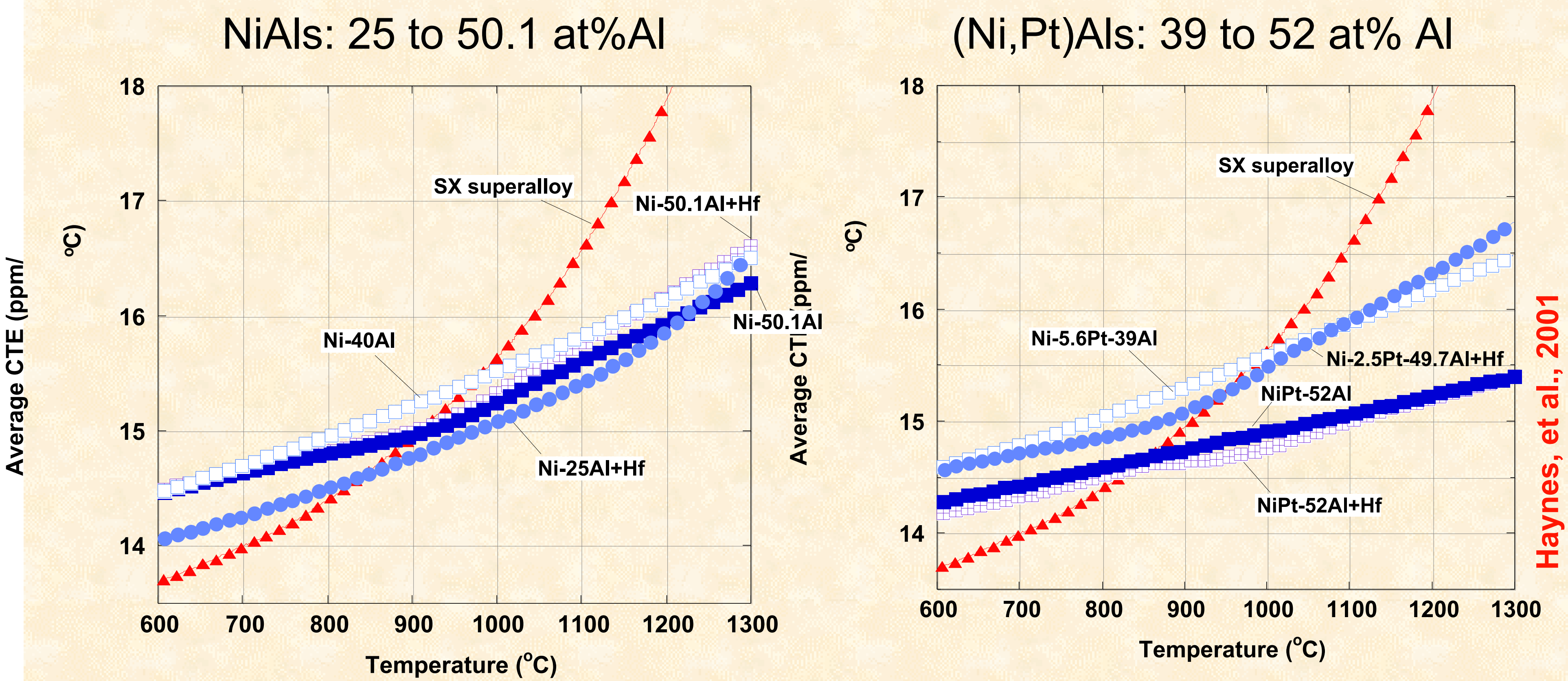
Deformation similar to aluminide coatings!





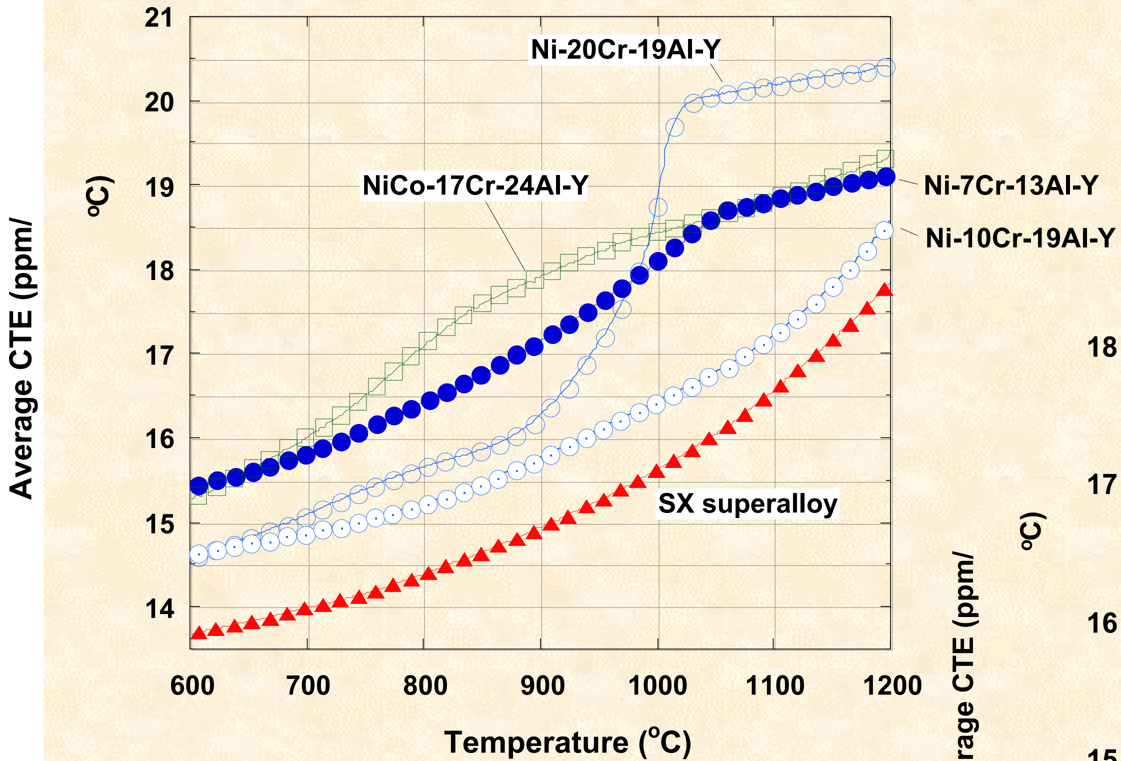
Pint, et al., 2001

Effect of Pt on CTE of Aluminide Bond Coating Alloys



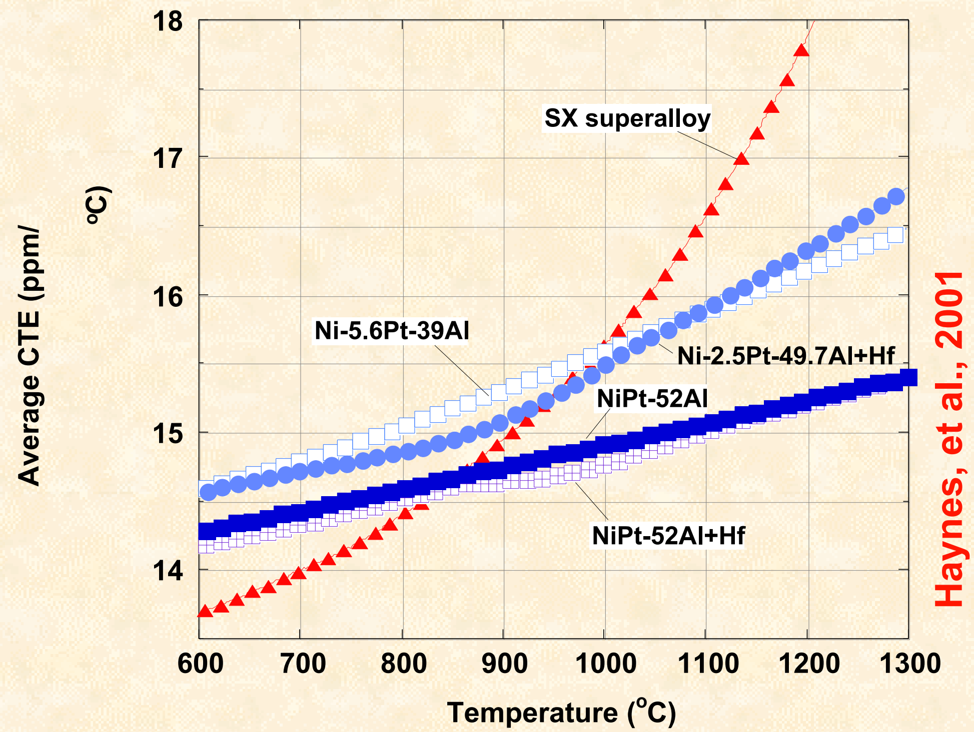
- The CTE difference generates stress in the BC at temperature, which could cause deformation

Comparison of CTE of Bond Coating Alloys

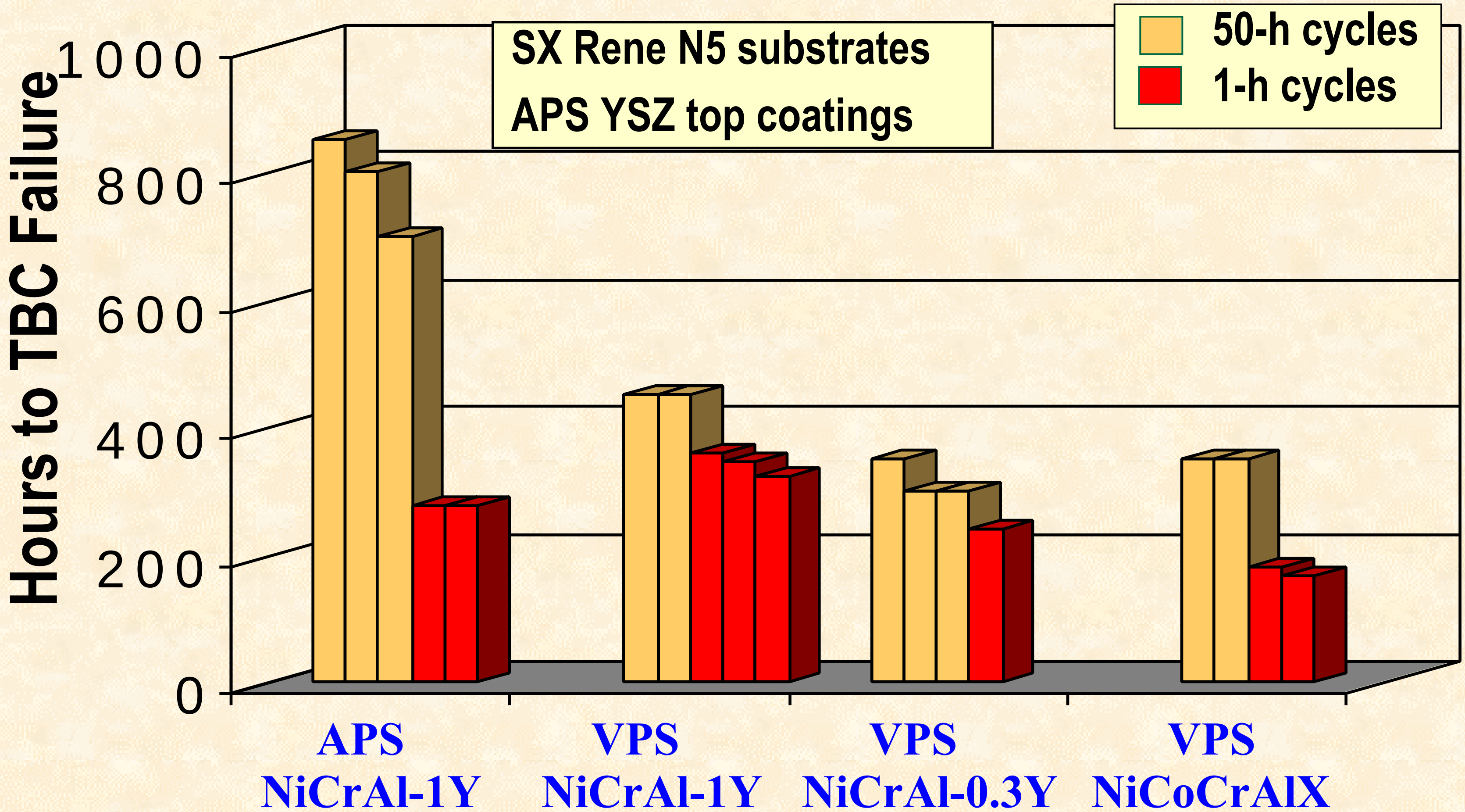


MCrAlYs: CTE > SC Superalloy

(Ni,Pt)Als: CTE < SC superalloy at 850/1000°C



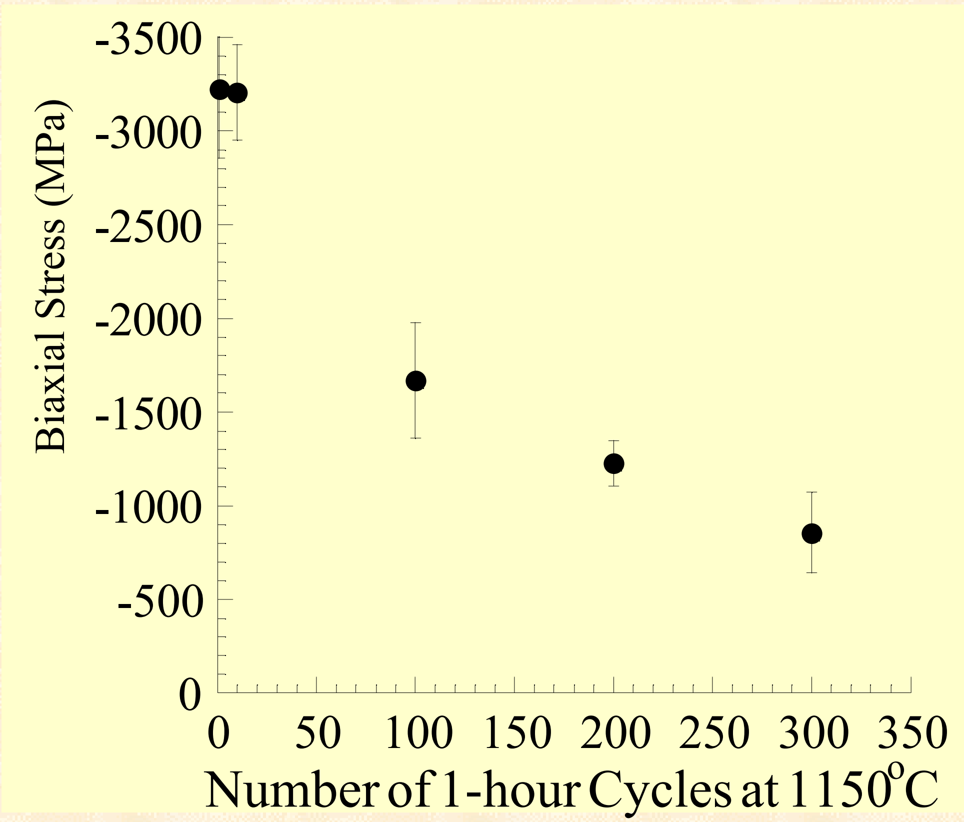
TBC Lifetimes: 1-h & 50-h cycles (1150^{o}C)



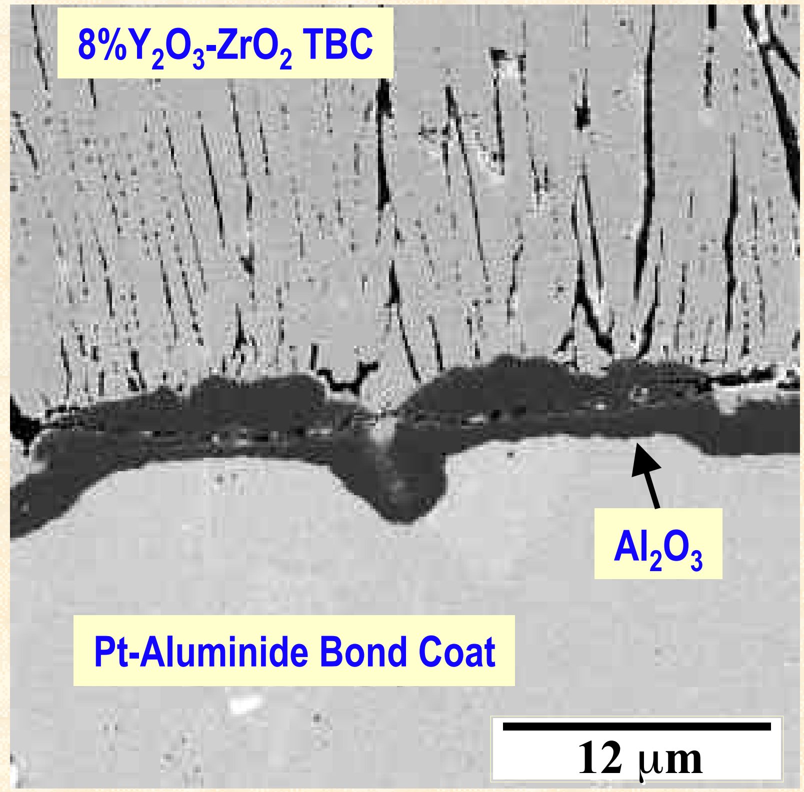
- For PS TBCs: lifetimes longer for longer cycles
- Suggests MCrAlX CTE more dominant than oxidation-related factors?

For EB-PVD/aluminide BC, stress in oxide decreases with thermal cycling

Thermal Cycling at 1150ºC



100 1-hr Cycles at 1150°C



Lance, et al., 2000

- The Al_2O_3 compressive stress gradually decreases during thermal cycling due to interface roughening and scale cracking

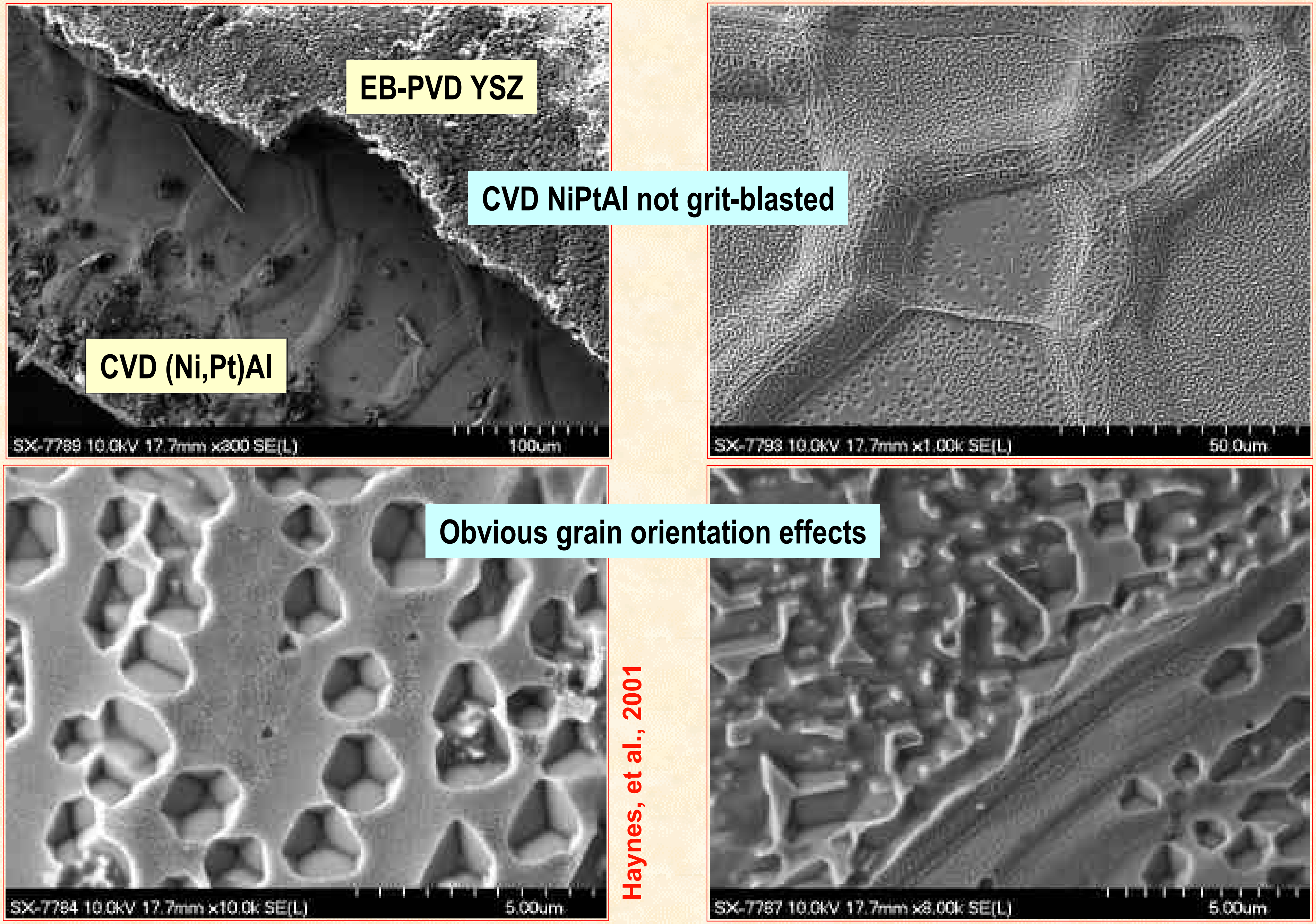
Condition Monitoring

- IR imaging (Siemens Westinghouse; ORNL)
  - hot spots/debonding
- Laser flash (ANL)
  - oxide-BC interface roughness
  - thermal properties
- PSLS (UCSB; UConn; Howmet; ORNL; NPL and Imperial College, UK; Universita' di Trieste, Italy)
  - stress levels in BC oxide layer
  - phase content of oxide
- Eddy current techniques (Jentek; EPRI; Structural Analysis Assoc.)
  - BC Al content change with time
- EIS (U. Central Florida)
  - debonding

Summary

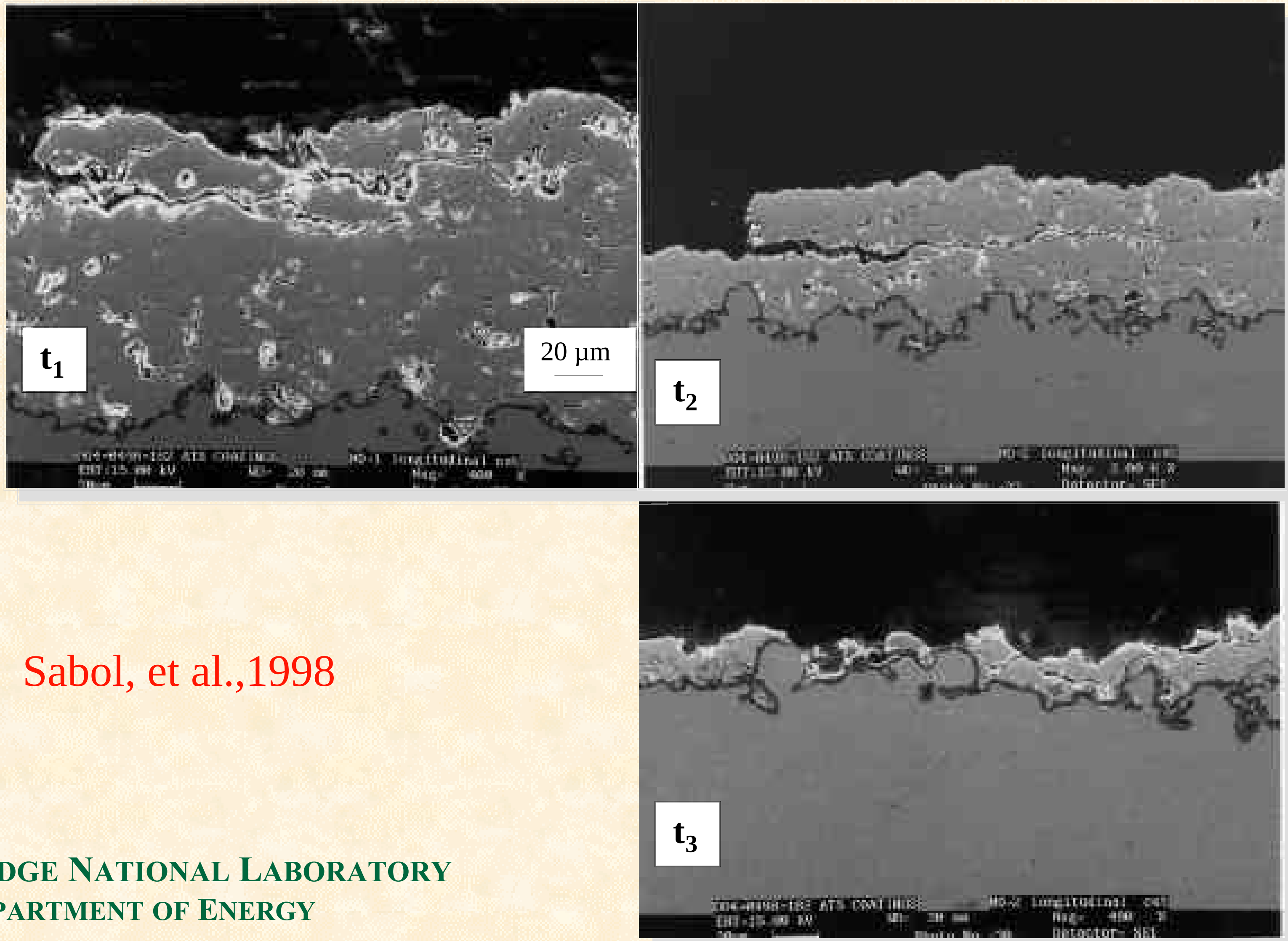
- **Many variables contribute to the performance of TBCs**
  - **application route for ceramic: APS vs EB-PVD**
  - **bond coating composition; structure; mode of application, surface finish**
  - **superalloy substrate composition and structure**
  - **vendor-to-vendor differences (processing parameters, e.g. surface preparation)**
- **The factors to be addressed to optimize TBC performance depend on the mode of degradation, *i.e., are system-specific***
- **Need to understand the processes involved in TBC degradation in order to identify the factors that have the largest contributions**

Voids in As-Deposited (Ni,Pt)Al Surfaces After EB-PVD Processing



Haynes, et al., 2001

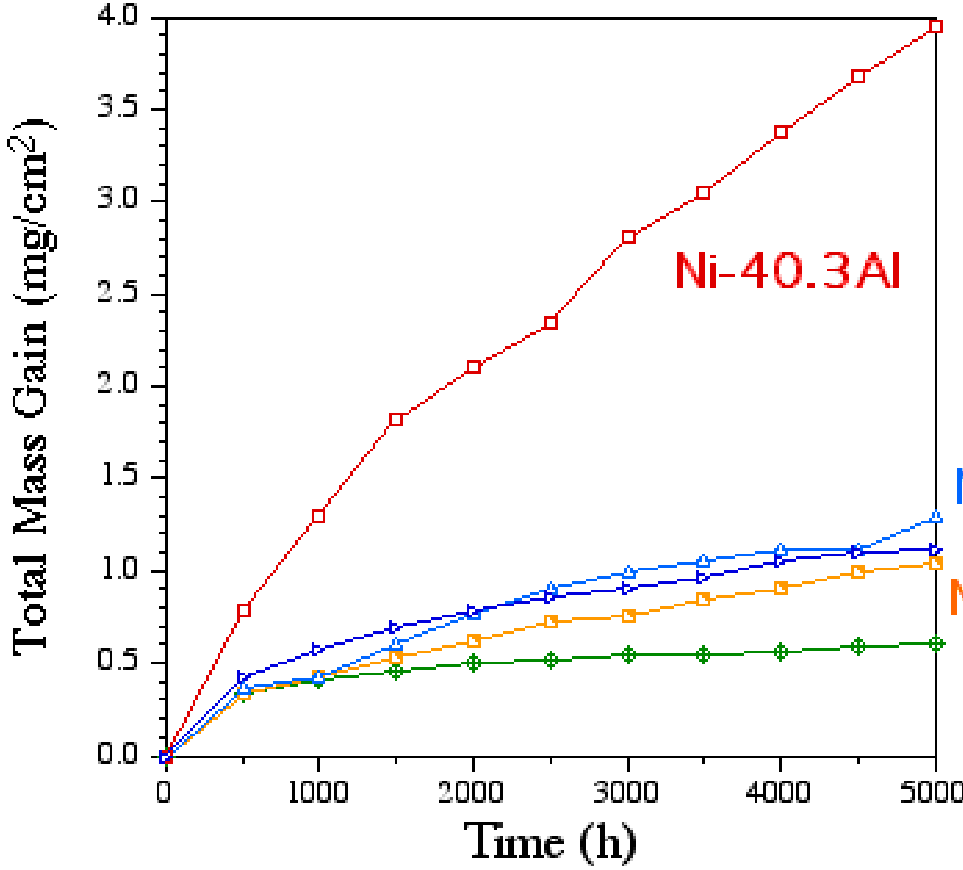
Progressive failure of an APS TBC in a high thermal gradient cycling test



Sabol, et al.,1998

Improved selective oxidation with Pt

Total Mass Gain during 500h cycles at 1000°C



1000°C, 1832°F

Only Pt added, no Hf

Total = specimen+spall

NiAl+Hf - lower because of better adhesion and slower growth rate

Ni-42.6Al & Ni-50.1Al - undoped alumina growth + some spallation

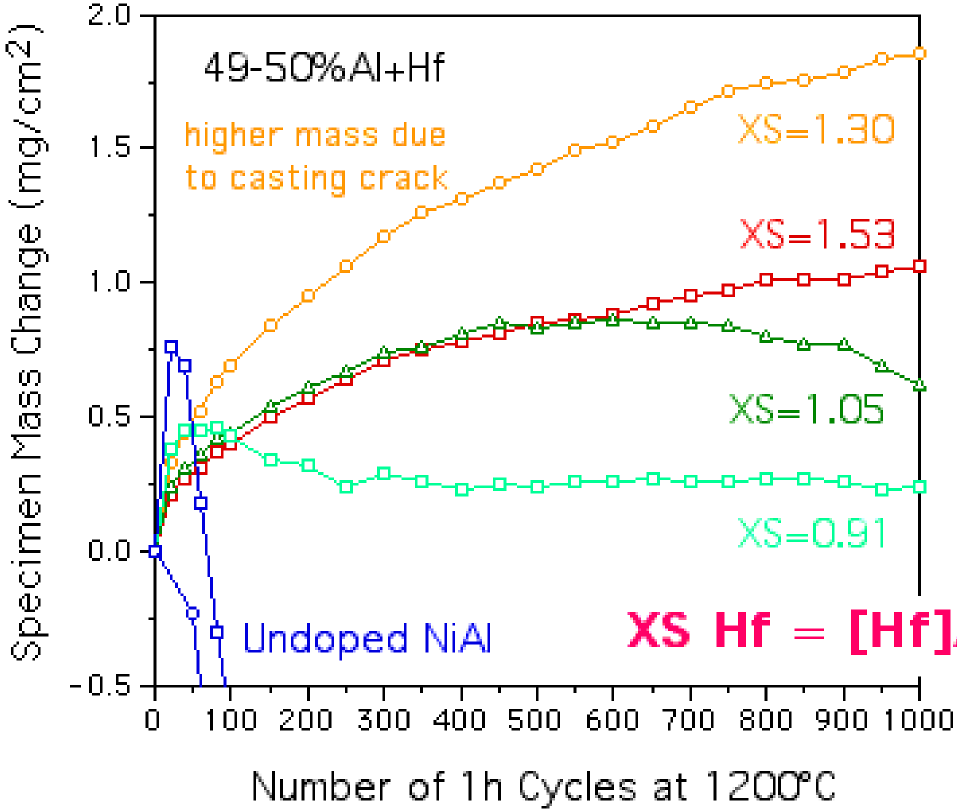
Ni-40.3Al - spinel formation increased total mass + some spallation

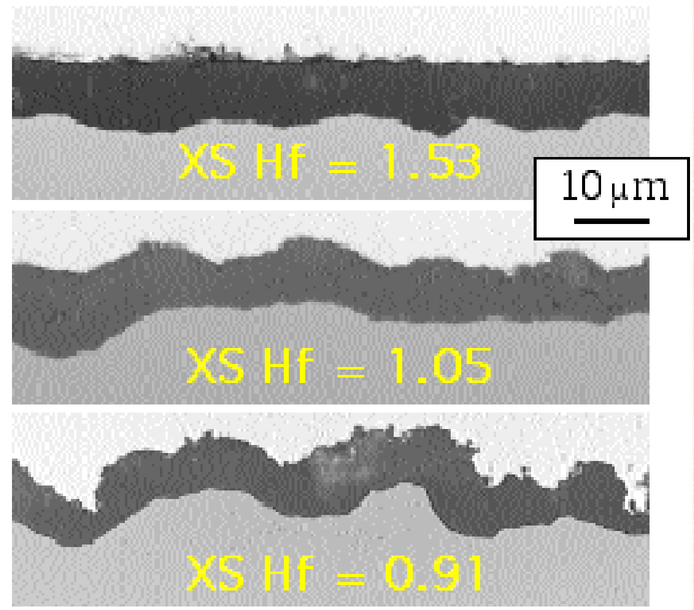
Ni-38.7Al-5.6Pt(20wt%) - better selective oxidation, i.e. no spallation

Pint, et al., 2001

Effects of C-Hf interactions on NiAl+Hf

testing in 1h cycles at 1200°C





XS Hf = [Hf]/([C]+0.5[O]+[N])

after 100h at 1200°C

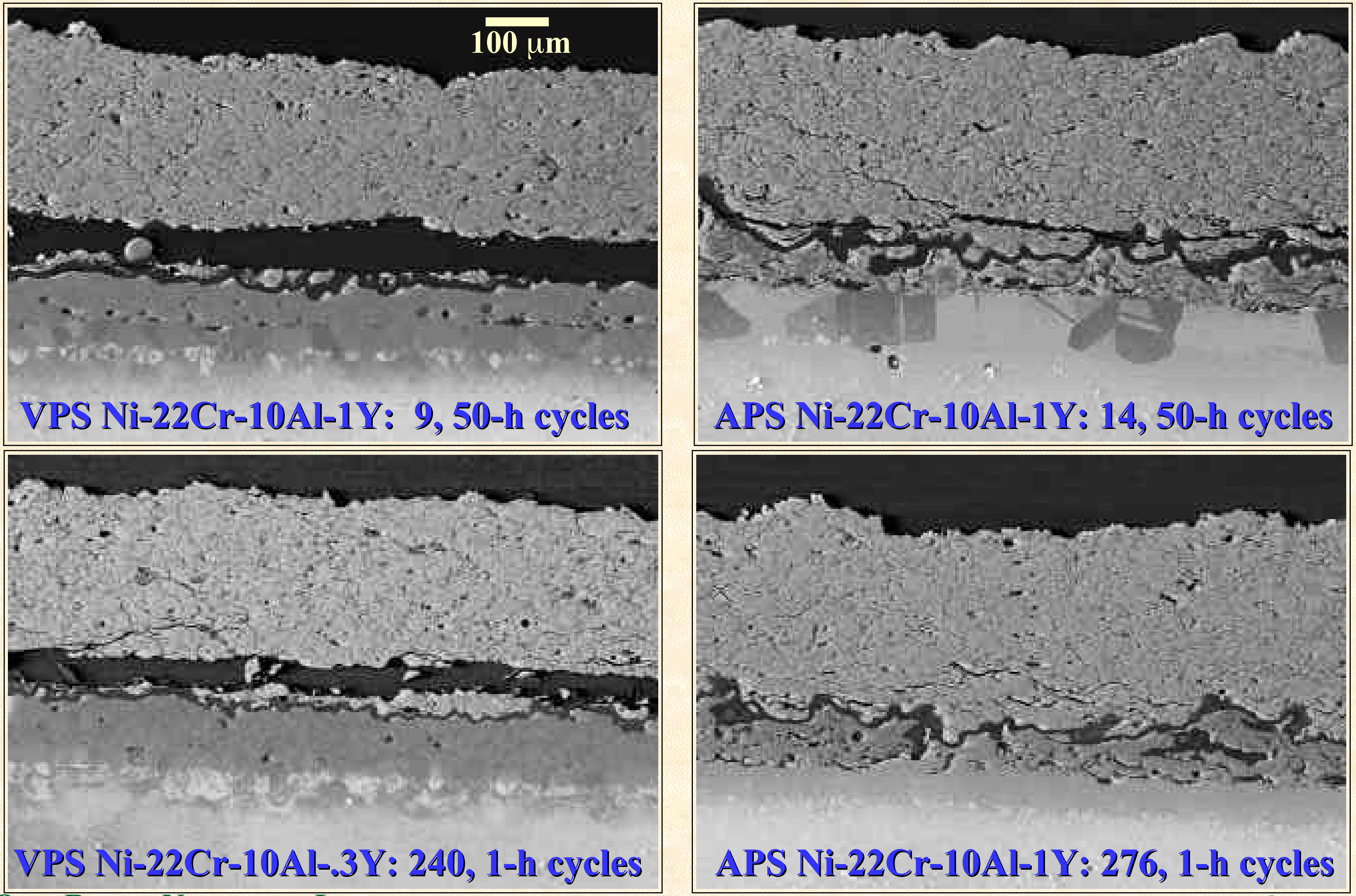
Typically, [Hf] = 450-550ppma (plasma analysis)
[N] = <4ppma (LECO) [S] = <2 ppma (by GDMS)
[O] = 20-30ppma (LECO)

XS varied by changing [C] -> making graphite additions to the casting

Is XS Hf > 1 a critical parameter?

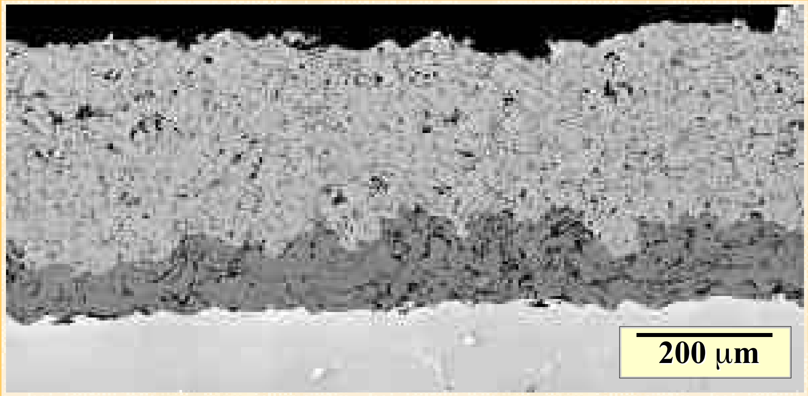
Pint, et al., 2001

PS-TBC Microstructures at Failure

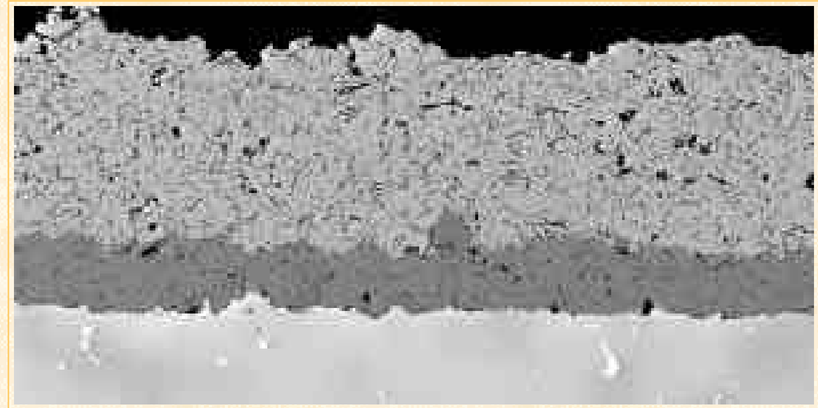


Haynes, et al., 2000

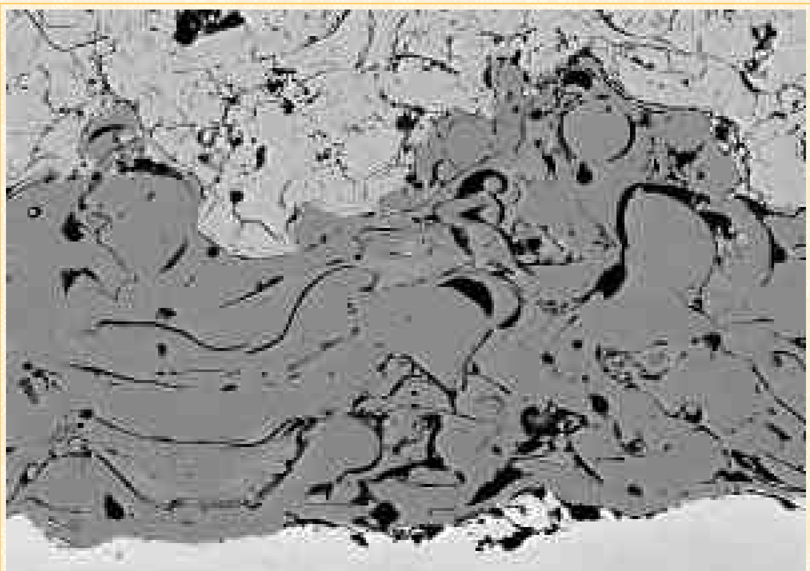
As-Deposited TBC & BC Microstructures

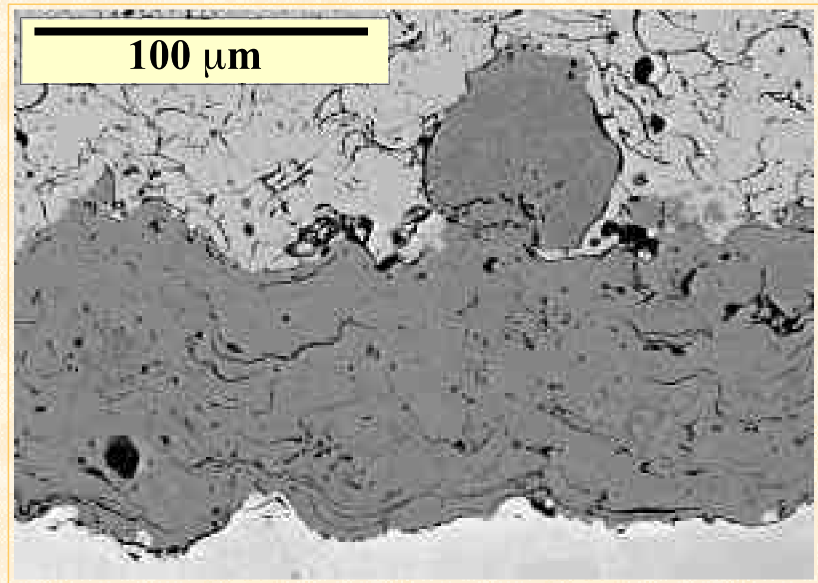


APS NiCrAlY on René N5



VPS NiCoCrAlYHfSi on René N5

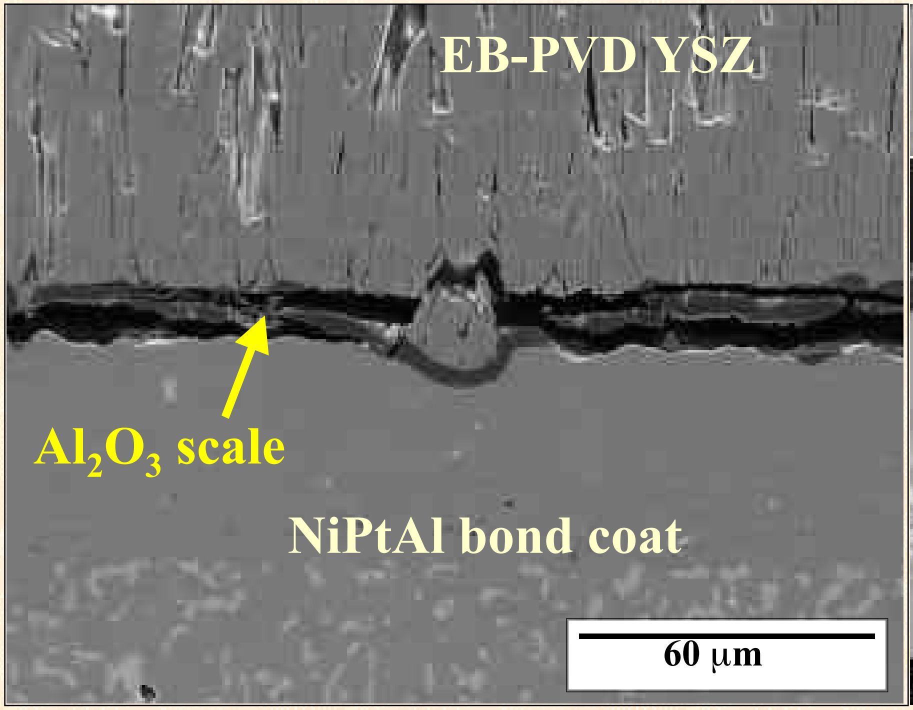


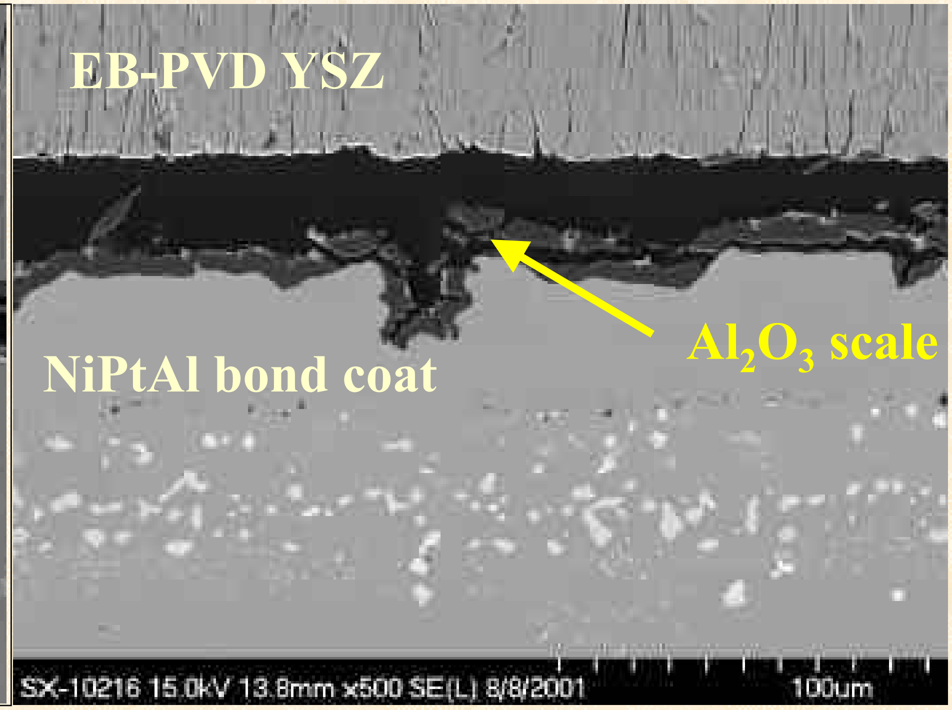


Haynes, et al., 2000

Conventional wisdom: VPS bond coats provide superior TBC lifetimes

EB-PVD Microstructures at Failure





Haynes, et al., 2001

- TBC failure mode = delamination and spallation of the Al_2O_3 scale and/or the overlying YSZ top coating at or near the metal-ceramic interface.
- Interfacial degradation is associated with bond coat oxidation and, in some cases, surface deformation