Factors Affecting the Performance of Bond Coatings

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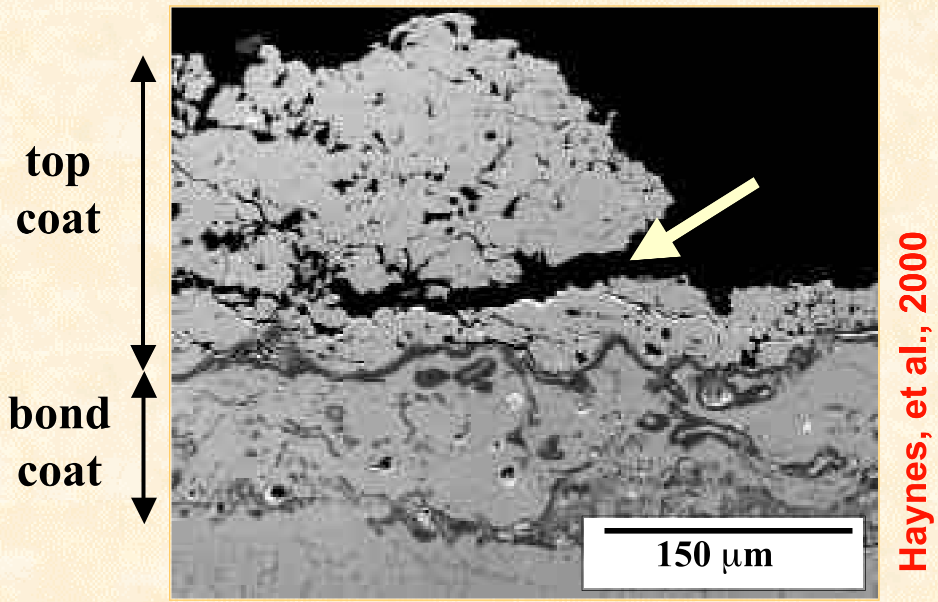
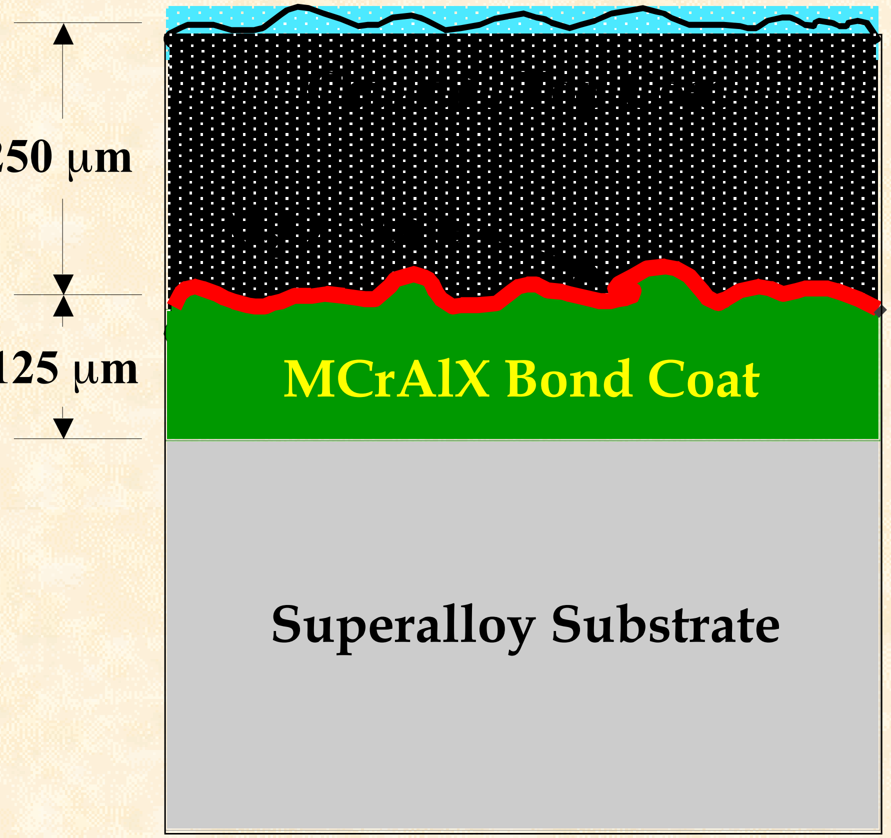
Outline

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

Plasma-Sprayed Thermal Barrier Coatings



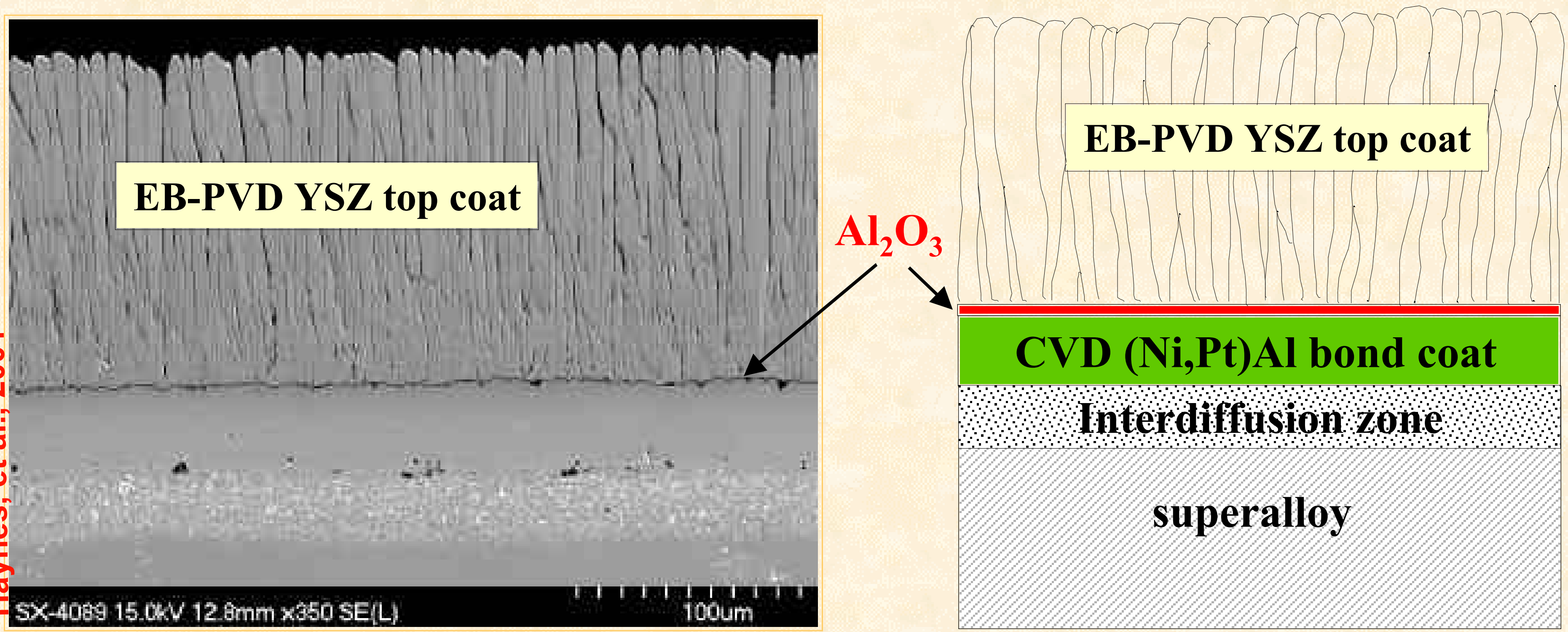


- Y_2O_3-ZrO_2 (YSZ) top coat
  - provides thermal insulation
- Metallic bond coat
  - provides oxidation resistance
  - facilitates YSZ adherence
- Interfacial Al_2O_3 scale

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

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

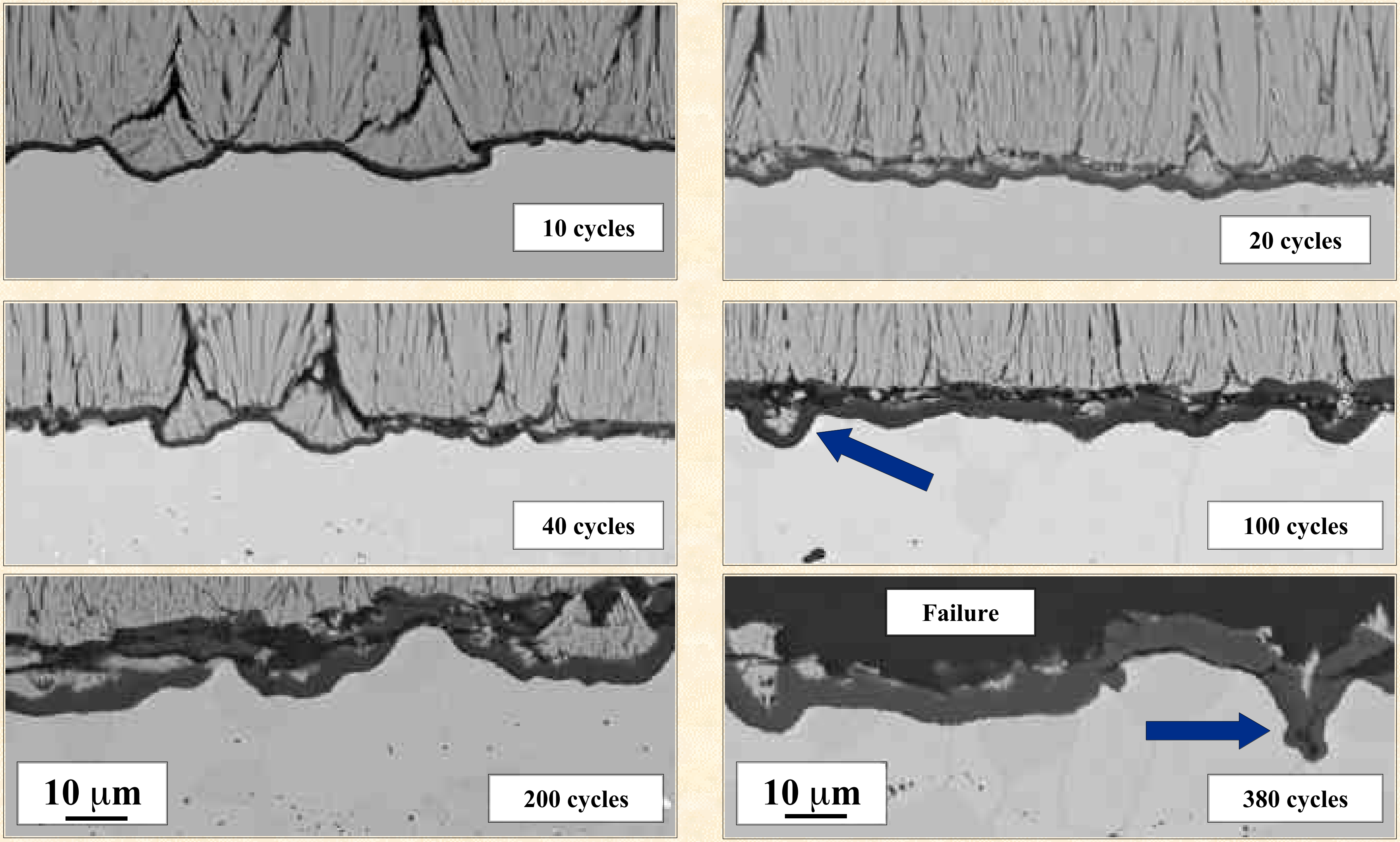
EB-PVD Thermal Barrier Coatings



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

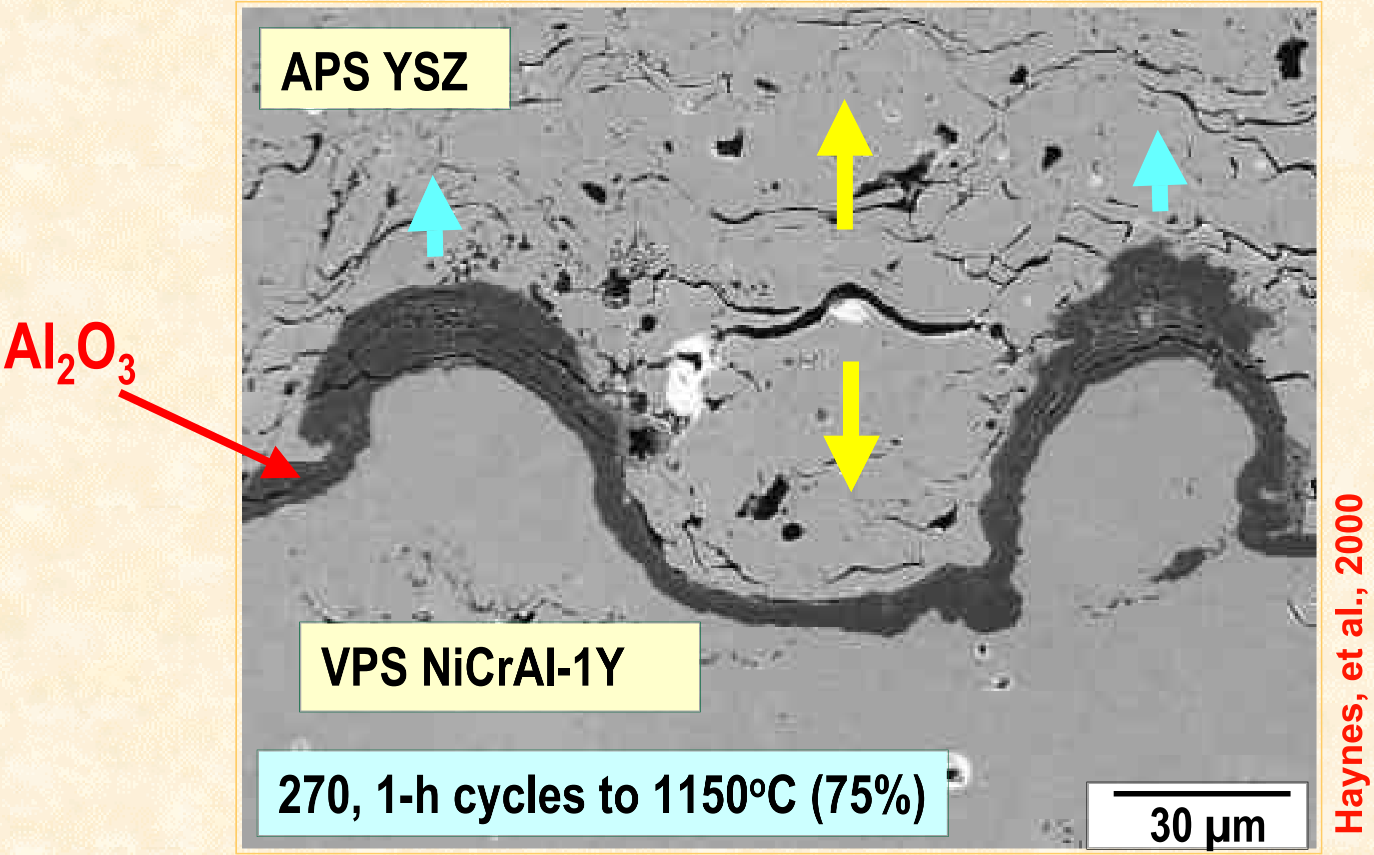
Major TBC Life-Determining Issues

- **TBC application:** ability to apply the specified coating (composition, thickness, structure)
- **Operating temperature:** TBC must provide the design ΔT at design conditions
- **Cyclic operation:** effects on oxidation behavior/coating durability
- **Loss of ceramic:** especially erosion/FOD: local T increase
- **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
  - effect of t at T
- **Microstructure and thickness**
  - complexity of shape ±determines processing route
- **Cost**
  - low infant mortality

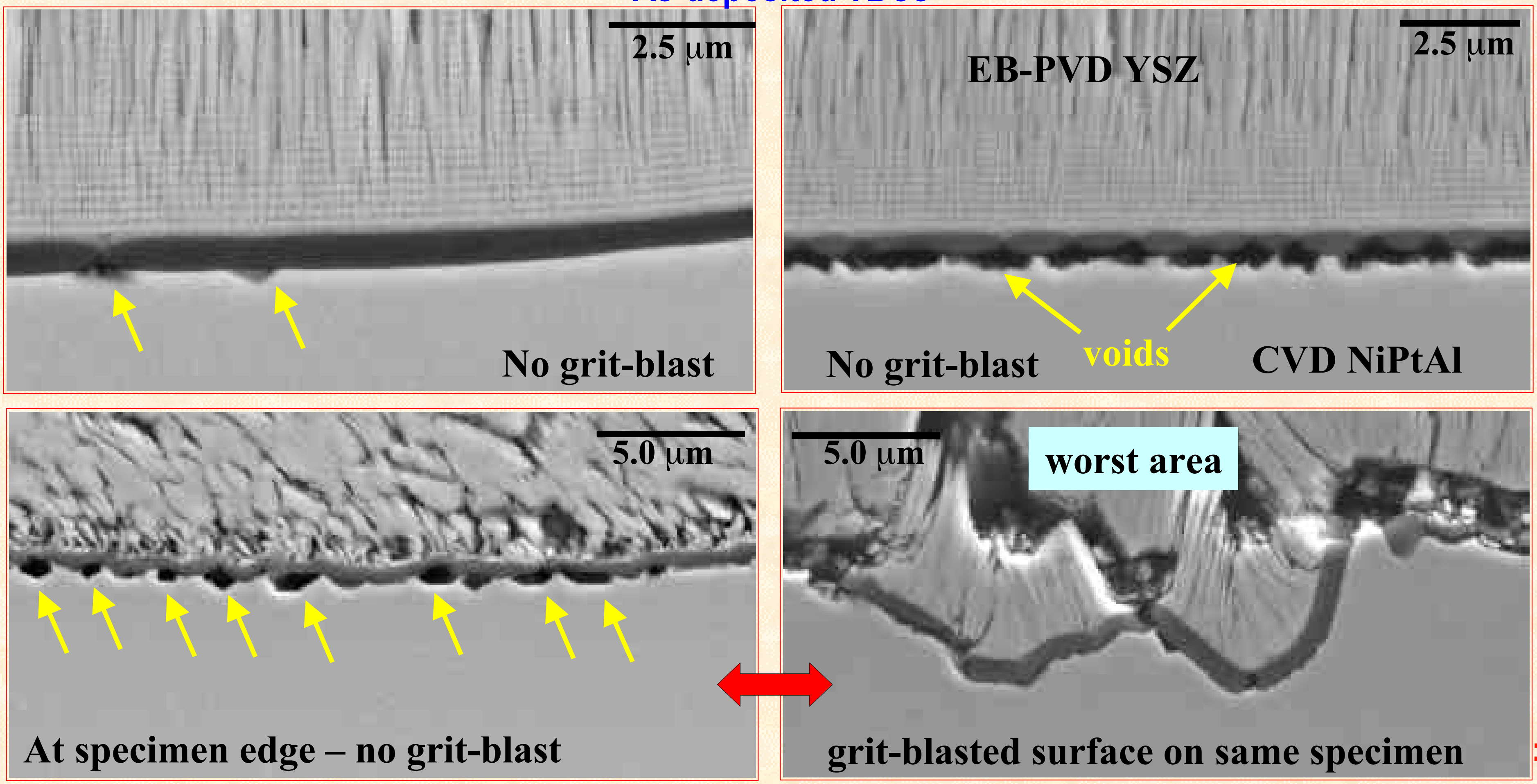
Rough BC surface is an intrinsic feature & problem of PS TBCs



- Evidence of localized oxidation-induced YSZ damage
- Localized Al_2O_3 scale damage very variable—not clear whether it is 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

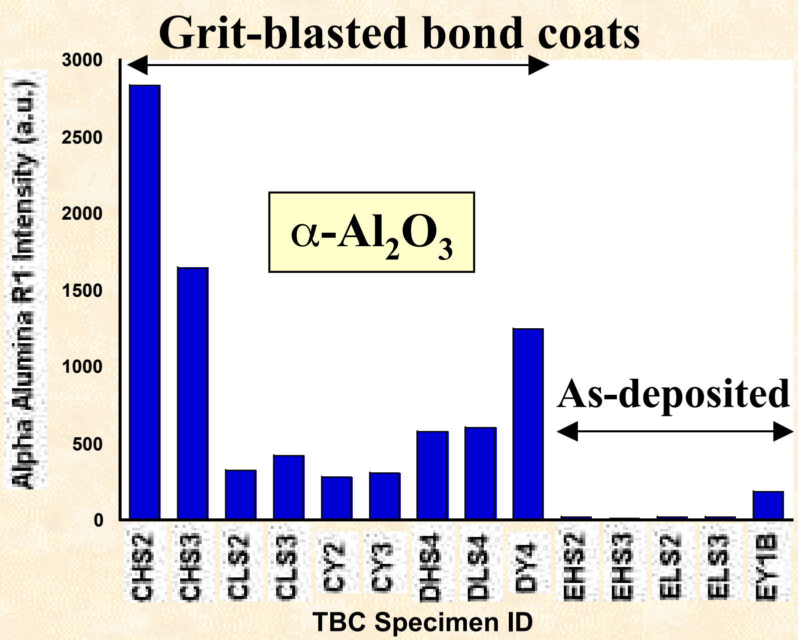
As-deposited TBCs

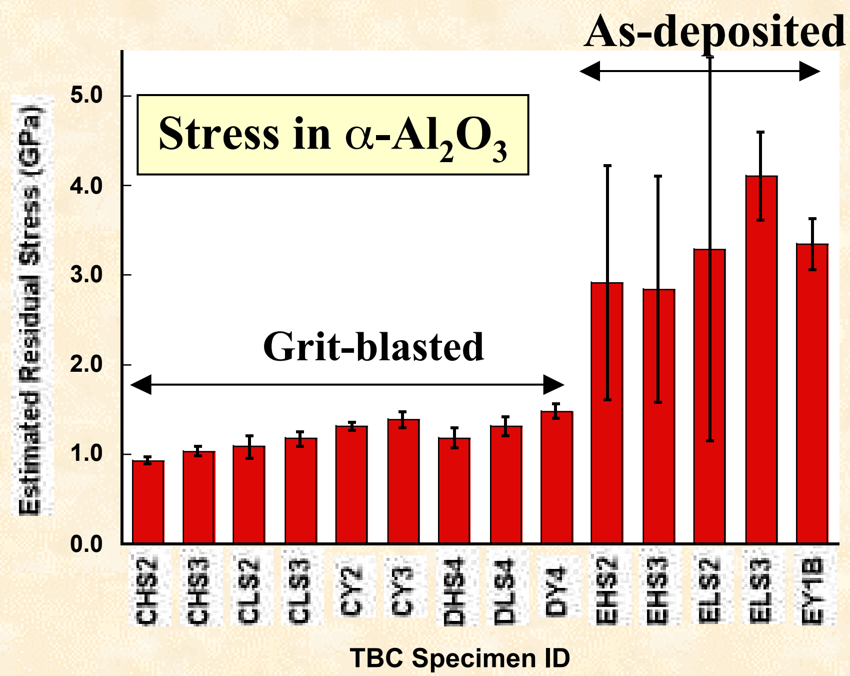


Haynes, et al., 2001

- 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



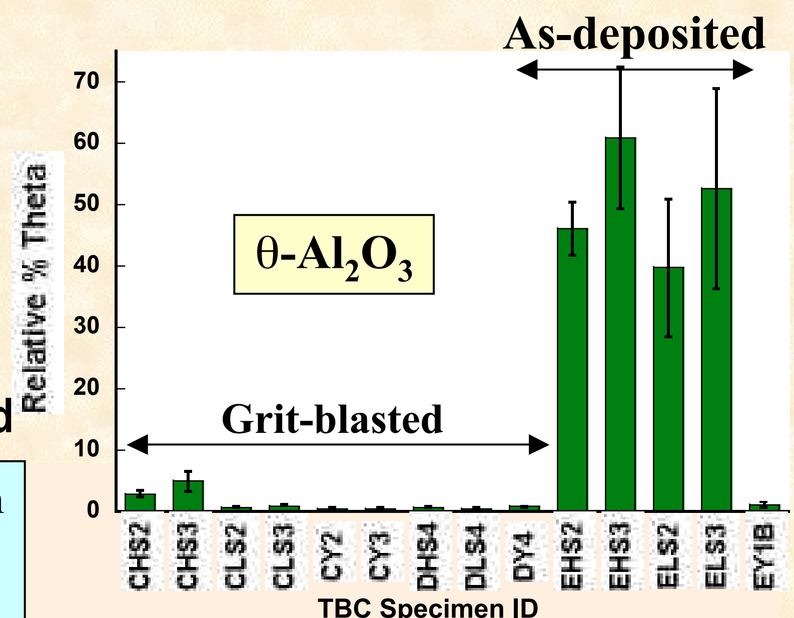


Laser fluorescence of as-deposited EB-PVD TBCs

- 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

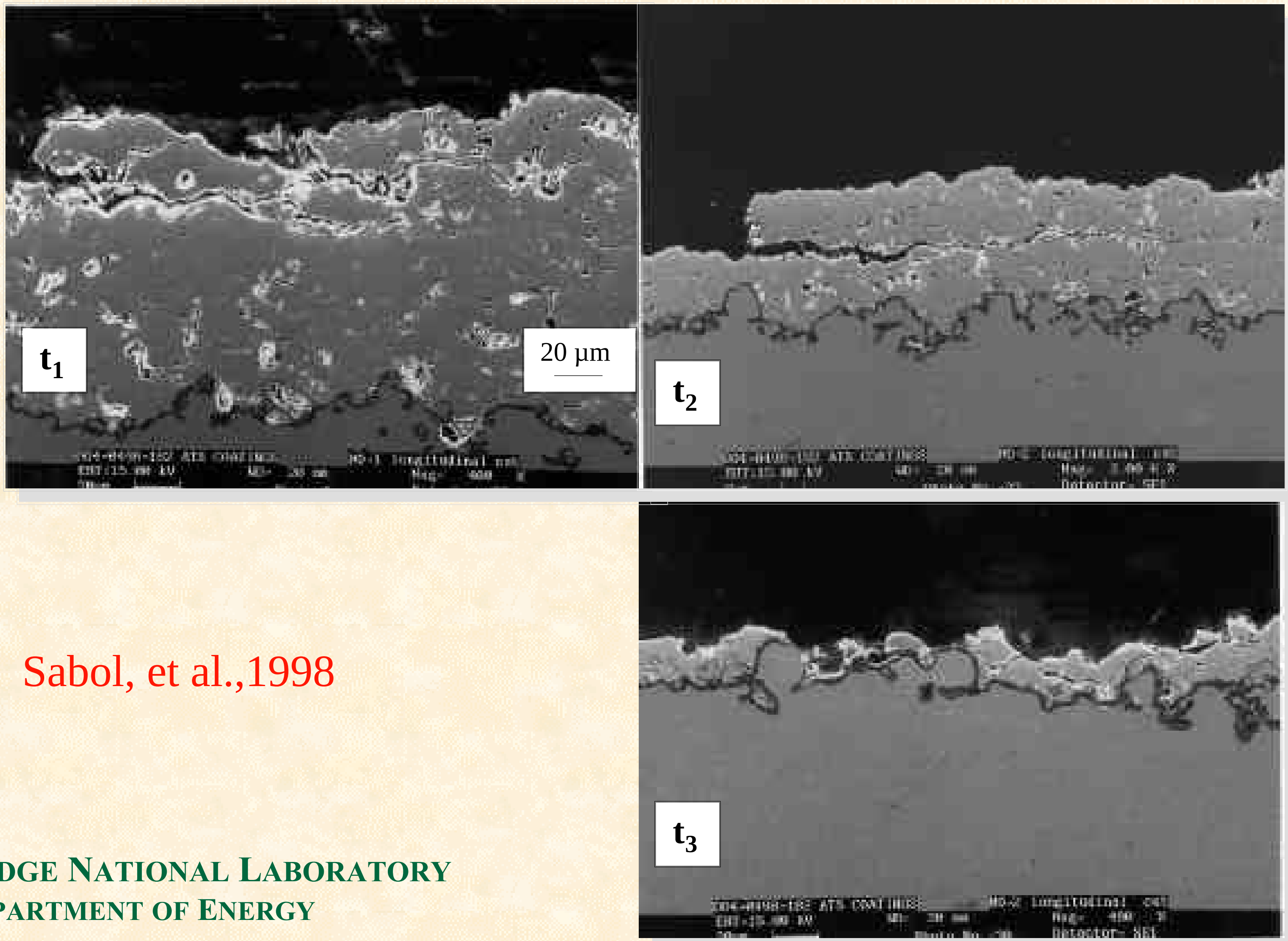


Operating Temperature Issues

Concerned with the effects of time at temperature:

- Effects on the ceramic layer
  - phase change of YSZ
  - sintering of ceramic surface
    - can it occur?
    - 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

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



Sabol, et al.,1998

Operating Temperature Issues

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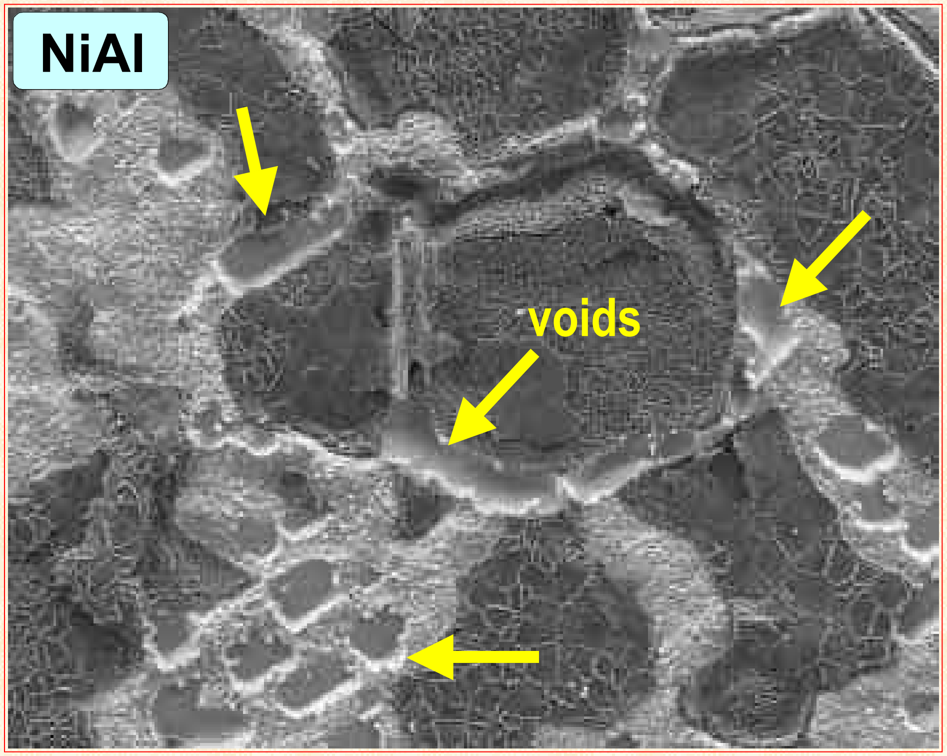
Factors Affecting BC Oxide Thickness

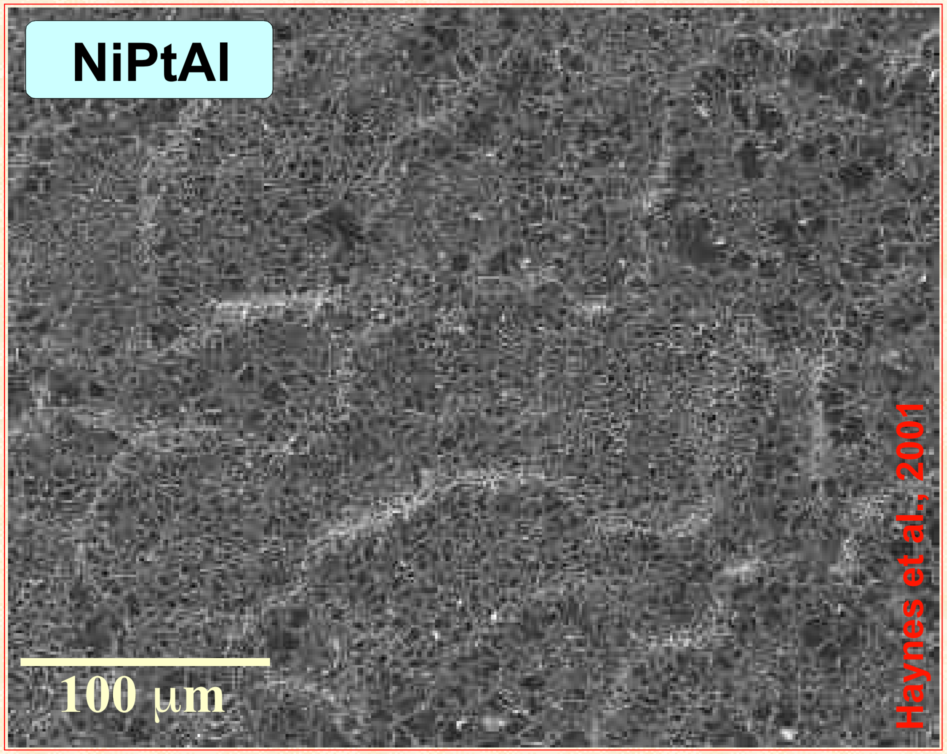
- Increasing oxide thickness equates to:
  - *increased stress generation*
    - increased tendency for scale spallation
  - *increased consumption of Al reservoir*
    - loss of β-phase in BC (lower-Al phases do not form the desired oxide)
    - approach to non-protective oxidation (voluminous scales)
    - 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 (control of initial oxidation stages; Pt effects)*
  - *controlled addition of a reactive element (Y, Hf, …)*
    - MCrAlYs
    - aluminides
- Resistance to scale spallation can be improved by:
  - *removal of alloy/BC tramp S to <<1 ppm*
  - *Pt additions*
  - *RE additions*
  - *reducing the CTE mismatch*

'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)



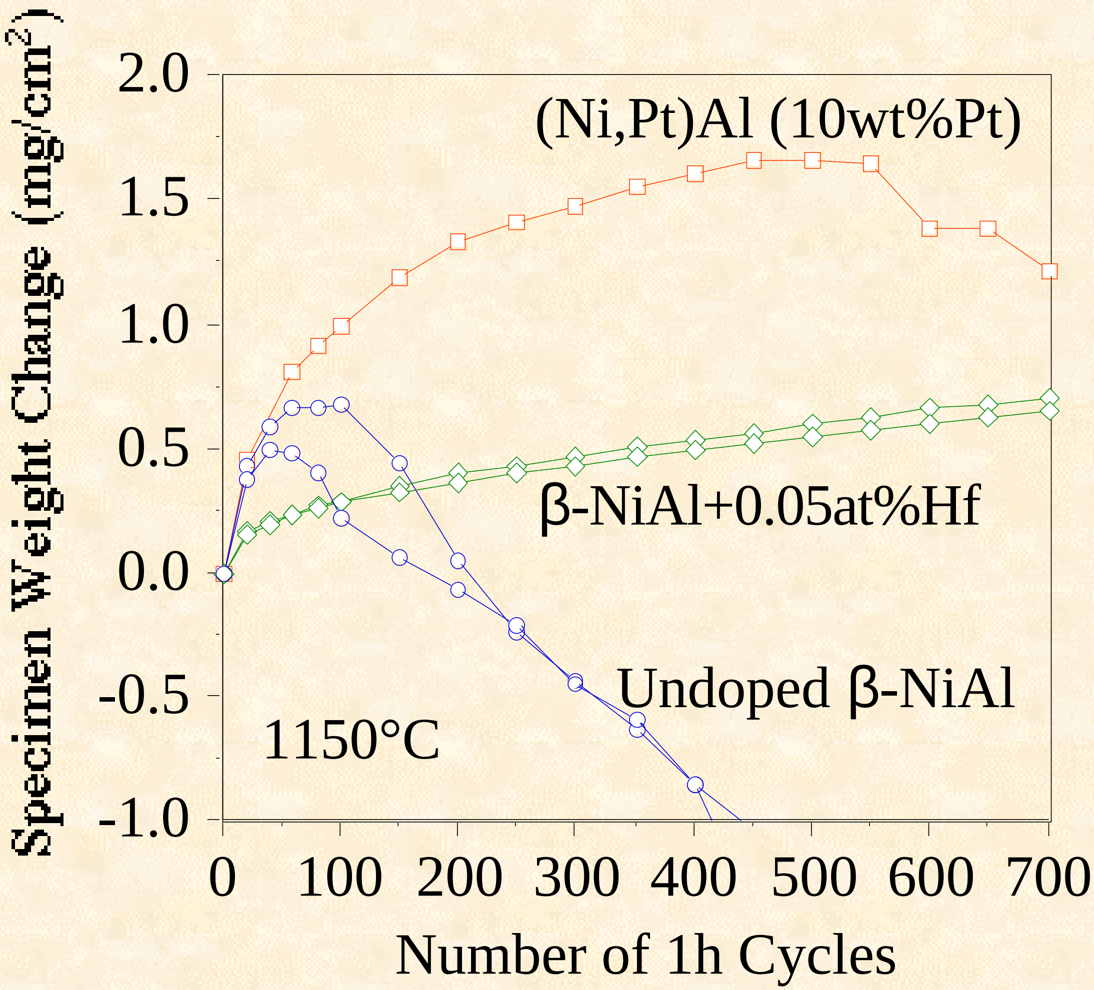
NiAl on High-S Rene N5



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)

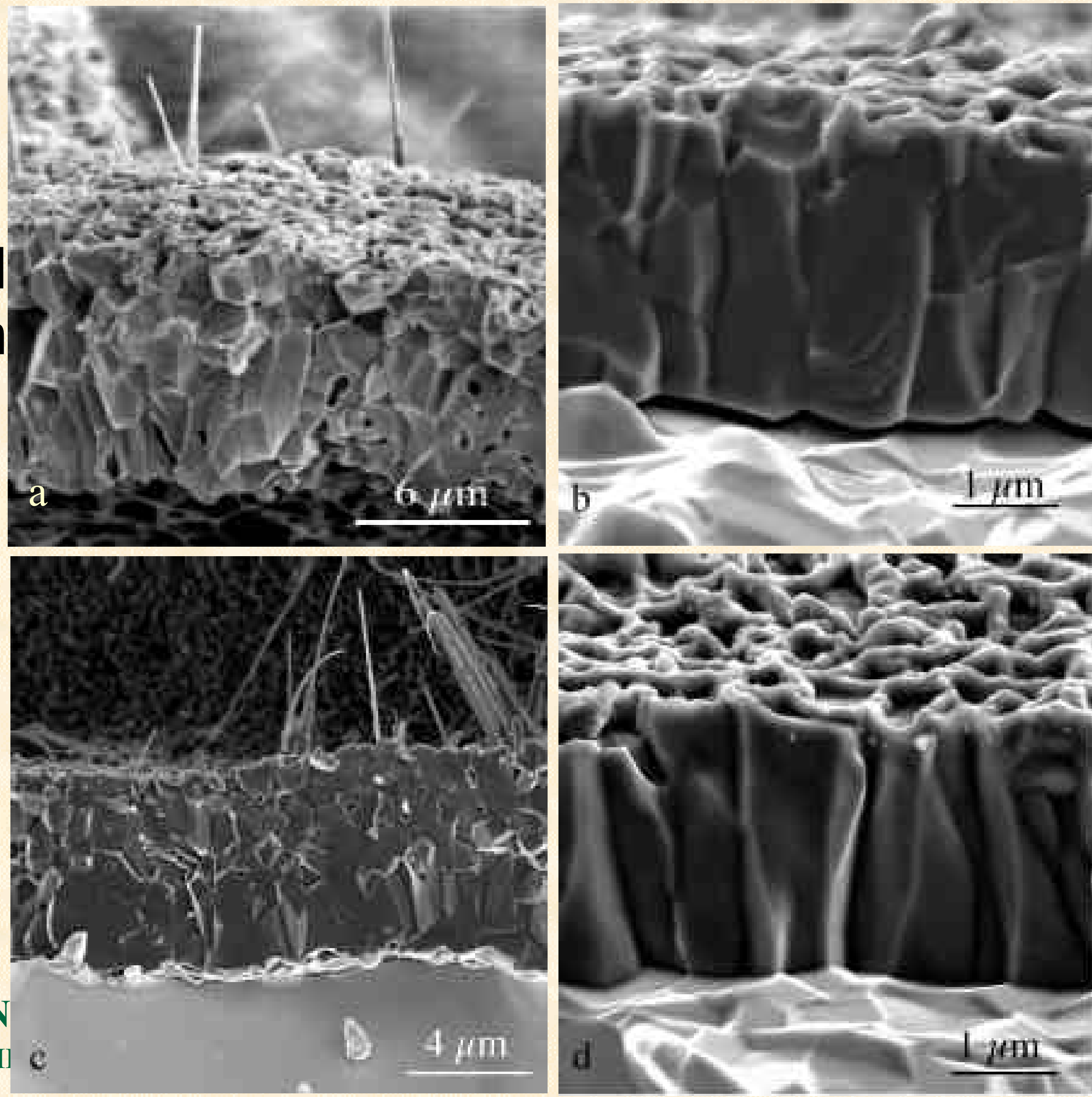
RE additions modify scale morphology and reduce growth rate; Pt does not (1200°C)

Undoped βNiAl, 200h

βNiAl+Hf, 100h

PtAl, 100h

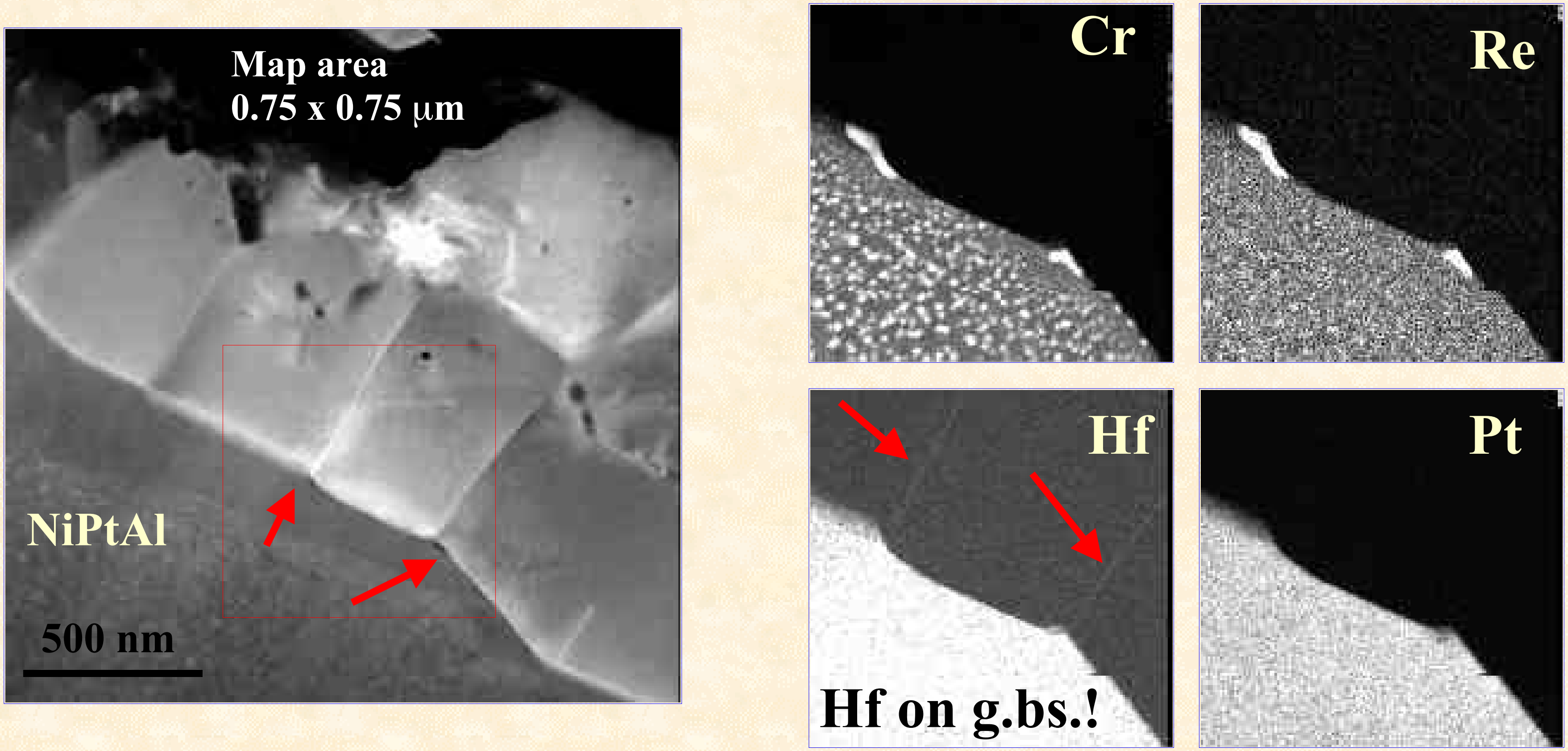
NiPtAl+Hf, 100h



Pint et al., 1998

STEM/EDS Mapping of Alumina Scales on (NiPt)Al

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

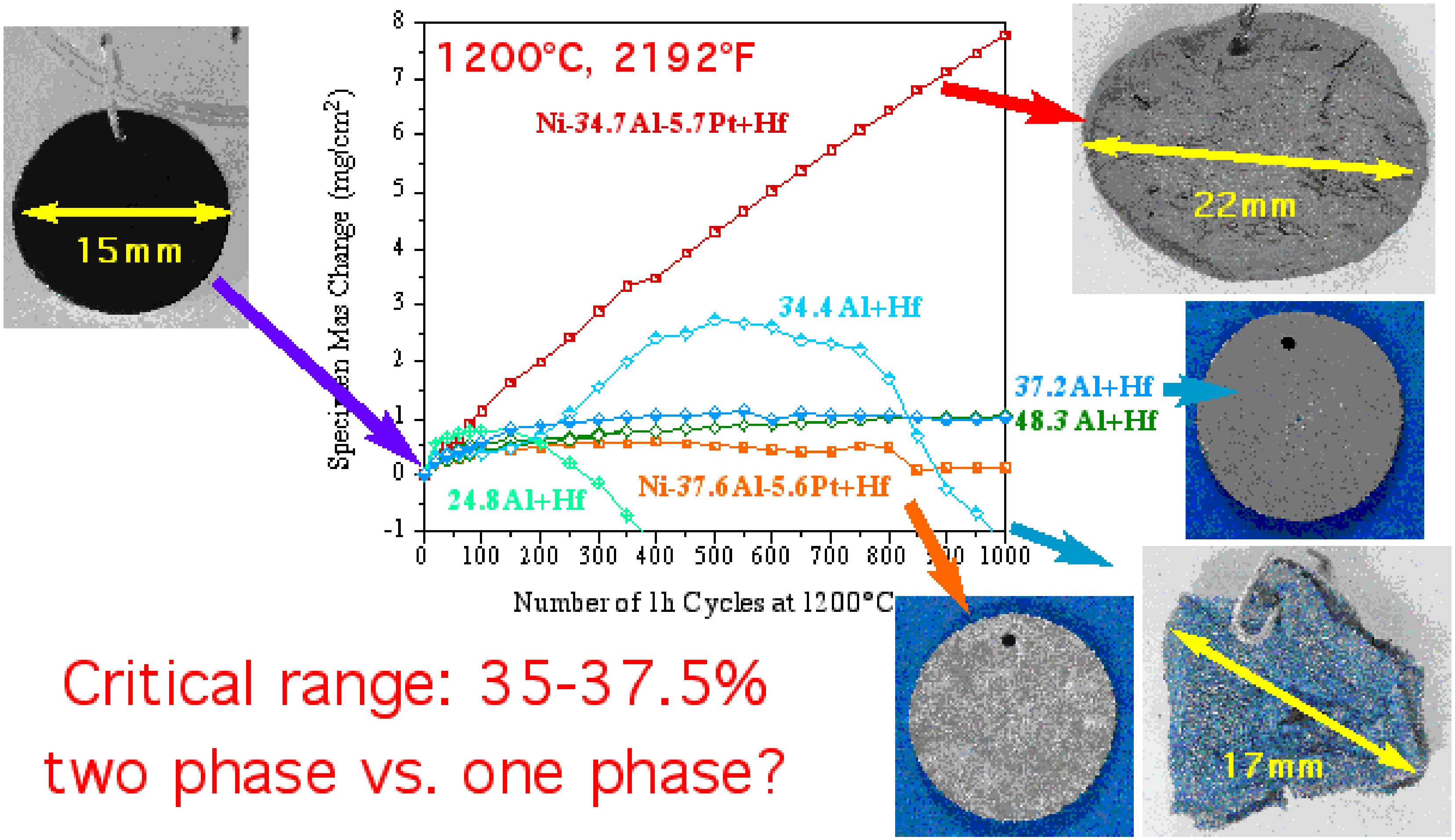
- **Concern over loss of Al reservoir**
  - minimum Al level for maintaining α-Al_2O_3
  - Pt beneficial (stabilizes β-phase?)

- **Ingress of other elements** is typically detrimental to the protective nature of the oxide scale
  - Ti, Cr, Re…
  - Hf: from good to bad, i.e. both under-doping and overdoping are detrimental

- **NiAl BC phase change as Al is consumed**
  - critical range appears to be 35-37.5 at% Al
  - at RT: γ' + β; at 1100°C: one phase (β?)
  - effects of Al (and Pt) 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%

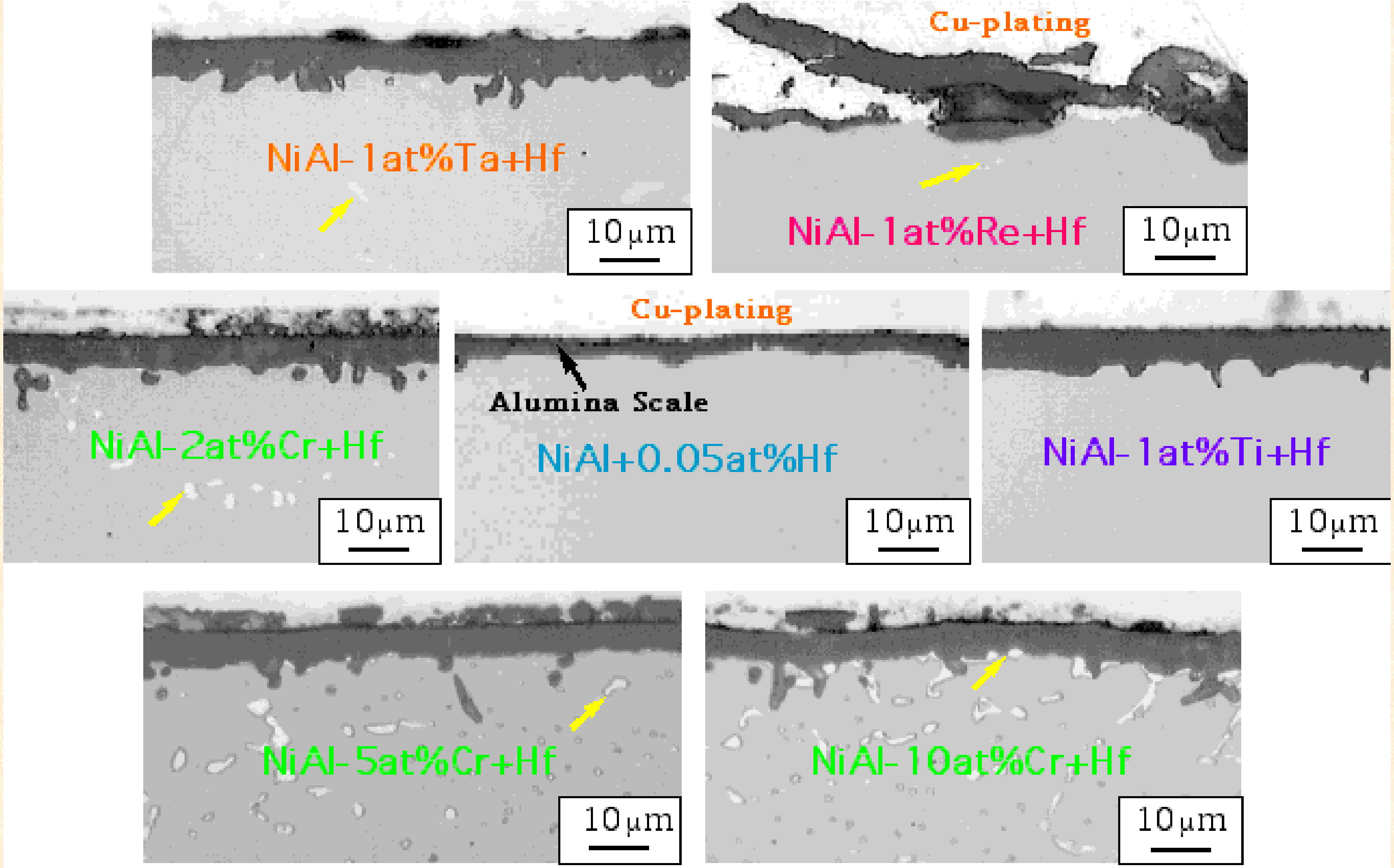
two phase vs. one phase?

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

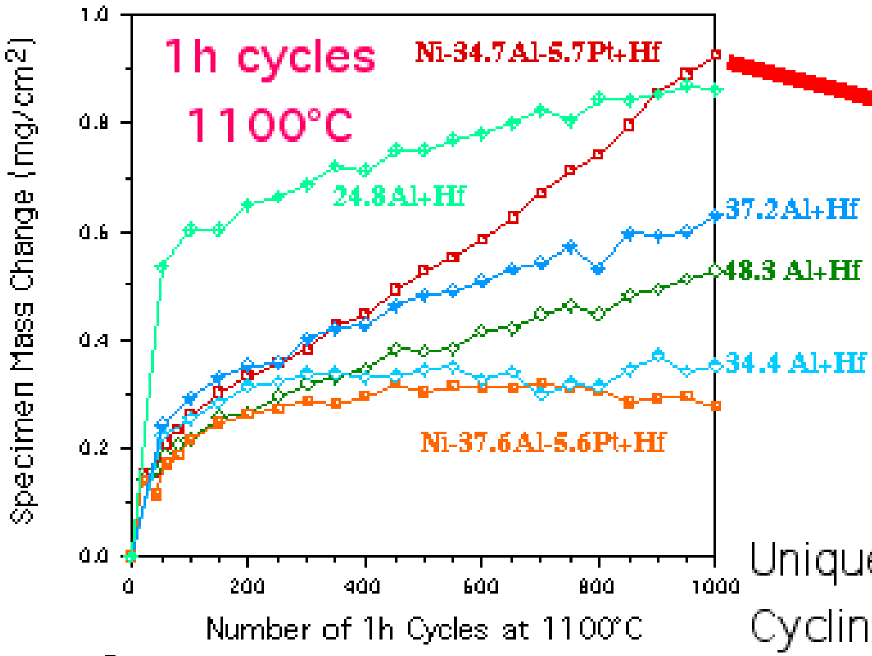
All additions accelerate scale growth rate compared to NiAl+Hf

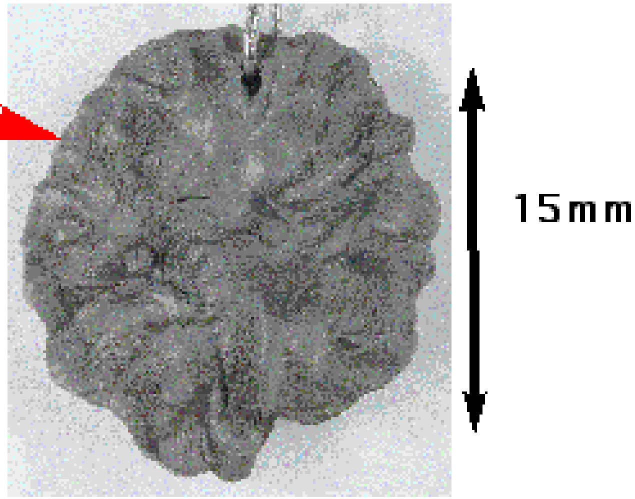
Problems with scale adhesion with Cr and Re -> precipitates

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
- How detrimental is thermal cycling?
  - 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

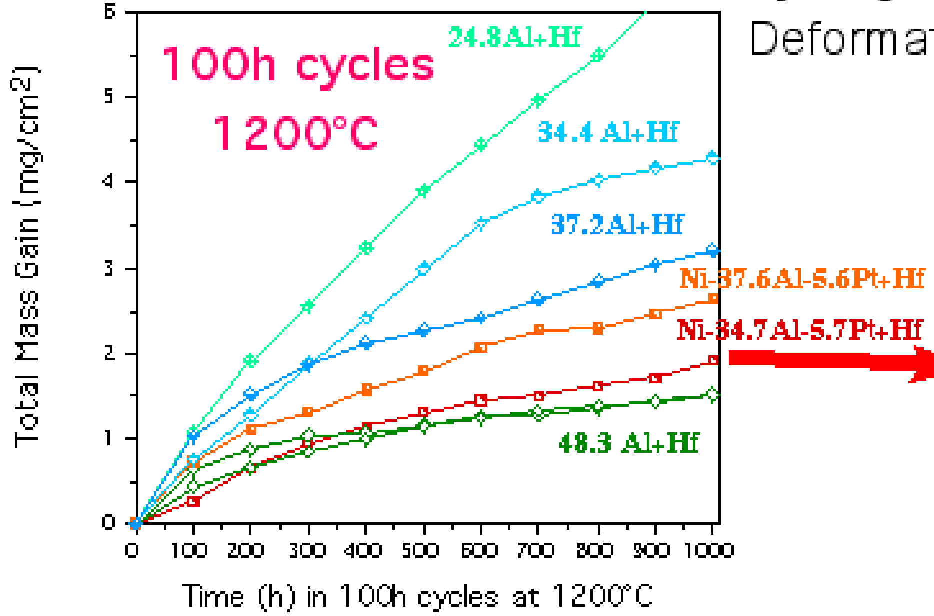


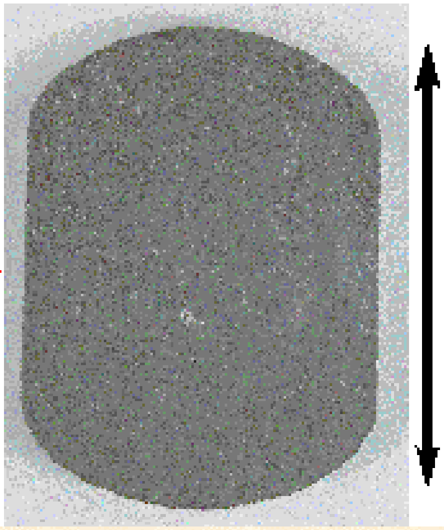


Unique behavior of Ni-34.7Al-5.7Pt+Hf

Cycling causes repeated phase change

Deformation similar to aluminide coatings!



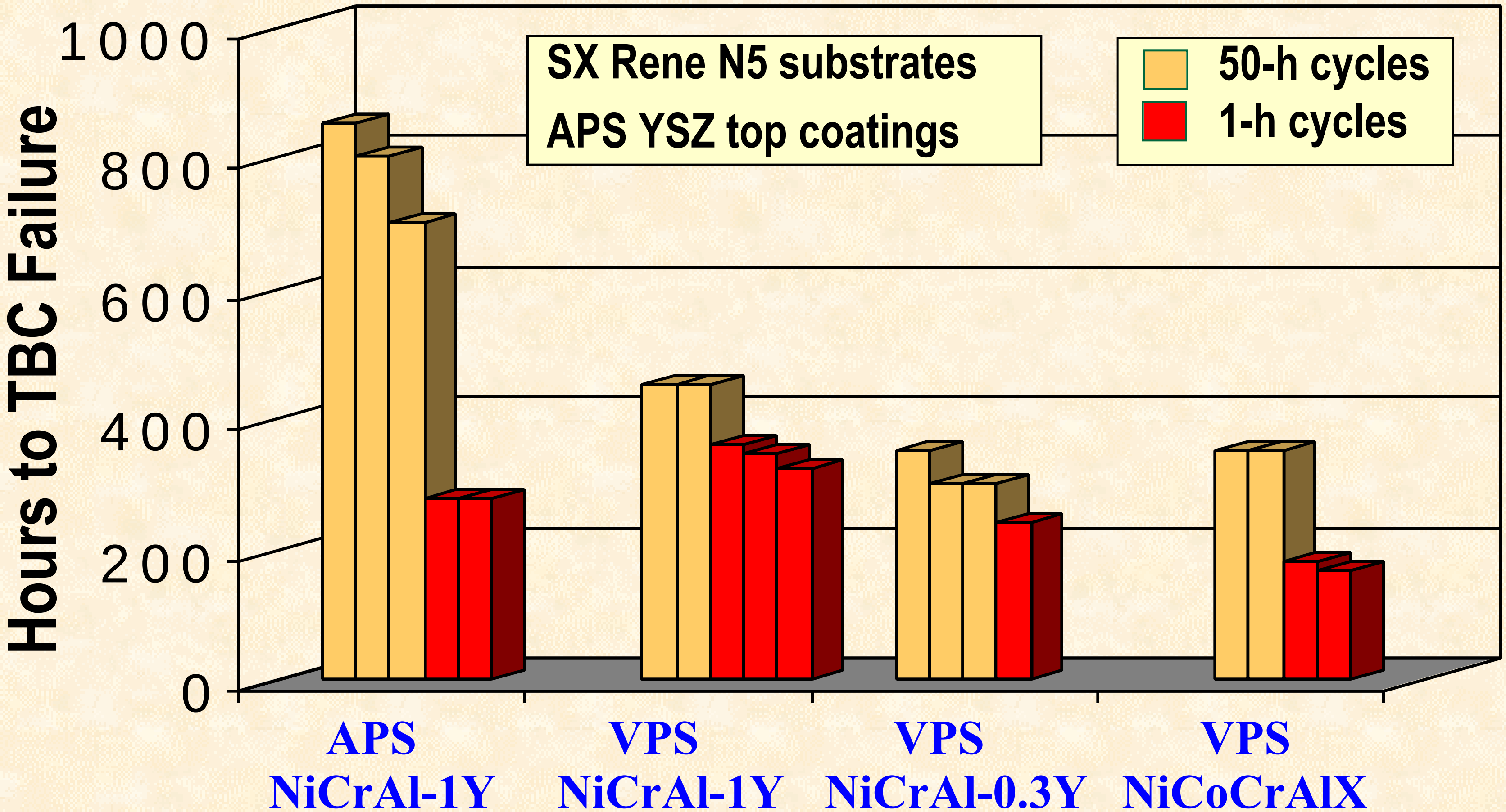


sides
ground to
fit in
crucible

15mm

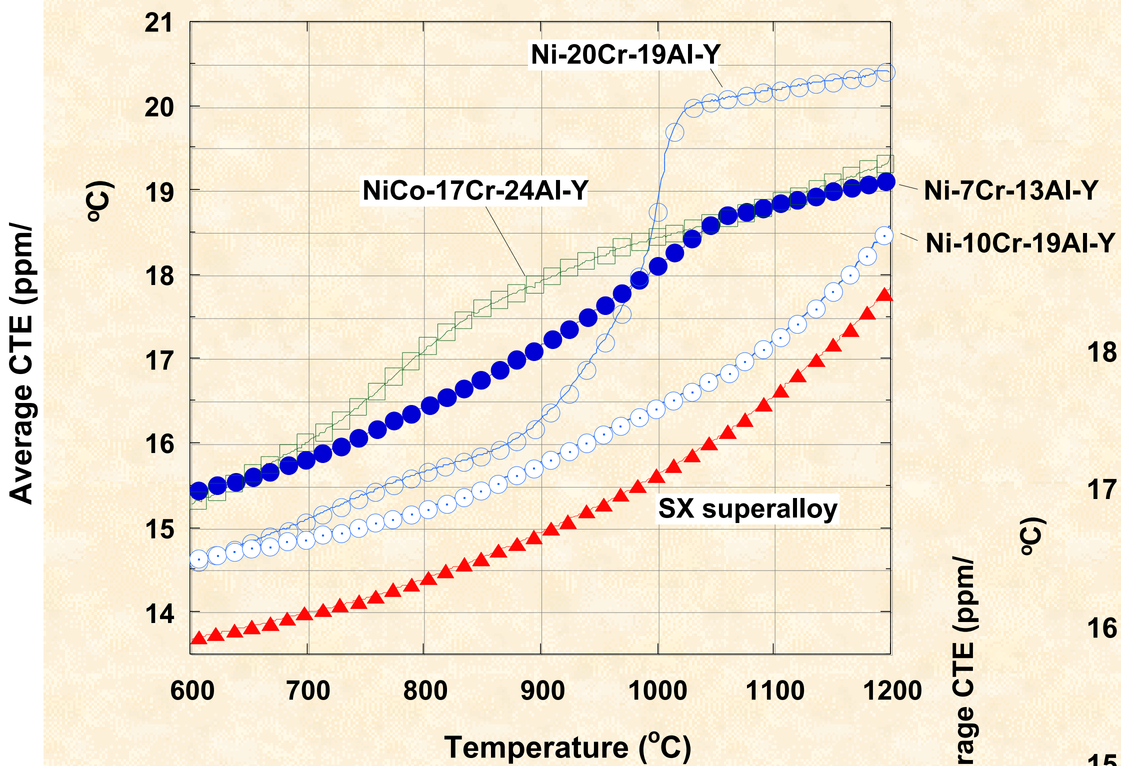
Pint, et al., 2001

TBC lifetimes are influenced by the length of thermal cycles



- For PS TBCs: lifetimes longer for longer cycles (at 1150°C)
- Suggests MCrAlX CTE more dominant than oxidation-related factors?

CTE of NiCrAl > aluminide BC alloys

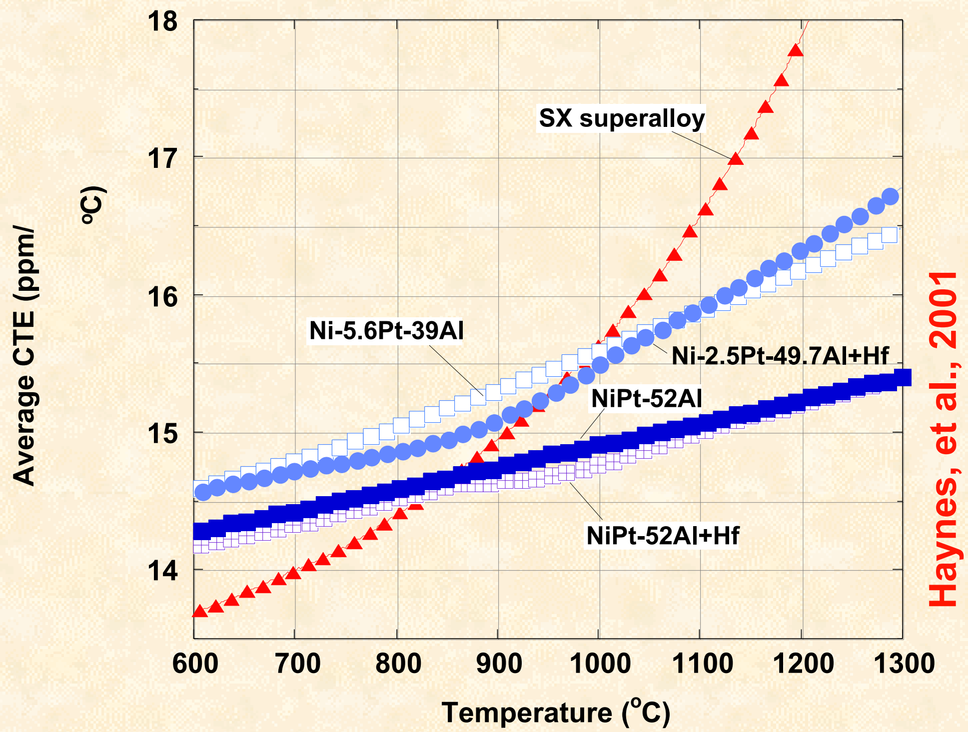


MCrAlYs: CTE > SC Superalloy

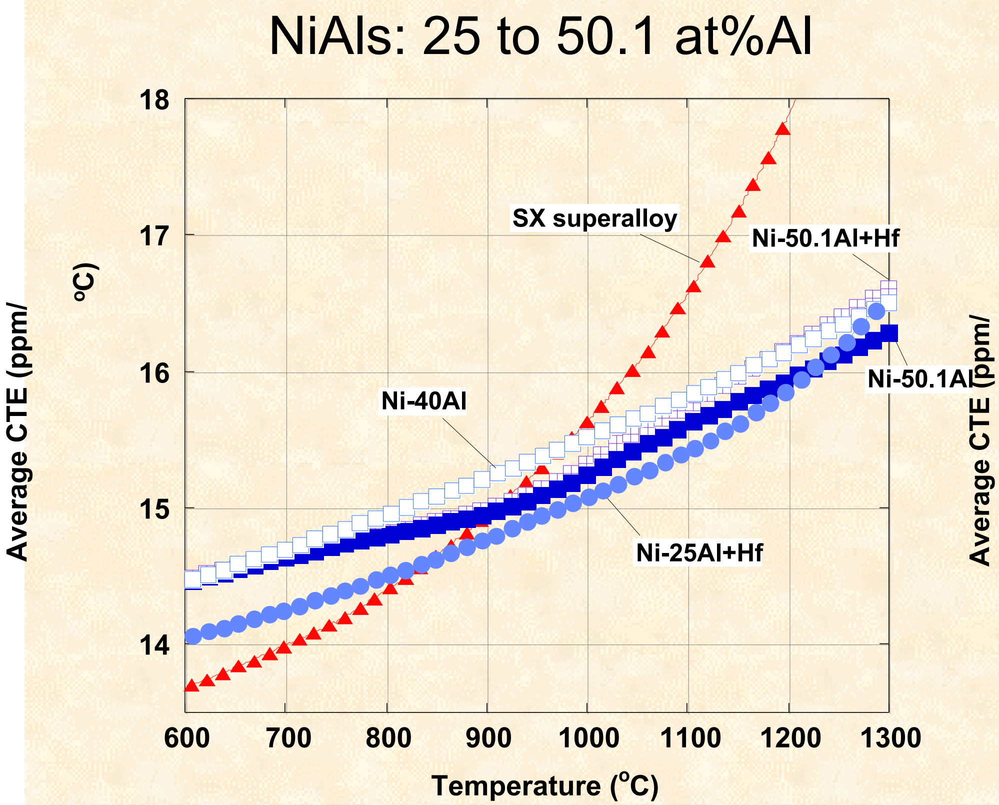
- BC in compression during heat-up
- compressive creep at T?
- in tension during cooling

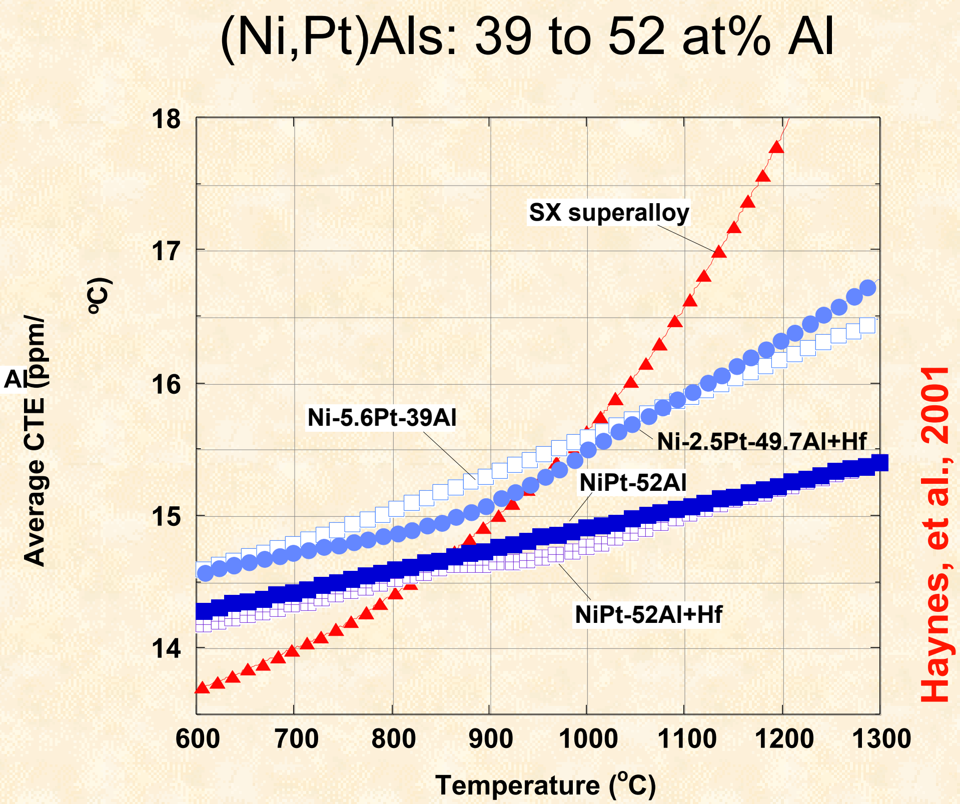
(Ni,Pt)Als: CTE straddles that of the SC superalloy

- compression to tension during heating
- tensile creep at T?
- on cooling, into compression then tension



Pt lowers CTE of of Al-rich aluminide BC alloys





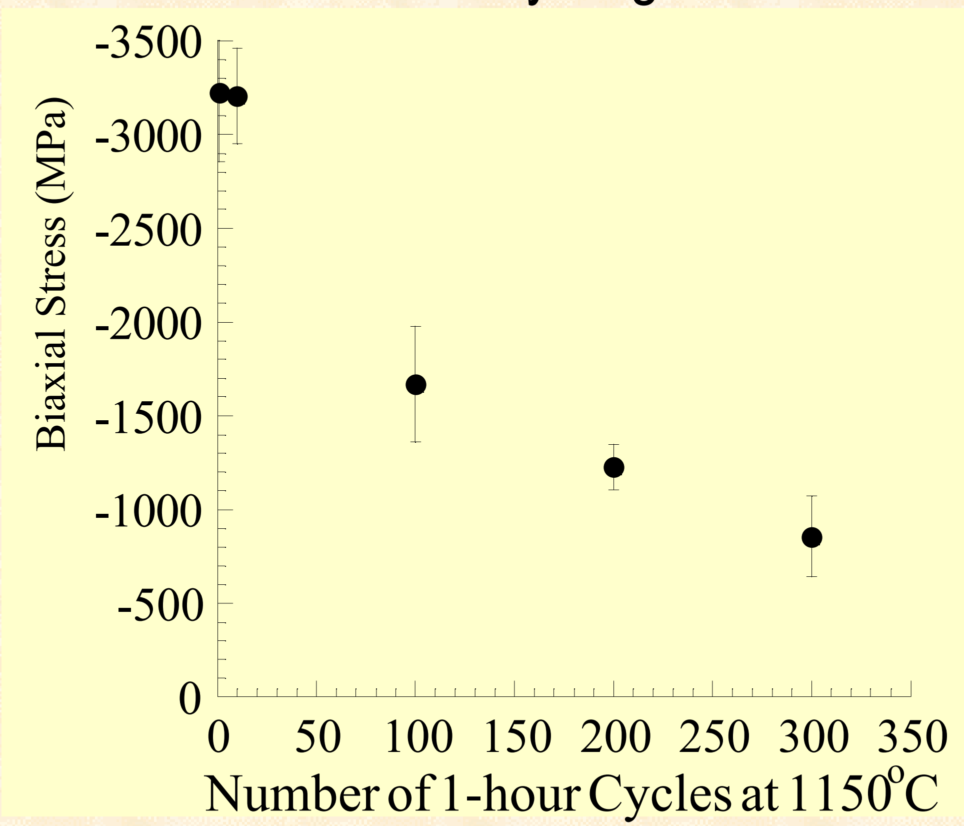
- Pt reduces CTE for Al-rich (Ni,Pt)Al alloys, but ±no effect for lower (relevant) Al contents
- No great difference in ΔCTE with superalloy that would suggest positive effects for scale adherence

Does CTE correlate directly with oxidation life?

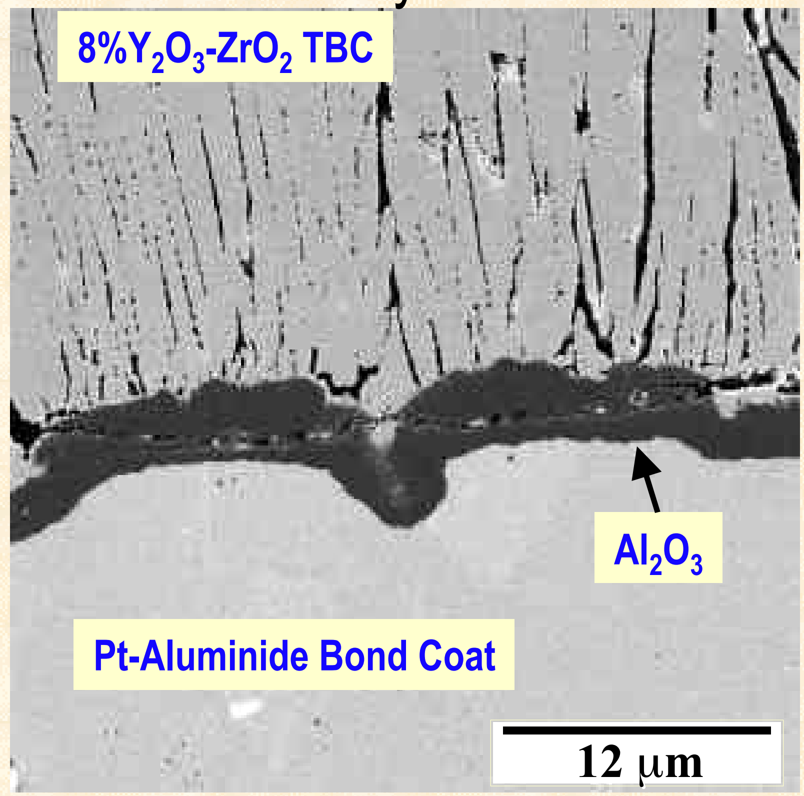
- Comparisons are complicated by other influences:
  - RE doping (optimized vs nominal)
  - substrate strength
- Our data show:
  - Ni-7Cr-13Al: lifetime of 100 h in 1-h cycles at 1150°C (ΔCTE vs Al_2O_3 = 10.2 ppm°C^{-1})
  - Ni-7Cr-13Al+Y (same ΔCTE): lifetime of 625 h
  - René N5 (optimized RE, stronger, ΔCTE = 7.1): lifetime of 1,000 h
  - NiAl+Hf, Ni(Pt,Al)+Hf (ΔCTE = 5.9-6.0): lifetime ≈10,000h, but
  - Ni_3Al+Hf; $Ni_3Al+Y_2O_3$ (lower Al, ΔCTE = 5.5): ≈820 and 250h, resp^y
- Maybe RE > CTE > substrate strength? But it is difficult to separate the interactions…

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

How can understanding of oxidation behavior contribute to TBC condition monitoring?

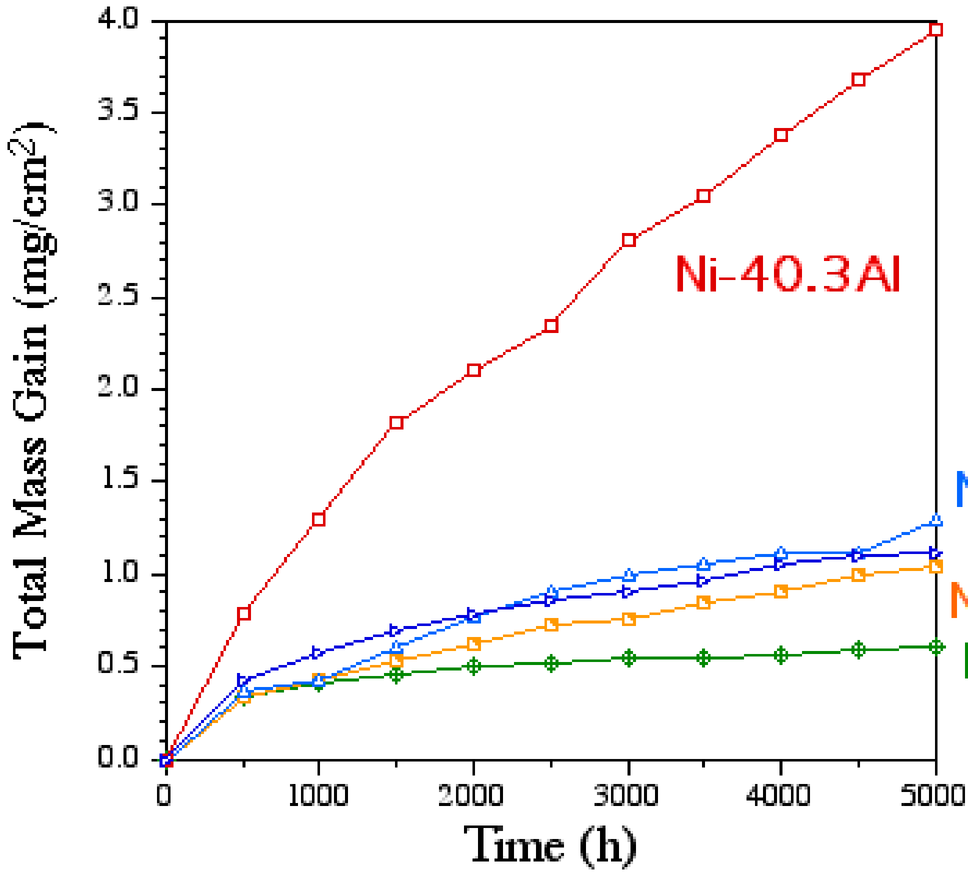
- IR imaging (Siemens Westinghouse; ORNL)
  - hot spots/debonding
- Laser flash (ANL)
  - oxide-BC interface roughness
  - thermal properties
- PSLS (UCSB; UConn; Howmet; ORNL; NPL and Imperial College, UK; Universita' di Trieste, Italy)
  - stress levels in BC oxide layer
  - phase content of oxide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

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

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

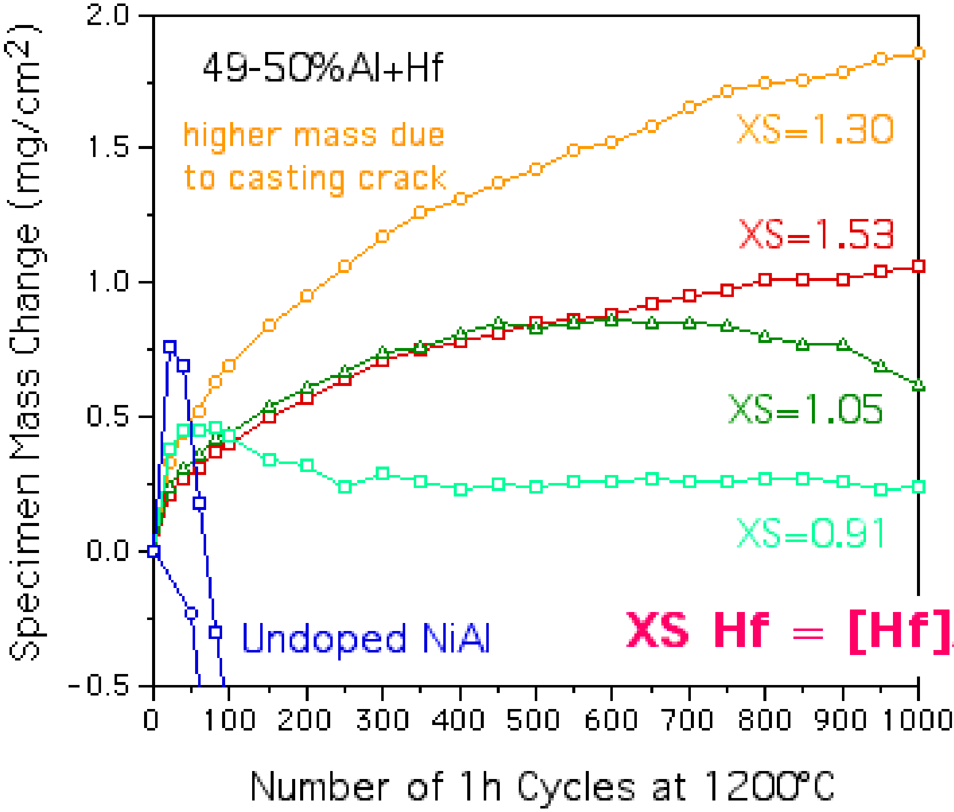
Ni-40.3Al - spinel formation increased total mass + some spallation

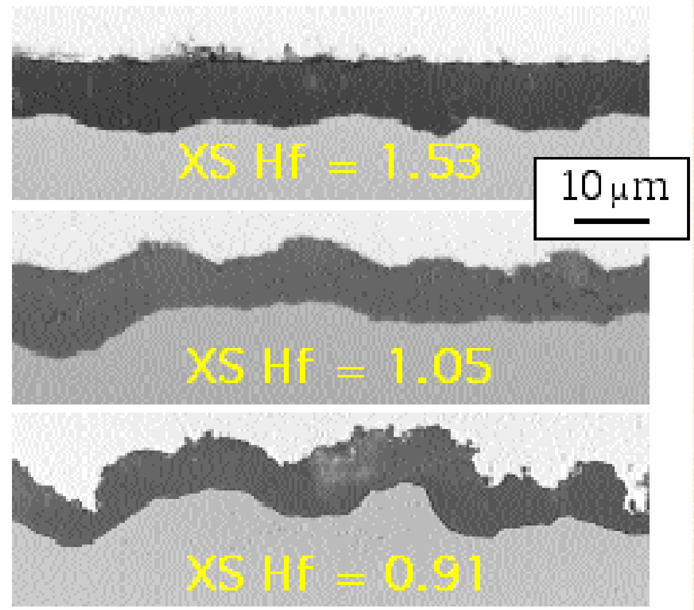
Ni-38.7Al-5.6Pt(20wt%) - better selective oxidation, i.e. no spallation

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