Coating Issues in Coal-Derived Synthesis Gas/Hydrogen-Fired Turbines

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Acknowledgments

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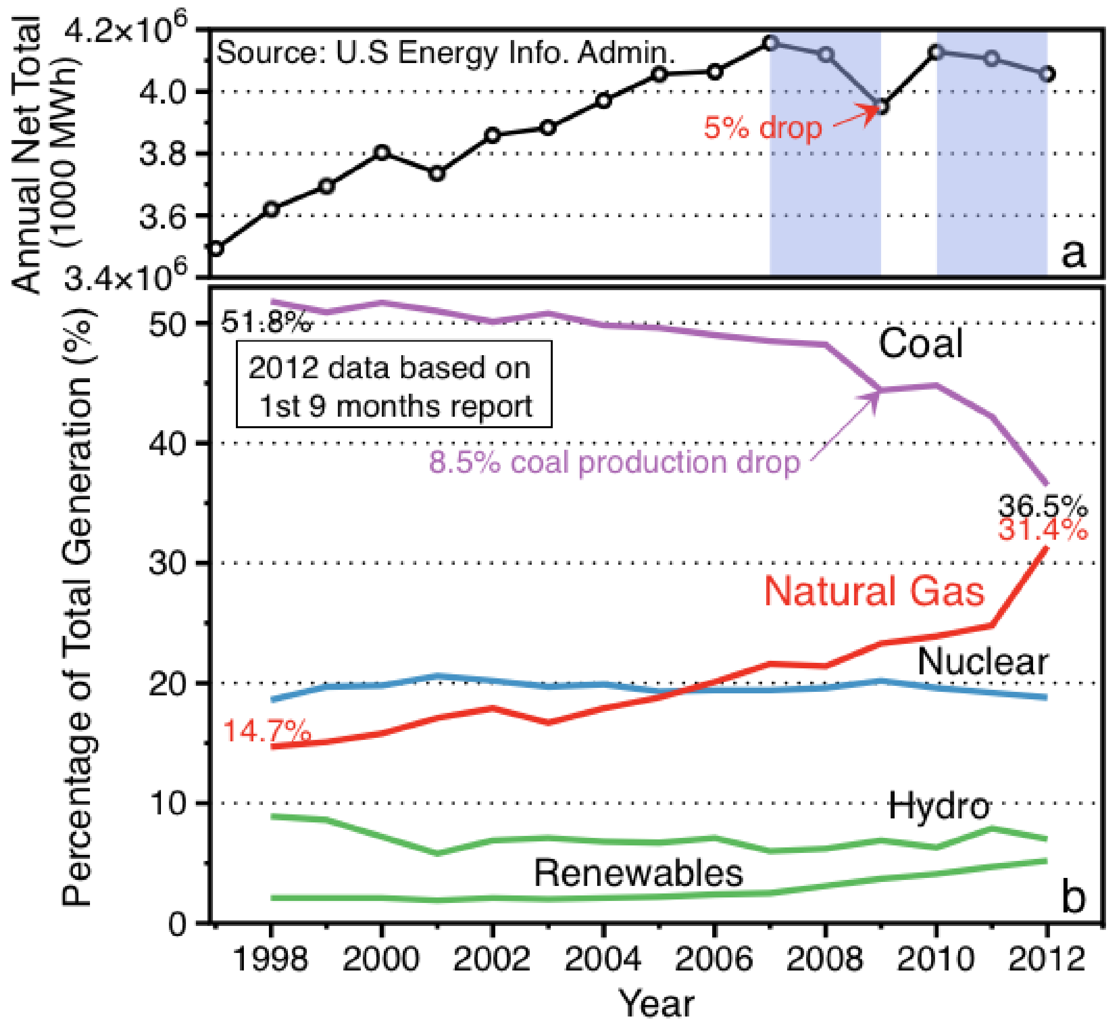
M. Lance - PSLS, 3D LM
G. Garner, M. Stephens - oxidation experiments
T. Lowe - characterization
D. W. Coffey - TEM specimen preparation, FIB
T. Jordan - metallography
D. Leonard - EPMA

George Garner

Ken Murphy, Howmet - X4 superalloy substrates
Anand Kulkarni, Siemens - 1483 superalloy substrates
Dan Vicario, Capstone Turbines - 247 superalloy substrates
Jacqui Wahl, Cannon-Muskegon - CMSX7,X8 substrates
Ben Nagaraj, GEAE - N515 alloy, YSZ deposition
S. Sampath, Stonybrook U. - HVOF, APS coatings

Research sponsored by: U. S. Department of Energy, Office of Coal and Power R&D, Office of Fossil Energy

How does coal compete?



Demand not growing

NGCC + Renewables increasing

In a stagnant U.S. market where natural gas is cheap?

Is coal gasification the solution?

Integrated gasification combined cycle (IGCC)

- similar turbine/steam generator as NGCC
- method to control NO_x,SO_x, Hg, CO_2...
- two full size IGCC plants coming on line in the US

Edwardsport, IN (Duke Energy)
$2.88 billion (Carbon capture ready)
618MW, GE Energy turbines, 2013 start

Kemper County, MS (Southern Co.)
$2.67 billion, ~60% CO_2 capture (oil recovery)
550MW, Siemens turbines, 2015 start

The U.S. will find out.

What are the issues with IGCC?

#1 IGCC "syngas" turbines are "de-rated"

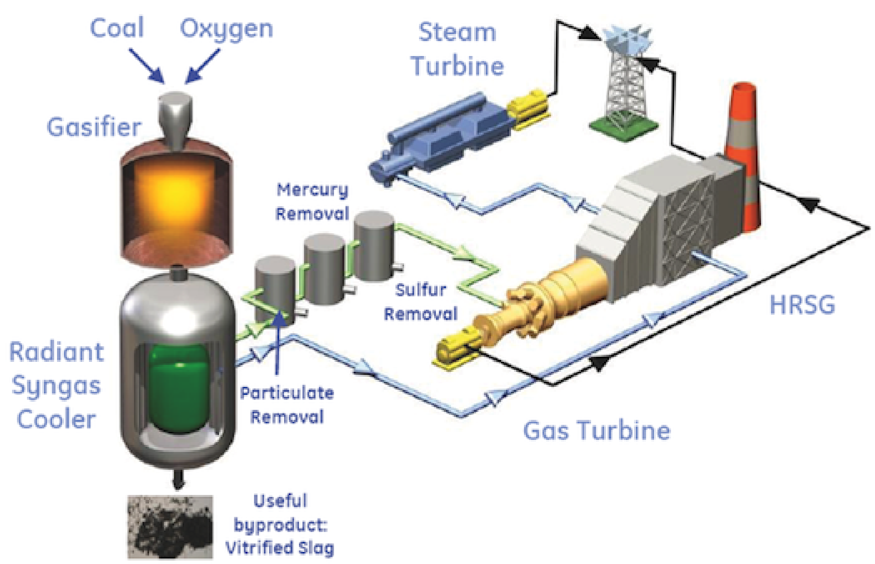
Need to understand what drives that decision

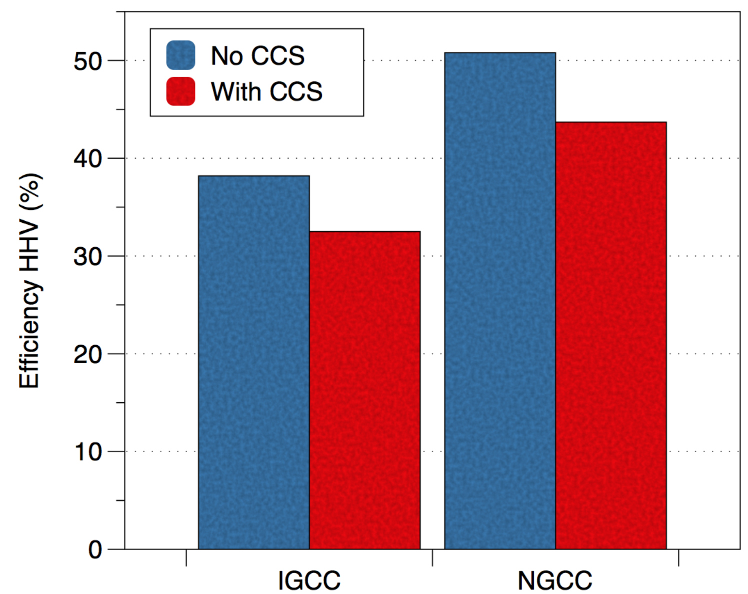
- higher H_2O, sulfur and/or ash from coal?

5-10X more fuel (syngas lower caloric value)

Current ORNL focus: more durable coatings

- potential IGCC and NGCC benefit





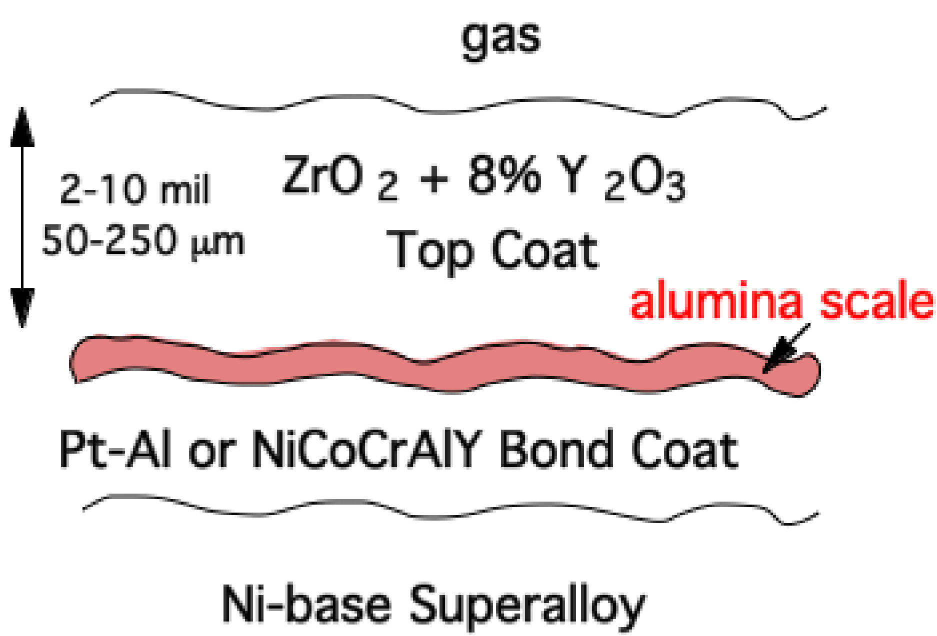
Looking for coating solutions

New environments (higher H_2O, CO_2, SO_2)

CTSR: new top coat

New bond coatings?

Different substrates



#1 More durable coatings will benefit IGCC and NGCC

#2 Focus on alumina scale as "weak link"

Outline

FY10 (initiated 3 related "pre-competitive" tasks)

Task 1: superalloy ppm Y, La dopant effects

Task 2: water vapor effects "Wet vs. Wetter"

Task 3: characterization

FY14

Task 1: Superalloy effects (Cr, Re, Hf, Ti...)

Task 2: Environment effects (H_2O, CO_2, SO_2)

Task 3: Characterization

- supports other tasks

Task 4: New compositions and processes

- B-doped bond coating

FY15

Future directions

- Partnership with Stonybrook

Several TBC groups investigated

(3 YSZ samples per condition + 1 without YSZ)

Group	Alloy	Bond coating	Top coating	Comment
	N5	Diffusion β/γ+γ’	EB-PVD	“quick start”
1	X4±RE	HVOF Y±Hf	APS	RE/H_2O effect
	N5/N515	Diffusion β/γ+γ’	EB-PVD	repeat/low Re
2	1483/X4	HVOF YHfSi	APS	rougher,1483
3	247/83/X4	HVOF YHfSi	CTSR APS	add 247
4	247	VPS ±B, ±Si	APS	rcvd 10/2014

HVOF: High velocity oxygen fuel (plasma spraying)
EB-PVD: electron-beam physical vapor deposition
APS: Air plasma spraying
N5 - GE SX (single crystal) ~3 wt.%Re; N515 - 1.5%Re
X4/1483/247 - Siemens recommended

Task #1: Superalloy de-evolution

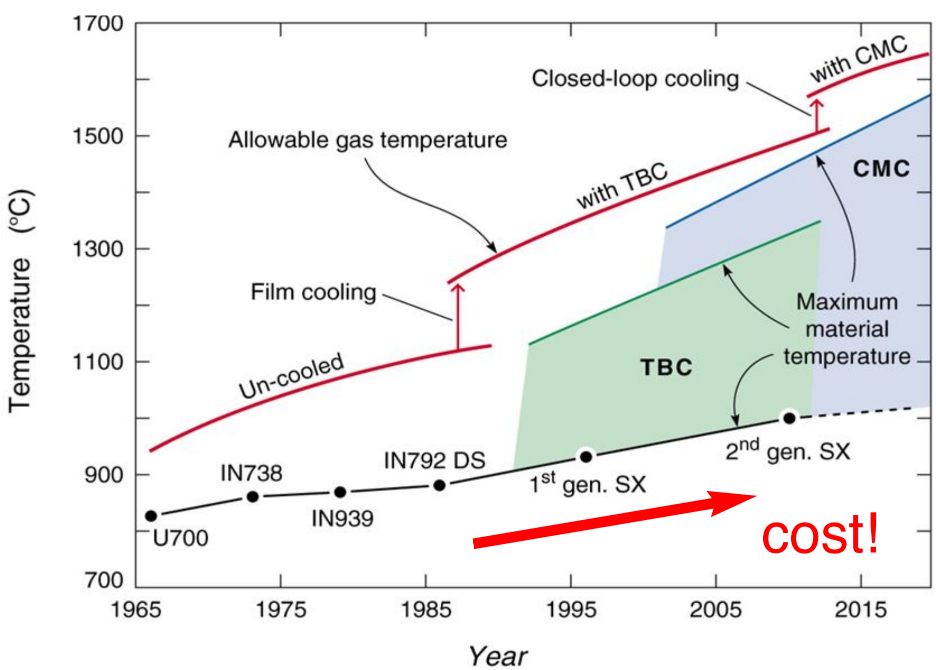
Land-based turbine drivers:

first cost drives sales

temperature/efficiency (not with cheap gas)

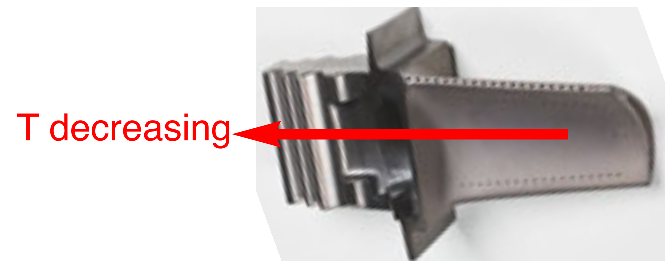
low-k TBC (lowers blade temperature)

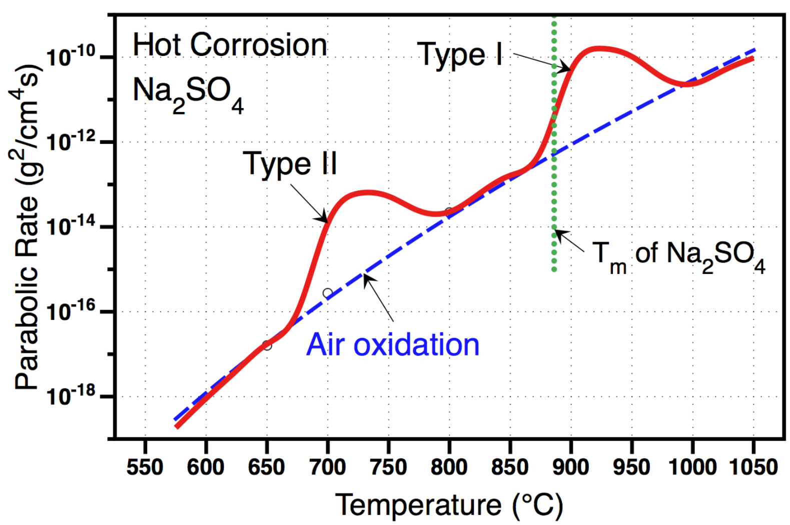
hot corrosion in blade root (want higher Cr)



MarM247 <- PWA1483 <- CMSX4

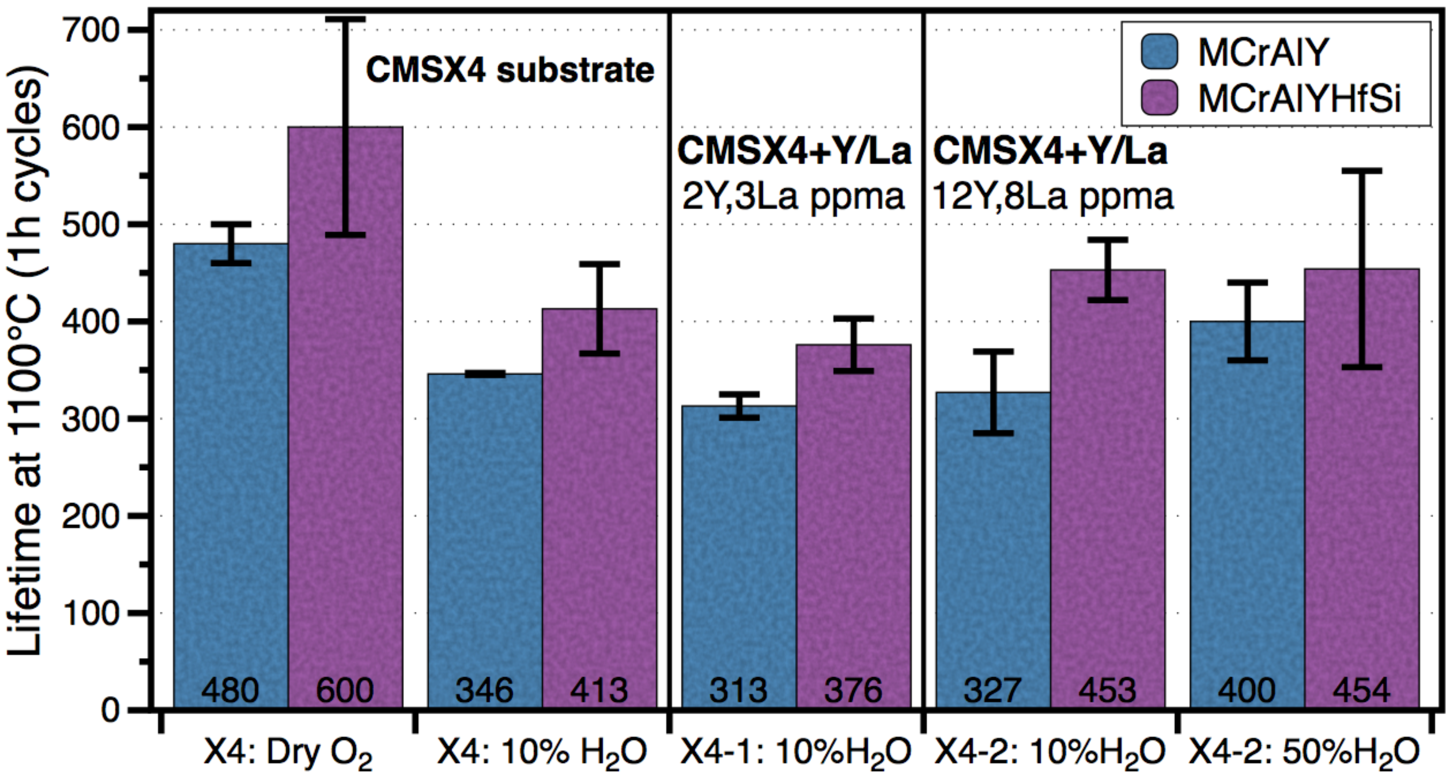
8Cr+1Hf 12Cr+4Ti 6Cr+3Re





Superior YHfSi bond coating used

CMSX4 + APS YSZ: compared HVOF Y vs. YHfSi

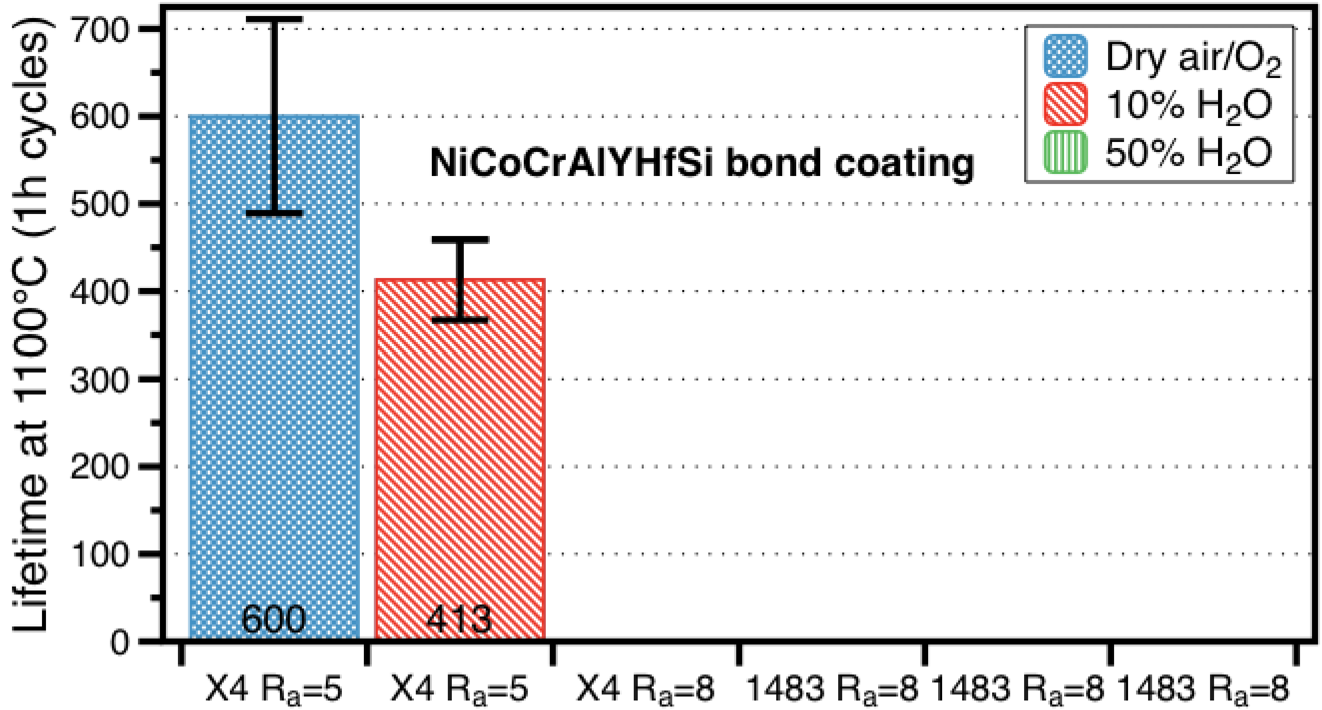


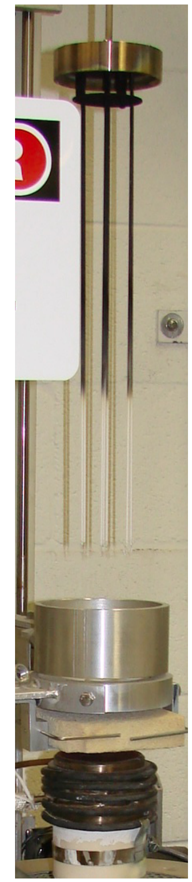
Average lifetime of 3 similarly coated specimens

All conditions/substrates higher lifetime than NiCoCrAlY bond coat made by same process

APS/HVOF: 1st batch baseline

1100°C, 1-h cycles: average 3 samples





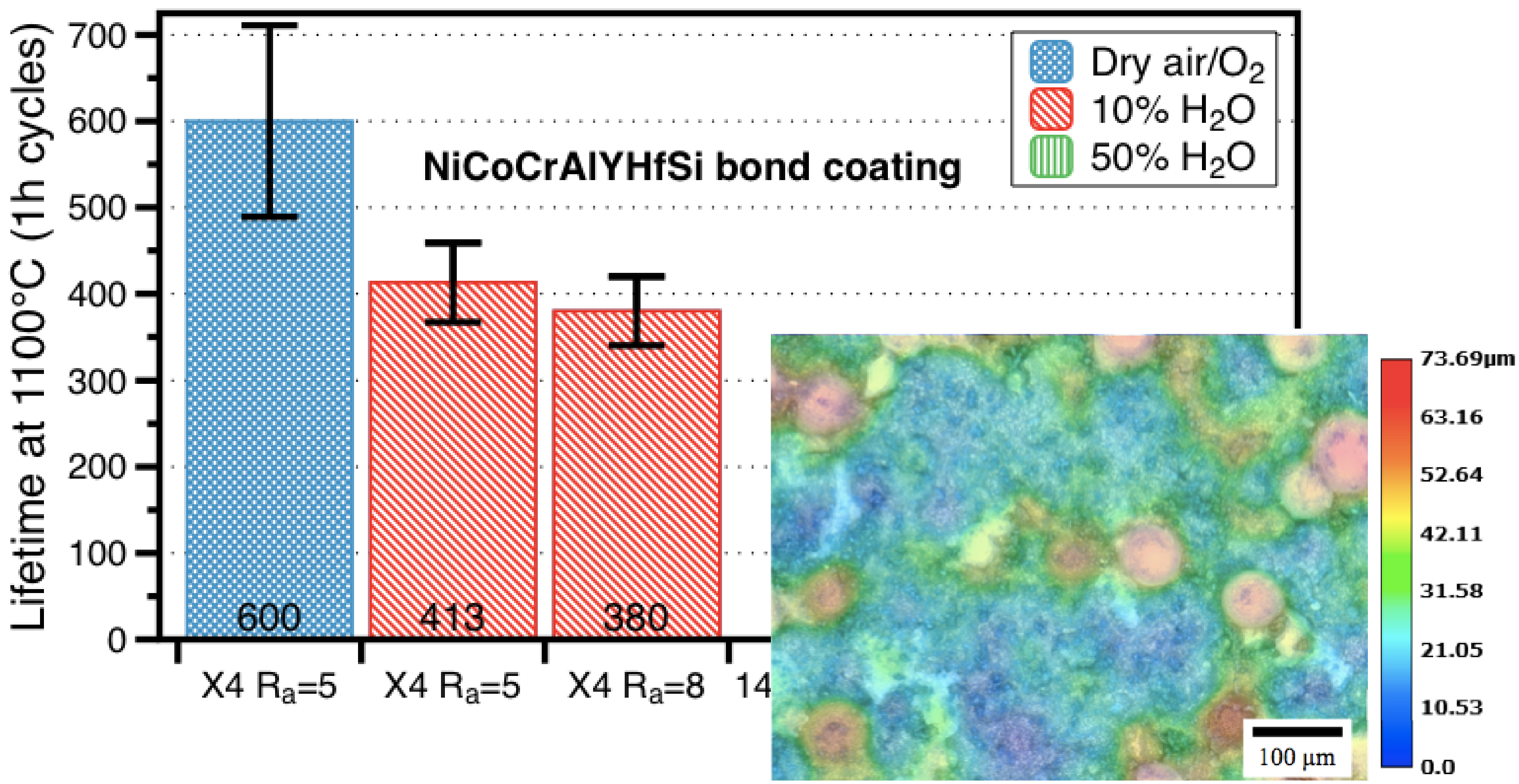
X4 substrate (2nd generation SX with 3%Re,1%Ti)

Negative effect of H_2O observed

Air plasma spray YSZ top coating

Batch 2: R_a~8μm-similar lifetime

Air+10%H_2O: 1100°C, 1-h cycles

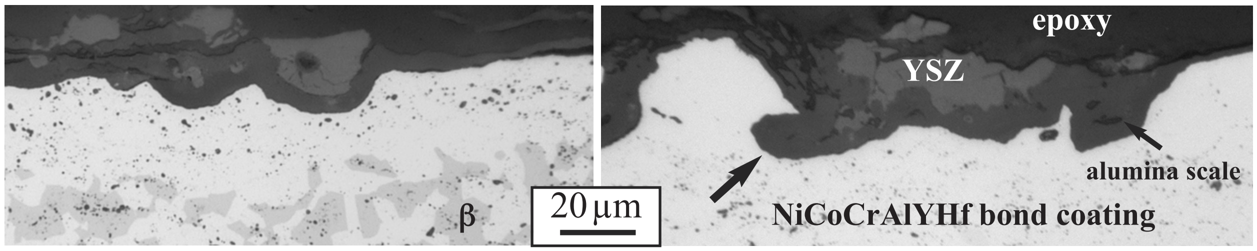


Higher roughness (R_a~8μm) closer to industry

Lower coating thickness likely reduced lifetime

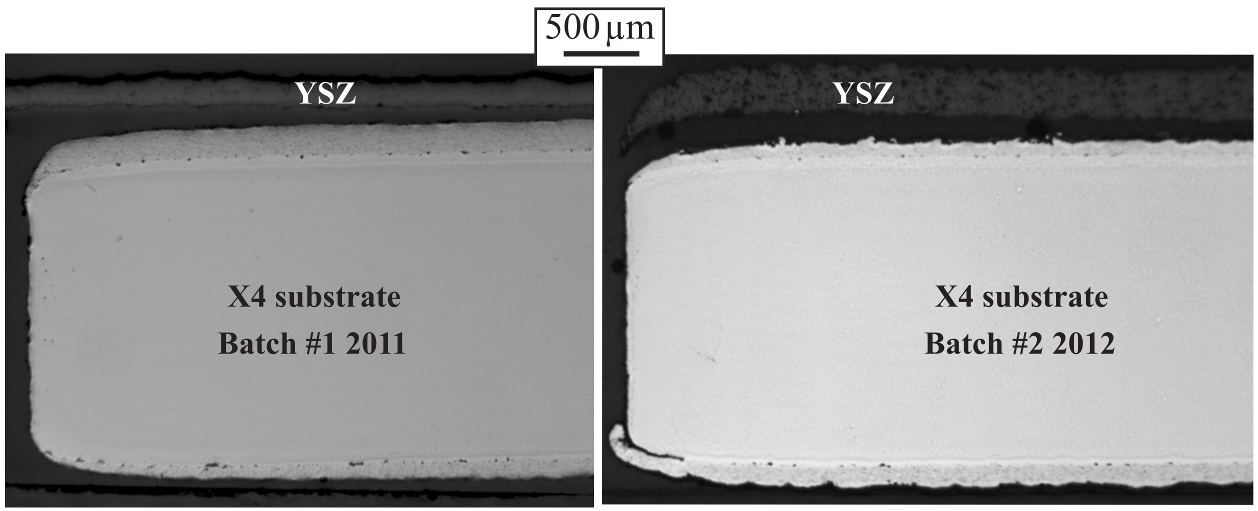
1 vs. 2: thickness & roughness varied

HVOF NiCoCrAlYHfSi on X4, 10%H_2O at 1100°C



Ra~5 440 cycles

Ra~8 380 cycles

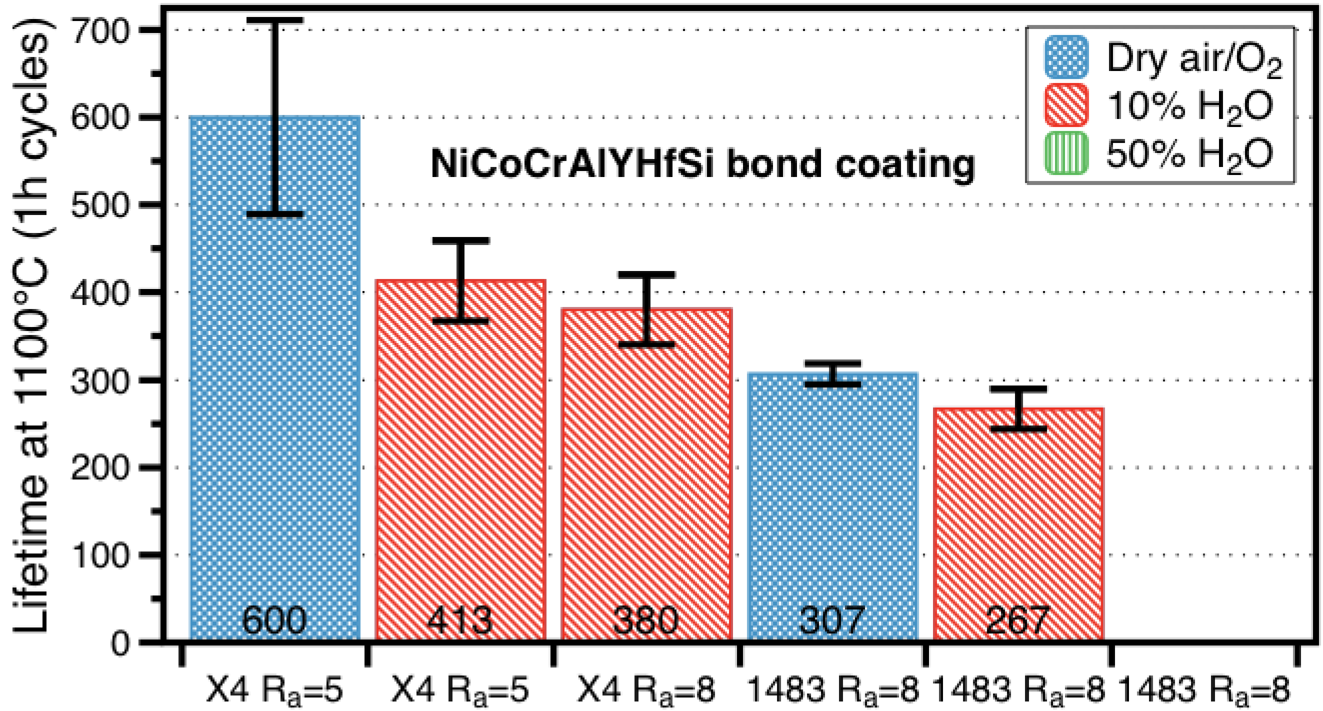


Rougher coating had similar ~150μm coating
highest peak to substrate!

Much lower Al reservoir than prior coating

1483: lower lifetimes

Air+10%H_2O: 1100°C, 1-h cycles



Compare batch #2: R_a to ~8μm

Lower cost 1483 substrate: no Re, 3.4%Al, 4%Ti

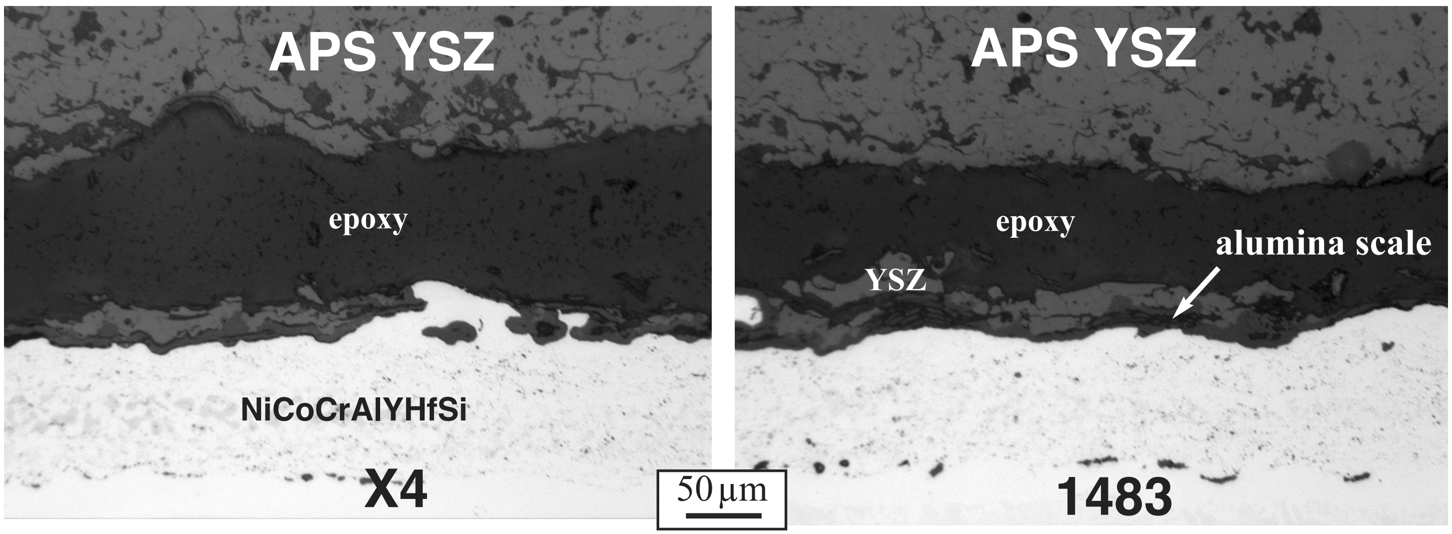
1st generation single-crystal superalloy

X4: 2.9%Re, 5.8%Al, 1%Ti

Similar morphologies with 1483

Light microscopy after exposure in air+10%H_2O

340, 1-h cycles, Ra~8 | 280, 1-h cycles, Ra~8

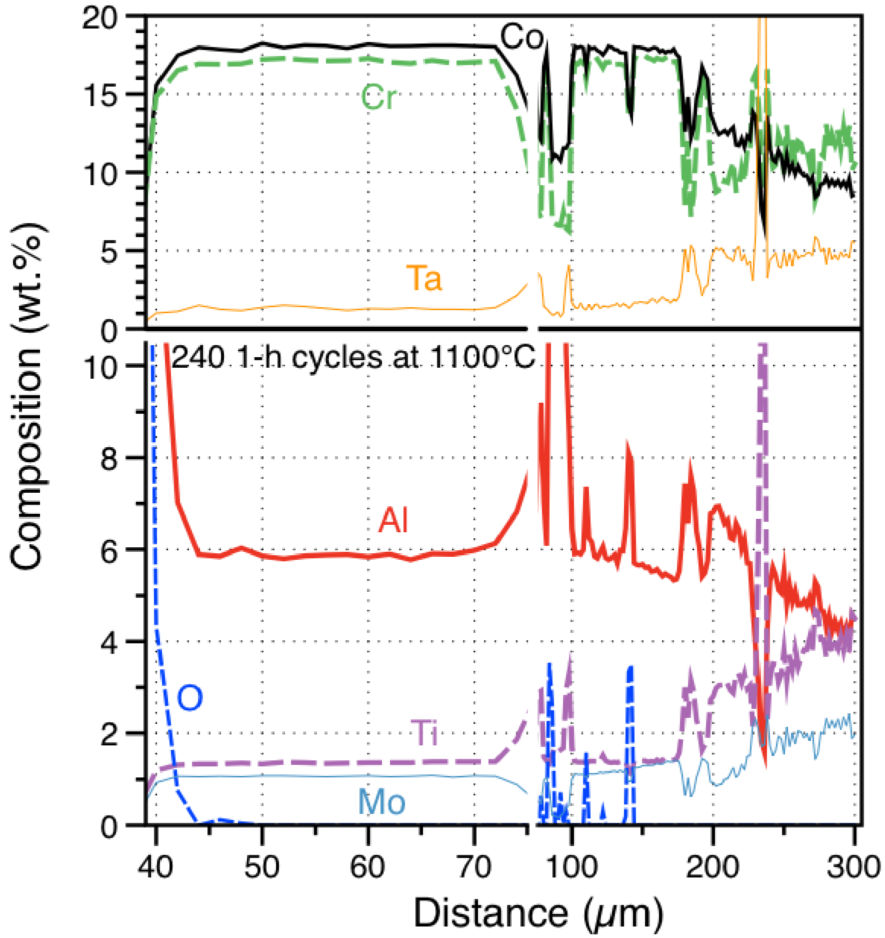


Lower Al content in 1483: more interdiffusion

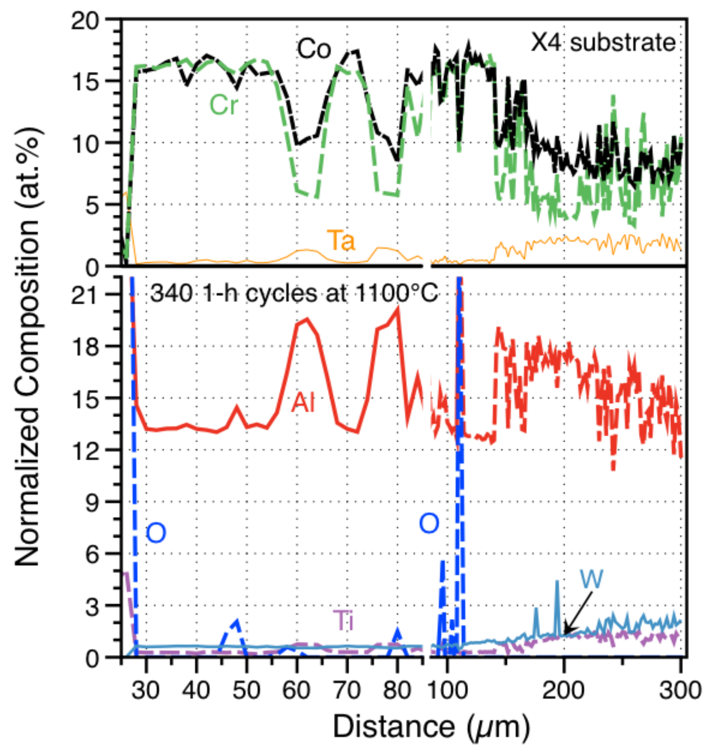
Significant interdiffusion with 1483

1100°C, 240 1-h cycles, 50%H_2O

1483 substrate



X4 substrate



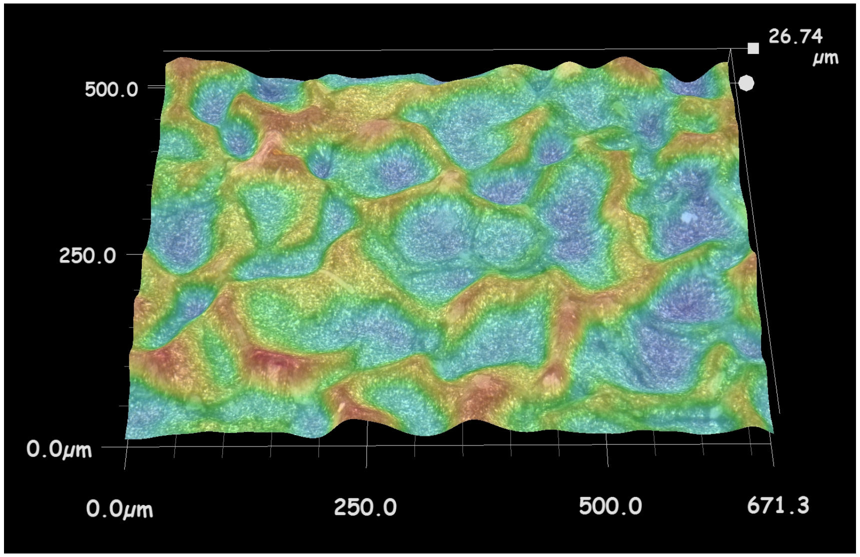
Al content dropped from 12% to 6wt%

1.4%Ti in the coating: what effect?

- 0.3%Ti in model NiCrAlYHf alloys: no debit

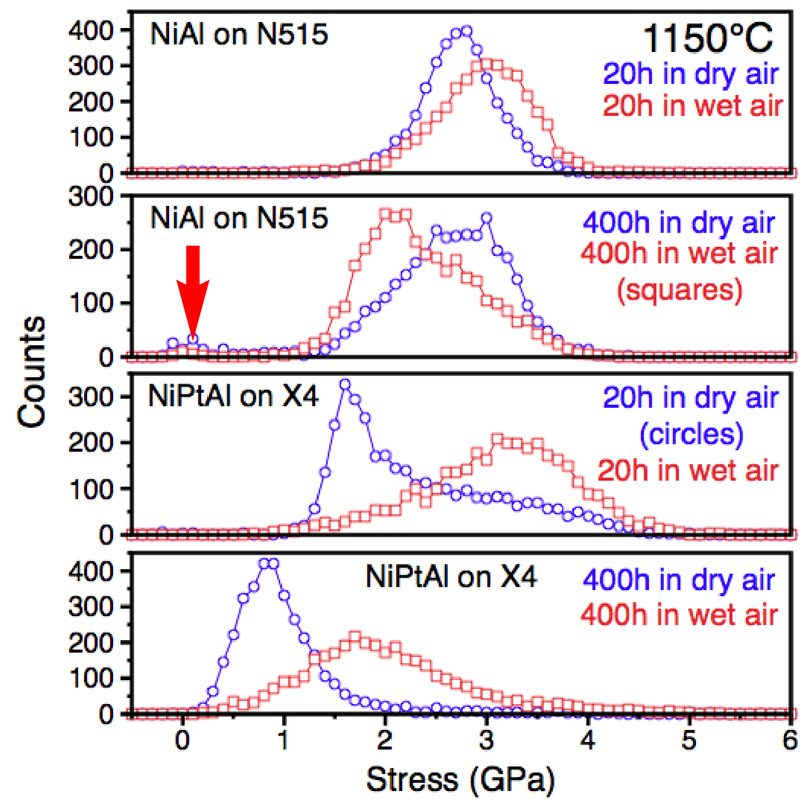
Next gen. stress/3D measurements

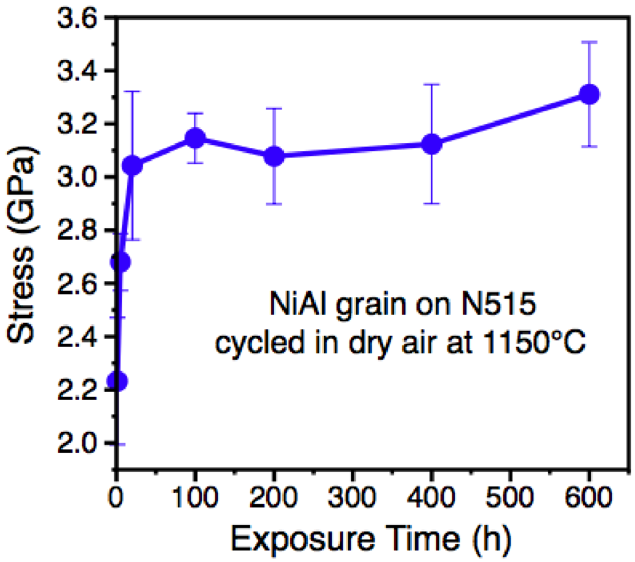
PSLS/Z measurement as a function of location



NiPtAl on N5 after 400h
at 1150°C in wet air

wet vs. dry air histograms



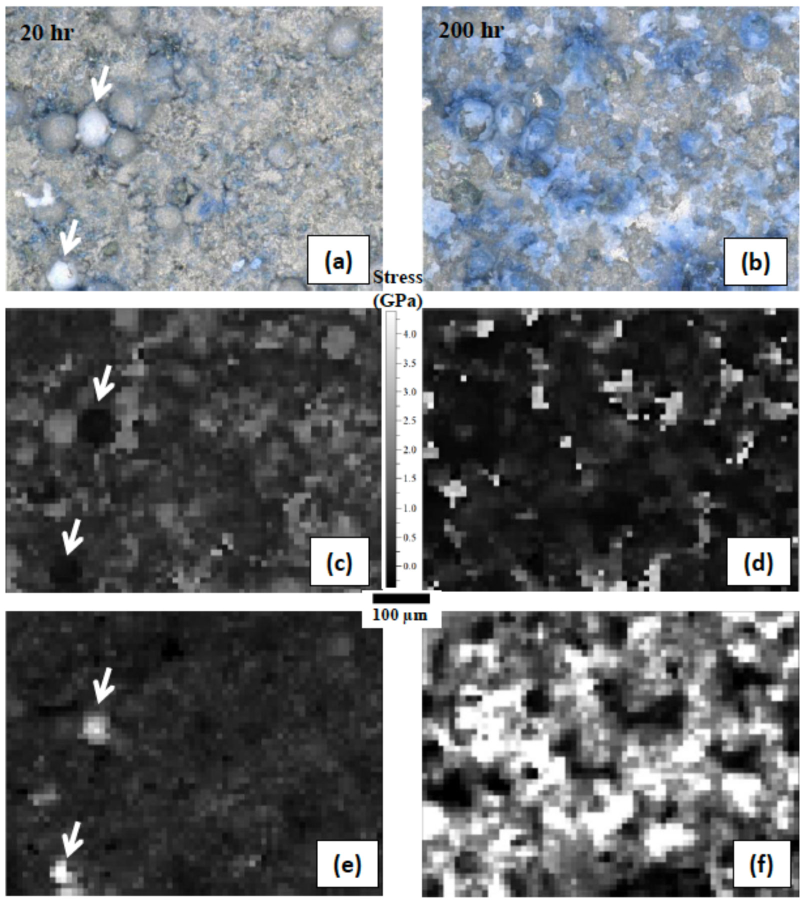


stress in single grain in β coating

Last step: microstructure
at key locations (FIB)

3D image + PSLS: maps & histograms

1483: 1100°C, dry air, 1h cycles



3D Light microscopy (Keyence)

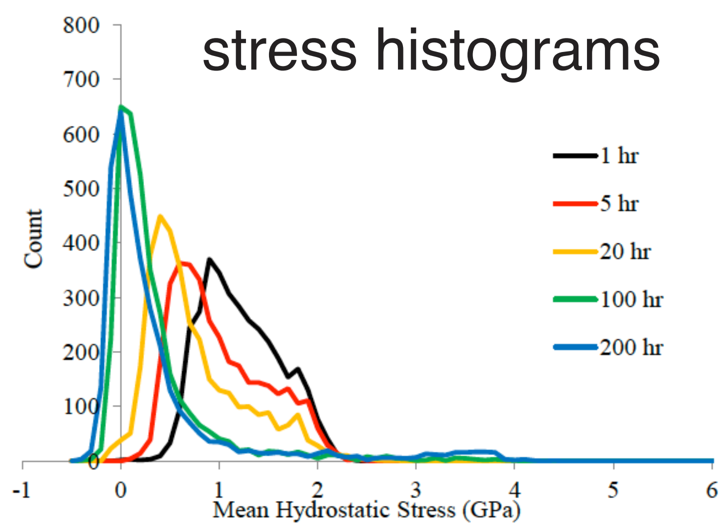
Photo-Stimulated Luminescence Spectroscopy: mean stress

PSLS: total R-line area

20 cycles

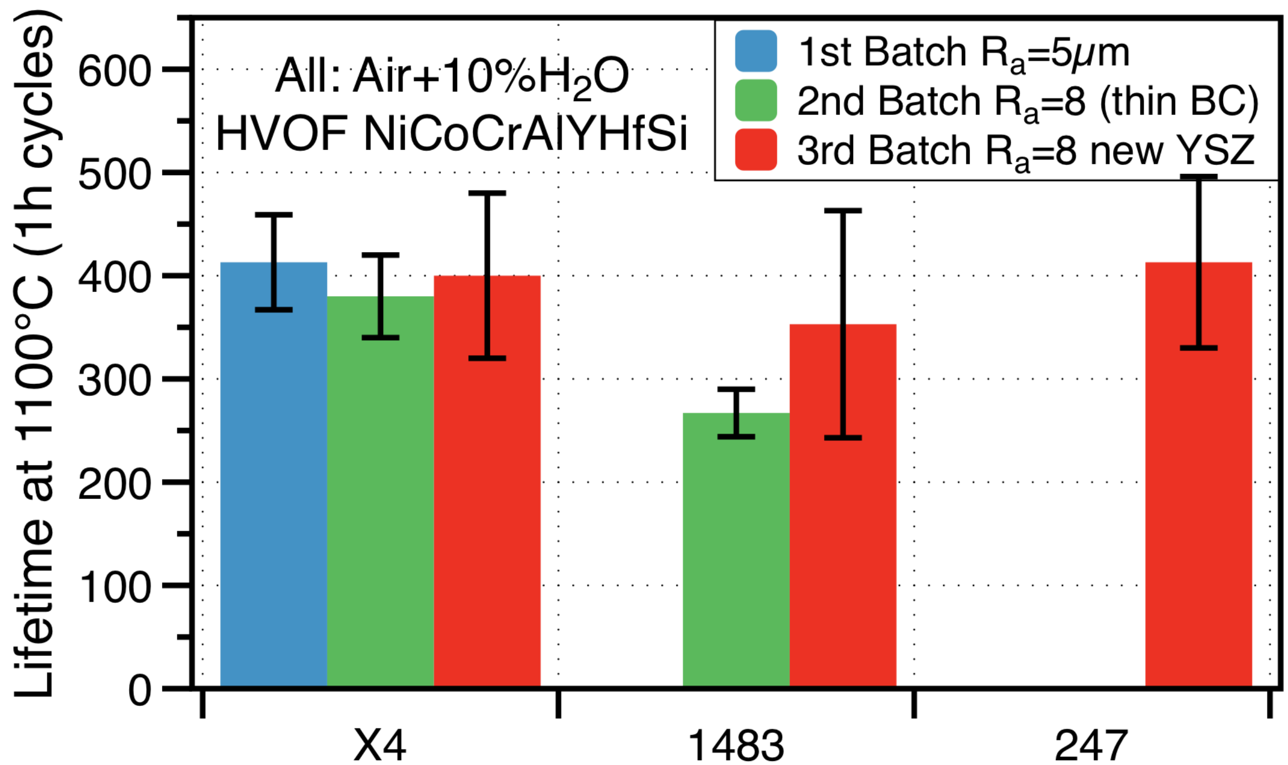
200 cycles

No YSZ top coat:
nothing to constrain spallation



DS MarM247 similar to X4

HVOF NiCoCrAlYHfSi/APS YSZ coatings



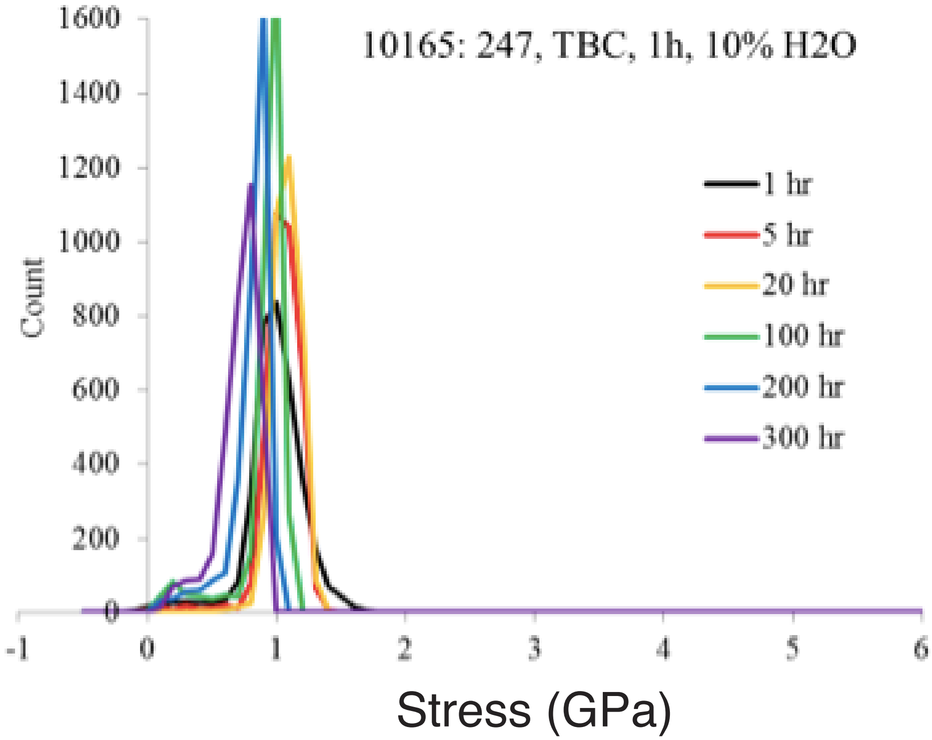
5.8wt.%Al 3.4%Al 5.5%Al

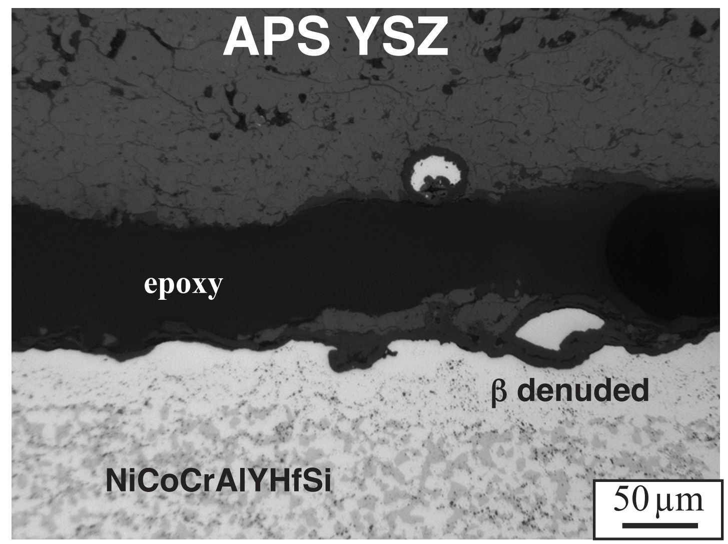
Average lifetime of 3 similarly coated specimens

Characterization of failed specimens in progress

Stress/failure: substrate independent
1100°C, 1-h cycles, 10%H_2O

PSLS: through the YSZ top coat

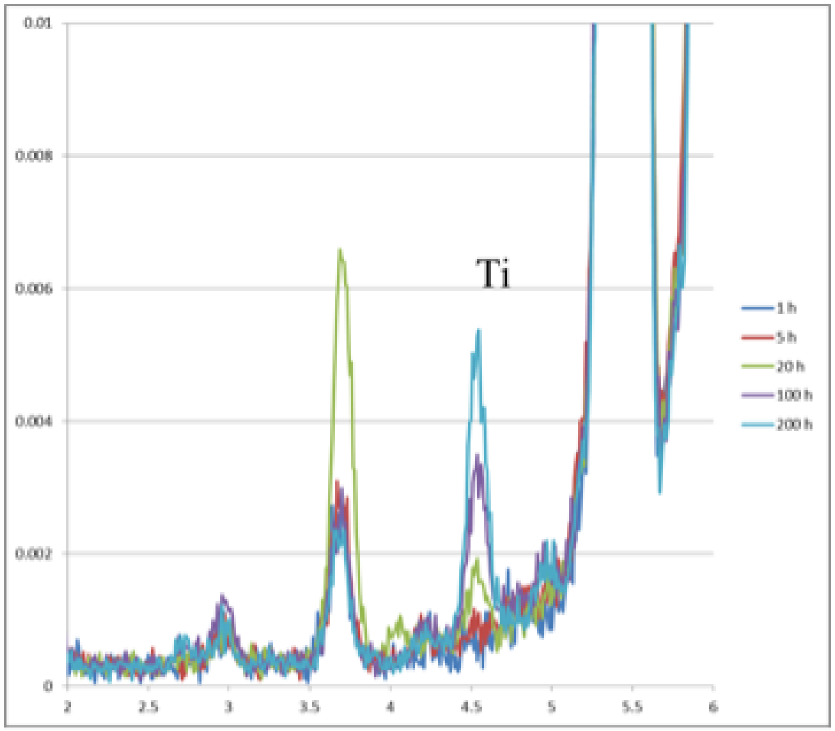




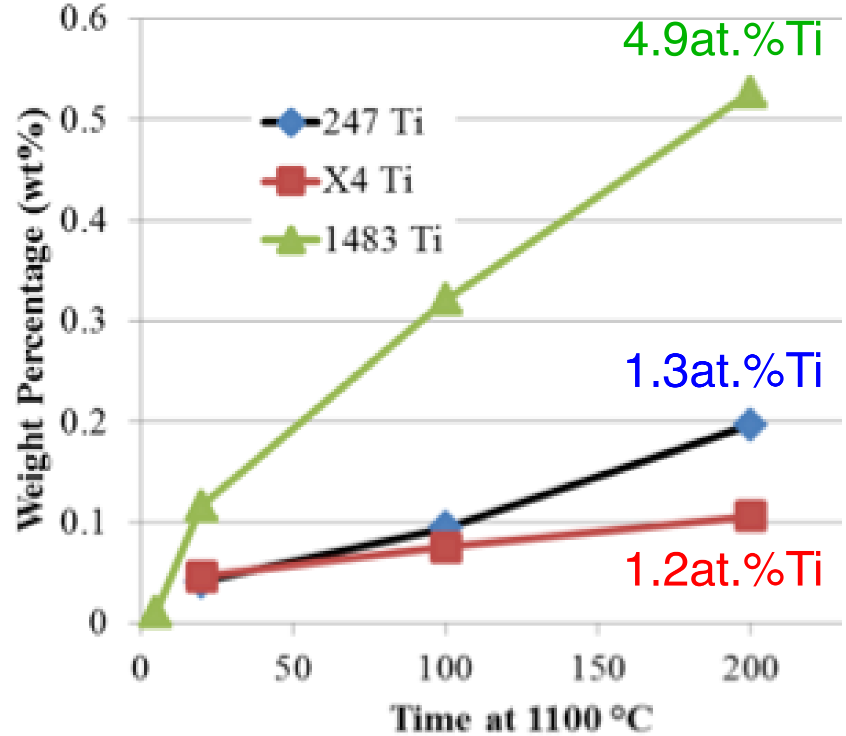
1483 substrate: 280 cycles

Similar results for X4, 1483 and 247

New micro-XRF spectrometer tracked interdiffusion on bare bond coating



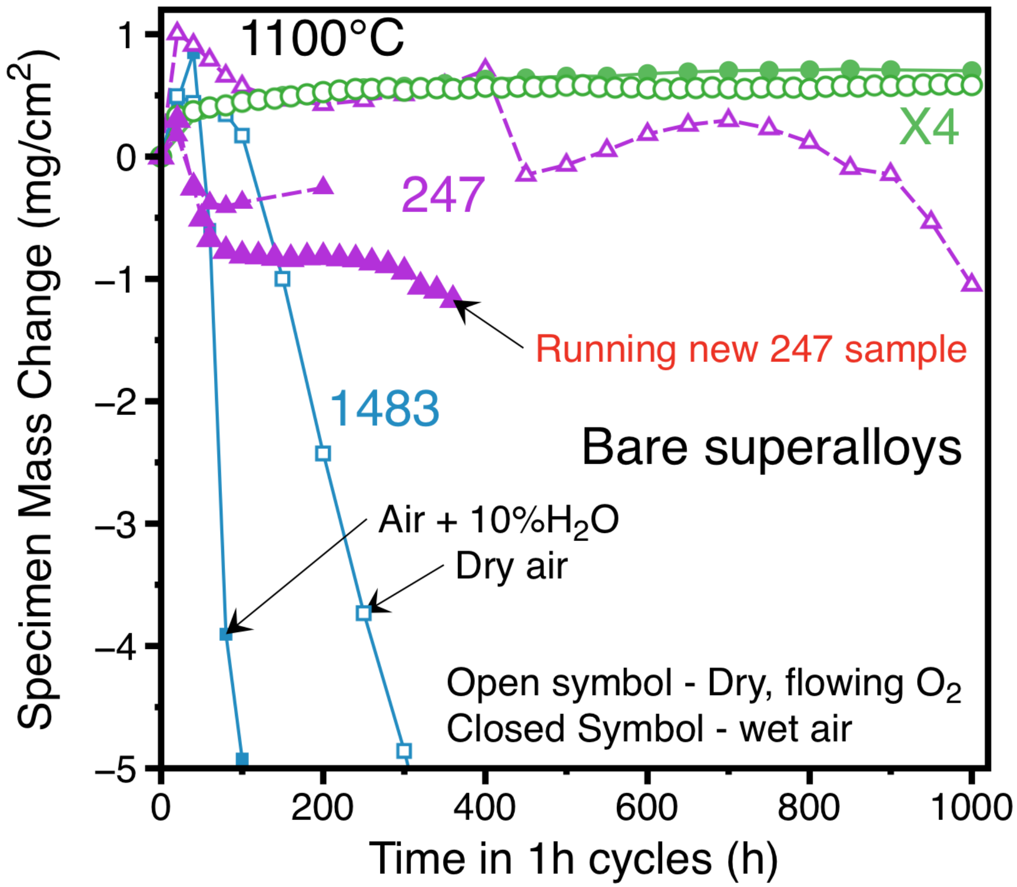
Energy



Signal from ~10μm into substrate
Surprising increase for 247 compared to X4
How much does Ti play a role?

Concern testing 1483 at high T

Bare 1483 severely attacked at 1050°/1100°C



1h cycles: dry O_2 and wet air (worse)

247 a little bit worse than X4

Component metal temperature ~900°C

Task 2: Does H_2O explain de-rating?

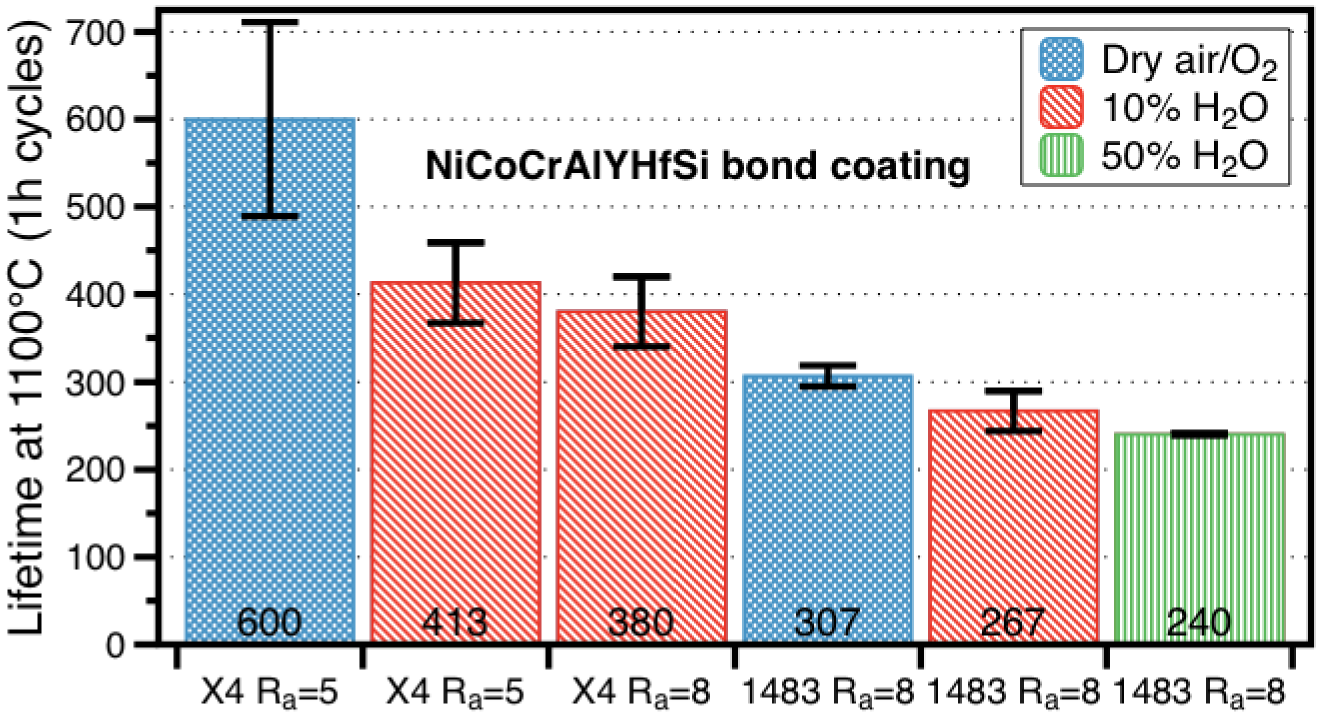
Motivation for original task:

- Experiments done in dry O_2 or air - convenience
- All turbines contain some H_2O
    - Natural gas - 10-15 vol.%
    - Syn. gas - ~30%
    - Hydrogen - ~60%
        - higher levels with diluent
- Literature discussion on H_2O effect on TBC
    - Anomaly of testing without H_2O
    - Negative effect on lifetime when H_2O added
    - Syngas-firing question:

What is difference in TBC lifetime when H_2O increased from 10% to 30%-50%?

(not dry vs. wet, but wet vs. wetter)

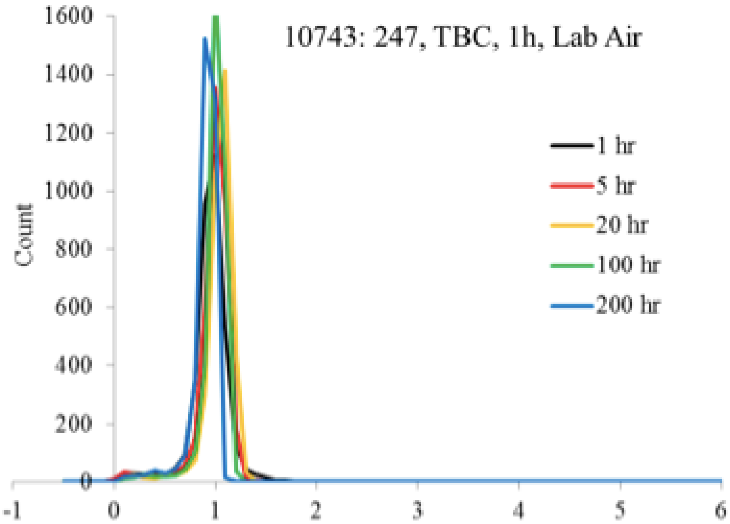
$50\%H_2O$: slight lifetime reduction
1483 substrate, 1100°C, 1-h cycles

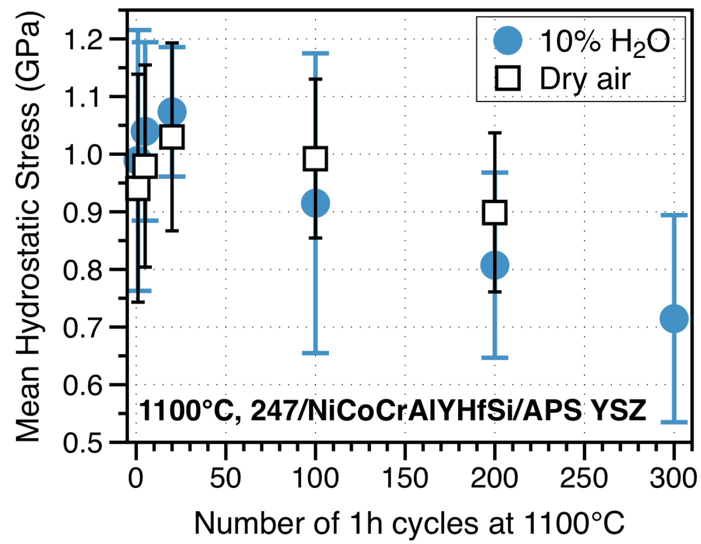


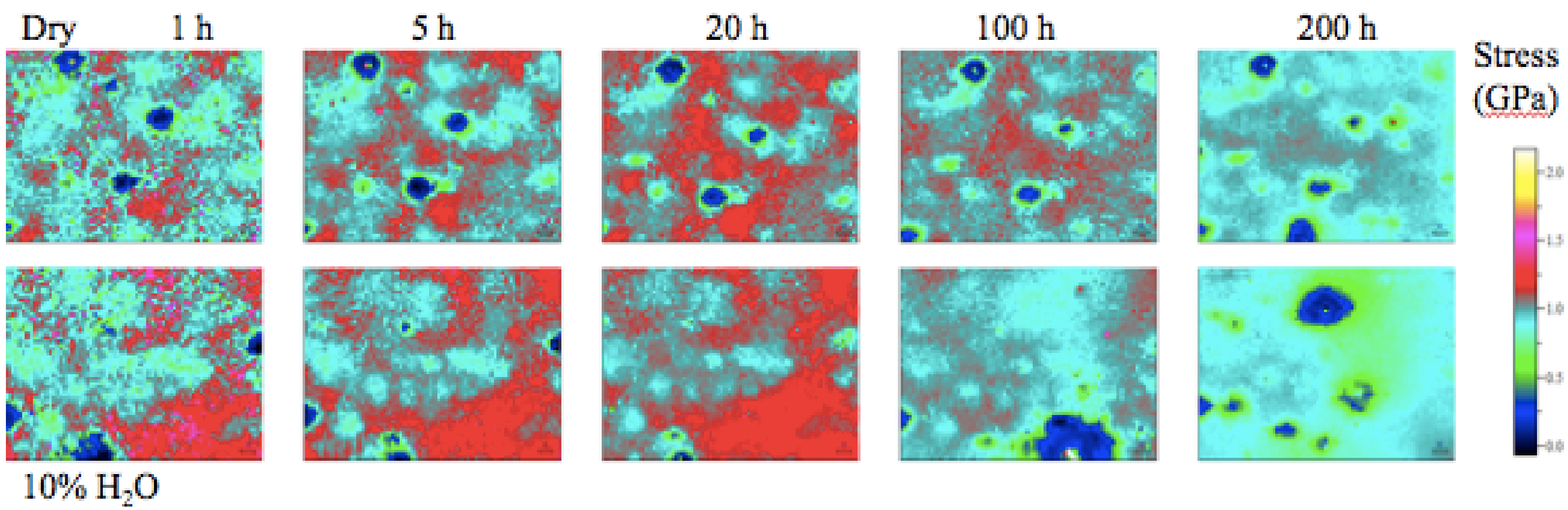
Lower scatter in the 1483 specimens (groups of 3)

Current: tracking 247 dry/wet air

DS 247 substrate, 1100°C, 1-h cycles



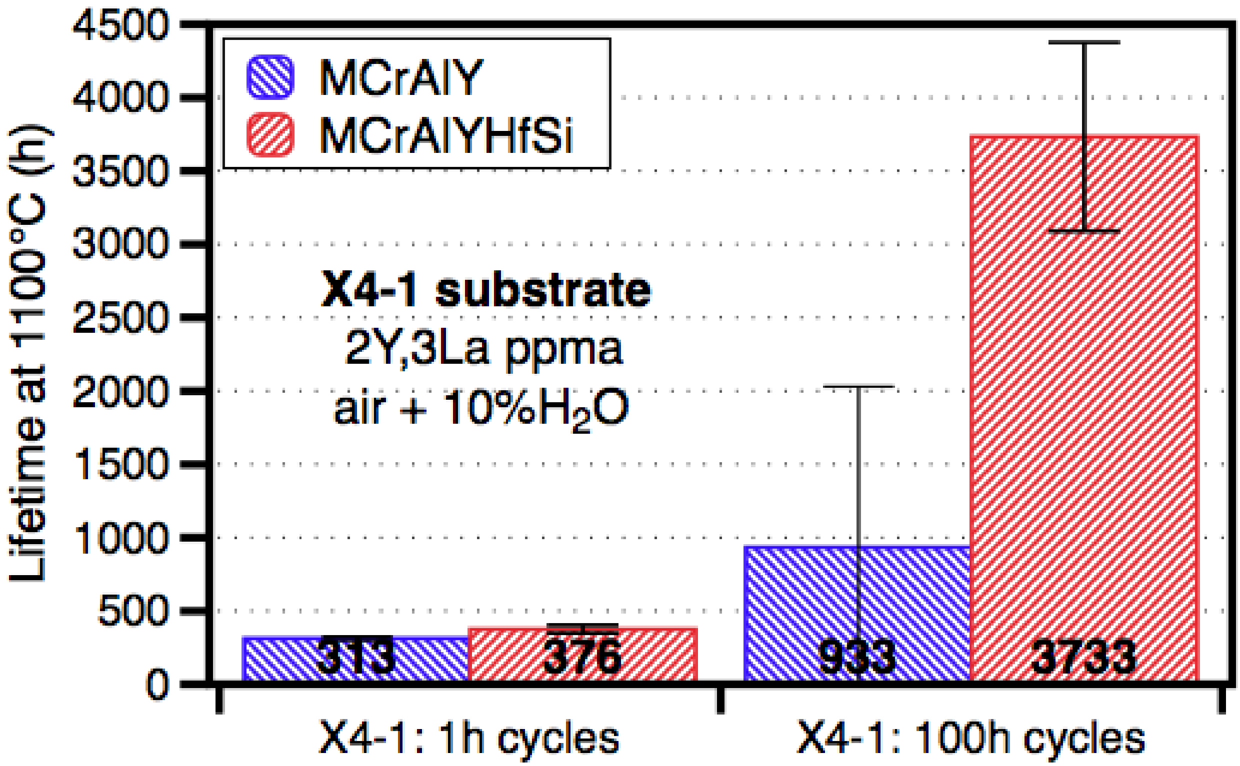


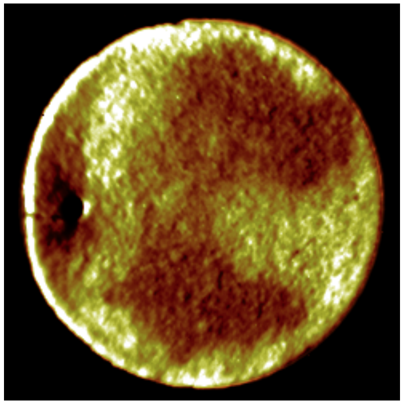


Coatings failed ~400h in both environments

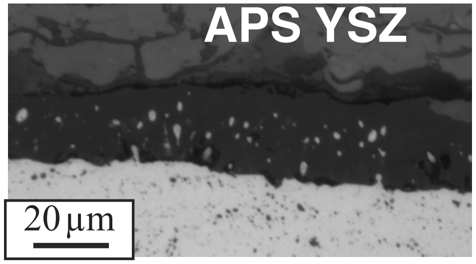
100h cycles increased lifetime

1100°C: two bond coatings on X4+La + APS YSZ





bright areas delaminated in thermal flash at 42 cycles



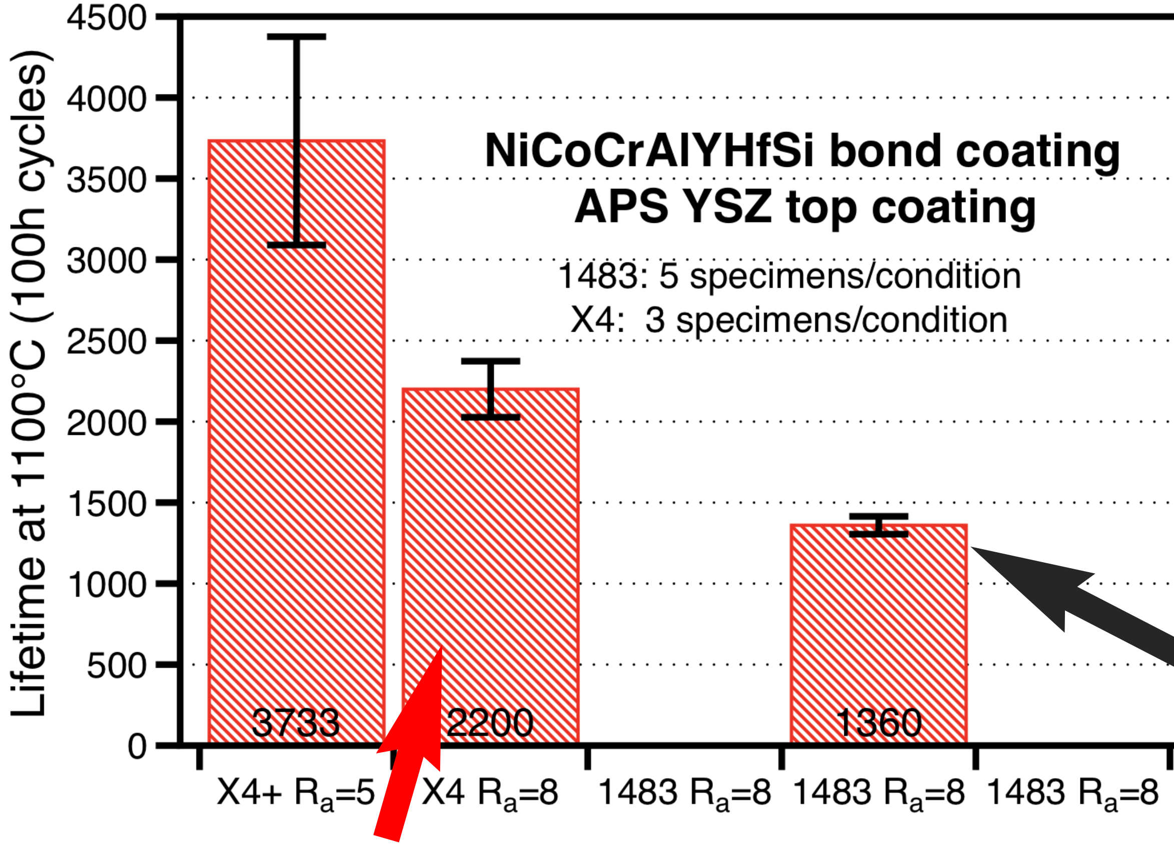
Cycle more representative of land-based turbine

Aero-engine (~15 kh); Power-gen (~25-50 kh)

100h cycles in tube furnace with slow heat/cool

100h: similar trends as 1h cycles

1100°C: HVOF NiCoCrAlYHfSi + APS YSZ

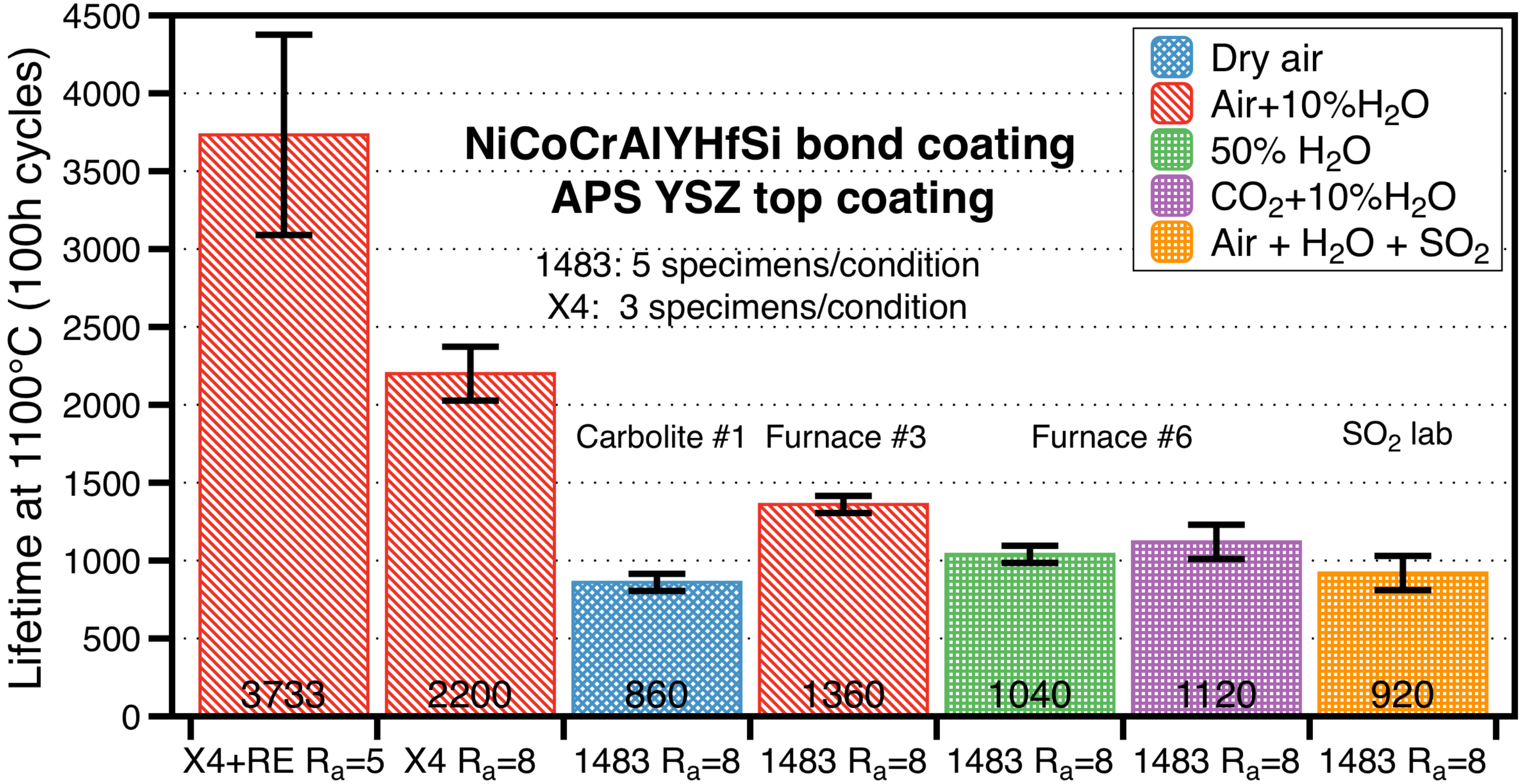


2nd batch: rougher, thinner BC = shorter life

1483: shorter life

1483, 100h: environment no factor

1100°C: HVOF NiCoCrAlYHfSi + APS YSZ



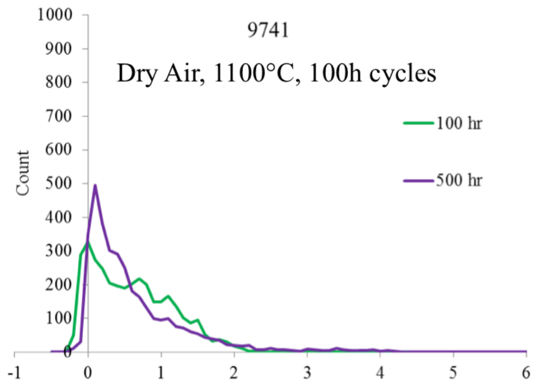
Five samples per 1483 group

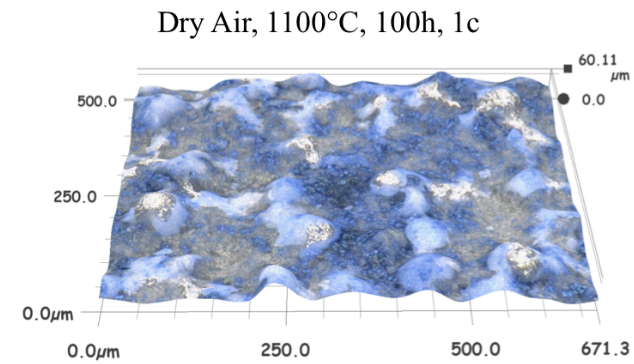
Longest life in 10%H_2O

Test with 10%H_2O and 1000ppm SO_2 in progress

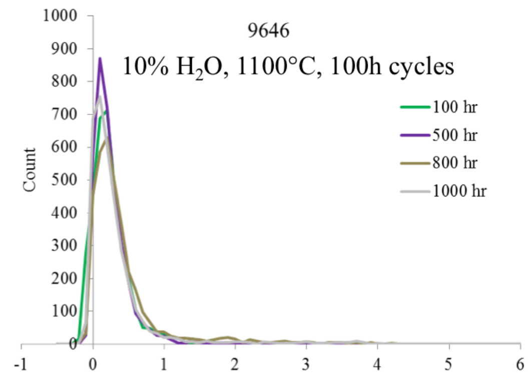
PSLS: maps & histograms
1483: 1100°C

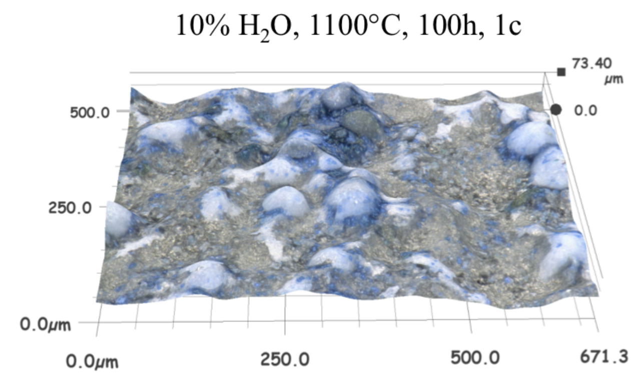
Dry air



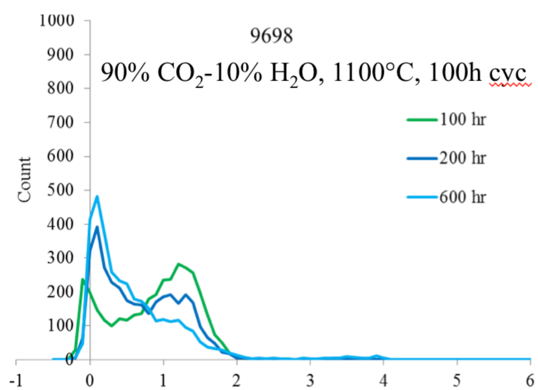


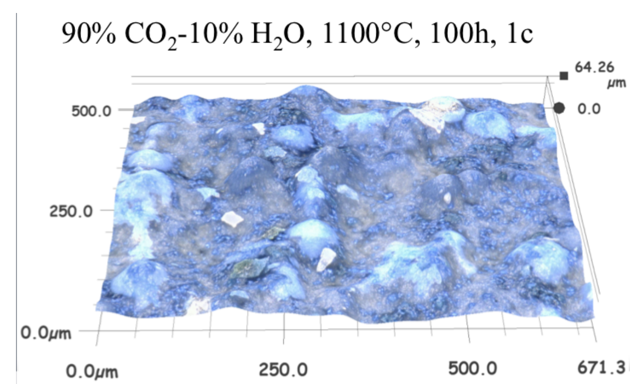
air+10%H_2O





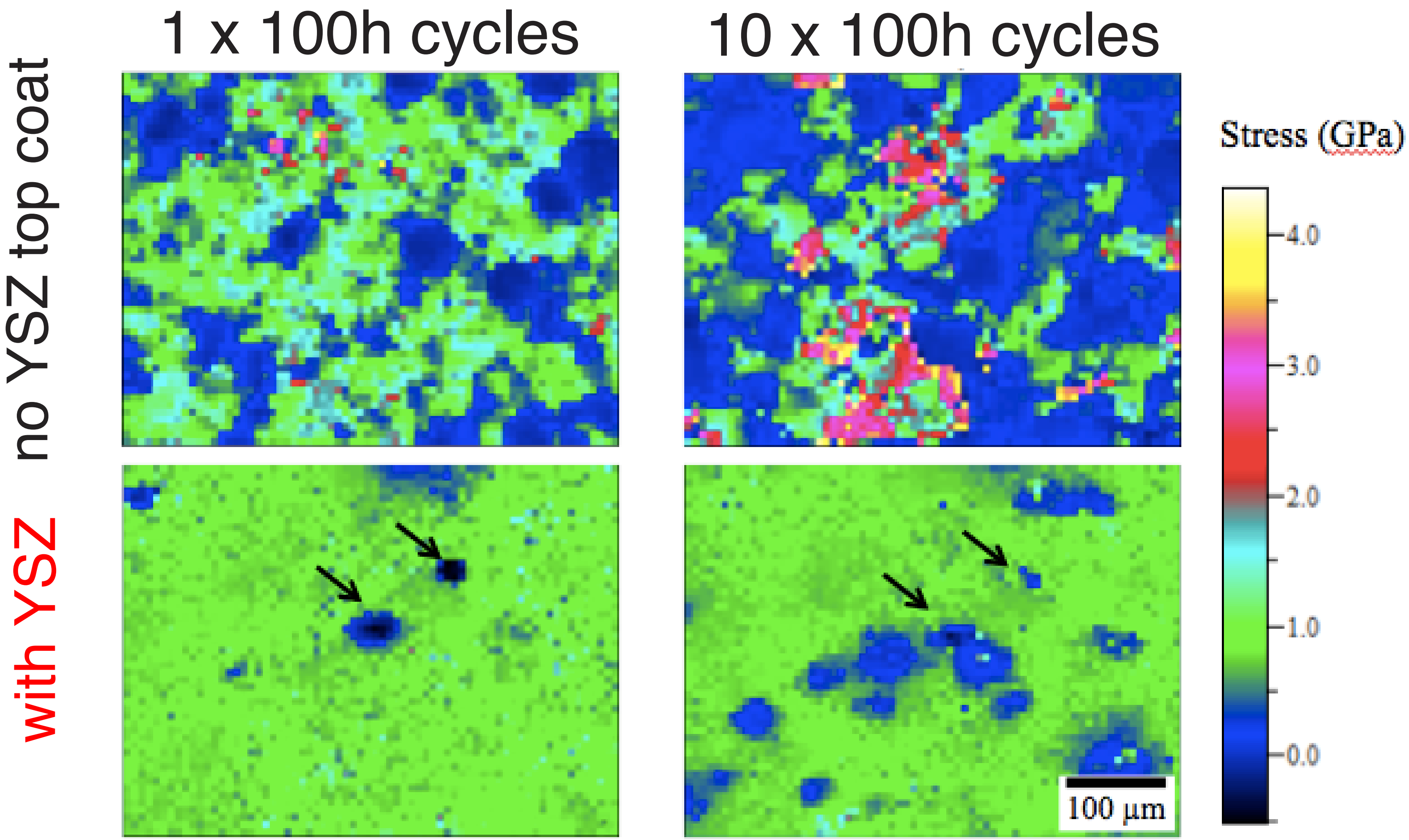
CO_2+10%H_2O





Measuring stress under APS YSZ

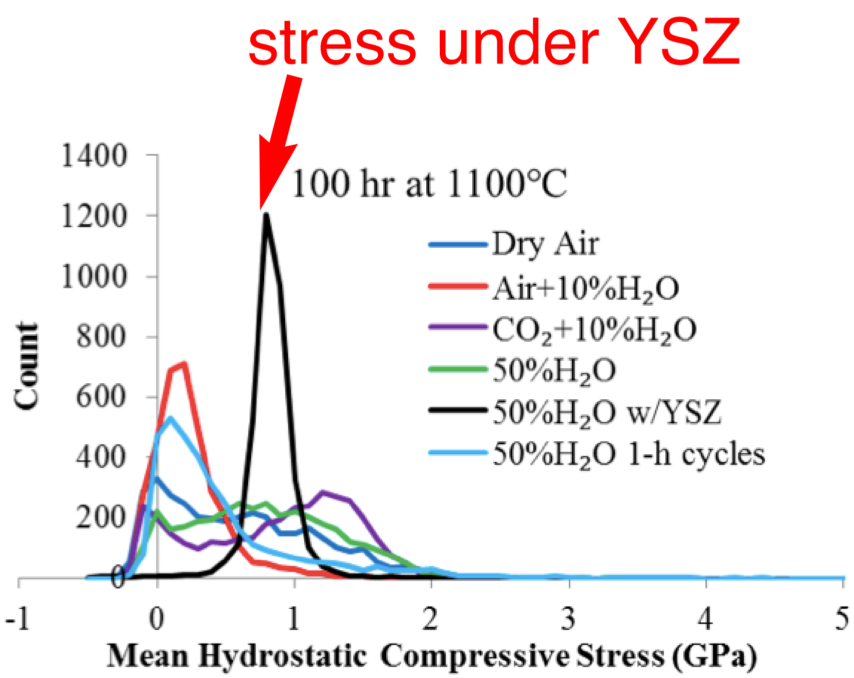
HVOF NiCoCrAlYHfSi on 1483 in 50%H_2O



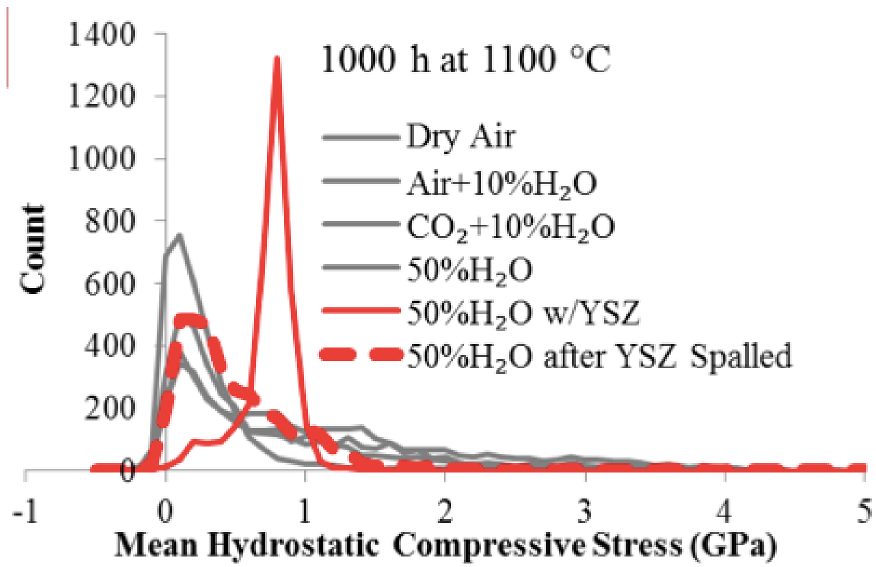
Stress in alumina scale measured by PSLS or PLPS

Measuring stress under APS YSZ

HVOF NiCoCrAlYHfSi on 1483 in 50%H_2O



1 x 100h cycles



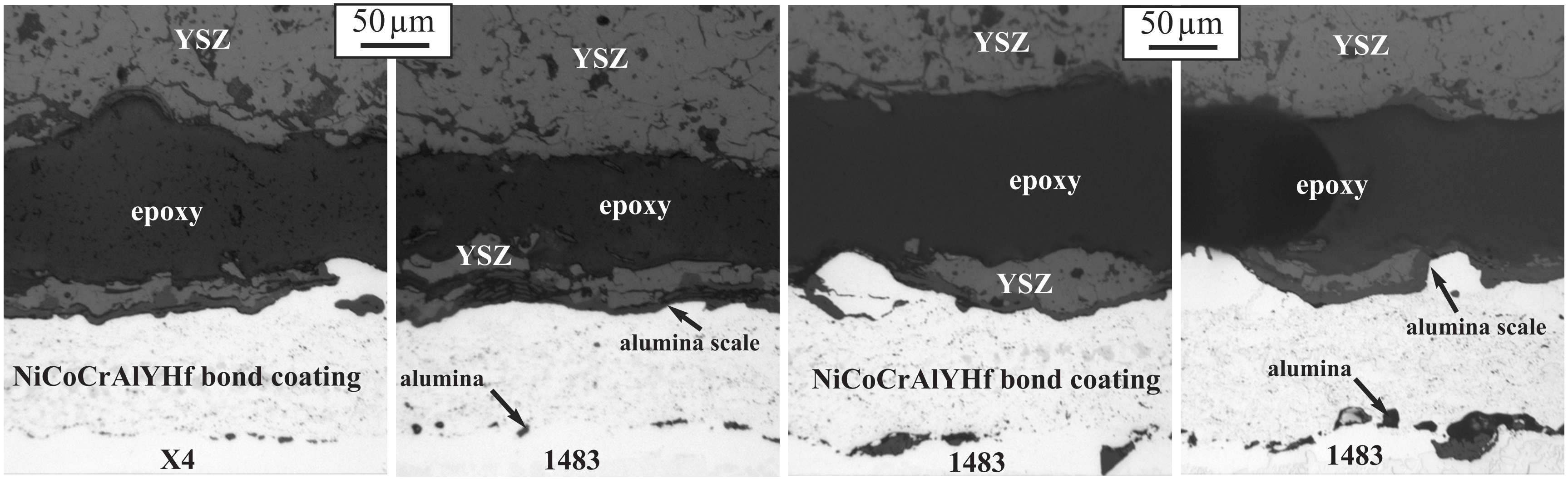
10 x 100h cycles

11 cycles spall: stress distribution just like no YSZ

Future: no more PSLS on bare bond coatings

General concern about 1483 results

Various 1100°C exposures

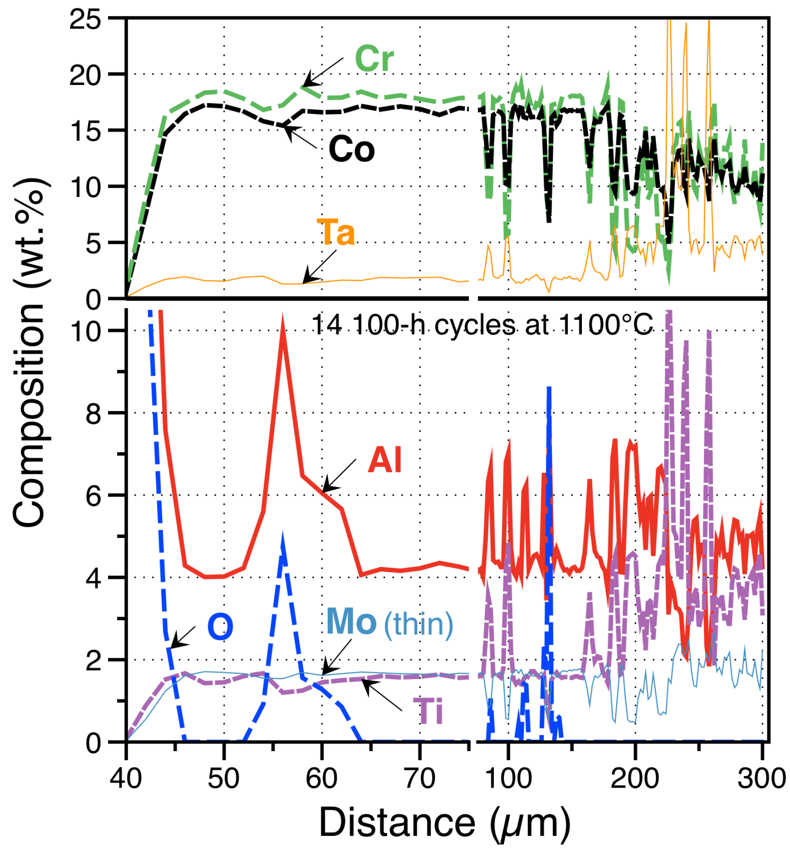


340x1h 10% | 280x1h 10% | 240x1h 50% | 14x100h 10%

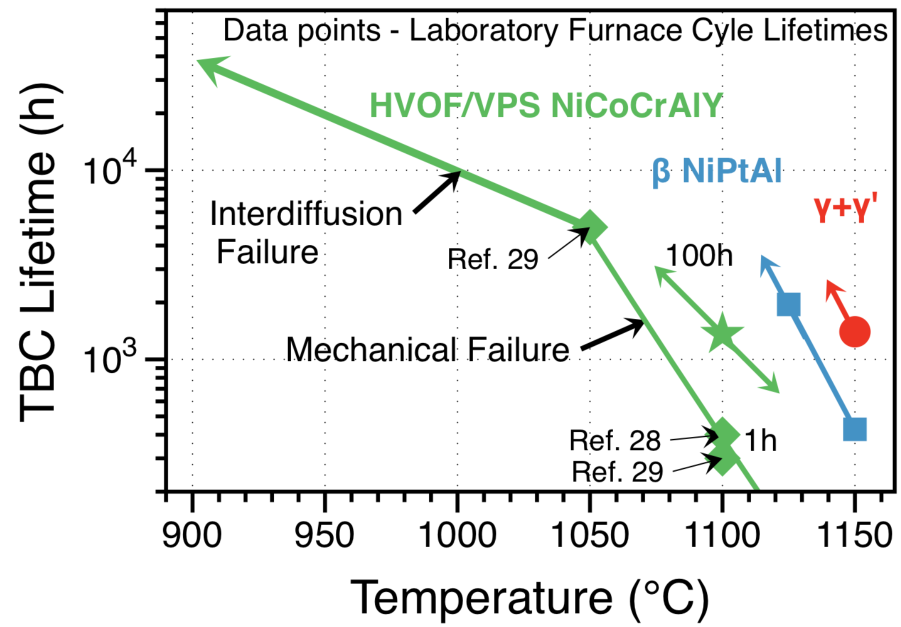
Higher alumina formation at coating-1483 interface
- was interface compromised?
- 1483 very poor behavior at 1100°C without coating

Al diffusion limits 100h cycle life

Especially interdiffusion with 3%Al 1483



1483 substrate: 1400h 1100°C



Eschler, Renusch, Schütze 2004+2008

If interdiffusion limits life, does environment matter?

Could other bond coatings do better?

Task 4 focused on solutions for syngas

Motivation for task:

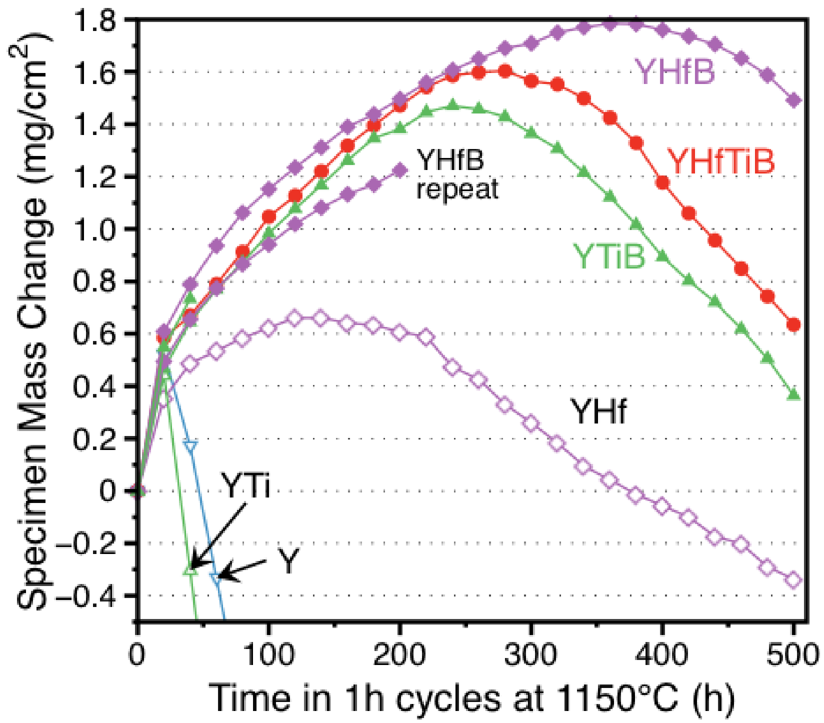
- Other tasks concern understanding
- This task added to develop/study coating solutions
- Also to investigate new coating technologies
  (often difficult to get specimens)

FY14 work:

- followup on B improving oxidation resistance
  making MCrAlYHfSi coatings with B

Is B a bond coating solution?

Cast NiCrAl: 1h cyclic testing at 1150°C



air + 10%H_2O

0.01wt%Y-0.16Hf vs.
0.03wt%Y-0.13Hf-0.07B
0.03Y-0.14Hf-0.3Ti-0.06B

PWA286 (YHfSi, AMDRY 386) base, ±B, ±Si

- VPS deposition at Stonybrook

  coatings arrived last week

- if B promising, look for industrial partner

Coating summary–take aways

Environment:

H_2O is relevant & detrimental for furnace cycle life

Higher water vapor does not appear to explain
IGCC de-rating

No indication that CO_2 is detrimental to TBC life

100h cycles: environment less important (?)

Bond coating:

Y + Hf in bond coating yields higher TBC lifetimes

- Does B affect performance?

Substrate:

- Land-based turbines focused on cheaper alloys

Lower TBC life for 1483 compared to X4 substrates

- lower Al, higher Ti in 1483: not surprising

FY15: develop understanding

Begin coating/testing round specimens