Effect of Environmental Exposures on Fatigue Life of P/M Disk Superalloys

As the temperature capability of Ni-base superalloy powder metallurgy disks is steadily increased, environmental resistance and protection of advanced nickel-based turbine disk components are becoming increasingly important. Localized surface hot corrosion attack and damage from oxidation have been shown to impair disk fatigue life and may eventually limit disk operating temperatures. NASA Research Announcement (NRA) contracts have been awarded to GE Aviation and Honeywell Aerospace to separately develop fatigue resistant metallic and ceramic coatings for corrosion resistance and the corrosion/fatigue results of selected coatings will be presented. The microstructural response of a bare ME3 disk superalloy has been evaluated for moderate (704°C) and aggressive (760-816°C) oxidizing exposures up to 2,020 hours. Cross section analysis reveals sub-surface damage (significant for aggressive exposures) that consists of Al2O3 “fingers”, interfacial voids, a recrystallized precipitate-free layer and GB carbide dissolution. The effects of a Nichrome corrosion coating on this microstructureal response will also be presented.

Effect of Environmental Exposures on Fatigue Life of P/M Disk Superalloys

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2011 Annual Technical Meeting
May 10–12, 2011
St. Louis, MO

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<u>Honeywell Aerospace</u> (NNC08CA62C Final Report)

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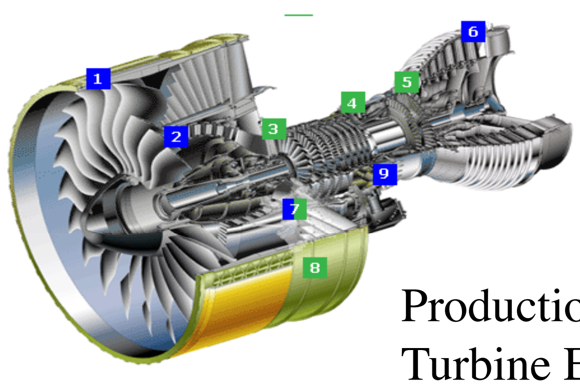
Background

- The drive in aerospace propulsion applications towards higher turbine inlet temperatures, which should improve engine efficiency and decrease fuel consumption, is leading to higher disk rim temperatures.

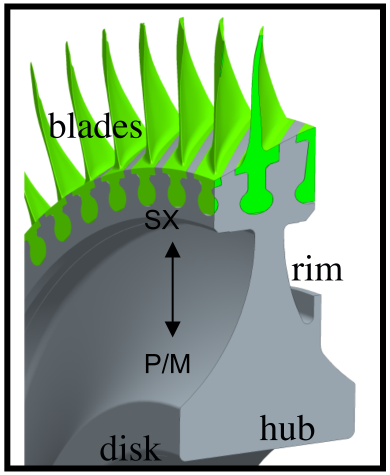
  Currently at 650 °C → Long-range goal of 800 °C

- Advanced powder metallurgy (P/M) alloys have been developed by industry, AFRL and NASA to address the properties needed at these elevated temperatures e.g. Alloy 10, LSHR, ME3 (R104), RR1000

- Corrosion and oxidation is accelerated at the higher temperatures and can lead to reduced fatigue life in disk alloys. Protective coatings may be required.

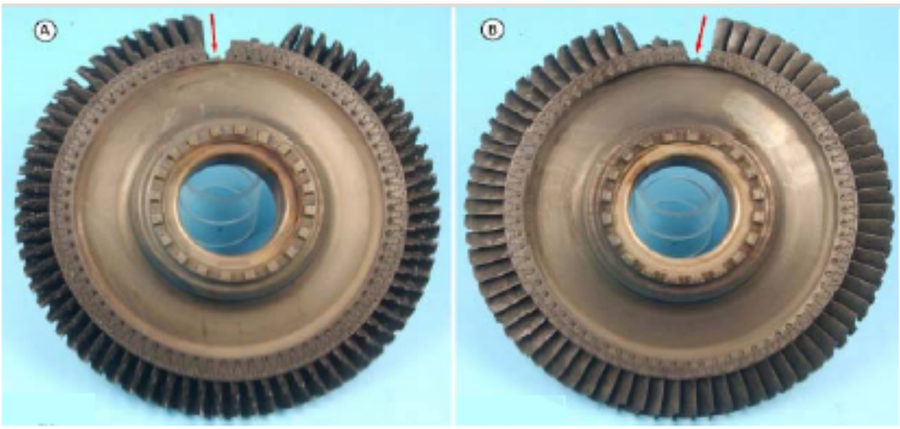


Production Turbine Engine

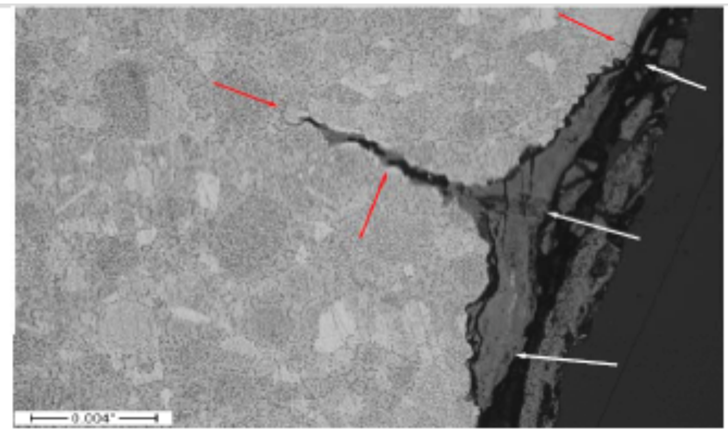


Turbine stage schematic

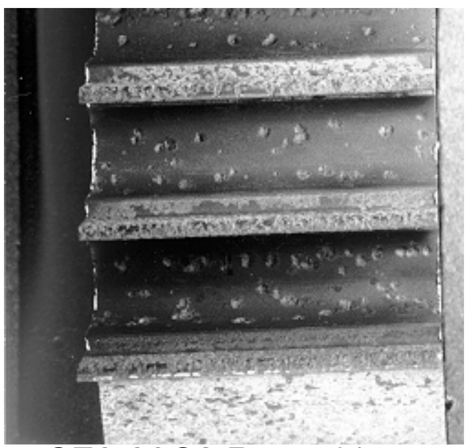
Hot Corrosion Pits Observed in Service



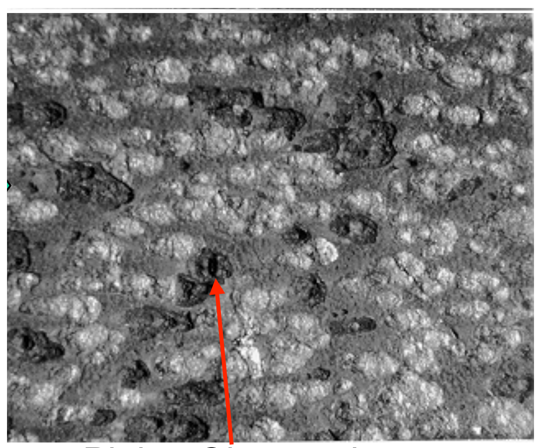
PM Astroloy Disk Post Separation



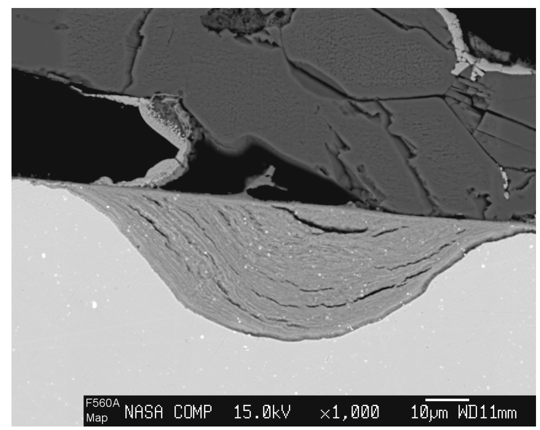
White Arrows Point To Corrosion Deposit



CF6-80C2 Rene 41
Thermal Shield

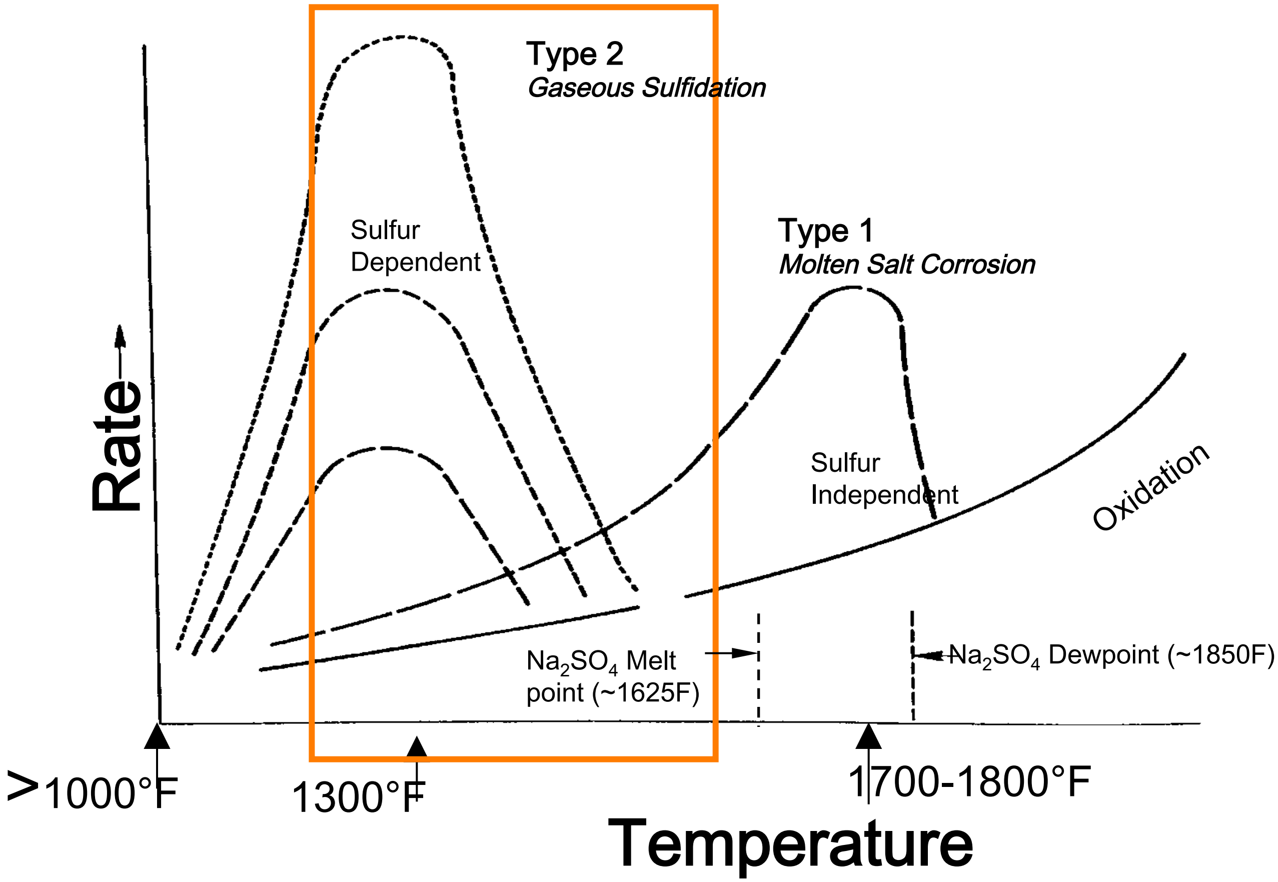


Pitting Observed on
HPT hardware.



ME3 Corrosion Pit

Traditional Hot Corrosion/Oxidation Map



Engine Dirt

Major Components
SiO_2
$CaSO_4$

Minor Components
Na_2SO_4
$MgSO_4$
K_2SO_4
Chlorides (NaCl, $MgCl_2$, KCl)
Carbonates (Na_2CO_3, K_2CO_3)

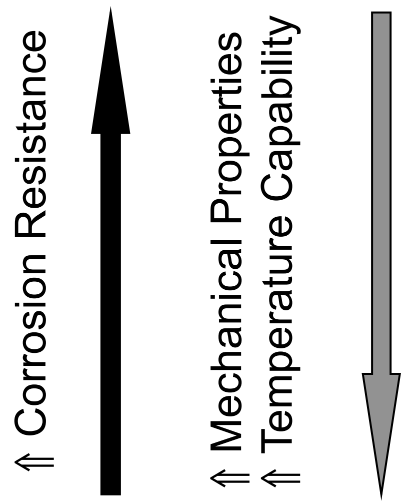
- **Corrosion Rate = Fn(dirt, time, temp, alloy)**

Why Disk Corrosion Now?

- Newer disk alloys have substituted environmental resistance (Al, Cr levels) for strength (Mo, W, Ta, etc.)

High Cr
Low Al

Cr_2O_3 formers



Disk Alloys	Cr	Al
Nichrome	22.0	0
Inconel 718	19.00	0.50
Waspaloy	19.50	1.25
IN100	12.40	5.00
René 95	13.00	3.50
Udimet 720	18.00	2.50
René 88 DT	16.00	2.10
RR1000	14.60	3.00
René 104/ME3	13.00	3.40
Alloy 10	11.54	3.50

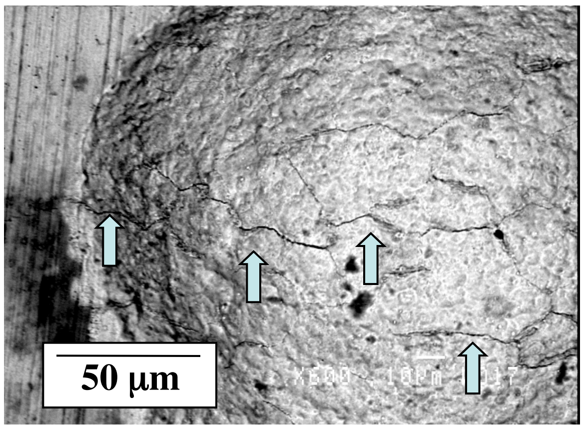
- Component time at temperature has steadily increased with newer engines

Corrosion Rate = Fn(Corrodant, Time, Temp, Alloy)

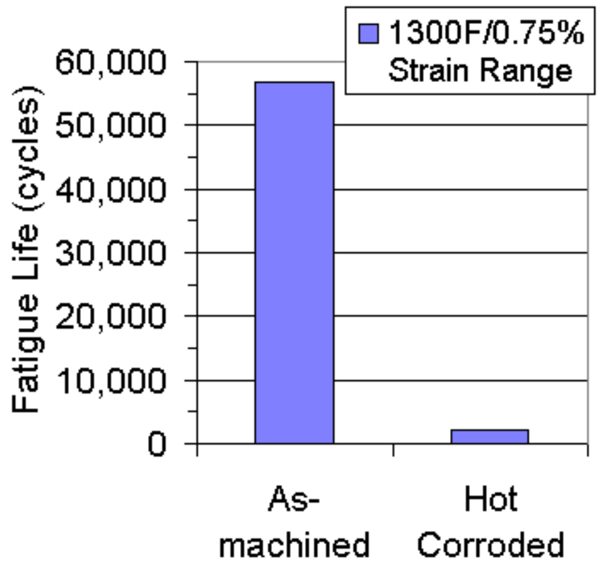
Hot Corrosion-Fatigue Interactions Limit Disk Fatigue Life

Hot corrosion damage limits ME3/R104 disk life and operating temperatures, with localized surface attack promoting premature fatigue cracking

Hot Corrosion Pit



Severe Effects on 1300°F Life



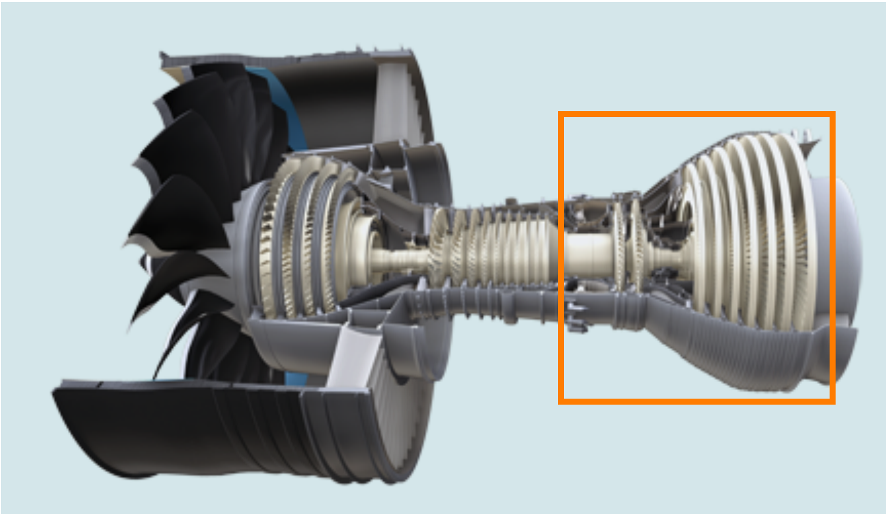
- Severe fatigue life effects and detailed microprobe damage mapping techniques have been demonstrated.

Objective

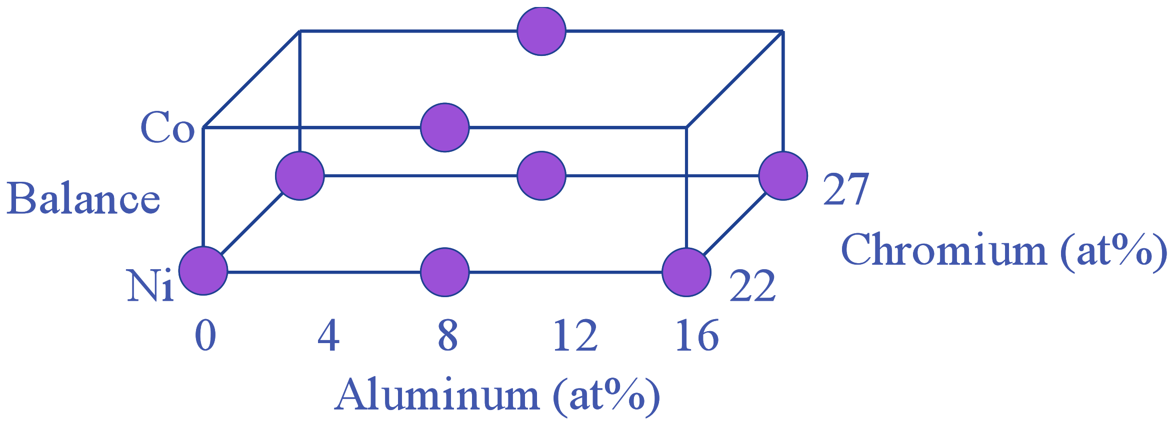
Mitigate Effects of Environment on Mechanical Properties of P/M Ni-base Disk Alloys

Goals:

- Develop coatings to protect advanced P/M alloy turbine disks from hot corrosion. Contracts awarded to both GE Aviation and Honeywell Aerospace in 2008 to develop coatings.
- Determine effects of oxidation on microstructure and low cycle fatigue life.
- Investigate oxidation behavior of hot corrosion coatings/Ni-base disk alloy system.



GE Approach: Ductile Coating – Compositions*



Assess Ni with three levels of Al and two levels of Cr.
Al → interdiffusion for coating adhesion
Cr → corrosion resistance

Coating Procedure:
- Physical Vapor Deposition onto R'104 substrate.
- Shot Peen and heat treat coating and substrate.

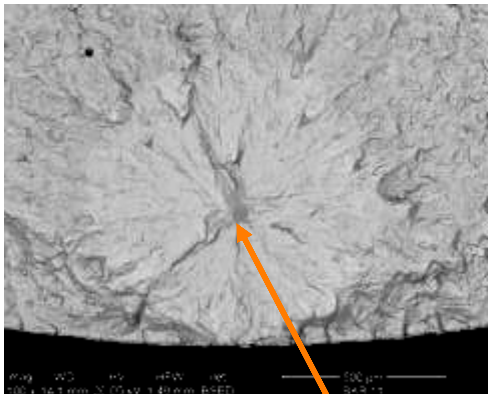
Corrosion Procedure:
- Corrodant (salt mixture) applied and sample thermally exposed in box furnace for 8 hours.
- Remaining residual corrodant removed and samples inspected for pitting.
- Corrodant reapplied and samples exposed to 2nd and 3rd exposures.

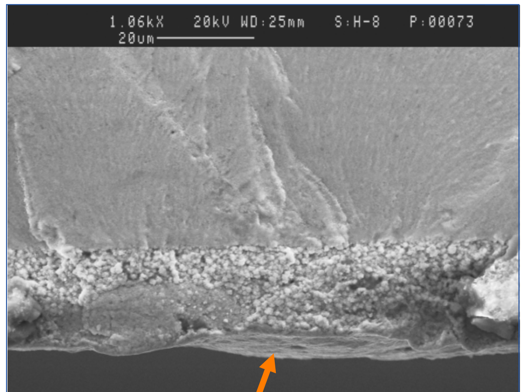
* US Patent # 7364801

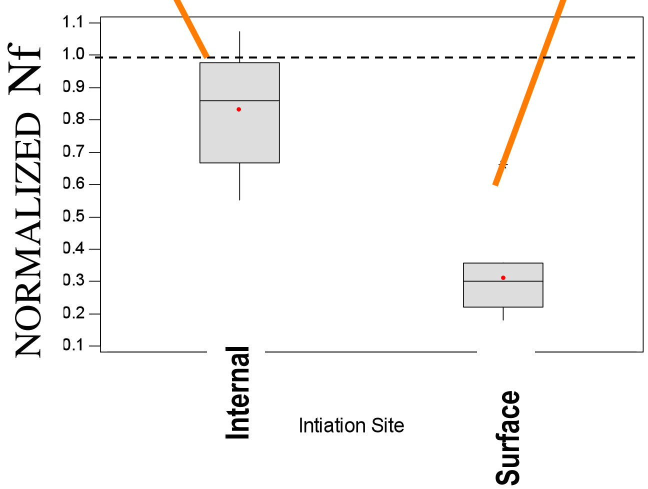
GE Coating LCF & Fractography

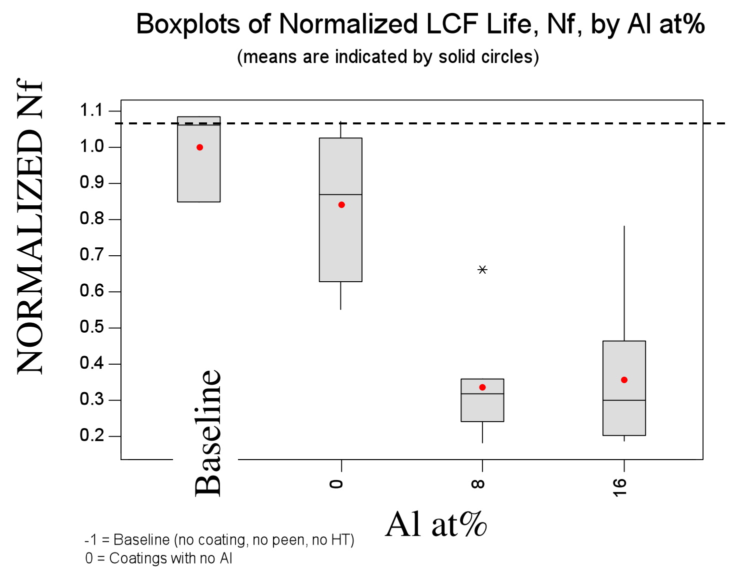
Ni-22Cr:
Internal Initiation

Other:
Surface Initiation







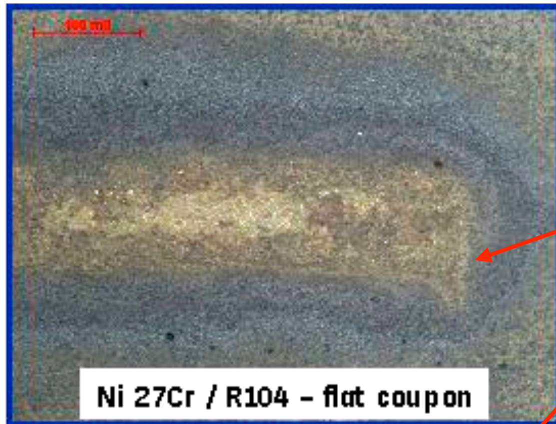


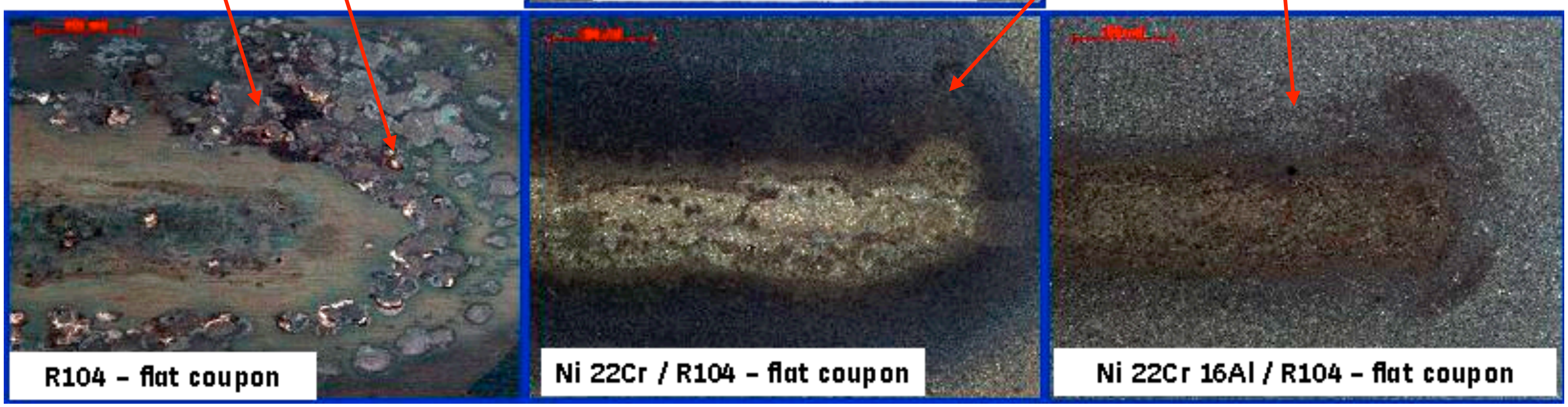
Surface initiated failures vs. internal failures correlate with the coating chemistry.

GE Coating Corrosion Resistance

Corrosion with pits on bare R'104 – 8 hr

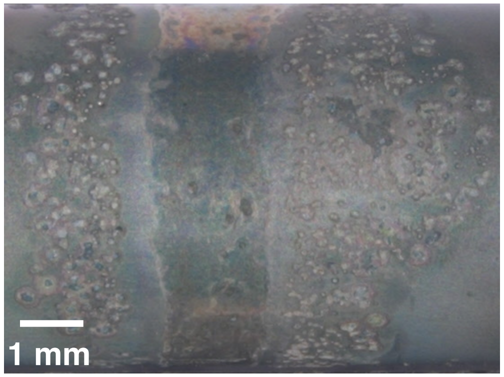
No Pitting on Coated Samples – 24 hr



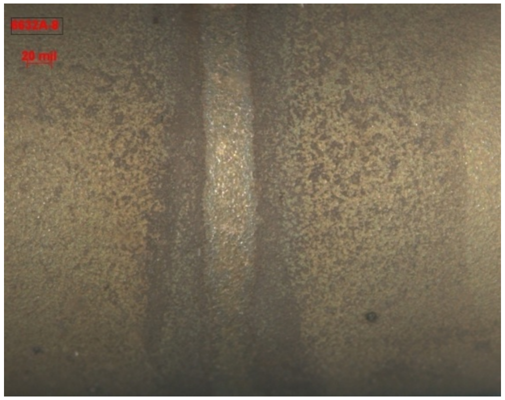


Coatings demonstrate at least three times the corrosion resistance of bare R'104.

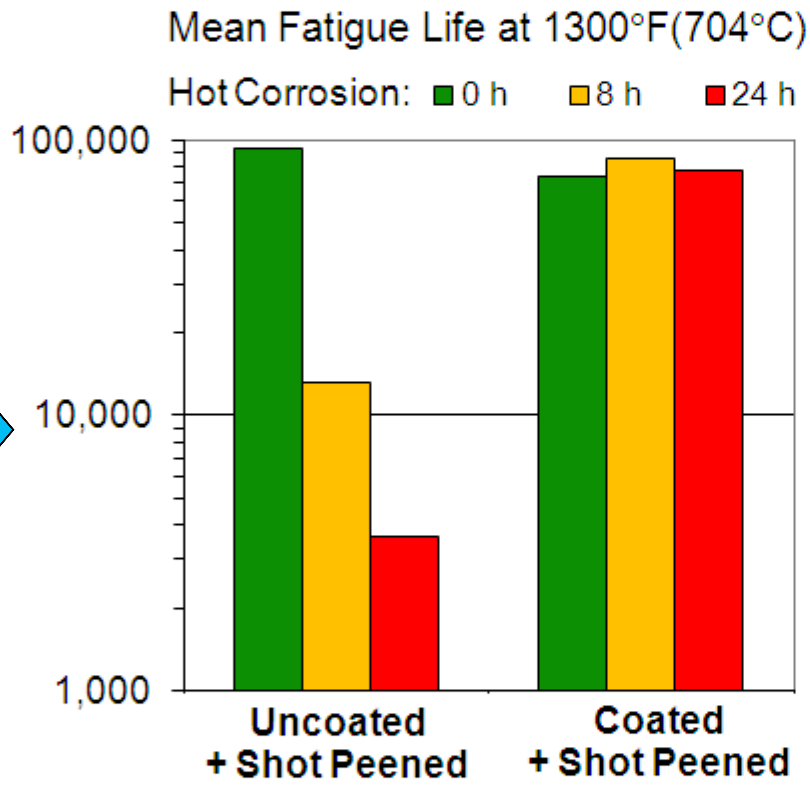
Key GE Results: Effects of Hot Corrosion Exposures on Uncoated vs. Coated Fatigue Life



Uncoated + 8h Hot Corrosion:
Oxidation plus excessive pitting

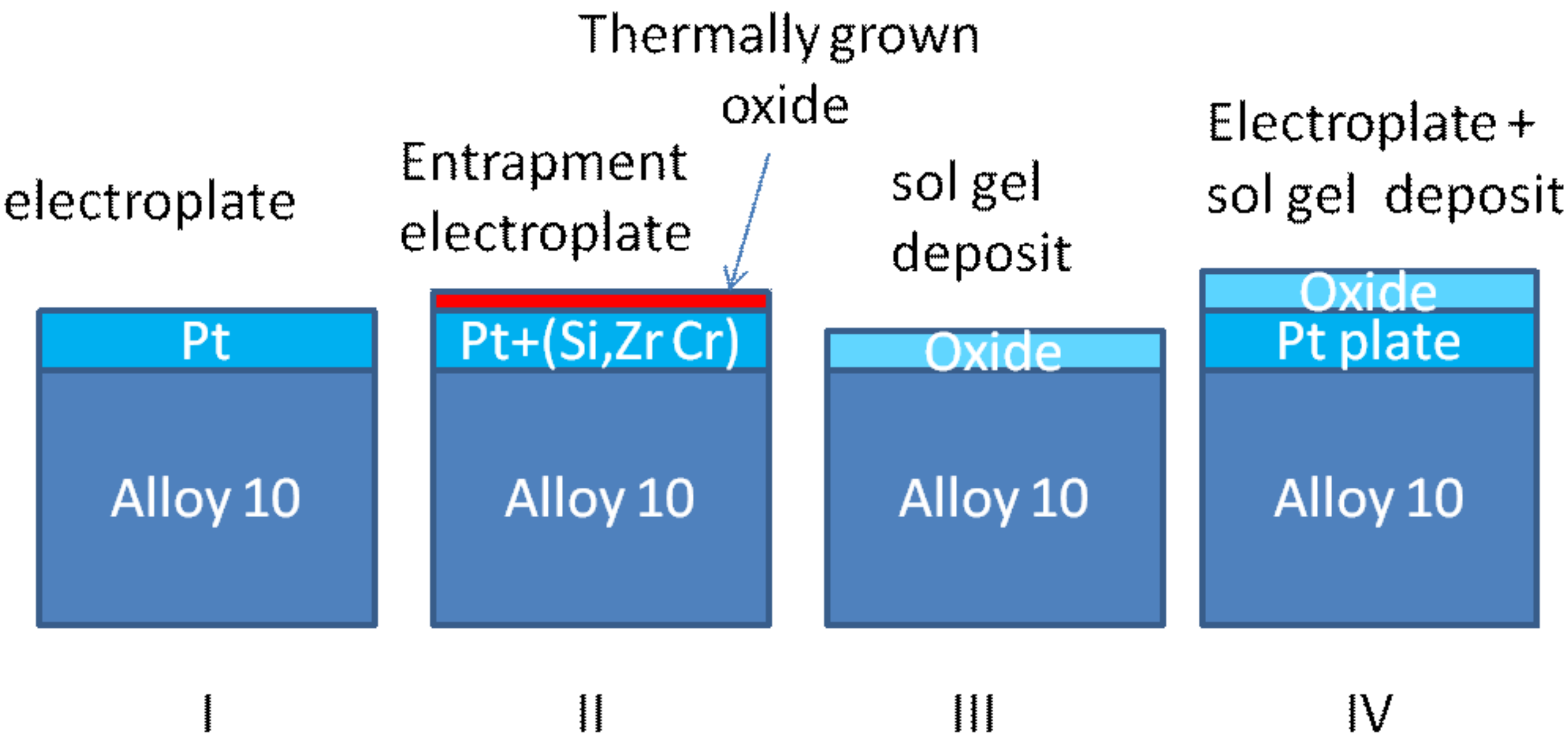


Coated (~0.0005" thick Ni22Cr coating)
+ 8 h Hot Corrosion:
Oxidation, but no evidence of spallation, pitting, or exposure of the R'104 substrate under 32x optical inspection.



Mean fatigue life no longer reduced by hot corrosion exposures

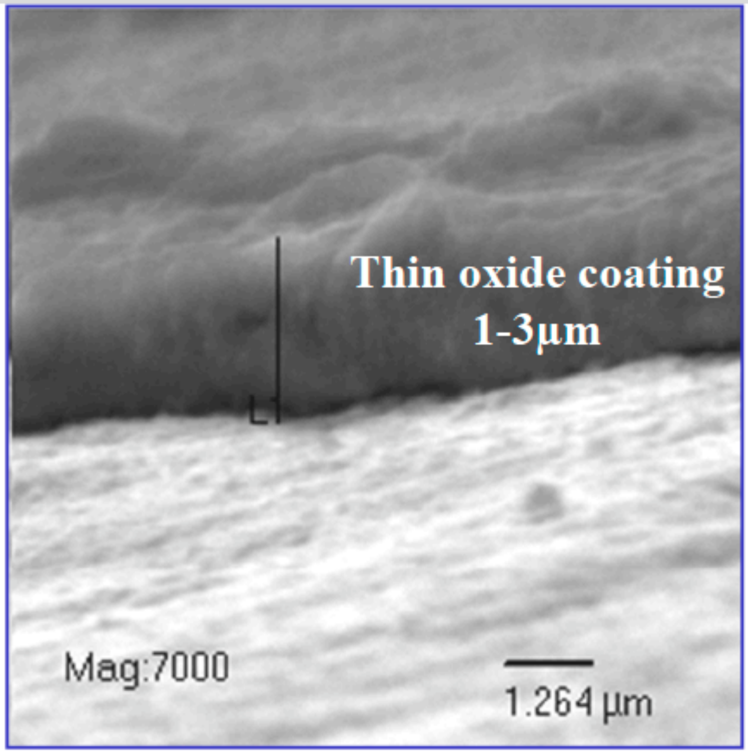
Honeywell Approach – Pt and Sol Gel Coatings



Corrosion Procedure:

- Sodium and Magnesium sulfates deposited on the surface
- 1292°F furnace with air + SO_2 gaseous environment

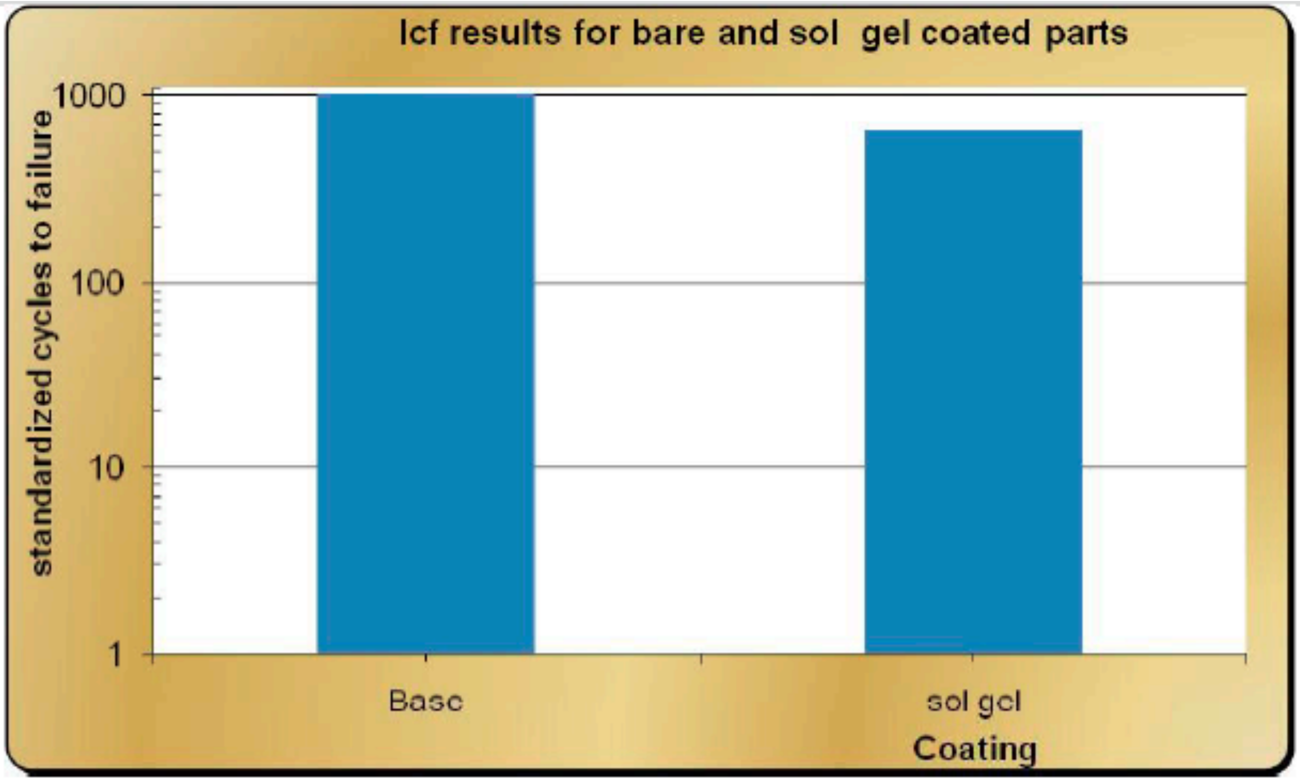
Honeywell Sol Gel Coating



Sol-gel processing:

- **Solution applied to substrate as a liquid at low temperature to form inorganic oxides.**
- **Controlled drying of the wet “gel” results in polymerization and a thin ceramic film.**
- **Densified by a thermal exposure/heat treatment.**

Honeywell Sol Gel Coating - LCF



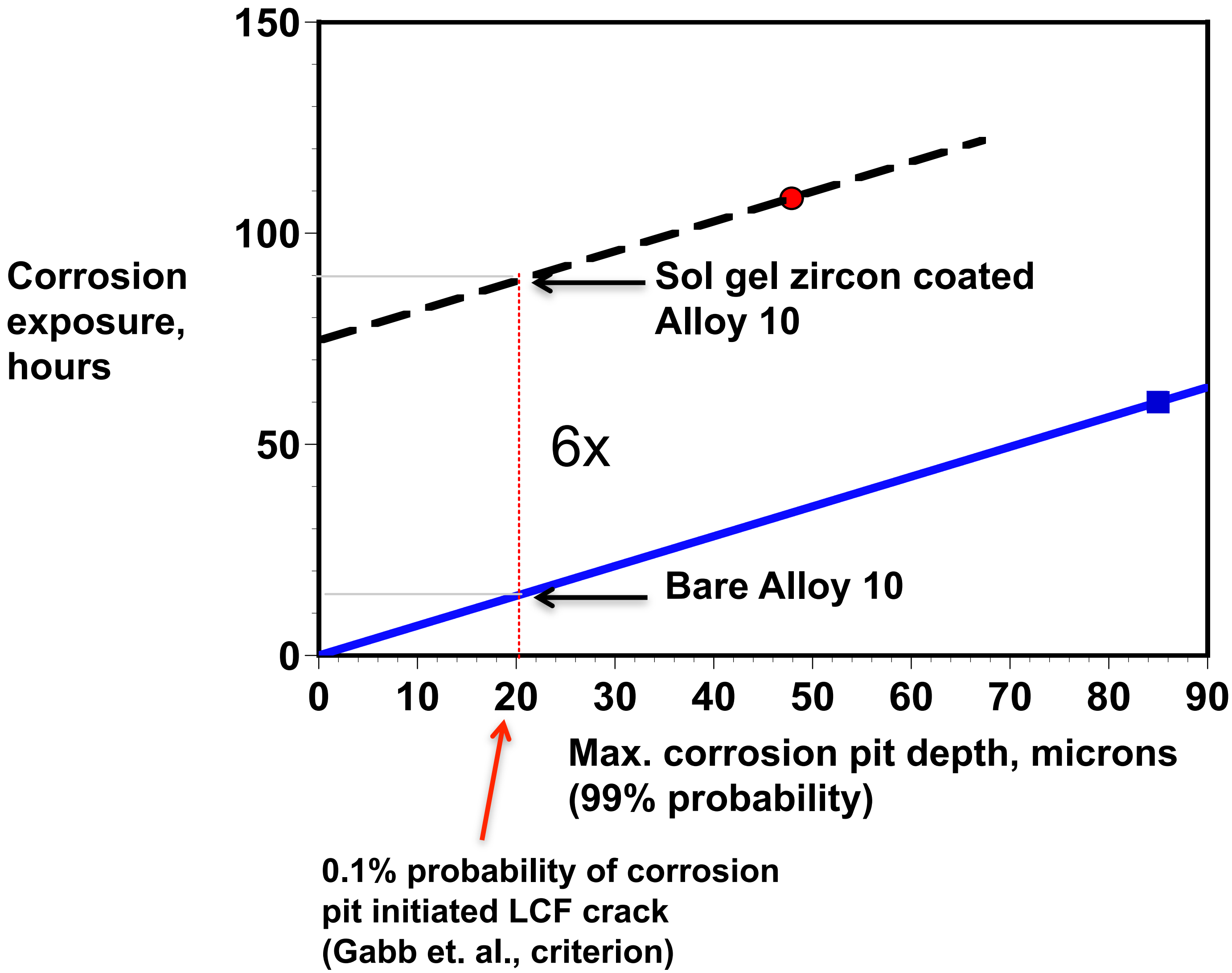
Normalized Cycles For 66% Probability Of Failure For The Baseline, (Uncoated) And Sol Gel Coated PM Alloy 10.

Data For Sol Gel Coating Within Scatter Of Bare Uncoated Alloy 10

No Or Minimal LCF Debit

Honeywell Sol Gel Zircon Coating Pit Initiation

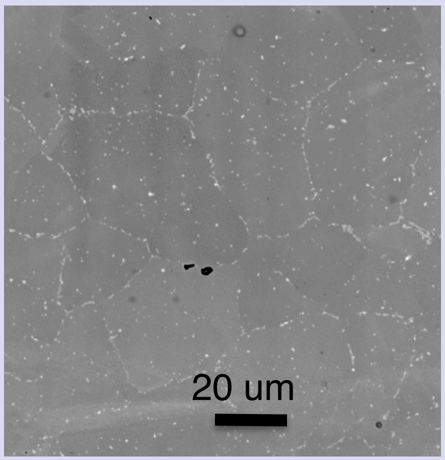
- 6x corrosion exposure time to form pits which initiate LCF

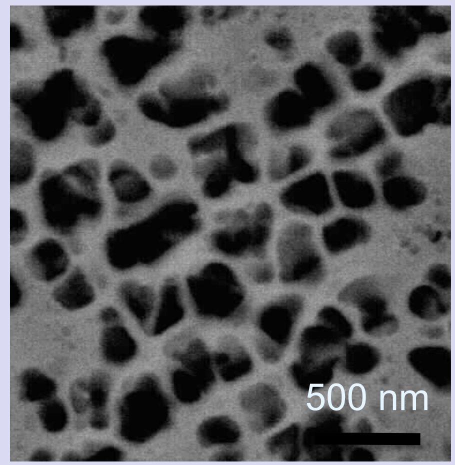


Effect of Oxidation Exposure on Microstructure and Fatigue Life

- ME3: Ni-21Co-13Cr-3.8Ti-3.7Mo-3.4Al-2.4Ta-2.1W-0.8Nb +
- Exposures in Air: 704 – 815 °C up to 2,020 hours
- Bare alloy vs. 12 um thick Nichrome coating
- GE Nichrome Coating: Excellent ductility, hot corrosion protection
  - **How will they respond in an oxidation environment?**

ME3





Grain size: 25 um – 34 um

Cr-rich $M_{23}C_6$ carbides ornament GBs

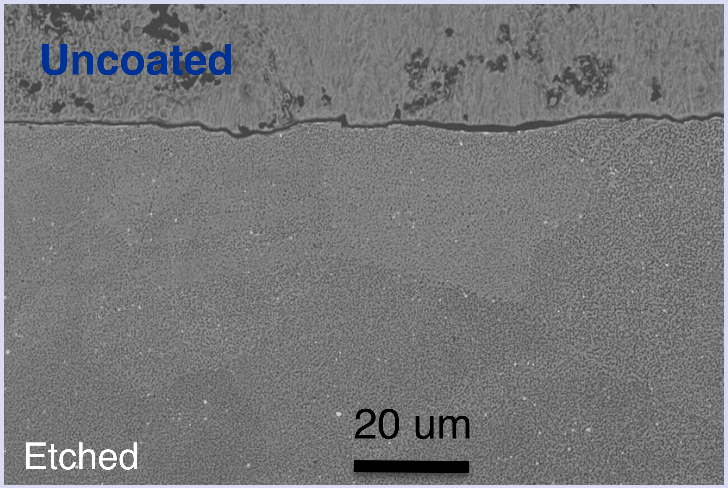
Ti-rich MC carbides, interior & GBs

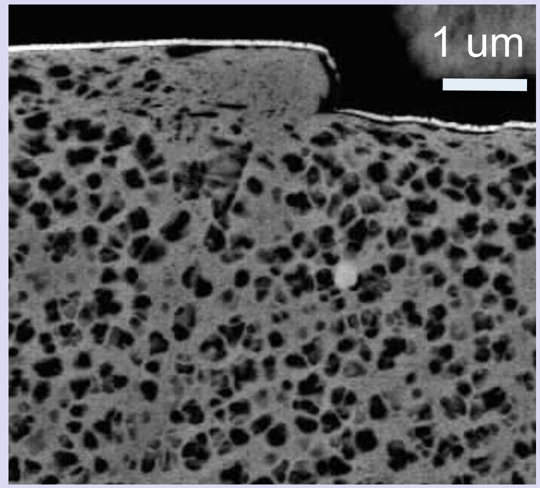
γ (fcc) with γ' ($L1_2$) precipitates

Secondary γ': 190 –330 nm

Tertiary γ', 18 – 39 nm

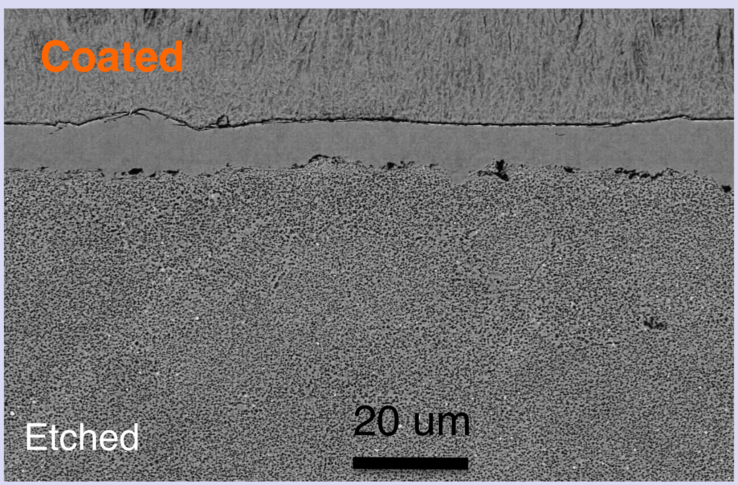
Nichrome Coated Samples-Supplied by GE, As-Processed

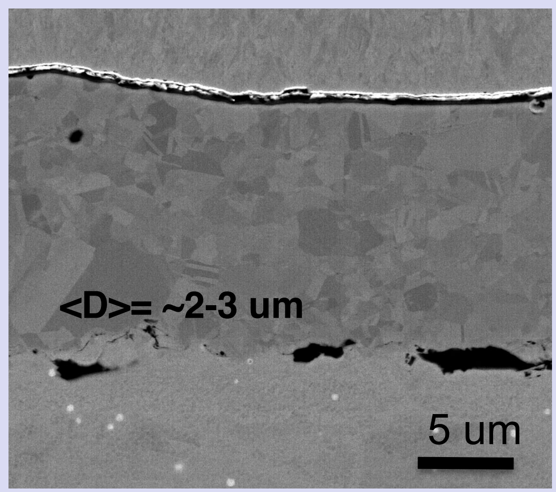




Low stress ground finish -32 RMS

Ni plated to preserve oxide



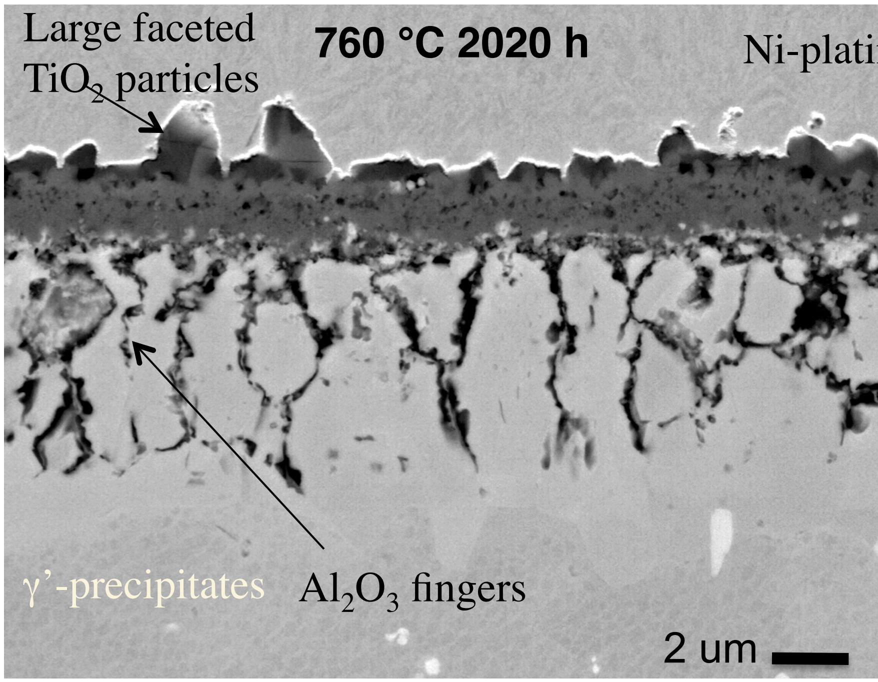


12 um of Nichrome (Ni-20Cr wt. %) deposited by PVD

Coated side shot-peened and vacuum heat treatment to reduce porosity

Representative Surface Microstructure after Oxidation

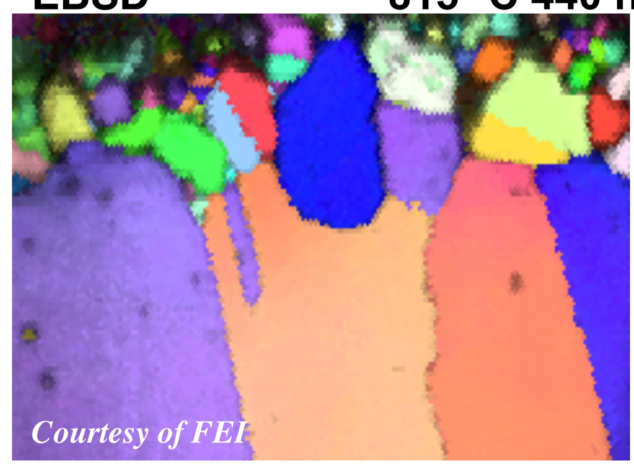
Uncoated ME3



Continuous external scale of Cr_2O_3 and TiO_2

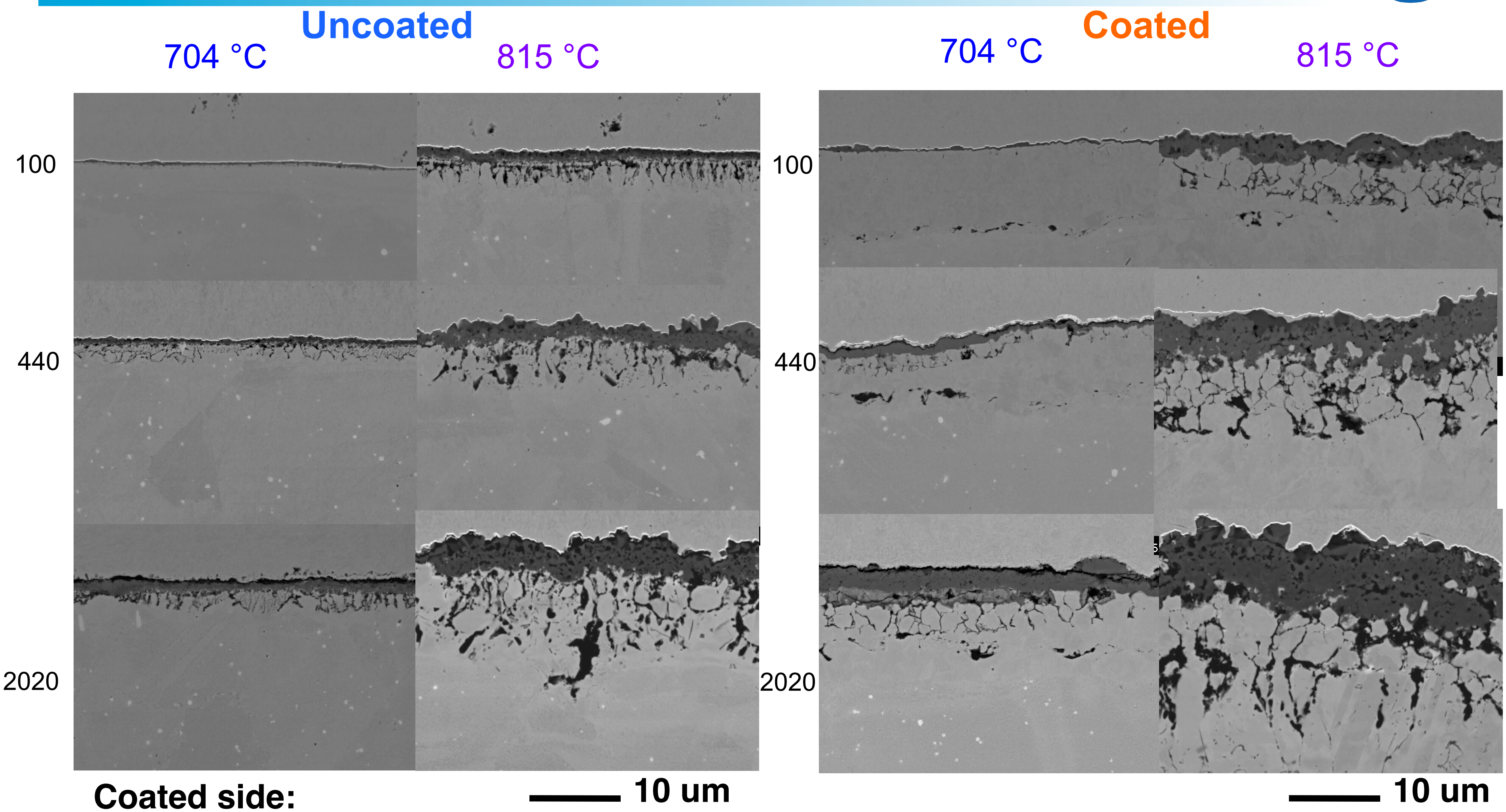
γ'-Denuded Zone
+
Recrystallized

EBSD **815 °C 440 h**



γ'-precipitate denuded zone recrystallized

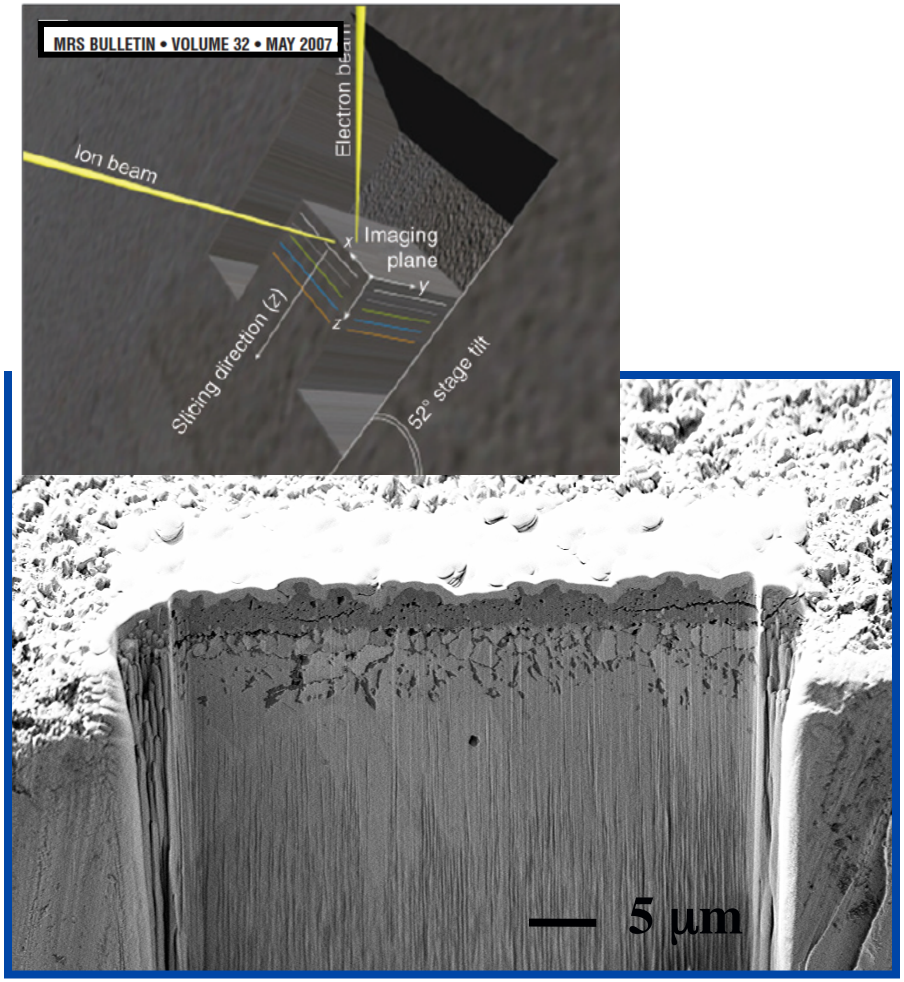
Surface Microstructure After Oxidation Exposures



Coated side:

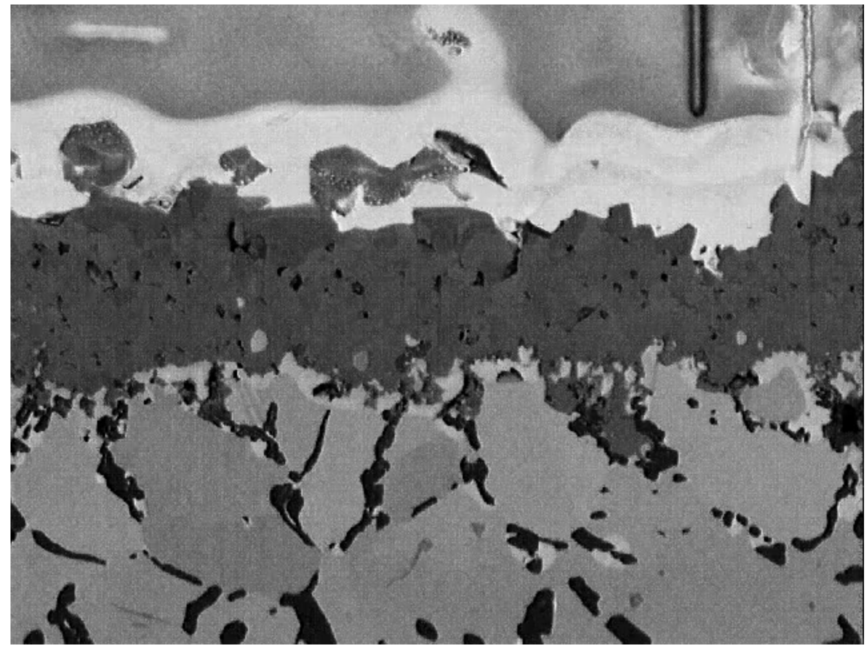
- Scale growth is faster than for the uncoated side
- XRD / Microprobe verify same phases: Cr_2O_3 +TiO_2 scale, Al_2O_3 fingers
  - Titanium migrates through the coating to form deleterious TiO_2

FIB 3D tomography: 6 h acquisition



Uncoated ME3: 440 h at 815°C

View area: 9.1 um x 12.4 um, 700 0.01 um slices



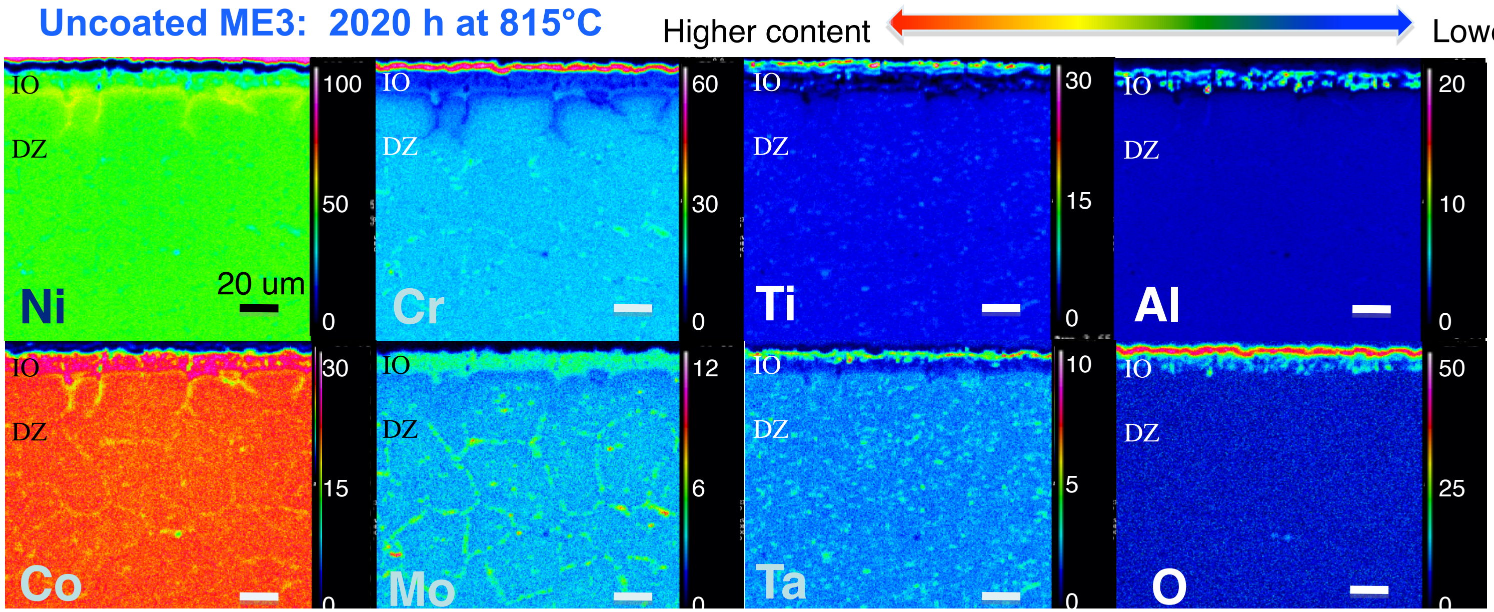
1 µm

- ***Atomic migration leads to the formation of near surface voids***

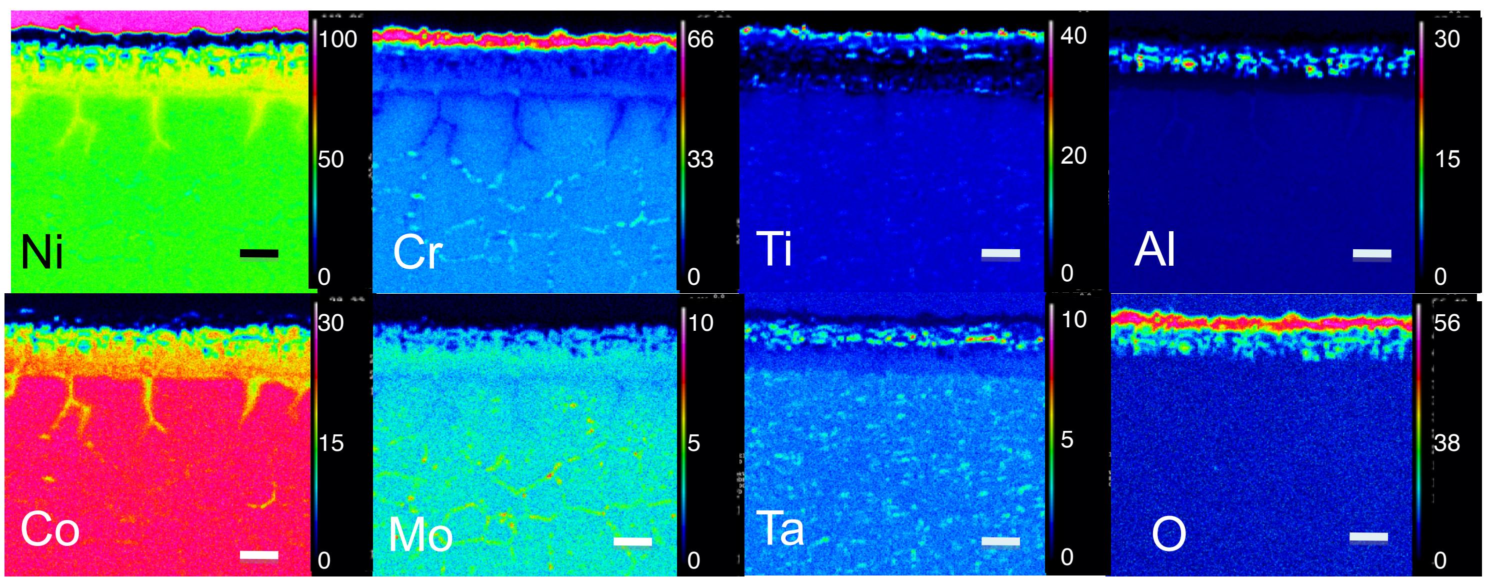
- **Watch: Al_2O_3 finger network evolve and near surface voids**
- **High imaging contrast present beneath external scale verified to be $CrTaO_4$**

Microprobe Chemical Mapping

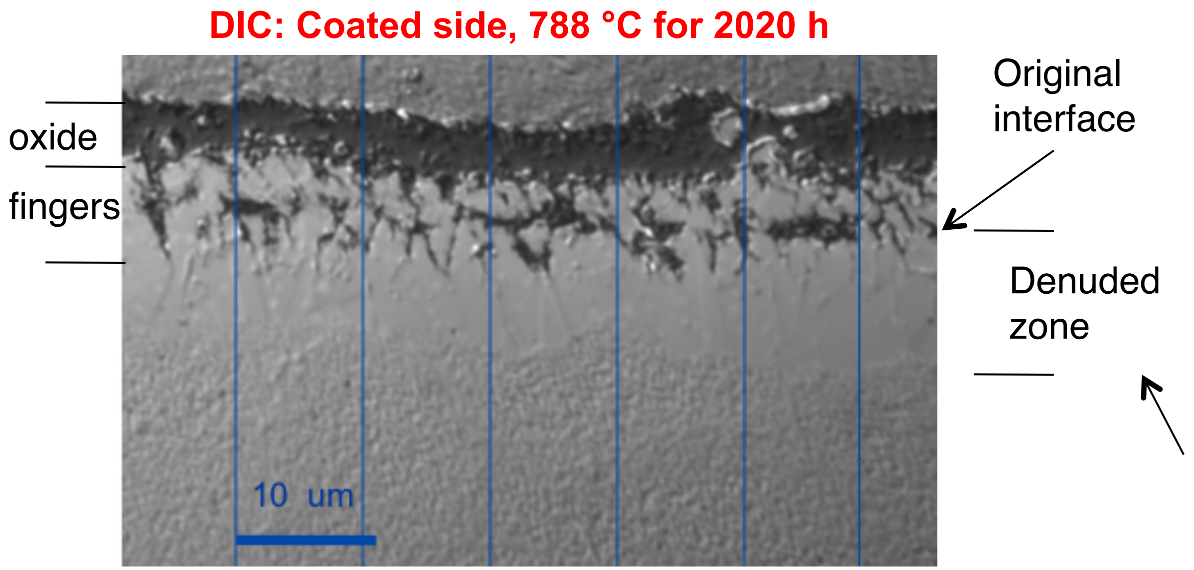
Uncoated ME3: 2020 h at 815°C



Coated ME3: 2020 h at 815°C



Quantification of Microstructural Changes due to Oxidation



•Scale thickness and Al2O3 finger depth measured from SEM photos

•Denuded zone depth measured from optical DIC photos

•Carbide dissolution measured by Microprobe analysis

Microstructual Characterization after 2020 h Exposure

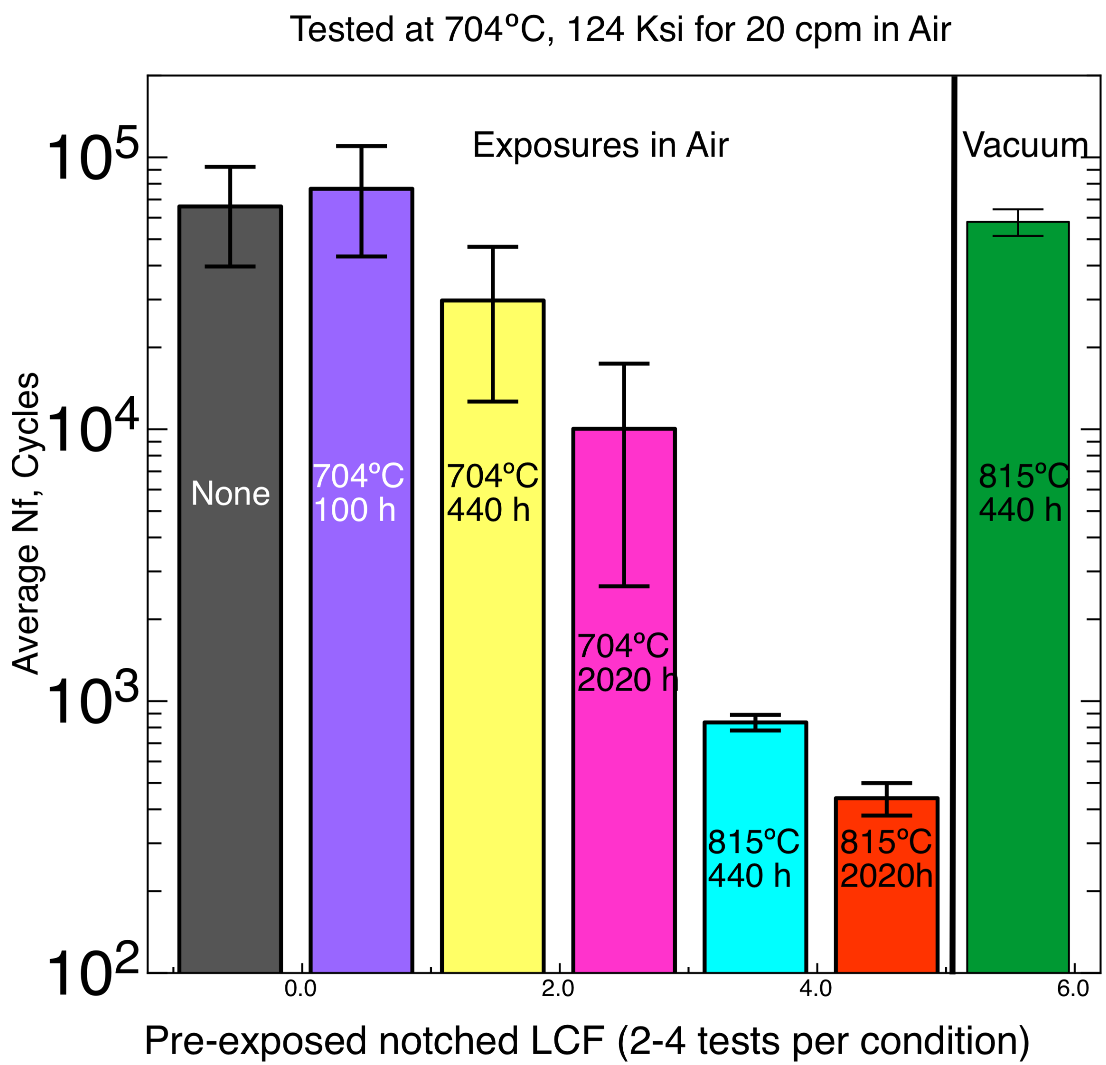
$$y = (k \cdot t)^n$$

Growth rate law. Diffusion rate constant, k, changes with temperature according to an Arrhenius relationship.

Uncoated	Scale Thickness (um)	Alumina Penetration (um)	Denuded zone (um)	Carbide dissolution (um)
Distributed	Log normal	Normal	Normal	–
n	1/3	1/2	1/3	
704°C	1.32 ± 0.61	2.88 ± 0.81	3.14 ± 1.01	9.6 ± 2.3
760°C	1.97 ± 0.67	5.23 ± 0.67	5.96 ± 1.20	16.4 ± 2.4
816°C	3.79 ± 1.57	10.00 ± 1.16	10.75 ± 1.13	21.0 ± 1.9

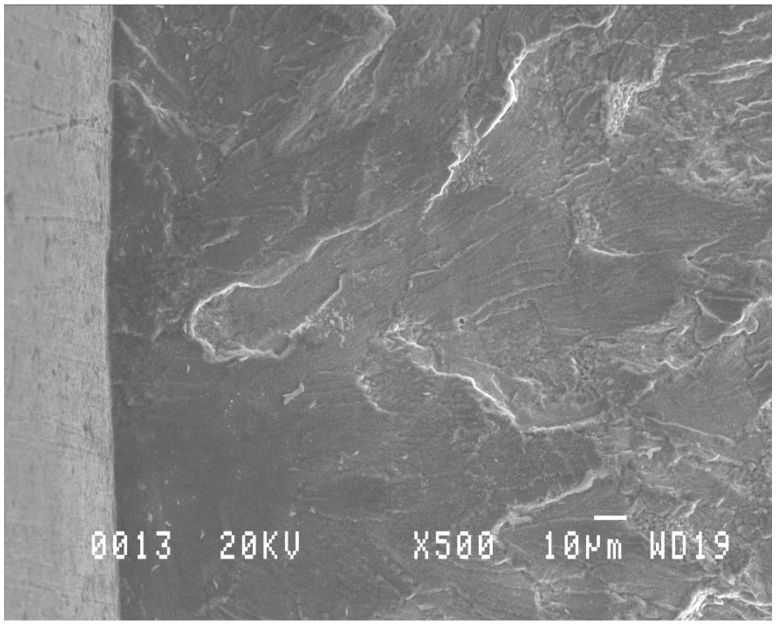
Coated	Scale Thickness (um)	Alumina Penetration (um)	Denuded zone (um)	Carbide dissolution (um)
Distributed	Log normal	Normal	Normal	–
n	1/2	1/2	1/2	1/2
704°C	2.55 ± 1.65	3.52 ± 0.82	4.42 ± 0.85	13.1 ± 1.3
760°C	5.29 ± 1.87	10.17 ± 1.33 (0.6)	10.85 ± 1.43	19.9 ± 2.2
816°C	6.23 ± 2.40	25.07 ± 1.66 (11.5)	14.60 ± 2.39	29.3 ± 1.5

Pre-oxidation Exposures Detrimental to Fatigue Life



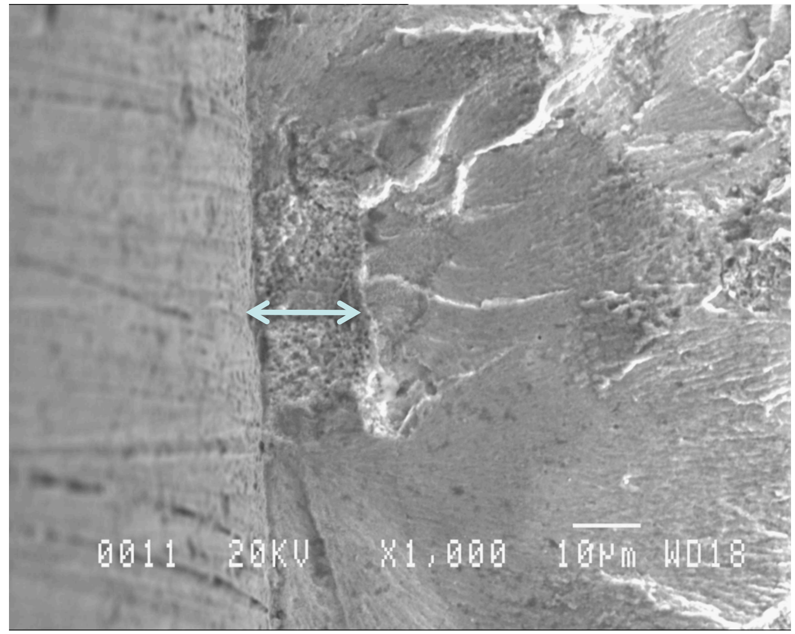
Pre-Exposures Change Fracture Initiation Mode

H111-NNR4
Exposure: None
Test 704°C – 20 cpm; N_f = 84588



Transgranular Fracture

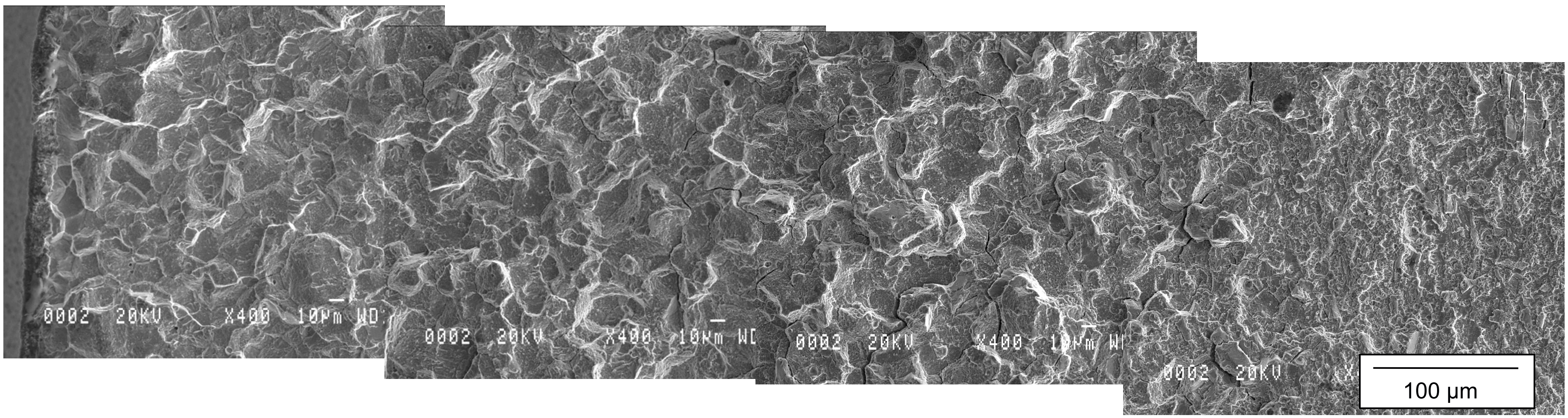
S101A – NER9
Exposure: 704°C – 440 h
Test: 704°C- 20 cpm; N_f = 4,531



16 µm Intergranular Fracture;
Transition to Transgranular Fracture

Extent of Intergranular Fracture Increases with Exposure

H101-NLR1
Exposure: 815°C – 2020 h
Test 704°C – 20 cpm; N_f = 482 cycles



Transition from Intergranular to Transgranular – 0.8 mm

Conclusions

- Environmental exposure, both corrosion and oxidation, has a detrimental affect on fatigue life of ME3.
- Initial investigations have identified two viable corrosion resistant coatings for PM superalloy disks, Ni-22Cr and sol-gel Zircon. Both systems are being further investigated under new NRA contracts with GE and Honeywell.
- Nichrome coating on ME3 accelerated the rates of scale, finger, and layer growth. Ti, Al, and Ta diffuse through the Cr-rich coating to form oxides.
- Al_2O_3 finger penetration shows a power law dependence of $(\text{time})^{1/2}$
- Scale growth and denuded zone of uncoated ME3 shows a power law dependence of $(\text{time})^{1/3}$, whereas coated ME3 shows $(\text{time})^{1/2}$
- Failure of pre-exposed LCF samples initiates at the surface and proceeds intergranularly before transitioning to transgranular fracture. Length of intergranular fracture increases with microstructural damage due to exposure.

Future work:

- Oxidation and fatigue study of sol-gel Zircon coated LCF samples.

Questions ?