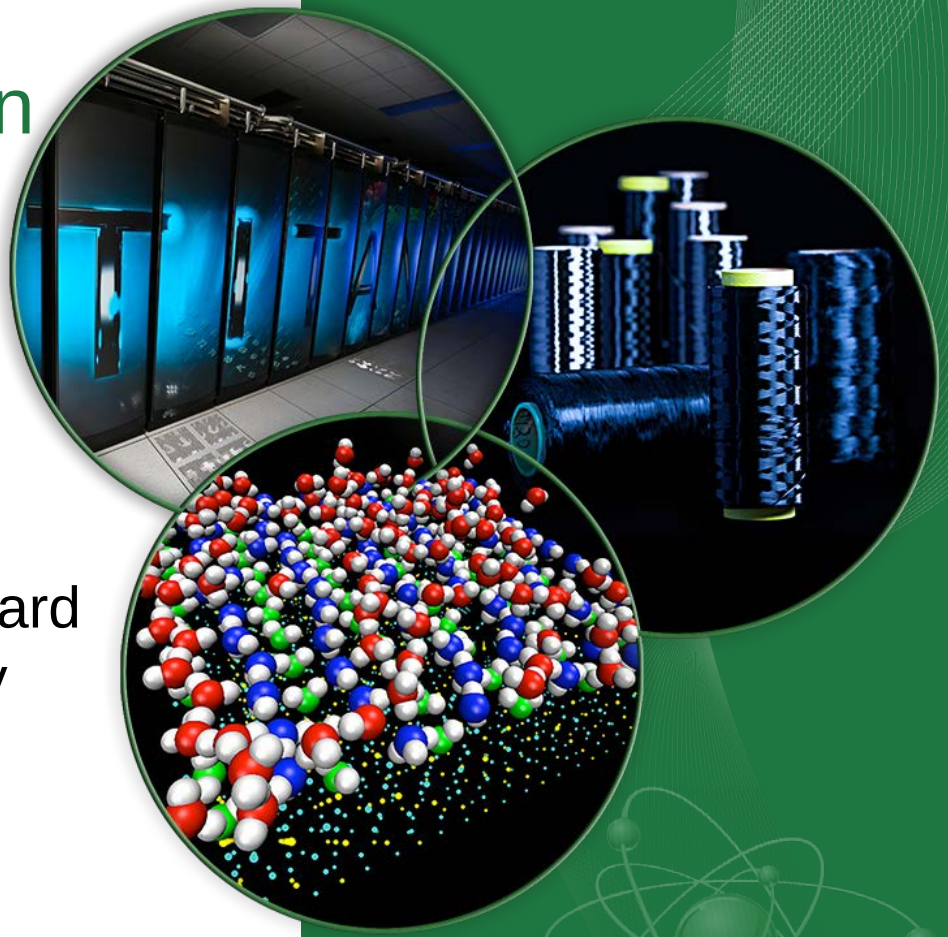
Characterization Of Turbomachinery Materials Exposed In 750°C, 20 MPa sCO_2



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Presentation Outline

- Background and motivation
- Description of ORNL test facilities
- Test plan
- Results of corrosion coupon exposures
  - weight change
  - light microscopy and SEM
- Results of C-ring sample exposures
  - weight change
  - light microscopy, SEM, electron microprobe
- Summary

ORNL Studies Supported Project On Advanced Turbomachinery For Supercritical CO_2 Power Cycles

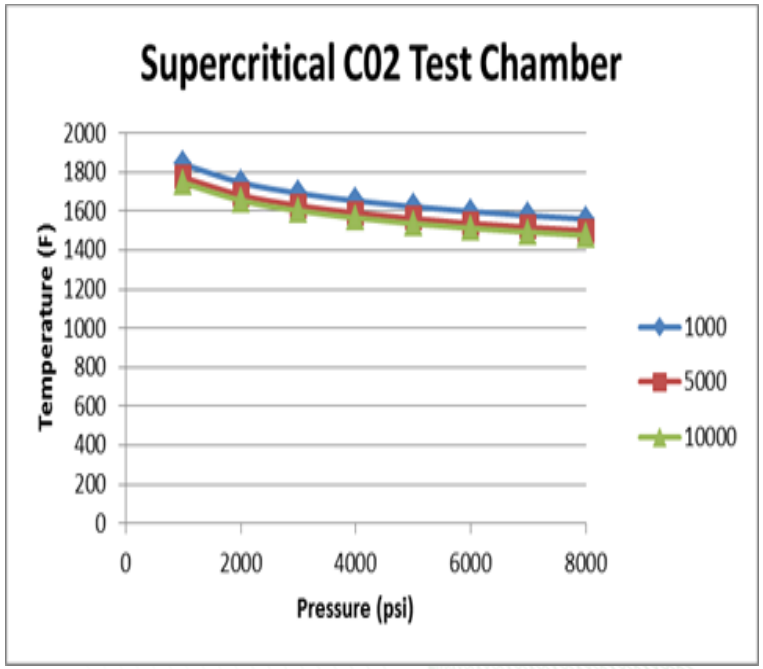
- ORNL is one member of the project team
- Project goal was to define sCO_2 turbomachinery concepts and applicability to indirectly and directly-heated cycles
- One task was to conduct compatibility tests of candidate materials in sCO_2
- ORNL was responsible for conducting exposure tests in sCO_2 and characterizing samples after exposure

Alloys Selected For Testing Represented Several Components In An Advanced Turbine

Material	Application	Flat Coupons	Stressed C-Rings
HK40	Housing	3	3
HK50	Housing	3	
CAFA7	Housing		3
DAFA30	Housing		3
Alloy 282 (cast)	Housing		3
Waspaloy	Disk	3	3
Udimet 720	Disk	3	
Alloy 718	Disk	3	3
A-286	Disk	3	
René 41	Disk	3	
CMSX-8	Blade		3
PWA 1483	Blade		3
René N4	Blade		3
CMSX-4	Blade		3

ORNL Autoclaves Used For This Project Were Designed To Achieve Extreme Test Conditions

- Autoclaves are fabricated from Haynes 282 (UNS N07208) alloy which was developed for hot-gas-path components of aircraft engines and land-based gas turbines
- Alloy is a gamma-prime strengthened superalloy with excellent creep strength in the 649-927°C (1200-1700°F) range
- As shown on the chart, the system is capable of pressures as high as 55.2 MPa (8000 psi) at a temperature of about 816°C (1500°F) or 20.0 MPa (2950 psi) at 871°C (1600°F)



ORNL Autoclaves Are Designed For Safe And Versatile Operations

- Autoclave positioned vertically in a 3 zone furnace
- 99.995% purity sCO_2 is fed to the bottom of the autoclave and flows up over the samples
- Fluid is provided by a dual piston pump at a rate up to 24 ml/min; but generally 1-2 ml/min
- Back pressure control valve is used to maintain system pressure
- Rupture disc and a pressure relief valve prevent over pressurization
- Thermowell in center of autoclave permits measurement of sample temperature

ORNL Conducted Three sCO_2 Tests Then Examined Samples After Exposure

- Tests were conducted for 500 hours at 750°C and 20 MPa (2900 psi)
- First test exposed 21 corrosion coupons
- Second test exposed 16 C-rings
- Third test exposed an additional 14 C-rings
- Post exposure characterization included weight change determination as well as light microscopy, scanning electron microscopy and microprobe examinations

Corrosion Coupon Studies

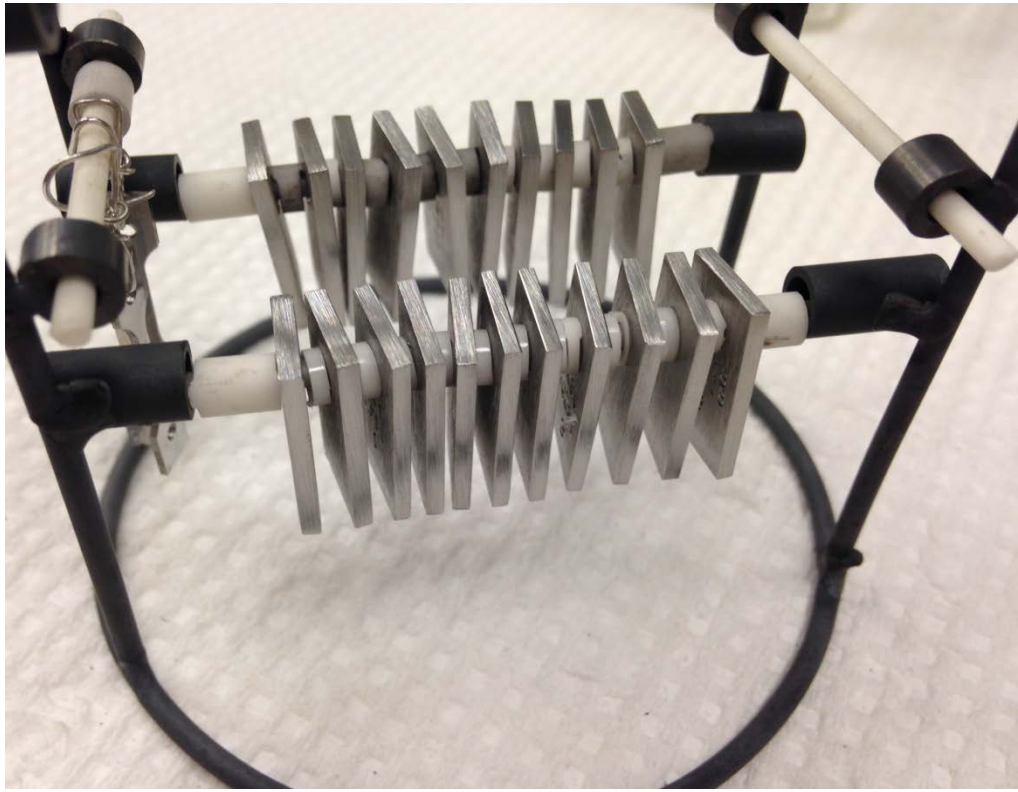
Seven Alloys (3 samples of each) Were Exposed As Corrosion Coupons

Alloy	Application	Ni	Cr	Co	Mo	Fe	Al	Ti	C	Other
		wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%
Alloy 718	Disk	52	19		3.0	19	0.5	0.9	0.04	Nb 5.1
HK50	Housing	20	26		0.5	Bal			0.5	
Waspaloy	Disk	58	19	14	4.3	2	1.5	3.0	0.08	
HK40	Housing	20	26		0.5	Bal			0.4	
Udimet 720	Disk	55	18	15	3.0		2.5	5.0	0.03	W 1.3
René 41	Disk	52	19	11	10	5	1.5	3.1	0.09	
A-286	Disk	26	15		1.3	54	0.2	2.0	0.05	

Three samples of each alloy were exposed in the first sCO_2 test

The 21 Corrosion Coupons Were Supported On a Rack Near The Bottom Of The Autoclave

- Samples are supported on alumina bars which are held in an alloy 282 metal rack with alumina insulators separating the samples
- Fluid is pumped into the autoclave through a tube that extends to the bottom of the autoclave



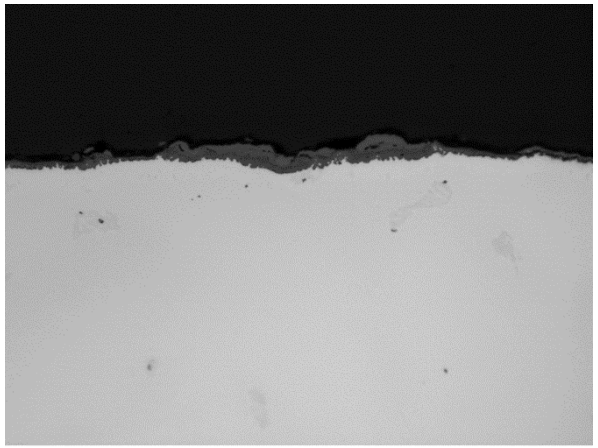
- A thermowell in the center of the autoclave permits temperature measurement of the fluid very near the samples

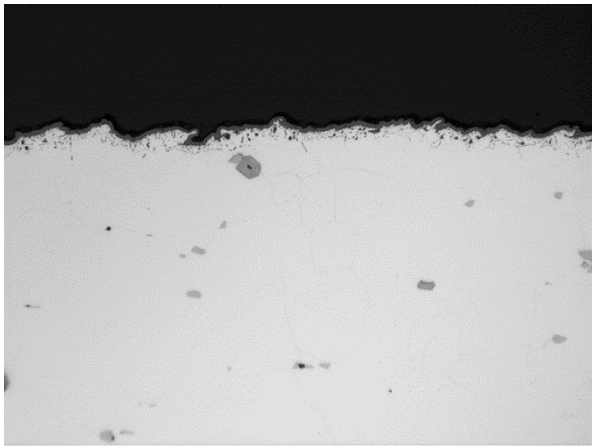
After 500 h Exposure, Weight Change Varied Considerably Between The Alloys

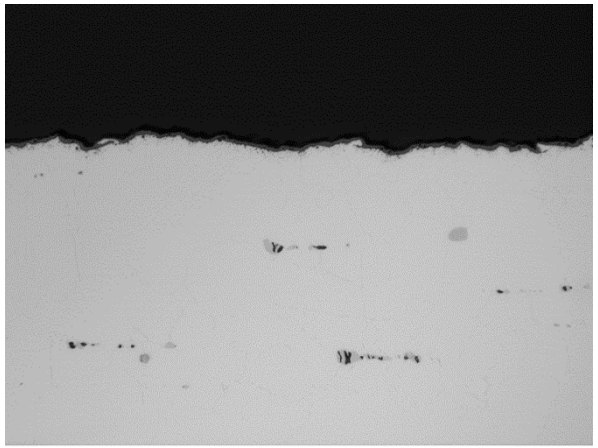
	Sample #1	Sample #2	Sample #3	Average
	mg/cm^2	mg/cm^2	mg/cm^2	mg/cm^2
A-286	17.27	17.70	17.88	17.62
René 41	0.55	0.54	0.56	0.55
Udimet 720	0.53	0.55	0.55	0.54
HK40 (cast)	0.49	0.49	0.56	0.51
Waspaloy	0.40	0.34	0.37	0.37
HK50 (cast)	0.41	0.32	0.28	0.34
Alloy 718	0.28	0.27	0.34	0.30

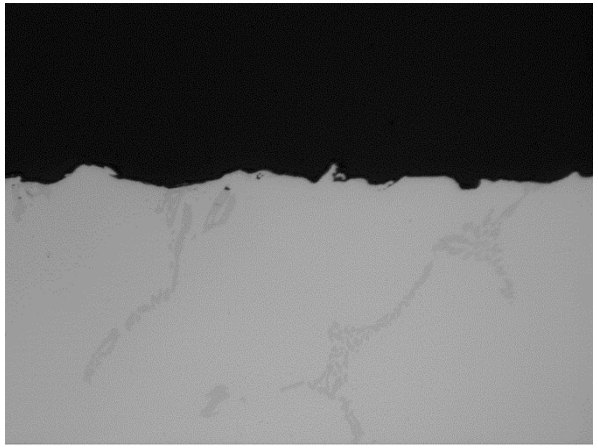
On the basis of these results, the A286 alloy was dropped and three of the others were selected for testing as C-rings

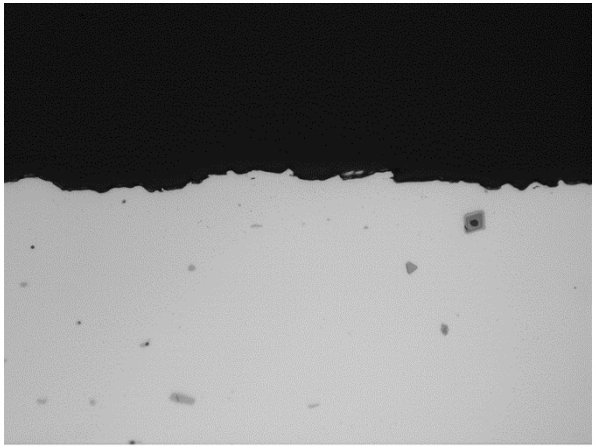
Micrographs Of Exposed Samples Showed Thin, Continuous Oxide Versus Control

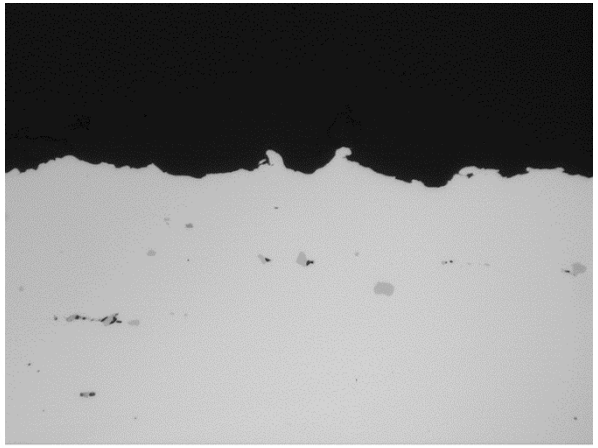












Exposed Waspaloy had shallow subsurface attack

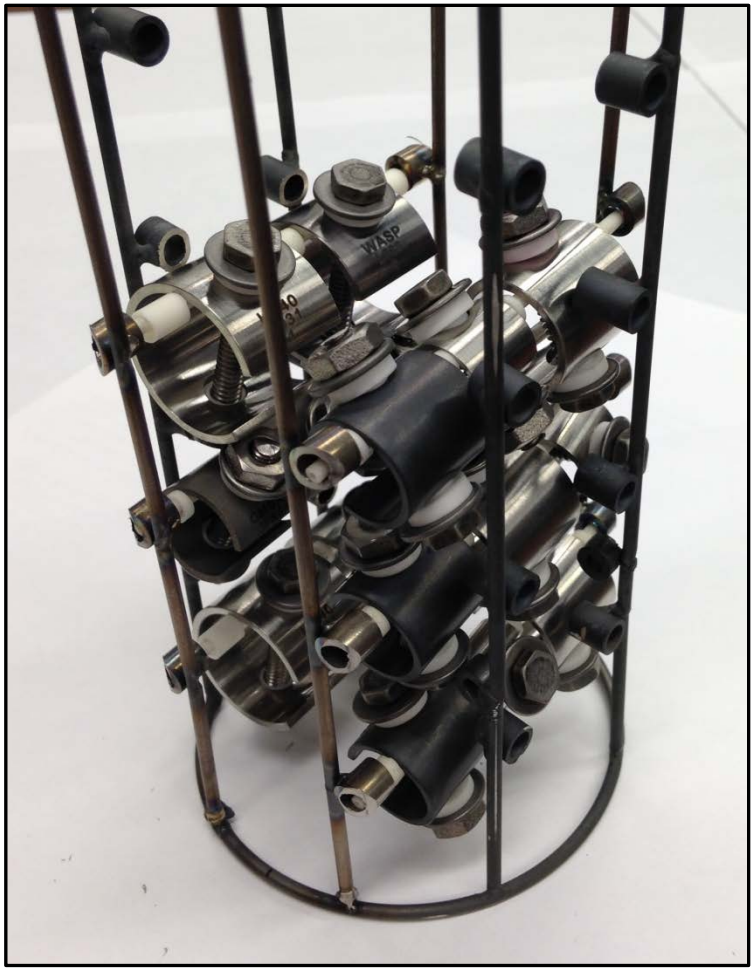
C-Ring Sample Studies

To Further Evaluate The Effect Of sCO_2 On Alloys, Stressed Samples Were Tested

Alloy	Application	Ni	Cr	Co	Mo	Fe	Al	Ti	C	Other
		wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%
PWA1483	Blade	Bal	12.2	9.0	1.9		3.6	4.1		W 3.8, Ta 5.0
CAFA7	Housing	25	15		2.0	Bal	3.5		0.4	W 1.0, Nb 1.0
René N4	Blade	Bal	9.0	8.0	2.0		3.7	4.2		W 6.0, Ta 4.0, Nb 0.5
Waspaloy	Disk	58	19	14	4.3	2	1.5	3.0	0.08	
HK40	Housing	20	26		0.5	Bal			0.5	
CMSX-4	Blade	Bal	6.5	10	0.6		5.6	1.0		W 6.0, Ta 6.0, Re 3.0
H 282 (cast)	Housing	57	20	10	8.5	1.5	1.5	2.1	0.06	
DAFA30	Housing	33	14			Bal	2.7	1.6	0.1	Nb 2.8
CMSX-8	Blade	Bal	5.4	10	0.6		5.7	0.7		W 8.0, Ta 8.0, Re 1.5
Alloy 718	Disk	52	19		3.0	19	0.5	0.9	0.04	Nb 5.1

C-ring samples of these alloys were prepared and stressed to 75%, 85% and 95% of the 500 hour rupture stress

C-Ring Samples Were Also Supported On Alumina Rods On The Metal Rack



- Second sCO_2 test with 16 of the C-ring samples before exposure

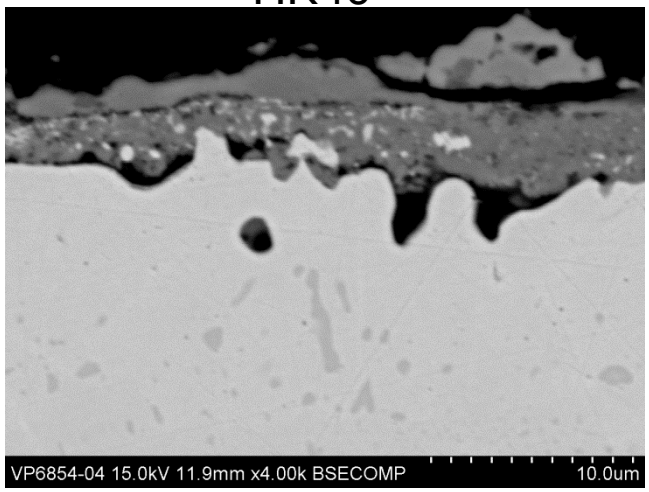
First Set Of C-Rings Showed Varying Degrees Of Attack

After 500 h, Measured Weight Changes Showed Considerable Differences Between Alloys

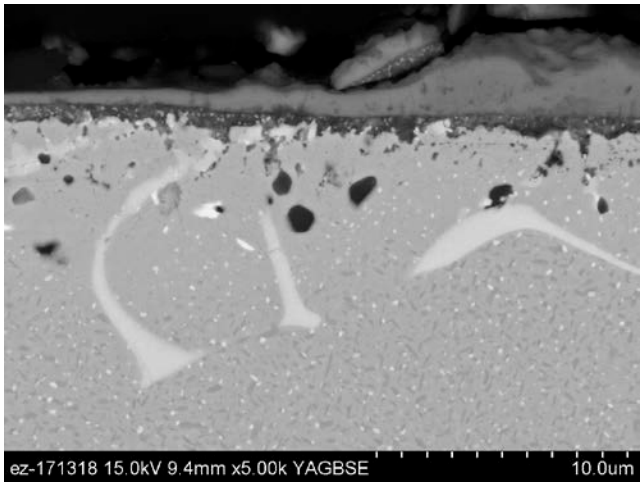
Alloy	Application	Sample 1	Sample 2	Sample 3	Average
		mg/cm^2	mg/cm^2	mg/cm^2	mg/cm^2
DAFA30	Housing	0.94	1.11	1.09	1.05
HK40	Housing	0.82	0.71	0.69	0.74
CAFA7	Housing	0.52	0.56	0.58	0.55
PWA1483	Blade	0.43	0.50	0.52	0.48
Waspaloy	Disk	0.27	0.29	0.24	0.27
Cast H282	Housing	0.29	0.22	0.26	0.26
Alloy 718	Disk	0.20	0.24	0.25	0.23
CMSX-4	Blade	0.20	0.19	0.21	0.20
René N4	Blade	0.10	0.19	0.11	0.13
CMSX-8	Blade	0.11	0.13	0.04	0.09

SEM BSE Micrographs Of Housing Alloys

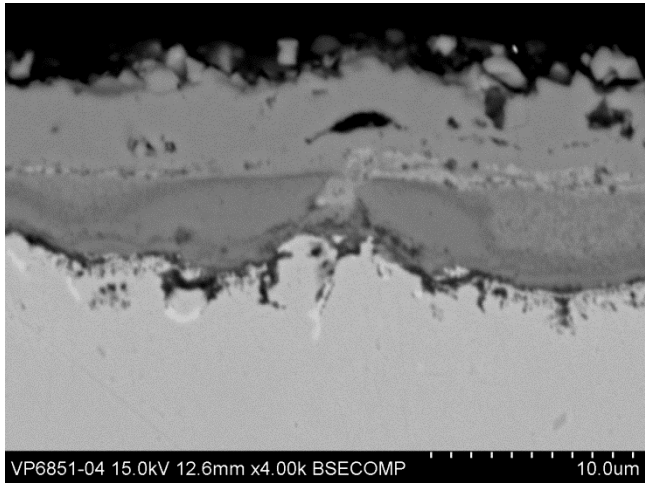
HK40



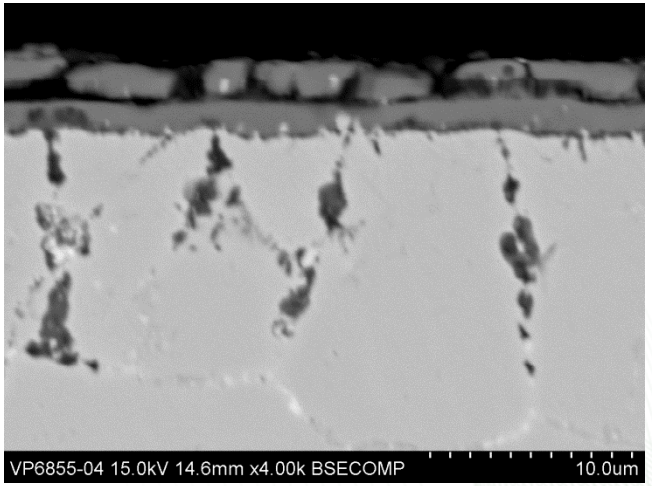
CAFA7



DAFA30



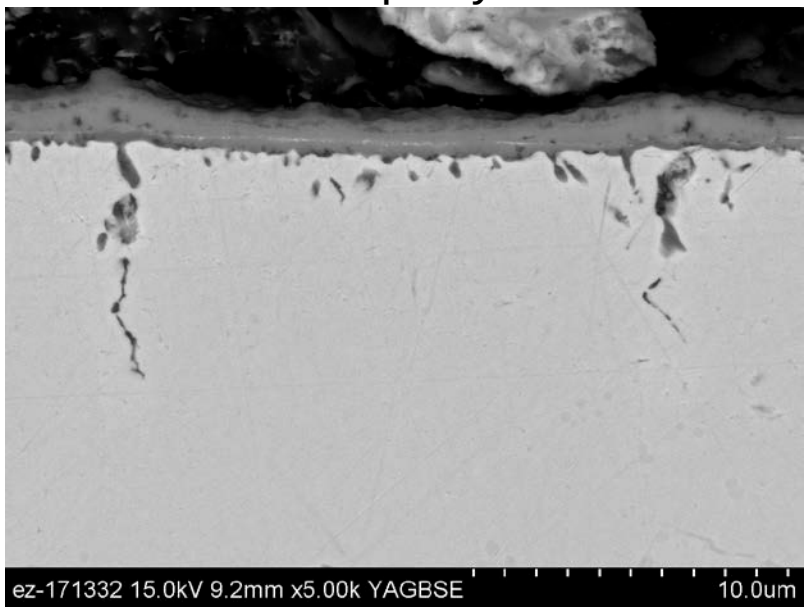
Cast H282



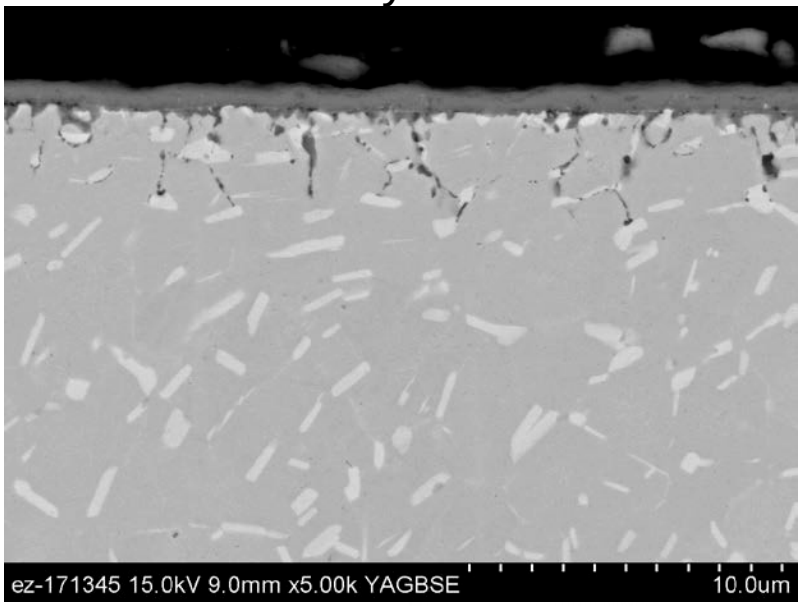
Find continuous oxide and subsurface attack

SEM BSE Micrographs Of Disk Alloys

Waspaloy



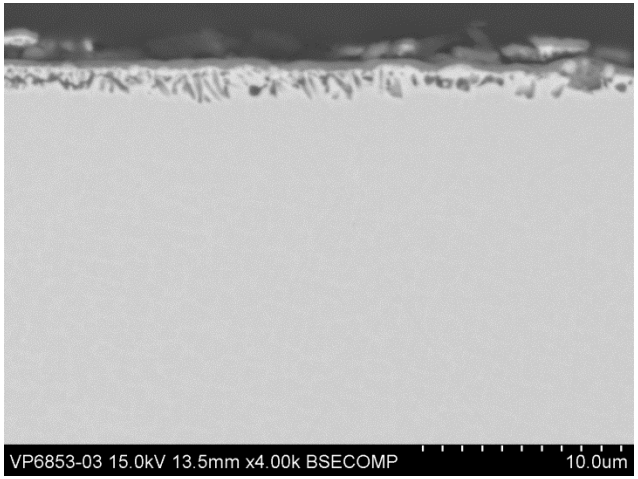
Alloy 718



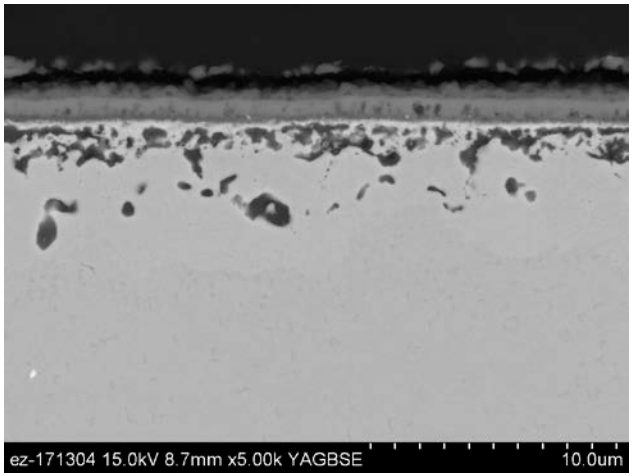
Find continuous oxide and subsurface attack

SEM BSE Micrographs Of Blade Alloys

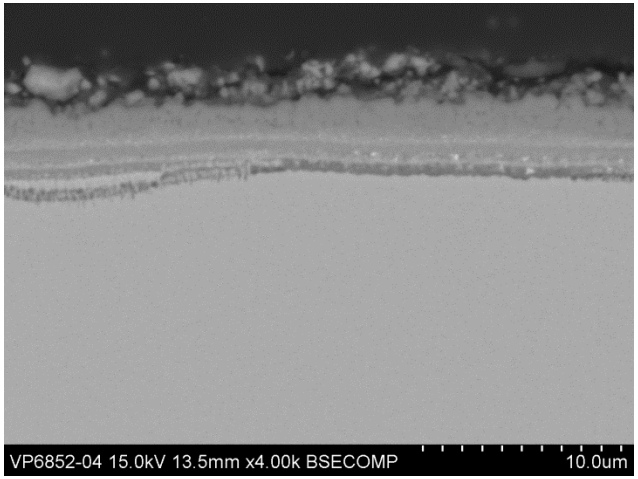
CMSX-8



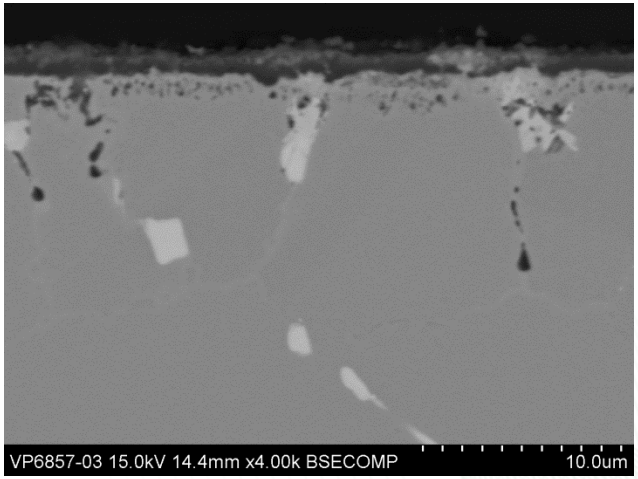
PWA 1483



CMSX-4



René N4



Find continuous oxide and subsurface attack

Observations From SEM Examination Of Cross Sections Of C-Ring Samples

- Alloys proposed for the housing showed the greatest weight change while the blade alloys showed the least
- Cross sections of all alloys showed a continuous surface oxide layer
- Nearly all alloys showed subsurface attack
- No evidence of significant cracking was found
- Exposures were only for 500 h, so only preliminary conclusions should be drawn

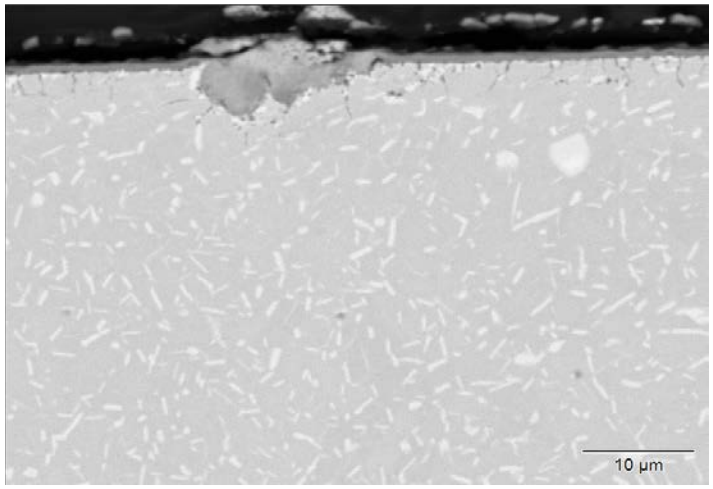
Four Samples Were Examined With Electron Probe Micro Analyzer

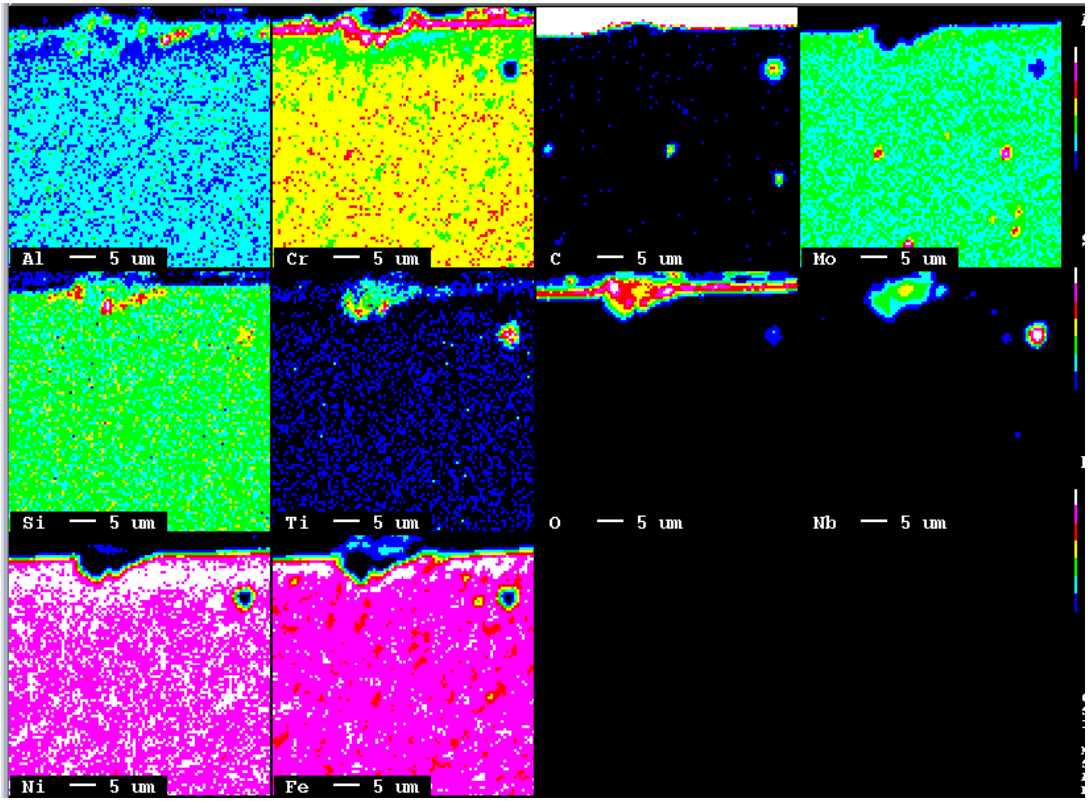
- Provided information on composition of surface layers
- Identified composition of precipitates or second phase particles
- Defined the variation in carbon concentration as a function of distance from surface

  - all four samples showed higher carbon concentration at the surface than in the bulk

  - further studies are in progress

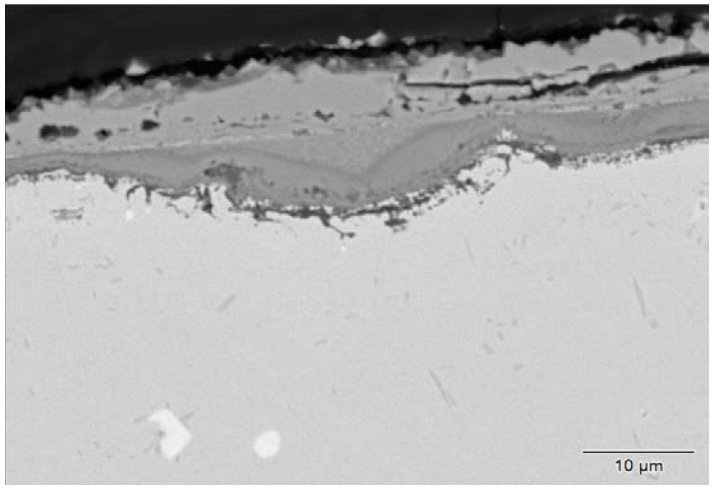
Microprobe Examinations Conducted On Four Samples – Alloy 718 Shown

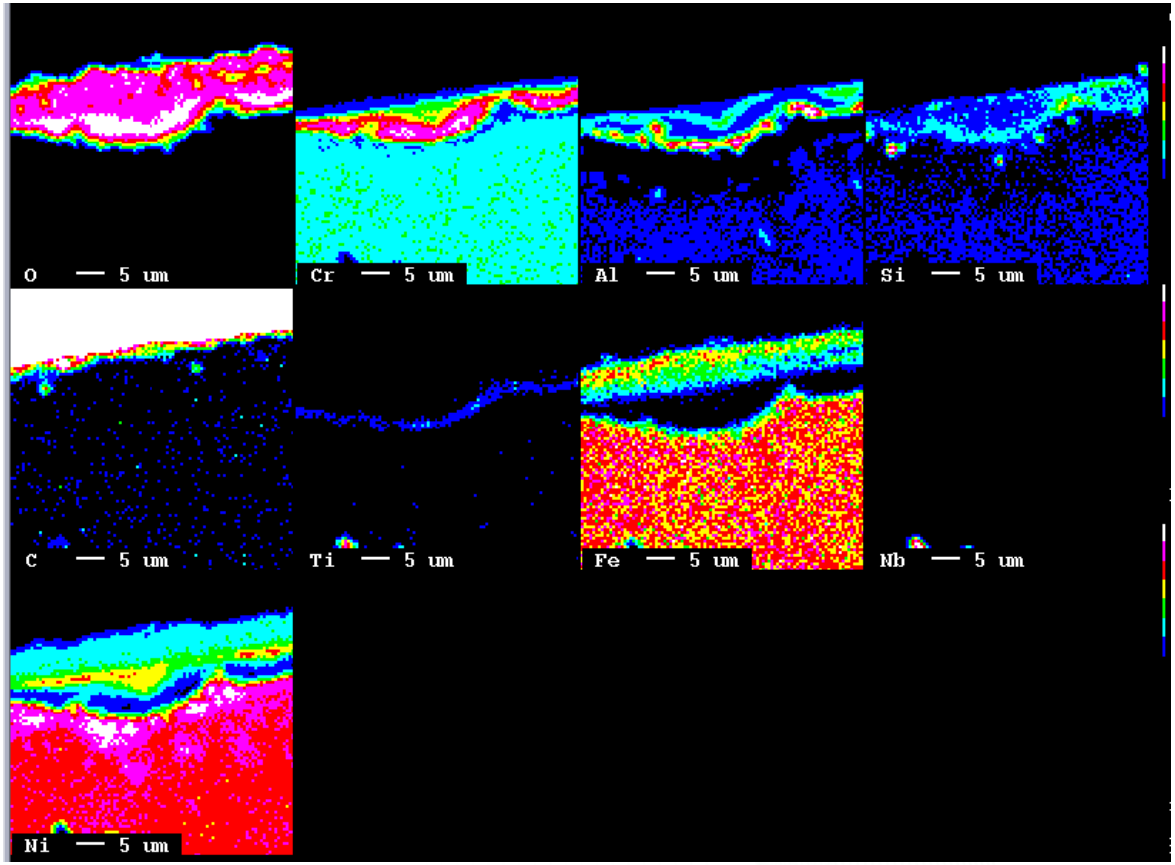




Microprobe exam of Alloy 718 C-ring cross-section shows Cr rich surface oxide with some near surface Cr depletion and a Ti-Nb rich carbide precipitate

Microprobe Results For DAFA30 Show Several Oxide Layers





The outer oxide is primarily an iron oxide with some nickel content. The inner oxide is primarily chromium oxide with some Al, Si and Ti content.

Summary

- Corrosion coupons and C-ring samples of selected alloys were exposed to sCO_2 at 750°C and 20 MPa
- For the limited exposure time, there were significant differences in the weight changes of alloys for each application
- Electron microprobe provides results on the composition of microstructural features
- Electron microprobe examination revealed possible evidence of carburization
- Longer exposure times along with thorough microprobe examinations will be needed to better define the suitability of each alloy

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- Tyson Jordan – light metallography
- Tracie Lowe – SEM examination

THANKS FOR YOUR ATTENTION

I'LL TRY TO ANSWER ANY OF YOUR QUESTIONS