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Task 3: Cracking of Nickel Alloys and Welds – CGRs of Alloys 600 and 690 in PWR Water

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Experimental Effort: Ed Listwan and Loren Knoblich

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Work sponsored by the US Nuclear Regulatory Commission

Outline

- Experiment
- CGR of Nozzle #3 Alloy 600 from Davis-Besse
- CGR of Alloy 690

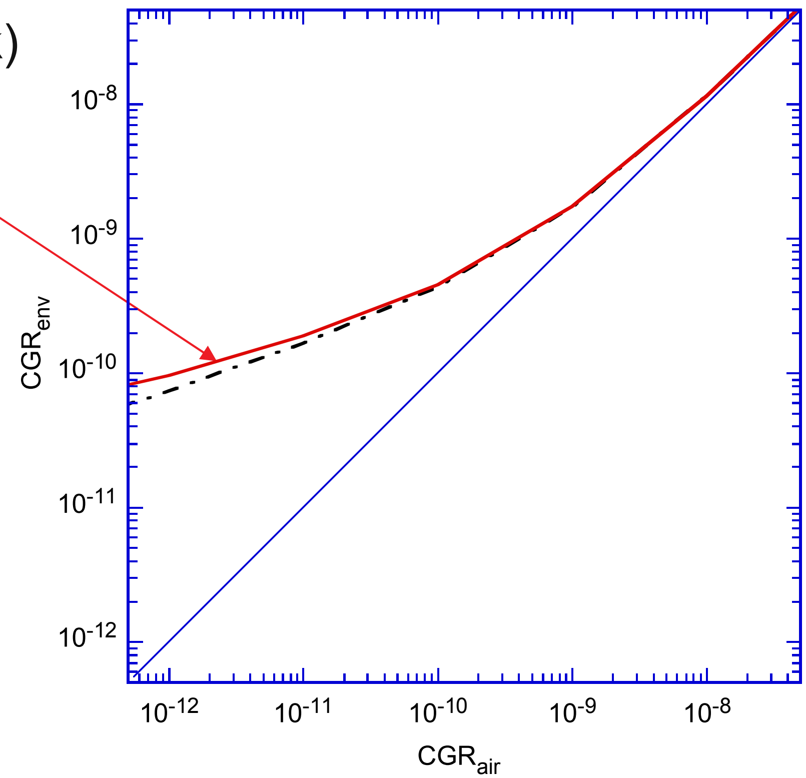
Experiment

- Temp: 320°C
- PWR Water (<10 ppb DO, 1000 ppm B, 2 ppm Li, ≈2 ppm hydrogen
- Flow Rate: ≈55 mL/min
- Conductivity: ≈20 μS/cm
- Loading sequence chosen to facilitate the transition from transgranular fatigue cracking to intergranular SCC cracking:
  - Precracking carried out in the PWR environment
  - Load Ratio R: 0.3–precrack;
    0.5-0.7–sawtooth with up to 1000s rise time;
    1.0–constant load

The Analysis of Cyclic CGR Data for Ni-alloys

- Superposition model (Kassner & Shack)

$$\dot{a}_{env} = \dot{a}_{air} + \dot{a}_{CF} + \dot{a}_{SCC}$$



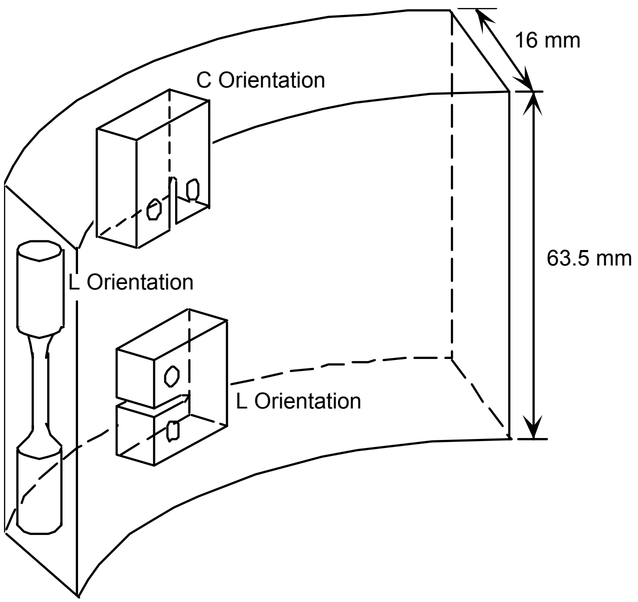
- For Alloy 600:

$$\dot{a}_{air} + \dot{a}_{CF} = \dot{a}_{air} + 4.4 \times 10^{-7} \cdot (\dot{a}_{air})^{0.33}$$

$$\dot{a}_{SCC} = \alpha \exp\left[-\frac{Q}{R}\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right](K - K_{th})^{\beta}$$

Cracking of Nozzle Alloy 600 from Davis-Besse

CGR of Nozzle #3 Alloy 600 from Davis-Besse



- Specimens tested in 316°C simulated primary water:

  1/4T-CT

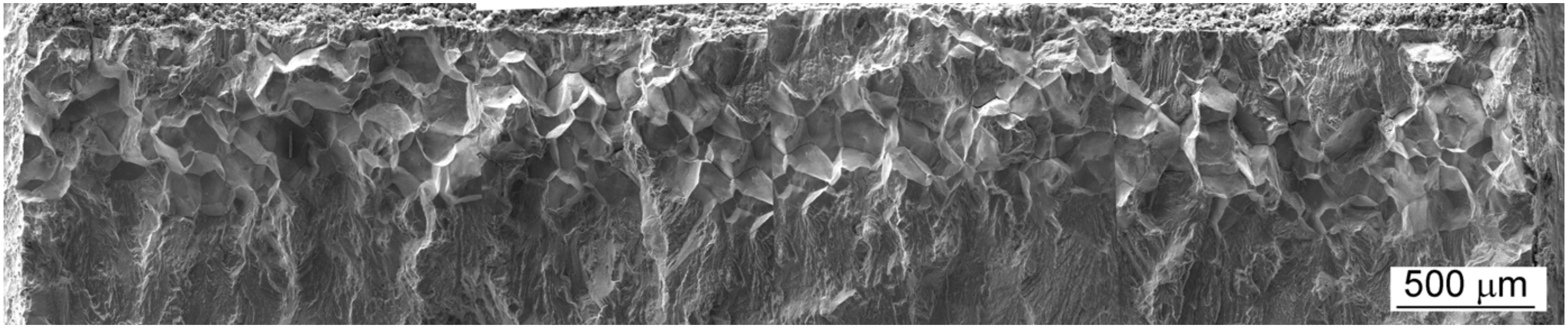
  N3CL-1

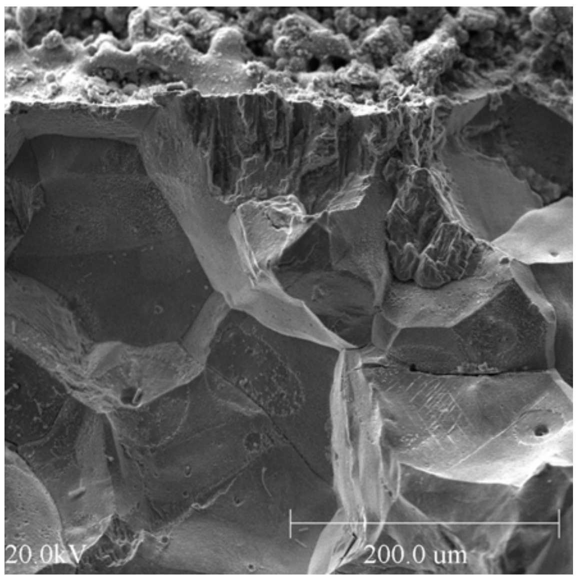
  N3CC-2

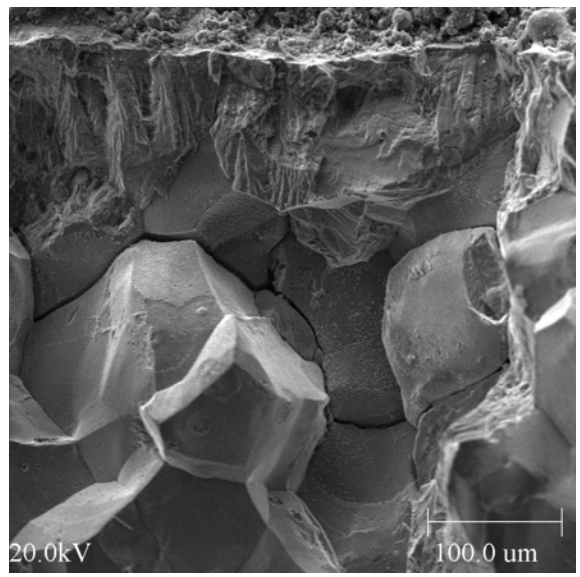
  1/2T-CT

  N3CC-3

Fracture surface of specimen N3CL-1







- Completely IG fracture right from the notch

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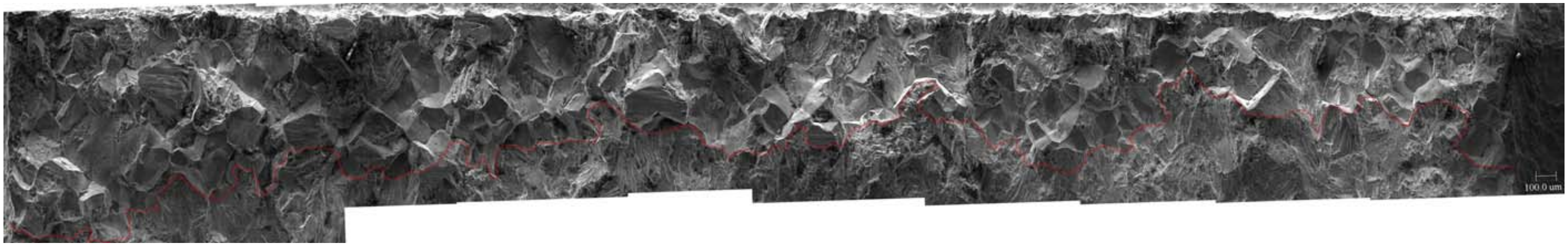
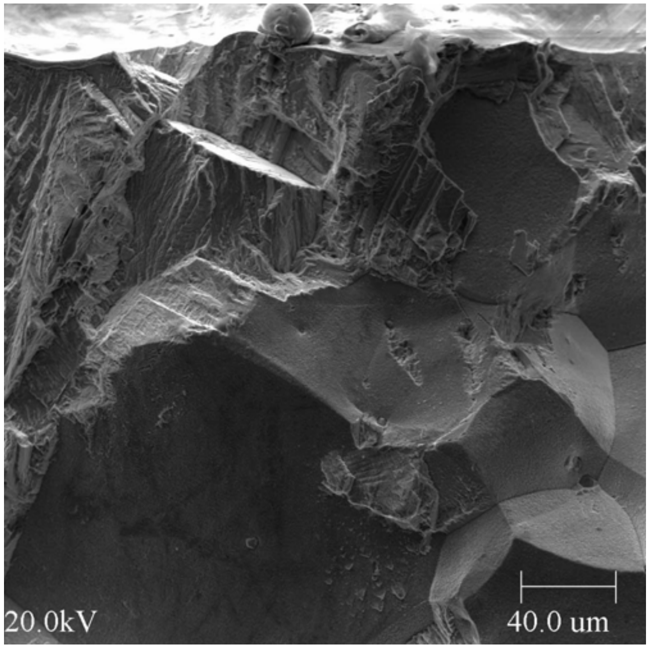
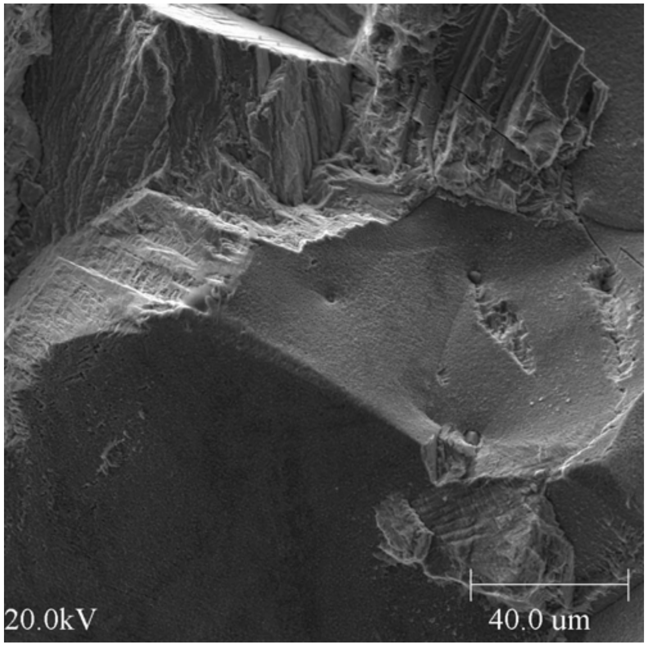
Fracture surface of specimen N3CL-4

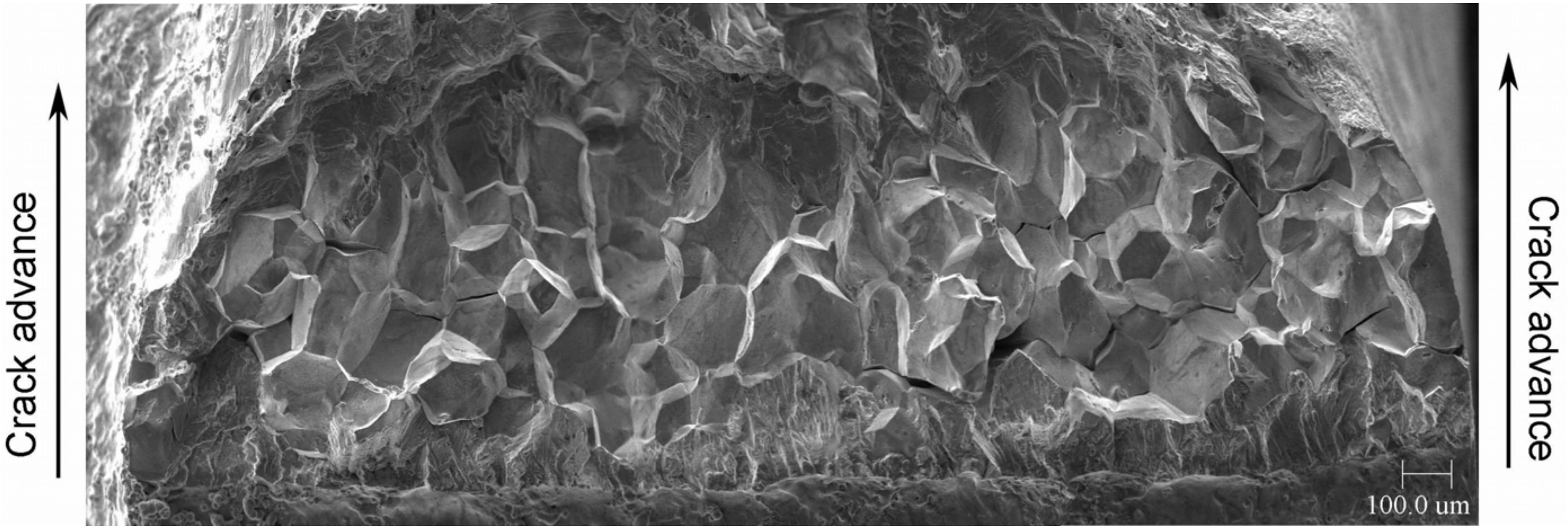


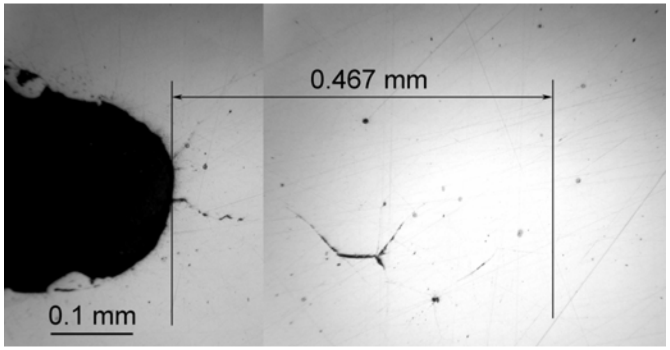




- Completely IG fracture right from the notch

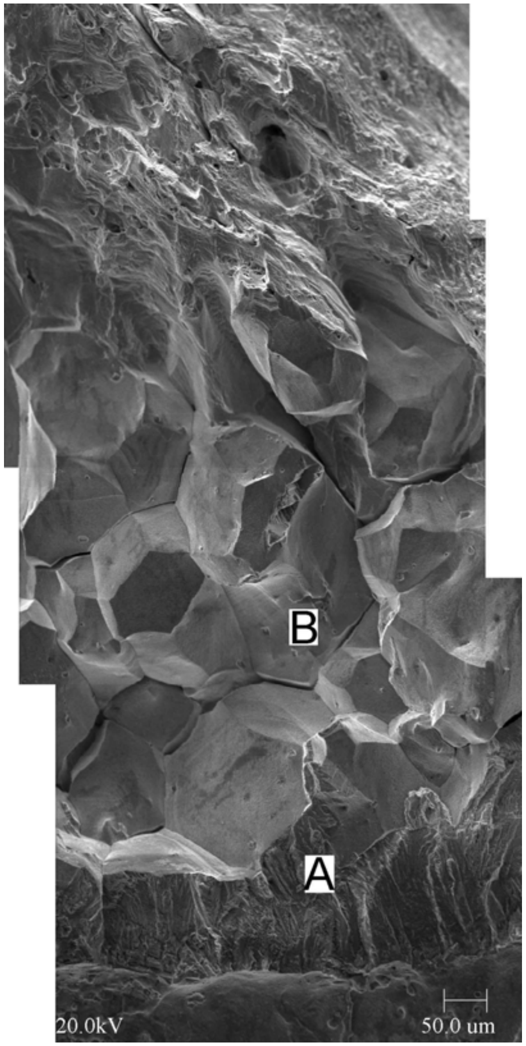
Fracture surface of specimen N3CC-2

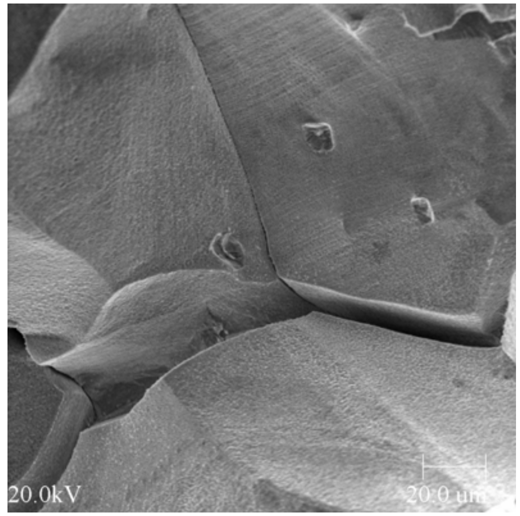


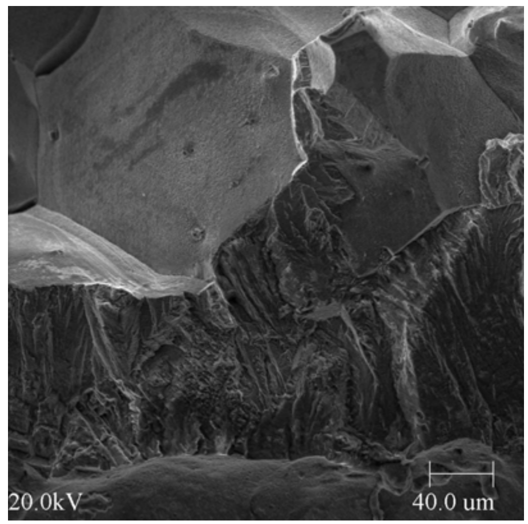


- Completely IG fracture right from the notch

Fracture surface of specimen N3CC-2

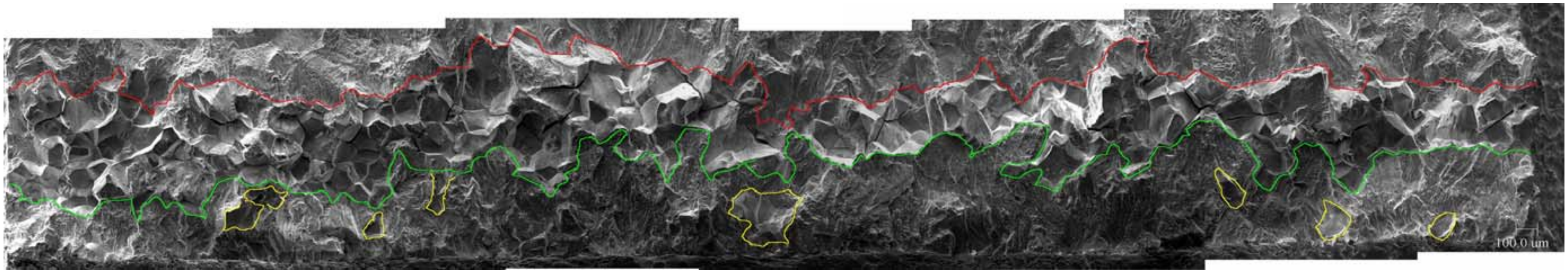


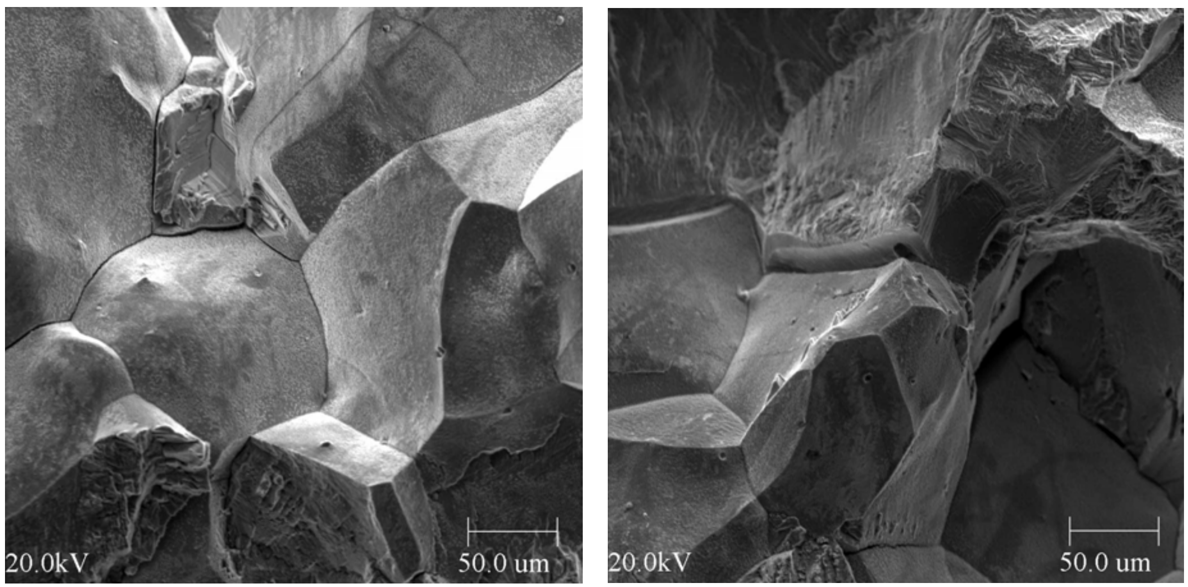




- Completely IG fracture right from the notch

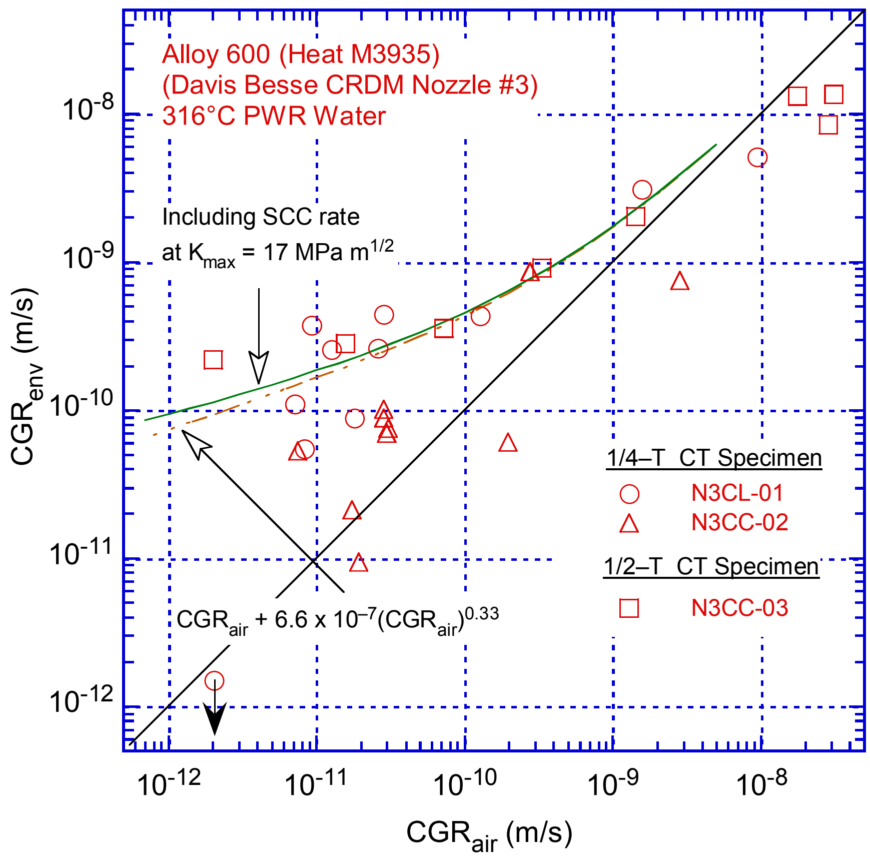
Fracture surface of specimen N3CC-3





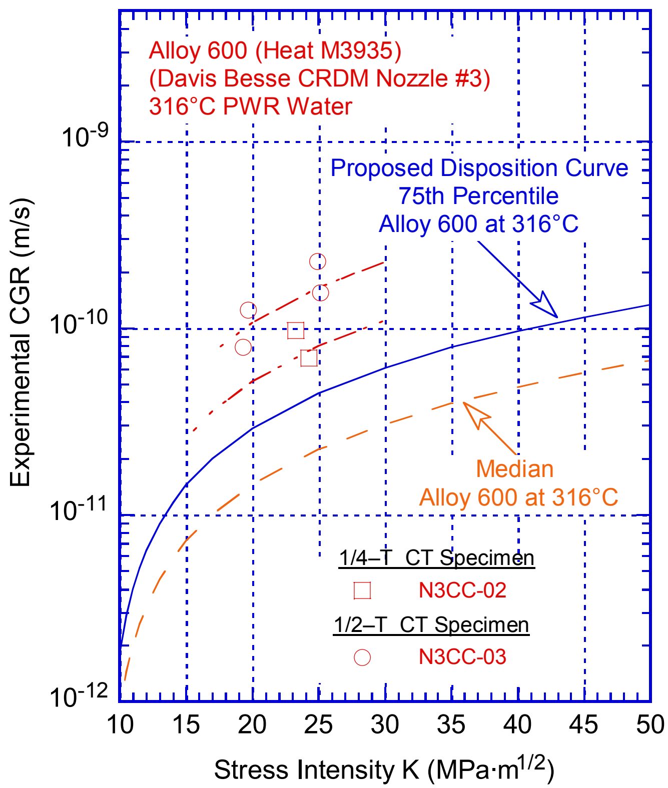
- Did not start as IG fracture right from the notch, elements of IG are present in the TG region

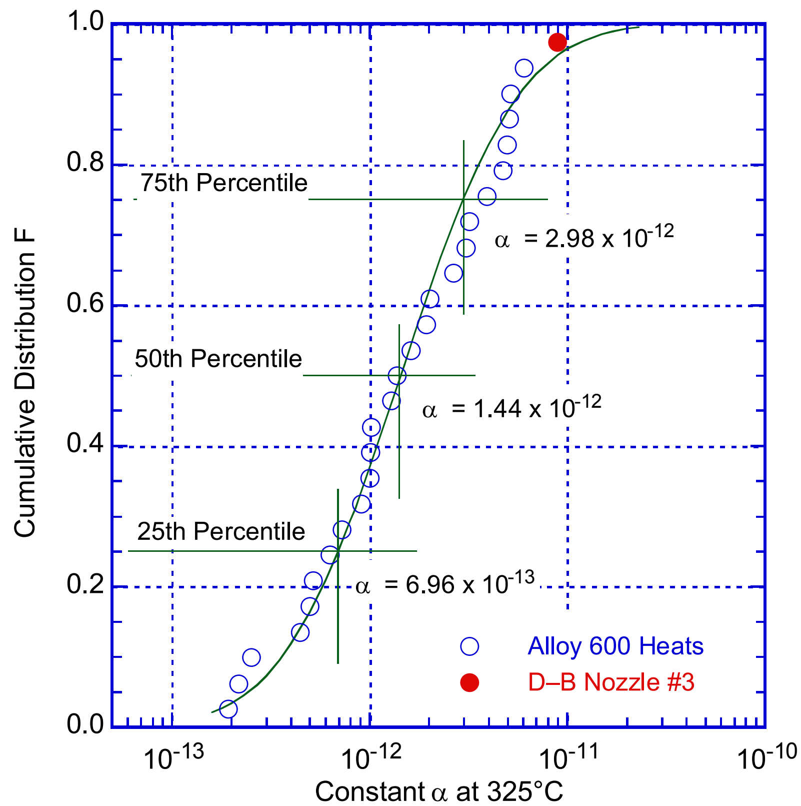
Cyclic CGRs for Nozzle #3 Alloy 600 from Davis-Besse



- Cyclic CGRs show environmental enhancement

SCC CGRs for Nozzle #3 Alloy 600 from Davis-Besse vs. K





- SCC CGRs are 2-4× the proposed disposition curve
- Heat ranks at 95% of the distribution (26 heats)

Nozzle #3 Alloy 600 from Davis-Besse – Summary and Remaining Issues

- Very high crack growth rates
- IG fracture mode during precracking

Very high SCC CGRs unexpected because:

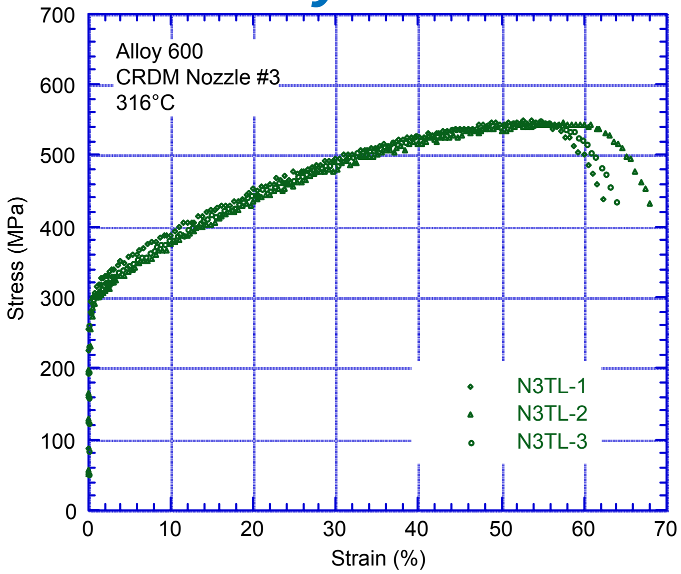
- Alloy with average strength
- Grain boundary carbide coverage (50–60%)

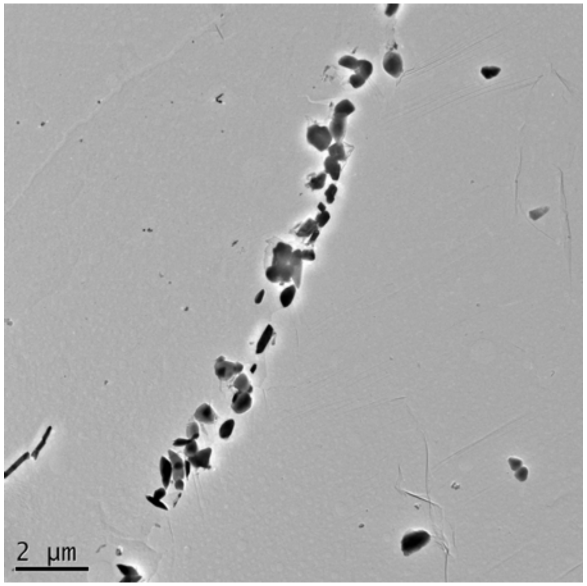
More recent investigations

- Good grain boundary carbide coverage
- Low special boundary fractions

  - could explain the high SCC CGRs

  - can not explain IG fracture mode during precracking





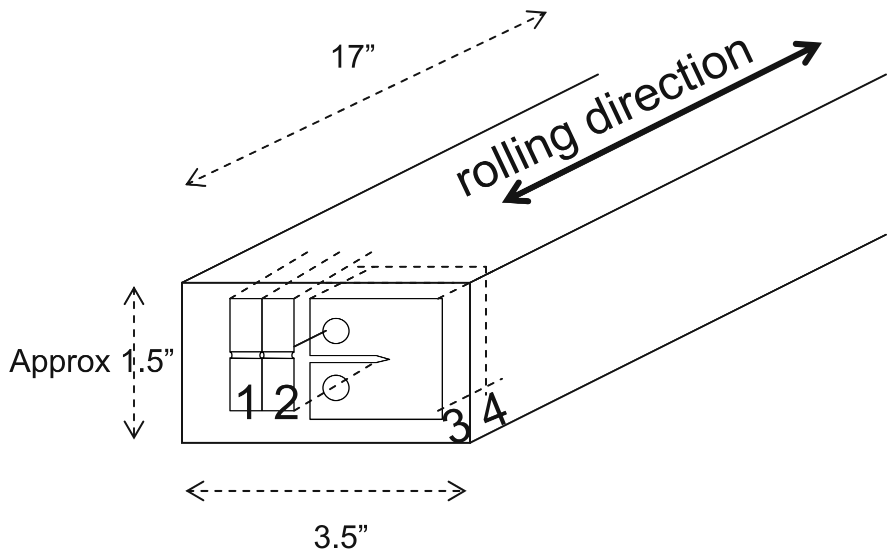
Stress Corrosion Cracking of Alloy 690

Alloy 690 specimens

- Alloy 690 in plate form (MIL-DTL-24802*)

Alloy ID (Heat)	Analysis	C	Mn	Fe	S	P	Si	Cu	Ni	Cr	Ti	Nb	Co
A 690WC (NX3297HK12)	Vendor	0.03	0.20	9.9	<0.001		0.07	0.01	59.5	29.5			
	ANL	0.04	0.33	8.53	0.001	0.003	0.02	0.04	59.67	30.82	0.47	0.01	<0.01

- Cold-rolled in three passes to achieve approx. 26% reduction in thickness
- Specimens cut in both SL and ST orientations



- *MIL-DTL-24802
  - vacuum induction - melted
  - electro slag - removed
  - hot - rolled
  - de-scaled
  - annealed at 1900F for 2h
  - air-cooled

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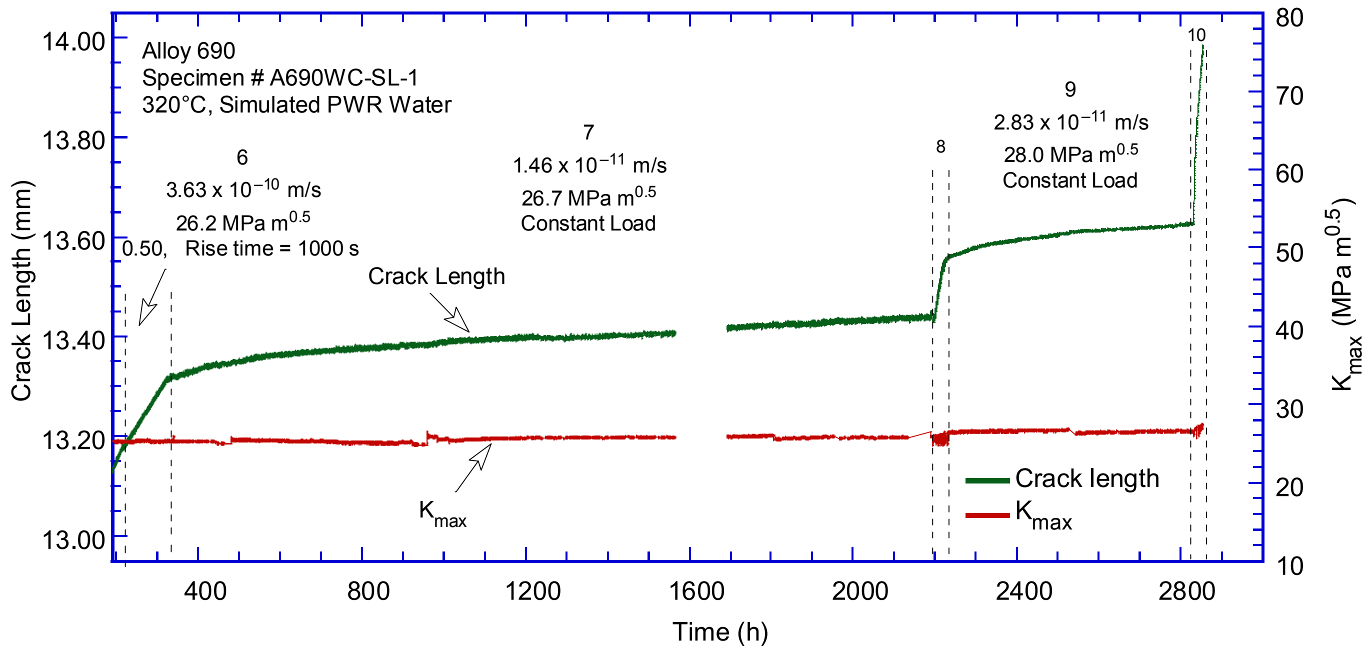
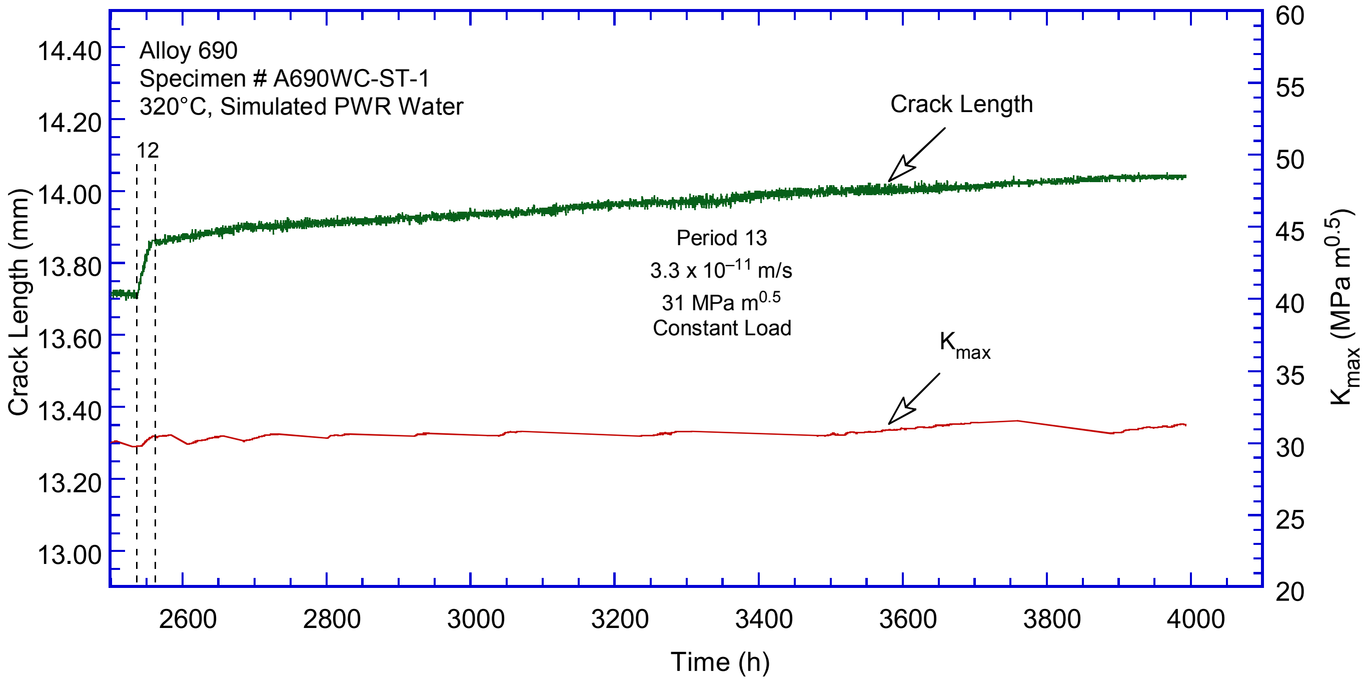
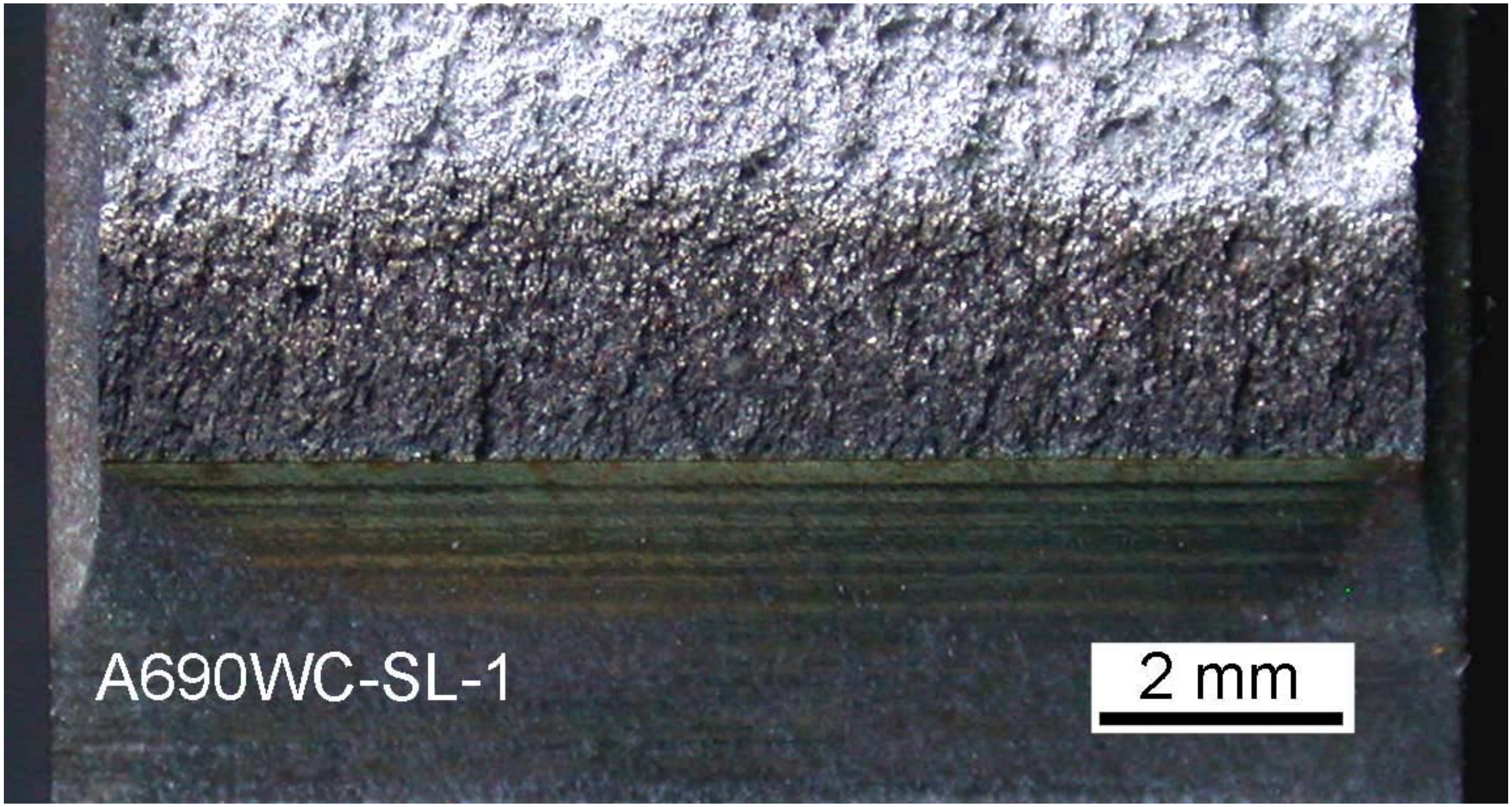
Results - Alloy 690 specimen A690WC-SL-1



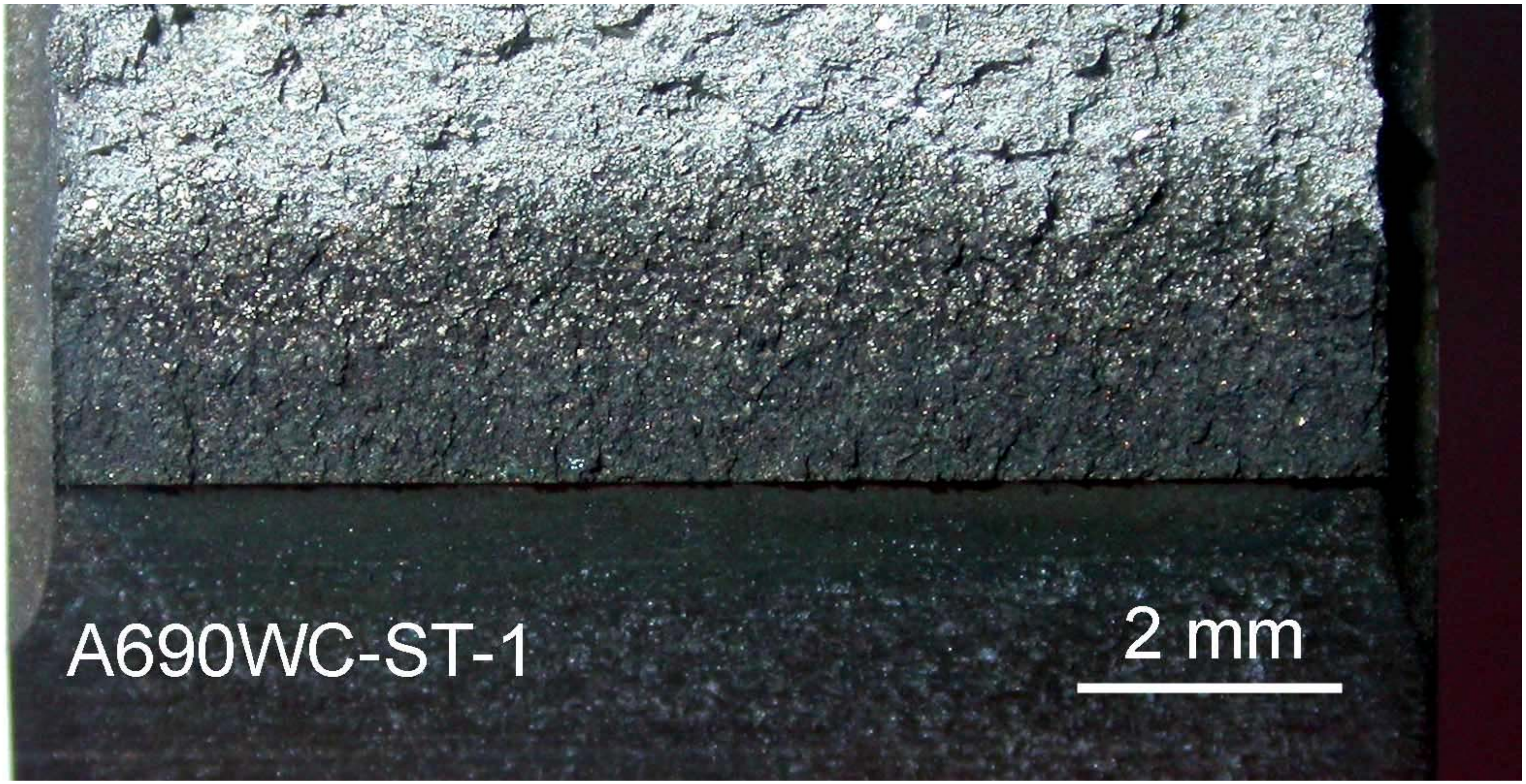
Results - Alloy 690 specimen A690WC-ST-1



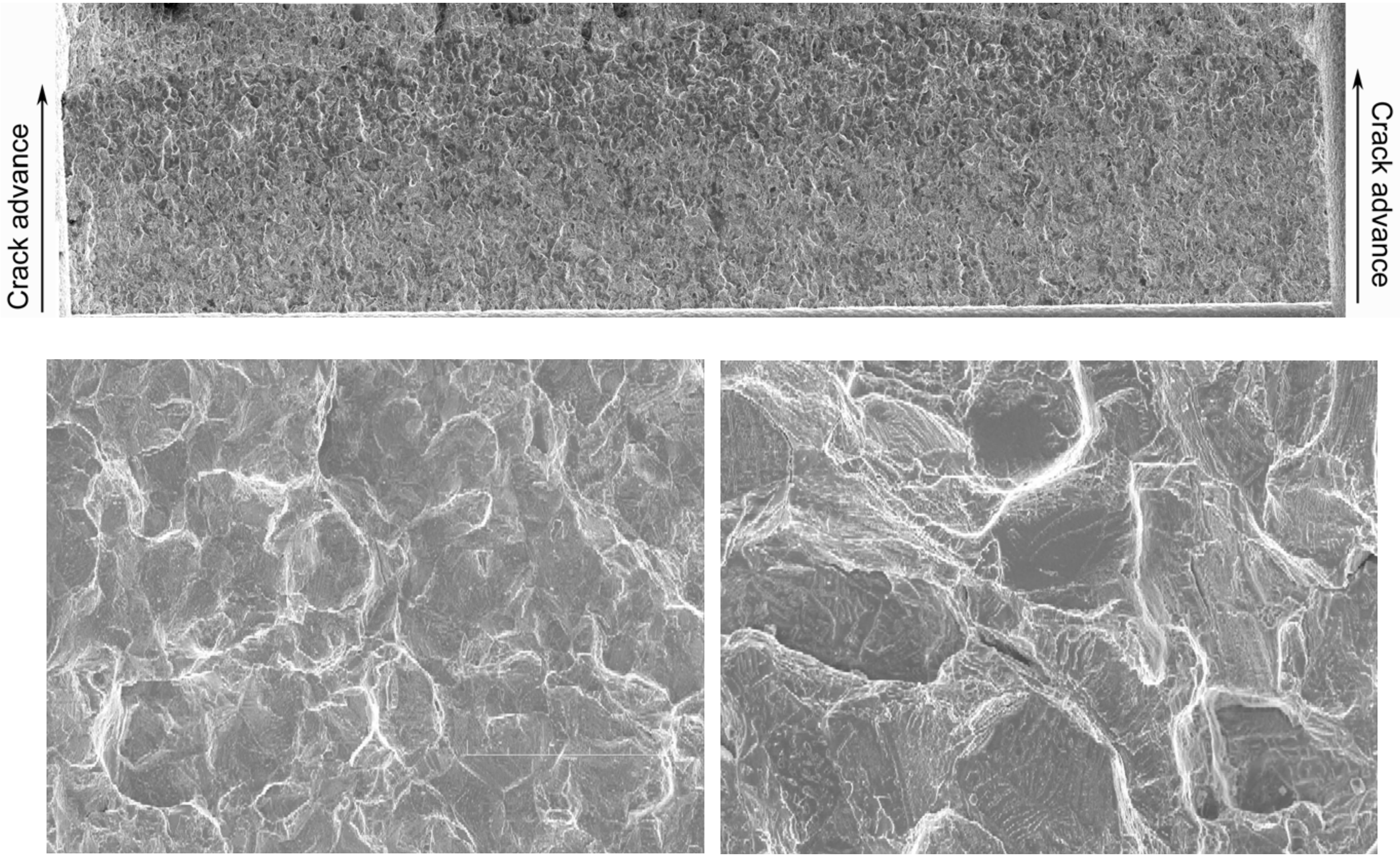
Fracture surface of A690WC-SL-1



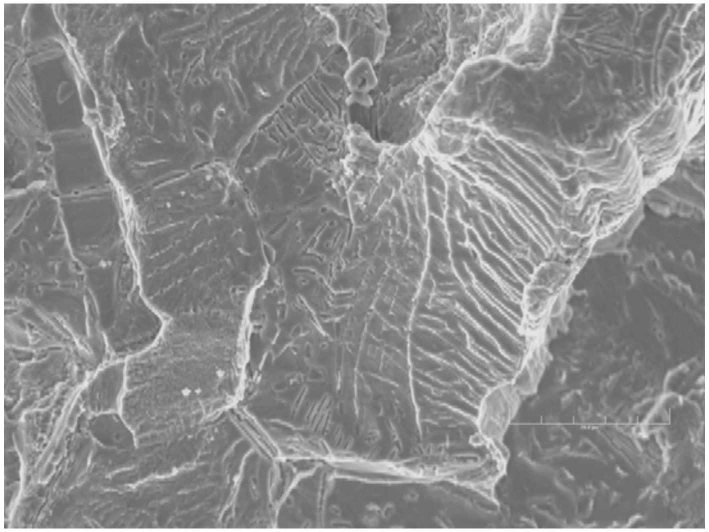
Fracture surface of A690WC-ST-1

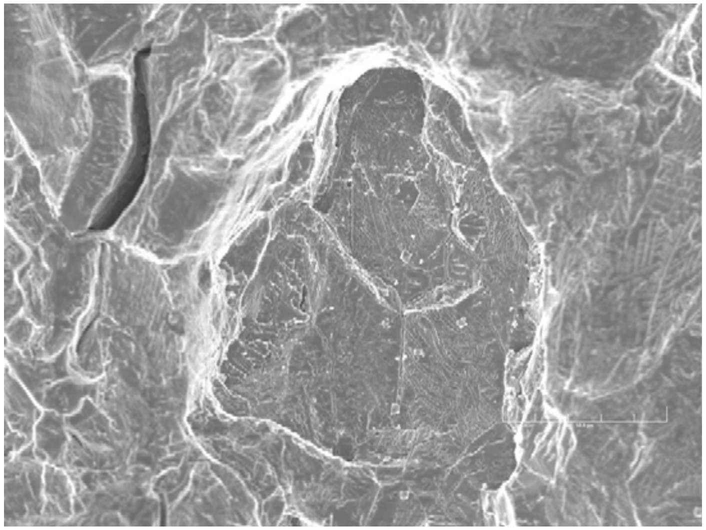


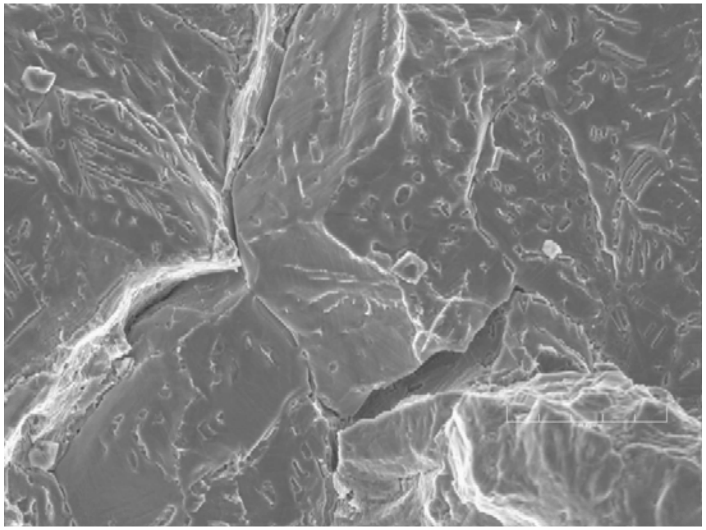
Fracture surface of A690WC-SL-1



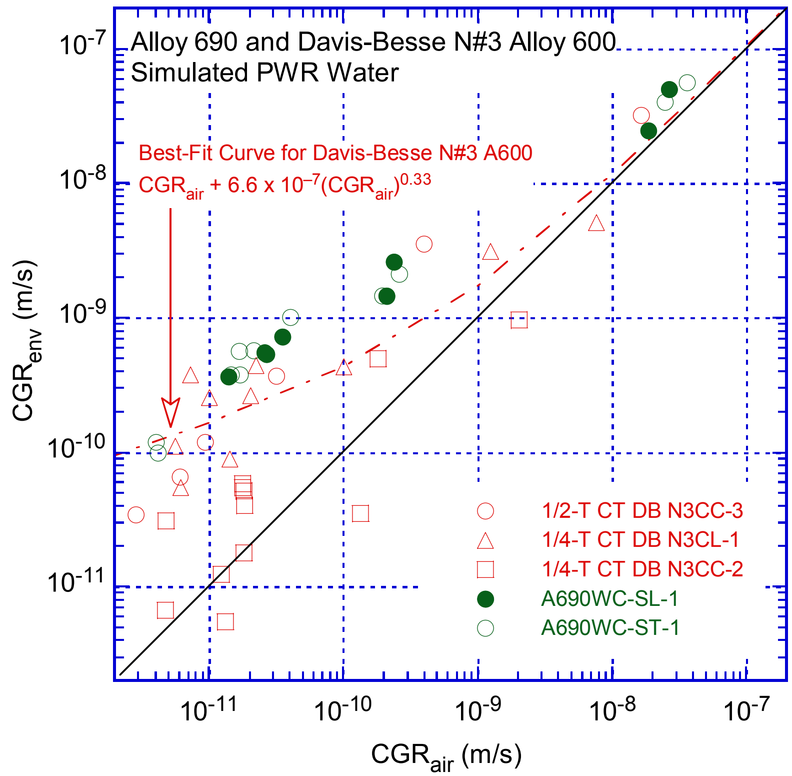
Fracture surface of A690WC-SL-1



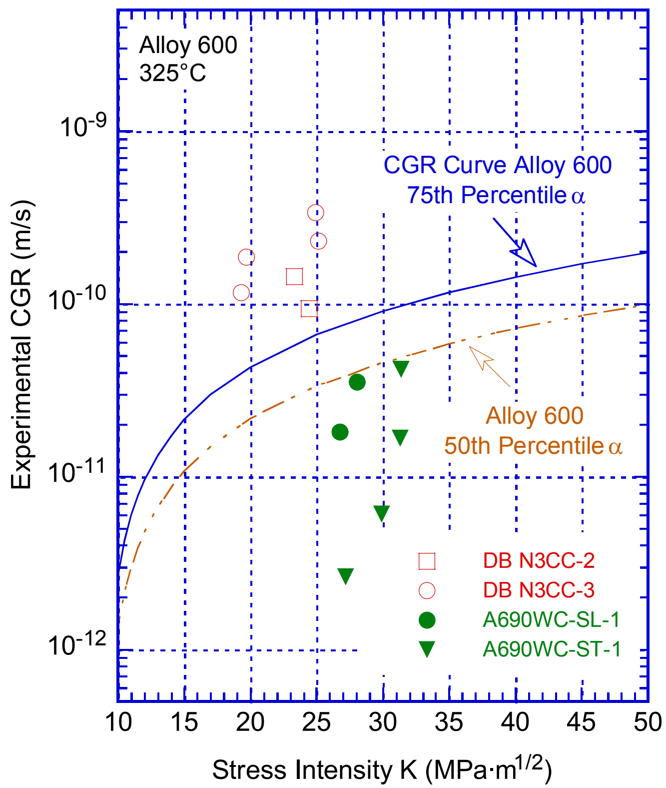




Cyclic CGR data for Alloy 690 and Davis-Besse Alloy 600



SCC CGRs for Alloy 690 and Davis-Besse Alloy 600 vs. K



Summary

Nozzle #3 Alloy 600 from Davis-Besse

- Fracture is predominantly IG, even during mechanical fatigue loading
- Cyclic CGRs show environmental enhancement in PWR water at 316°C
- SCC CGRs are a factor of 2-4 higher than the proposed disposition curve for Alloy 600; growth rates correspond to 95th percentile of the data

Alloy 690

- Fracture surfaces were uniform for both Alloy 690 specimens
- Cyclic CGRs of Alloy 690 show environmental enhancement
- The SCC CGRs in simulated PWR water at 320°C were as high as:

  $2.8\text{-}3.3 \times 10^{-11}$ m/s for K_{max} = 28-31 MPa $m^{1/2}$ for Alloy 690

  5.4×10^{-11} m/s for K_{max} = 30.2 MPa $m^{1/2}$ for Alloy 152