Argonne NATIONAL LABORATORY

... for a brighter future

Task 3: Cracking of Nickel Alloys and Welds - Prior Effort Overview

Investigators: Bogdan Alexandreanu, Omesh Chopra, Bill Soppet, Wes Ruther, and Bill Shack

Experimental Effort: Ron Clark, Tom Galvin, Loren Knoblich, Ed Listwan, and Don Perkins

September 25-26, 2007

Nuclear Engineering Division

Argonne National Laboratory, Argonne, IL 60439

U.S. Department of Energy

UChicago Argonne LLC

Office of Science U.S. DEPARTMENT OF ENERGY

A U.S. Department of Energy laboratory managed by UChicago Argonne, LLC

Work sponsored by the US Nuclear Regulatory Commission

Task Objective

- Provide technical data & analytical methods on cracking of Ni–alloys & welds
  - for determinations of residual life, inspection interval, repair criteria, etc.
- Compile & review available data; interact with Intl. Coop. groups & industry
  - to ensure acceptability & consistency of test & data analysis methods, & pedigree of materials
- Participate in round robin on CGR in A600 base metal & A182 weld metal
  - to ensure acceptability of results & provide means to relate with other data
- Develop confirmatory laboratory crack growth data on Ni–alloys & welds;
  - to determine CGRs as a function of water chemistry, loading, & fluence
  - to make additions to existing database where needed
- Provide validated methodology for predicting CGR in Ni–alloys & welds
  - to support assessment of industry's activities on this issue

Task Status

- Compiled & analyzed existing cyclic crack growth data in air
  - to develop correlations for estimating CGRs of Alloys 600 & 690, & Ni-alloy welds as a function of ΔK, R, & T
- Participated in round robin on CGR in A600 base metal & A182 weld metal
  - results are in agreement with data obtained by other participants
- Developed the procedure for test specimen precracking & cyclic loading
  - to transition the TG fatigue crack to IG crack, &
  - to ensure relatively straight crack fronts with uniform SCC engagement
- Completed testing of laboratory prepared Alloy 182 welds to obtain CGRs as a function of weld type, weld orientation, and temperature
  - determined the temperature dependence of CGRs in Alloy 182 welds
- Completed testing of Alloys 600 & 82/182 from Davis-Besse & V.C. Summer reactor components to obtain CGRs under cyclic & SCC conditions
  - determined the relative susceptibility of these alloys to EAC
- Performed extensive microstructural characterization (SEM, TEM, & OIM)
  - Established effect of GB orientation & relative grain orientation on CGRs

Cyclic Crack Growth Rates of Alloys 600 & 690 in Air

- Analyzed existing fatigue CGR data on for these alloys to develop a correlation for estimating fatigue CGRs in air

- CGR (m/cycle) is expressed as

$$da/dN = C_{A182} (1 - 0.82R)^{-2.2} (\Delta K)^{4.1}$$

where R is load ratio, ΔK is stress intensity factor in MPa $m^{1/2}$, and constants C_{A600} & C_{A690} are given by a third order polynomial of temperature T (°C)

$$C_{A600} = 4.835 x 10^{-14} + 1.622 x 10^{-16} T - 1.490 x 10^{-18} T^2 + 4.355 x 10^{-21} T^3$$

$$C_{A690} = 5.423 x 10^{-14} = 1.830 x 10^{-16} T - 1.725 x 10^{-18} T^2 + 5.490 x 10^{-21} T^3$$

Cyclic Crack Growth Rates of Ni-Alloy Welds in Air

- Analyzed existing fatigue CGR data on Ni-alloy weld metals to develop a correlation for estimating fatigue CGRs in air

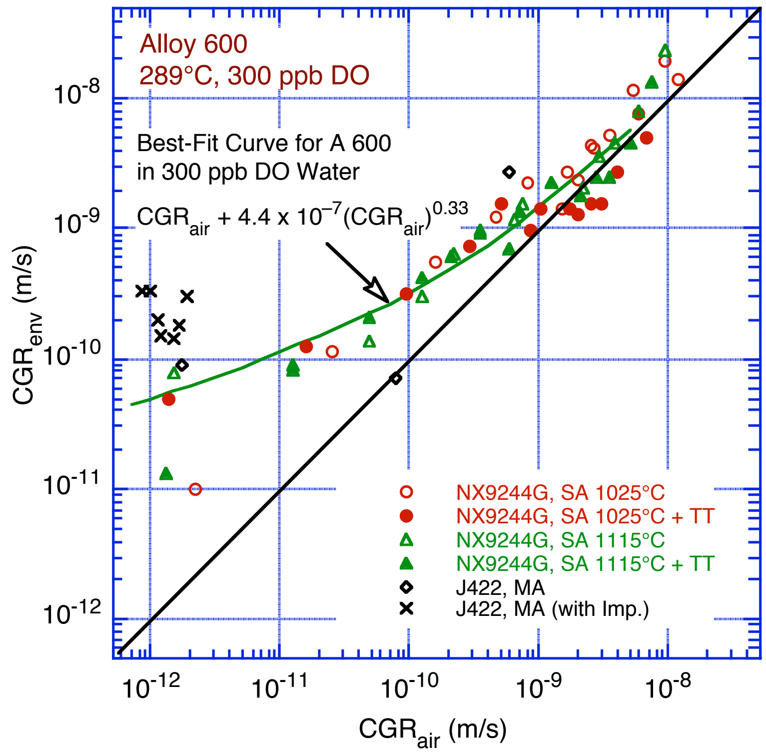
- CGR (m/cycle) is expressed as

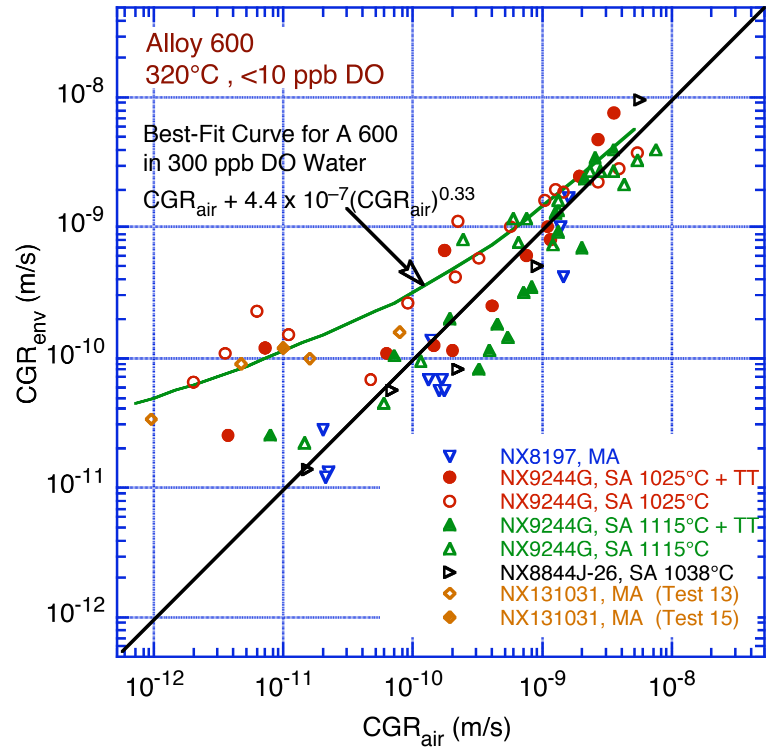
$$da/dN = C_{A182}\,(1 - 0.82R)^{-2.2}\,(\Delta K)^{4.1}$$

where R is load ratio, ΔK is stress intensity factor in MPa $m^{1/2}$, and constant C_{A182} is given by a fourth order polynomial of temperature T (°C)

$$C_{A182} = 8.659\text{x}10^{-14} - 5.272\text{x}10^{-17}\,T + 2.129\text{x}10^{-18}\,T^2 - 1.965\text{x}10^{-20}\,T^3 + 6.038\text{x}10^{-23}\,T^4$$

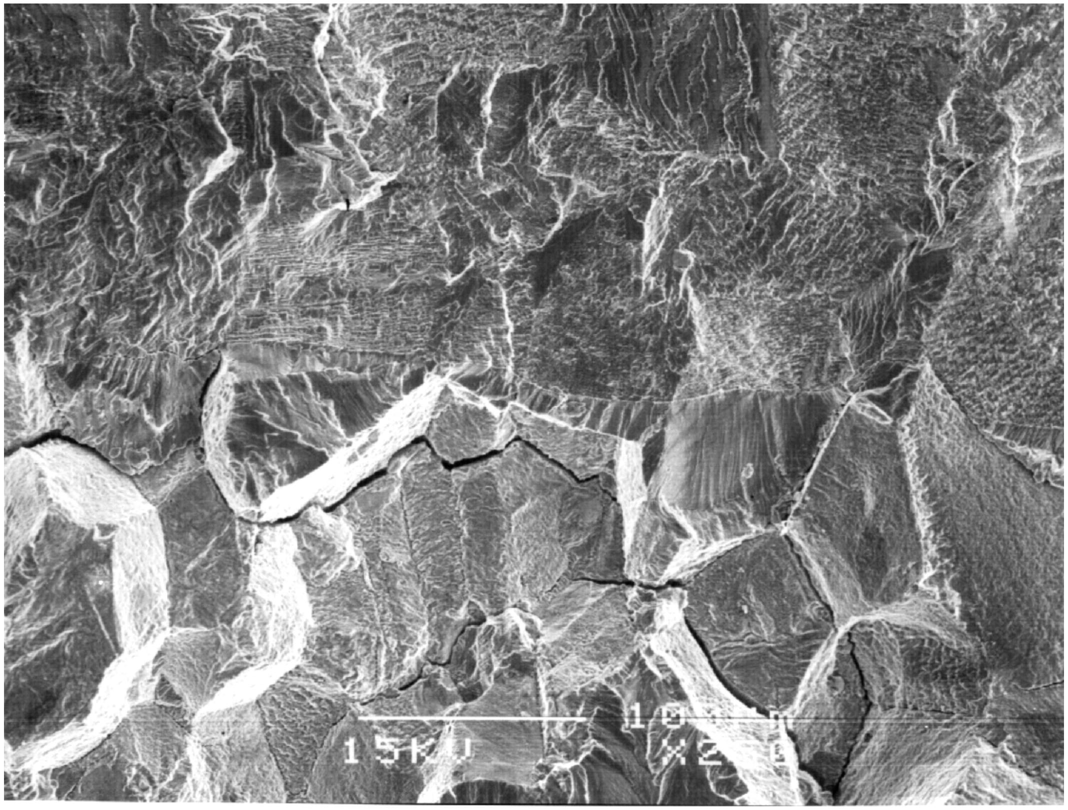
Cyclic CGR Data for Alloy 600 in High-DO & Low-DO Water





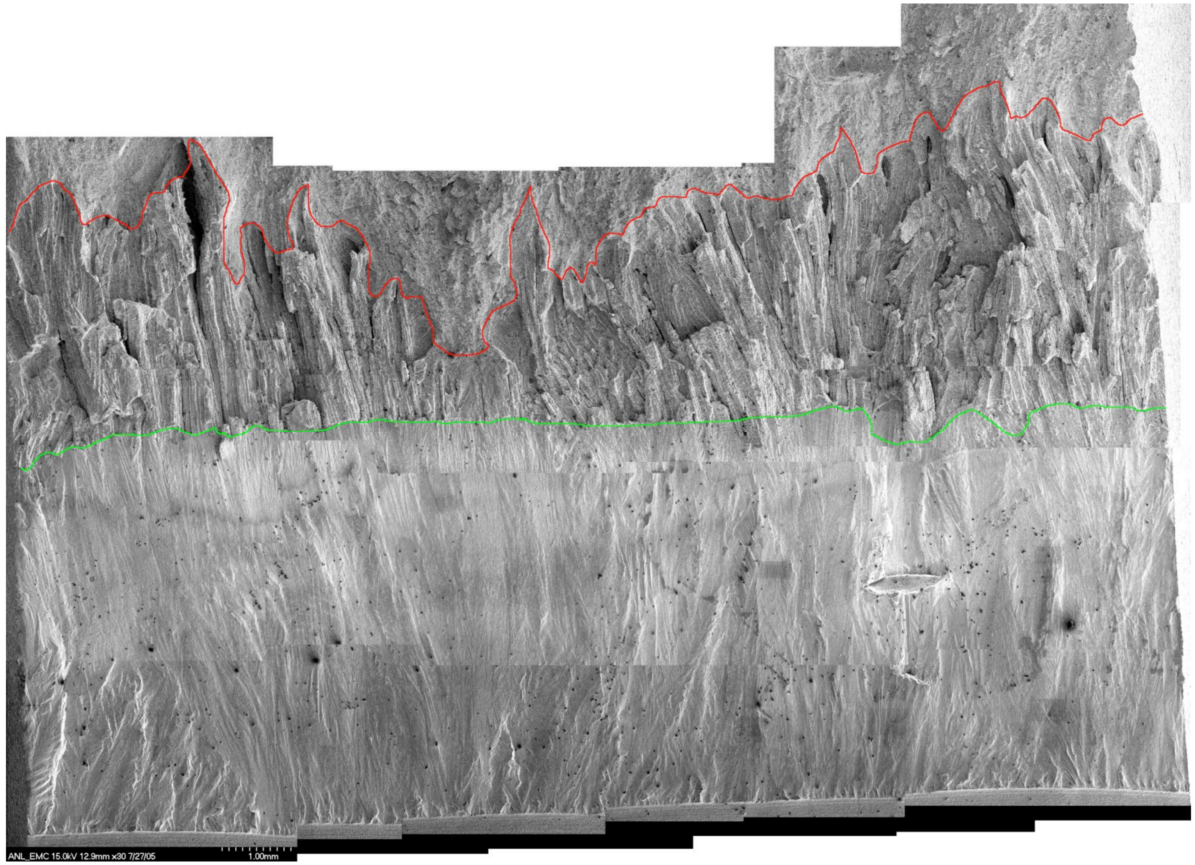
- In high–DO water, all heats or heat treatment conditions show enhanced CGRs
- In low-DO water, environmental effects are significant for few susceptible heats
  - alloys with high yield strength and/or poor grain boundary coverage of carbides

Transition from Transgranular to Intergranular Fracture



- Fracture surface after continuous cycling at 290°C in ≈300 ppb DO water

Fracture Surface of Alloy 182 Weld Specimen Tested in PWR Water



- Experimental procedure used in the study assured complete engagement and a relatively straight intergranular crack