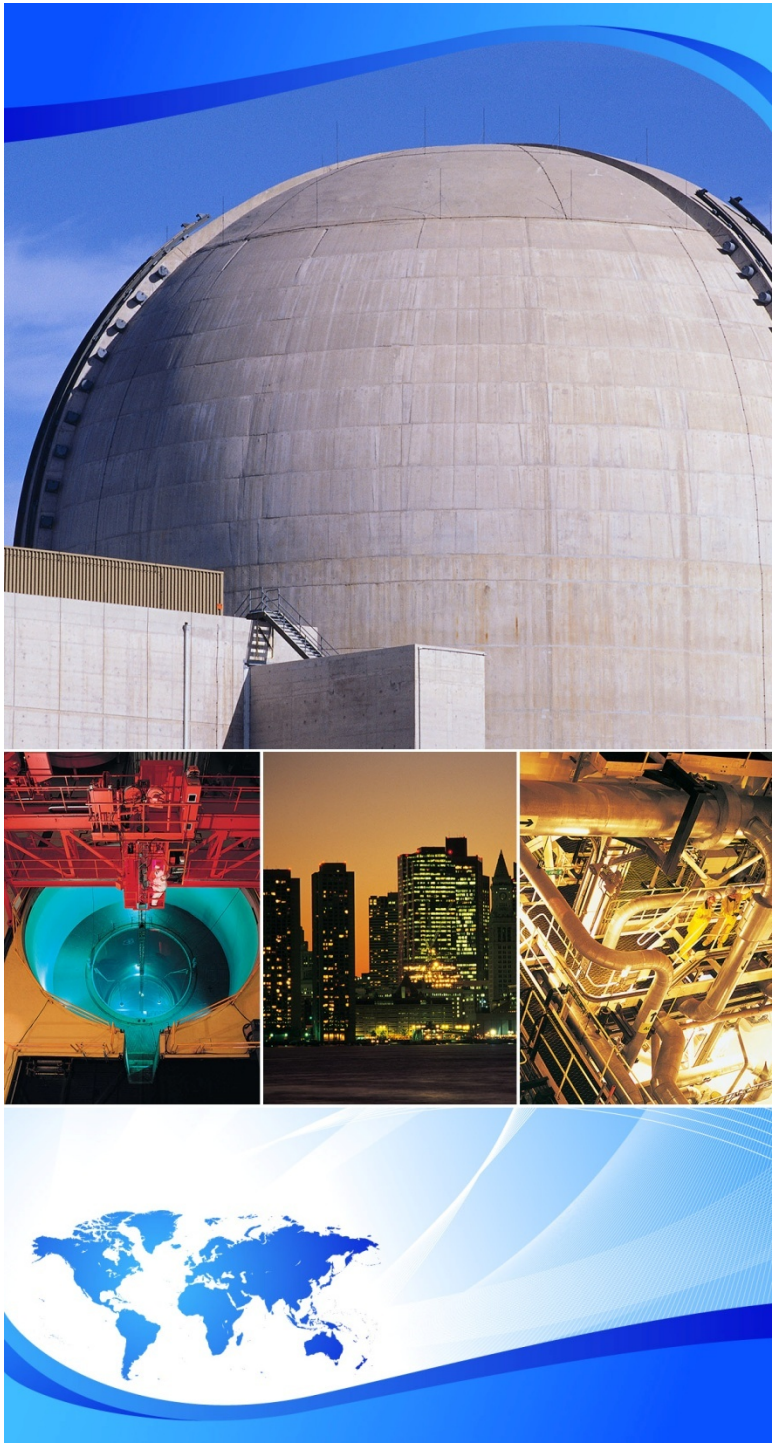

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SCC of Alloy 690, 690-Weld-HAZ, and Alloy 52/152 Weld Metal

Peter Andresen and Martin Morra

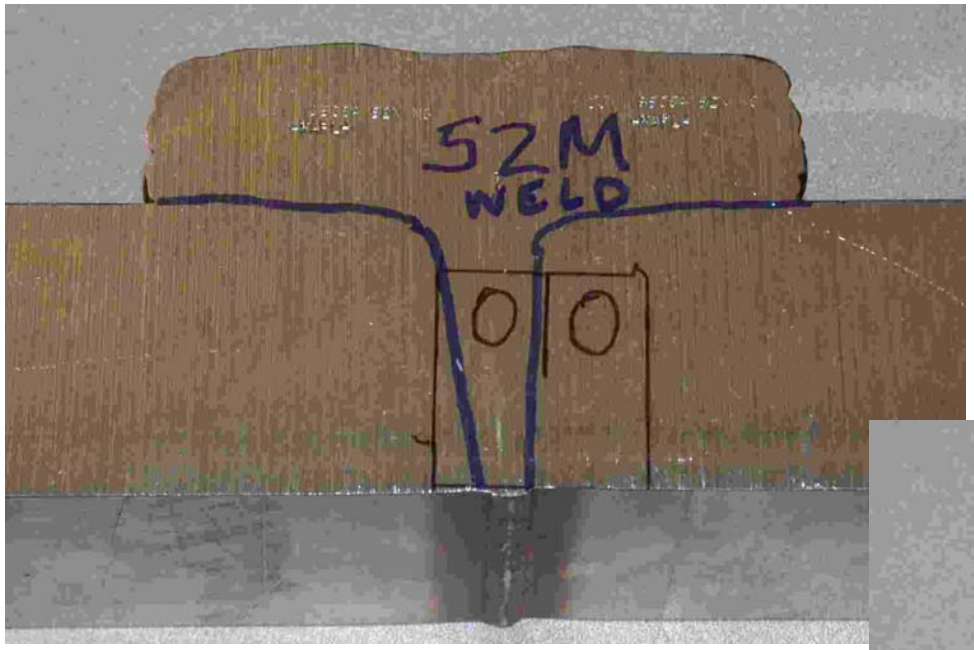
GE Global Research Center

Rockville, MD *August 2009*

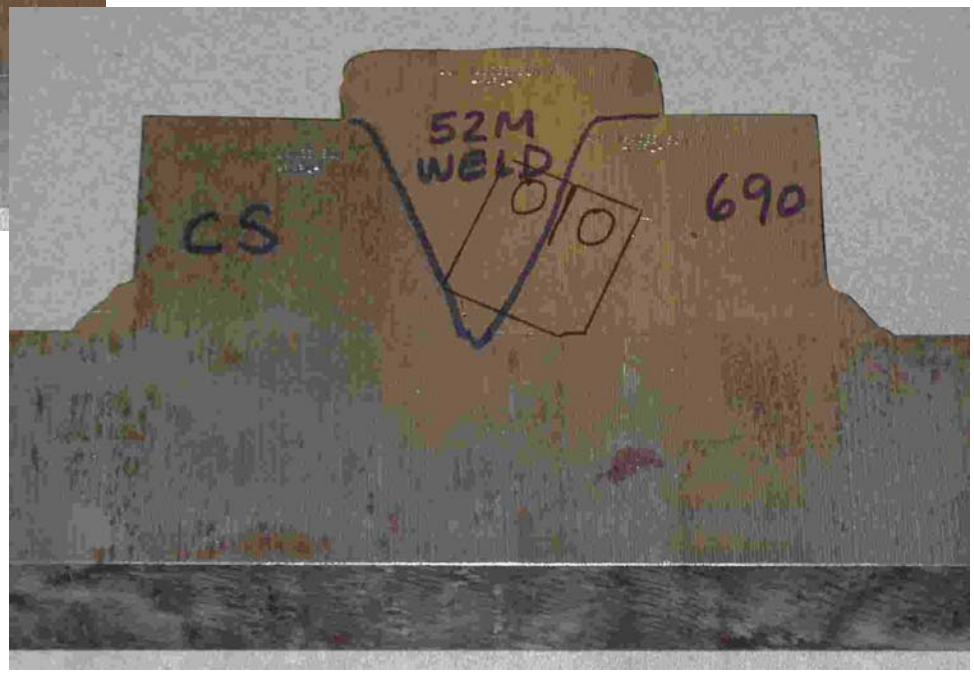
SCC in Alloy 690, Weld HAZ & Weld Metals

- *This EPRI program will examine Alloy 690 base metal, weld HAZ-aligned 690, and Alloy 52/152 weld metal.*
- *Recently started two weld HAZ-aligned specimens of KAPL EN52M welds: one narrow-groove HAZ, one V-groove HAZ.*
- *Considering HAZ-aligned electron beam welds of 690 plate*
- *Awaiting additional plate, billet and CRDM materials, as well as various weld metals.*
- *Characterization will be done in a parallel program by Morra*

HAZ-Aligned Specimens of KAPL EN52M

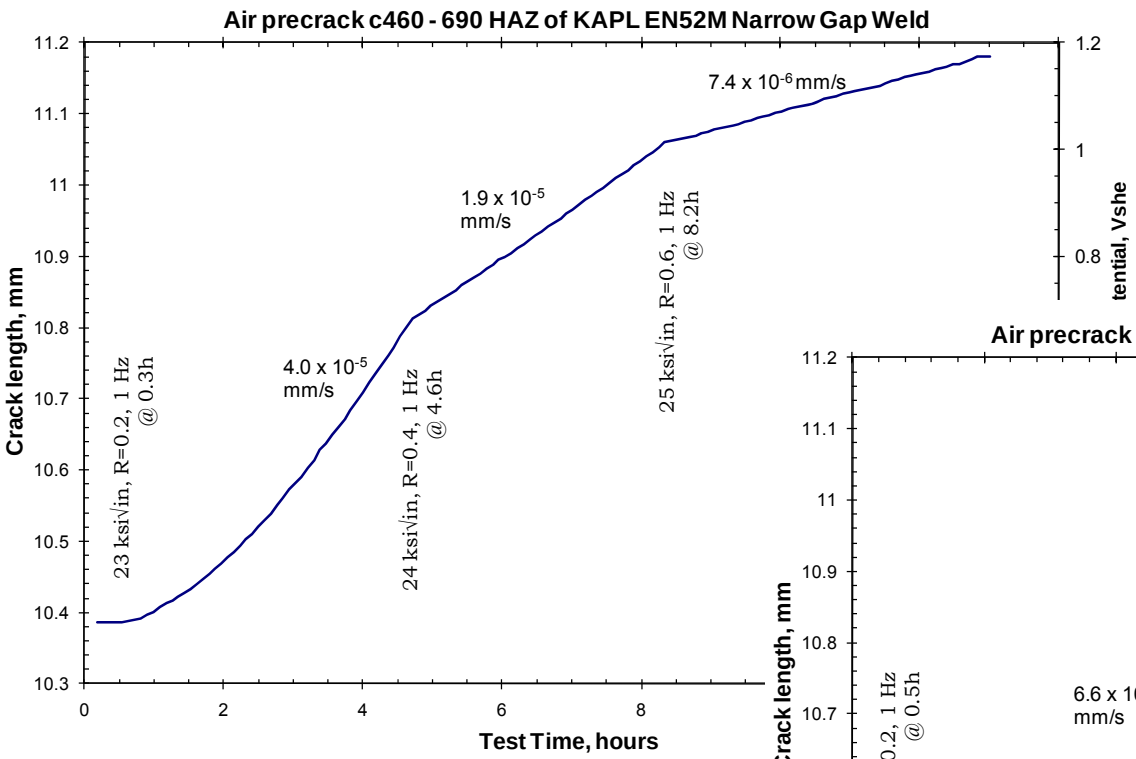


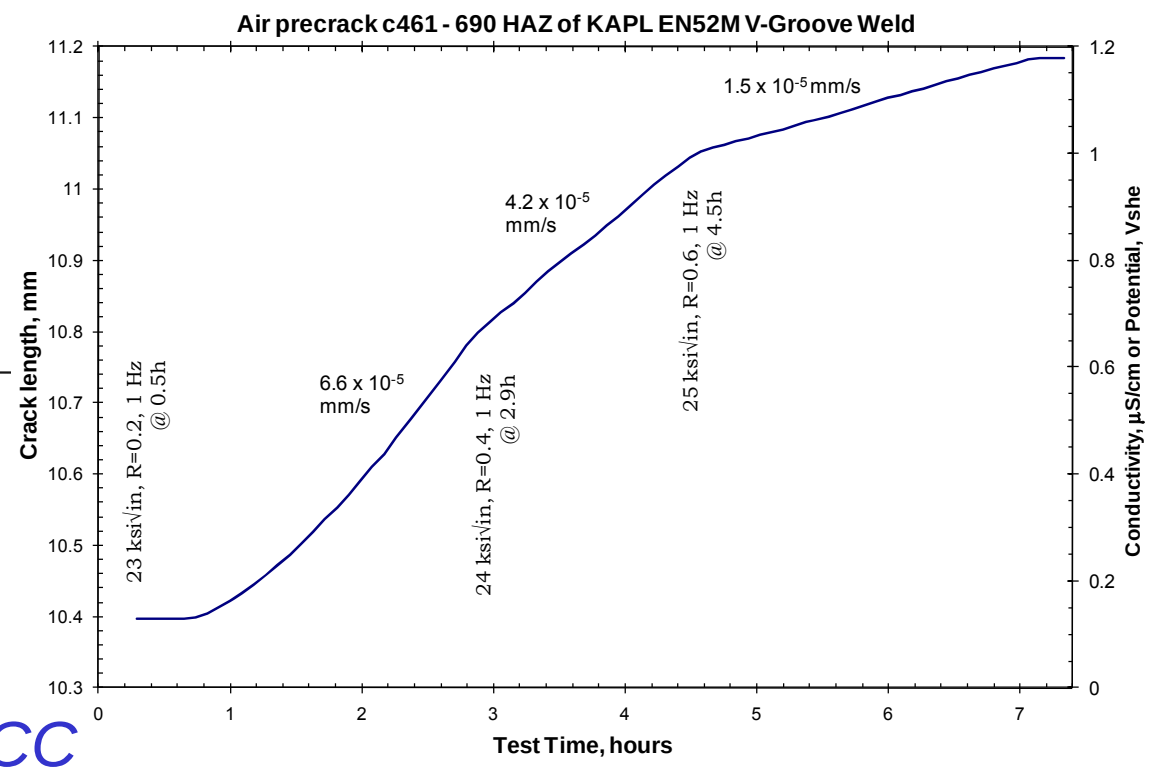
Narrow-groove HAZ



V-groove HAZ

HAZ-Aligned Specimens of KAPL EN52M



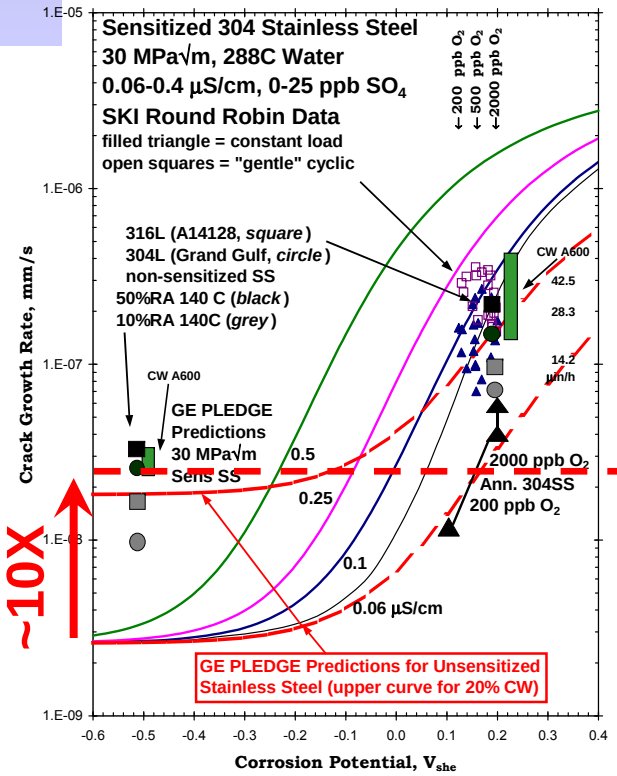


Narrow-groove HAZ

V-groove HAZ

Now transitioning to IGSCC

High Growth Rates in 690



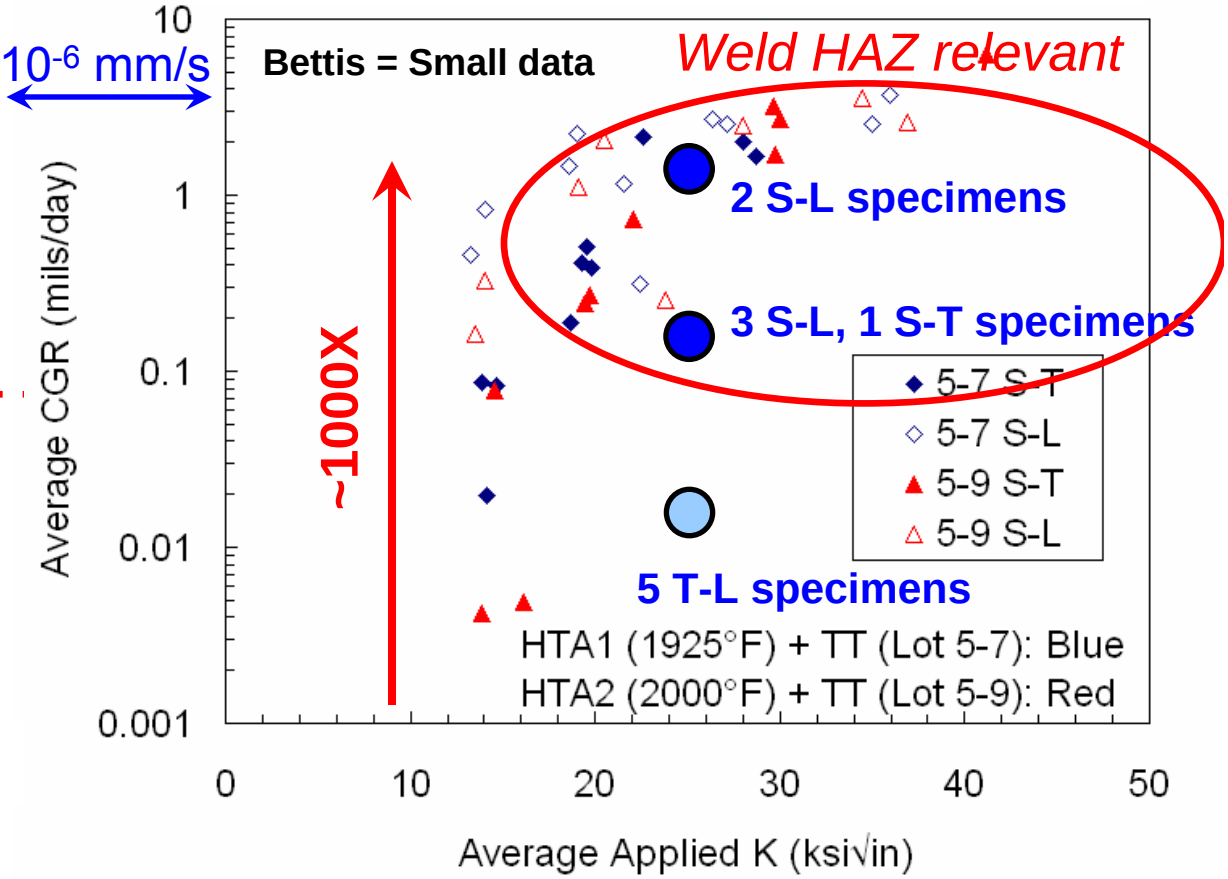
~10X

No SCC – SCC in plants in ~30 yrs

Sens & CW 304SS, BWR

24% Cold Rolled 690, PWR Water

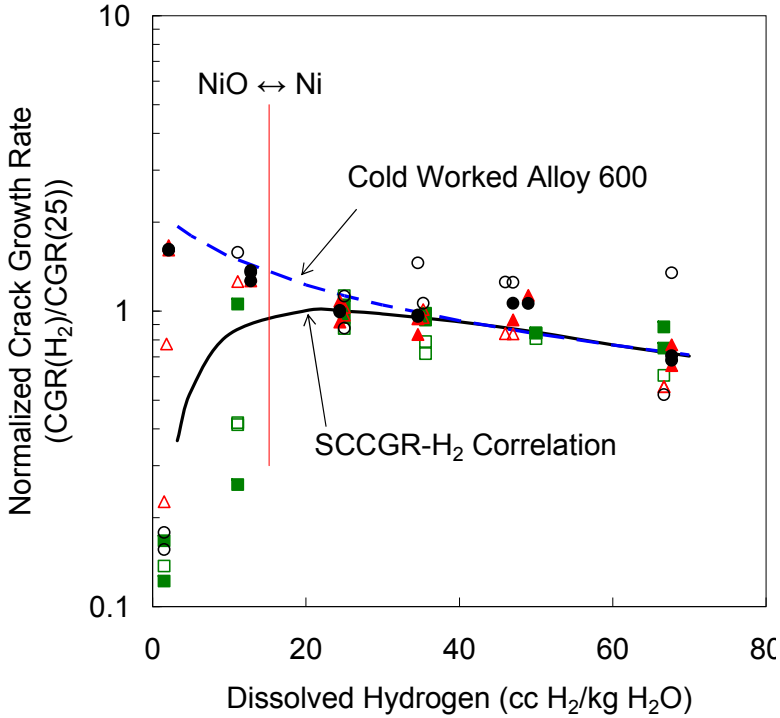
10^{-6} mm/s

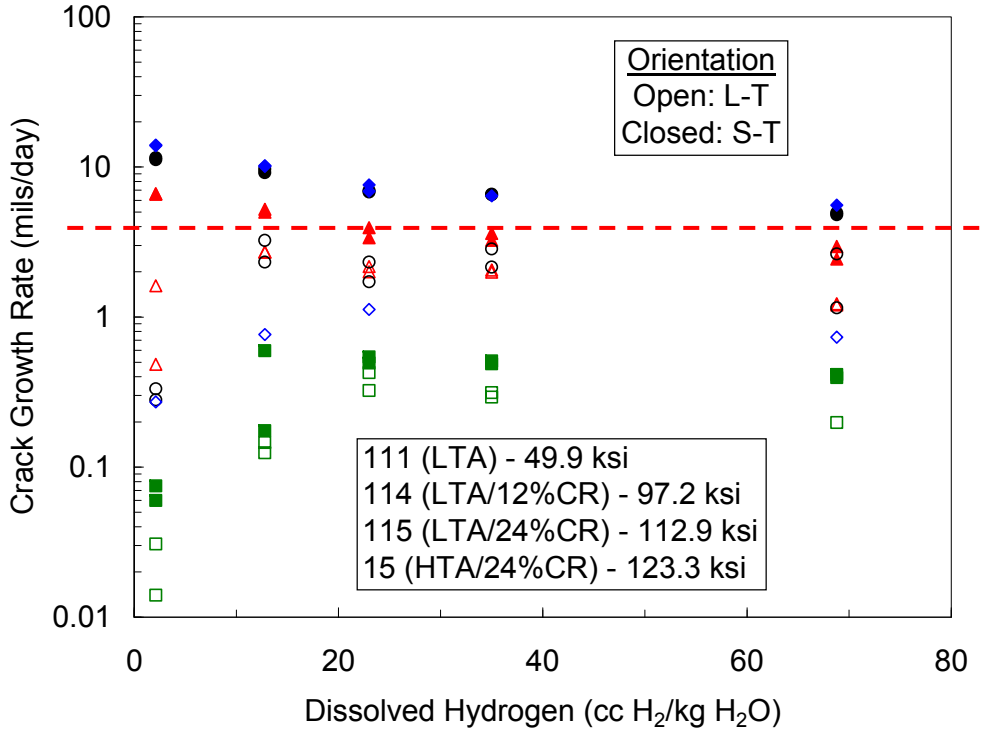


Some 690 – not necessarily with microstructure banding – exhibits growth rates higher than sensitized SS in BWR water.

1000X is an unprecedented CGR increase that must be understood

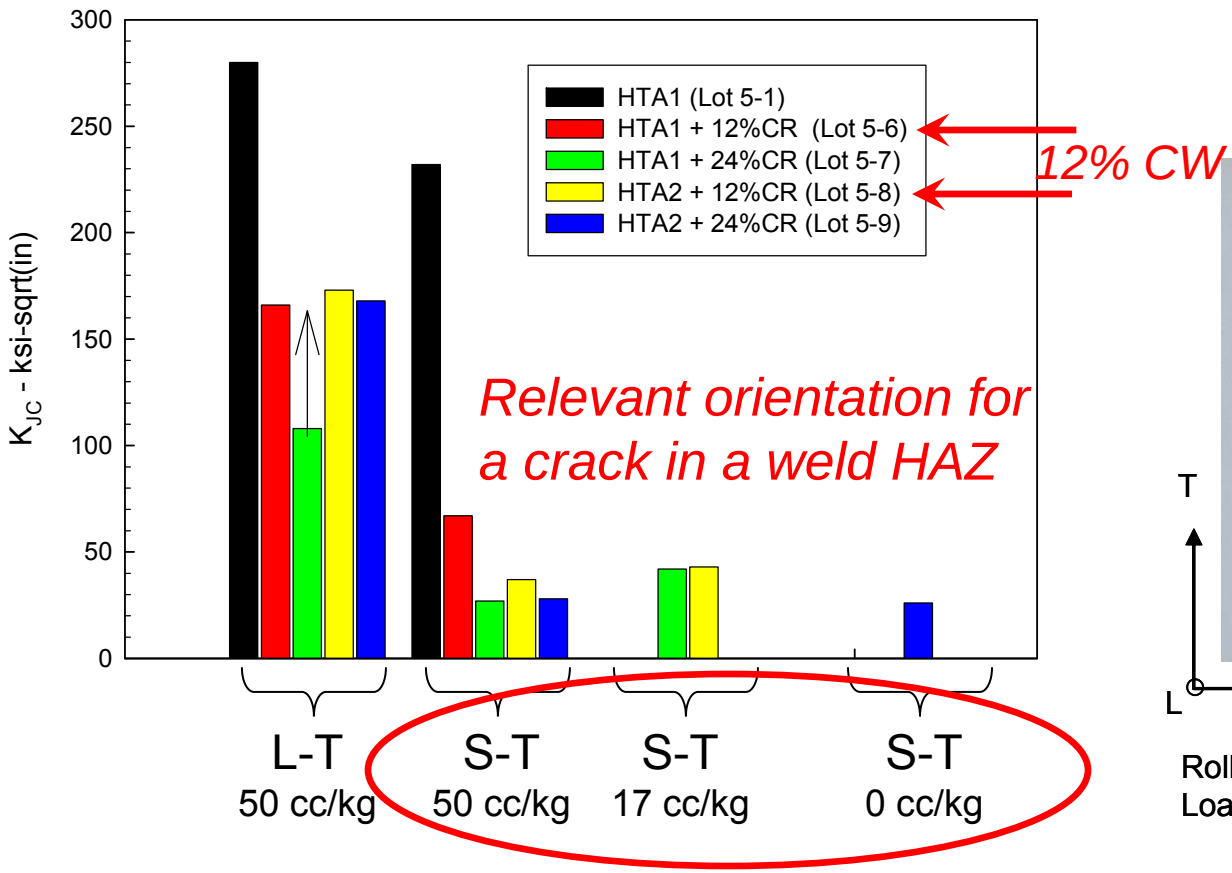
Limited CGR Difference Compared to CW 600



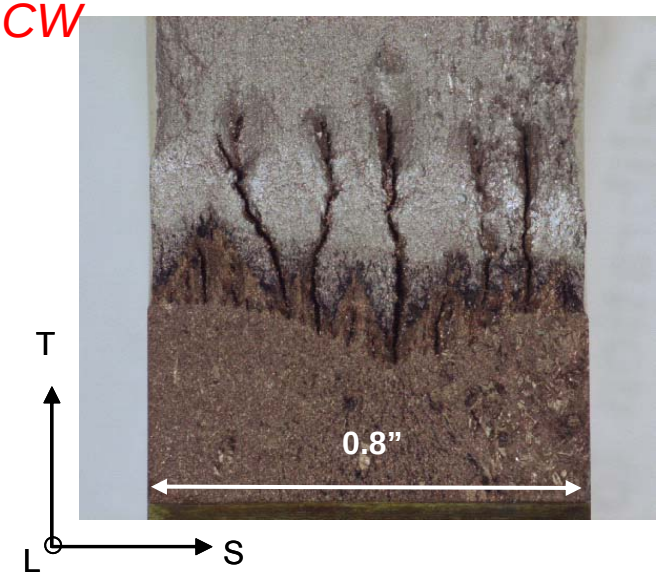


The 3 – 4 mils/day (~1 x 10^{-6} mm/s) upper range of the CW 690 data within about 2 – 3X of CW 600 data

Parallel Issues in Bettis LT Cracking Data



24% cold rolled, L-T
Rising Load Test



Rolling plane parallel to T direction.
Loading direction out of page.

K_{JC} In 130°F water degraded for S-T orientation in cold worked Alloy 690

Strong driving force to crack in rolling plane even with apparent high K_{JC}

Introduction to SCC in Alloy 690

- 690 is a 30% Cr alloy that can have good SCC resistance.
- Its high (30%) Cr content causes more pronounced segregation during solidification – that is, inhomogeneity of Cr, Nb, carbide distribution and grain size.
- The inhomogeneity may not be eliminated by standard processing – such as cogging, forging, extrusion, etc.
- ~1000X higher SCC growth rates have been observed in cold worked "rogue" heats – some without inhomogeneity
- Many weld heat affected zones have peak residual strain in the range of 20 – 25% equivalent 25C tensile strain

1000X is an unprecedented CGR increase that must be understood

Key Issues in SCC of Alloy 690

Key questions associated with high growth rates in 690:

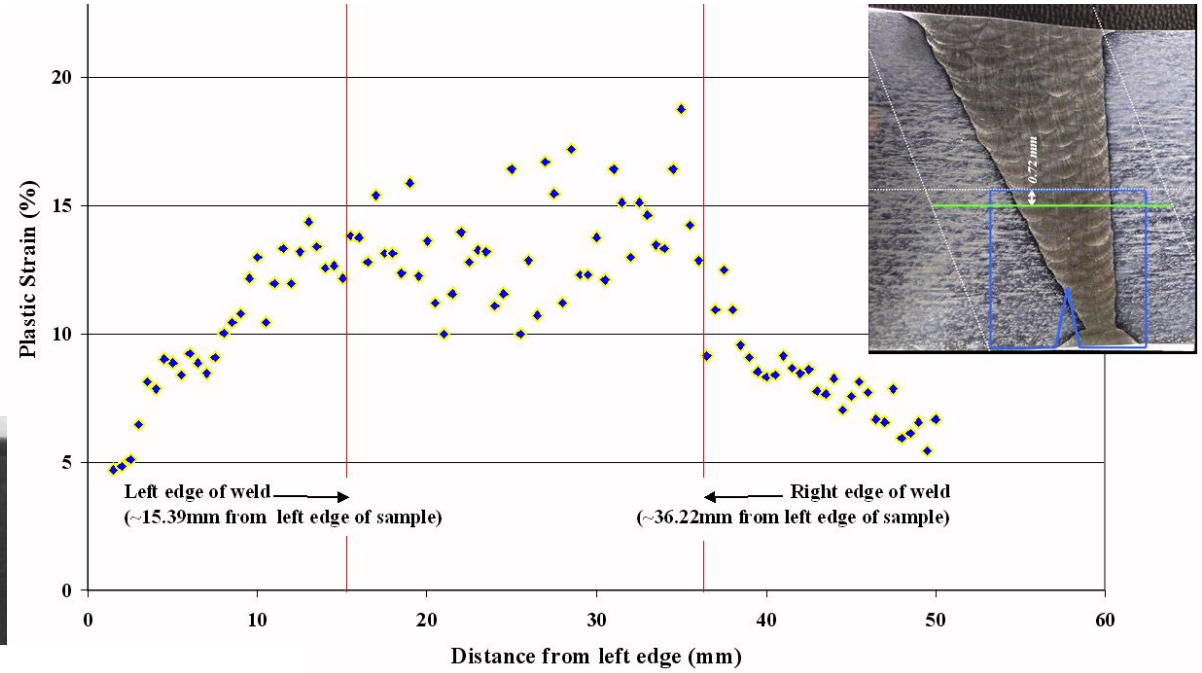
1. Are all high growth rate materials inhomogeneous?
Careful Bettis exam showed banding in 1 or 2 of 3 cases.
But no other good explanation exists for high CGR.

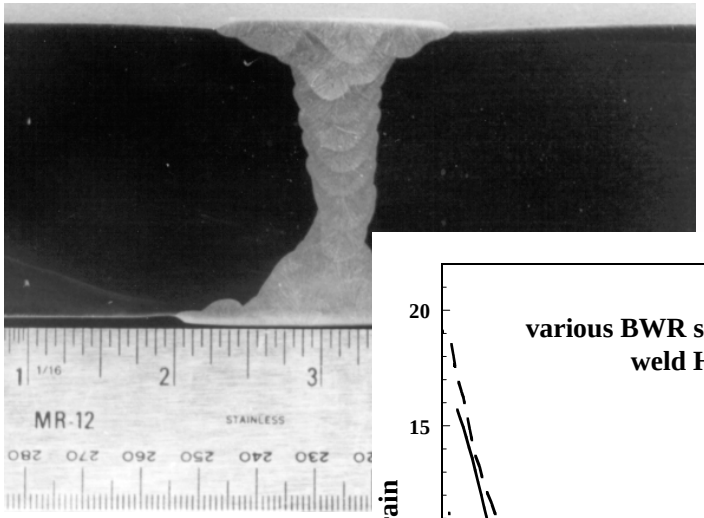
2. Are specific product forms of 690, such as extrusions or billet, guaranteed to be homogeneous and to exhibit low CGR?
Examples of inhomogeneity exist in all forms, but it's less likely after extensive processing, e.g., extrusion.
But high CGRs are observed in some homogeneous 690.

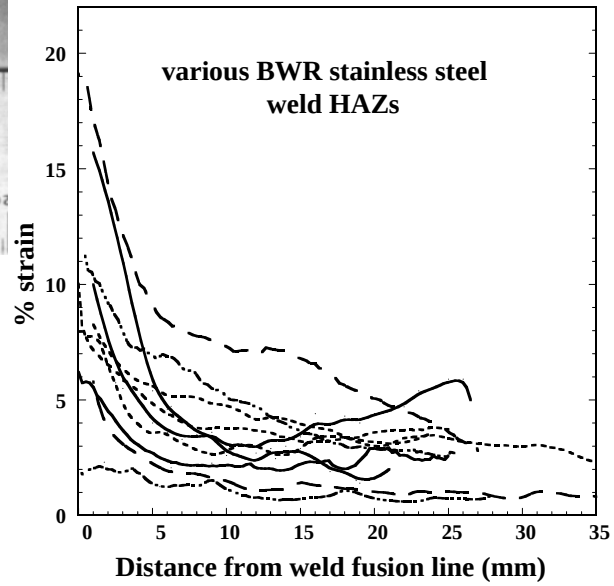
3. Are weld HAZ shrinkage strains able to produce high CGR?
Observed in dozens of cases in SS and A600.

4. Can the "tensile" weld shrinkage strain or forging produce the same high growth rates in 690 as cold rolling? <likely>

Weld Residual (Shrinkage) Strain



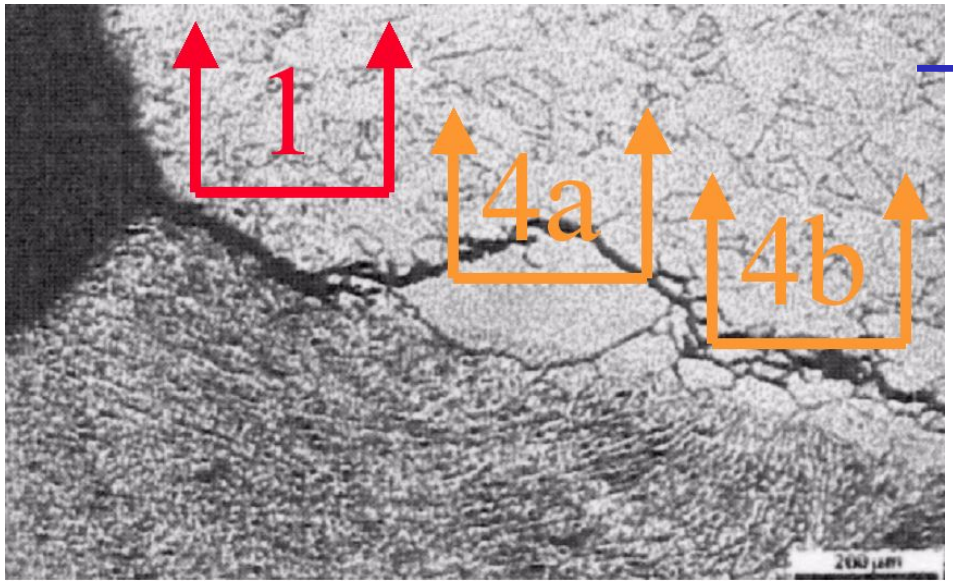


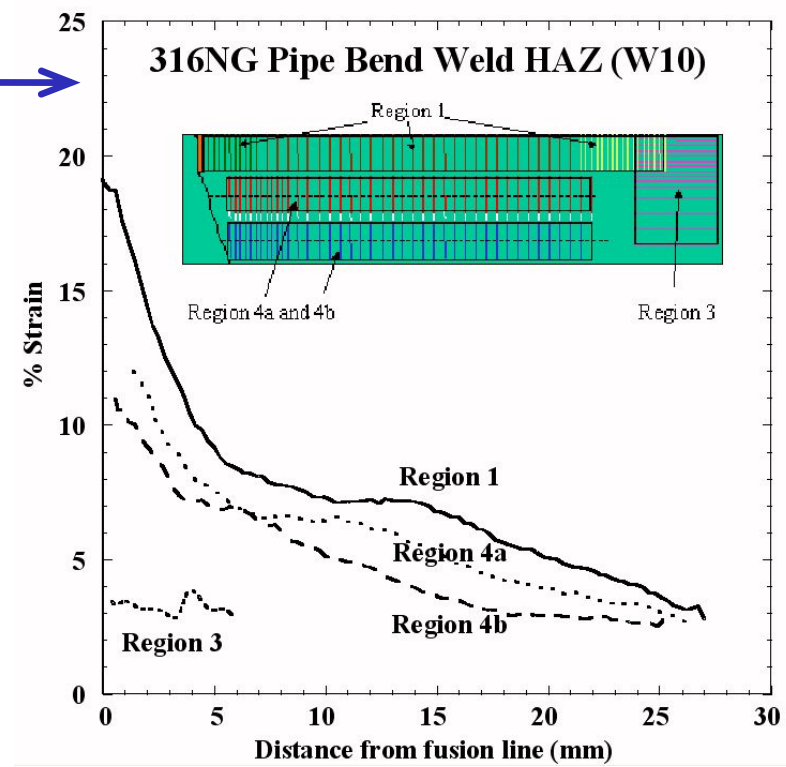


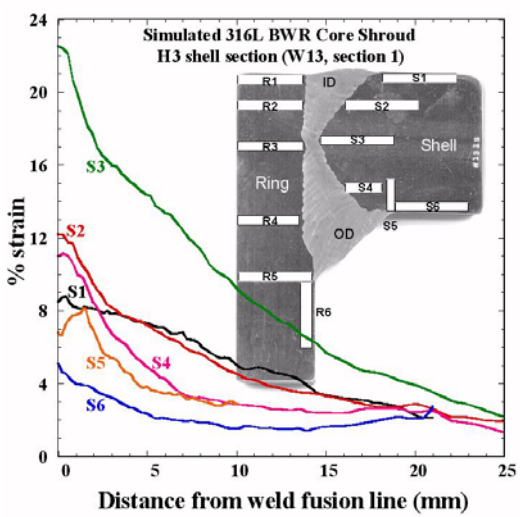
Weld residuals strains are highest at the fusion line and then drop off.

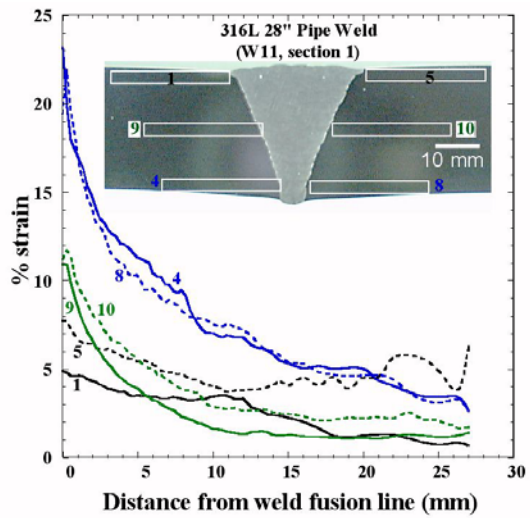
Residual strain is highest at weld root due to repeated weld passes.

Weld Residual Strain Effects on SCC



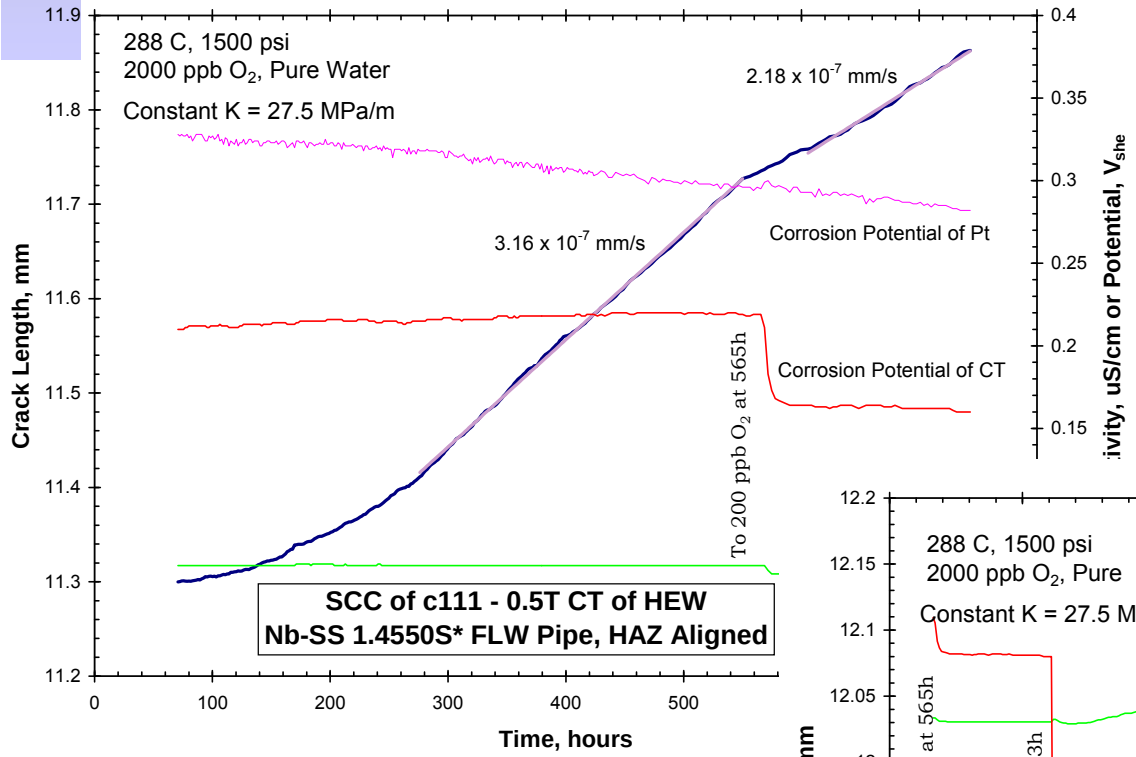




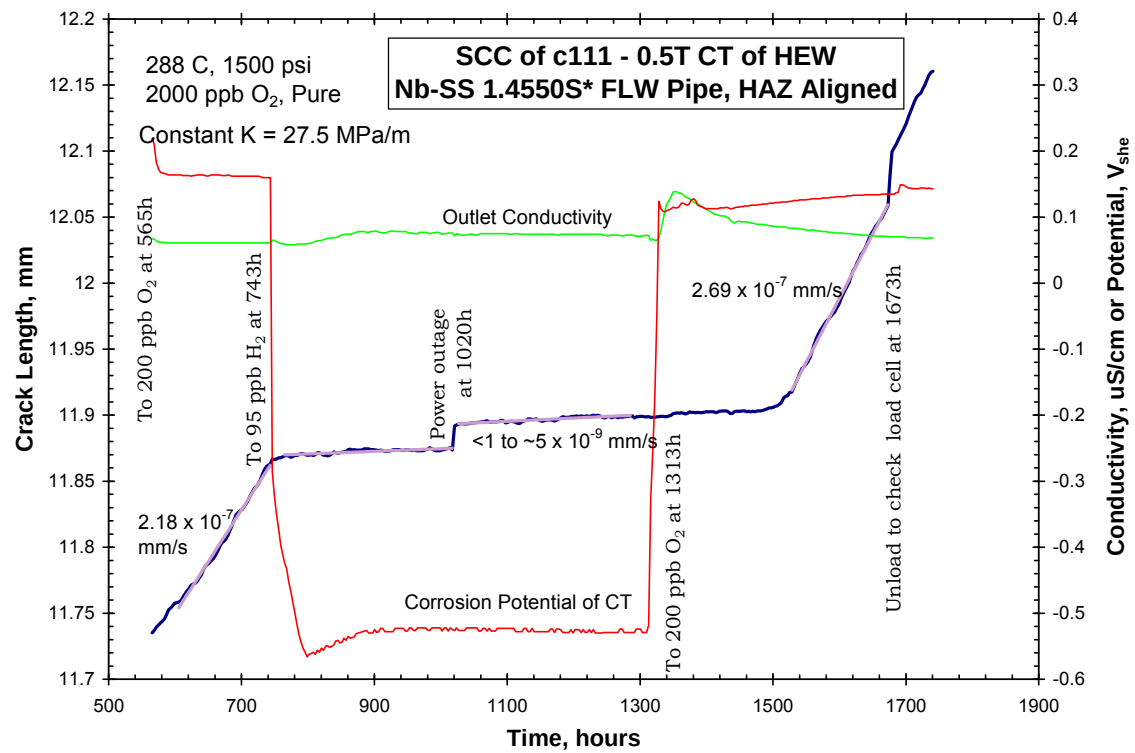


Weld residual strain often peaks at >20% equivalent room temperature strain

SCC of 690 & Welds



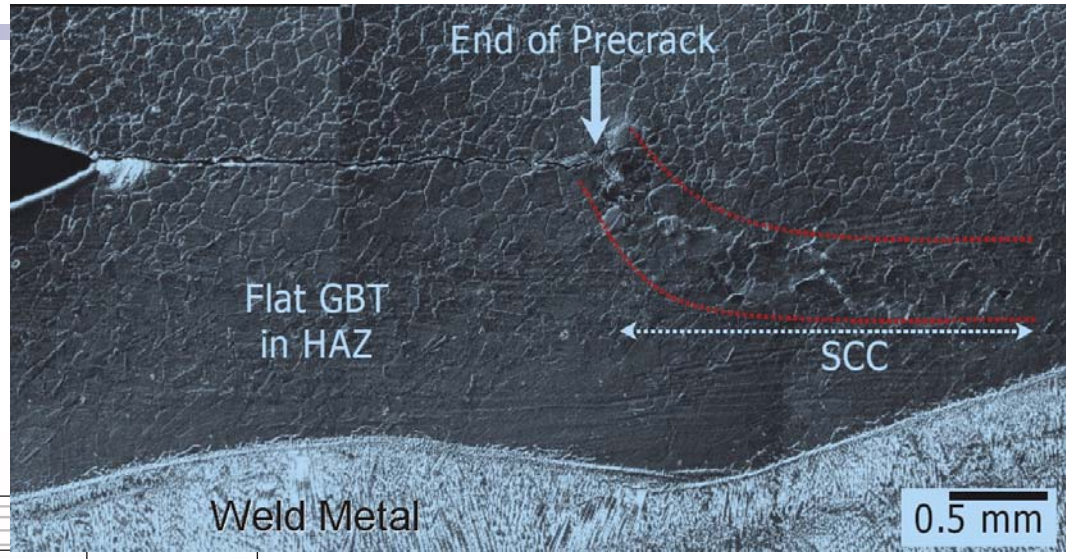
High SCC Growth Rates in SSs in Both Cold Worked and Weld HAZ

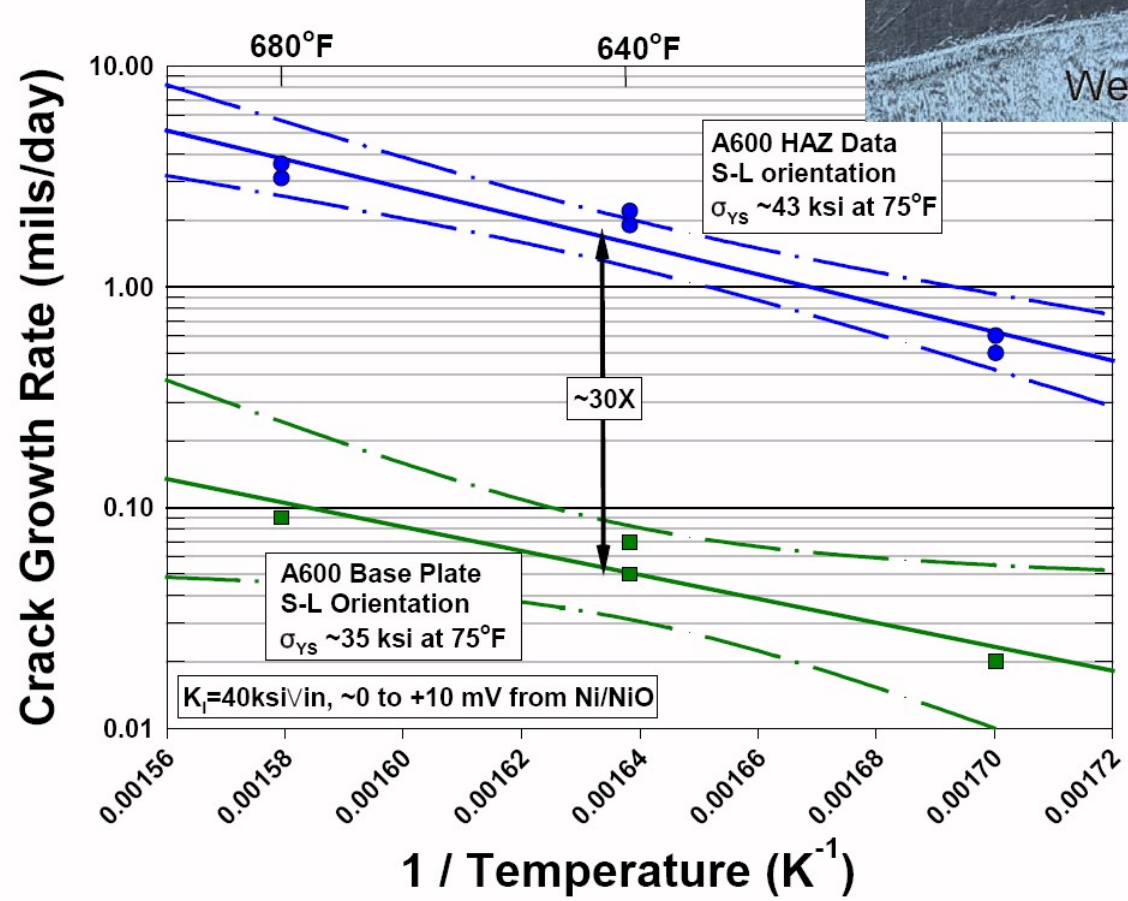


Crack plane naturally aligns along plane of weld HAZ shrinkage strain and yields high growth rates

Alloy 600 Weld HAZ

G.Young et al.





Weld HAZ can have degraded structure, weld dilution and high residual stresses & strains

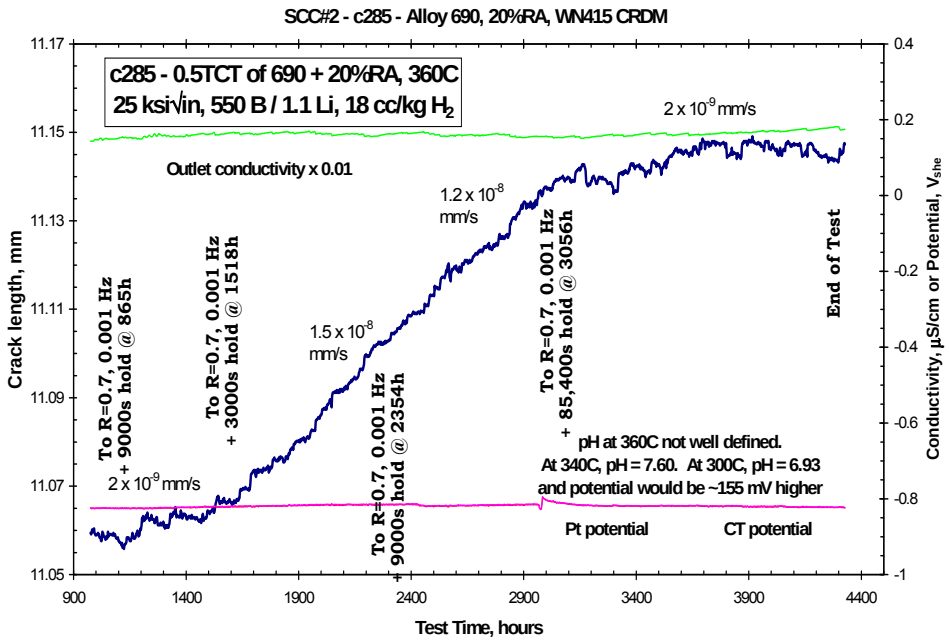
Testing Approach

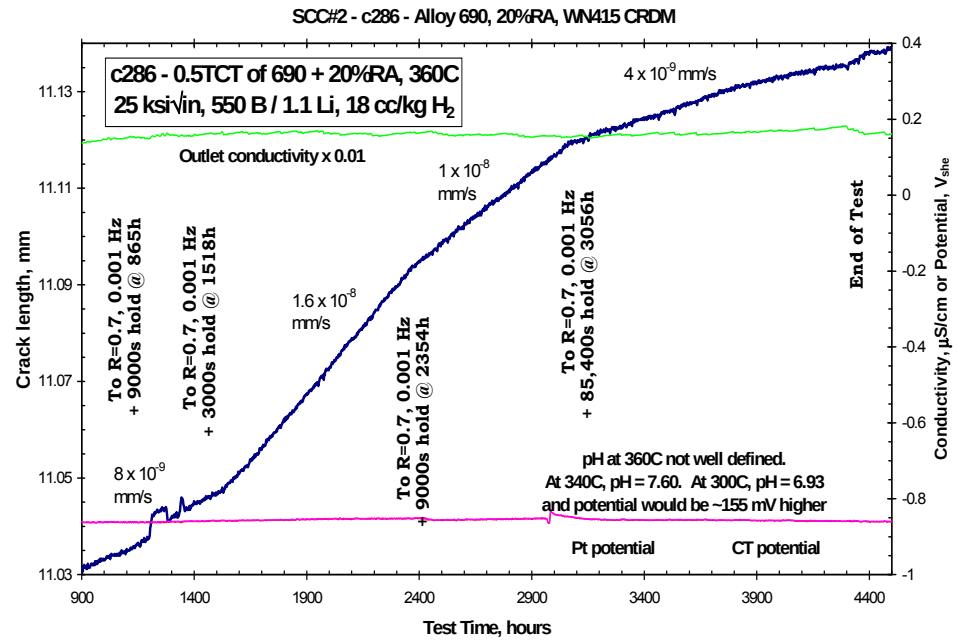
Crack growth rates conditions for alloy 690 and 152/52 welds:

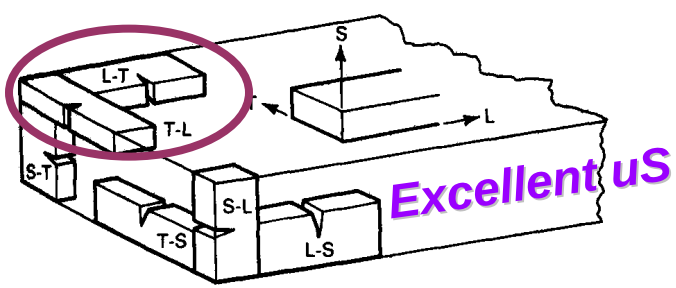
- *690 cold worked by forging or 1-D rolling at 25 ºC*
  - *by 20, 26 and 40% reduction in thickness*
  - *S-L, S-T and T-L orientations, 5 heats, 12 specimens*
  - *cold work broadly simulates weld residual strain in HAZ*
  - *152/52 weld: T-S orientations, 4 heats, 4 specimens*
  - *used resistivity coupon for dcpd correction*
- *0.5T CT specimens in 360 ºC (290–340ºC) PWR primary water*
- *testing at 25 – 35+ ksi√in, including "Varying-K"*
- *H_2 level designed to be near Ni/NiO at the test temperature*
- *good water chemistry: ~2 volume exchanges per hour, full-flow demineralization, and active H_2 sparging*
- *measured potentials of 690 & Pt vs. $Cu/Cu_2O/ZrO_2$*

Specimens c285, c286

20% Cold Work Alloy 690 CRDM

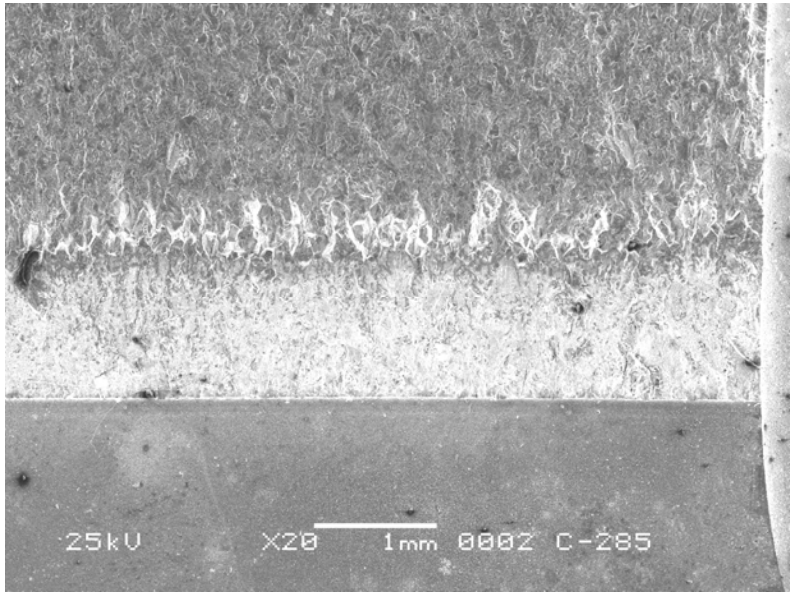


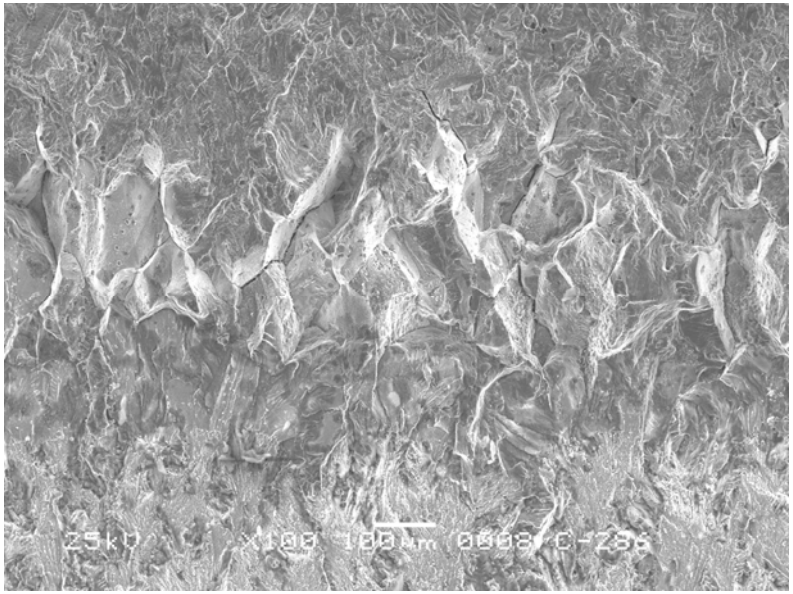


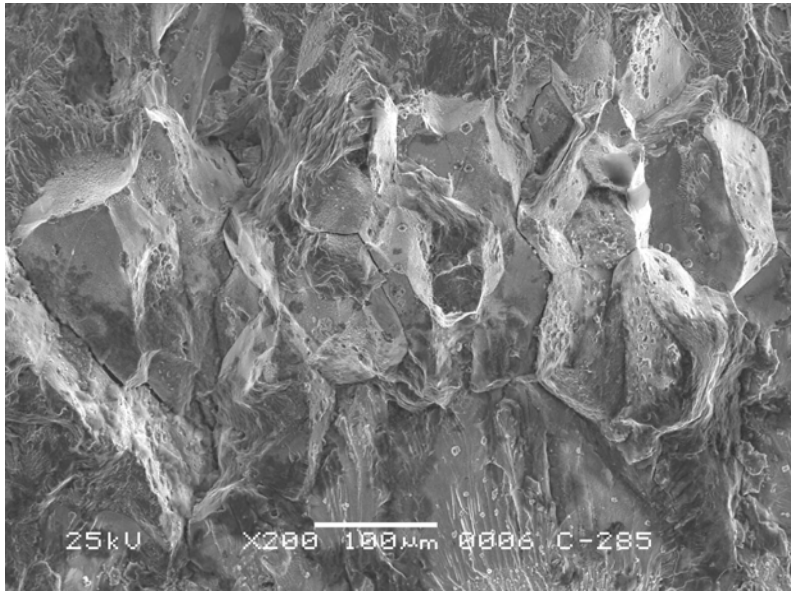


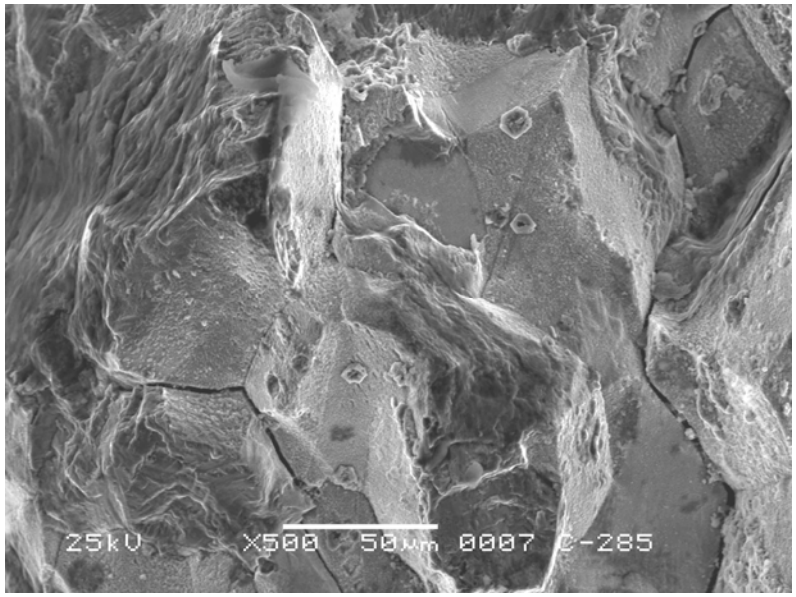
L-T Orientation (good)
Very homogeneity microstructure
Orientation doesn't reflect weld HAZ

c285/c286 SEM Fractography



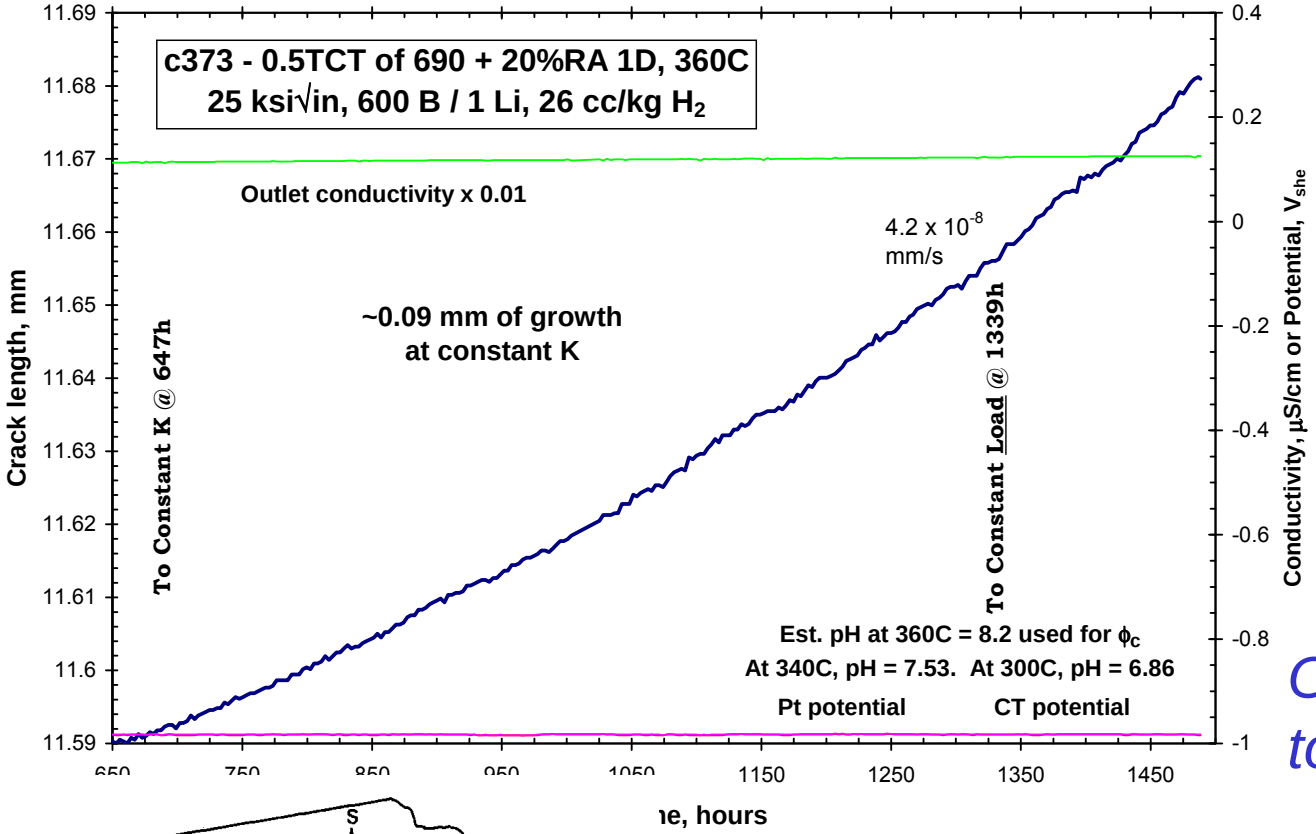




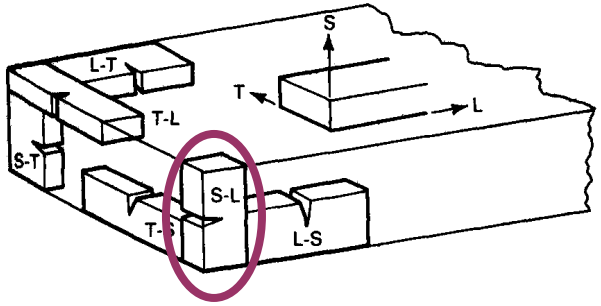


Specimen c373

1D, 20% Cold Worked GE GRC Alloy 690



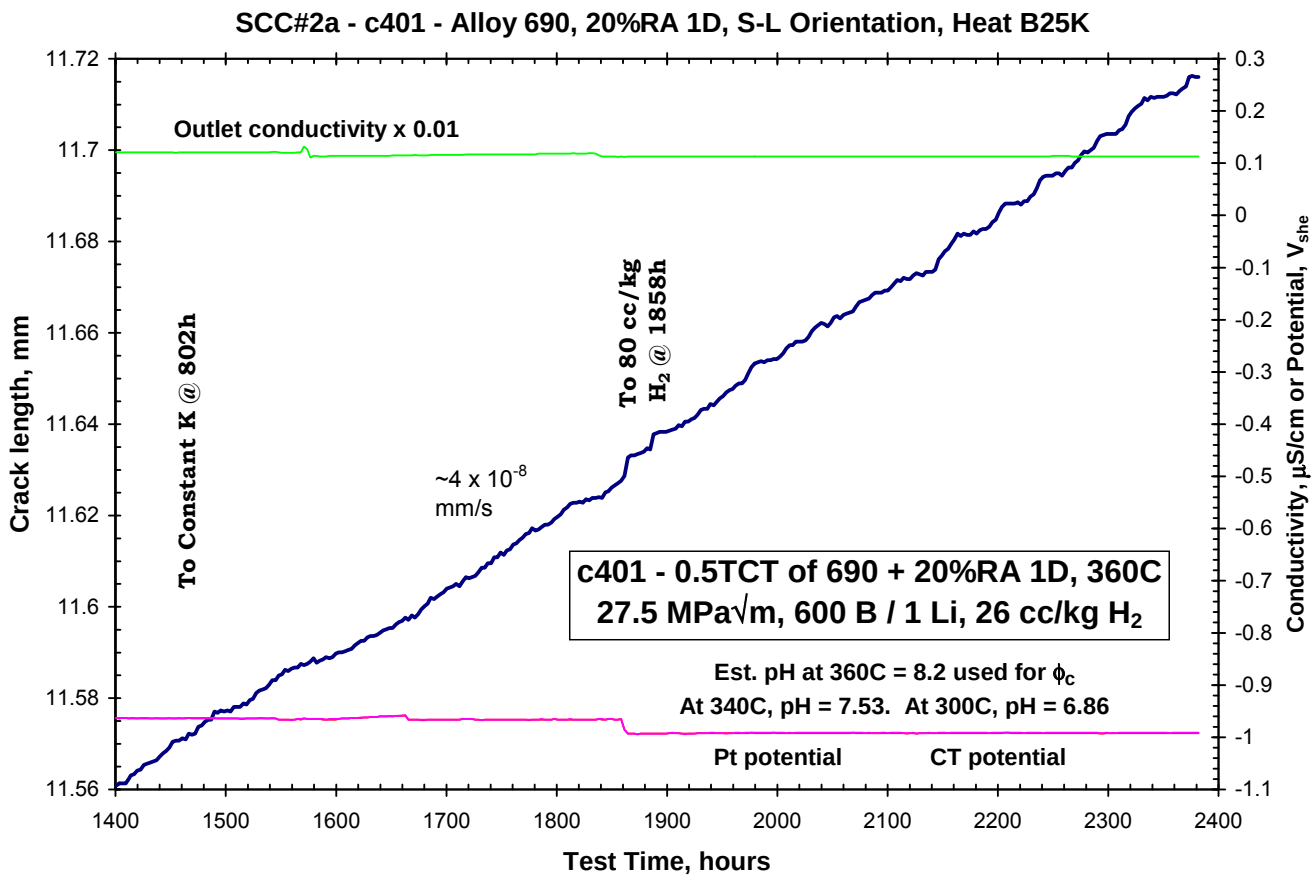
Orientation is relevant to SCC in weld HAZ



Medium CGR in S-L orientation
Very homogeneous microstructure
1D cold rolled = "1.5D" due to spreading

Specimen c401

1D, 20% CW GE CRD Alloy 690 – Test #2

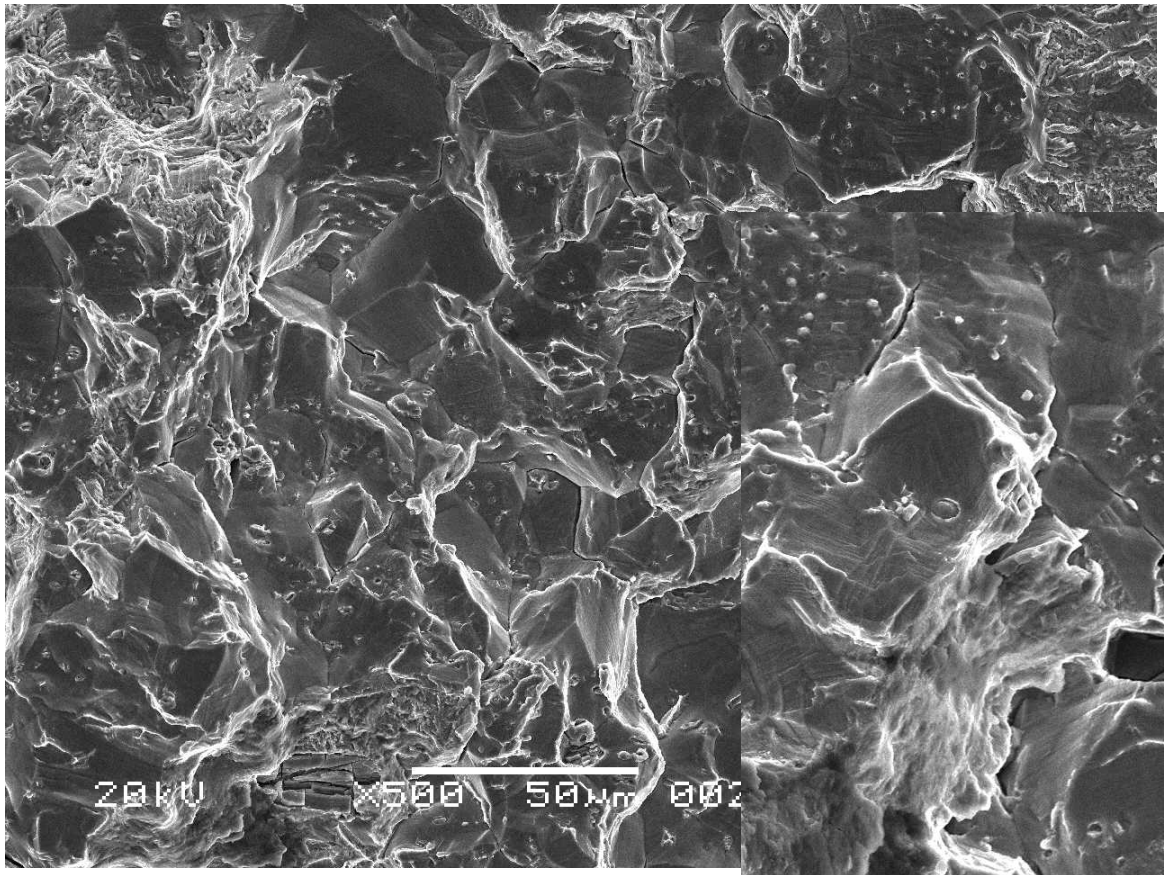


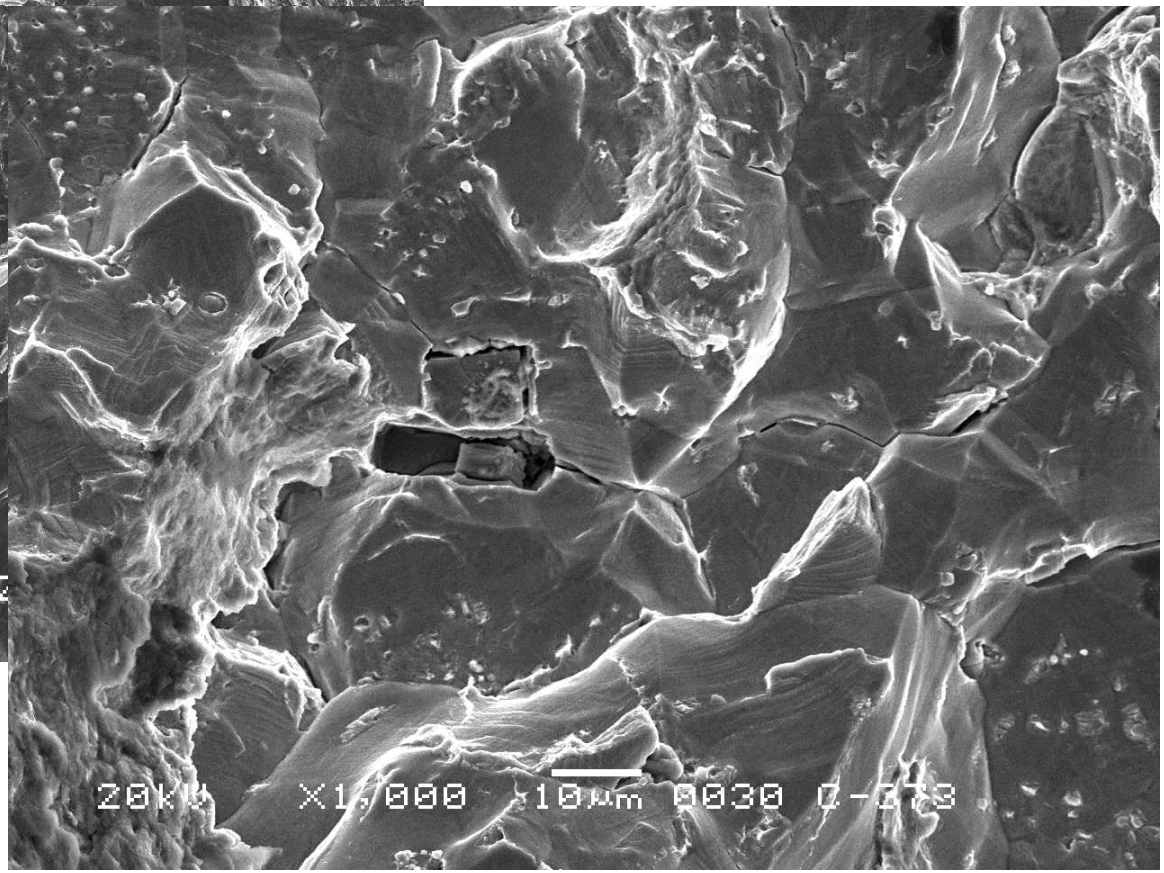
Similar data in second test on same material

No effect of dissolved H_2

Specimen c373

SEM Fractography of 1D, 20% CR GE 690

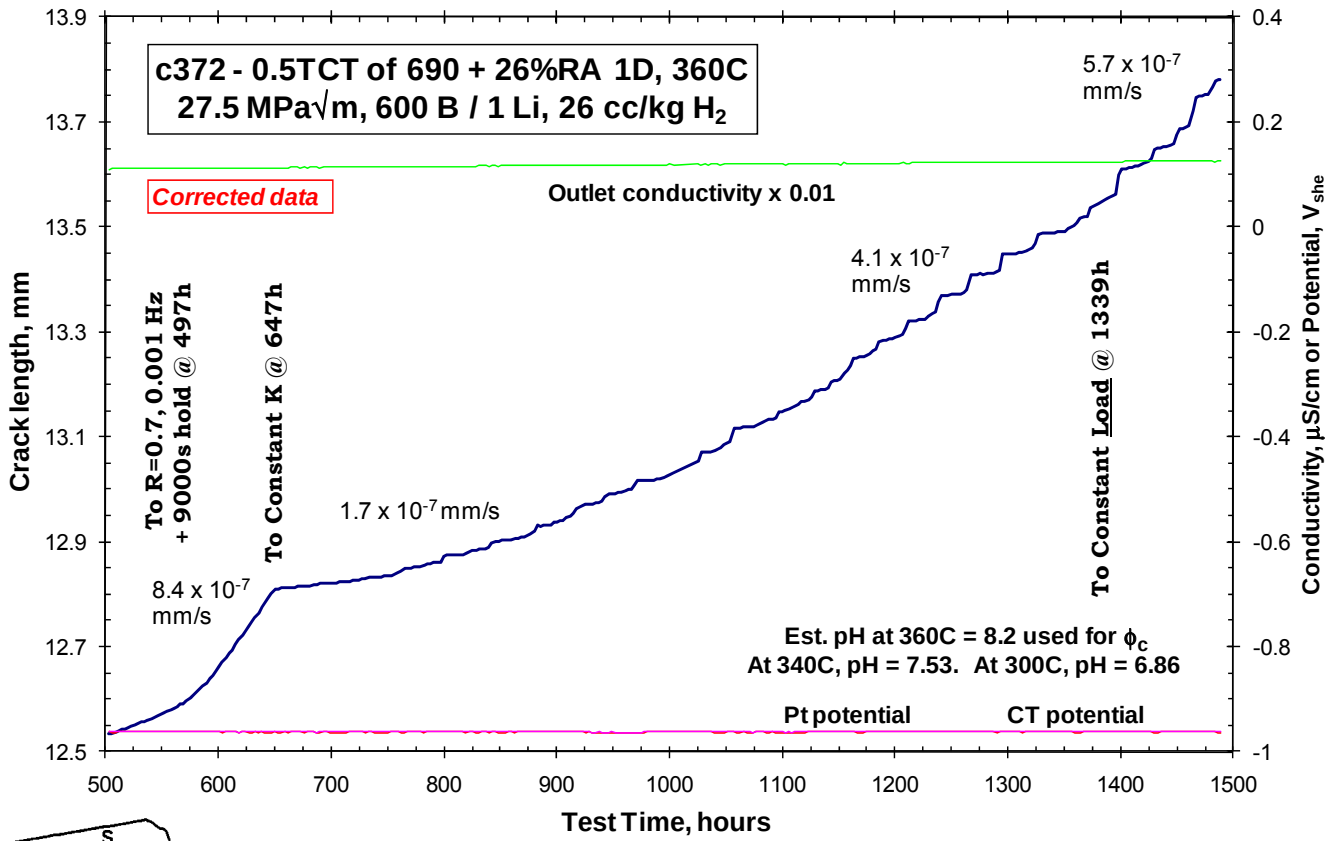


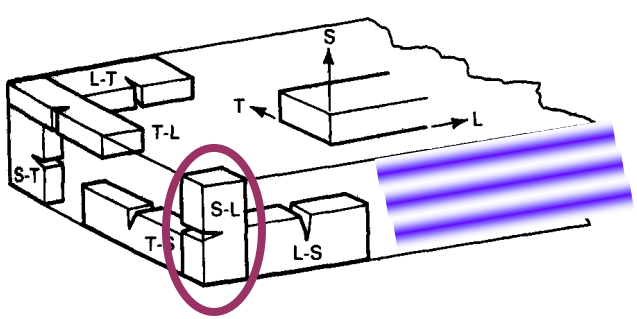


Very homogeneous microstructure – forged bar. Double melted: VIM-VAR

Specimen c372

1D, 26% Cold Worked ANL Alloy 690

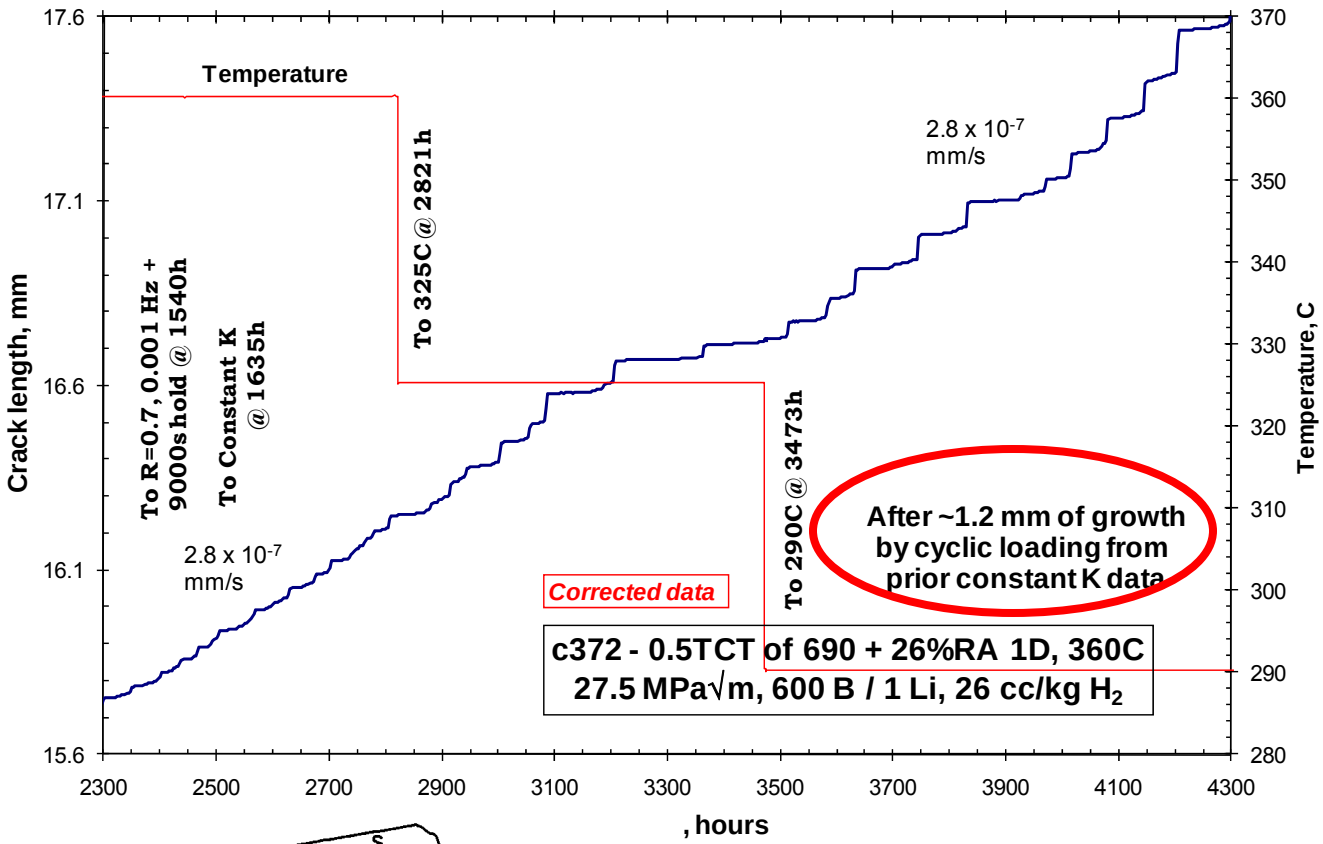




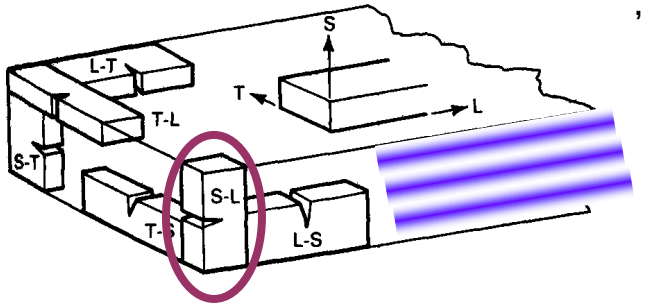
High CGR in S-L orientation
Inhomogeneous microstructure
1D cold rolled = "1.5D" due to spreading

Specimen c372

1D, 26% Cold Worked ANL Alloy 690



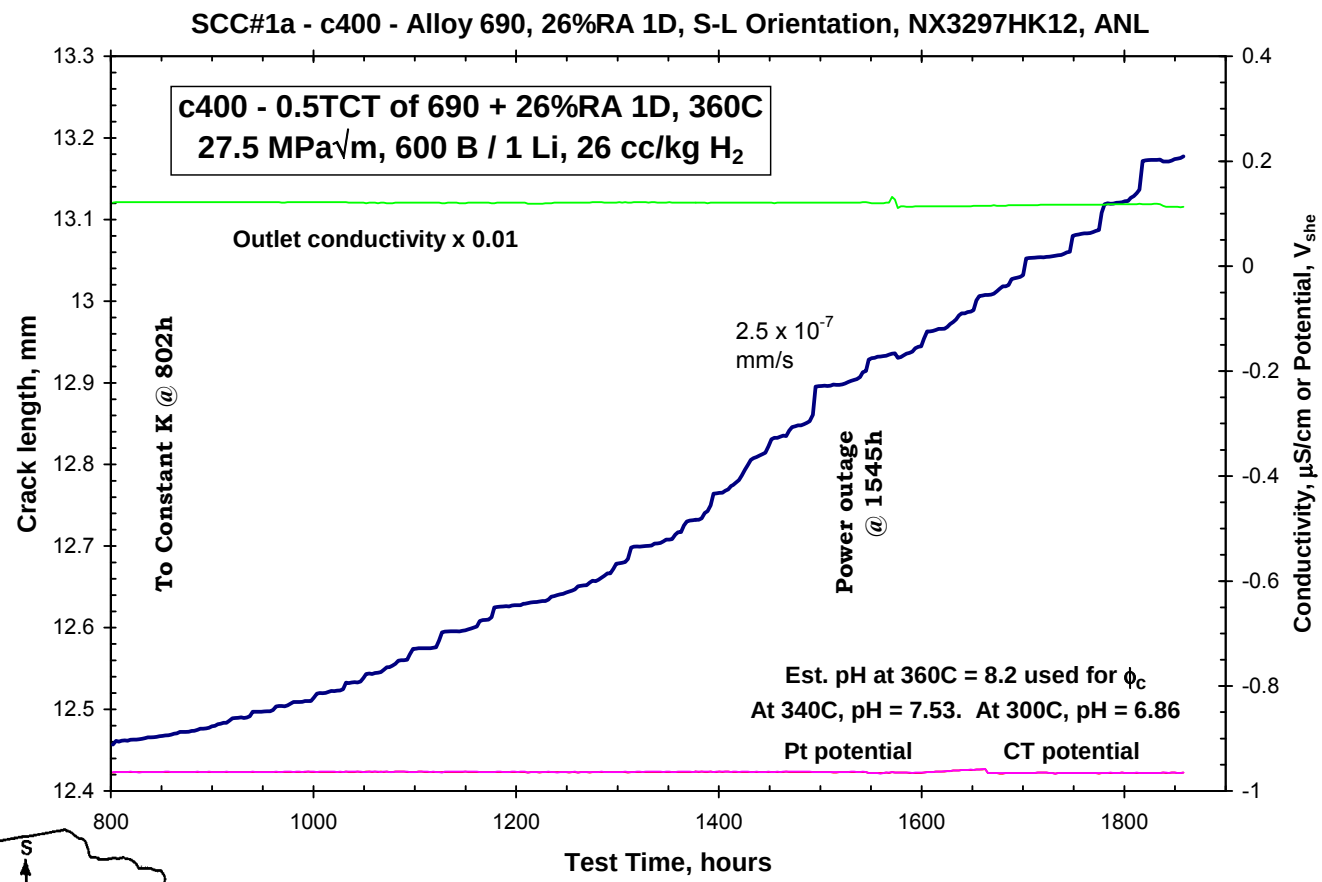
No temperature effect; would be 12X normally

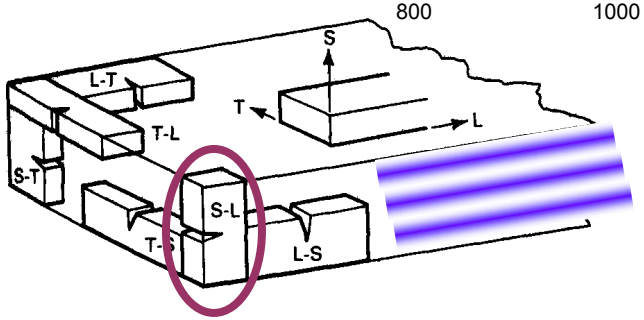


High CGR in S-L orientation
Inhomogeneous microstructure
1D cold rolled = "1.5D" due to spreading

Specimen c400

1D, 26% CW ANL Alloy 690 – Test #2

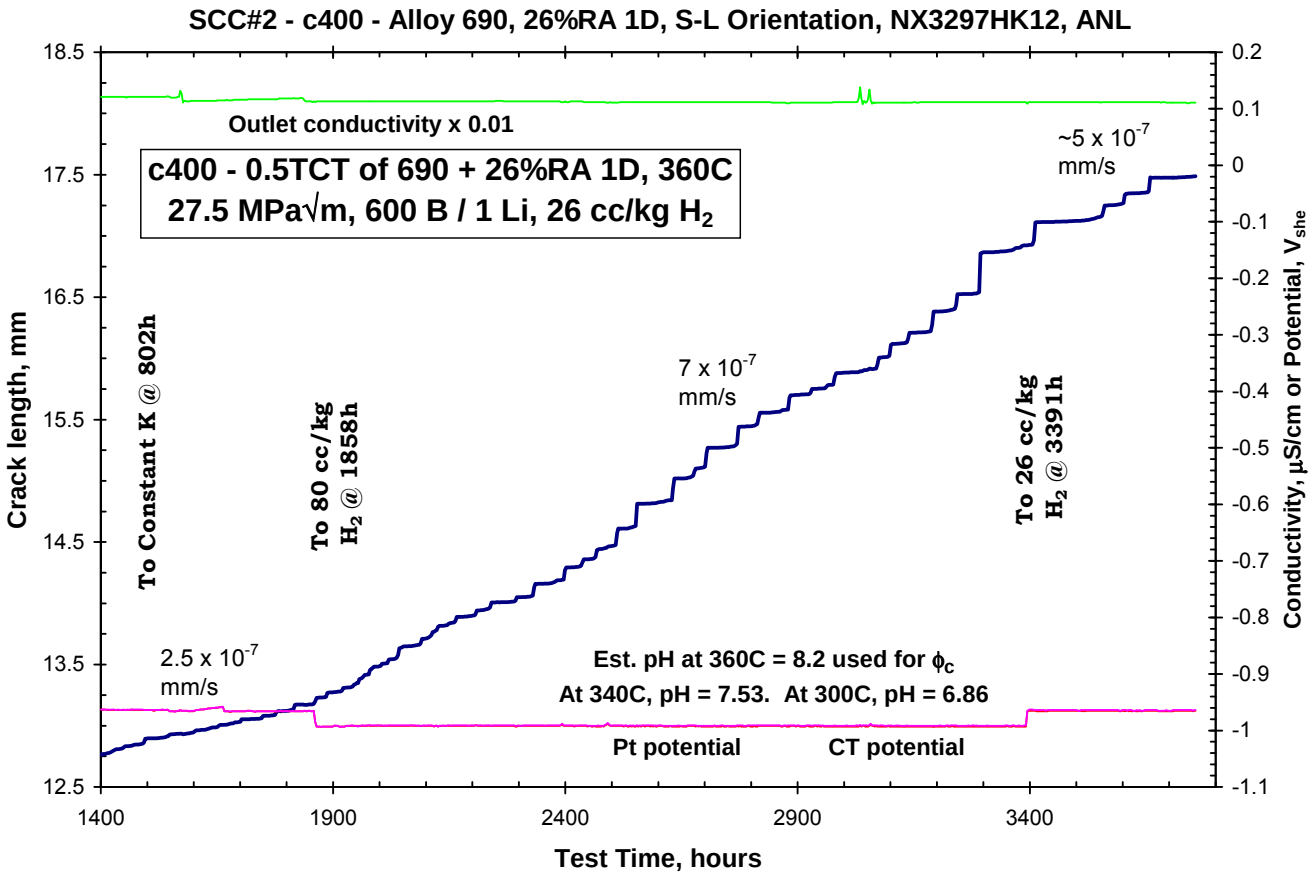




High CGR in S-L orientation
Inhomogeneous microstructure
1D cold rolled = "1.5D" due to spreading

Specimen c400

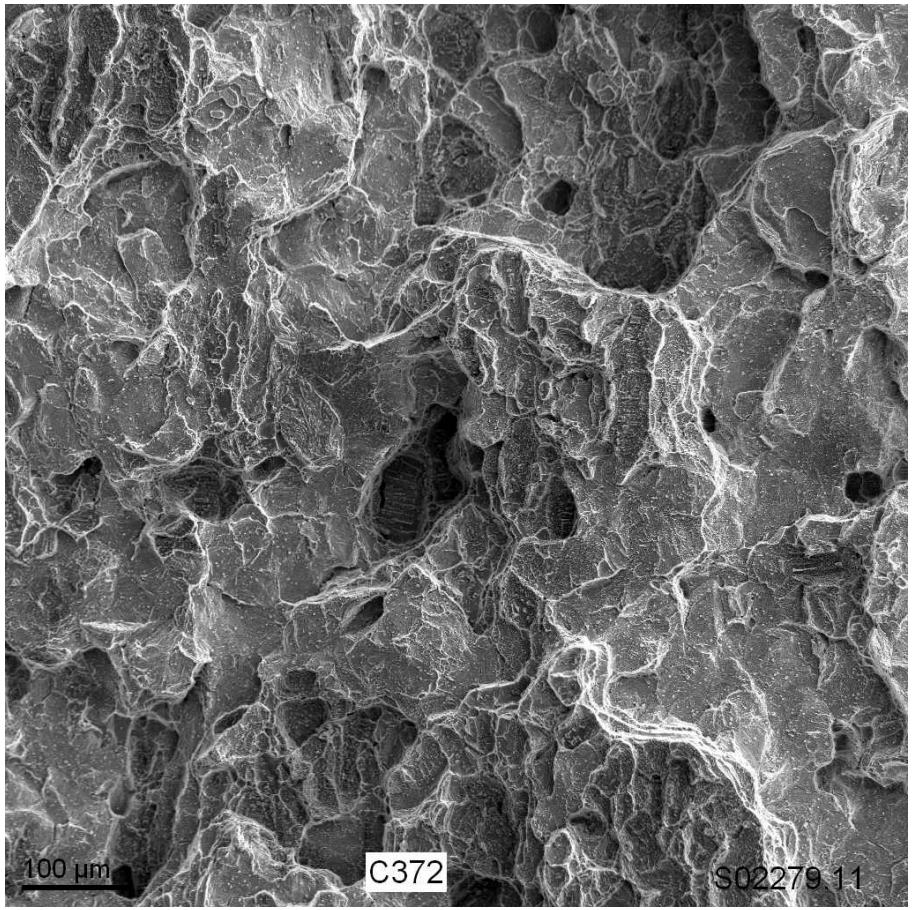
1D, 26% CW ANL Alloy 690 – Test #2

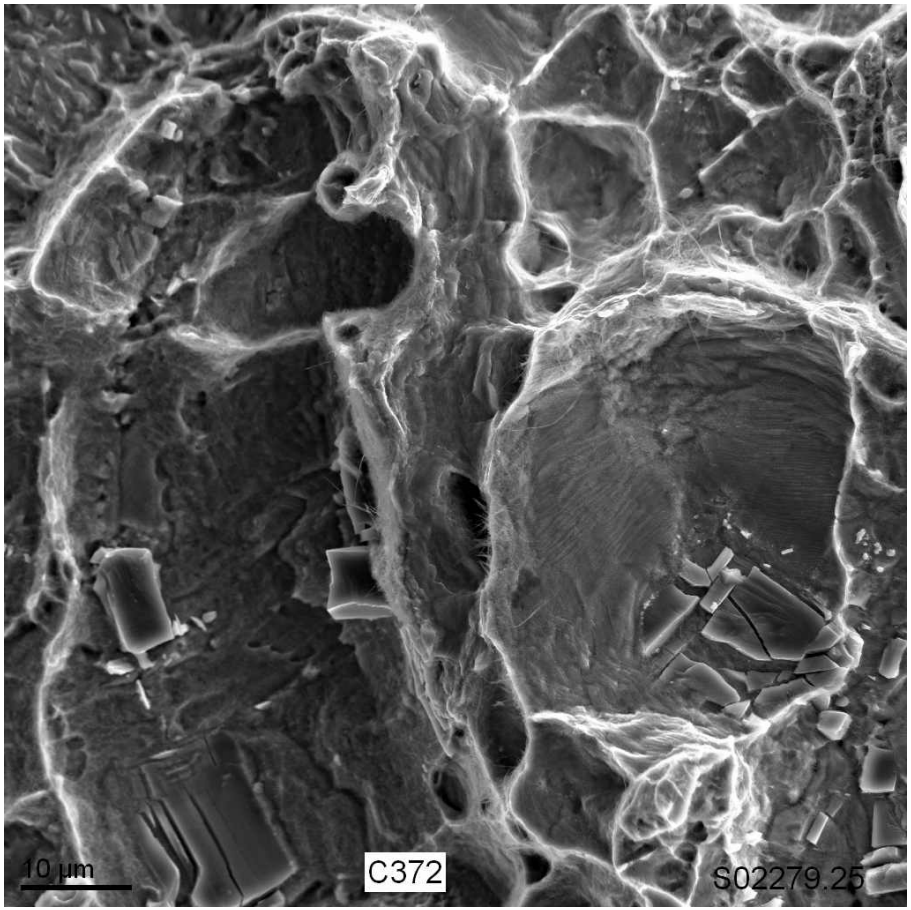


Similar data in second test on same materials;
Fast growth, no effect of dissolved H_2

Specimen c372

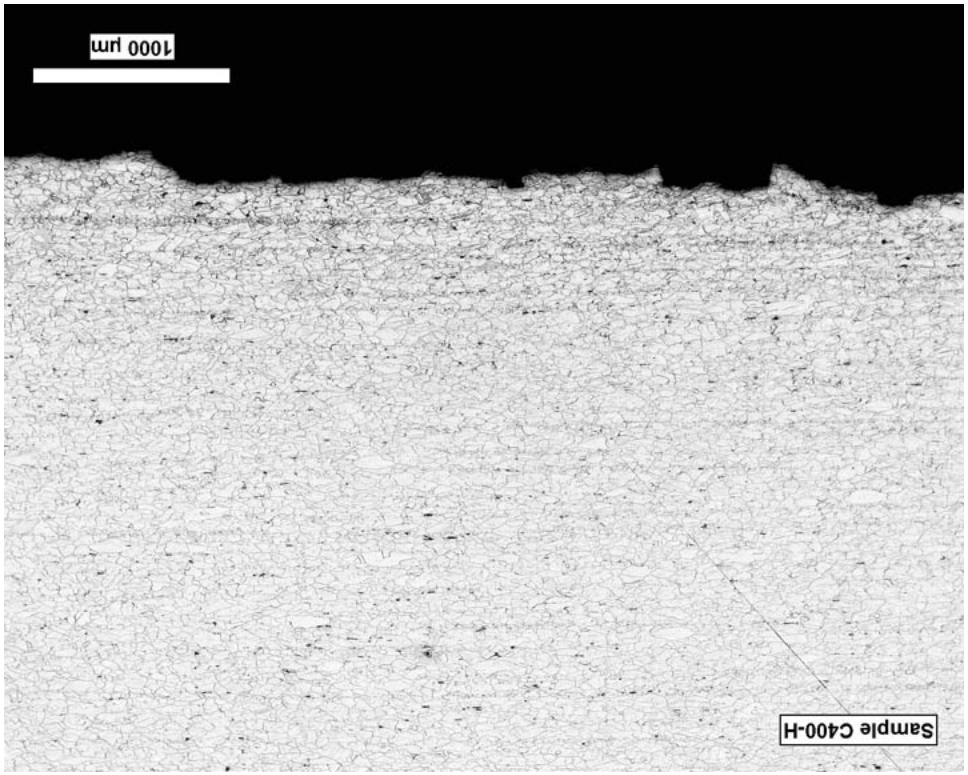
1D, 26% Cold Rolled ANL 690

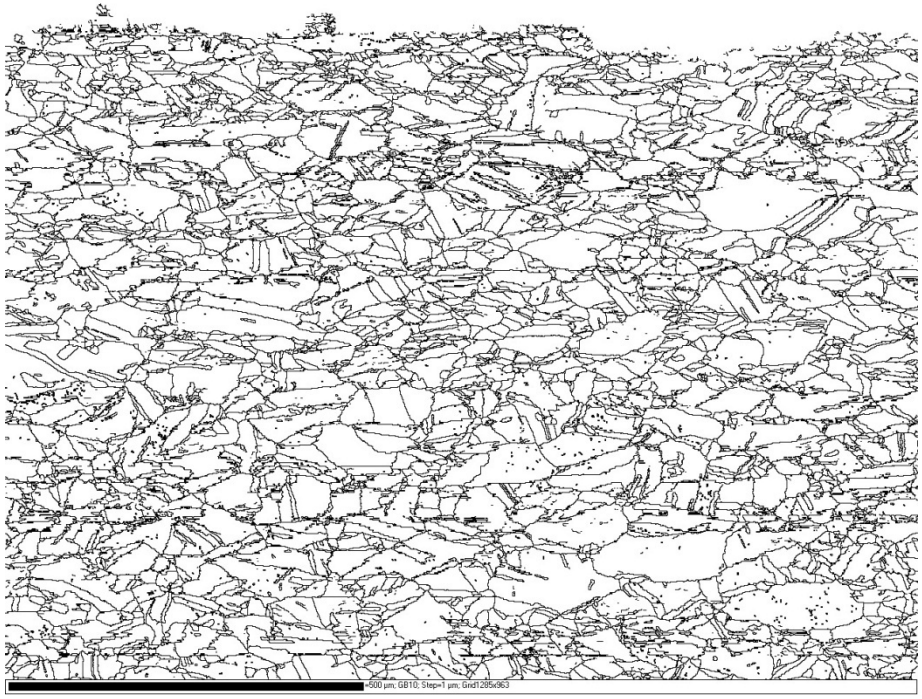




Fractography is "granulated" but not highly intergranular, not unlike what is observed in some cold worked stainless steels

Crack Path on c400



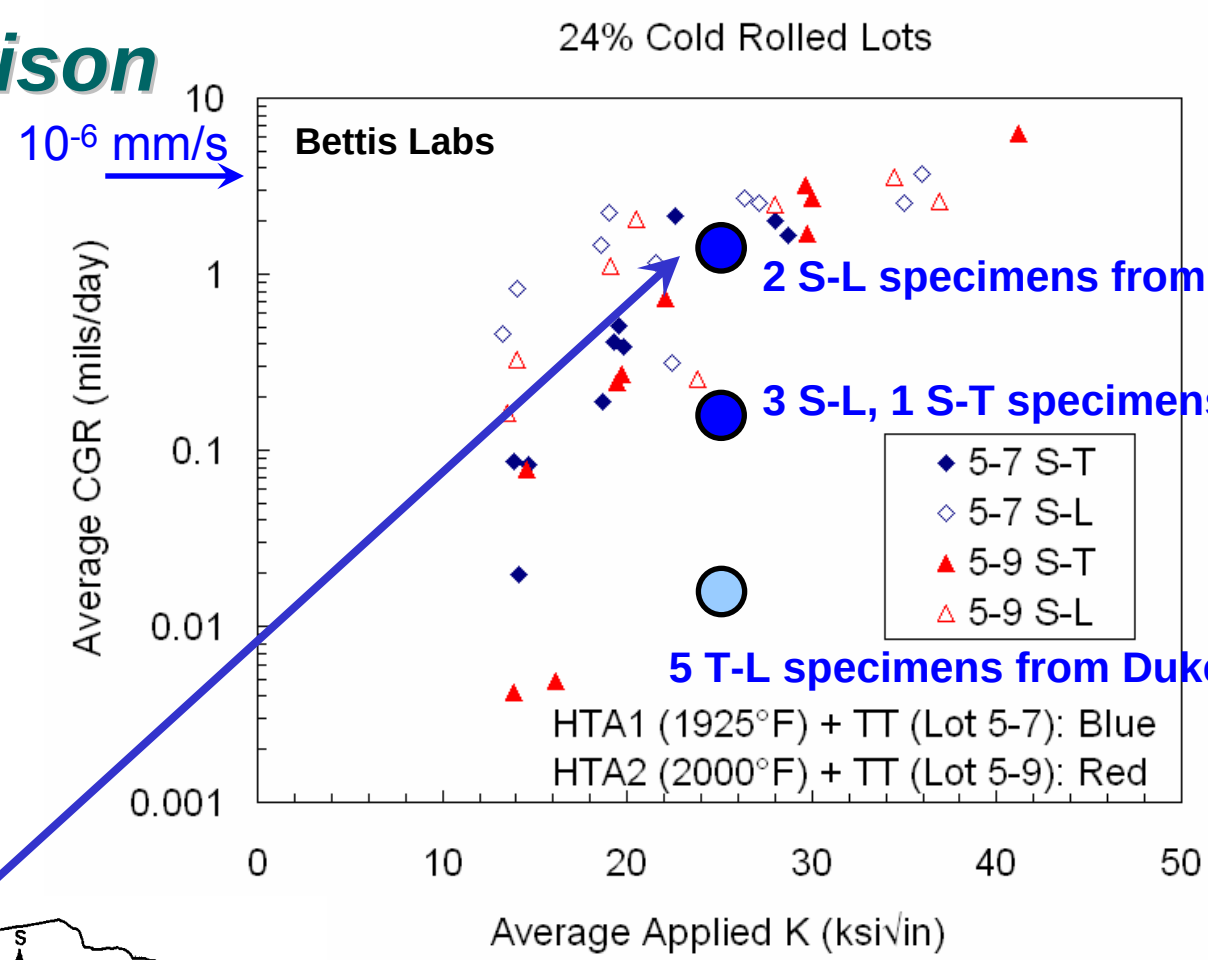


Optical cross-section

Back-scattered electron image

Crack appears to follow bands of high carbide density

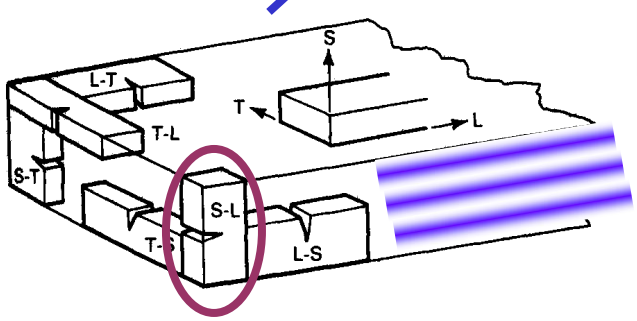
Comparison of GE & Bettis Data



2 S-L specimens from ANL material

3 S-L, 1 S-T specimens from GE & other materials

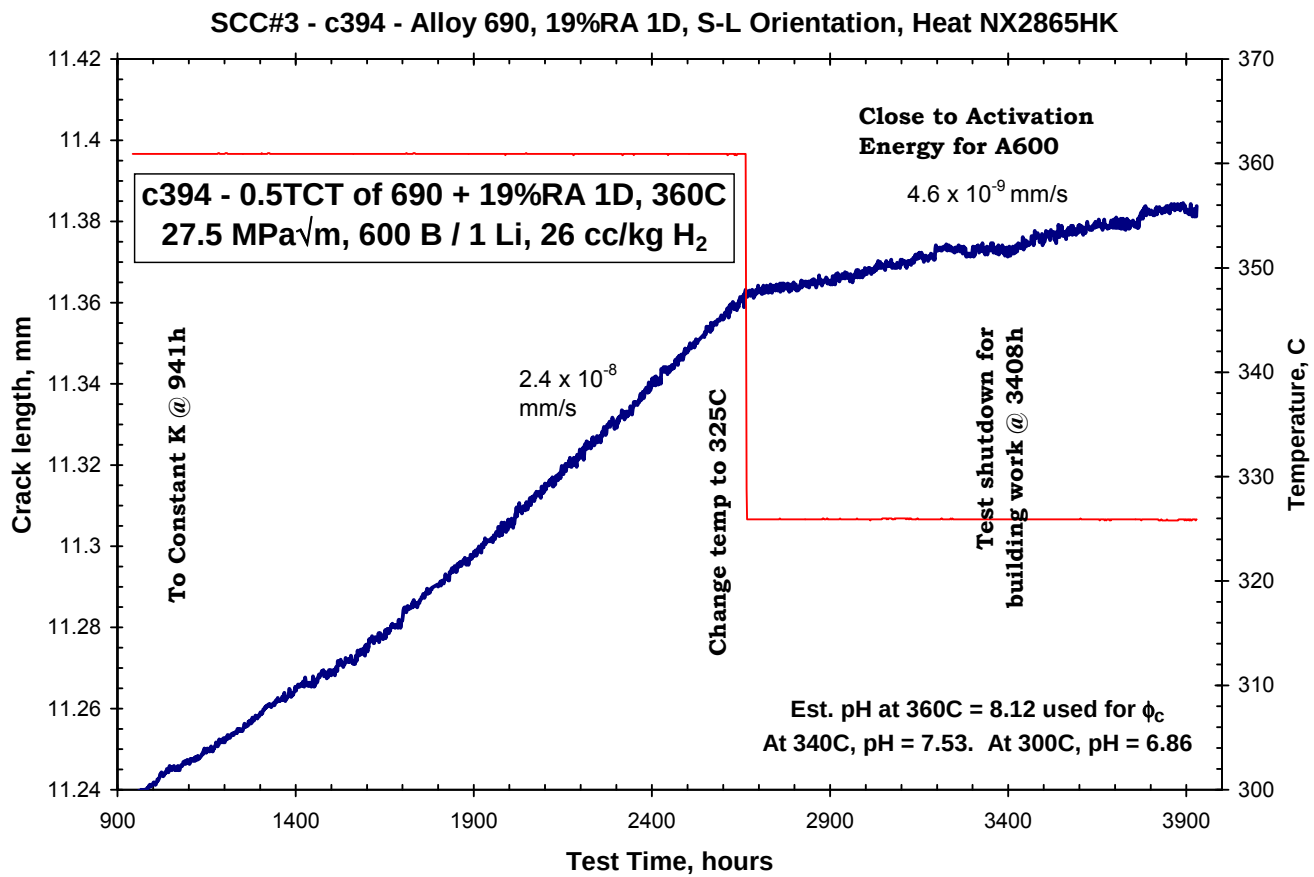
5 T-L specimens from Duke CRDM & EPRI materials



High CGR data in S-L orientation
Inhomogeneous microstructure
1D cold rolled = "1.5D" due to spreading

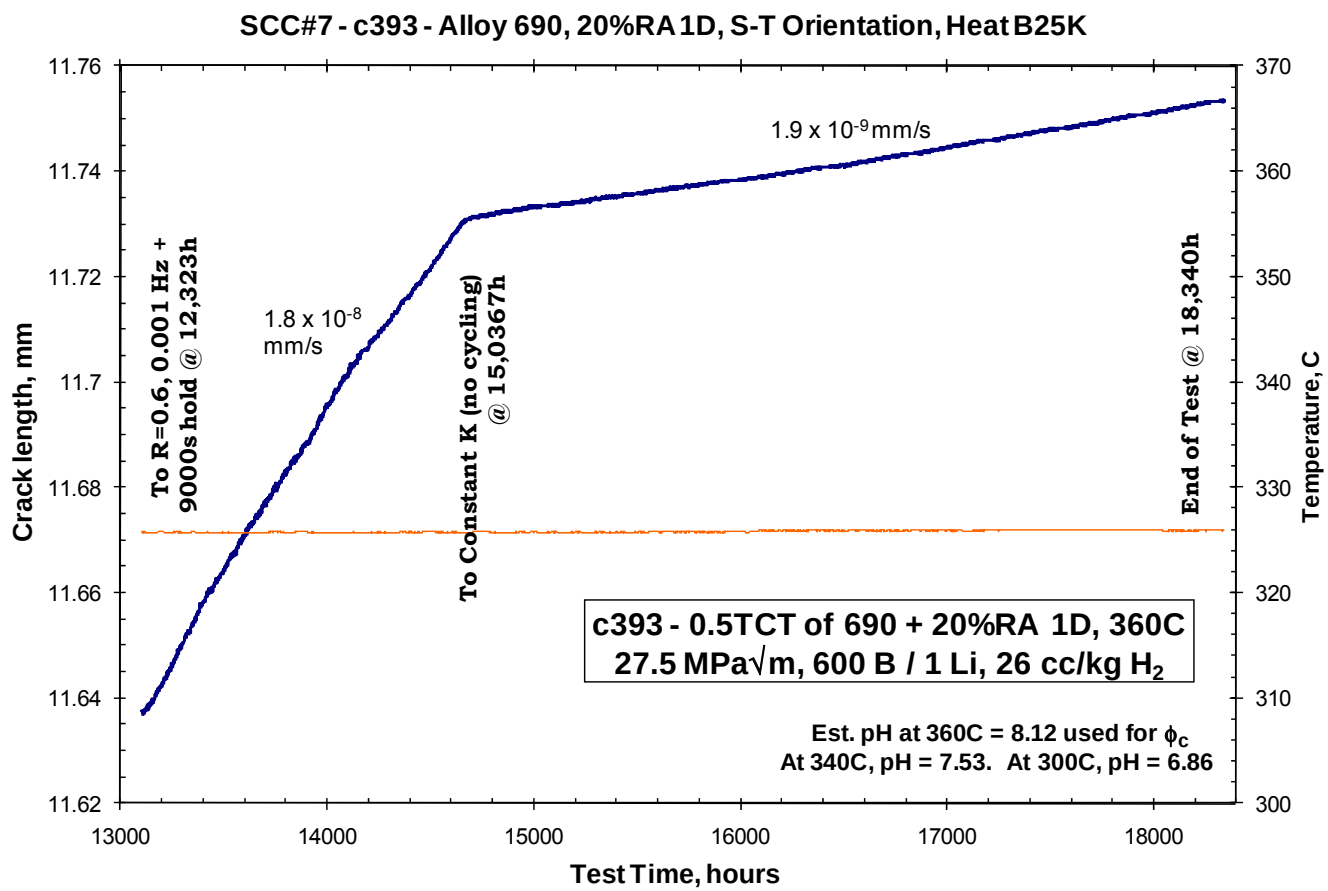
Specimen c394

1D, 20% CW 690, NX2865HK – S-L Orientation



This heat of 690 behaves similar to GE GRC 690.
Only ANL 1D, 26% cold roll grows very rapidly (5~10X faster)

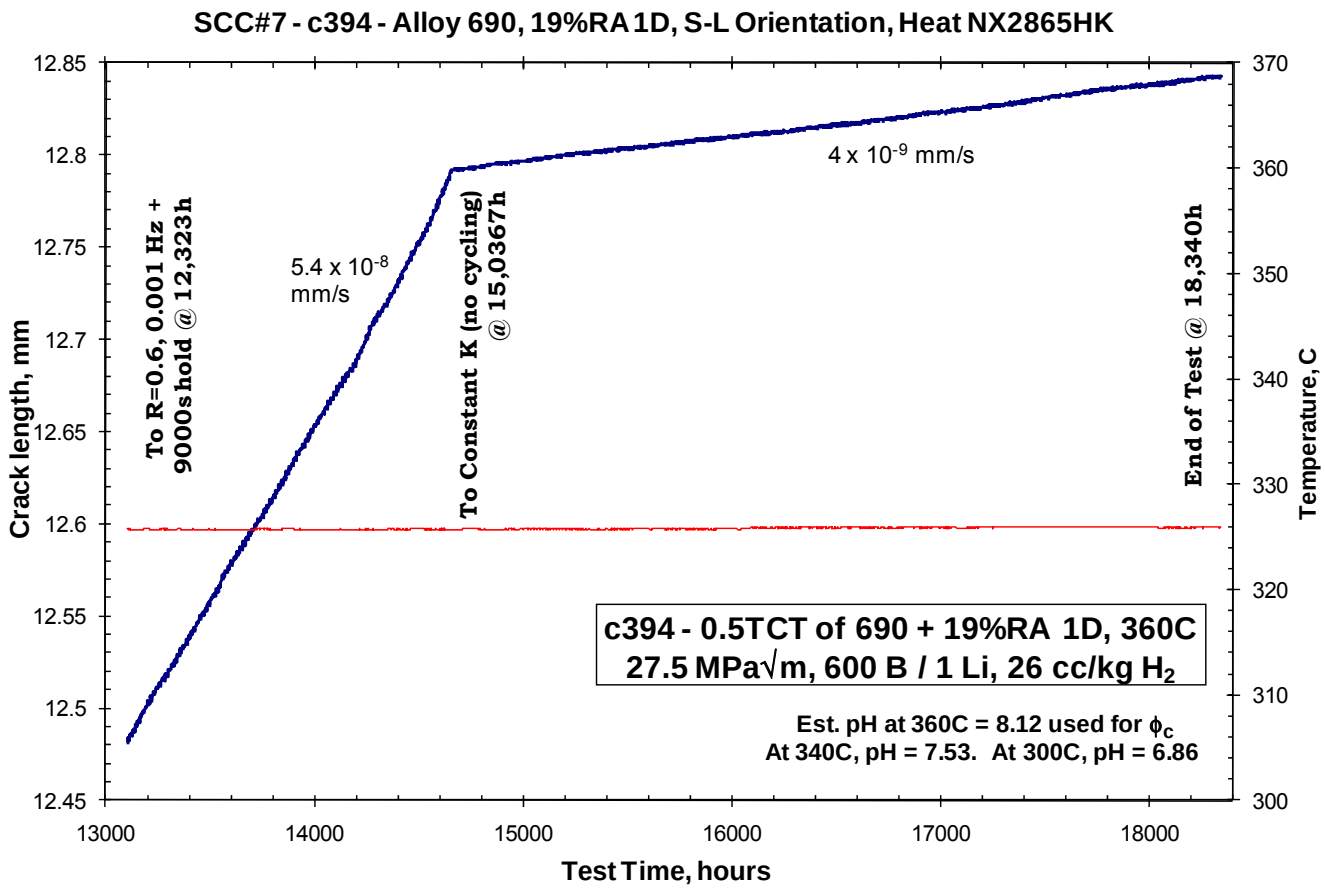
1D, 20% CW 690, B25K – S-T Orientation



2×10^{-9} mm/s is a very low growth rate of no concern

Specimen c394

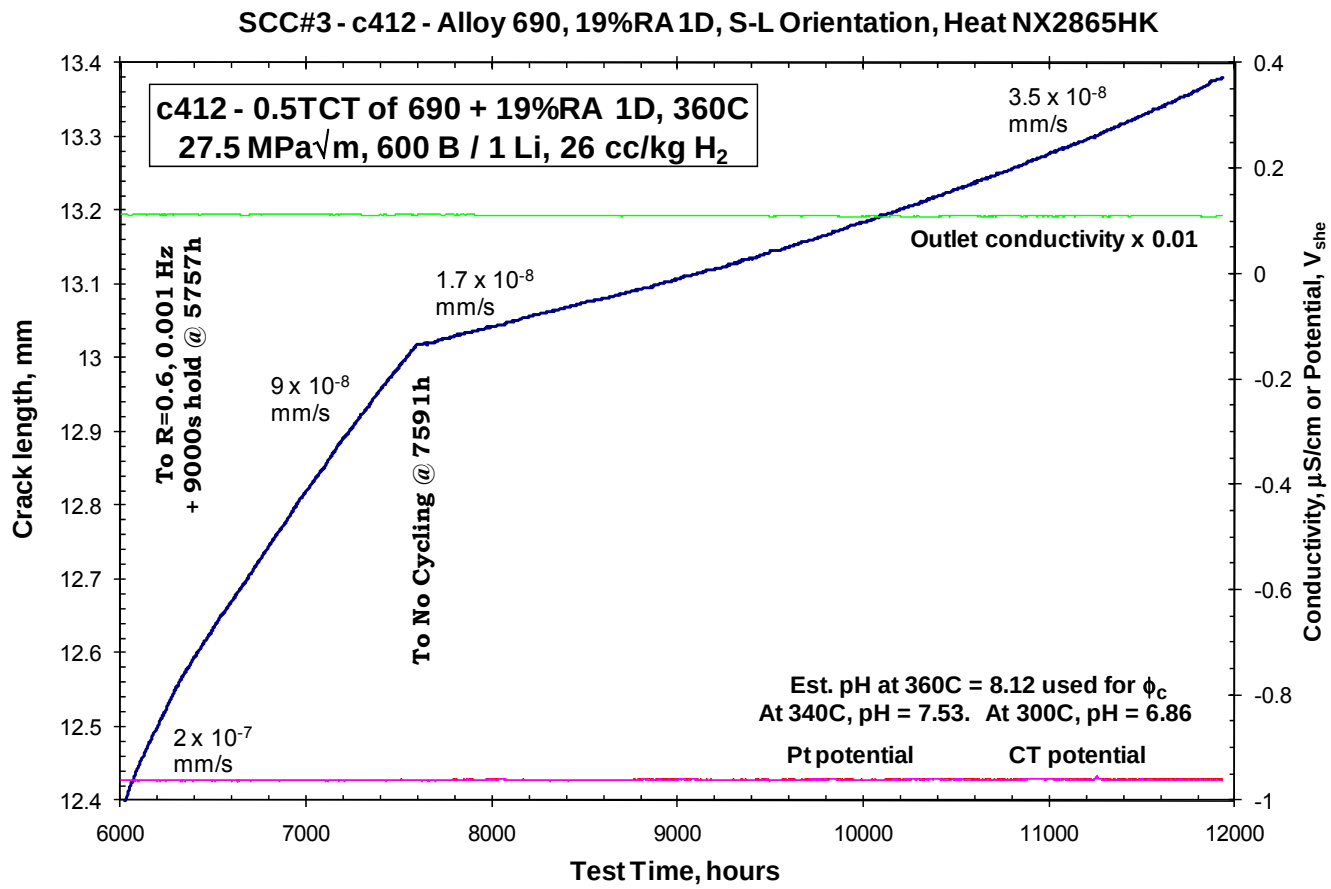
1D, 19% CW 690, NX2865HK – S-L Orientation



4×10^{-9} mm/s is a low growth rate of no concern

Specimen c412

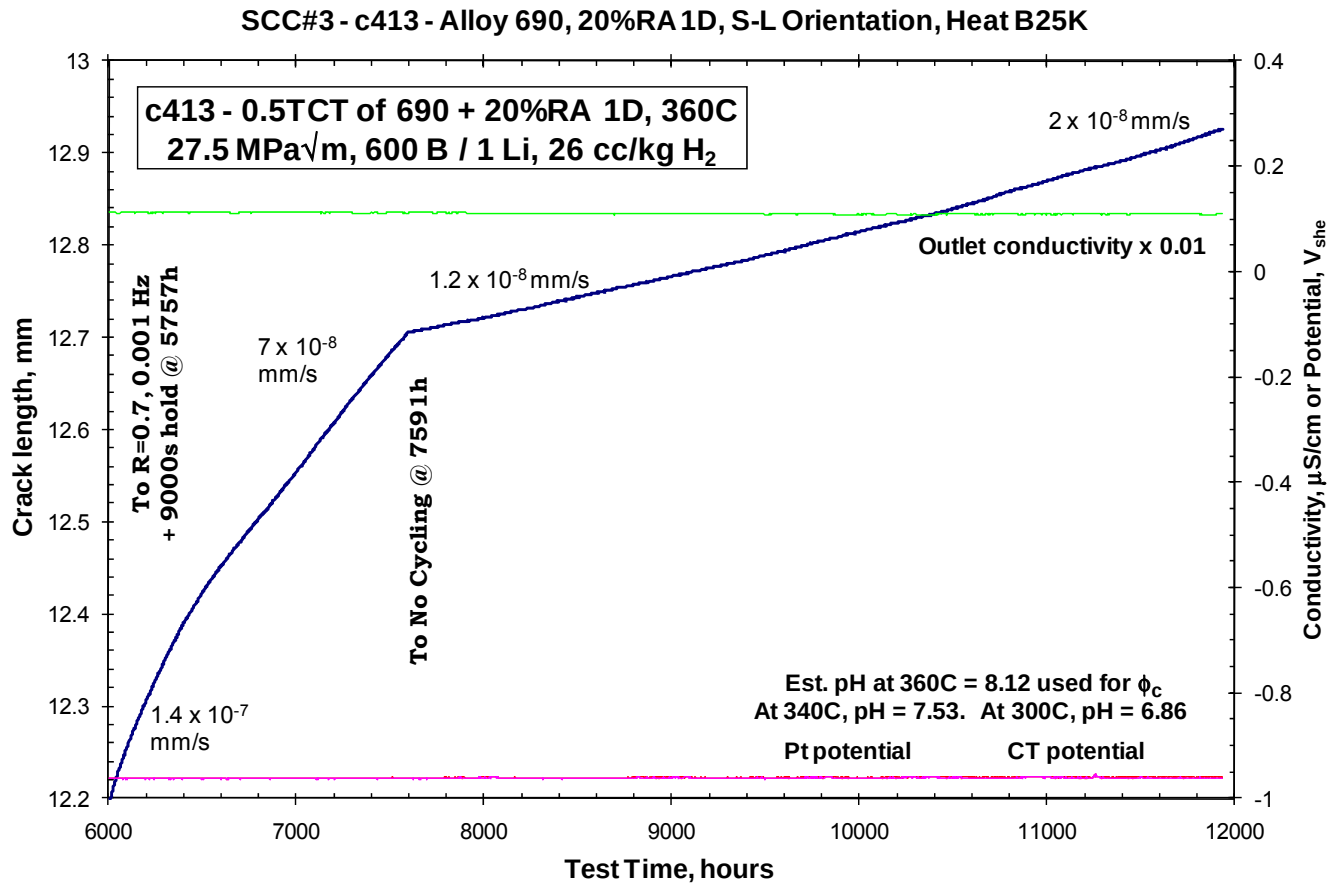
1D, 19% CW 690, NX2865HK – S-L Orientation



3.5 x 10^{-8} mm/s is a growth rate of some concern

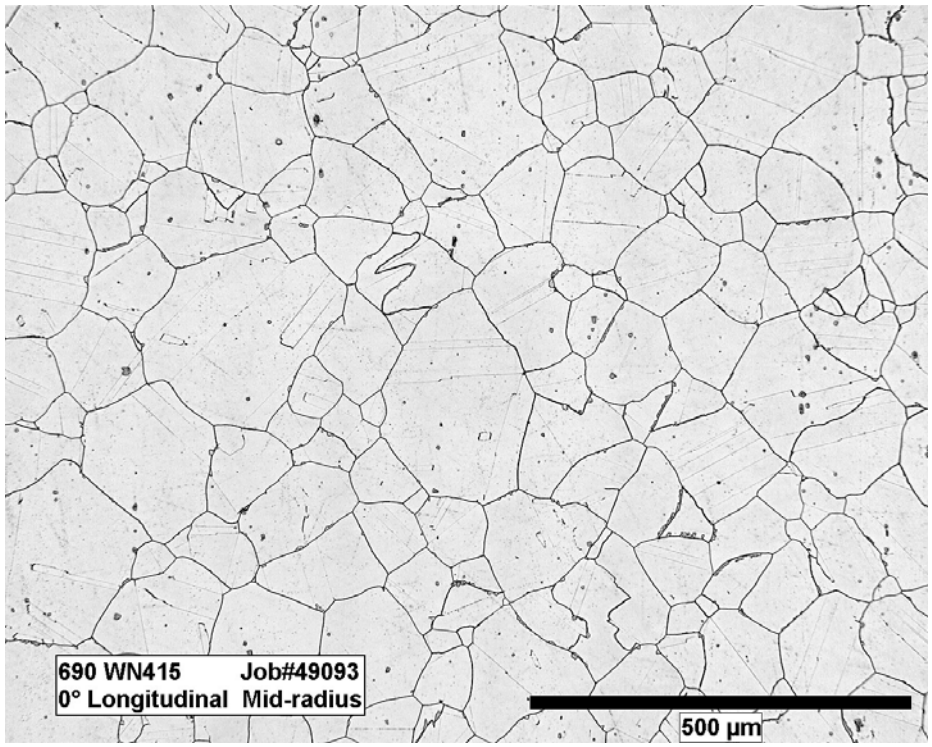
Specimen c413

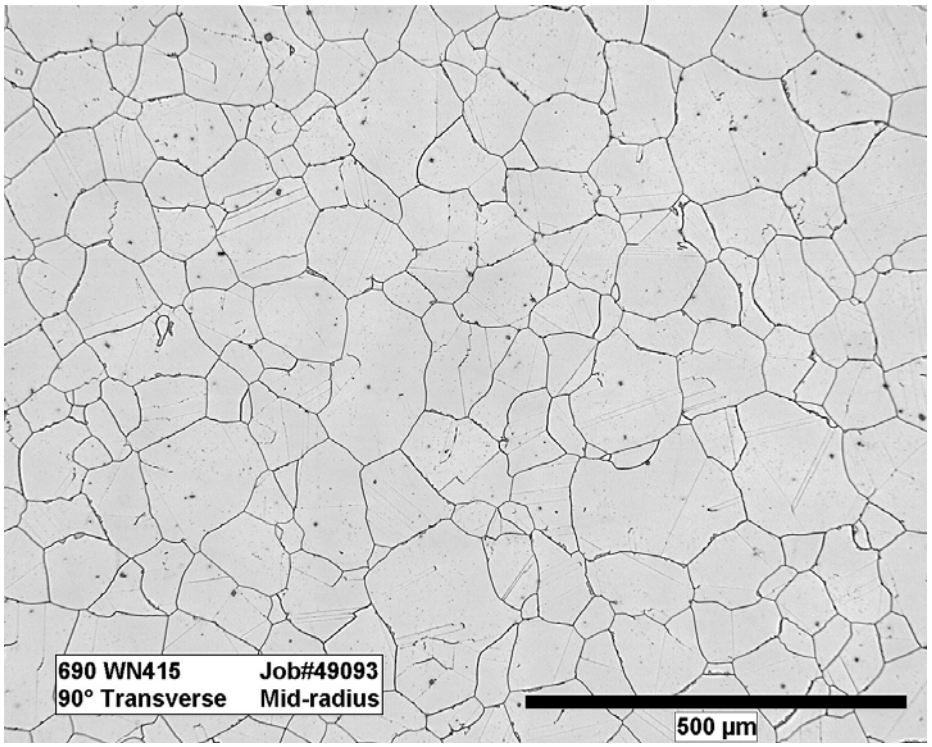
1D, 20% CW 690, B25K – S-L Orientation



2×10^{-8} mm/s is a growth rate of threshold concern

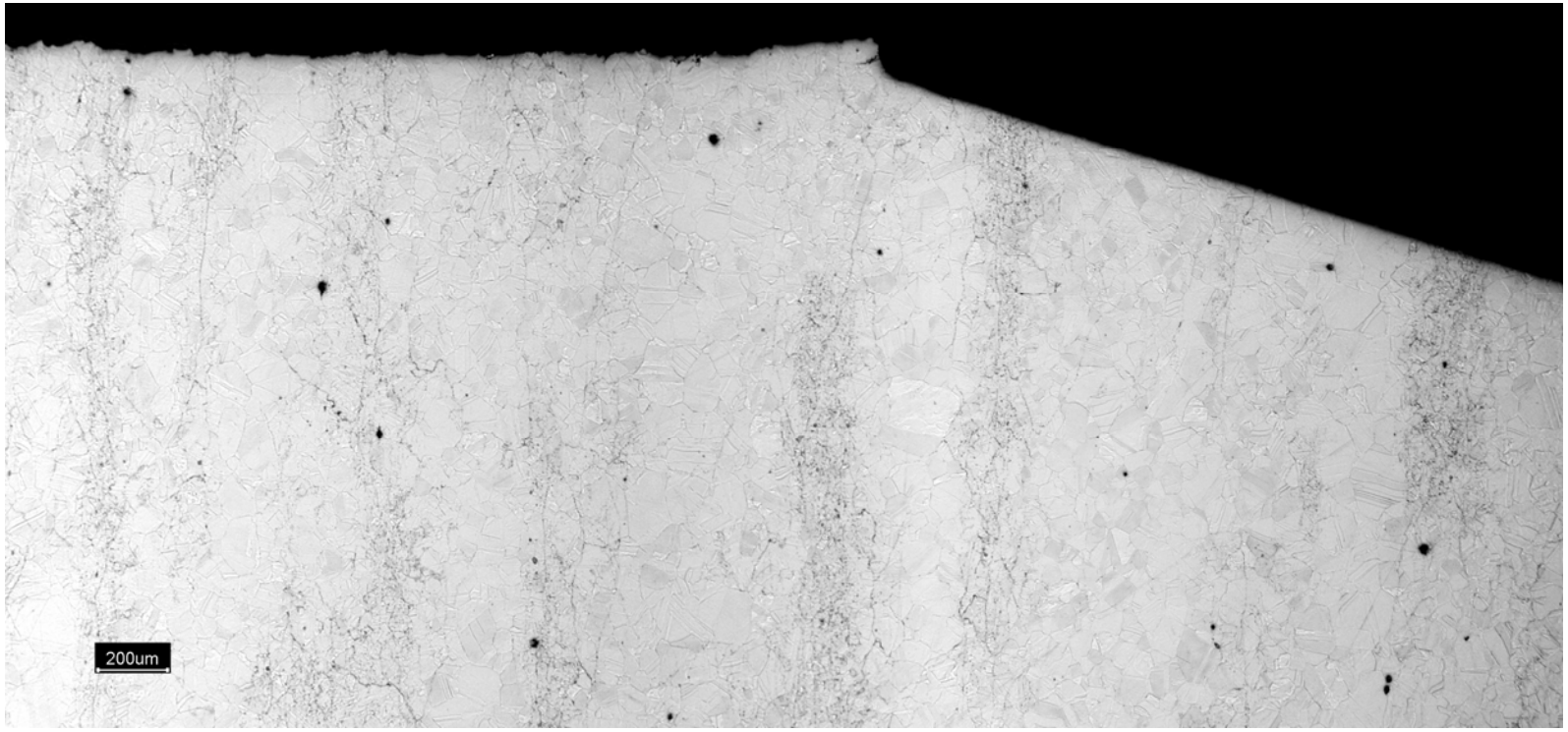
Metallography of Alloy 690 CRDM, c285/6





This extrusion shows very uniform & homogeneous microstructure

Metallography of Alloy 690, c248

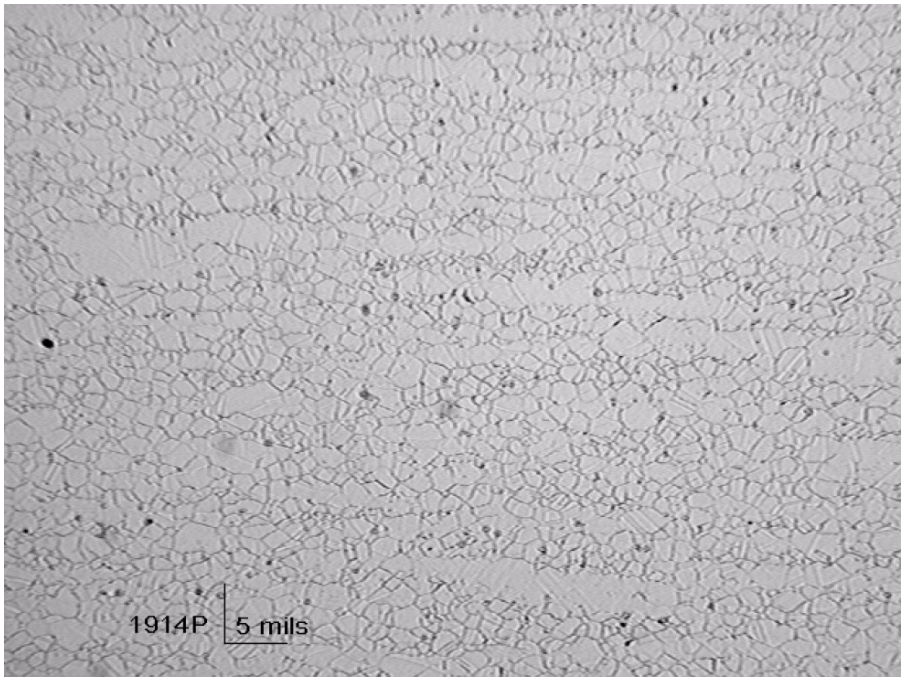


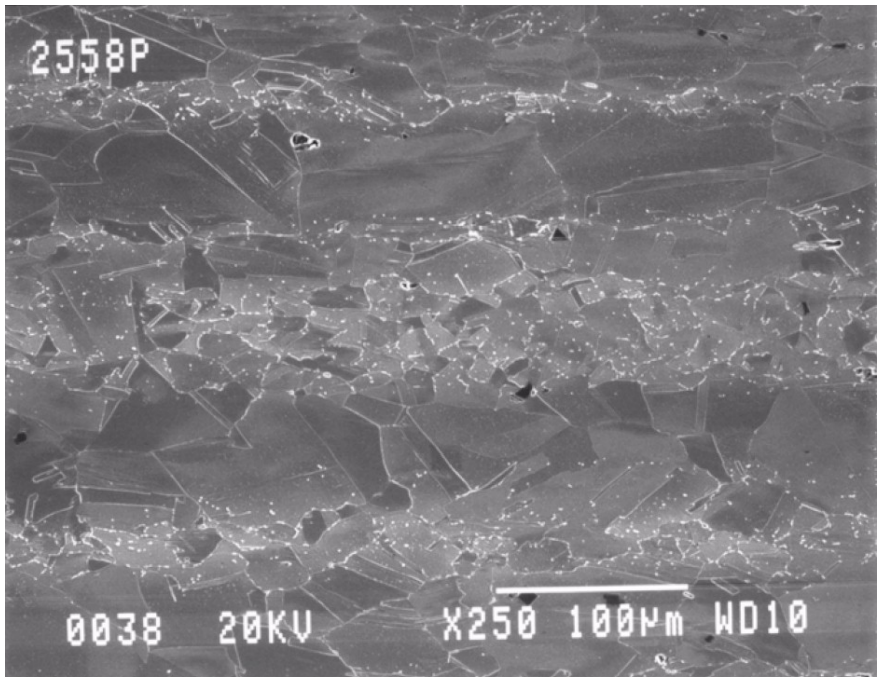
Microstructure of plate with 1800F anneal

shows compositional and carbide banding

Shows relative orientation of banding vs. crack plane

Inhomogeneity in Bettis 690



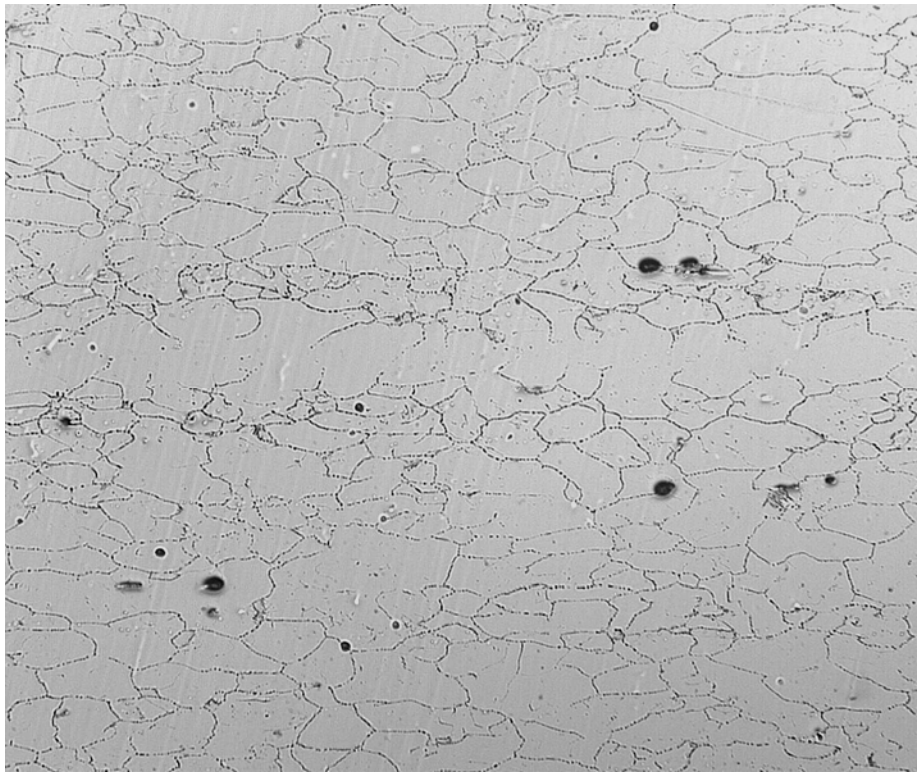


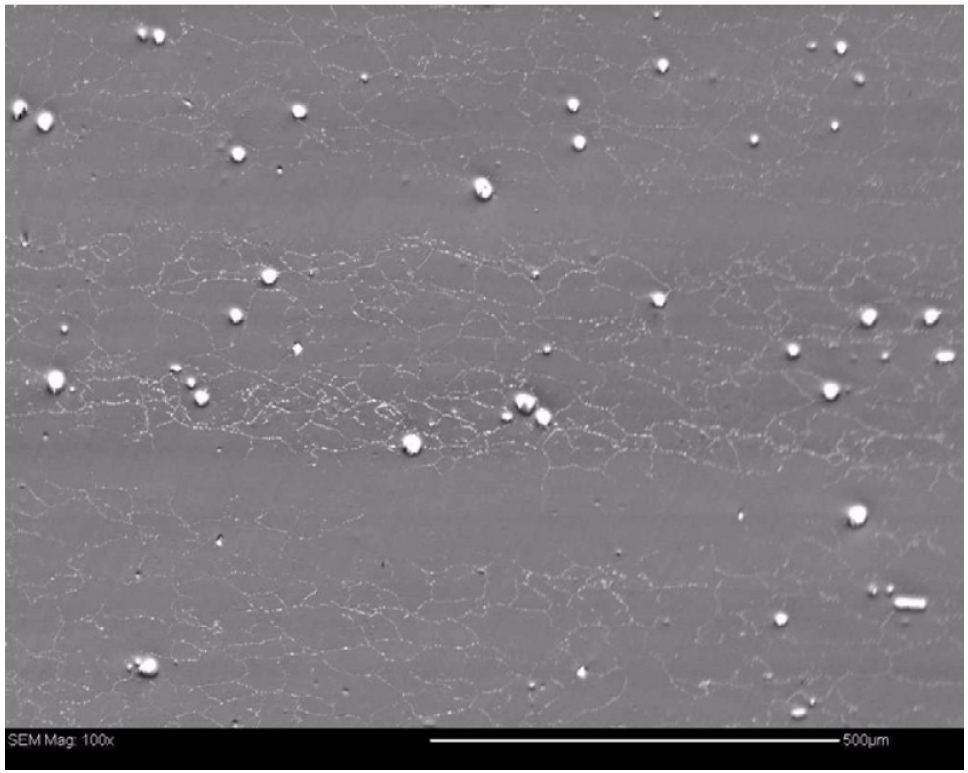
Composition & microstructural banding affects grain size and gb carbide decoration.

This banding only occurred in 1 or 2 of 3 high CGR heats.

Specimen c372

Inhomogeneity in 1D, 26% CR ANL 690

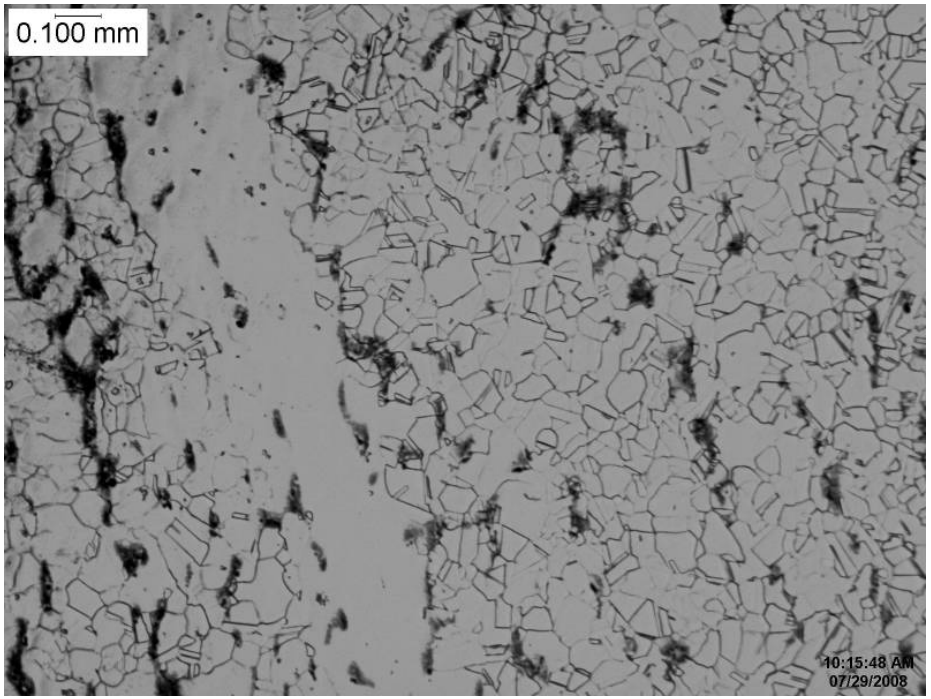


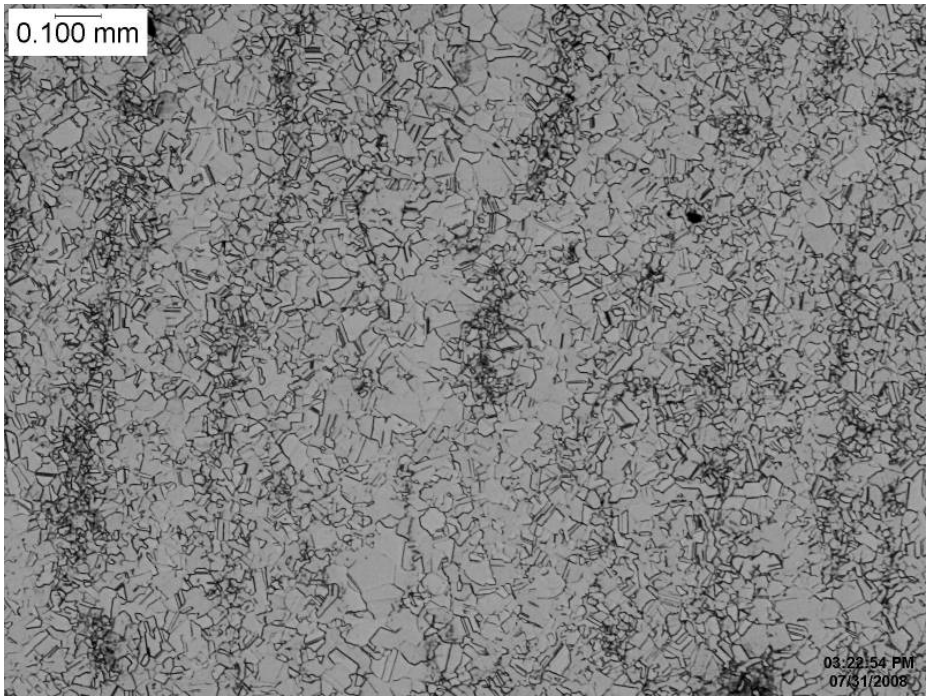


Composition and microstructural banding affects grain size and gb carbide decoration

Inhomogeneity in High Cr Ni-Alloys

Alloy 82 composition -- Alloy 52 composition





Composition & microstructural banding affects grain size and gb carbide decoration

Inhomogeneities

- *Inhomogeneity results from melting & processing:*
  - *dendritic segregation during solidification is inherent*
  - *more pronounced in highly alloyed (Nb,C): 690,718…*
  - *single melting – vs. double or triple melt*
  - *air melting gives more inclusions & perhaps loss of Cr*
  - *not achieving critical strains of ~70% during processing*
- *Inhomogeneities can include:*
  - *compositional banding – gives rise to gs & MC banding*
  - *large variation in carbide content, including gb carbides*
  - *stringers or sheets of oxide or C,N inclusions*
  - *large variation in grain size*
- *Processing causes uneven deformation & poor properties*
  - *SCC and toughness are both affected*

SCC Response in Alloy 690

Alloy 690 is not immune, and cracks grow at moderate rates if 2 & 3 are present, and fast if 1 & 2 & 3 are present:

1. *Certain "rogue" microstructures (not just banded)*
2. *Cold work, esp. directional deformation*
3. *Crack plane orientation relative to structure & deformation*

Weld residual strain and crack plane self-align in HAZ

SCC at relevant K, no cycling, temp., H_2, water chemistry

What constitutes a "rogue" microstructure and how a 1000X CGR increase develops must be understood

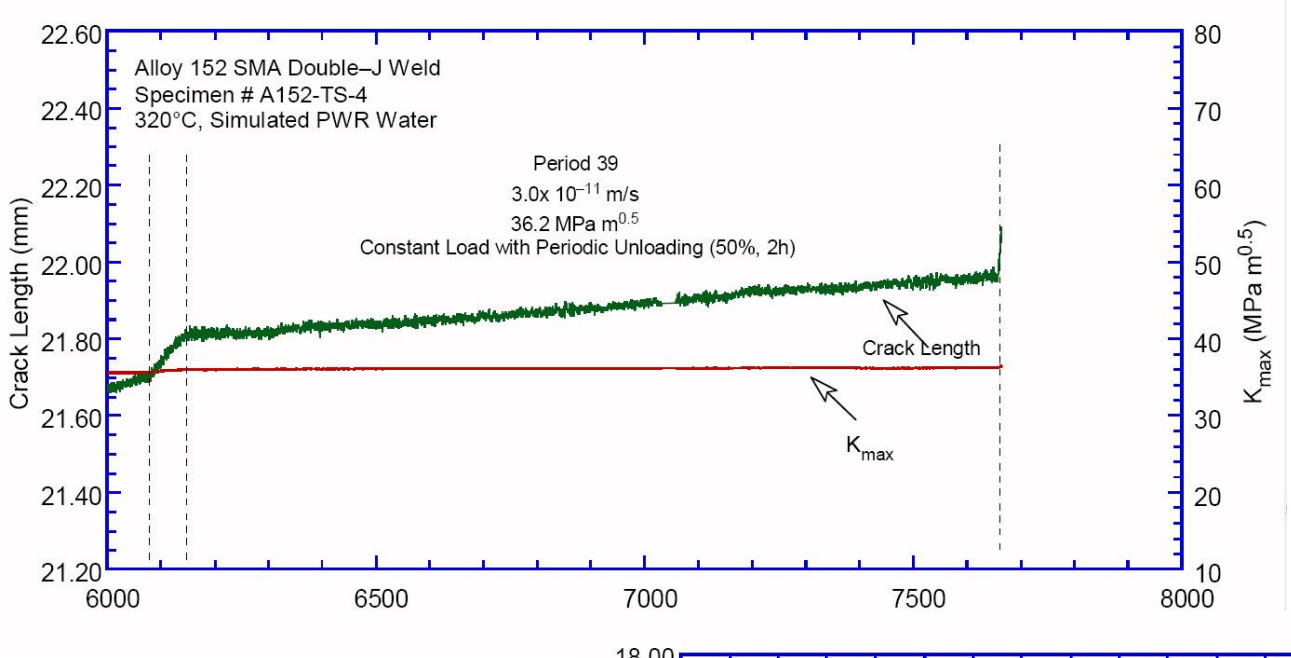
Key Unresolved Issues

Key unresolved issues in high growth rates in 690:

- *What causes high CGR if not at least subtle inhomogeneity?*
  Requires careful studies on tested & new heats
- *Can such microstructures exist in billets and extrusions?*
  Very difficult to guarantee that they don't exist.
- *Can forging (compression) or weld shrinkage strain (tension) produce the same high growth rates in 690 as cold rolling?*
  Comparisons needed on different heats of 690, but they act in a similar fashion in SS and Alloy 600.
- *Are weld HAZ shrinkage strains able to produce high CGR?*
  Test feasibility by creating specially aligned 690 welds

Alloy 152/52 Weld Metals

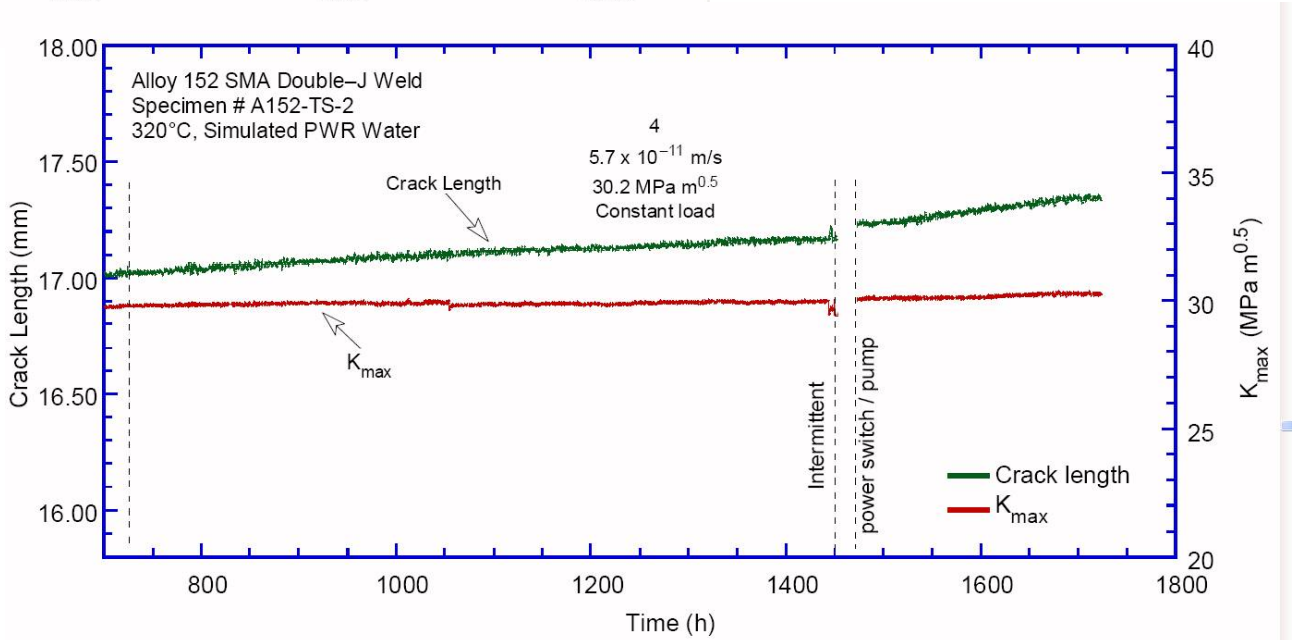
- *One significant vulnerability is weld cracking, from which SCC has been shown to nucleate (in Alloy 182)*
  - *the KAPL 27% Cr weld metal is vastly superior*
- *To date, no large vulnerability in SCC resistance of 52/152 weld metal has been observed at GE GRC.*
  - *the ANL weld should be tested & characterized to identify the origin of the ~10X higher growth rates*
  - *other welds should be procured or fabricated, including a repeat of the ANL weld*



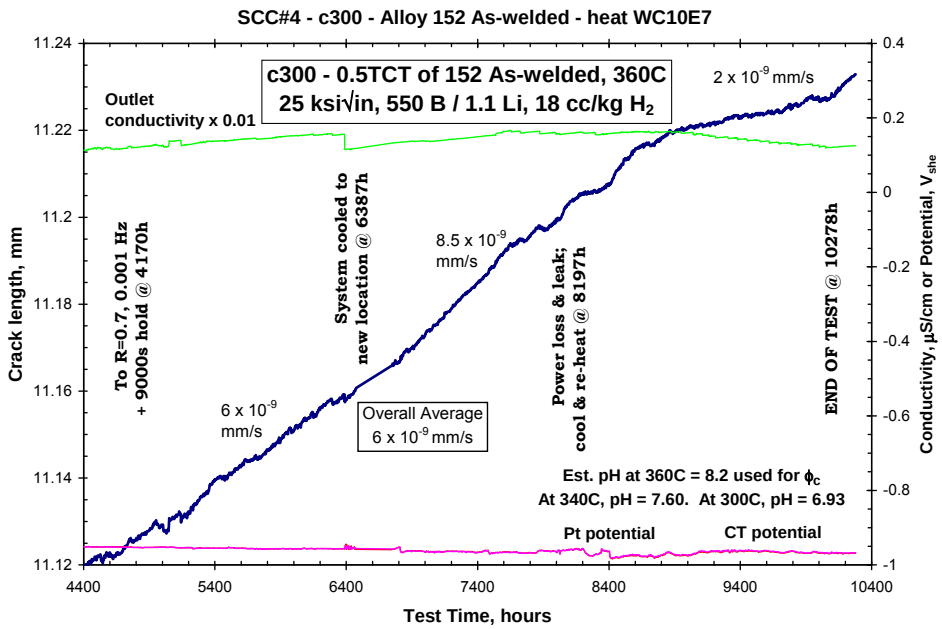
SCC of 52/152 Weld Metal

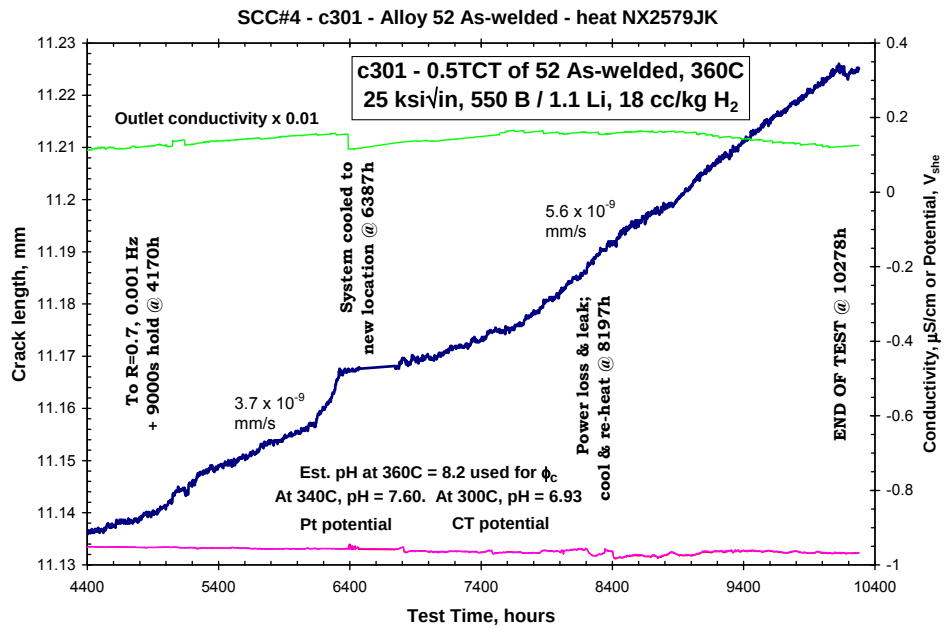
Moderate growth rates, but 10X lower than worst Alloy 690 base metal

"Specimen was transitioned to SCC twice, maintained growth under constant load conditions only in 2 of 7 attempts"



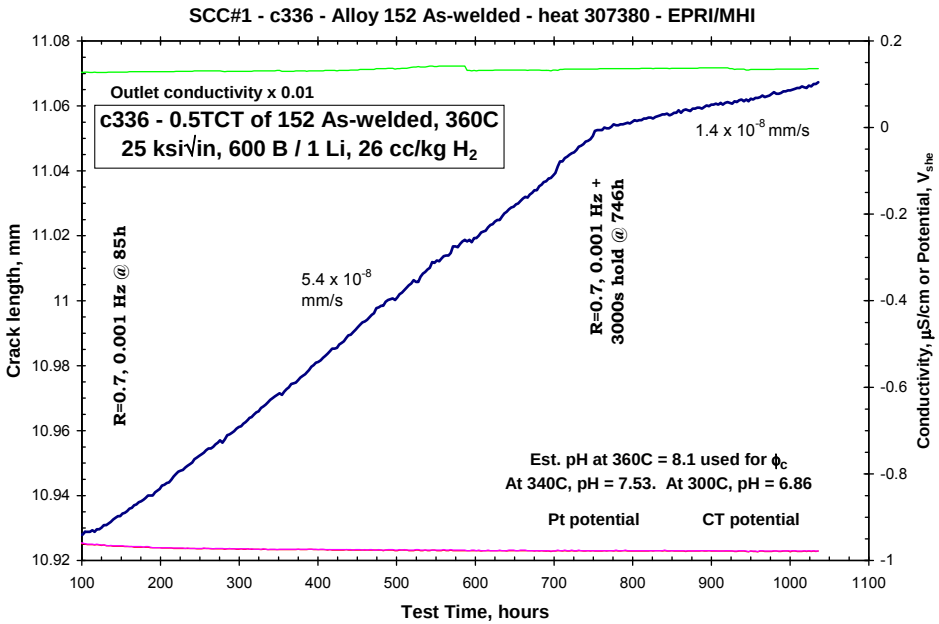
Alloy 152 & 52 Weld Metal

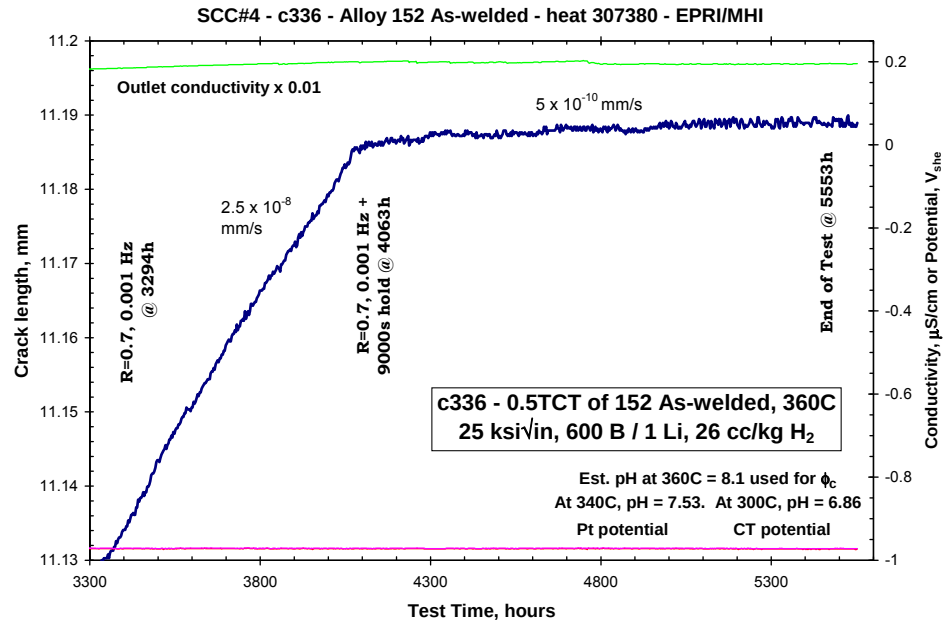


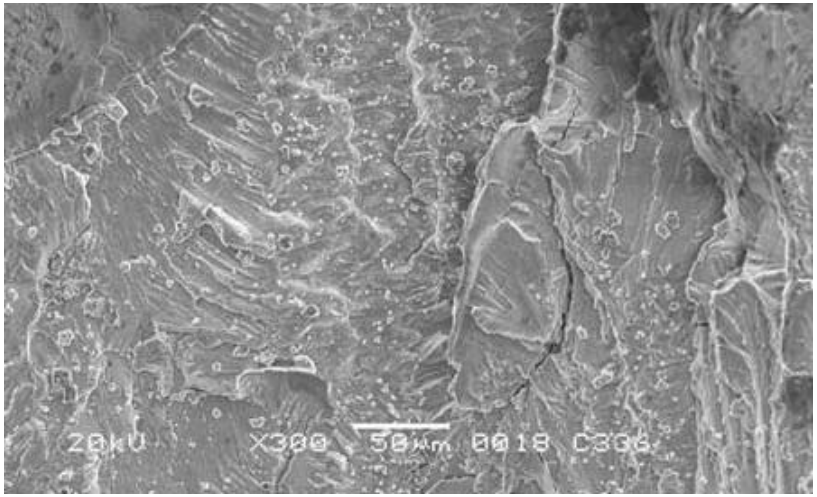


Growth rates are very low, < 2 x 10^{-9} mm/s

Alloy 152 Weld Metal

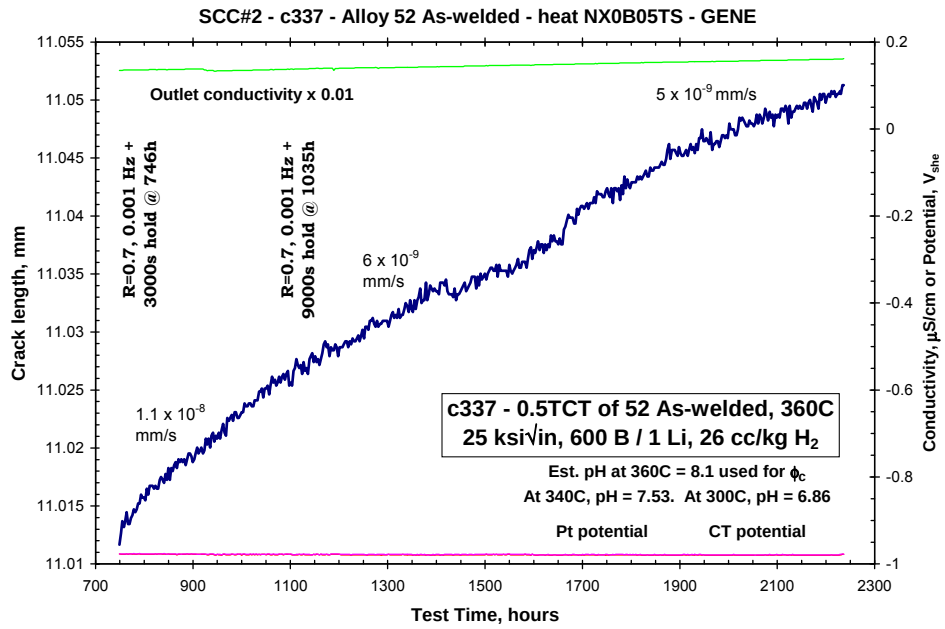


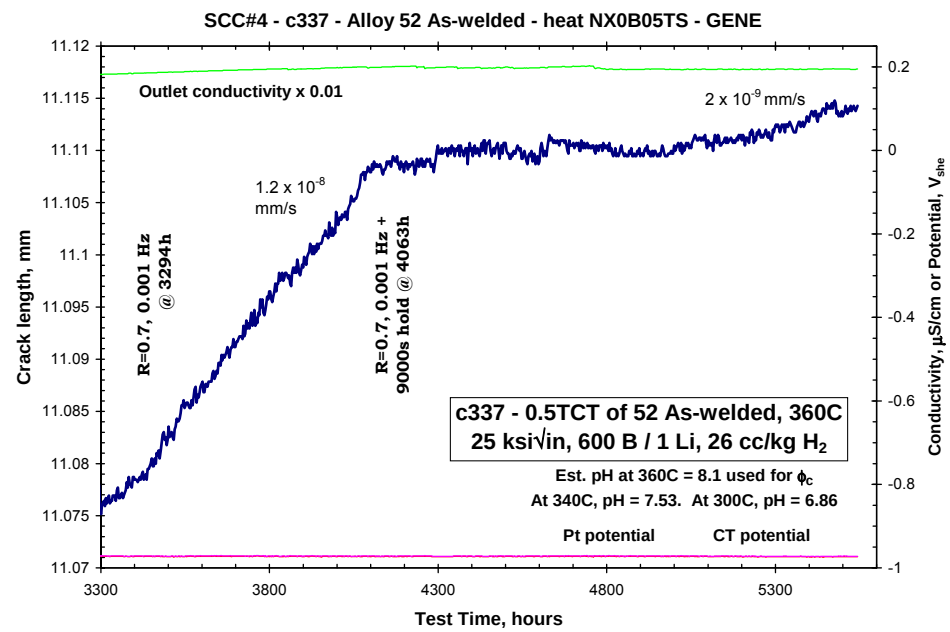




Growth rates are high enough to transition to IG, but remain low at long hold times or constant K

Alloy 52 Weld Metal





Growth rates are very low
< 2 x 10^{-9} mm/s

Evaluation of Alloy 52/152 Weld Metals

Characterization of welds for macro- and micro-cracking, compositional variations in dendrites, and EBSD strains

Characterization of ANL weld to determine origin of moderately high CGRs, and comparison to lower CGR welds

Re-creation of additional ANL weld metal, if possible

SCC evaluation of KAPL 25 & 27% Cr weld metals

Acquisition of additional plant and archive welds for microstructural characterization and SCC evaluation

**Dissimilar metal welds & dilution to CS/LAS and SS (SG)*

**OIM, EBSD, SEM for segregation, TEM for ID/ppt structures*