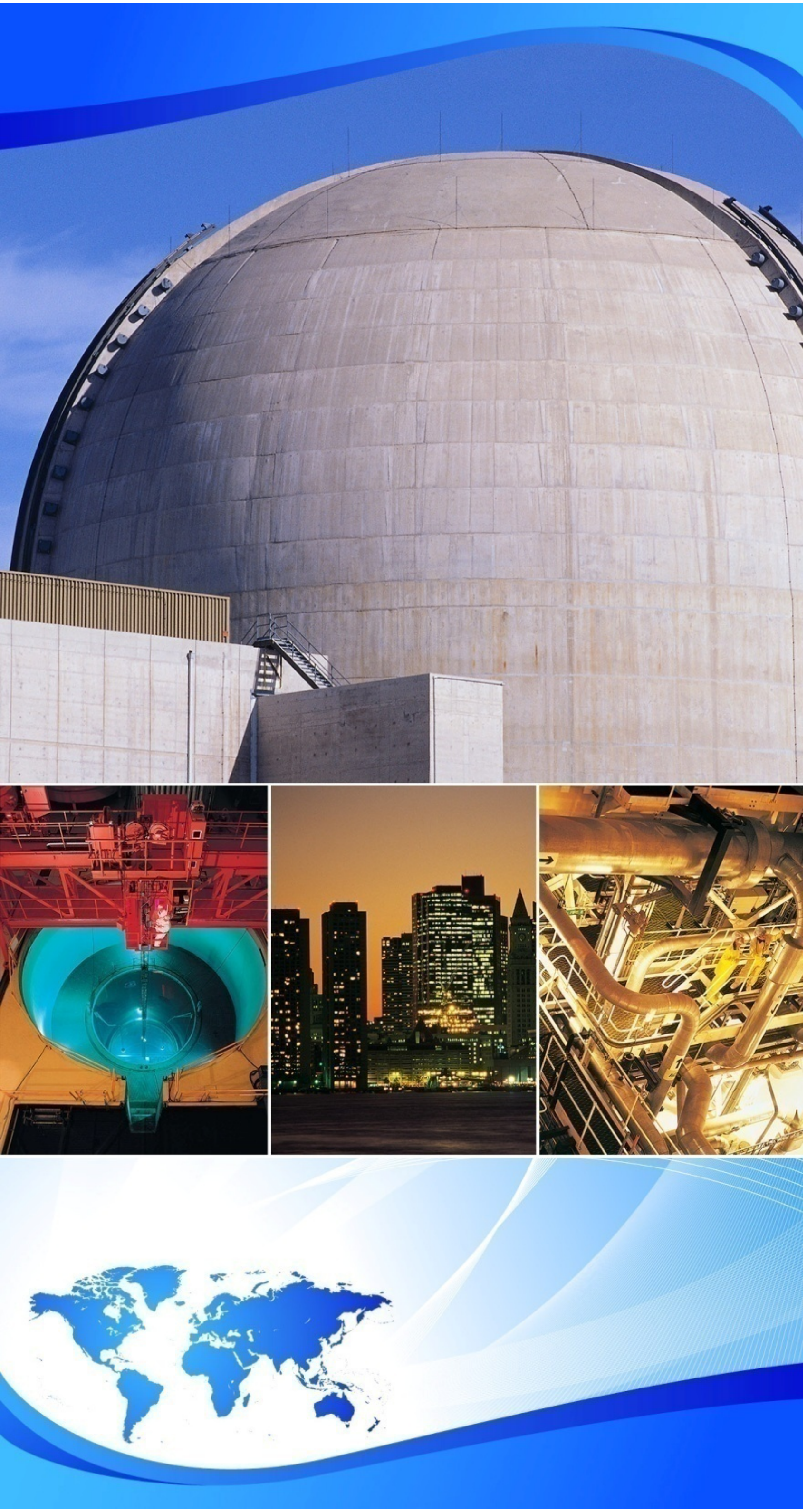

ELECTRIC POWER RESEARCH INSTITUTE

SCC Growth Rate of Alloy 690 and HAZ

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GE Global Research Center

Al Ahluwalia
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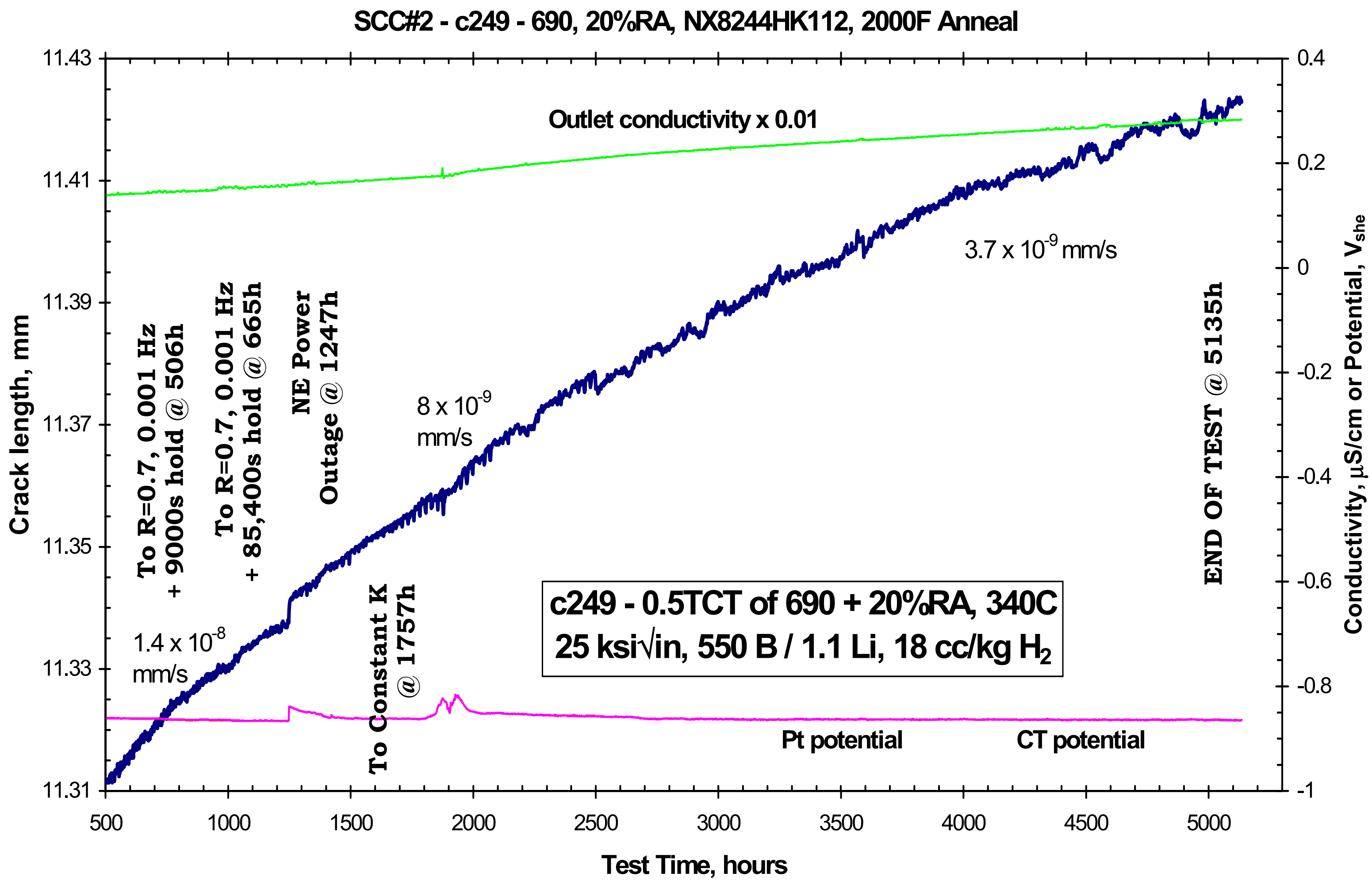
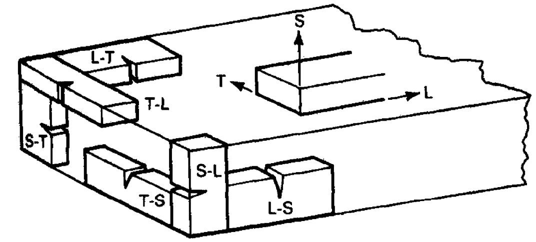
NRC – EPRI Meeting *June 2011*

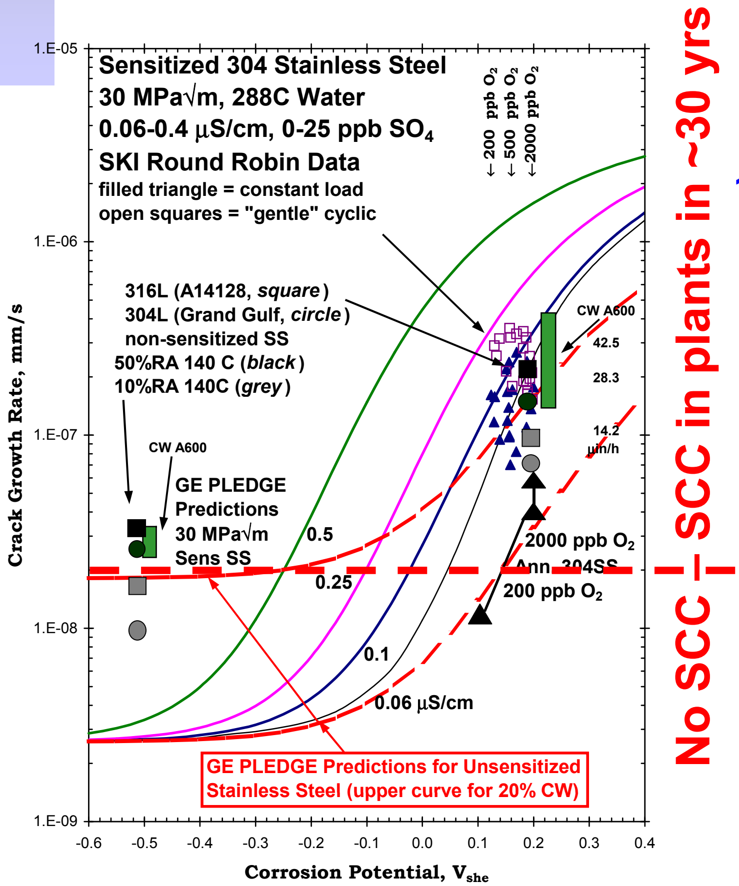
20% CW Alloy 690, 2000F Anneal



~9 years ago, the question of "690 immunity" was answered

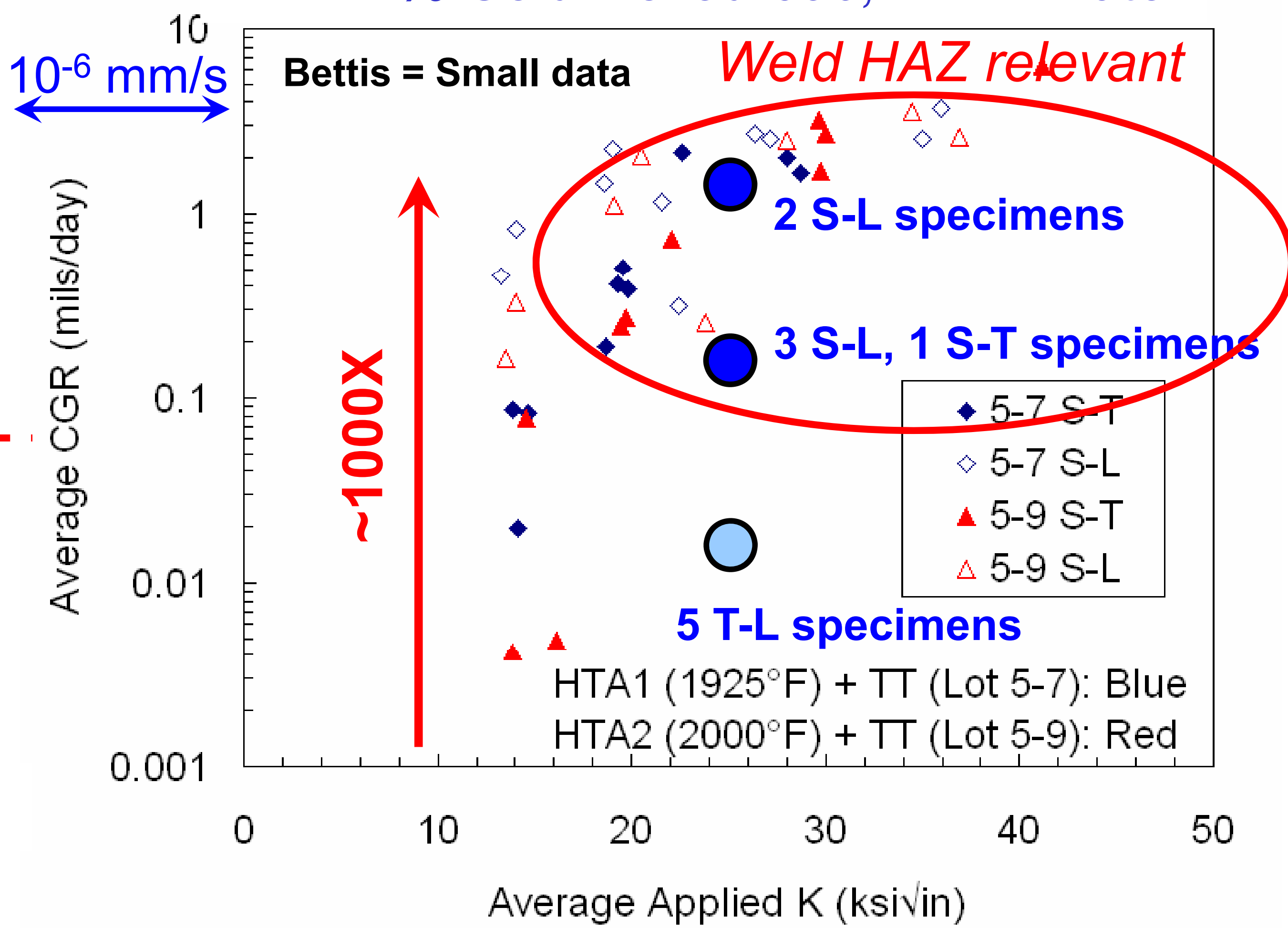
Alloy 690 SCC





Sens & CW 304SS, BWR

24% Cold Rolled 690, PWR Water



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

Origin of 1000X increase from CW needs to be understood.

Alloy 690 SCC

CT	Material	Source	Orient.	Condition	Hours	No Cycling CGR, mm/s	MPa/m	Mat'l - Heat	Location
Base metal					<5e-9	code	>5e-8	>3e-7 mm/s	
c524	Plate 114092		S-L	32% F	4300	1.10E-07	33	690 CW	84SK7
c523	Plate SP547		S-L	33% F	4300	7.50E-08	33	690 CW	84SK7
c522	Plate NX3297HK12		S-L	31% F	4400	5.00E-08	33	690 CW	84SK12
c521	Plate NX3297HK12		S-L	31% F	4400	7.00E-07	33	690 CW	84SK12
c509	Billet B25K		S-L	20% CR	6500	1.40E-08	38.5	690 CW	82SK5
c508	Plate NX3297HK12		S-L	26% CR	6500	6.00E-08	38.5	690 CW	82SK5
c507	Plate 114092		S-L	21% CR	6000	1.30E-08	38.5	690 CW	82SK4
c506	Plate SP547		S-L	22% CR	6000	2.90E-08	38.5	690 CW	82SK4
c505	CRDM WQ199		S-L	31% CR	6300	2.00E-08	38.5	690 CW	84SK12
c504	CRDM WQ199		S-L	31% F	6300	1.40E-07	38.5	690 CW	84SK12
c482	Plate 114092		S-L	21% F	5415	6.00E-09	27.5	690 CW	84SK2
c481	Plate SP547		S-L	21% F	5415	1.40E-08	27.5	690 CW	84SK2
c480	Plate 114092		S-L	21% 1D	5856	6.00E-09	33	690 CW	82SK4
c479	Plate SP547		S-L	22% 1D	5856	1.40E-08	33	690 CW	82SK4
c472	CRDM RE243 CM		S-L	31% 1D	8931	4.00E-09	27.5	690 CW	84SK12
c471	CRDM RE243		S-L	31% 1D	8931	6.00E-08	27.5	690 CW	84SK12
c413	Billet B25K		S-L	20% 1D	14155	2.00E-08	27.5	690 CW	84SK12
c412	Plate NX2865HL		S-L	19% 1D	14155	5.20E-08	27.5	690 CW	84SK12
c401	Billet B25K		S-L	20% 1D	4276	1.10E-07	27.5	690 CW	84SK12
c400	Plate NX3297HK12		S-L	26% 1D	4276	8.00E-07	27.5	690 CW	84SK12
c394	Plate NX2865HL		S-L	19% 1D	18341	8.00E-09	27.5	690 CW	82SK5
c393	Billet B25K		S-L	20% 1D	18341	8.00E-09	27.5	690 CW	82SK5
c373	Billet B25K		S-T	20% 1D	4618	3.00E-08	27.5	690 CW	84SK12
c372	Plate NX3297HK12		S-L	26% 1D	4618	5.70E-07	38.5	690 CW	84SK12
c286	CRDM WN415		T-L	20% 1D	4515	3.00E-09	27.5	690 CW	45A2
c285	CRDM WN415		T-L	20% 1D	4515	6.00E-09	27.5	690 CW	45A2
c280	CRDM WN415		T-L	41% F	16564	3.00E-09	38.5	690 CW	29A2
c249	Plate NX8244HK		T-L	20% F	5135	8.00E-09	27.5	690 CW	45A1
c248	Plate NX8244HK		T-L	25% F	5135	5.00E-09	27.5	690 CW	45A1
				TOTAL Hrs =	214048				

Key Issues in SCC of Alloy 690

Key questions associated with crack growth in 690:

1. *What contributes to elevated growth rates?*
   Cold work, orientation, inhomogeneity, microstructure…

2. *Are specific product forms of 690, such as extrusions or billet, guaranteed to be homogeneous and exhibit low CGR?*

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

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

5. *What gb carbide size/density – microstructure minimizes the crack growth rate?*

Misconceptions Resolved

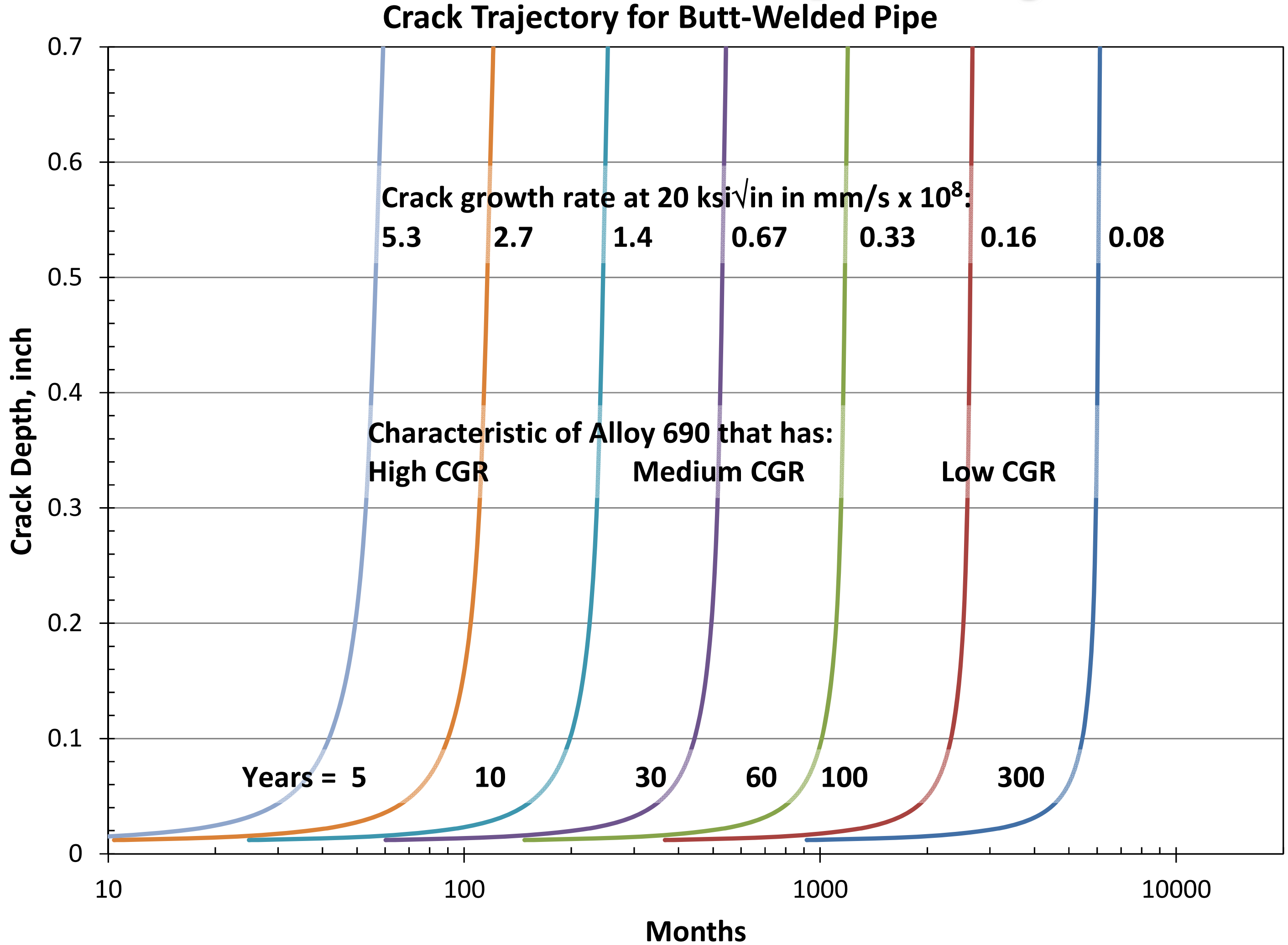
- Alloy 690 is immune to SCC.
- Most Alloy 690 is very homogeneous.
- Only plate forms are inhomogeneous.
- Only extruded material is used for CRDM.
- 1-D cold rolling is uniquely bad.
- Forged or tensile strained materials will show only low CGRs.
- CRDM forms, esp. if homogeneous, show only low CGRs.
- GB carbides are beneficial, and the more the better.
- EBSD is measuring artificial characteristics.
- Residual strains are always <10%.
- One or two "relevant" specimens (e.g., from mockups) provide clear evidence that there are no SCC concerns.

What CGR Is Adequately Low?

Calculations could be performed for many different component and geometries.

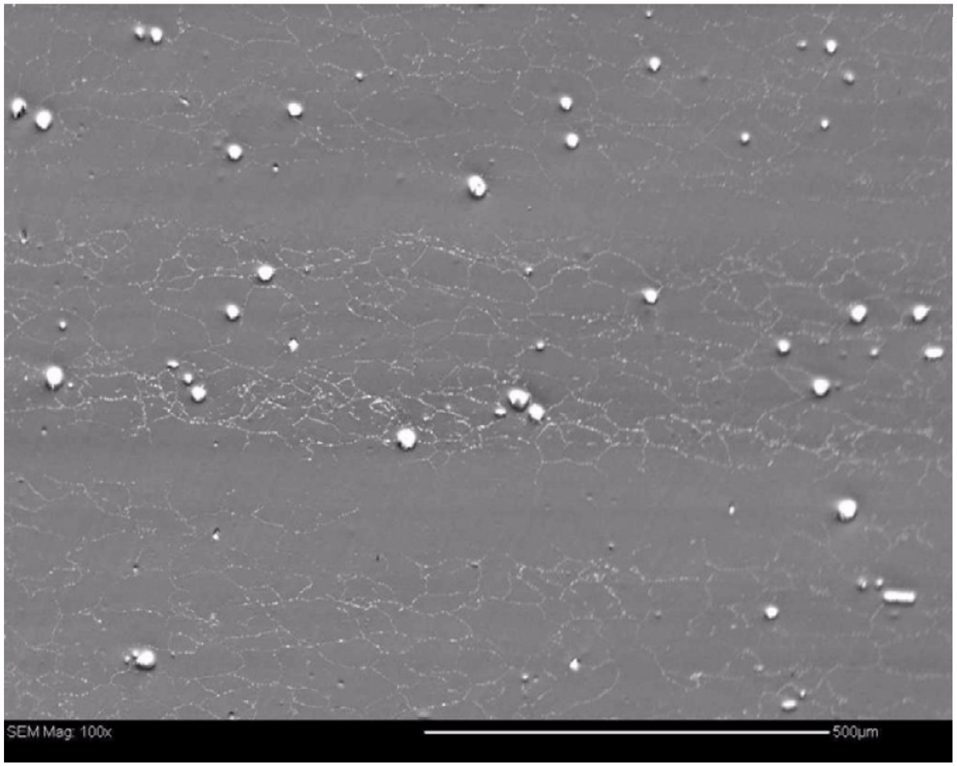
1. Assume butt welded pipe with a wall of ~20 – 25 mm
2. Perform the calculation to grow a small defect to about 80% of through-wall
3. Evaluate the growth rate when the K is ~30 ksi√in
4. The growth rate corresponding to 80 – 100 year life is in the vicinity of ~4 x 10^{-9} mm/s

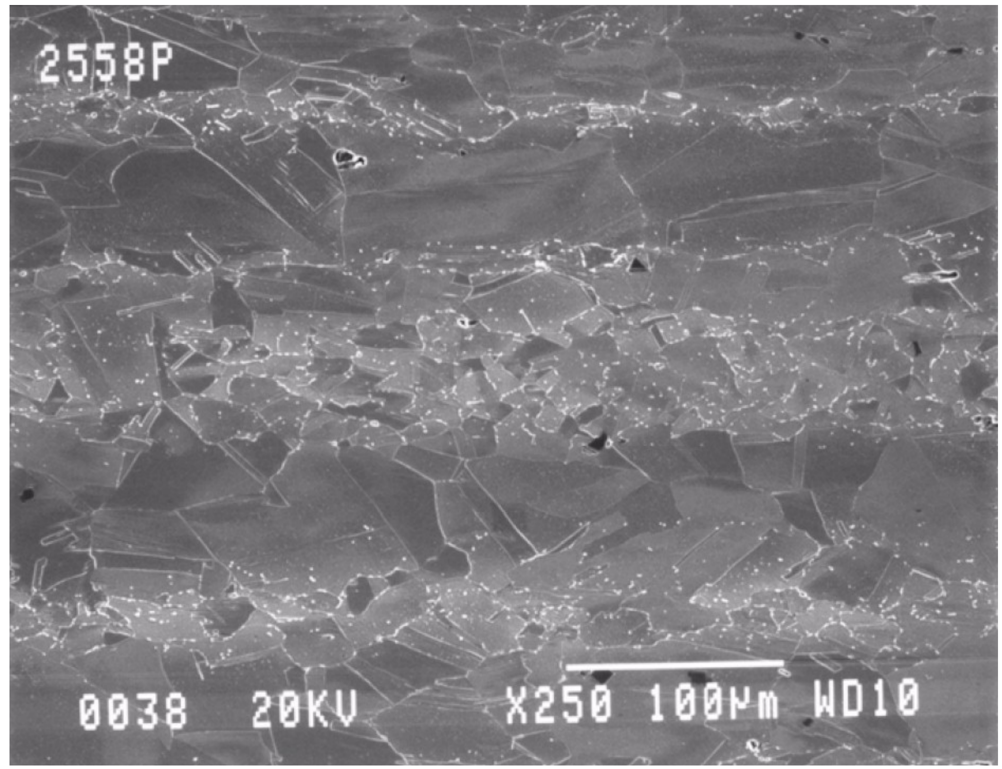
What CGR Is Adequately Low?



80 – 100 year life requires ~4 x 10^{-9} mm/s

Inhomogeneity in Alloy 690

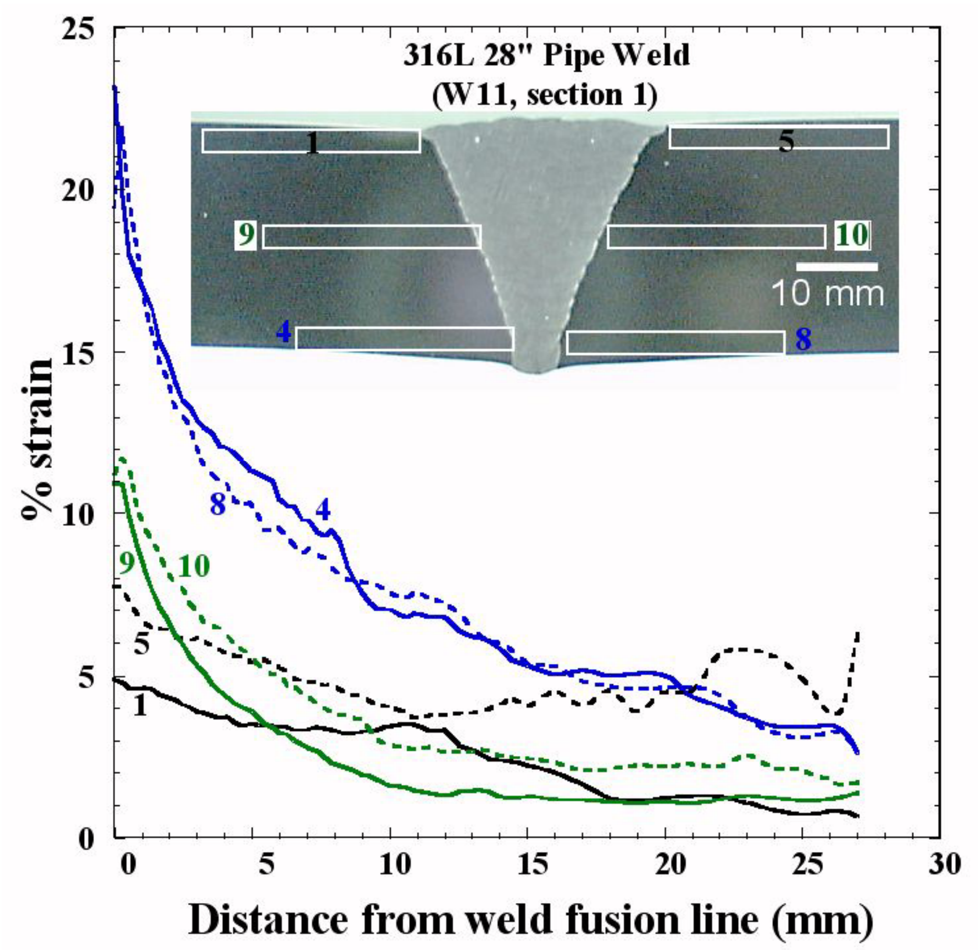


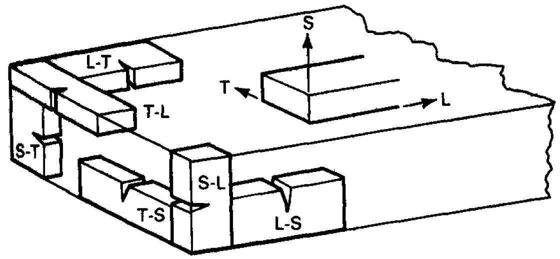


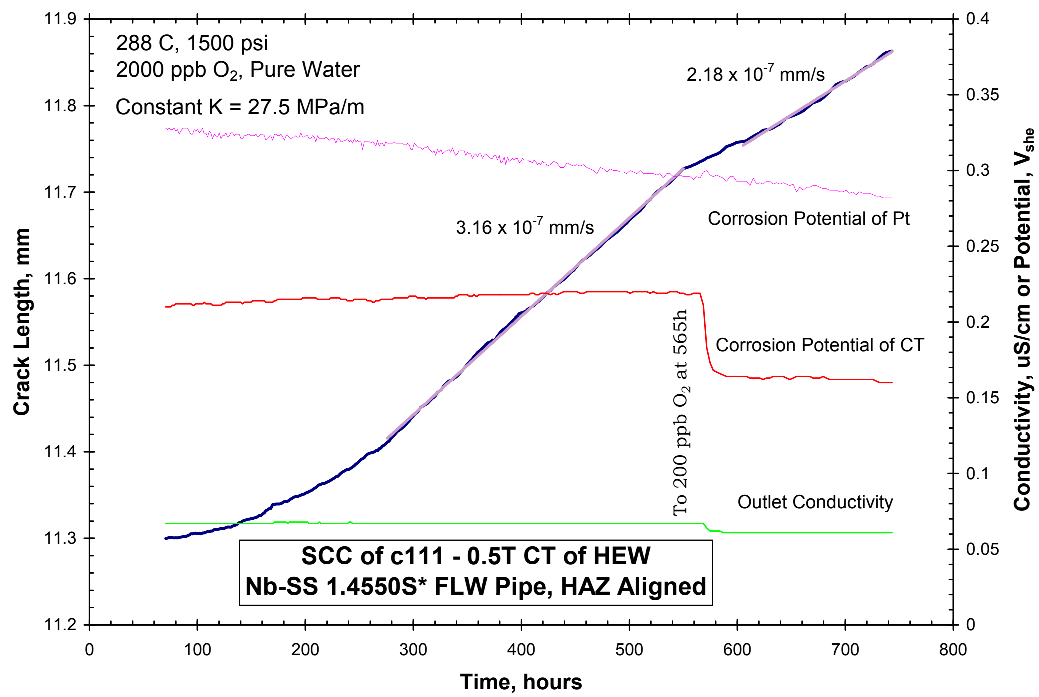
Composition & microstructural banding affects grain size and grain boundary carbide decoration.

Severe banding occurred in 1 of 3 high CGR Bettis heats.

Weld Residual Strain Effects on SCC







Weld residual strains are often >20% equivalent room temperature strain near fusion line at root of weld

Young HAZ Measurements

- *Residual plastic strain in Alloy 690 HAZ: 12 – 28%*
- *Residual plastic strain in 690 HAZ: 2 – 13% (best practice)*
- *For comparison, SS HAZ with 52M weld: 13 – 25%*
- *Residual strain of weld repair relative to original weld = 1X:*
  - *One repair: 2.1X*
  - *Two repairs: 2.7X*
  - *Three repairs: 3.0X*
- *Excellent correlation between EBSD strains and SCC CGRs*

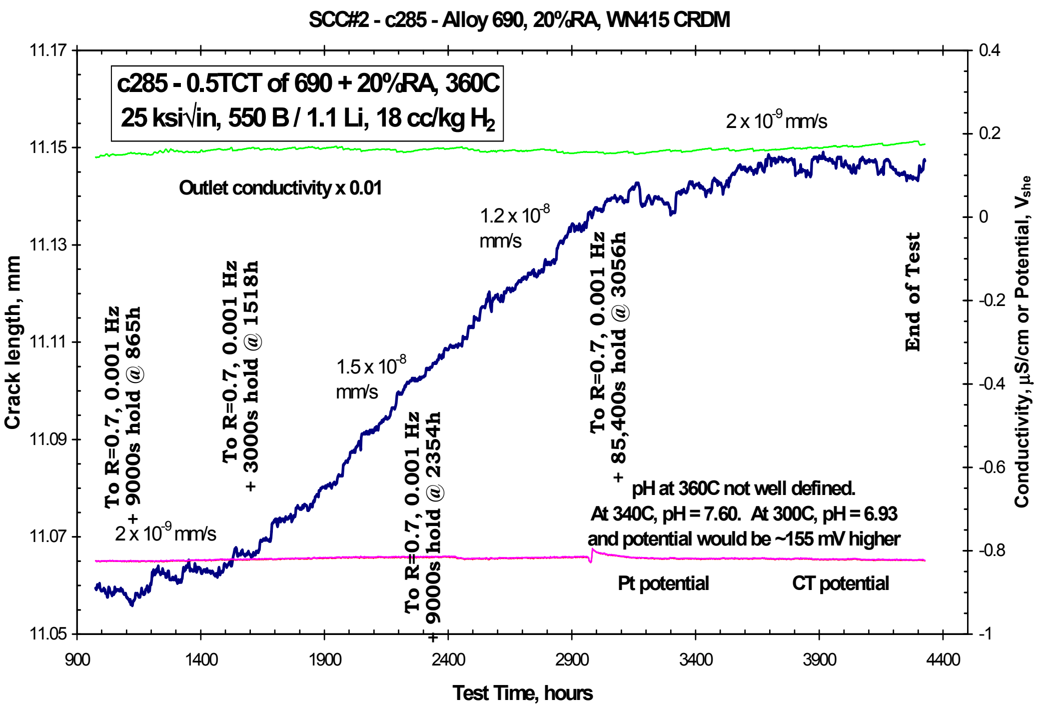
Testing Approach

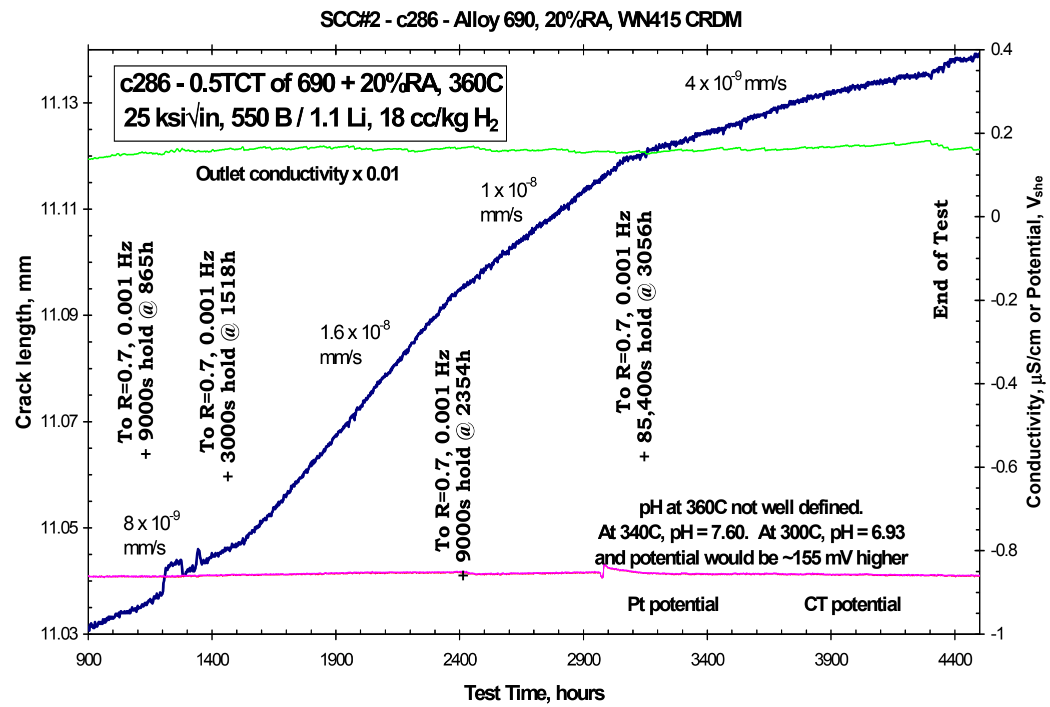
Crack growth rates conditions for alloy 690 and 152/52 welds:

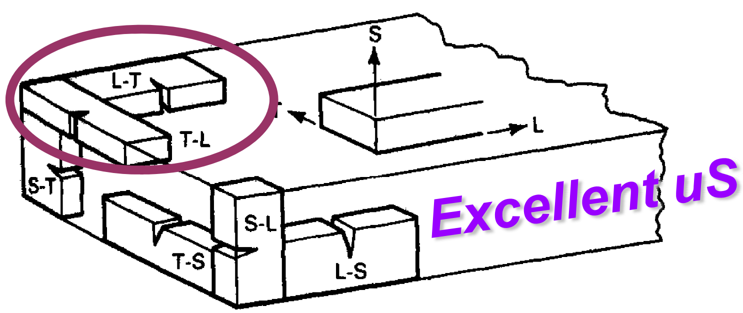
- 690 cold worked by forging or 1-D rolling at 25 ºC
  - by 20, 26 and 40% reduction in thickness
  - S-L, S-T and T-L orientations, ~10 heats, ~32 specimens
  - cold work broadly simulates weld residual strain in HAZ
  - 152/52 weld: T-S orientations, ~6 heats, 6 specimens
  - used resistivity coupon 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 Forged Alloy 690 CRDM

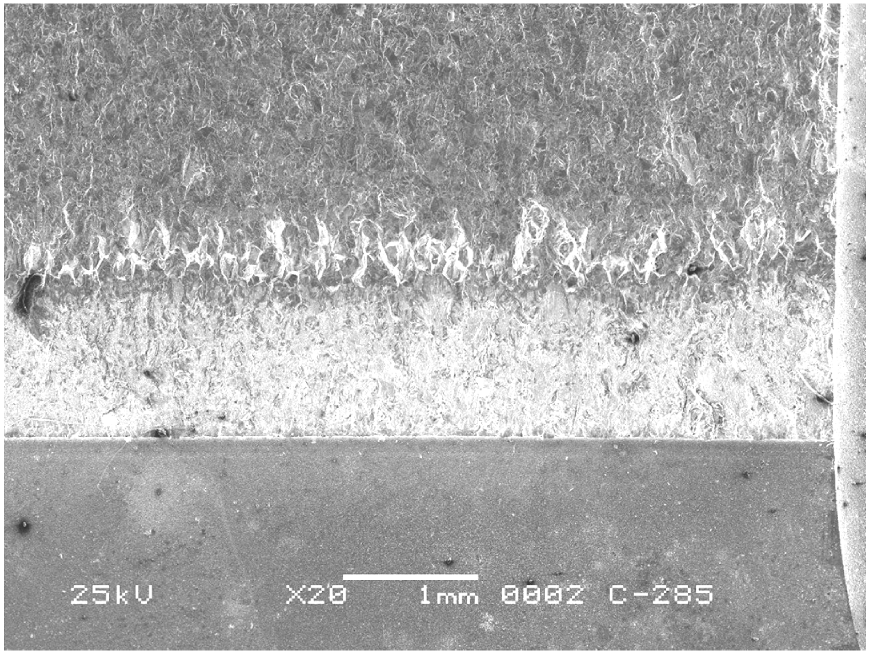


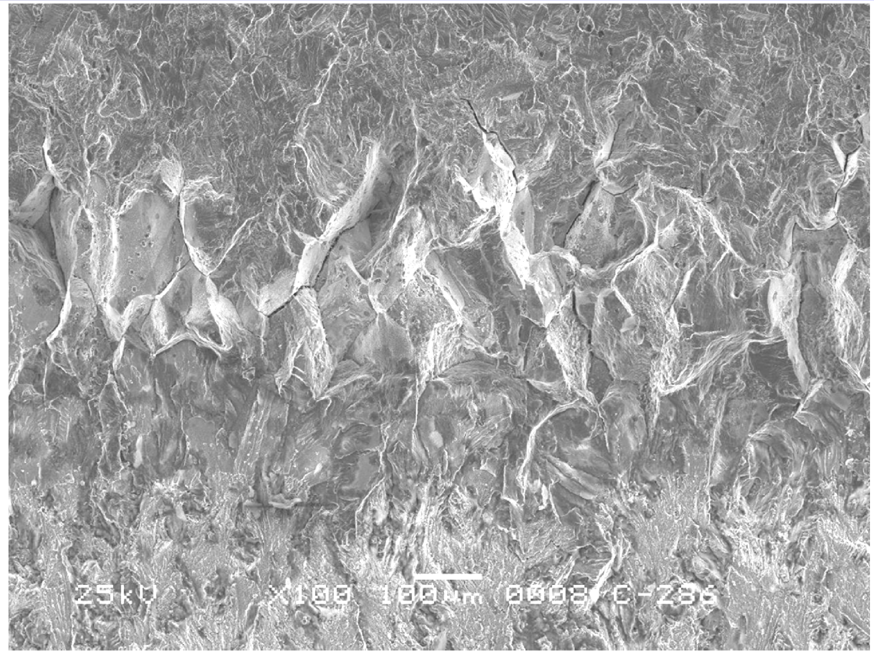


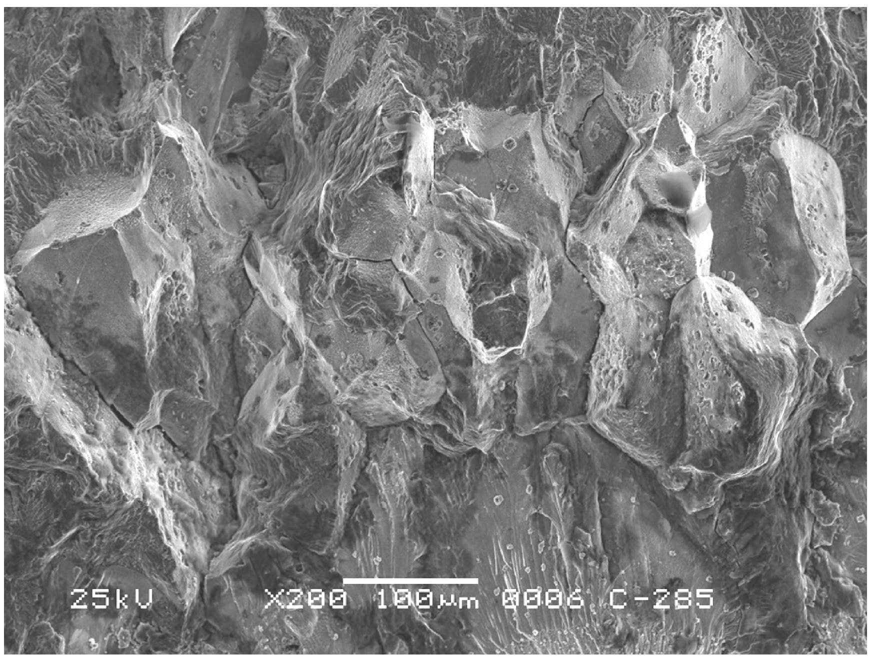


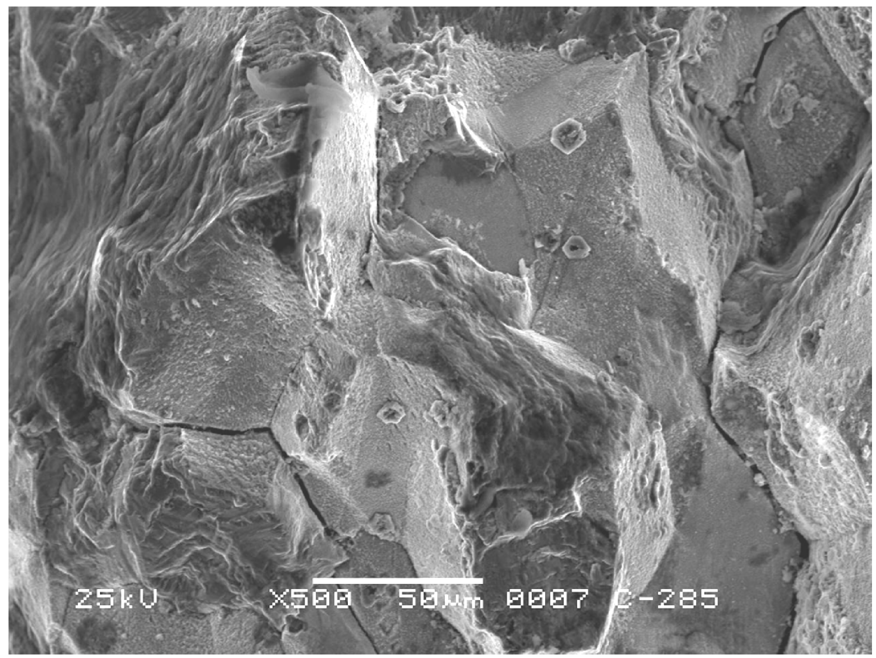
L-T Orientation (good)
Very homogeneity microstructure
Orientation doesn't reflect weld HAZ

c285/c286 SEM Fractography



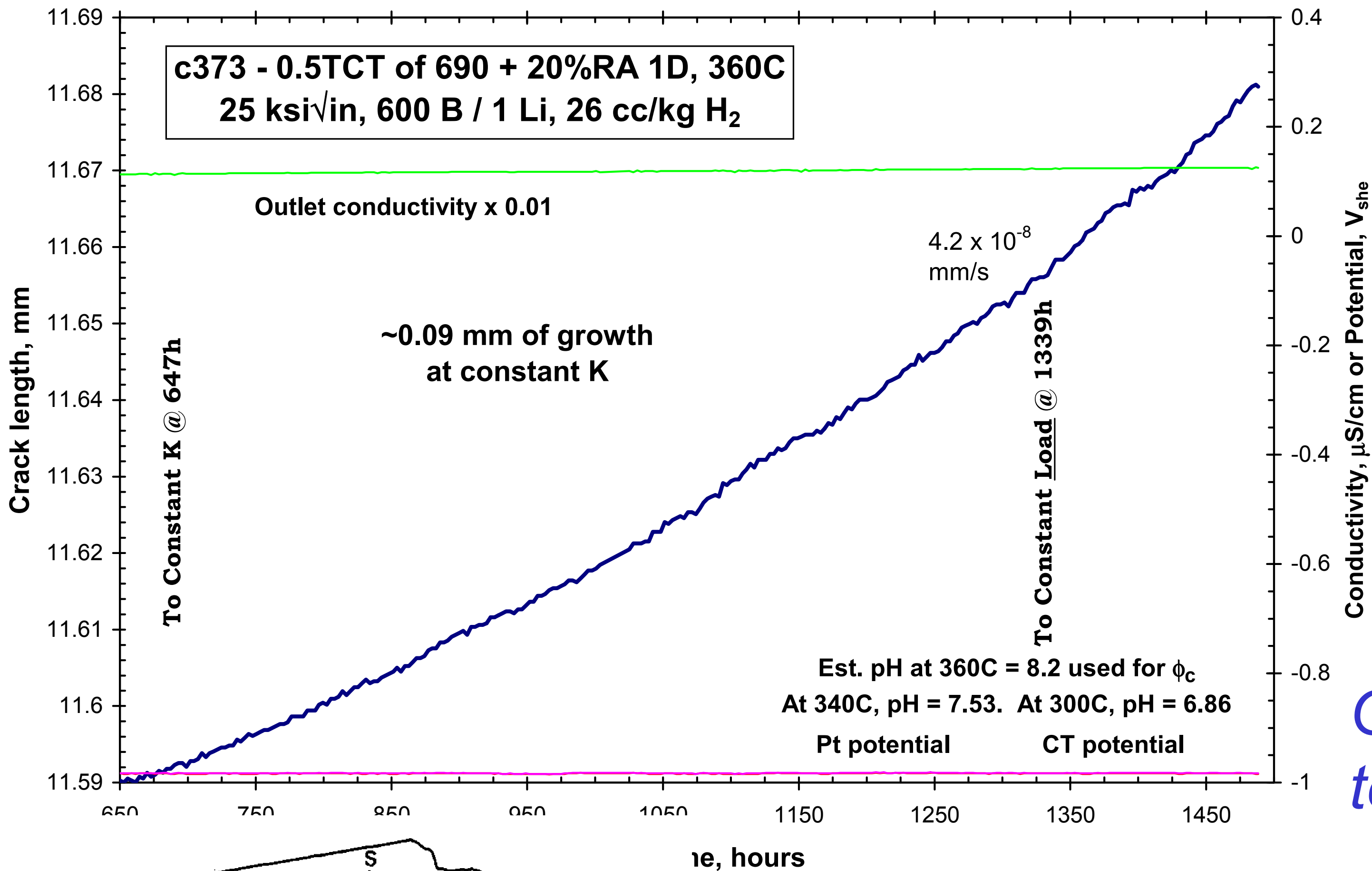




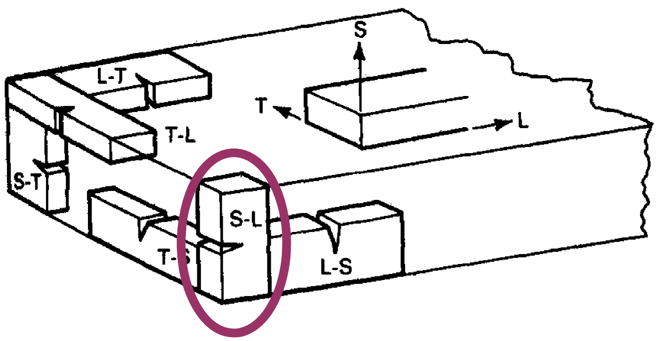


Specimen c373

20% 1D-Cold Rolled GE GRC Alloy 690

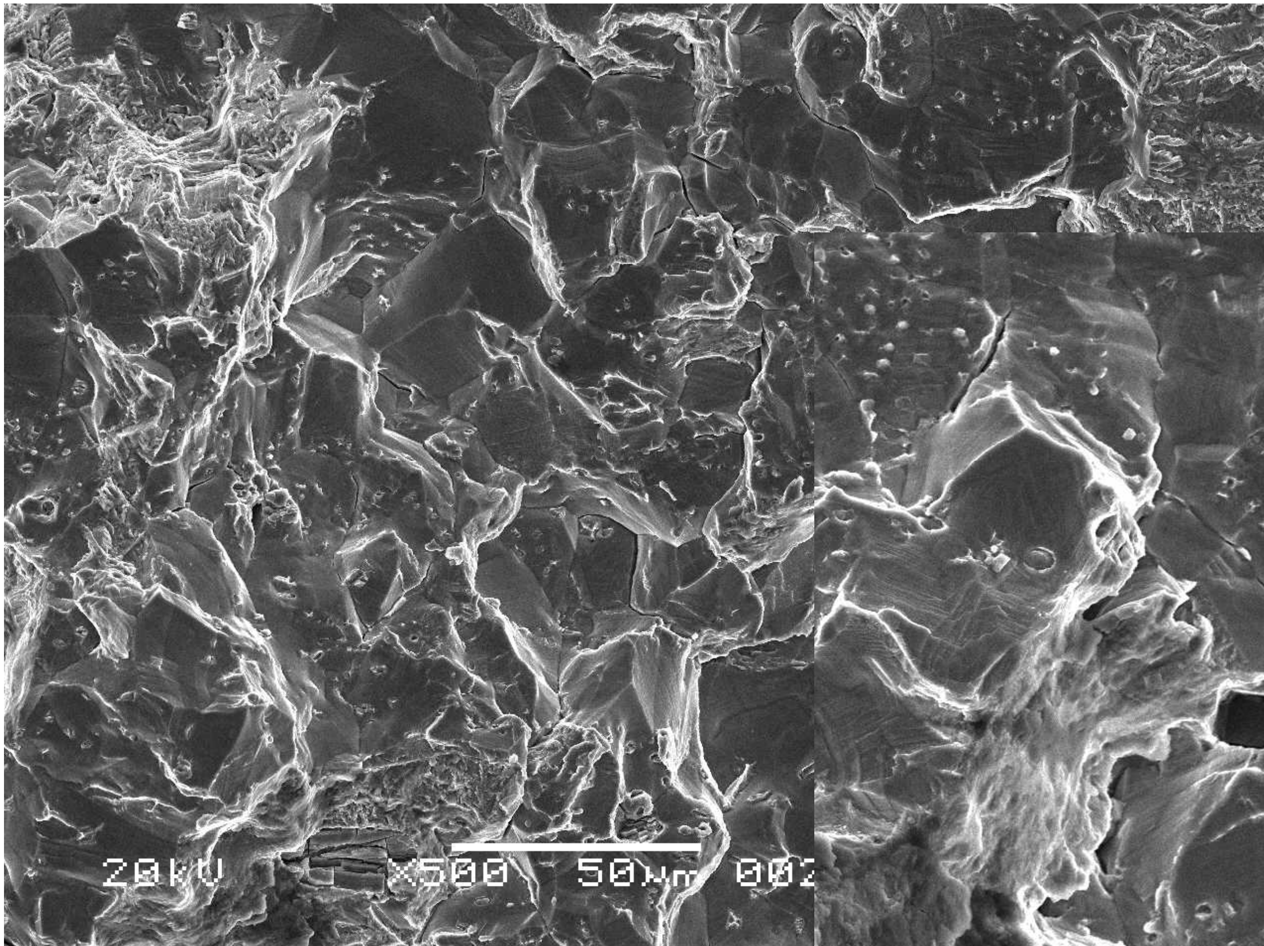


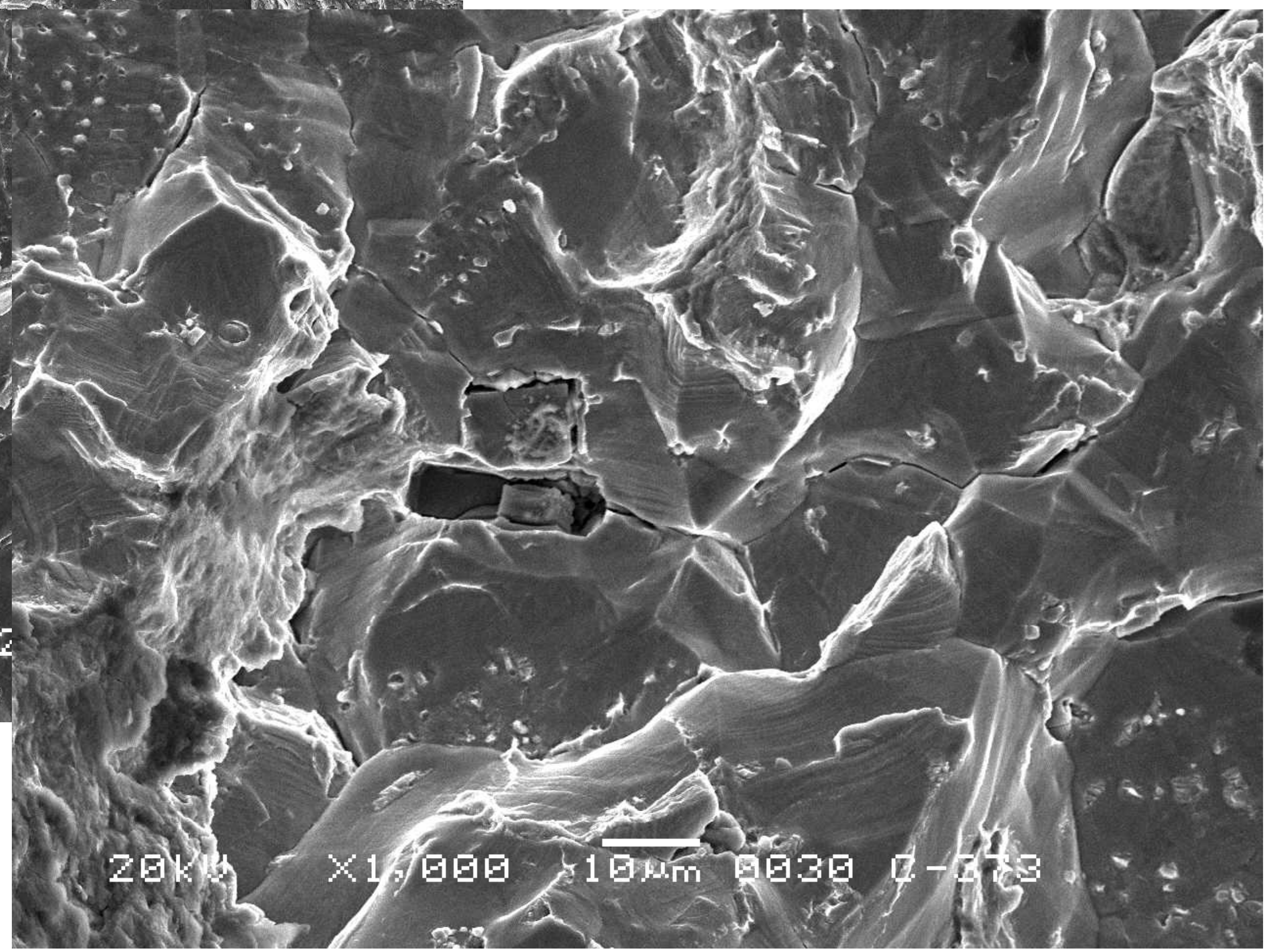
Orientation is relevant to SCC in weld HAZ



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

SEM Fractography of 20% 1D-CR GE 690

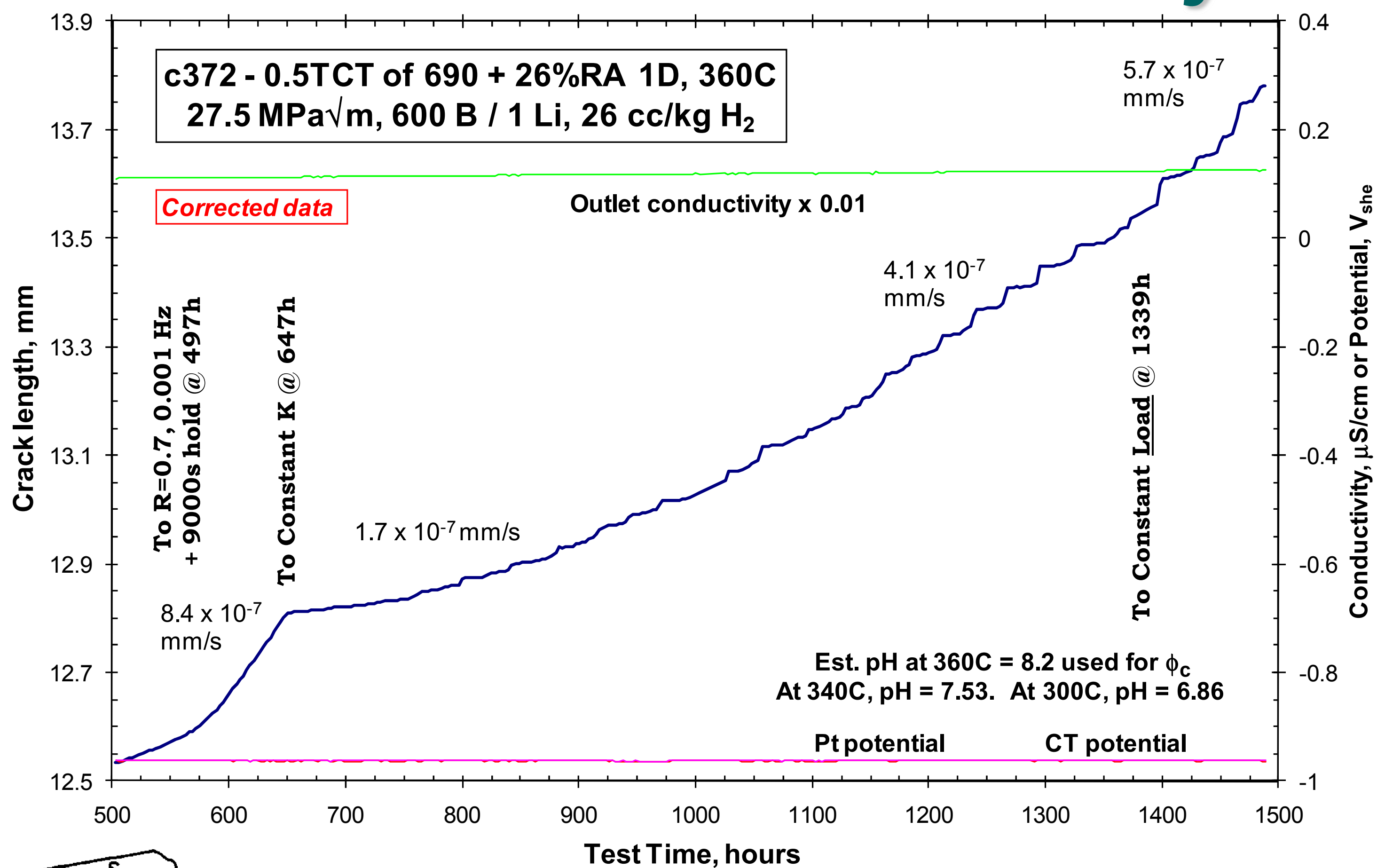


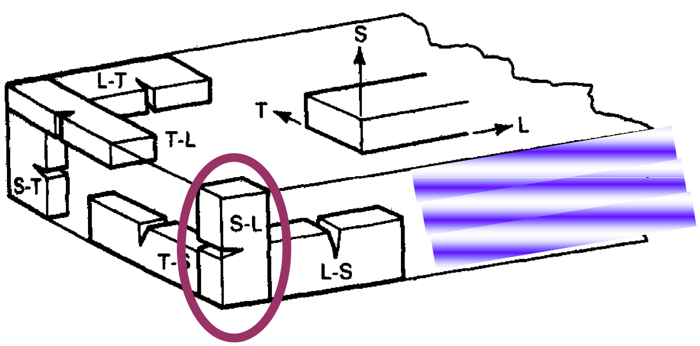


Very homogeneous microstructure – forged bar. Double melted: VIM-VAR

Specimen c372

26% 1D-Cold Rolled ANL Alloy 690

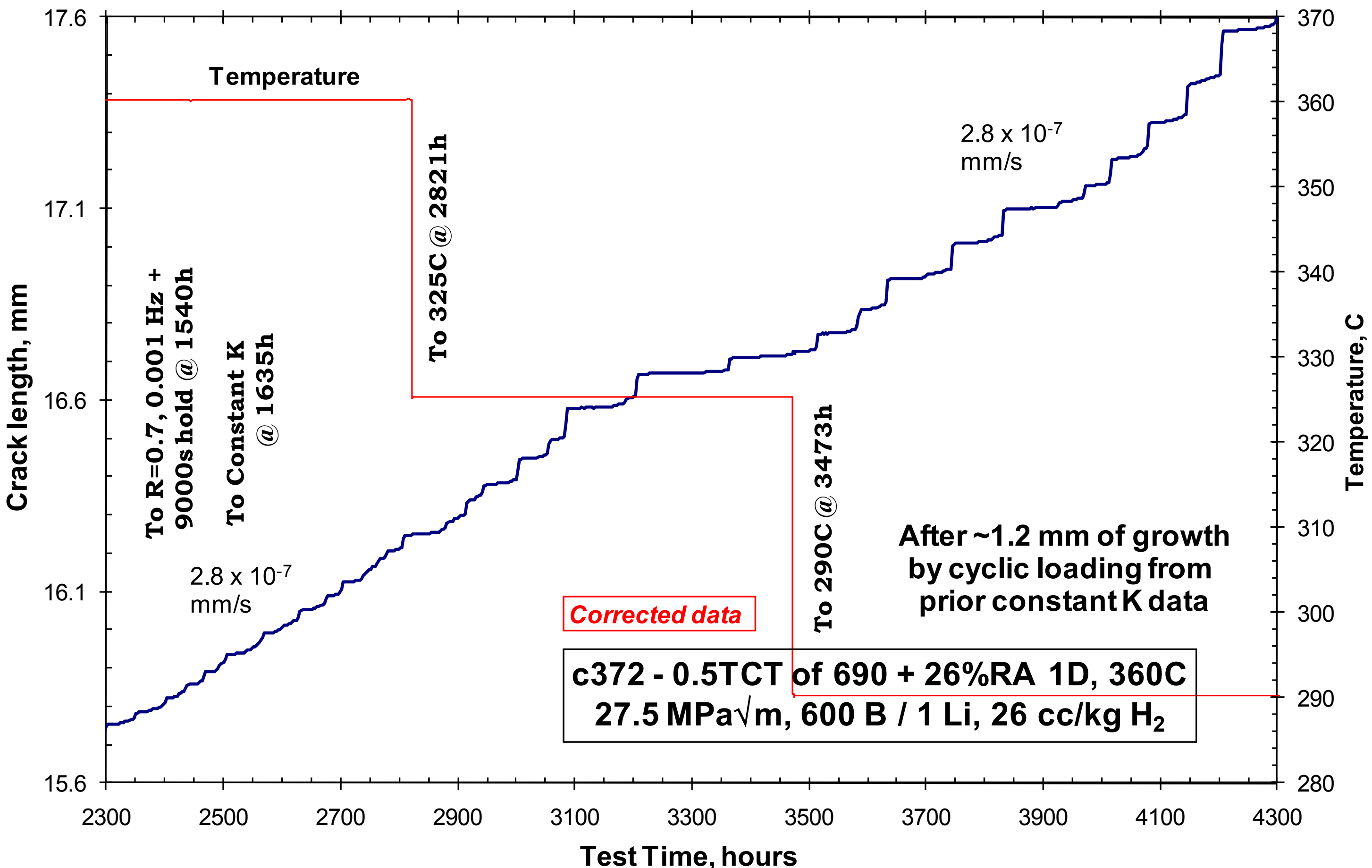




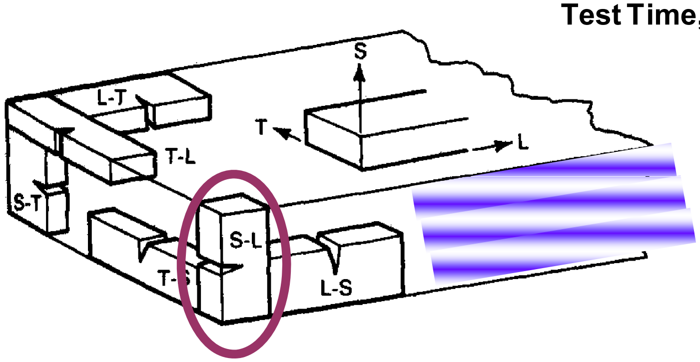
High CGR in S-L orientation
Inhomogeneous microstructure
1D cold rolled = "1.5D" due to spreading

Specimen c372

26% 1D-Cold Rolled ANL Alloy 690

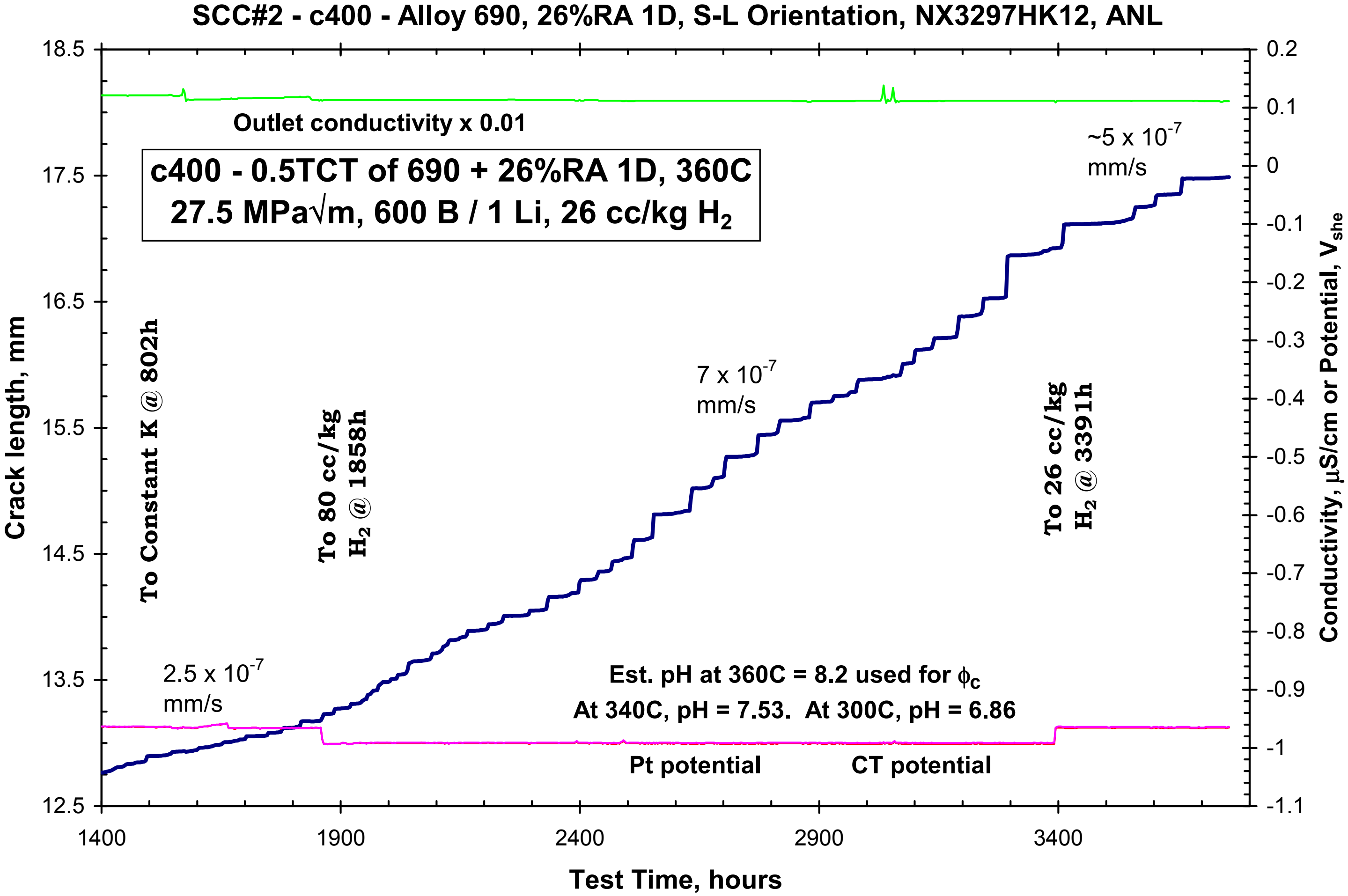


No temperature effect; would be 12X normally



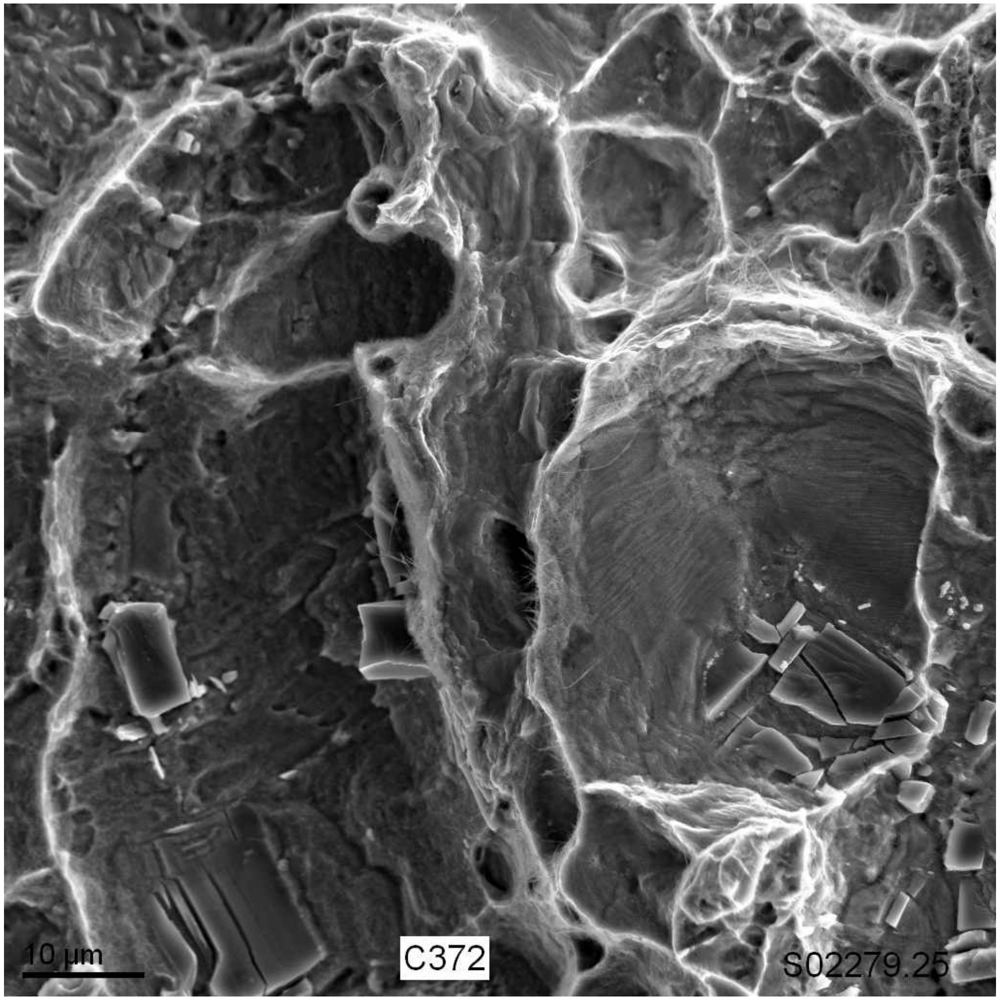
High CGR in S-L orientation
Inhomogeneous microstructure
1D cold rolled = “1.5D” due to spreading

26% 1D-CR ANL Alloy 690 – Test #2

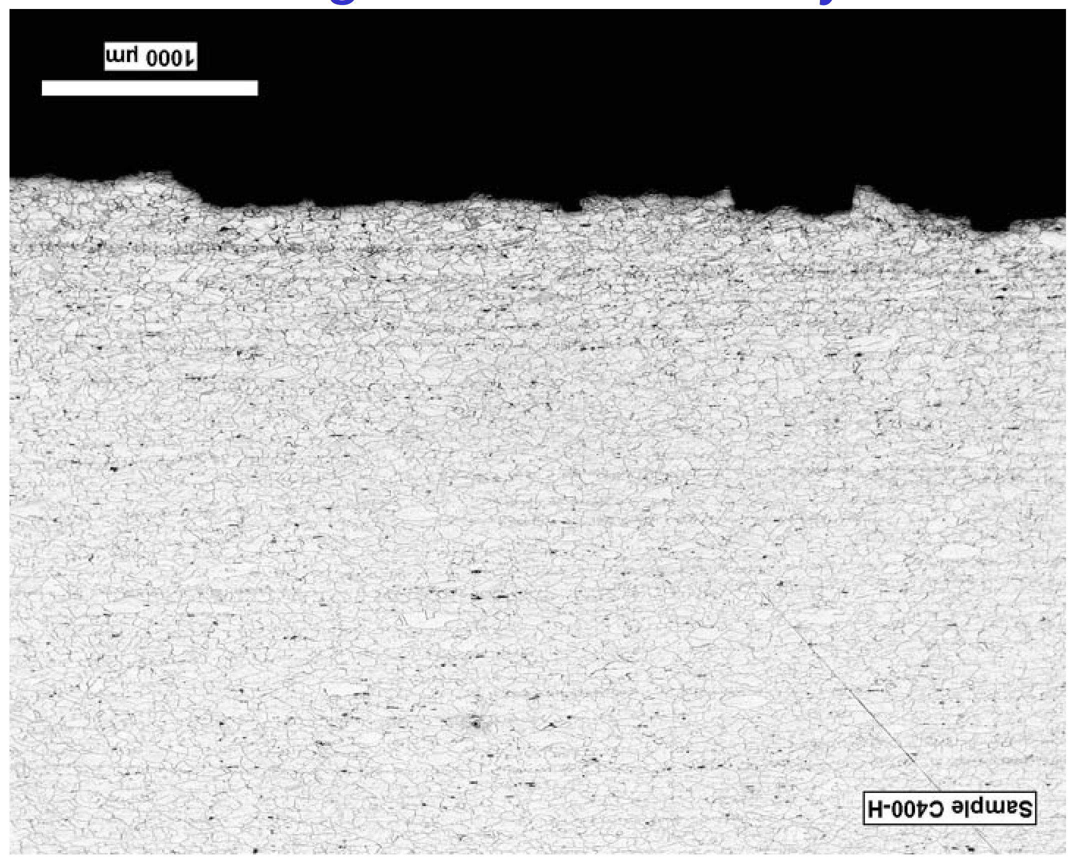


Similar data in second test on same materials;
Fast growth, no effect of dissolved H_2.
Similar to SERCO data; ANL & PNNL ~7-10X lower CGR.

26% 1D-Cold Rolled ANL 690

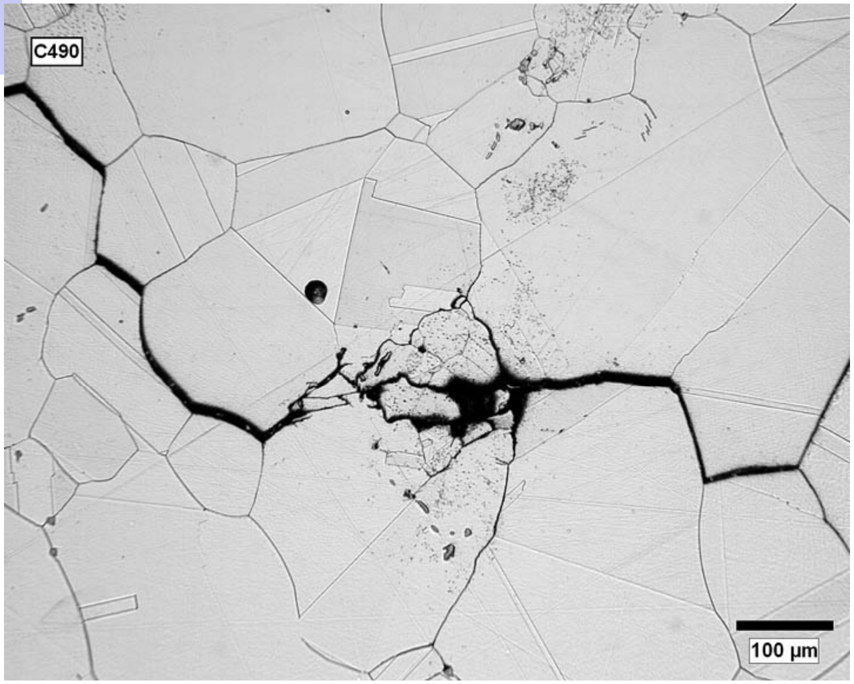


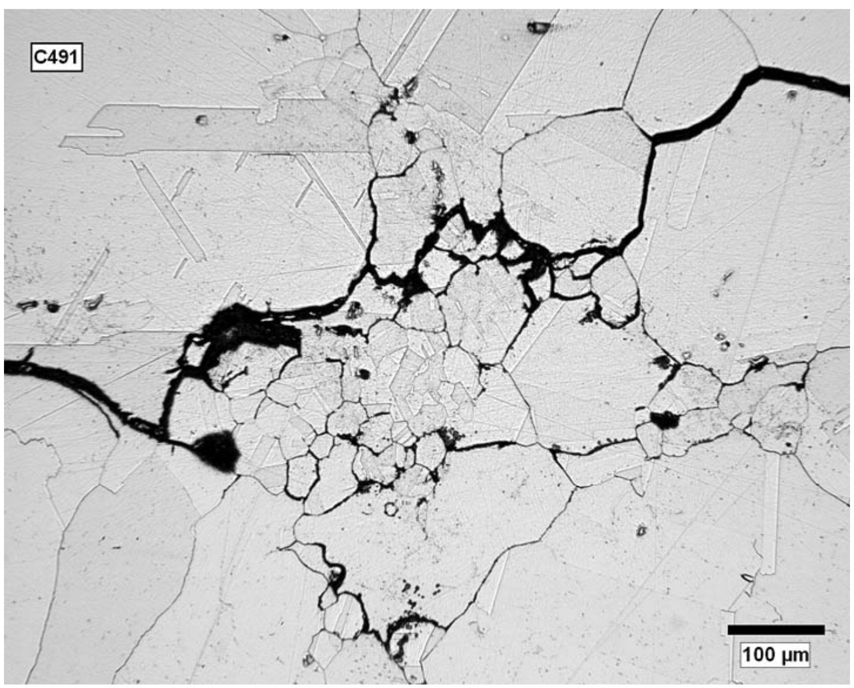
Crack appears to follow bands of high carbide density



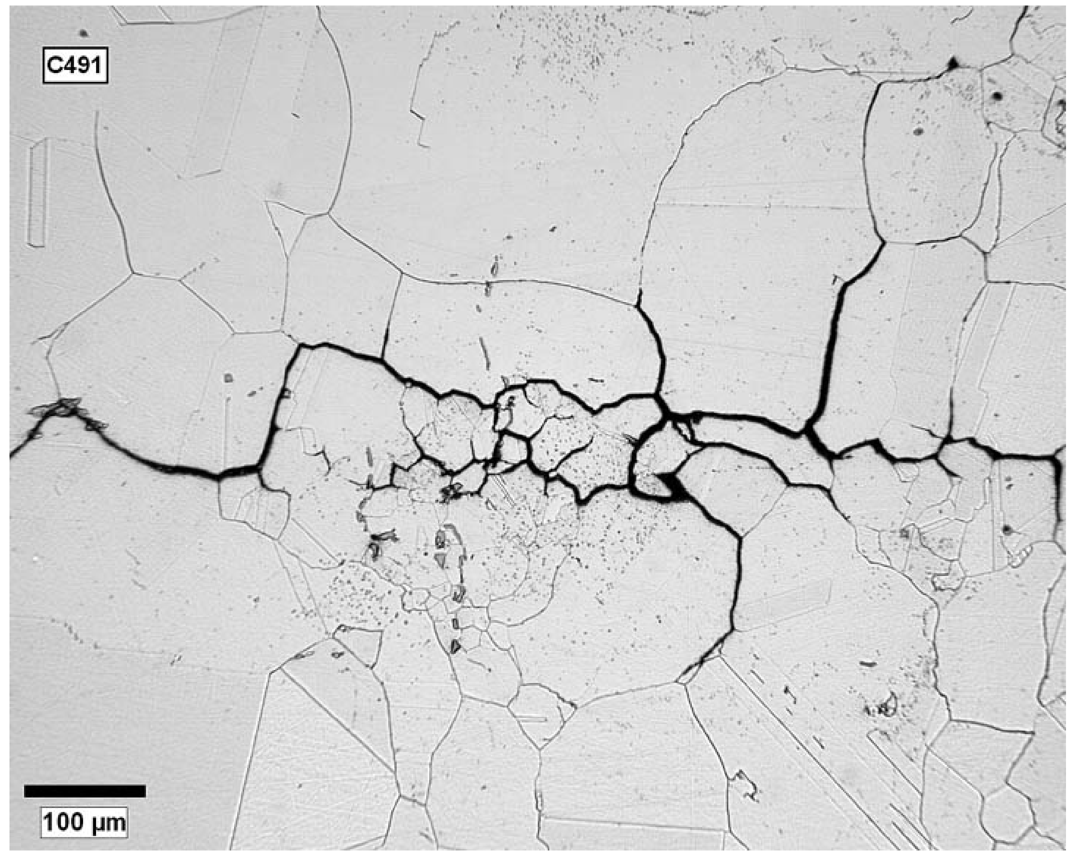
Fractography is "granulated" but not highly intergranular, not unlike what is observed in some cold worked stainless steels

Specimens c490/c491





Banded Alloy X-750 (not cold worked)



Cracks clearly grow differently in banded regions

Specimen c471/c472

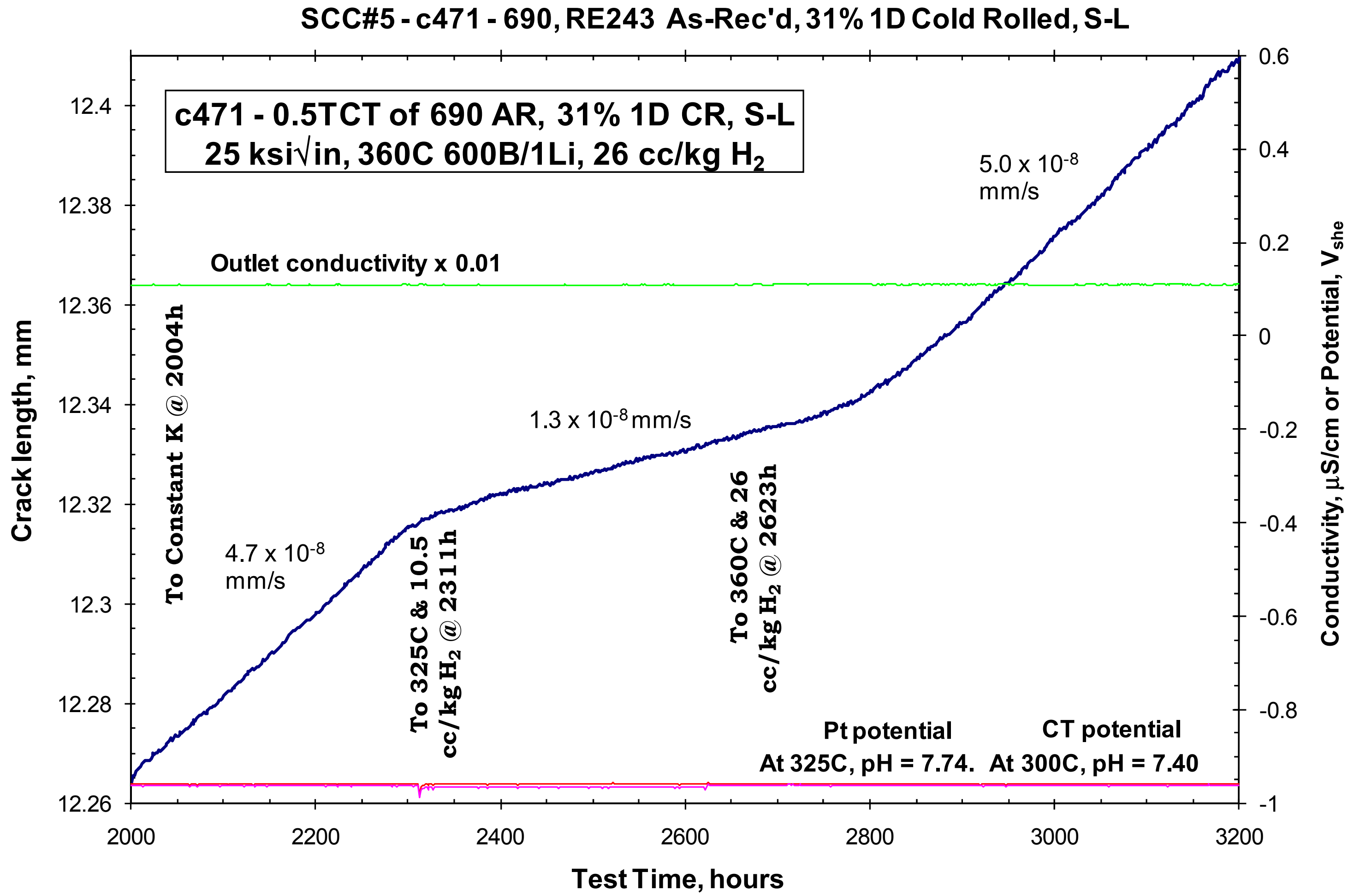
Excellent Microstructure,
Valinox Alloy 690 CRDM, RE243

31% 1D-Cold Rolled – S-L

Moderately high growth rates, very stable SCC response, temperature & hydrogen dependency.
Very good agreement with PNNL data.

Specimen c471

31% 1D-CR 690 CRDM, RE243 – S-L

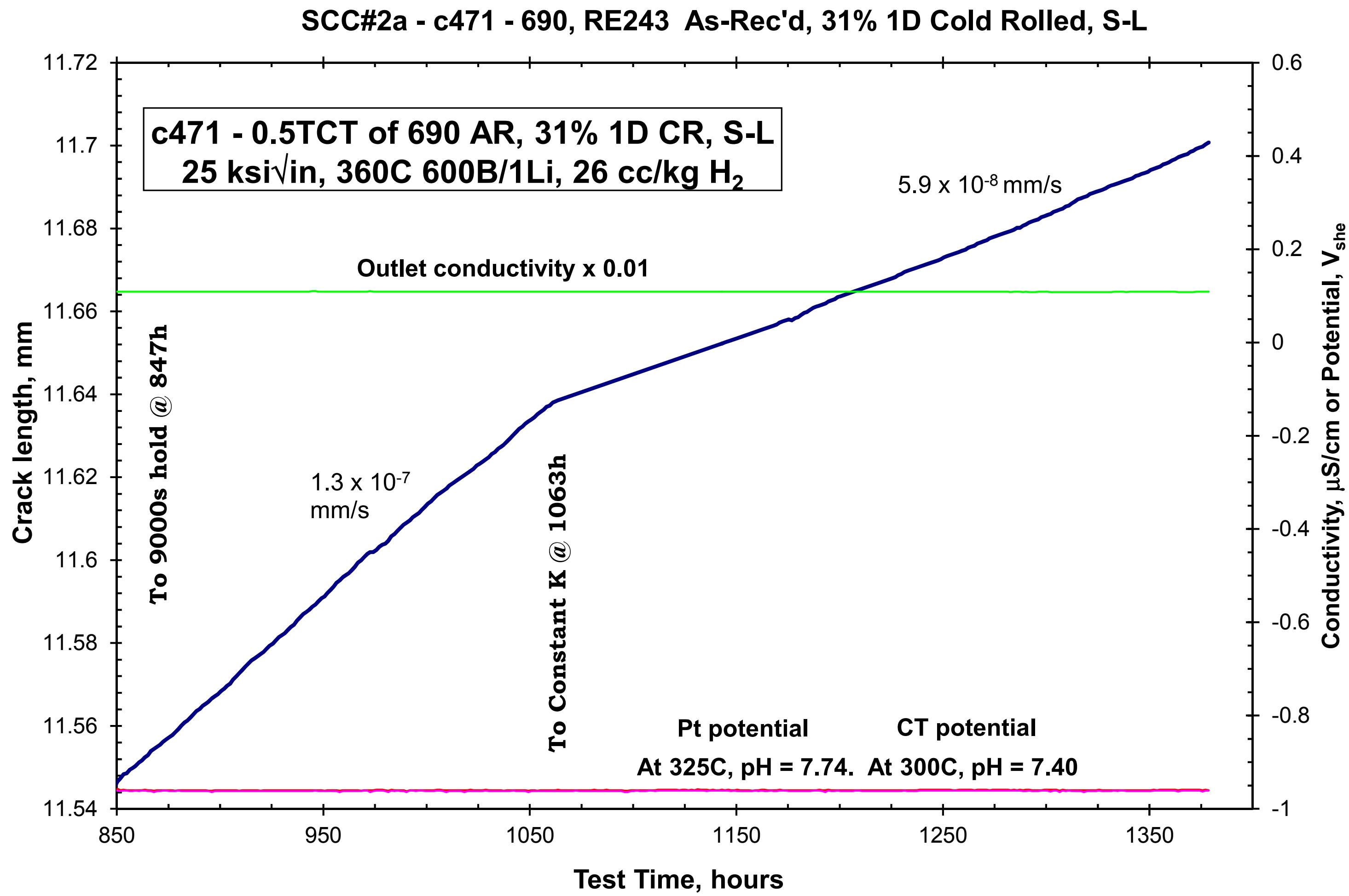


Moderately high growth rates, very stable SCC response, "normal" (but somewhat low) temperature dependency.

Very good agreement with PNNL data.

Specimen c471

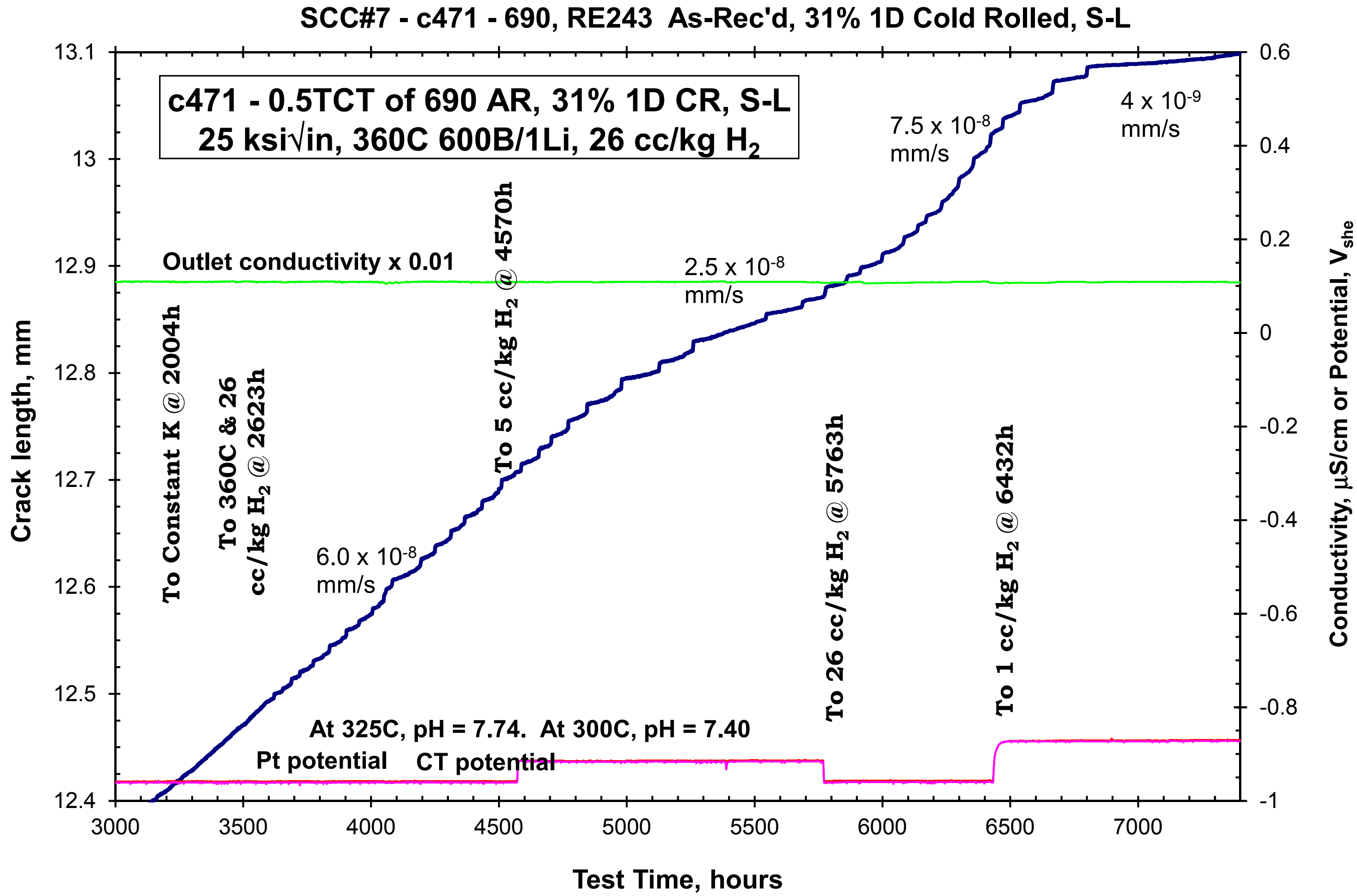
31% 1D-CR 690 CRDM, RE243 – S-L



Moderately high growth rates, very stable SCC response, "normal" (but somewhat low) temperature dependency.

Very good agreement with PNNL data.

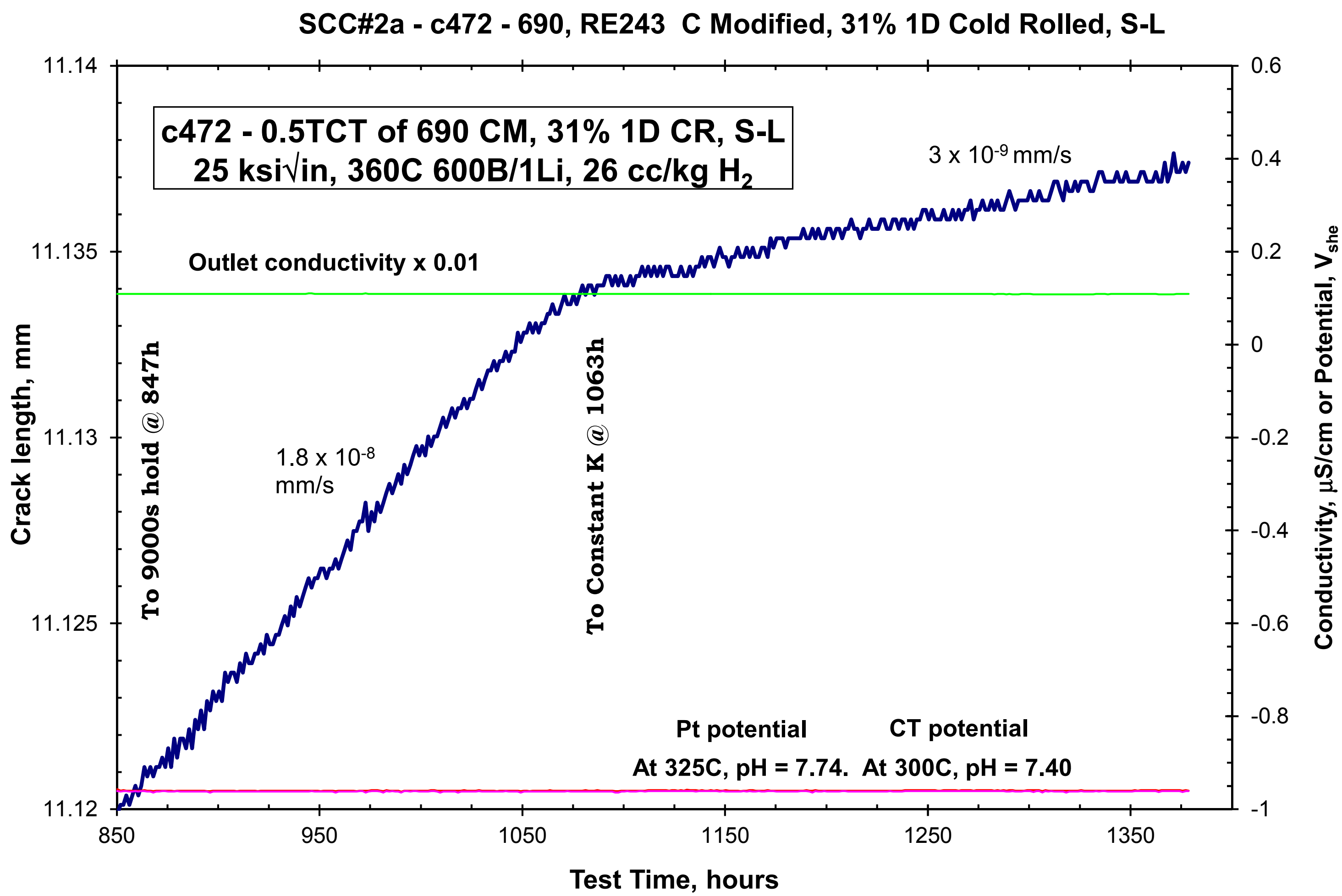
31% 1D-CR 690 CRDM, RE243 – S-L



Moderately high growth rates, very stable SCC response, "normal" (but somewhat low) temperature dependency.

Very good agreement with PNNL data.

31% 1D-CR 690 Carbide Modified, RE243 – S-L

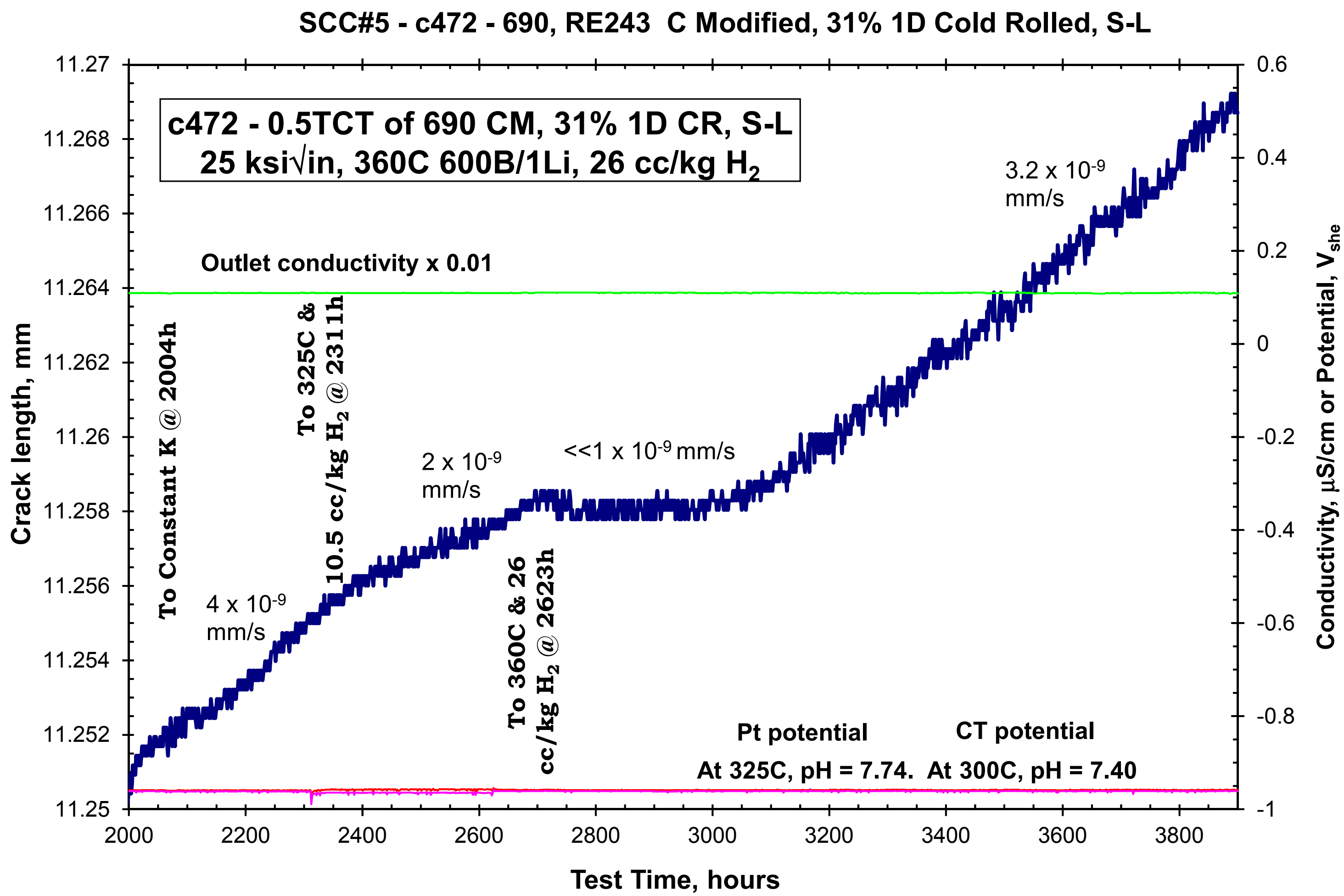


Much lower growth rates than standard microstructure.

Very good agreement with PNNL data.

Specimen c472

31% 1D-CR 690 Carbide Modified, RE243 – S-L

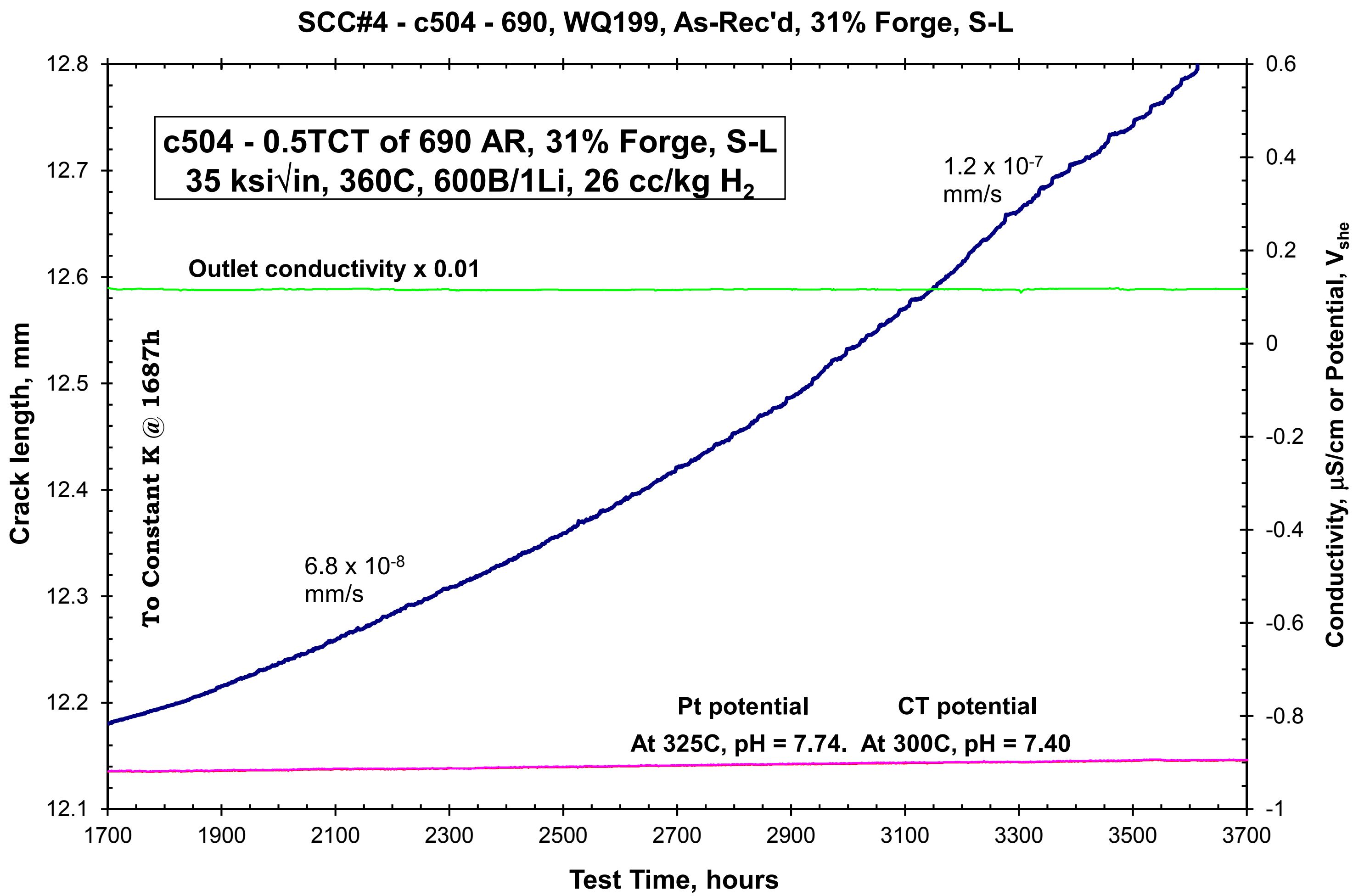


Much lower growth rates than standard microstructure.

Very good agreement with PNNL data.

Specimen c504

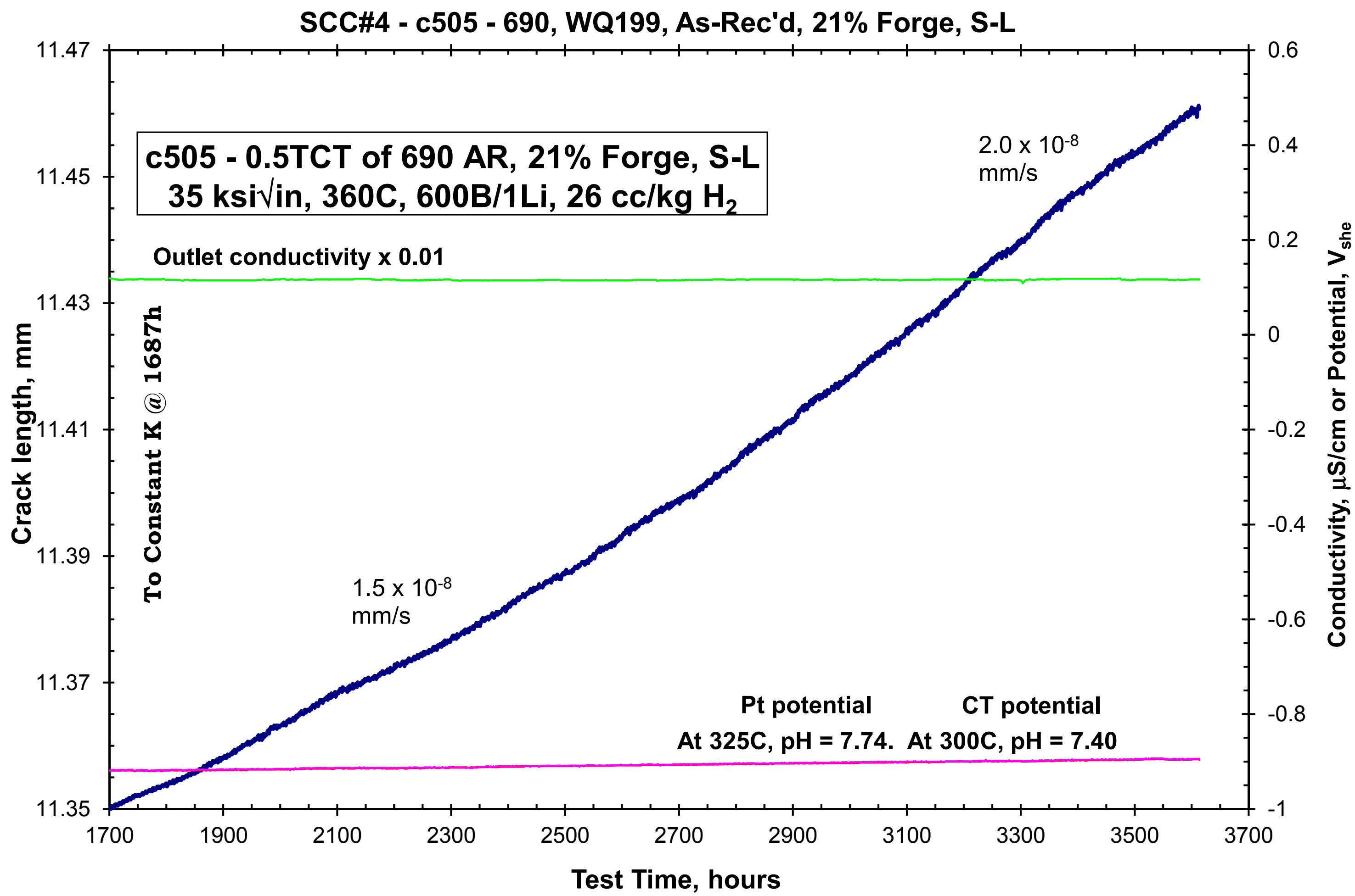
31% 2D-Deform (Forged) 690 CRDM, WQ199 – S-L



High growth rates, very stable SCC response. Note evolution of CGR vs. time.

Specimen c505

21% 2D-Deform (Forged) 690 CRDM, WQ199 – S-L



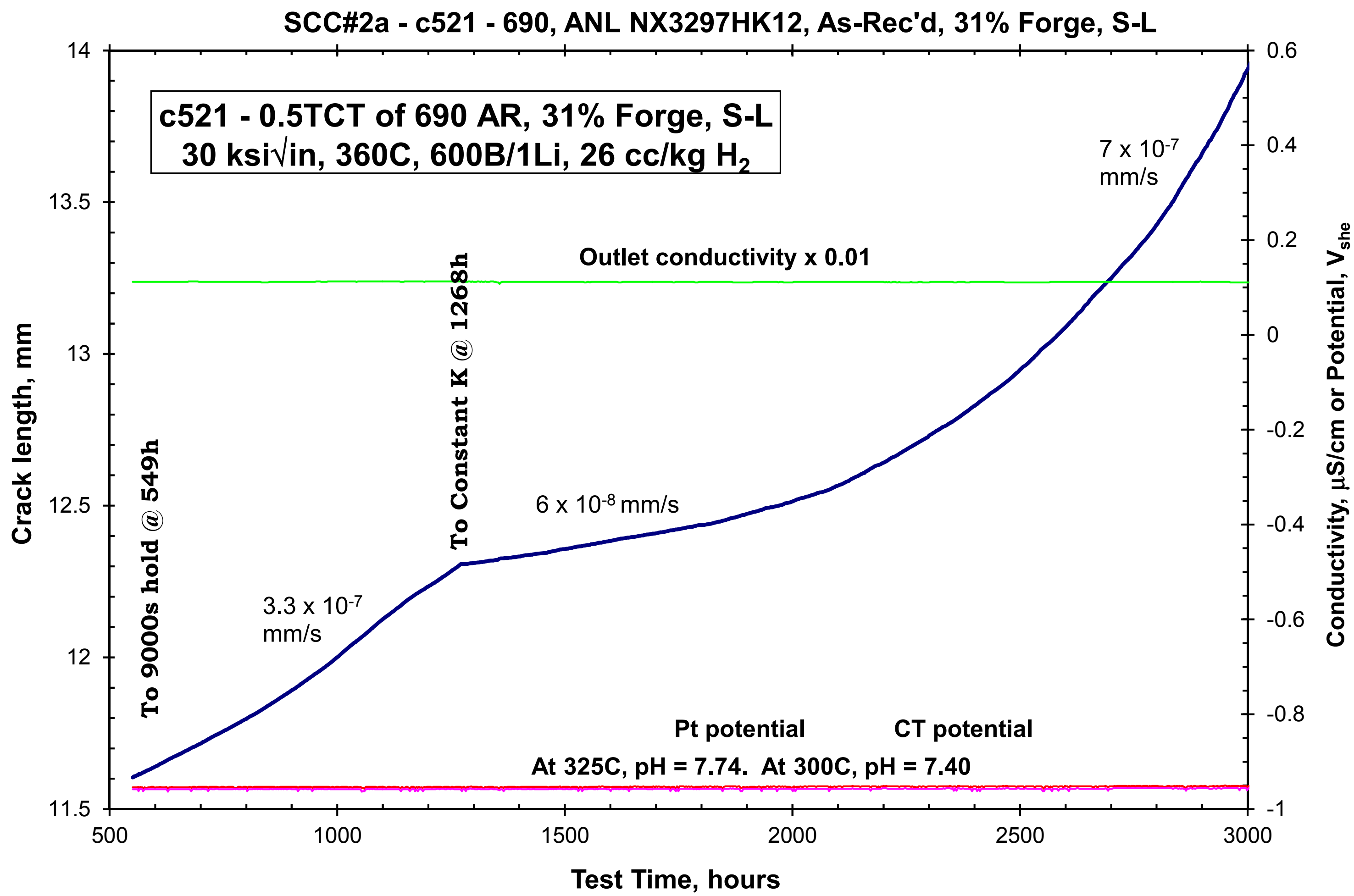
Medium growth rates, very stable SCC response.
K is slowly dropping because companion CT is growing faster.

Forged Microstructures Show Similar Growth Rates to 1-D Cold Rolled

High crack growth rates yet observed at GE on forged 690

Specimen c521

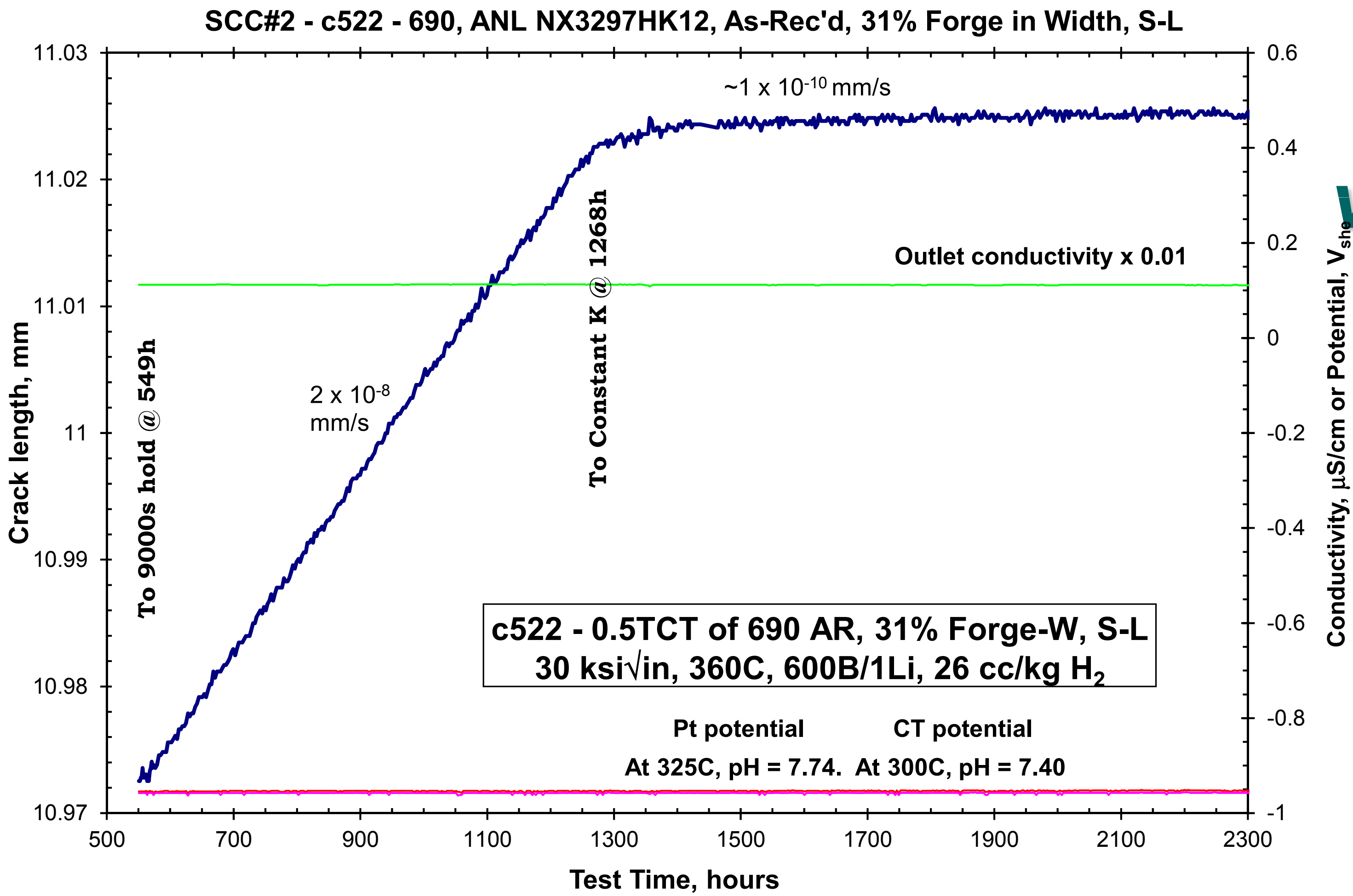
31% 2D-Deform (Forged) 690 Plate, NX3279HK – S-L



Very high growth rates, very stable SCC response.
Note continuing evolution of CGR vs. time.

Specimen c522

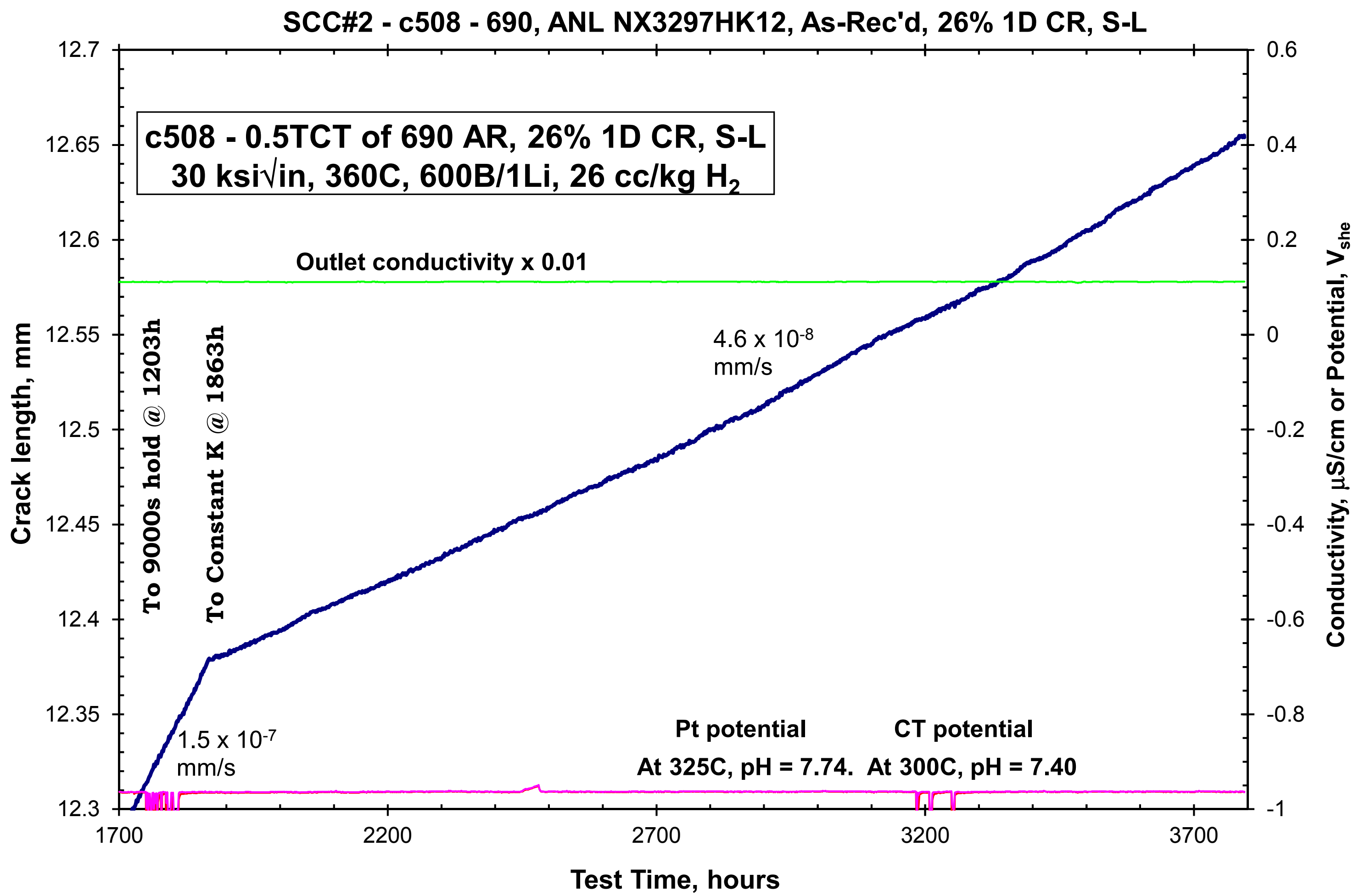
31% 2D-Deform (Forged) 690 Plate, NX3279HK – S-L – T-L vs. CW



Much lower growth rates when deformed in width rather than thickness of the plate.

Specimen c508

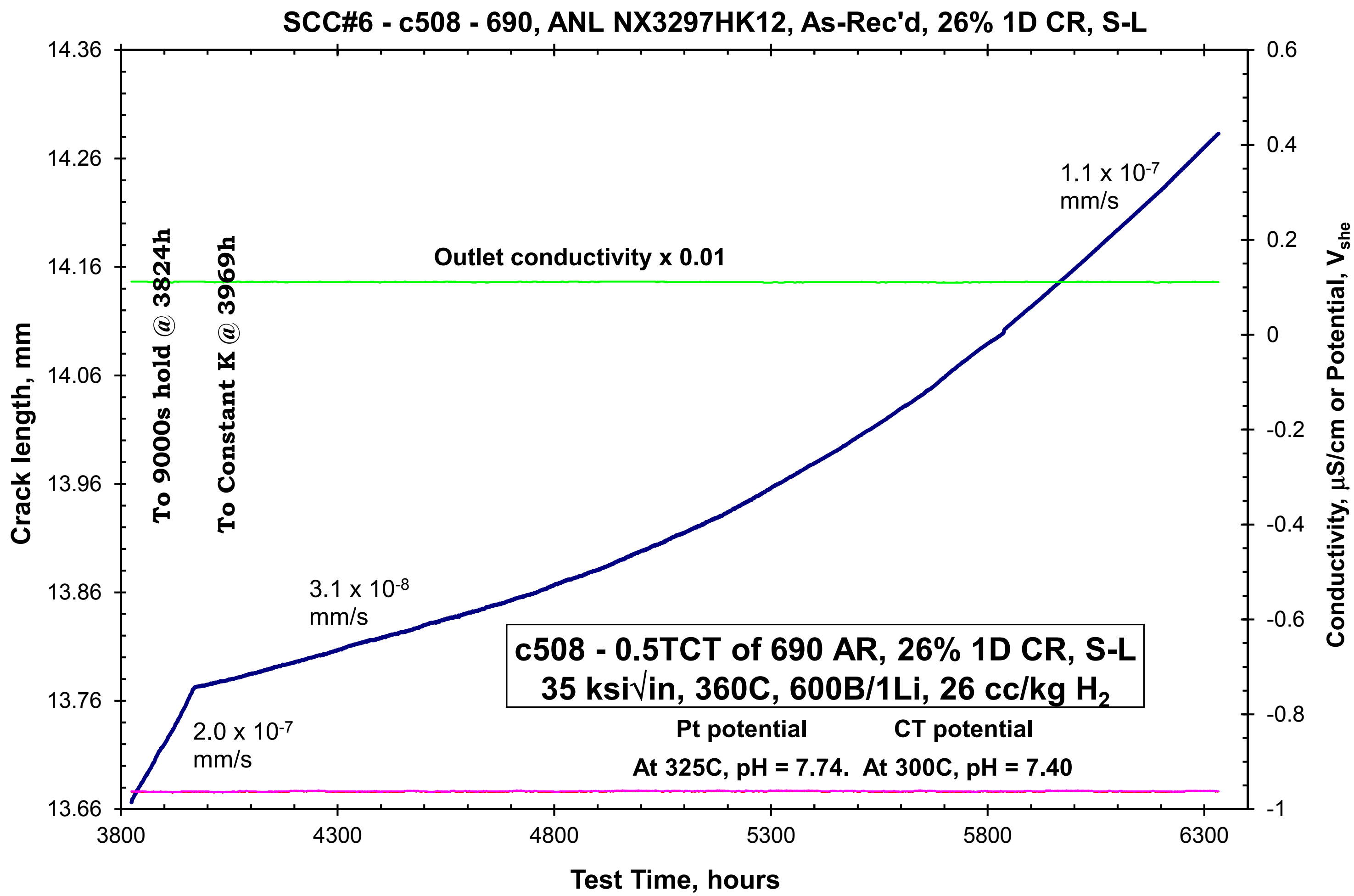
26% 1D-Deform (Rolled) 690 Plate, NX3279HK – S-L



High growth rates, very stable SCC response. Note evolution of CGR vs. time.

Specimen c508

26% 1D-Deform (Rolled) 690 Plate, NX3279HK – S-L



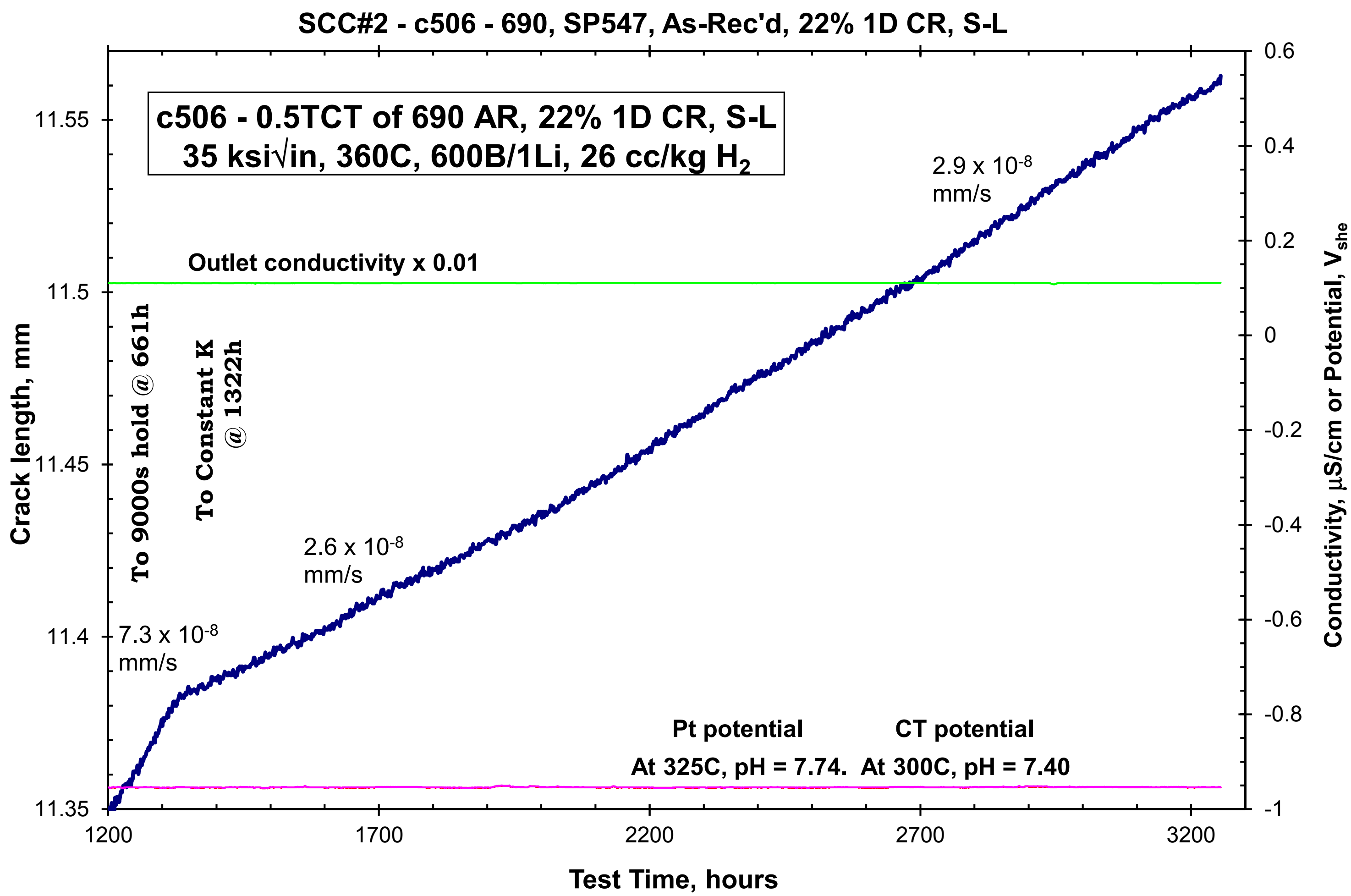
High growth rates, very stable SCC response. Note evolution of CGR vs. time.

Other 1-D Cold Rolled Plates

Neither then ENSA SP-547 nor T-K 114092 exhibit growth rates nearly as high as the ANL plate

Specimen c506

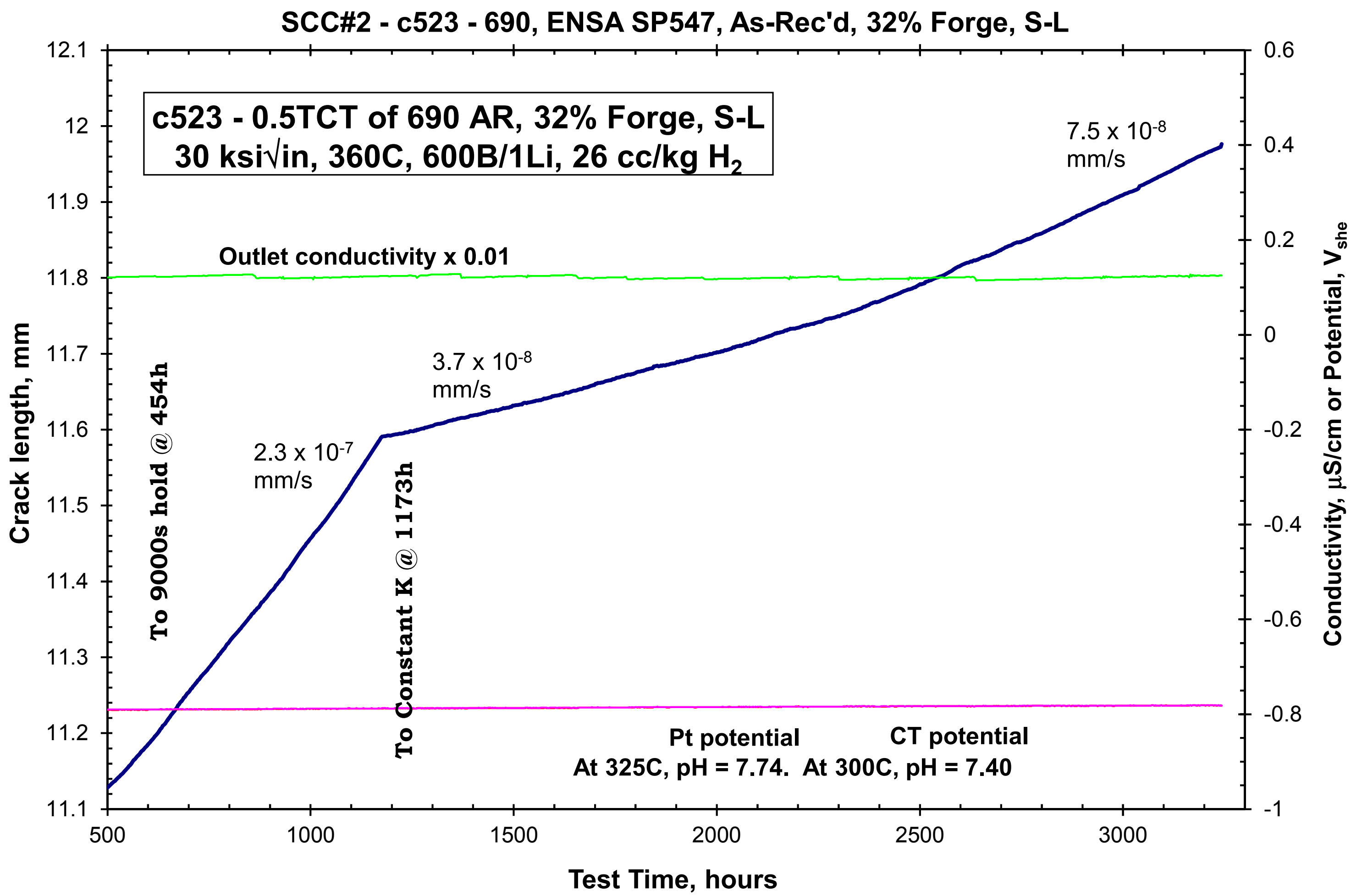
22% 1D-Deform (Rolled) 690 Plate, SP547 – S-L



Medium growth rates, very stable SCC response

Specimen c523

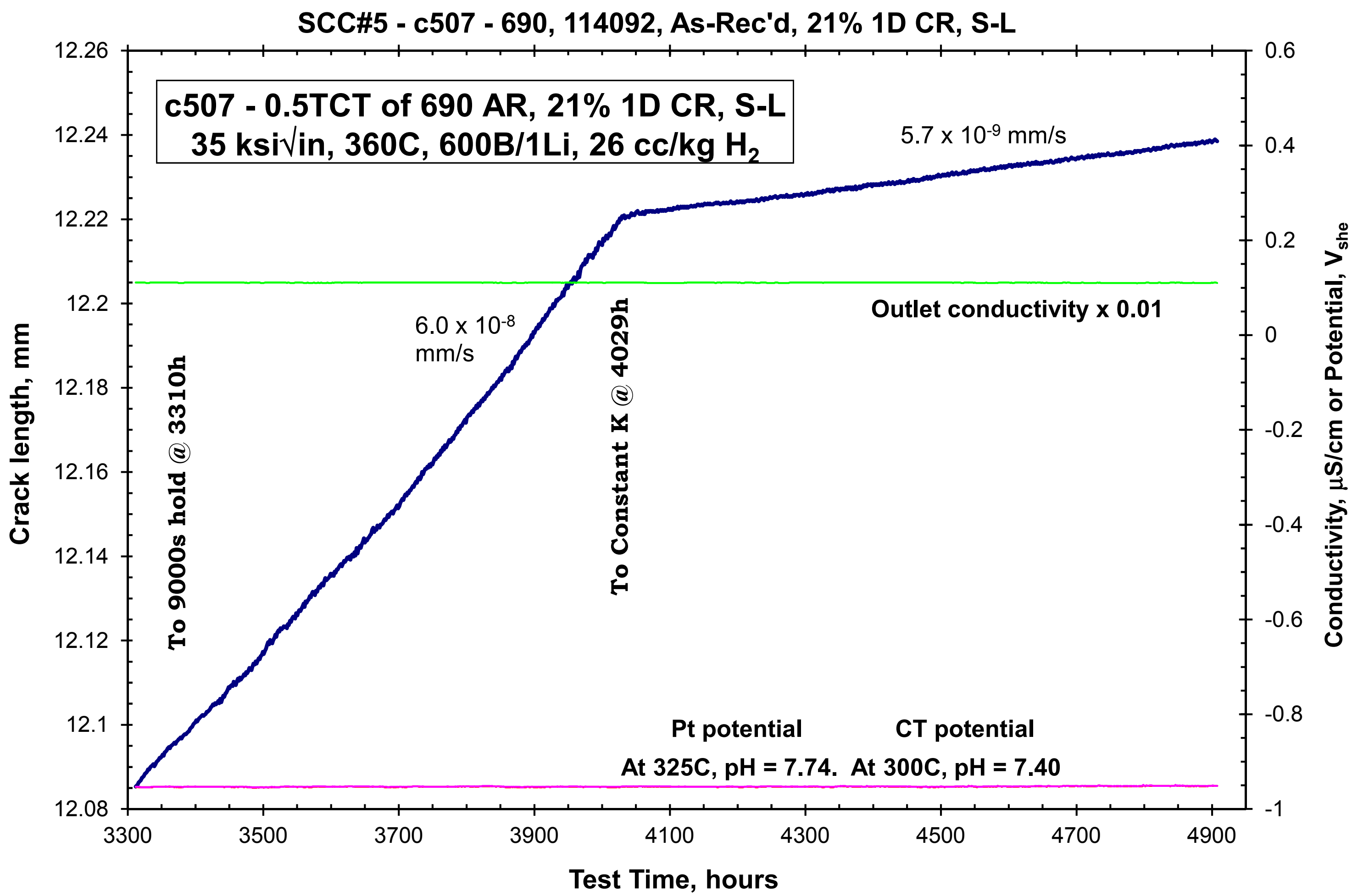
32% 2D-Deform (Forged) 690 Plate, SP547 – S-L



High growth rates, very stable SCC response. Note evolution in CGR vs. time.

Specimen c507

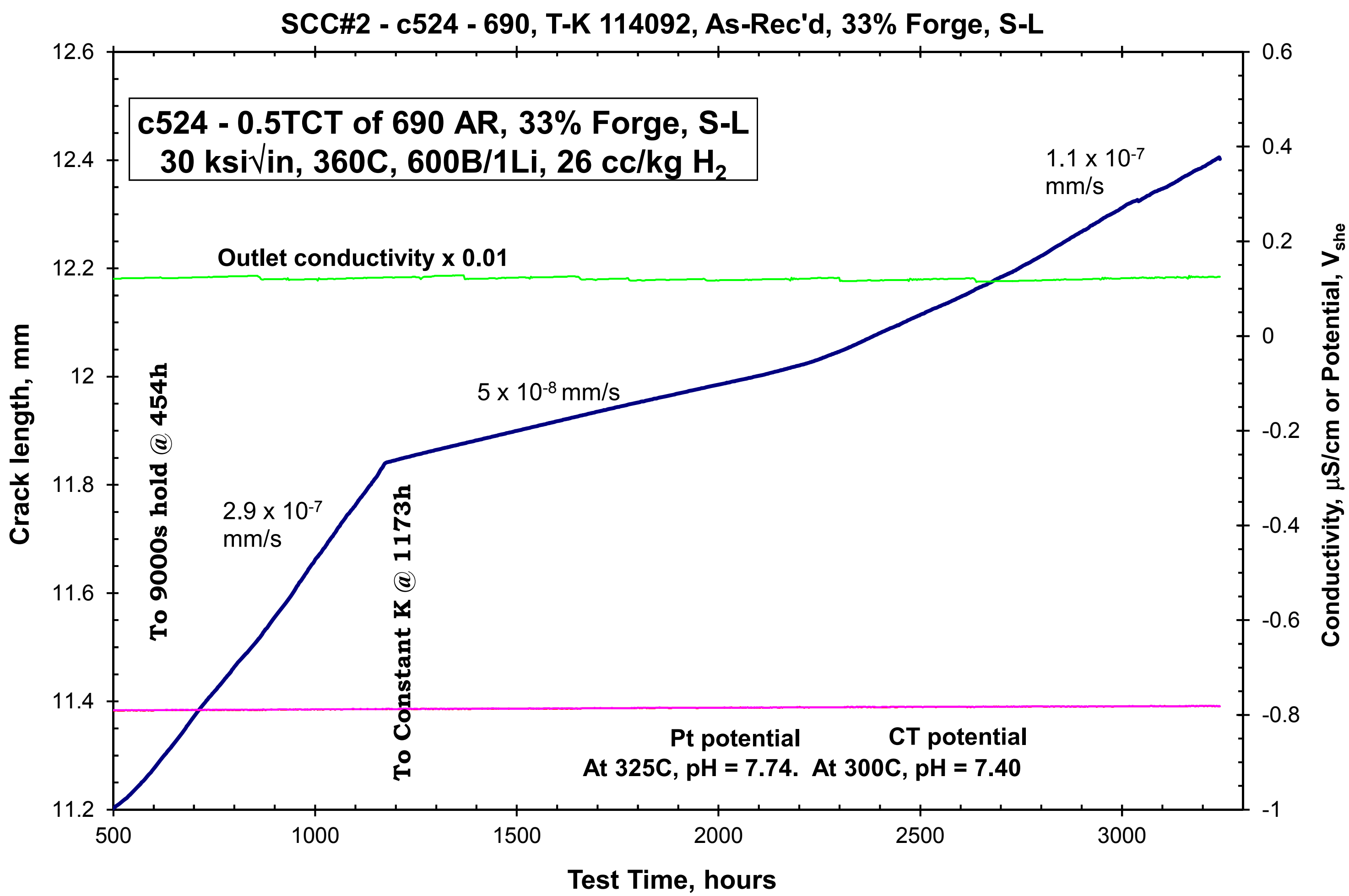
21% 1D-Deform (Rolled) 690 Plate, 114092 – S-L



Medium growth rates, very stable SCC response

Specimen c524

33% 2D-Deform (Forged) 690 Plate, 114092 – S-L

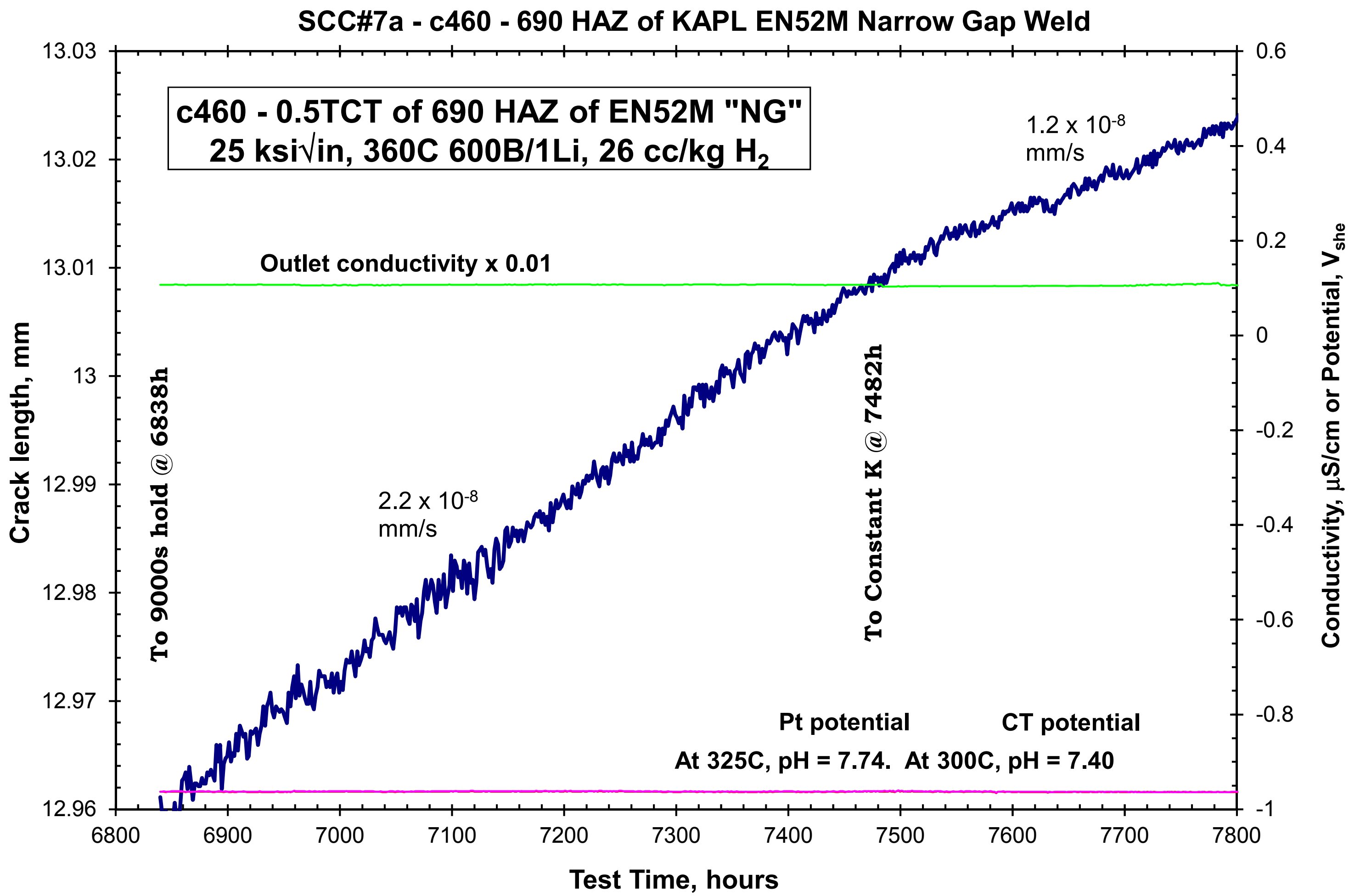


High growth rates, very stable SCC response. Note evolution in CGR vs. time.

HAZ

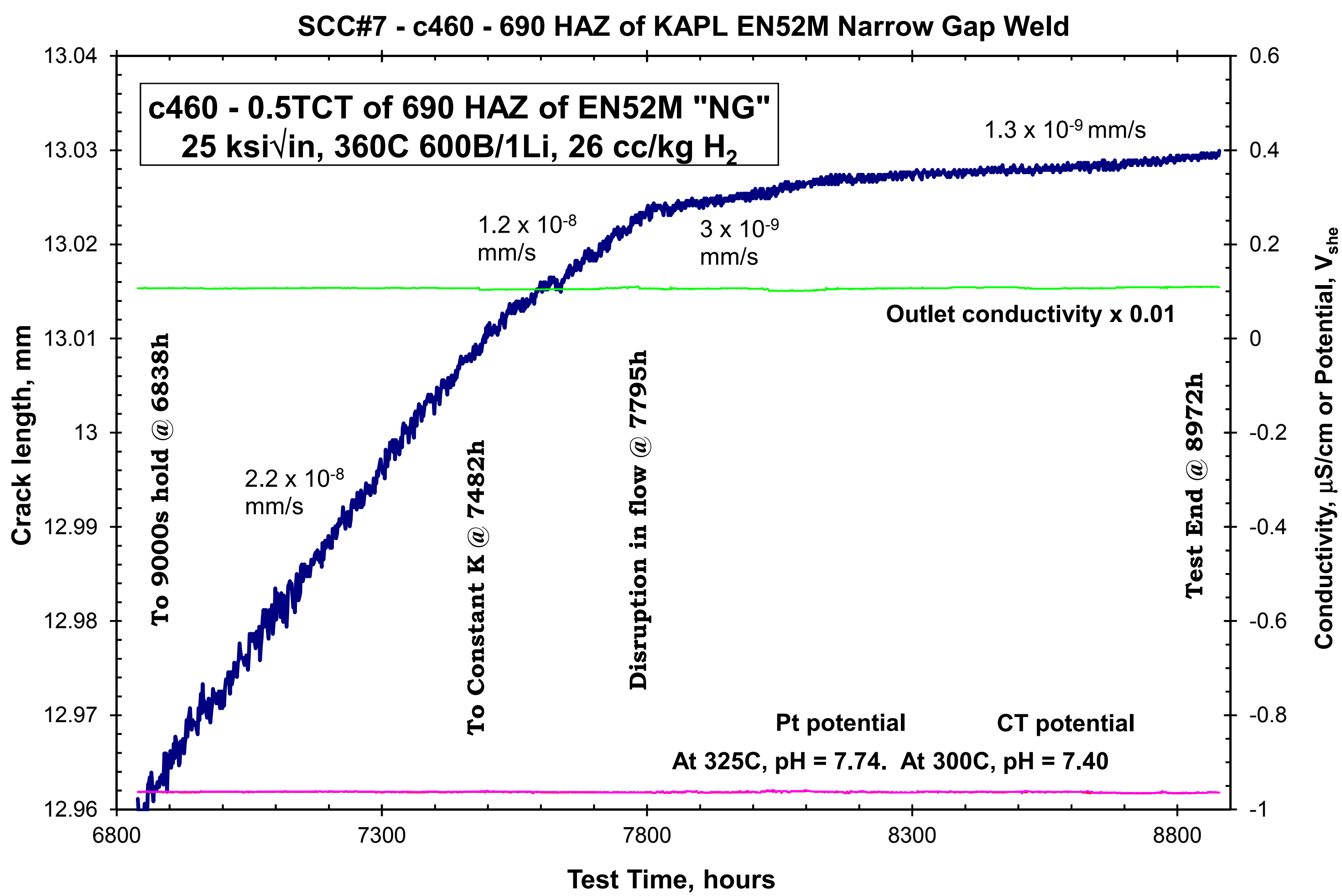
One of four HAZs showed medium growth rates

HAZ of KAPL EN52M Narrow Gap Weld



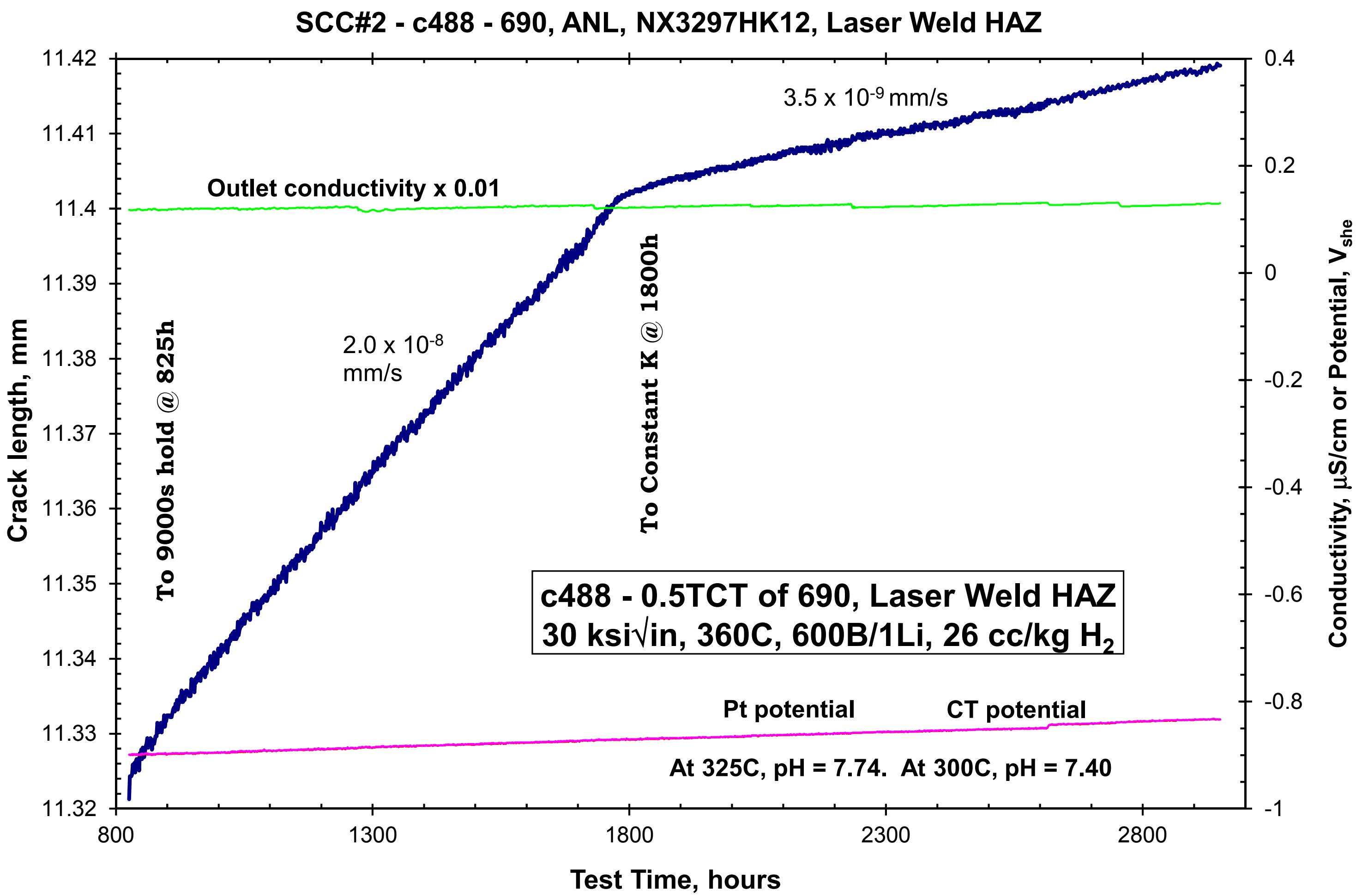
Moderate growth rates, but later disrupted by flow

HAZ of KAPL EN52M Narrow Gap Weld



Moderate growth rates, but later disrupted by flow

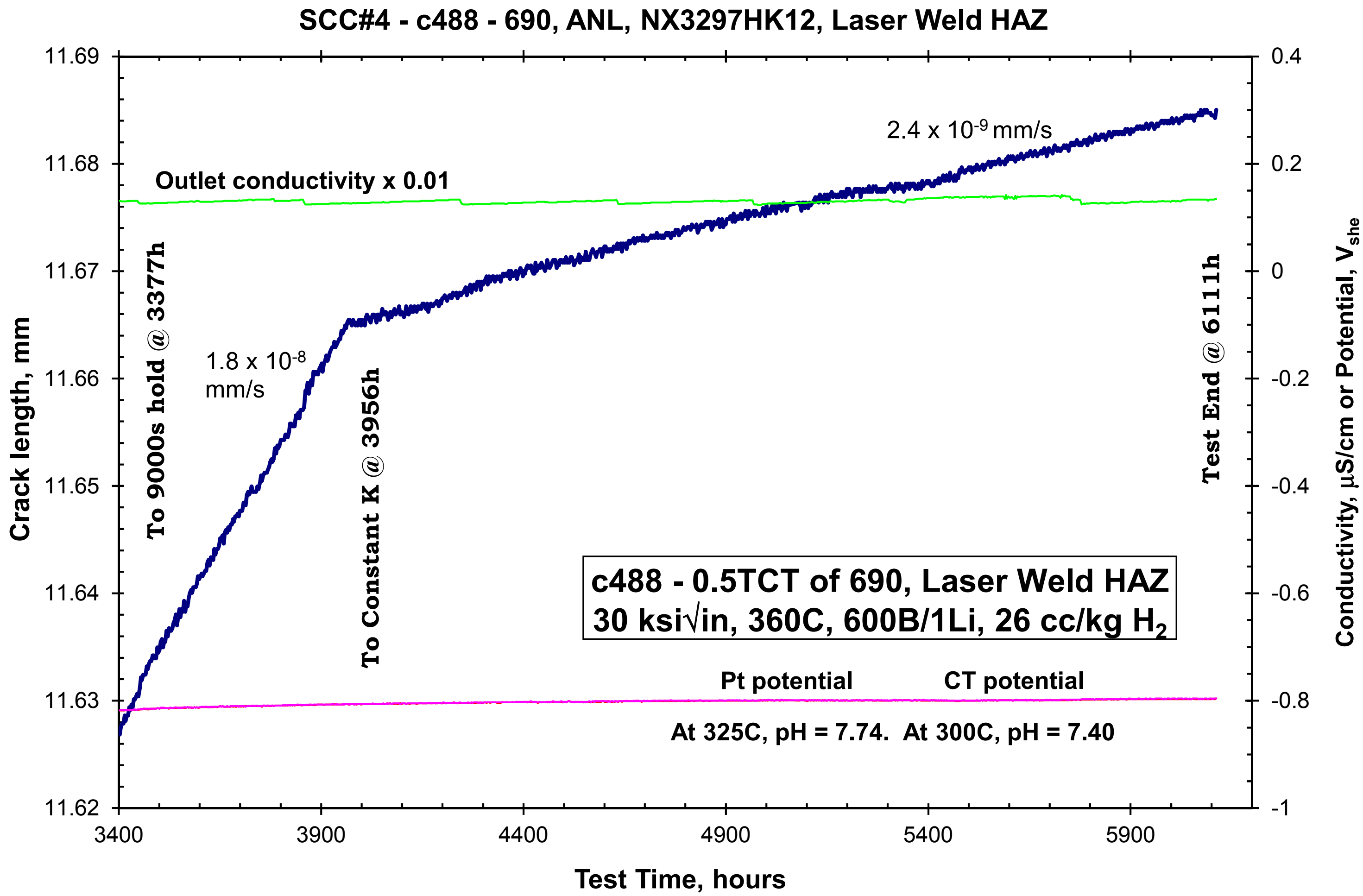
HAZ of ANL Laser Weld



Low growth rates, but consistent with some cold worked 690

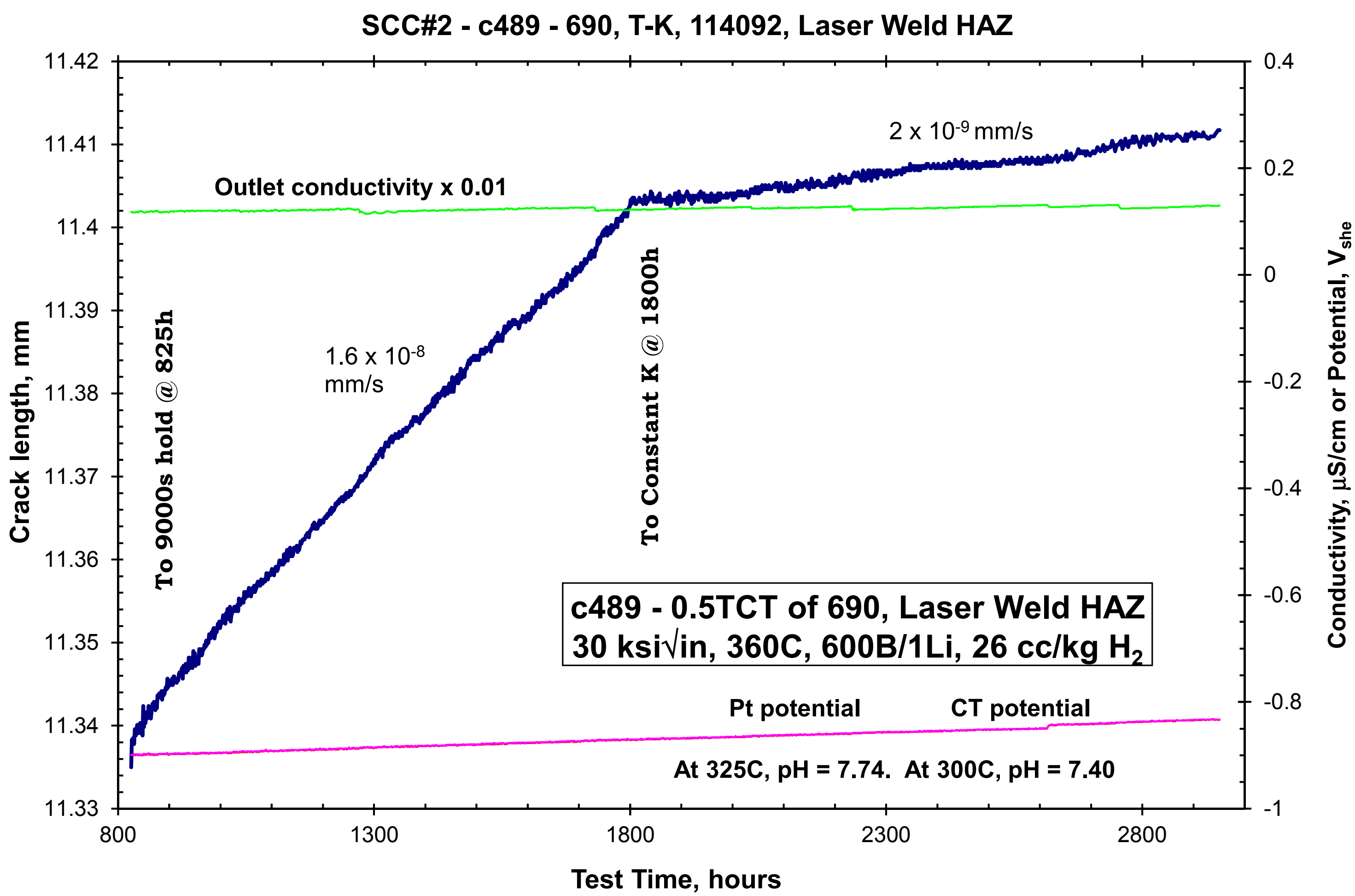
Specimen c488

HAZ of KAPL EN52M Narrow Gap Weld



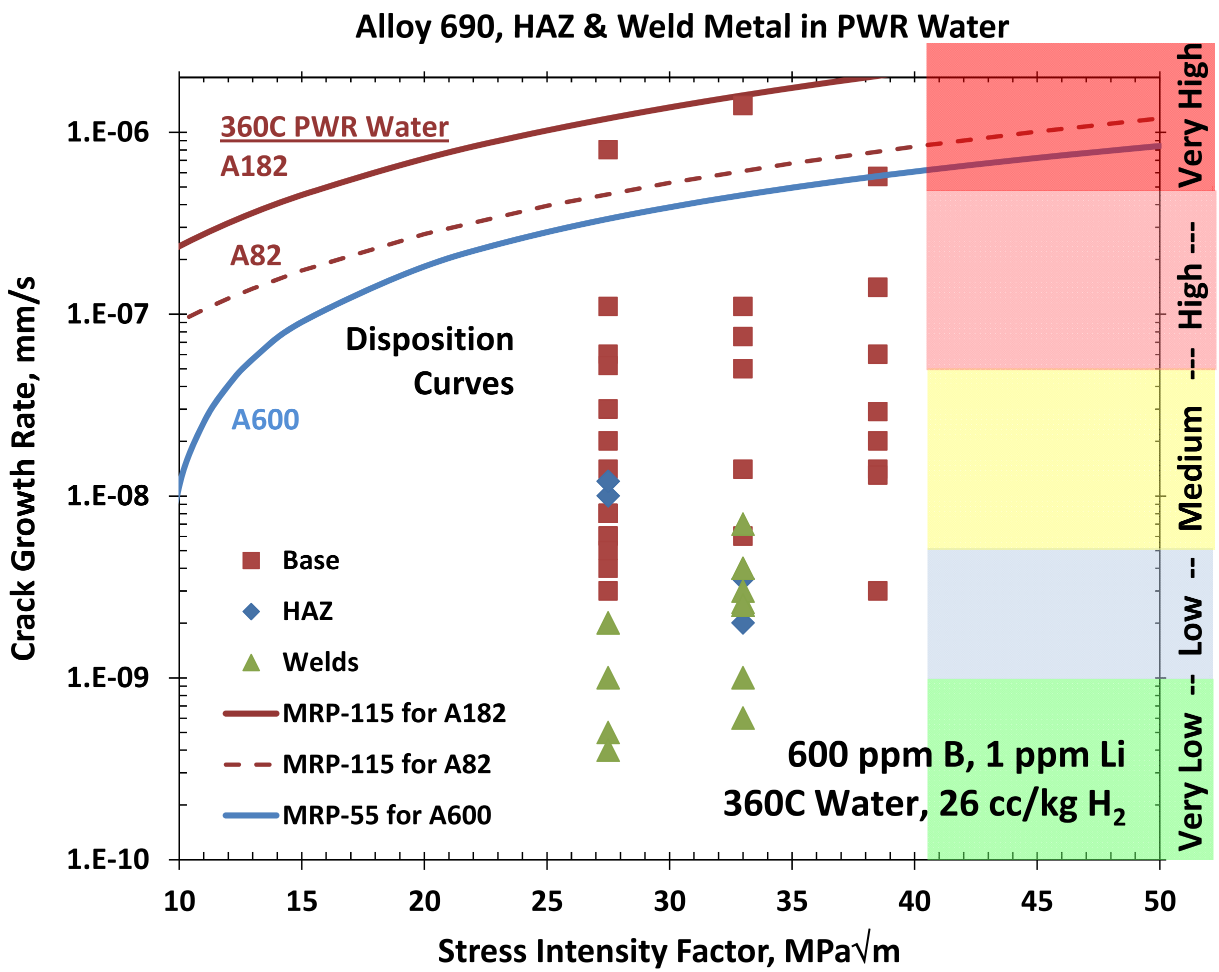
Low growth rates, but consistent with some cold worked 690

HAZ of KAPL EN52M Narrow Gap Weld



Low growth rates, but consistent with some cold worked 690

Summary of GE Data on High Cr Alloys



Alloy 690 is clearly not immune, and can grow at moderate or high rates in PWR primary water under certain conditions.

Conclusions

- *Very homogeneous CRDM materials can exhibit medium growth rates at 20% CW, and high rates at 30% CW.*
- *High growth rates in 2D-forged as in 1D-rolled materials in the S-L orientation.*
- *One plate (ANL) consistently shows high or very high growth rates – the only one to grow in the mid-10^{-7} to low 10^{-6} mm/s (apart from three other plates tested earlier by Paraventi).*
- *Growth rates in base metal often evolve over >1000 hours.*
- *All weld metals continue to exhibit low growth rates, and tend to decay – not accelerate – with time.*
- *Good CGR agreement with other labs when materials have been tested in common.*

Future Emphasis Alloy 690

1. Examine forging and tensile strained Alloy 690.
2. Examine cold work levels in the 10 – 20% range.
3. Examine wider range of CRDM materials, e.g., Sumitomo.
4. Examine orientation effects of microstructure vs CW vs SCC.
5. Examine “carbide modification” (sol’n annealing) effects.
6. Examine more “HAZ” and simulated “HAZ” microstructures. Consider effects of weld repairs and wash passes.
7. Examine SCC along the interface of dissimilar metal welds.

SCC Initiation Scoping Tests Using Blunt Notch CT Specimens of Alloy 690

Peter Andresen

GE Global Research

May 2011

Alloy 690 Crack Initiation

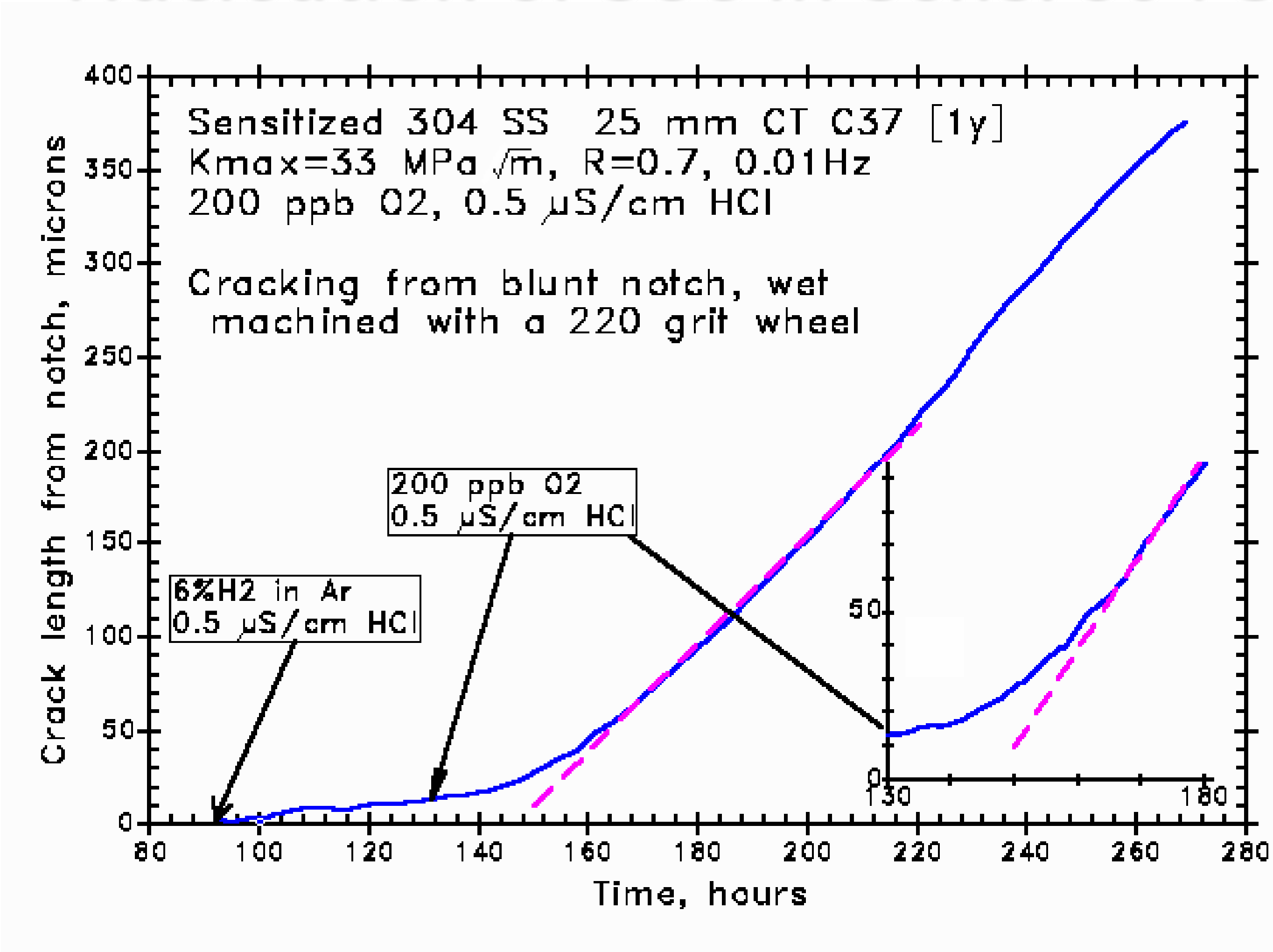
Initiation ***and*** ***Growth*** ***are both involved in emergence of detectable cracks in PWRs.***

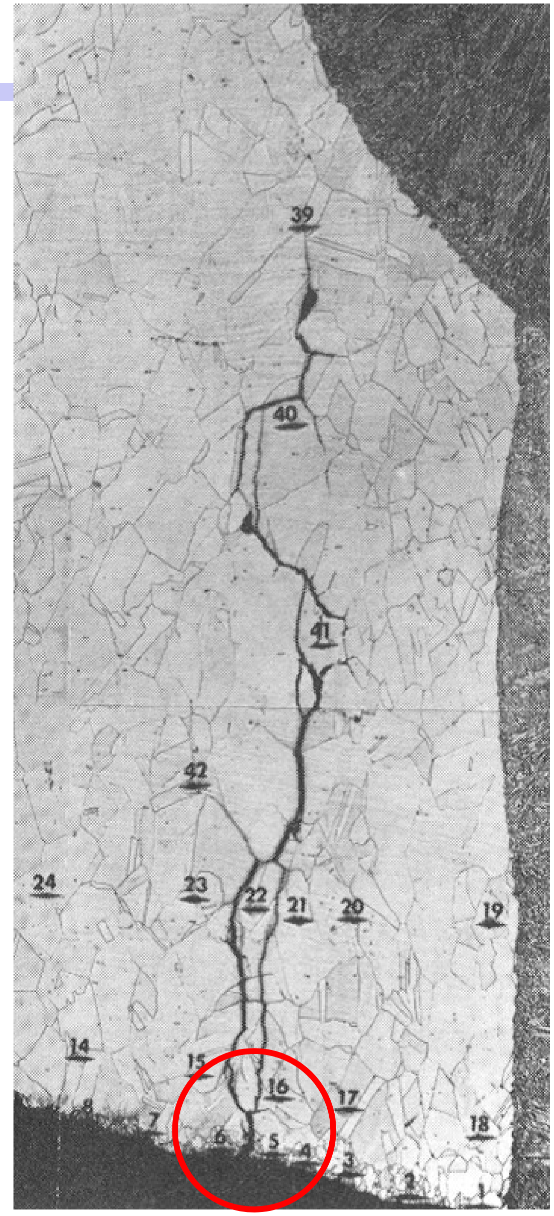
There are extensive studies on crack growth in Alloy 690, but little work on initiation apart from in steam generator tubing.

The objective of this scoping or proof-of-concept study is to use
blunt notch CT specimens of a heat of Alloy 690 that has exhibited high crack growth rates to determine whether initiation can be detected using a testing protocol shown effective for nickel weld metals.

4 – 6 specimens; 2 sets of tests each ~3 – 4 months; ~$60K

Nucleation of SCC in Sens. 304 SS





Blunt notch test permits high resolution observation of incipient crack initiation, coalescence and growth

Objective and Outline

Short crack SCC response using blunt notch CT specimens to characterize the transition from short to long crack response

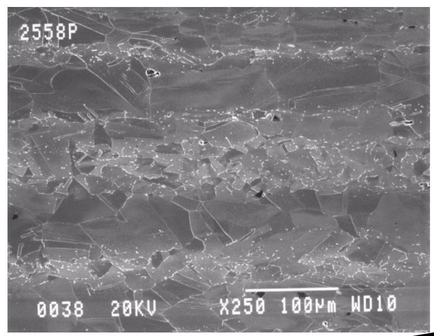
Experimental procedures use:

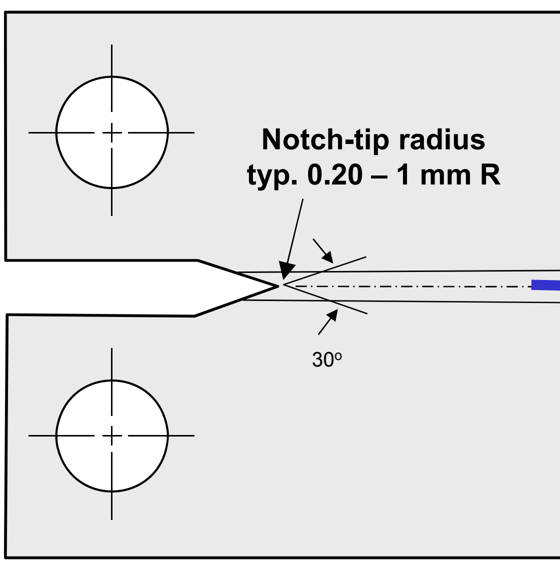
1. Carefully prepared, blunt notch CT specimens (e.g., diamond wheel)
2. Representative PWR primary water:
   340 °C, Blunt Notch, 1000 ppm B, 2 ppm Li, 15.2 cc/kg H_2
3. Two or three Alloy 690 specimens in series loading
4. Susceptible Alloy 690 heat with cold work
5. High resolution DC potential drop measurements + resistivity corr.
6. Long-time equilibration to form passive film & min. resistivity shift
7. Constant K, changing to rising K_{max} ramp
8. ~3 – 4 months test time for each of two runs; total ~$60K
9. SEM characterization of notch and fracture surface

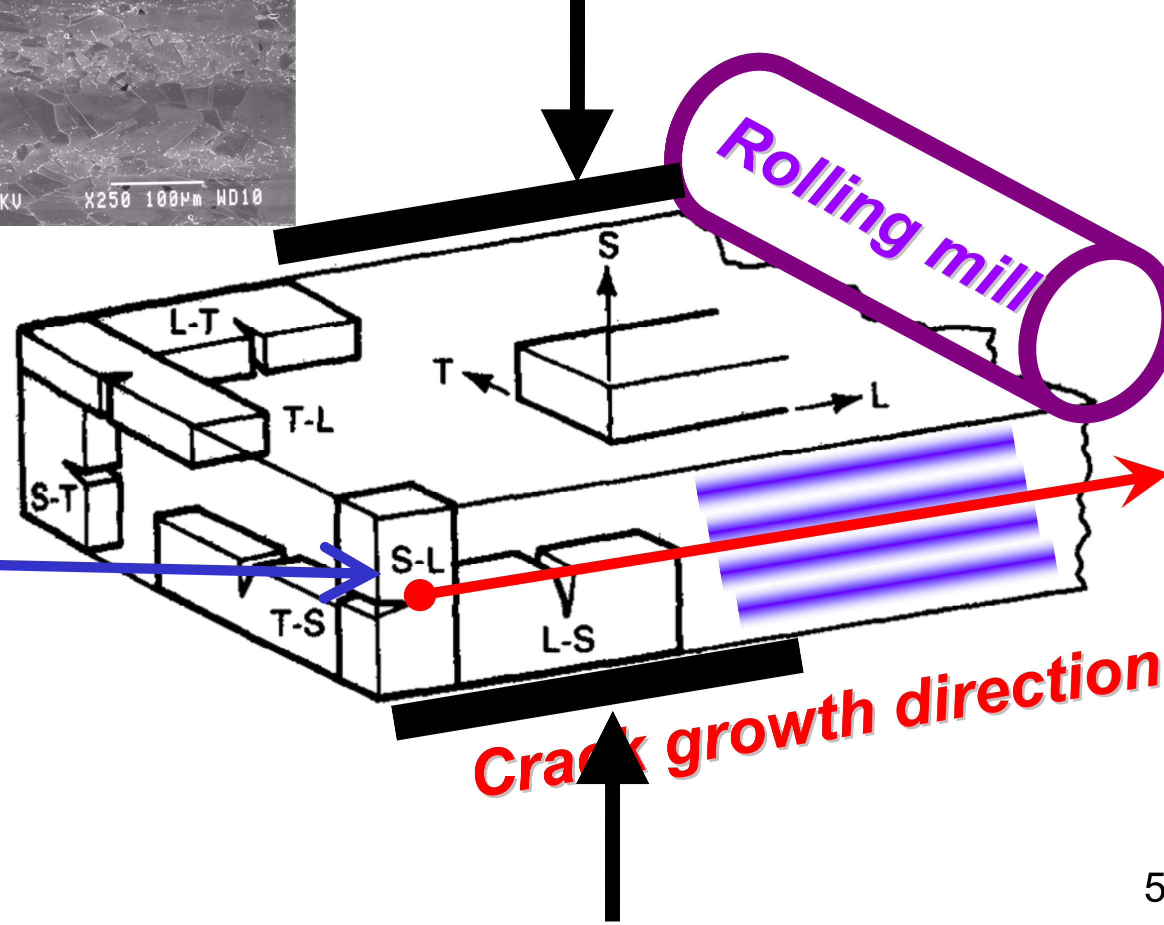
Alloy 690 Orientation

Position blunt notch CT in S-L orientation of susceptible Alloy 690 plate material; S-L is the most susceptible orientation.

Banded microstructure in NX3297HK12 plate. Forge to 15 – 30% CW

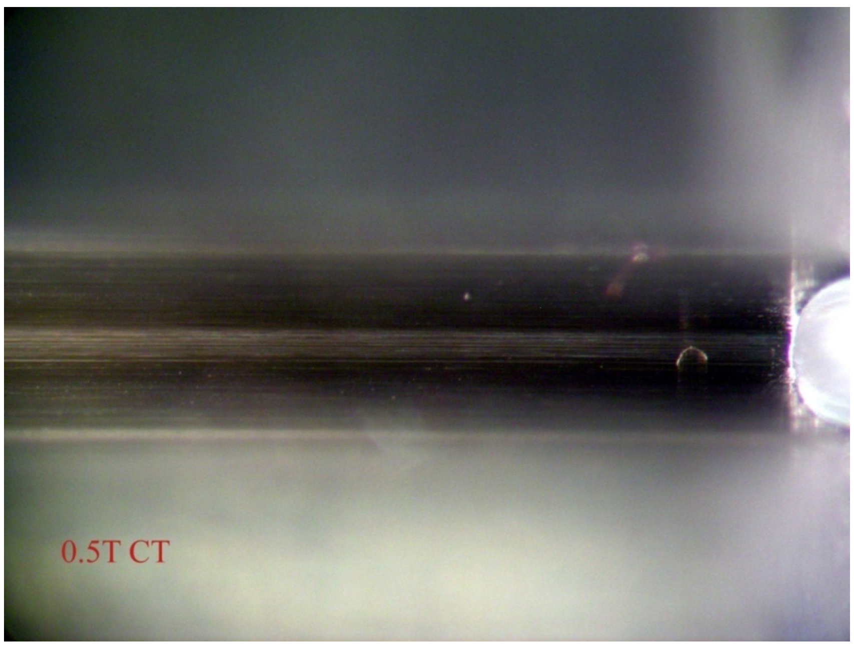


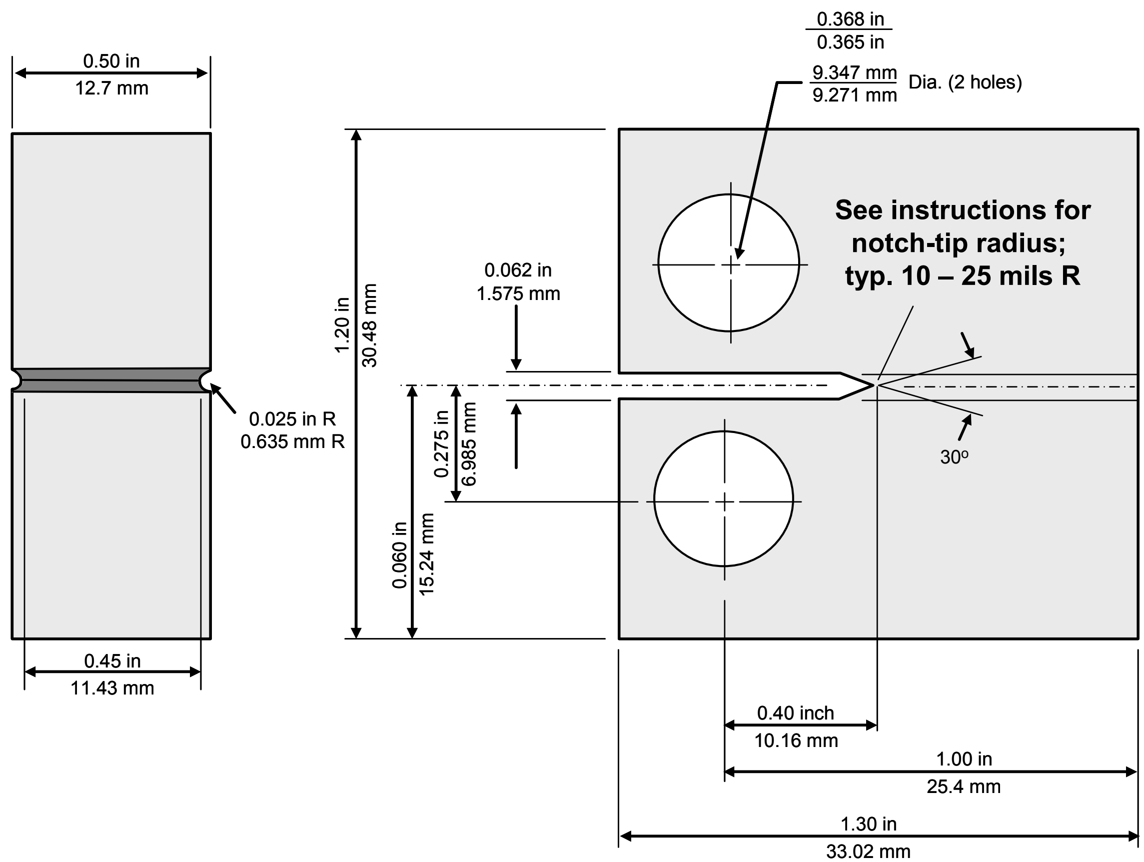




Blunt Notch Geometry

Uses 100 grit diamond wheel; ~0.8 mm radius notch gives moderate sample of microstructure for crack initiation

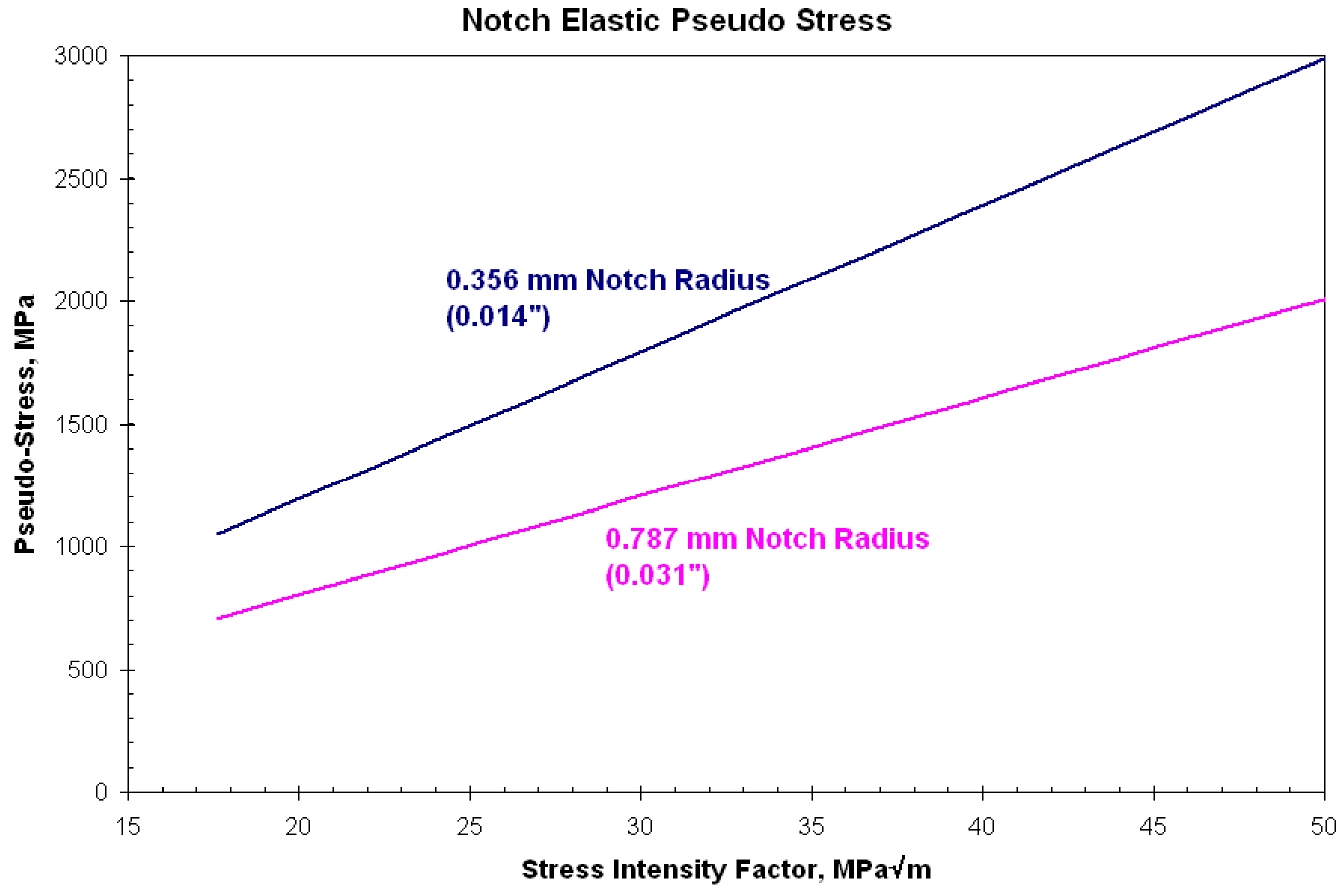


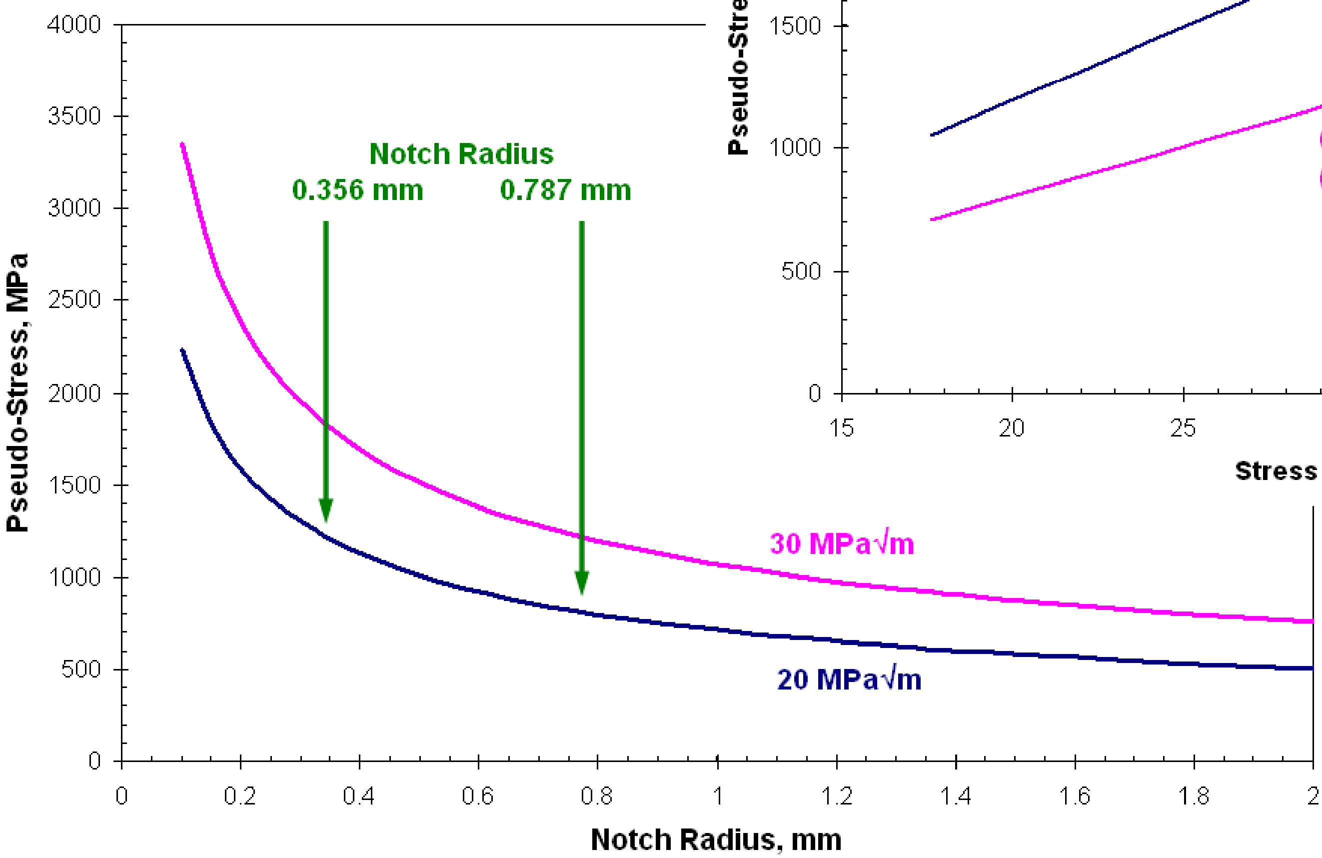


Position blunt notch in banded microstructure of ANL 690 plate

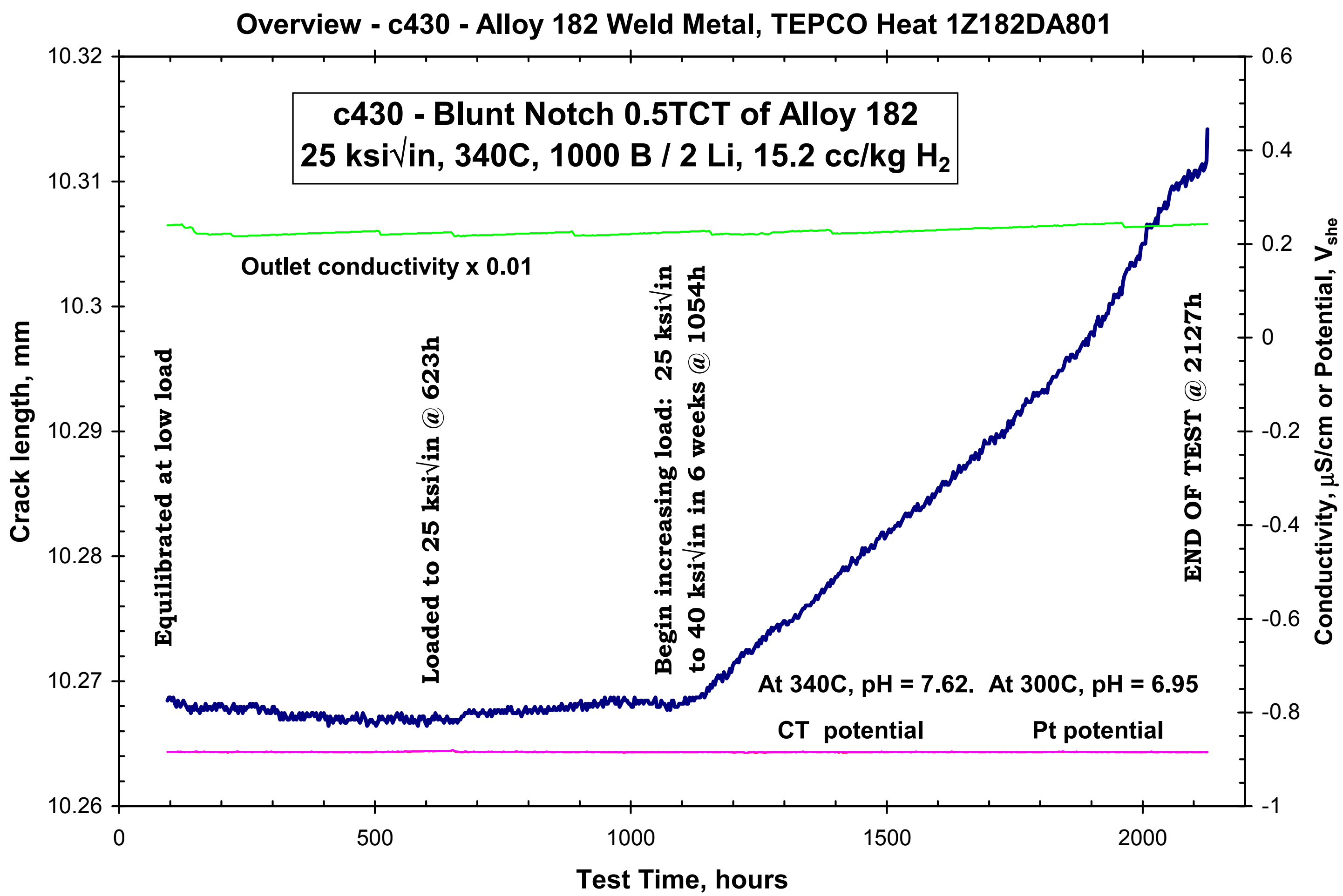
Blunt Notch Elastic Pseudo-Stress

$$\sigma_{notch} = \frac{2K}{\sqrt{\pi \rho}}$$



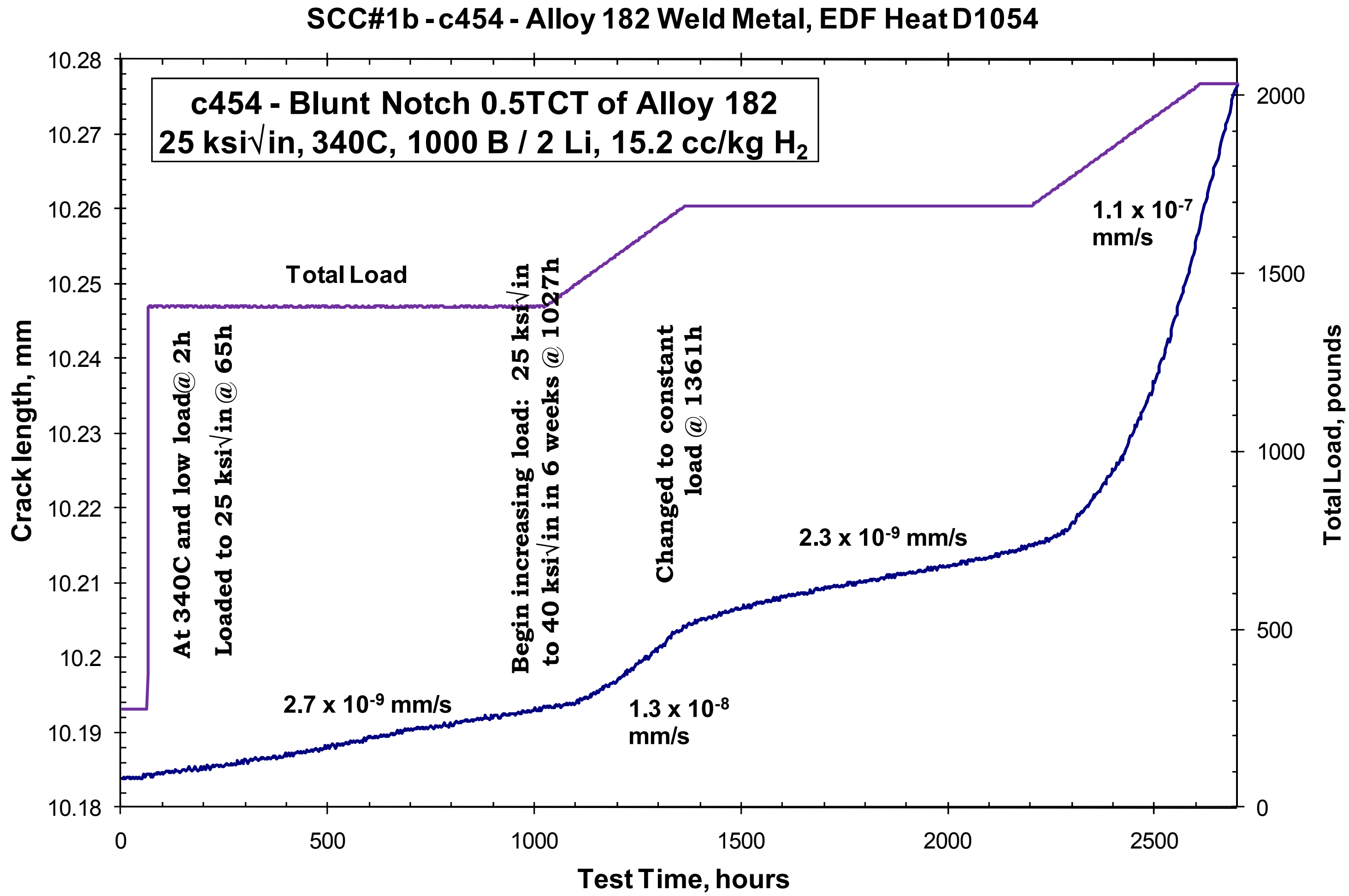


Example of Weld of Sensitivity of Technique



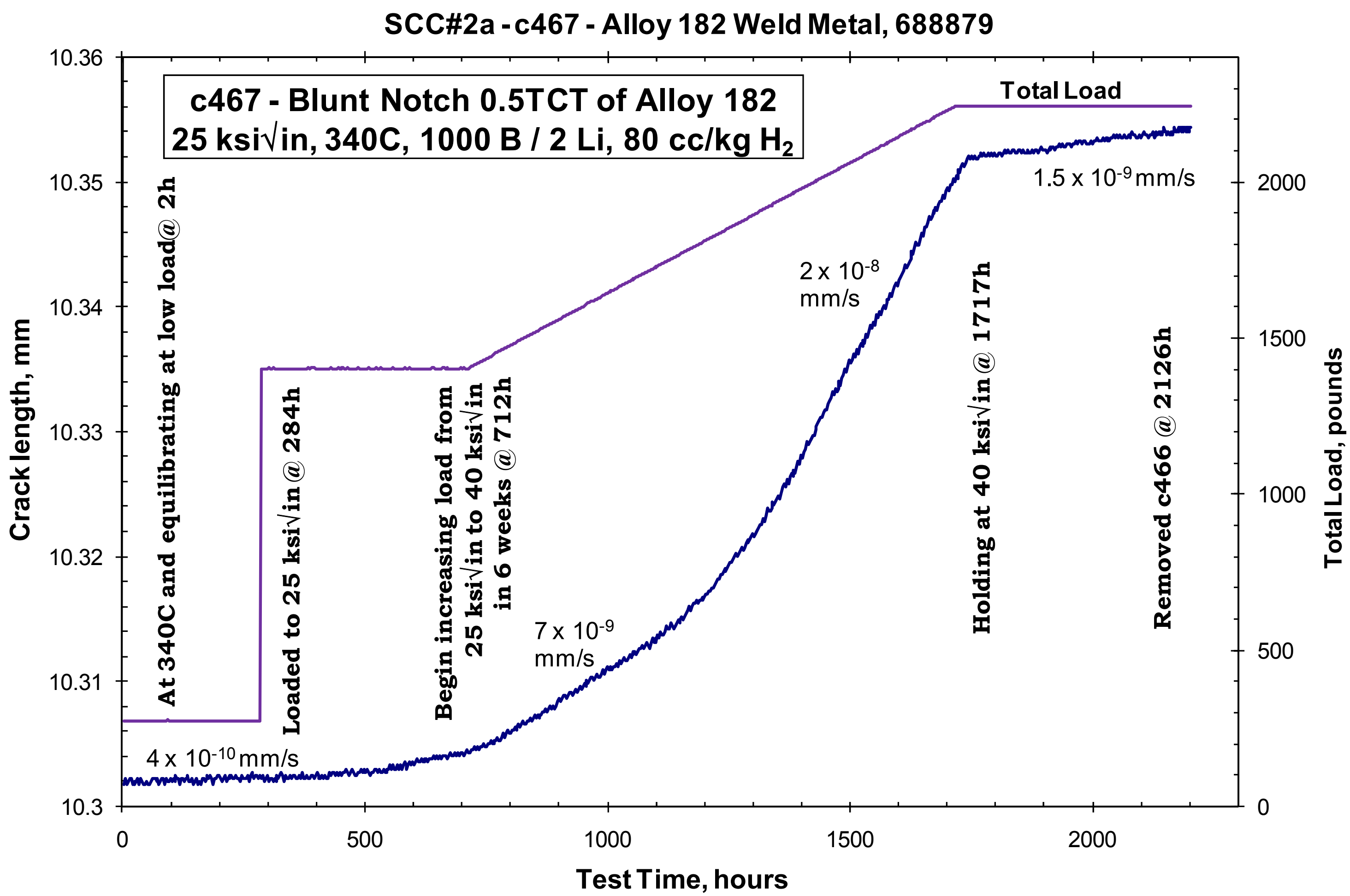
Crack nucleation and coalescence occurred in a short time period after rising K commences

Example of Weld of Sensitivity of Technique



Large effect of dynamic strain, not K per se

Example of Weld of Sensitivity of Technique



Progressive crack nucleation and coalescence