PWSCC Growth Rates of Alloy 690 and Its Weld Metals

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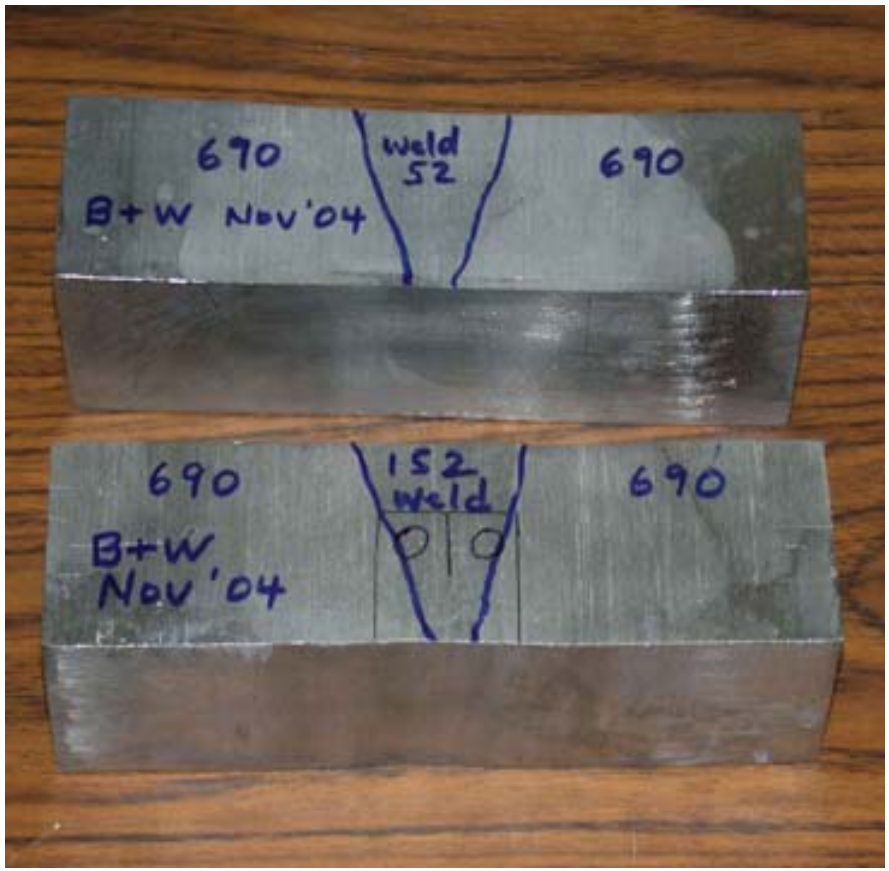
Alloy 690 CRDM & Alloys 52/152

CRDM of Alloy 690
(heat WN415, Duke)



Alloy 52 & 152 weld metal
(from B&W)

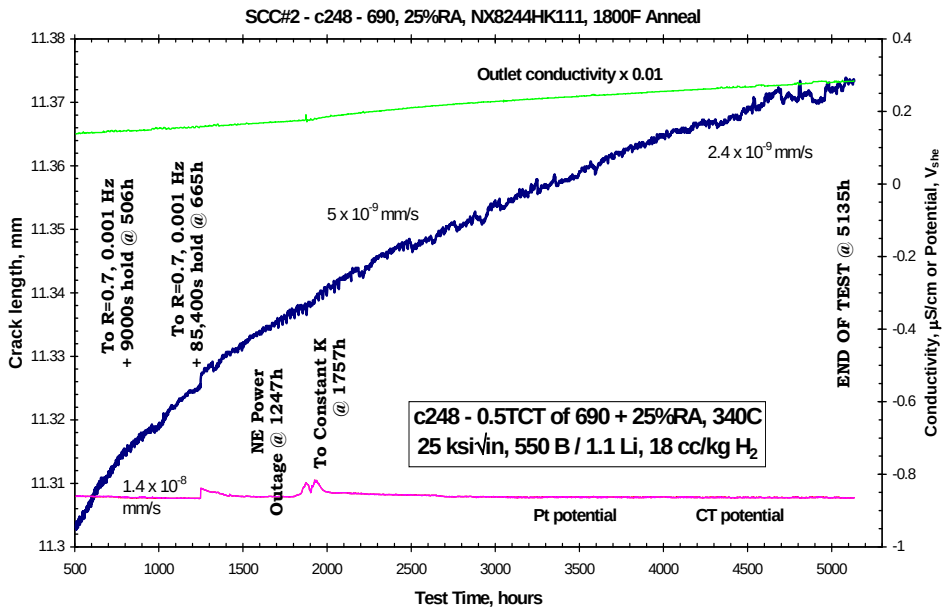
Testing Approach

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

- 690 cold worked by forging or 1-D rolling at 25 °C
  - 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 °C (290–340°C) PWR primary water
- testing at 25 – 35+ ksi $\sqrt{in}$, 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. $Cu/Cu_2O/ZrO_2$

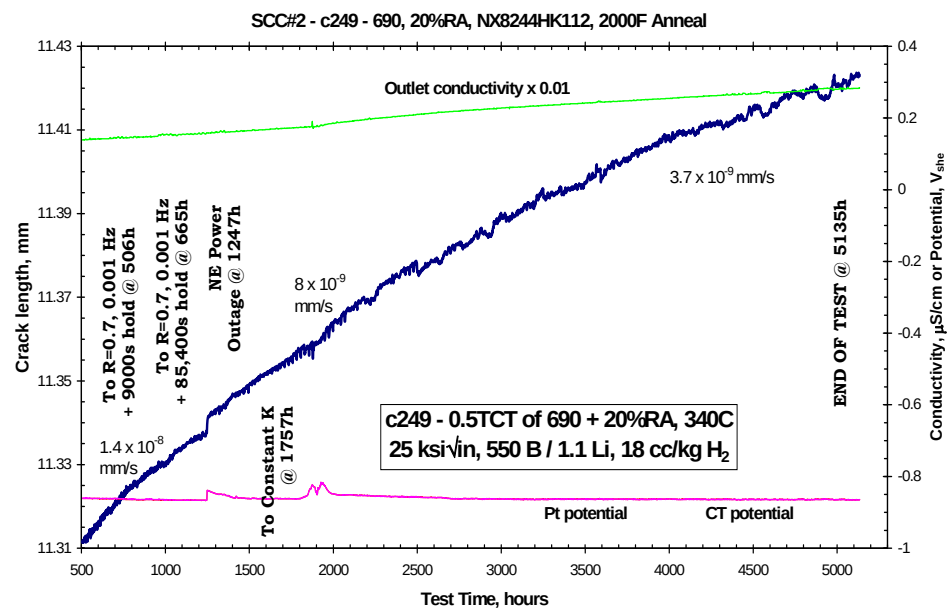
Specimens c248, c249

1800F Anneal



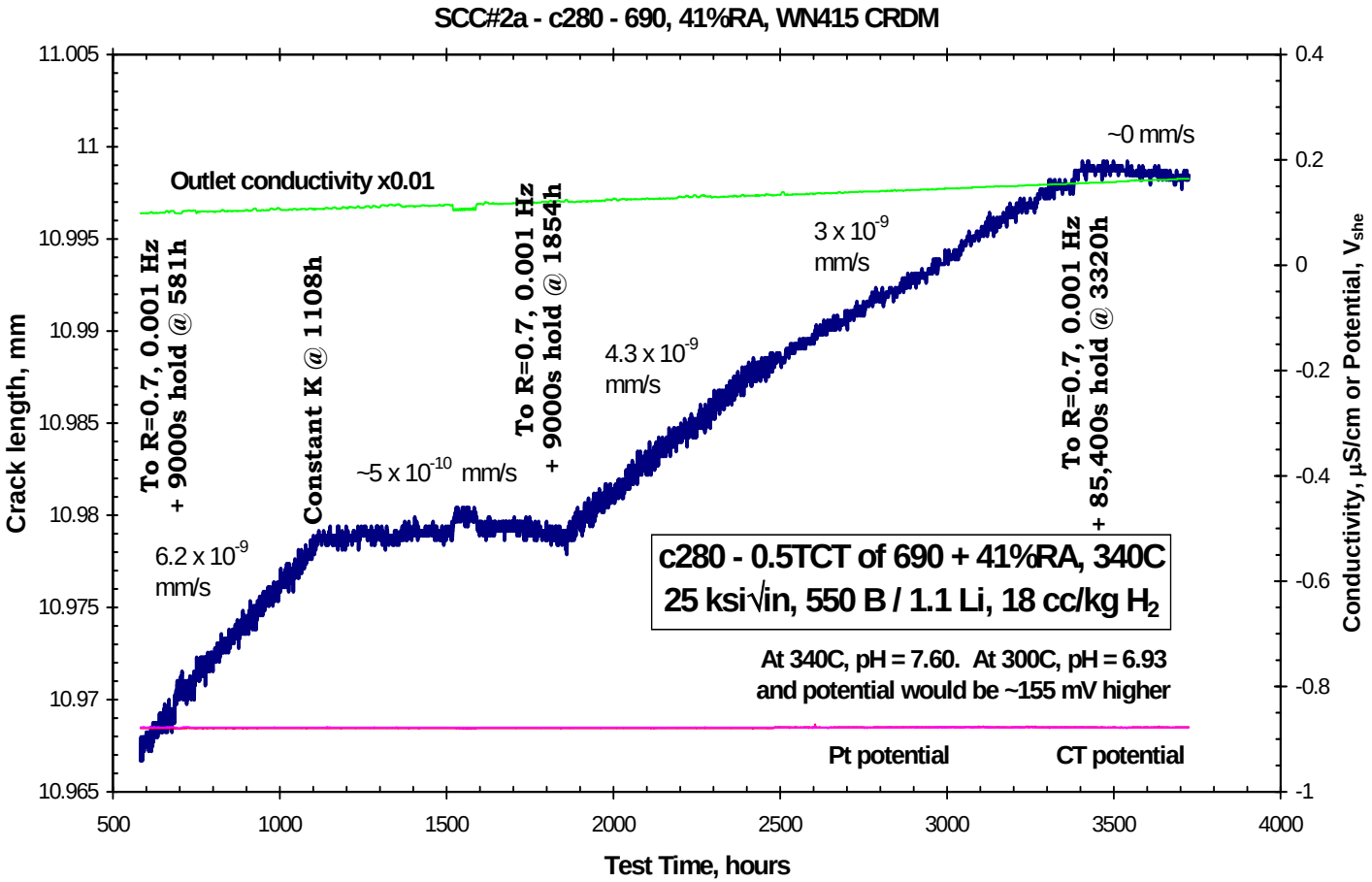
20% CW Alloy 690 L-T Orientation (good)

2000F Anneal



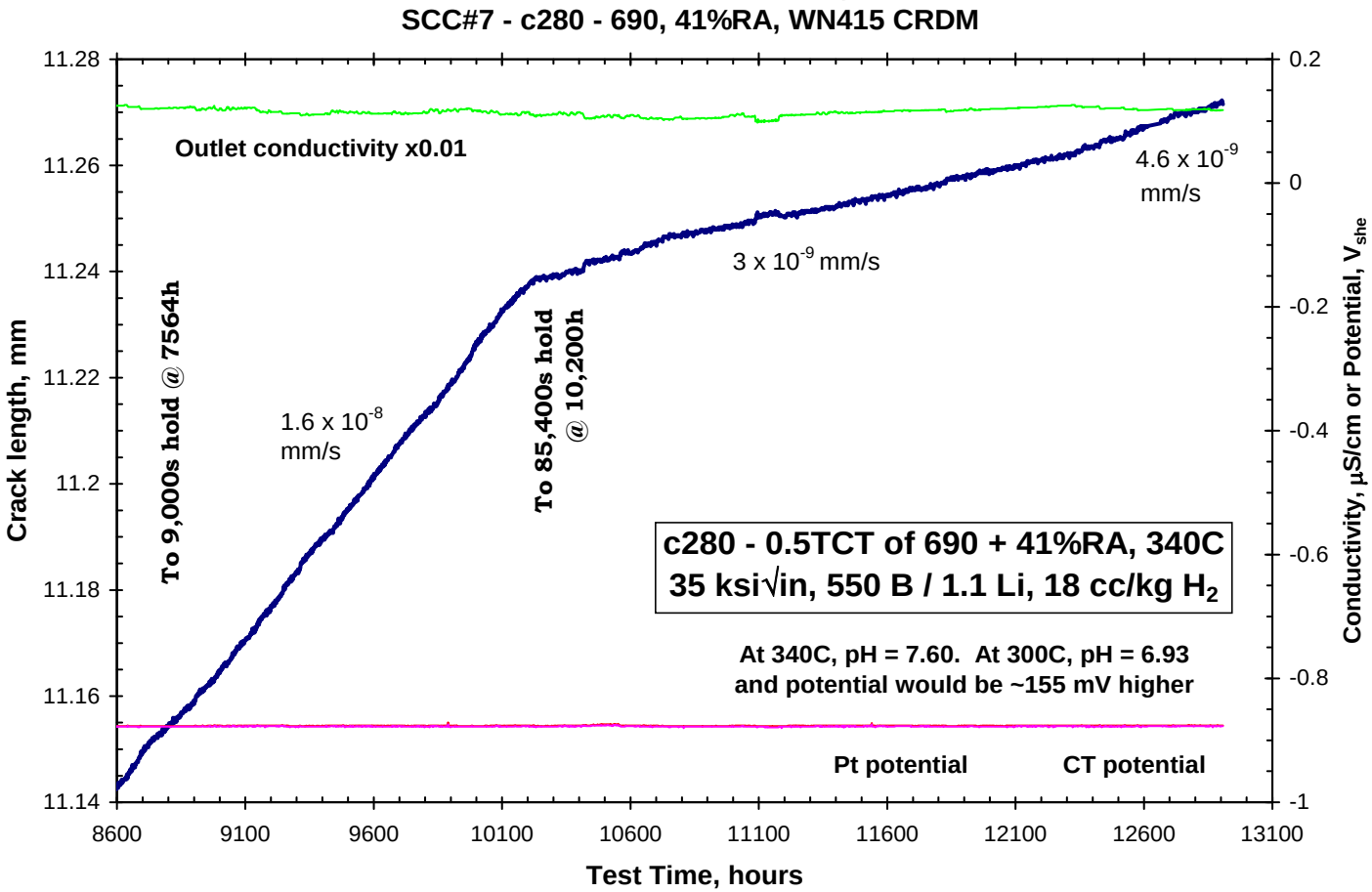
Well-behaved, low crack growth rate response during earlier proof-of-concept testing

41% Cold Work Alloy 690 CRDM



GE tests at Constant & Varying K (dK/da)
L-T Orientation (good)

41% Cold Work Alloy 690 CRDM



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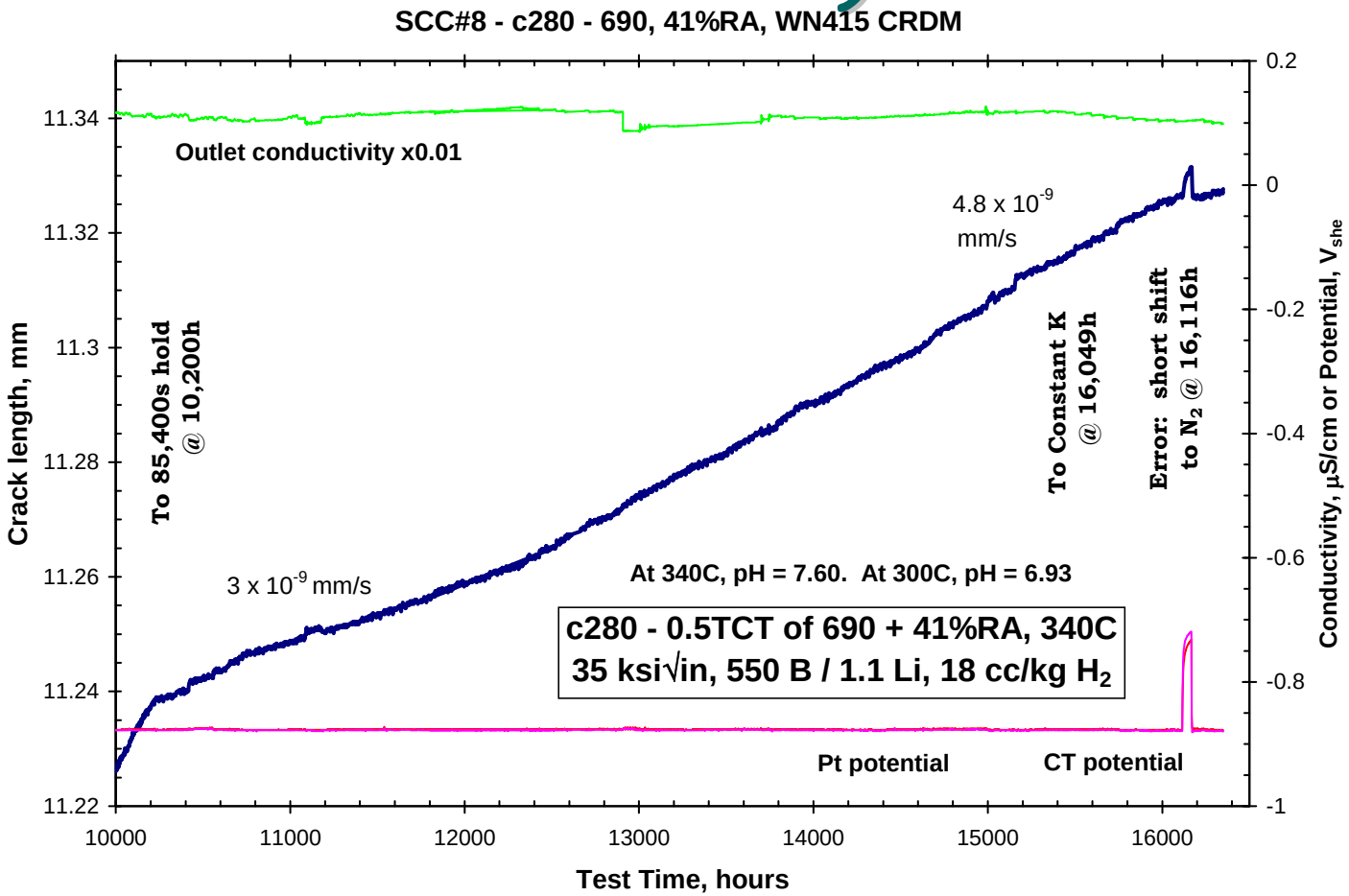

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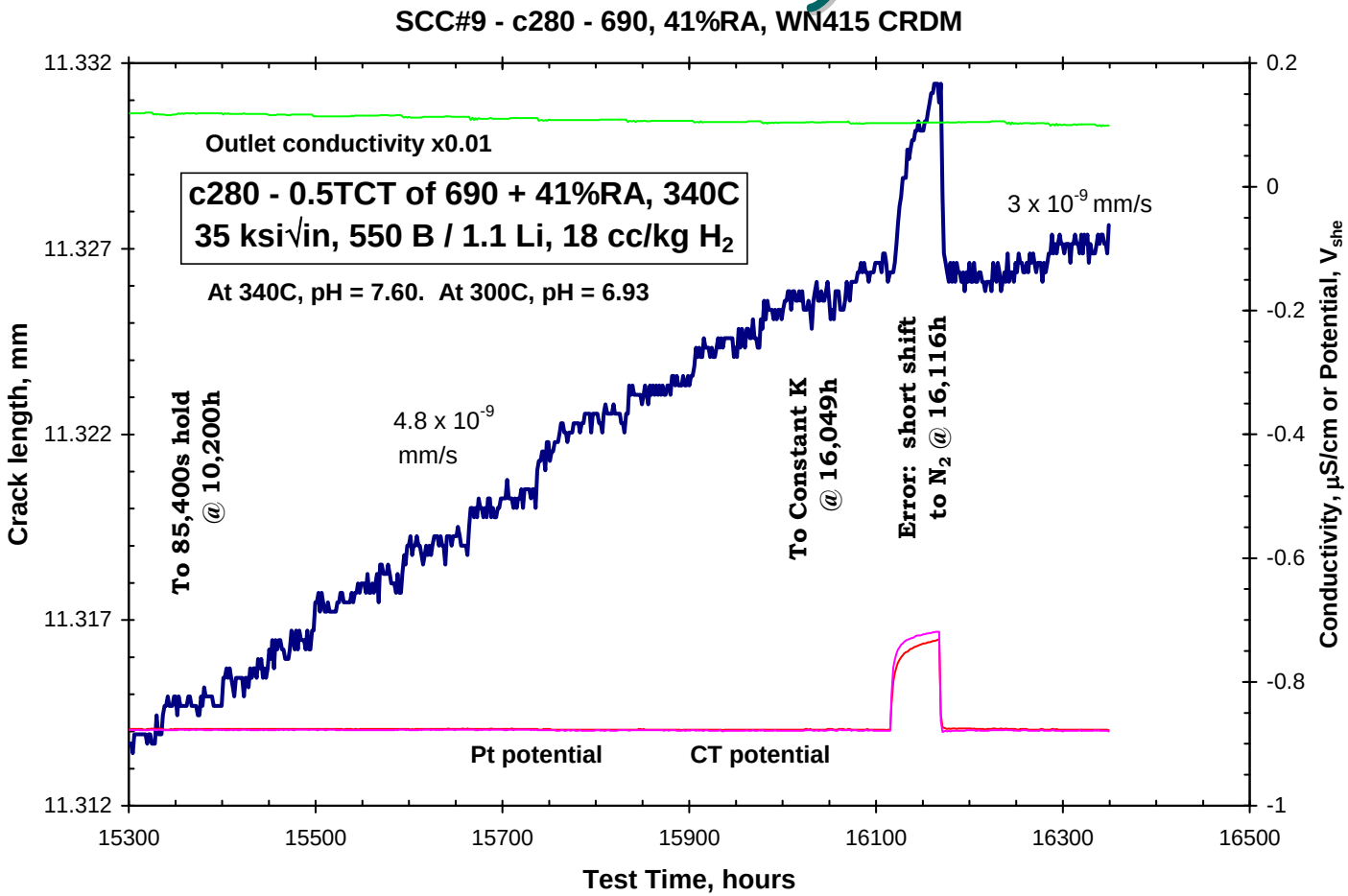
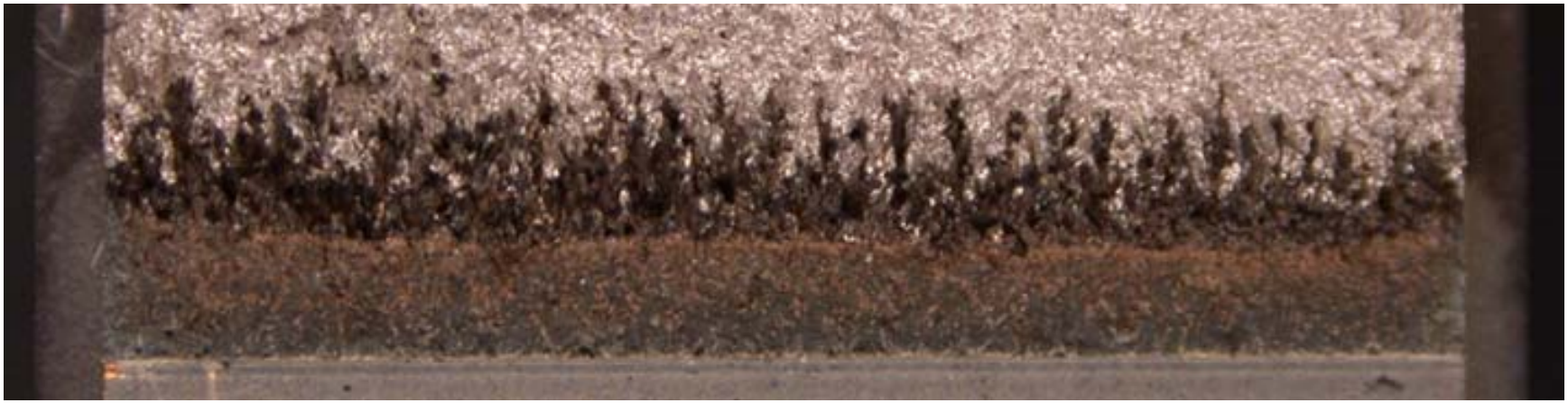
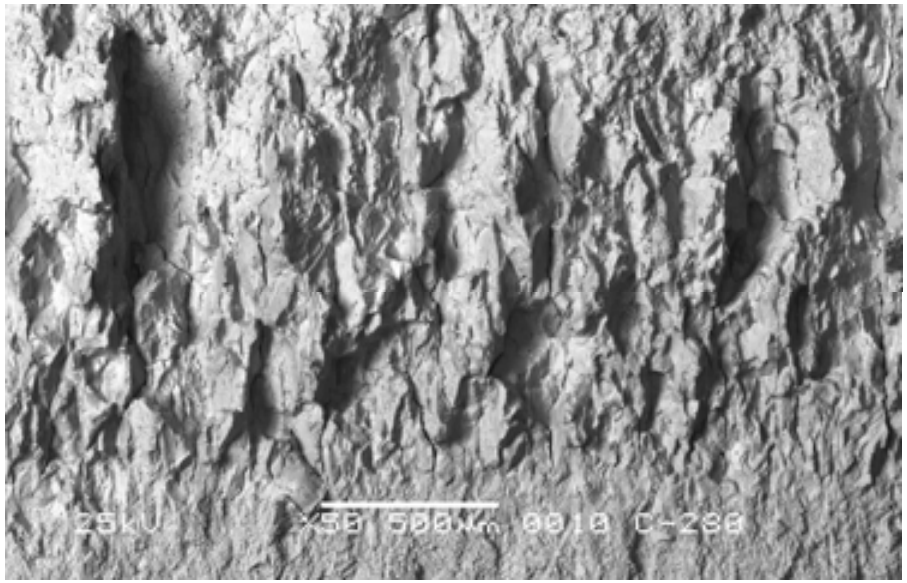


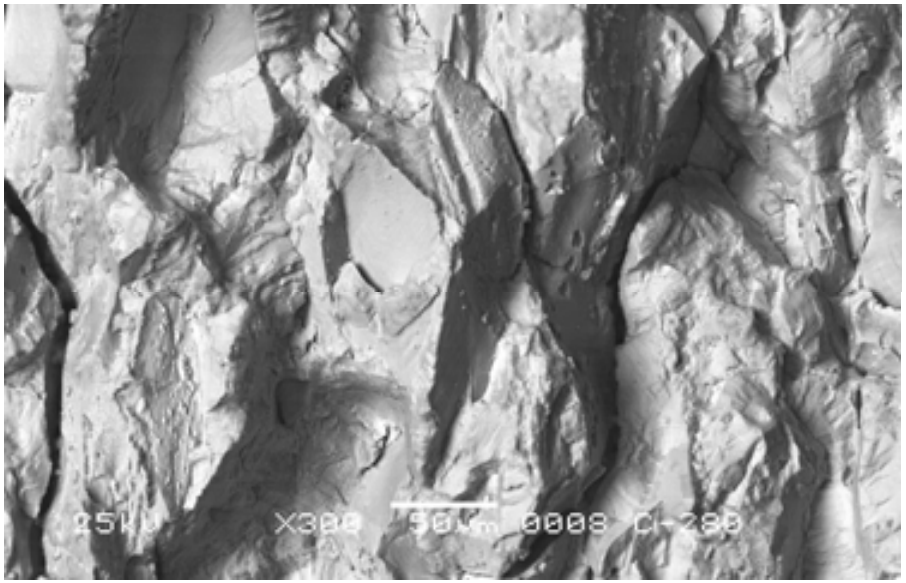
GE tests at Constant & Varying K (dK/da)
L-T Orientation (good)

Specimen c280

41% Cold Work Alloy 690 CRDM

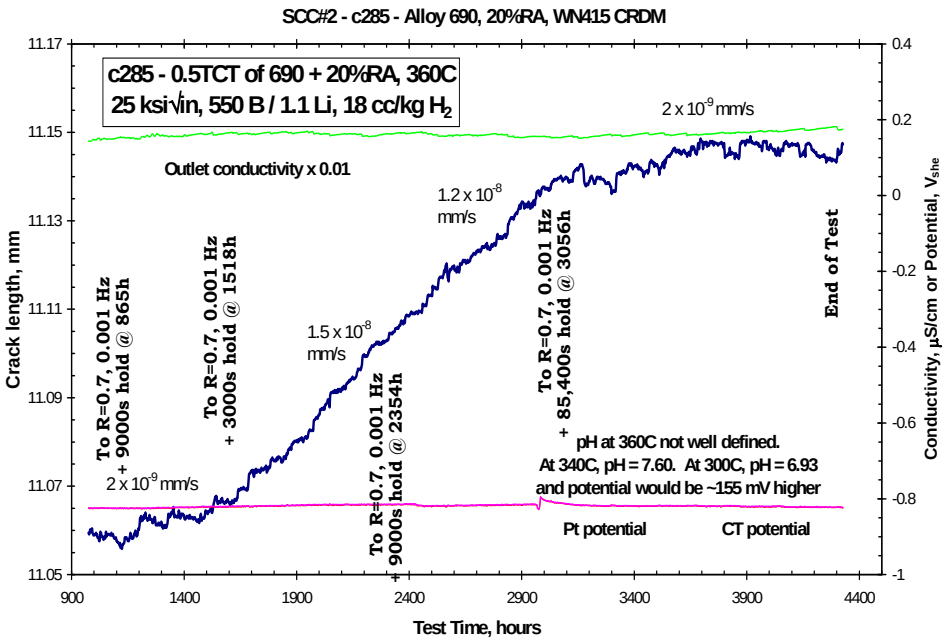


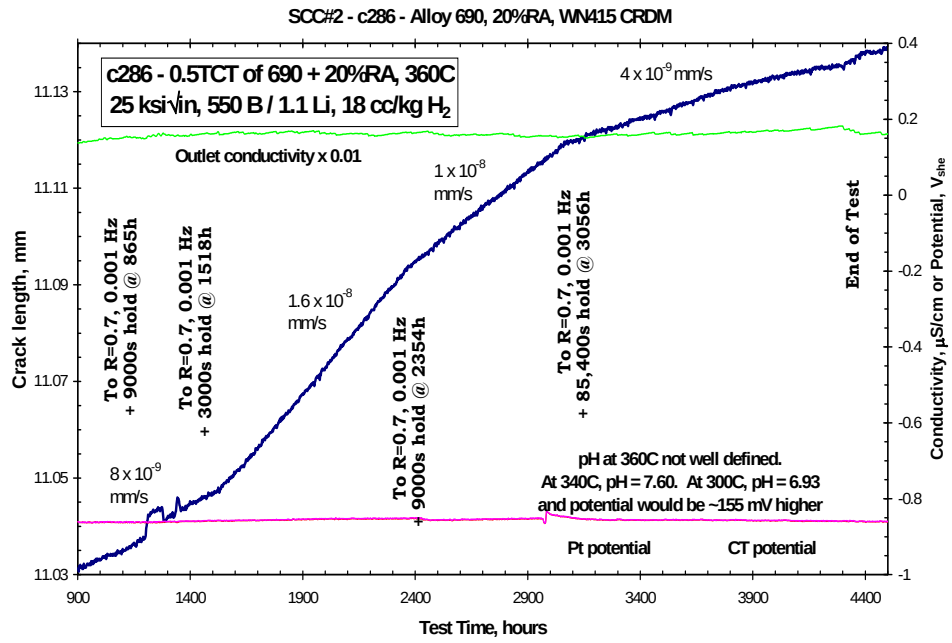




Specimens c285, c286

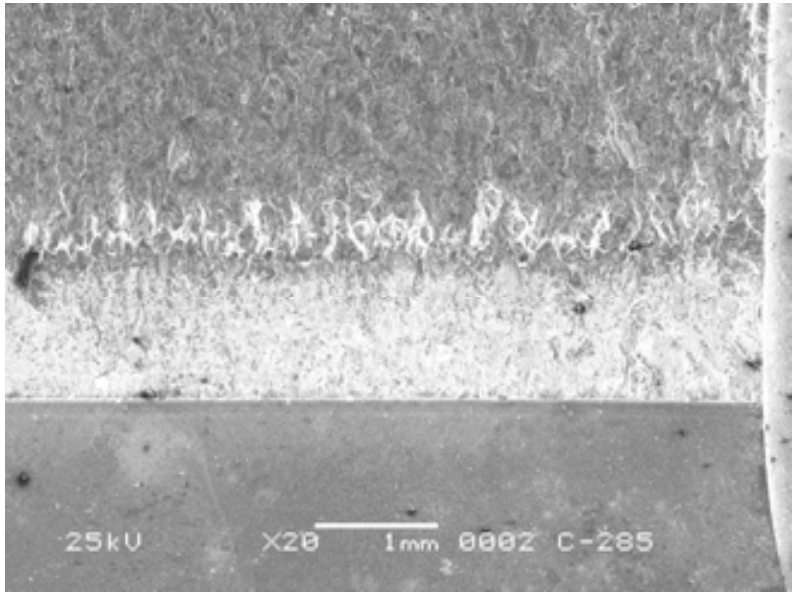
20% Cold Work Alloy 690 CRDM

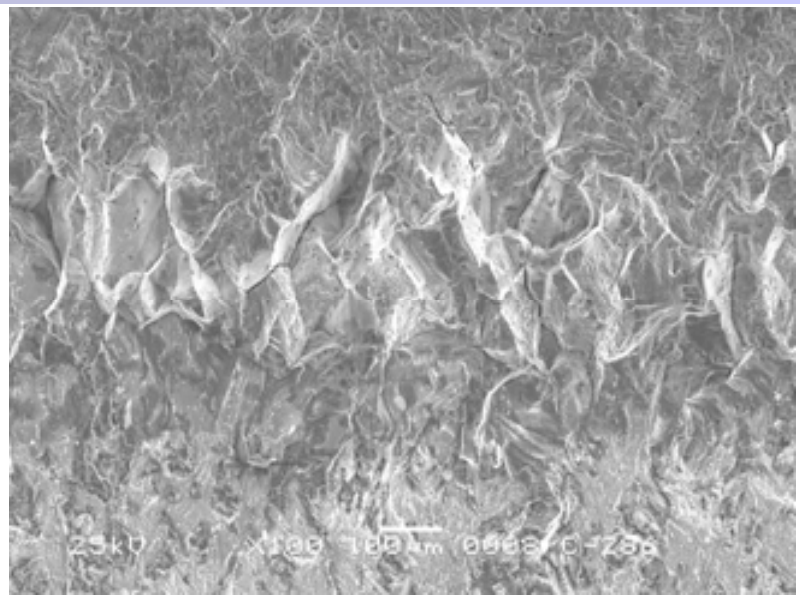


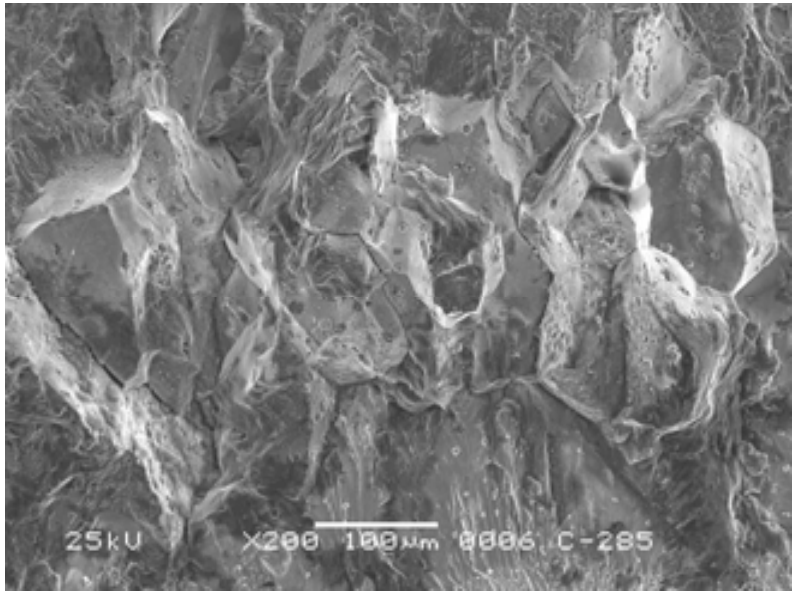


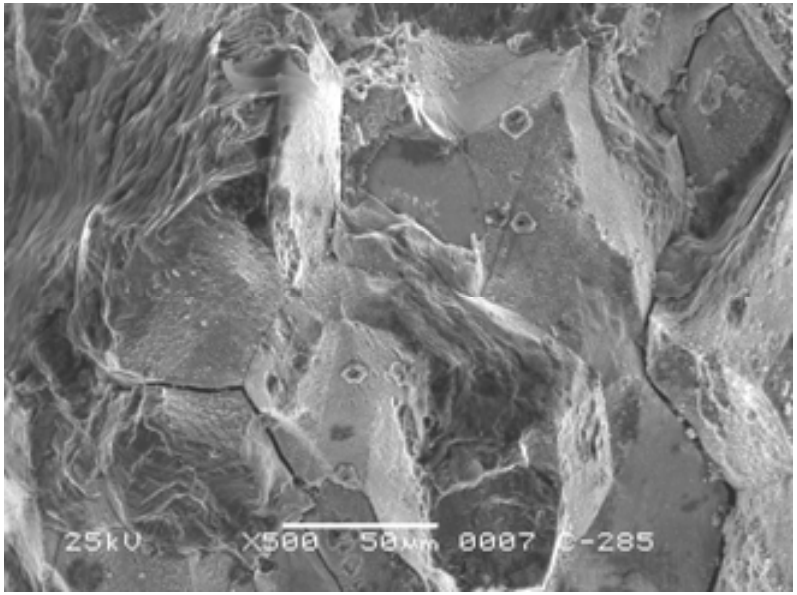
L-T Orientation (good)

c285/c286 SEM Fractography



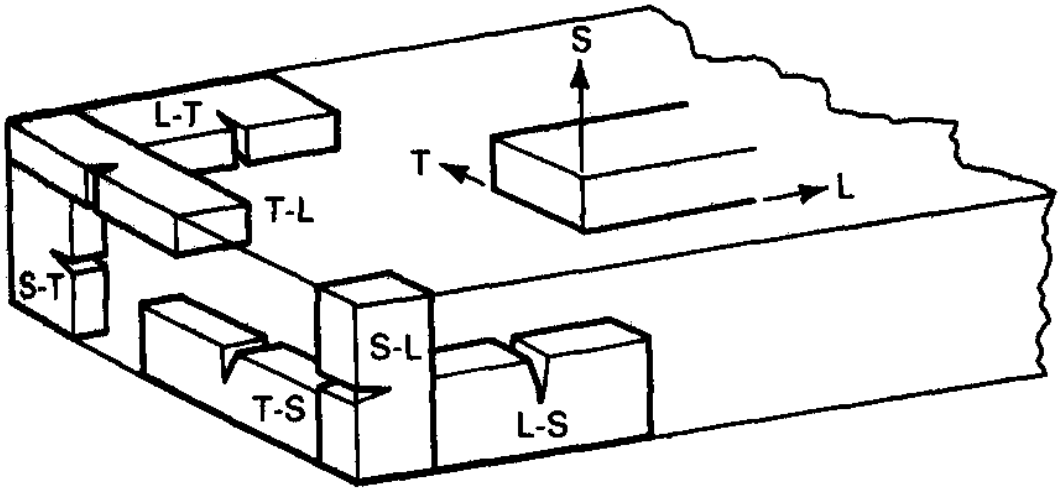






Testing on 1D Cold Rolled 690

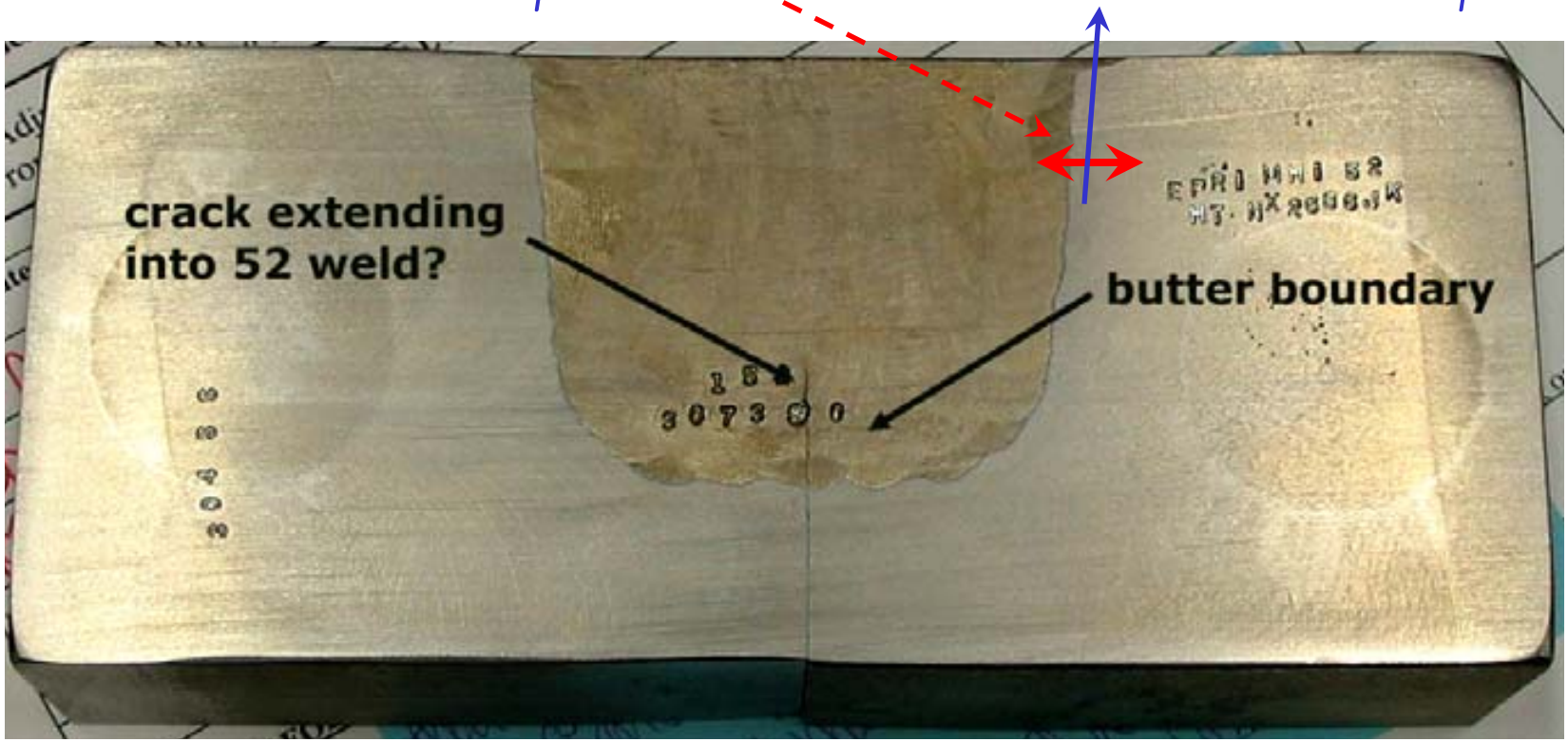
- Evaluation of two 0.5T CT specimens of Alloy 690:
  - cold worked alloy 690 by 1D rolling by 20 – 26%
  - use worst S-L orientation: crack plane = rolling plane
  - tested near peak in CGR (near Ni/NiO transition)
  - tested at 360C to accelerate testing
  - used periodic "gentle" cyclic loading to activate SCC
- Observed increased growth rates at constant K



Alloys 52/152 Weld Metals

Weld shrinkage strain = "tensile forging"

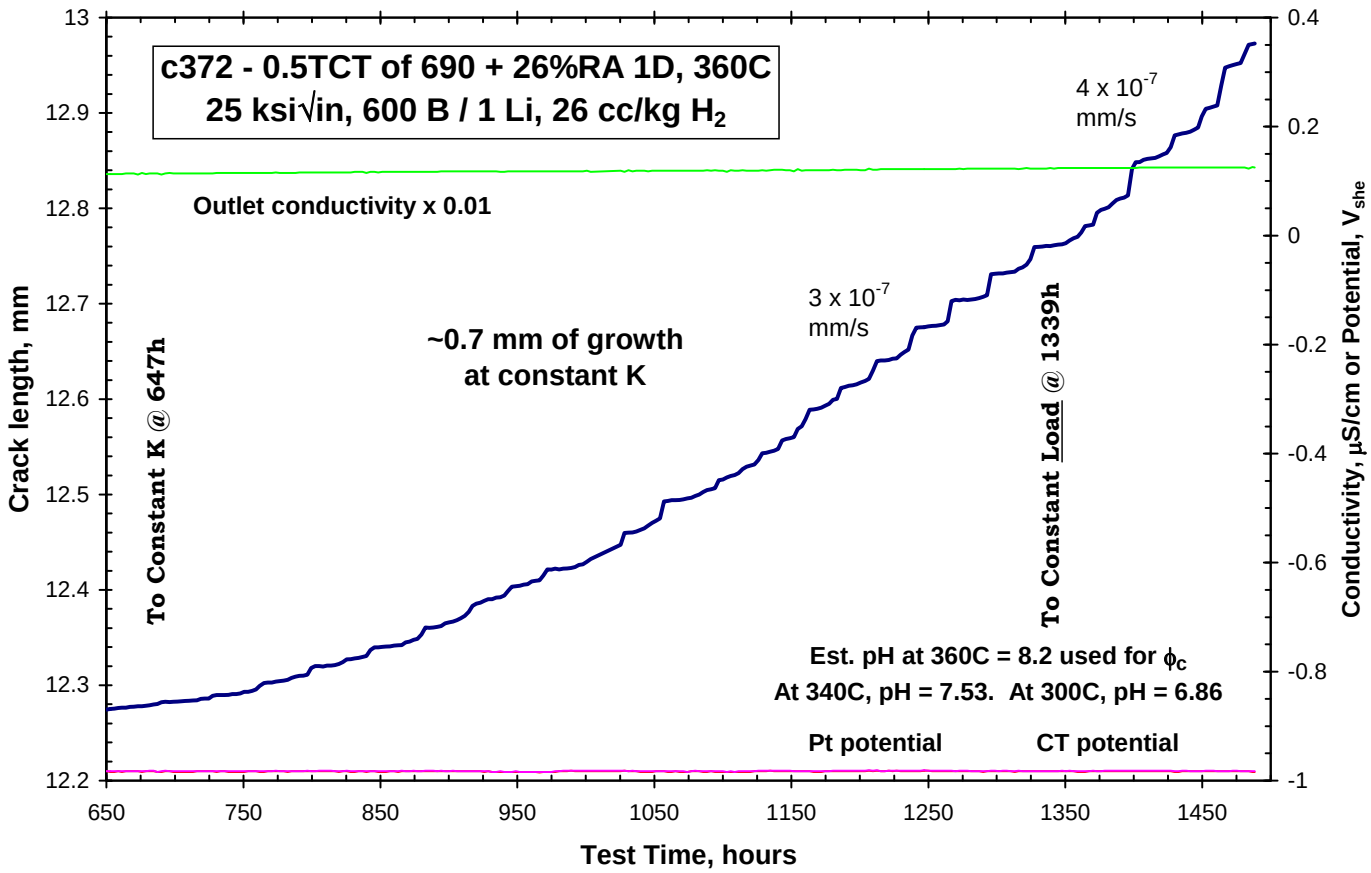
Can consider HAZ equivalent to ***S–L orientation*** *in rolled plate*



Hot crack found in Alloy 52 archive weld

Specimen c372

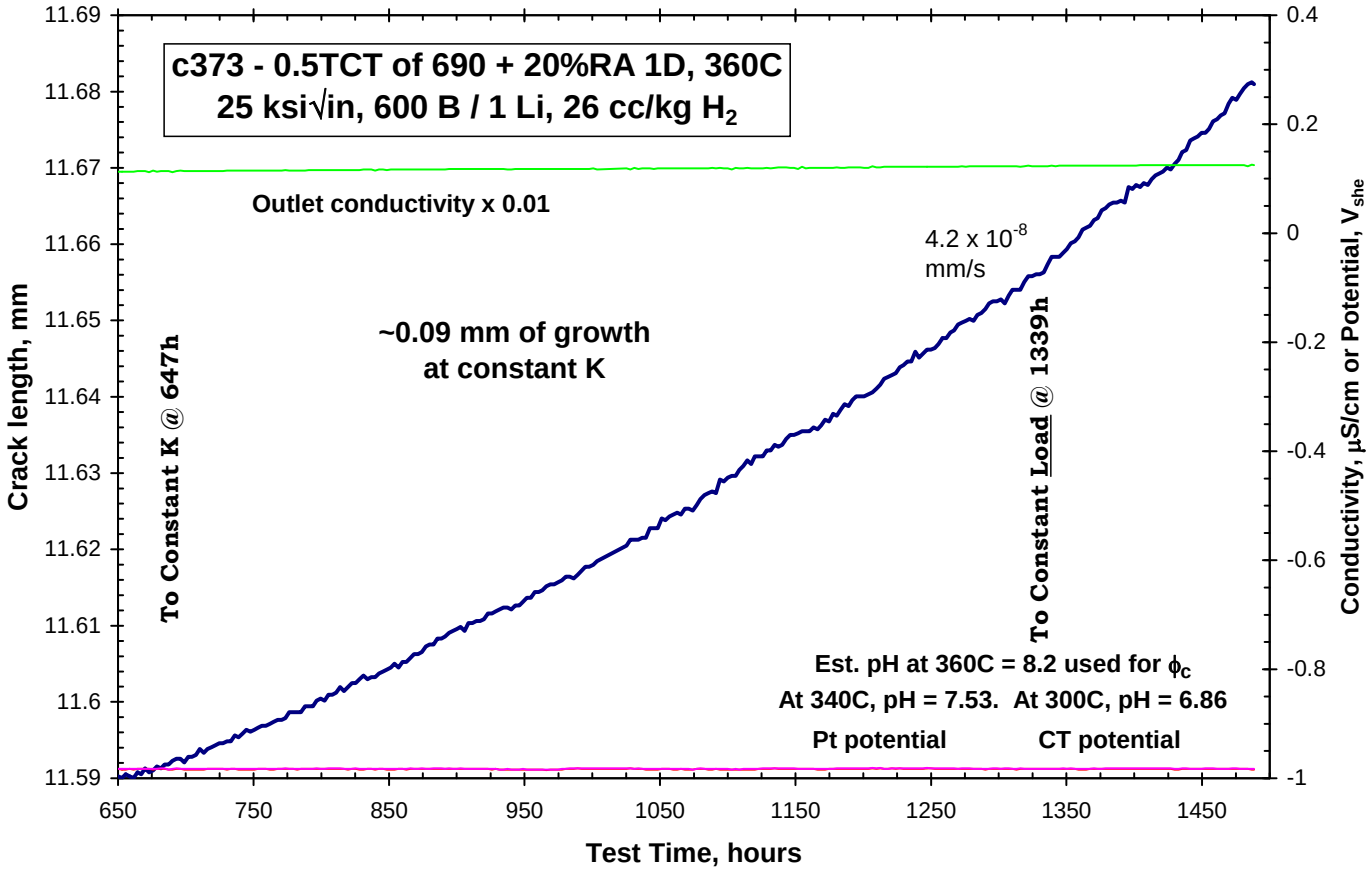
1D, 26% Cold Worked ANL Alloy 690



Increased growth rates in S-L orientation

Specimen c373

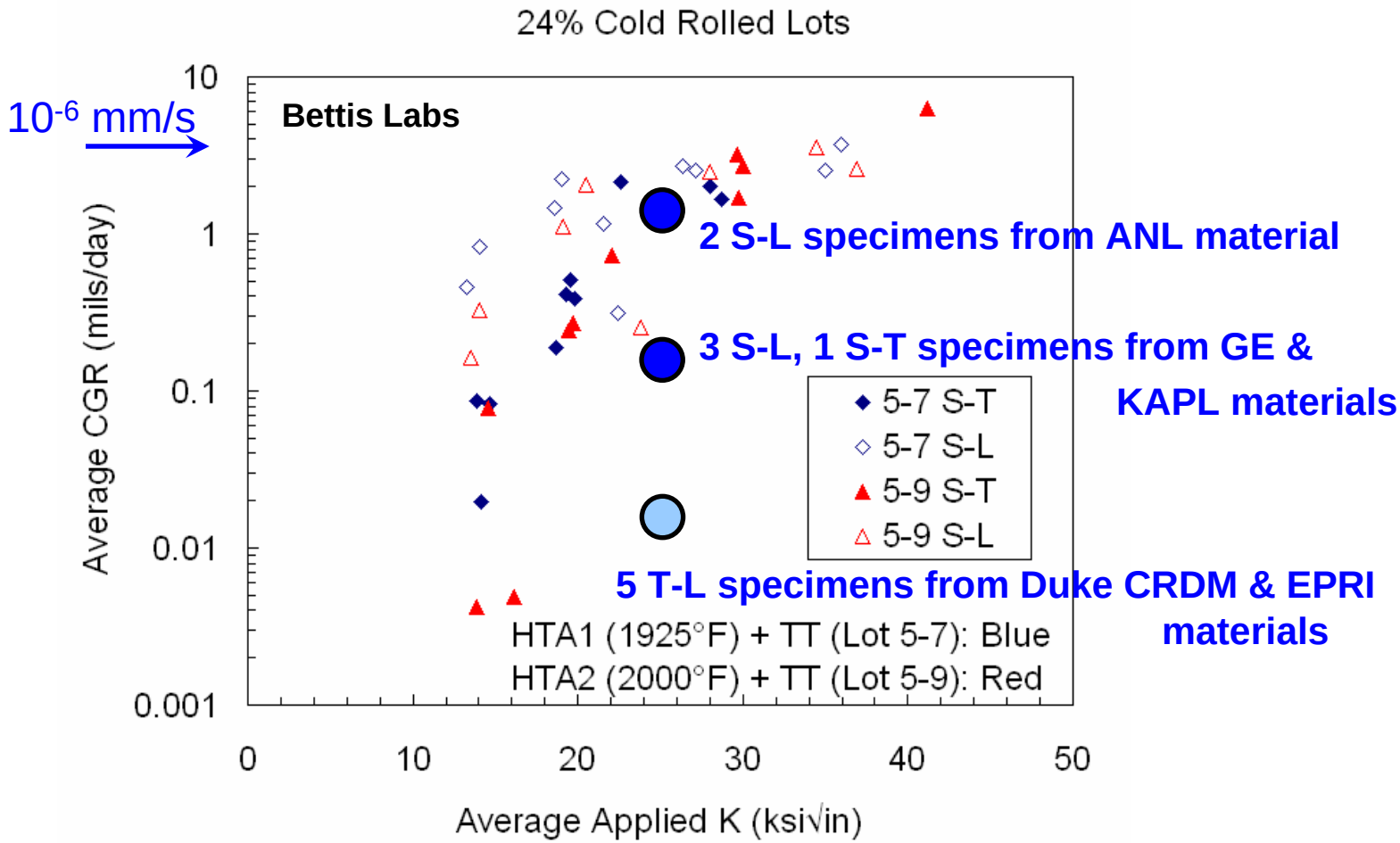
1D, 20% Cold Worked GE GRC Alloy 690



Increased growth rates in S-L orientation

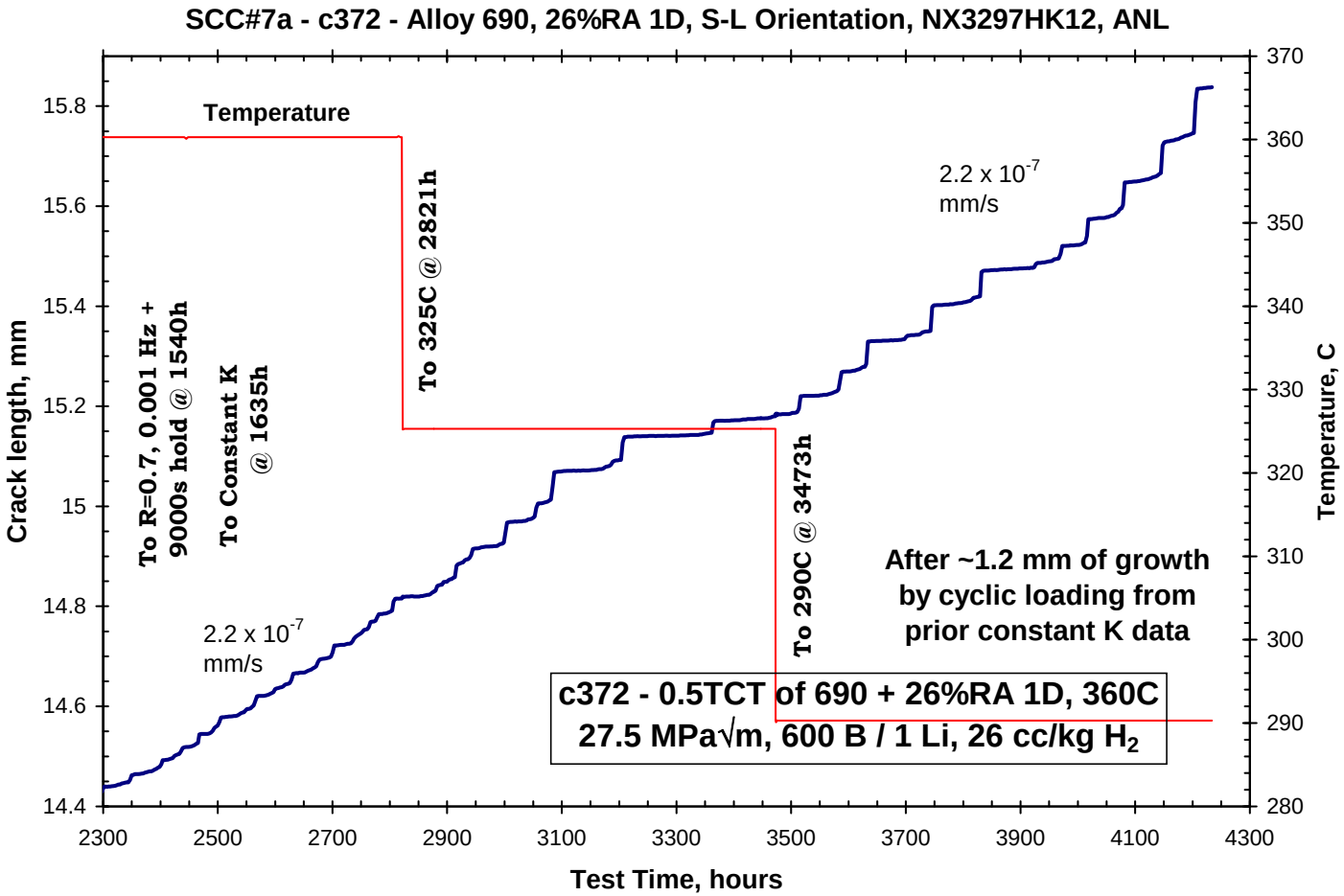
5~10X slower than 26% CW ANL 690 in S-L orientation

Comparison of GE & Bettis Data



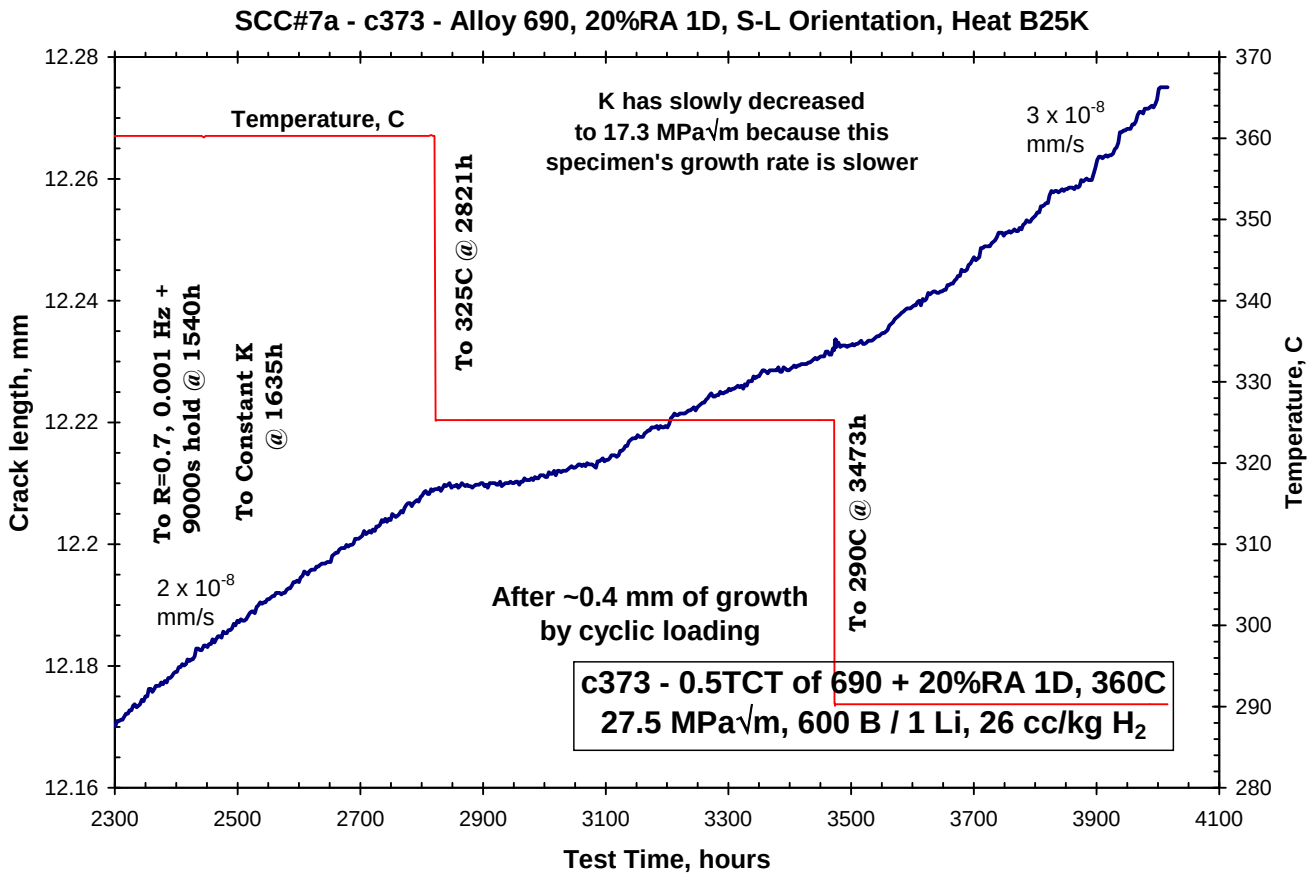
Increased growth rates in S-L orientation

1D, 26% Cold Worked ANL Alloy 690



No effect of temperature – would be 12X normally

1D, 20% Cold Worked GE GRC Alloy 690



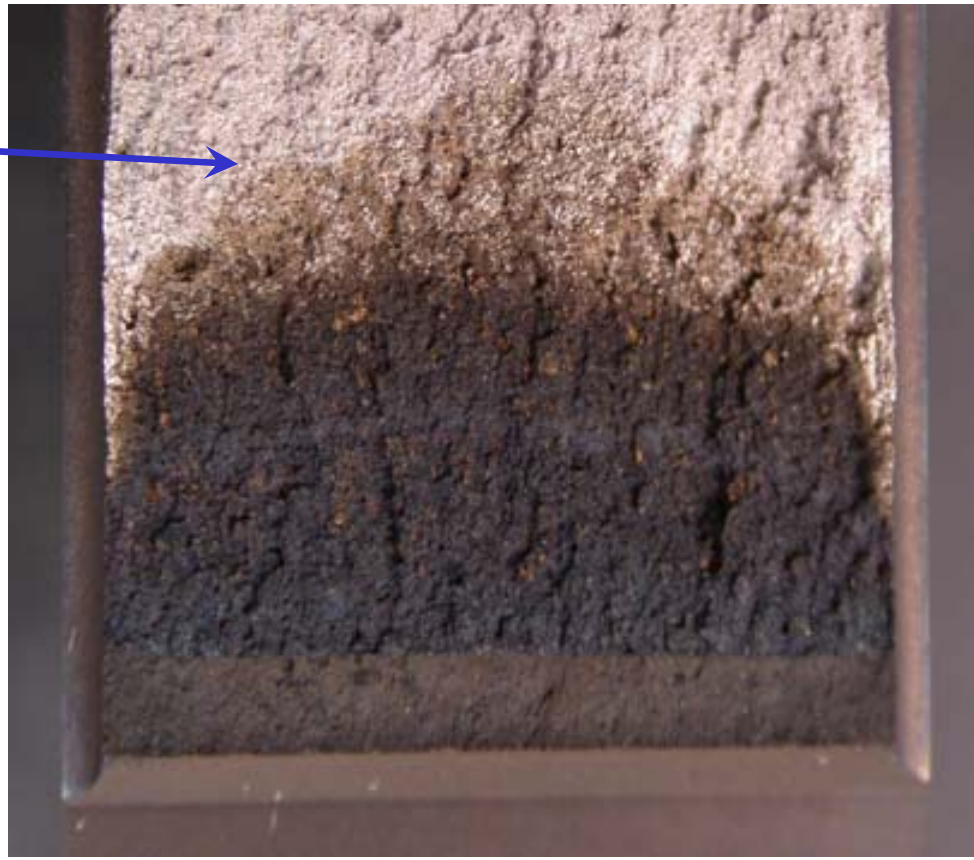
Little effect of temperature – would be 12X normally

Specimens c372, c373

1D, 20+% Cold Rolled Alloy 690

Lighter appearance is 325 & 290C data

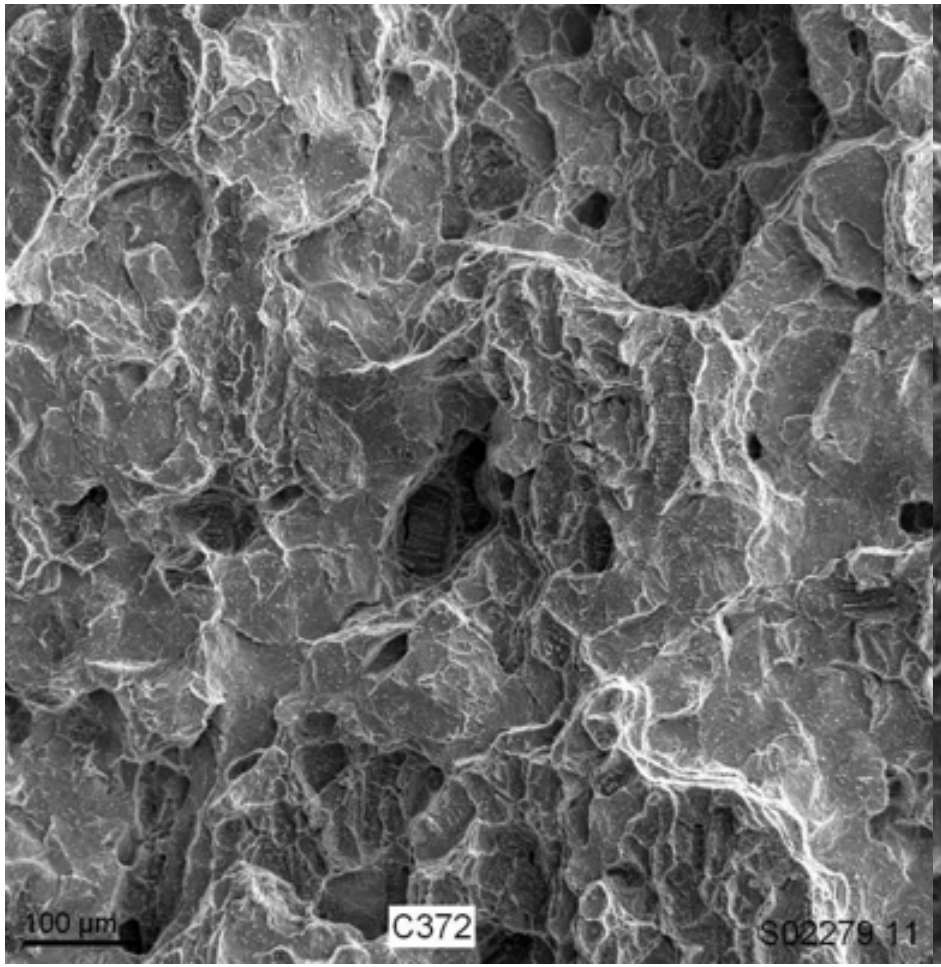
ANL 690 - c372

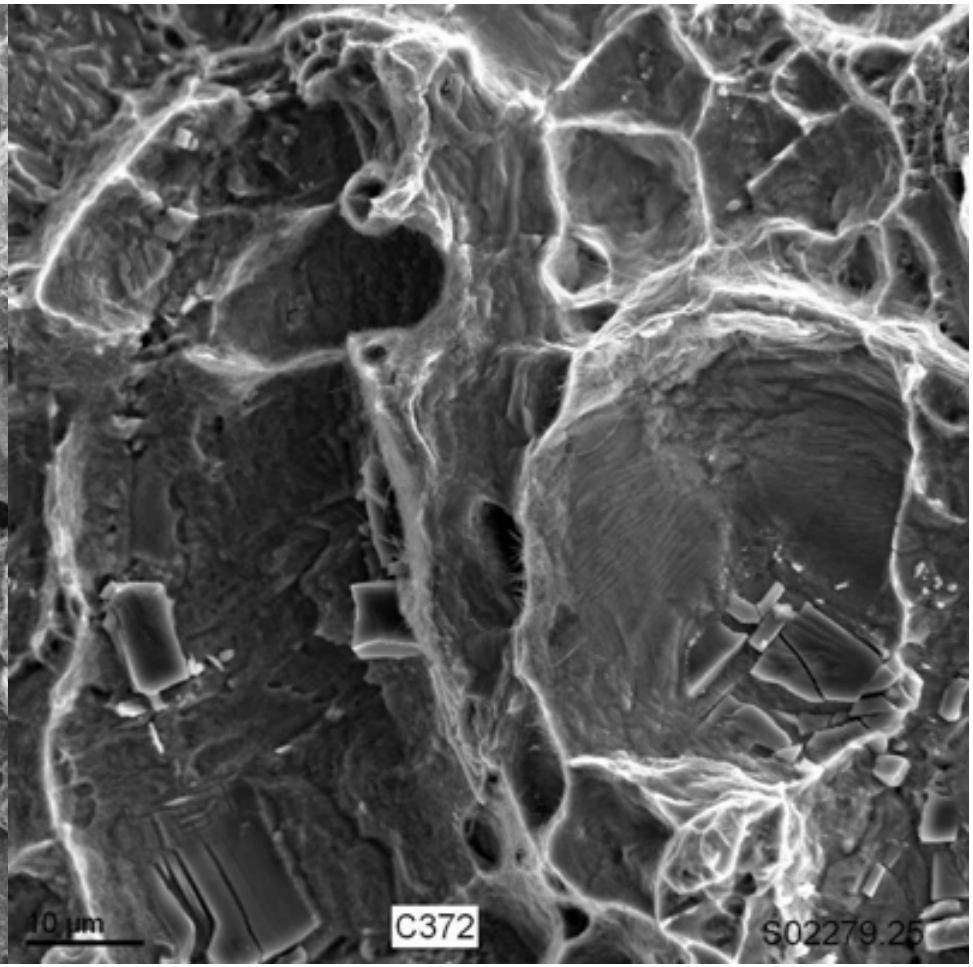


GE GRC 690 - c373

Specimen c372

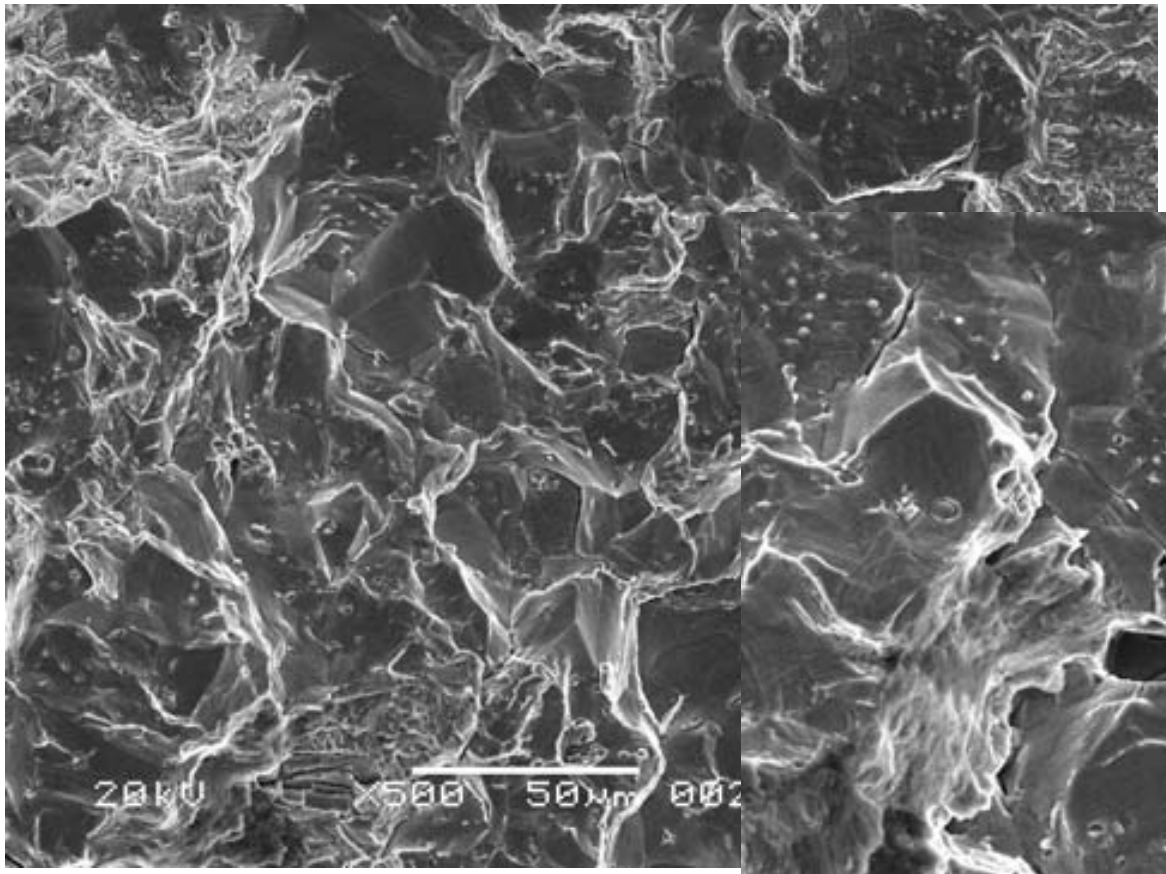
1D, 26% Cold Rolled ANL 690

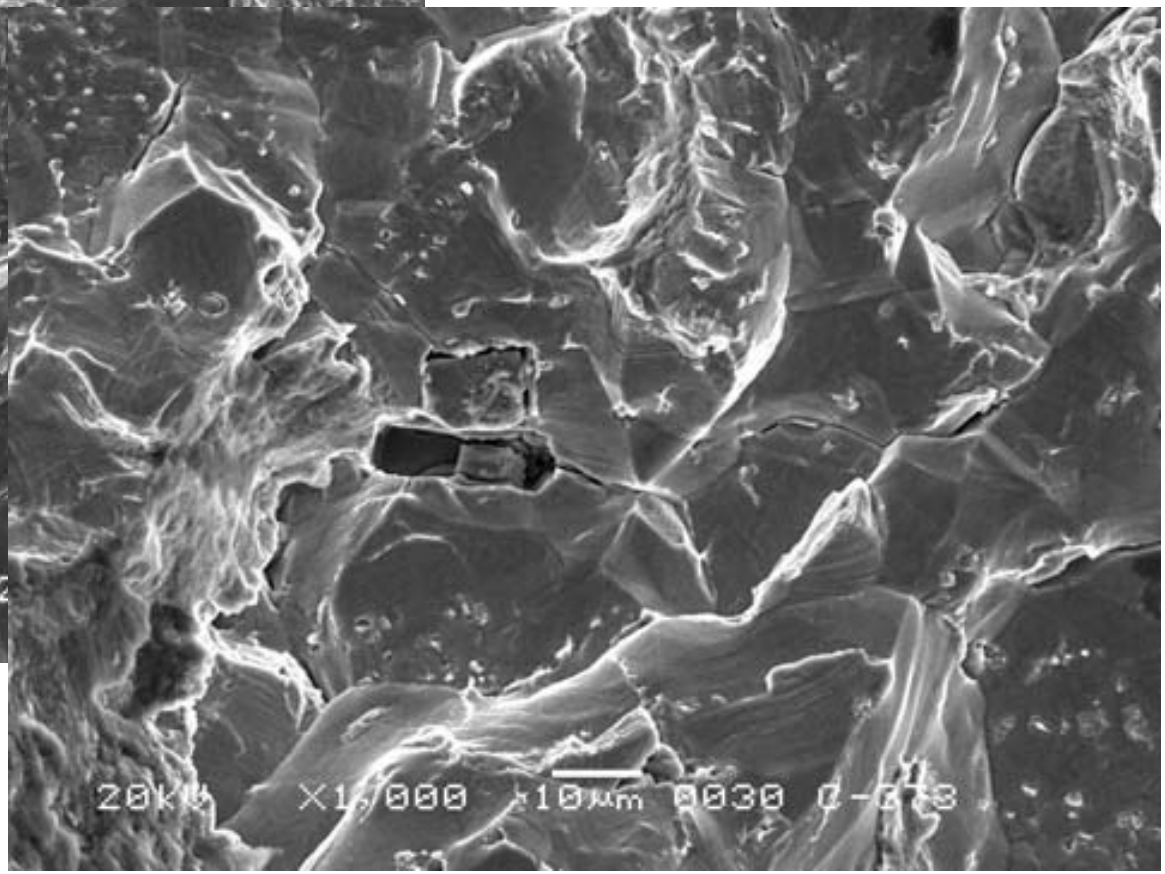




Specimen c373

1D, 20% Cold Worked GE GRC Alloy 690





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

Effect of Microstructure

- Inhomogeneity results from melting & processing, e.g.
  - single melting – vs. double or triple melt
    premium, critical alloys are ESR-VIM-VAR or VIM-VAR-VAR
  - air melting gives more inclusions & perhaps loss of Cr
  - not achieving critical strains of ~70% during processing
  - most pronounced in highly alloyed (Nb,C) mat'ls like 718
- Inhomogeneity can include:
  - compositional banding
  - large variation in carbide content, including gb carbides
  - stringers or sheets of oxide or C,N inclusions
  - large variation in grain size
- Processing then causes uneven deformation & poor properties

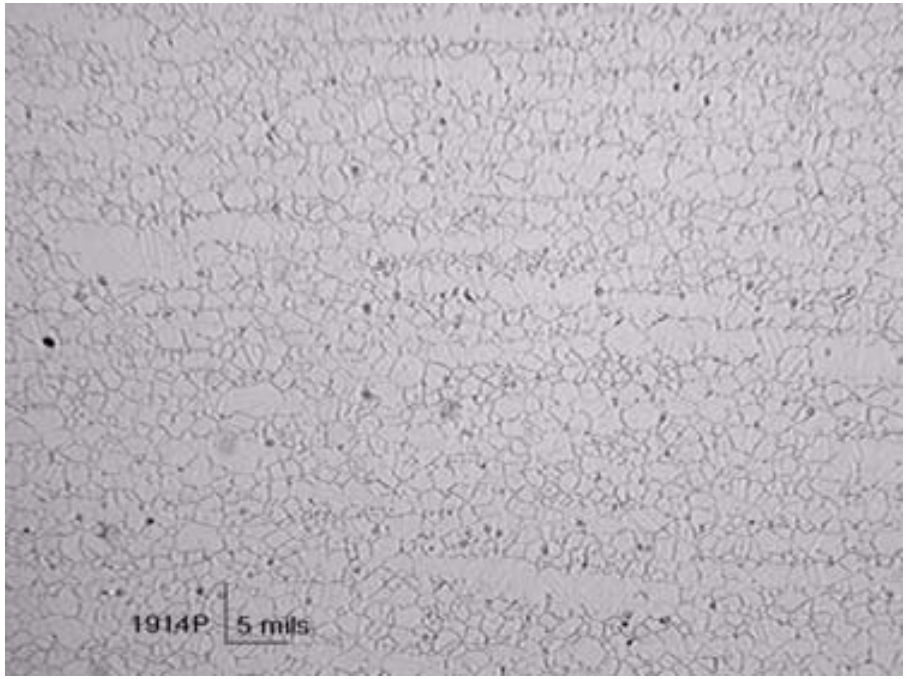
Effect of Microstructure

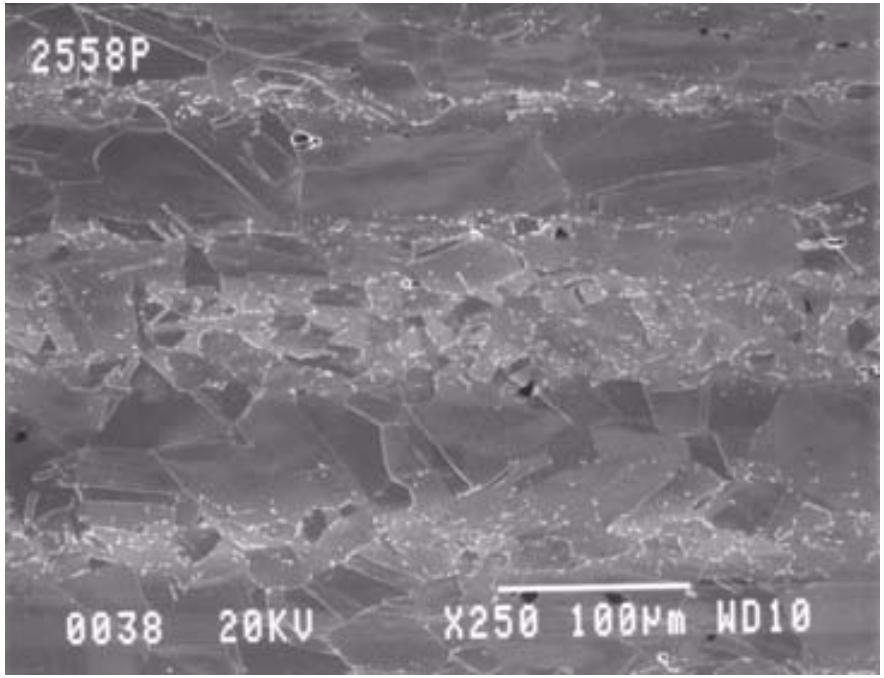
- Processing of inhomogeneous materials causes uneven deformation and can result in poor properties
  - Alloy 718 toughness can drop by 30+%, and is strictly correlated to banded microstructure
  - generally quality degrades from extrusion >> billet >> plate
- Cold work will affect inhomogenous alloys much more
  - worst is 1D cold rolling in plane of inhomogeneity
  - rolling produces ~2:1 or 3::1 lengthening:spreading but forging will produce the same effect at higher %RA
  - tensile straining does not produce the same type / severity of deformation as rolling in terms of grain <u>elongation</u> and <u>pancaking</u>, but can still be inhomogeneous.

Differences in Deformation

- %elongation or %reduction-in-area doesn't capture all of the important aspects of variations in deformation type
- rolling (1D) pancakes grains some, and elongates grains to the maximum extent
- forging or cross-rolling (2D) pancakes the grains but does not elongate as much as rolling
- tensile straining (2D) pancakes the grains the least. That is, it's somewhat similar to cross-forging (on two sides). Grain elongation occurs, but little pancake effect.
  - tensile straining can still occur locally / unevenly in banded / Inhomogeneous microstructure

Inhomogeneity in Bettis 690

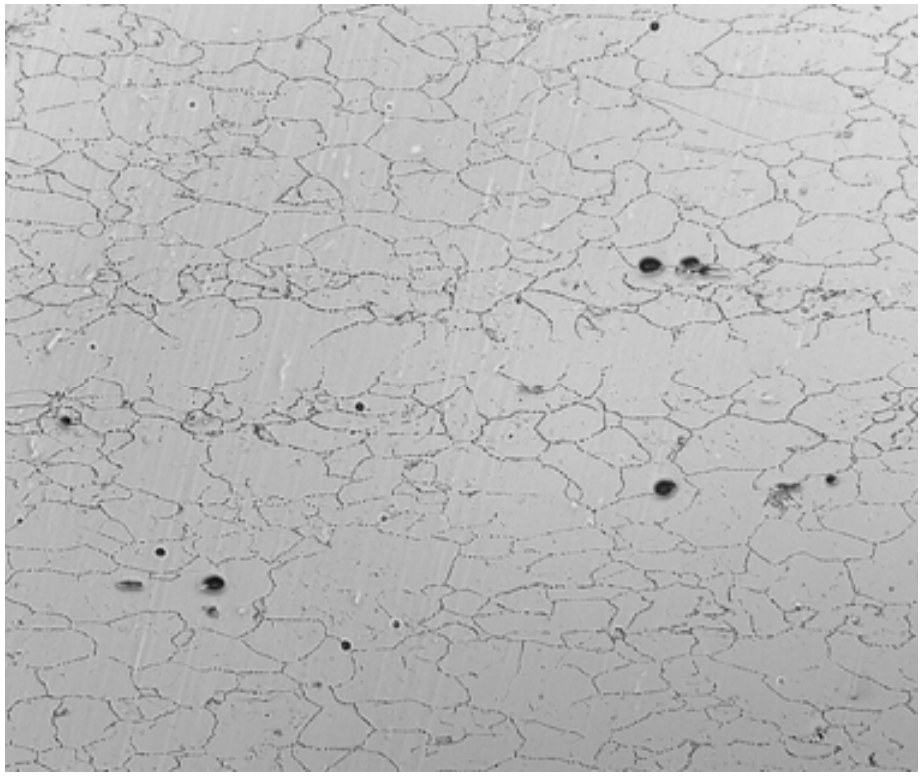


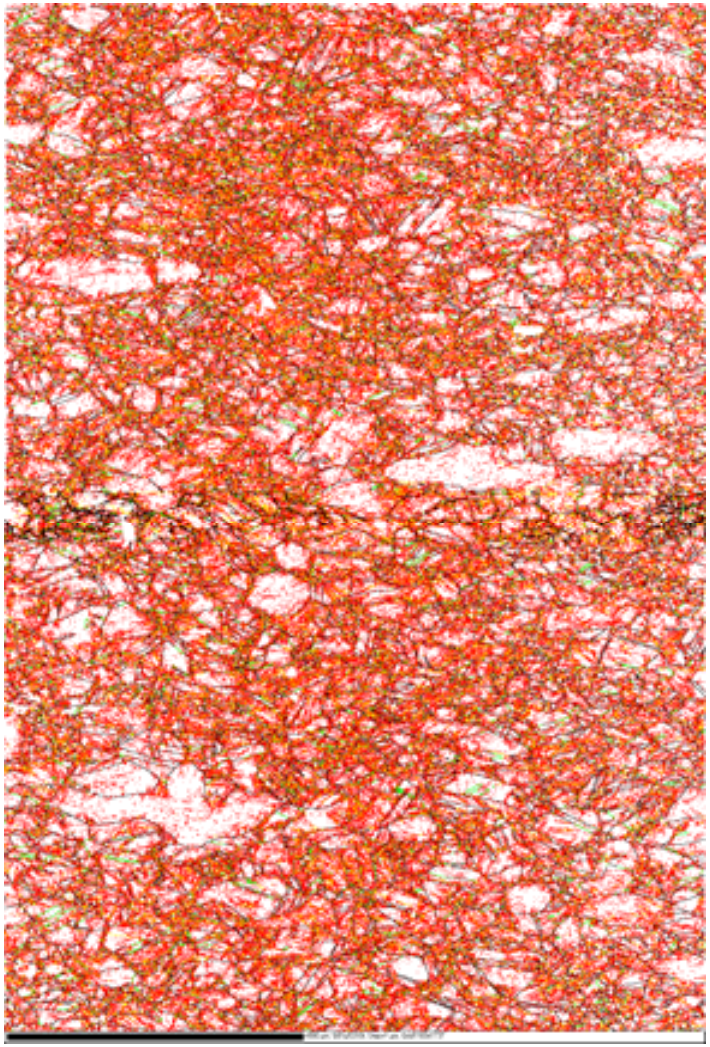


Composition & microstructural banding affects grain size and gb carbide decoration

Specimen c372

Inhomogeneity in 1D, 26% CR ANL 690





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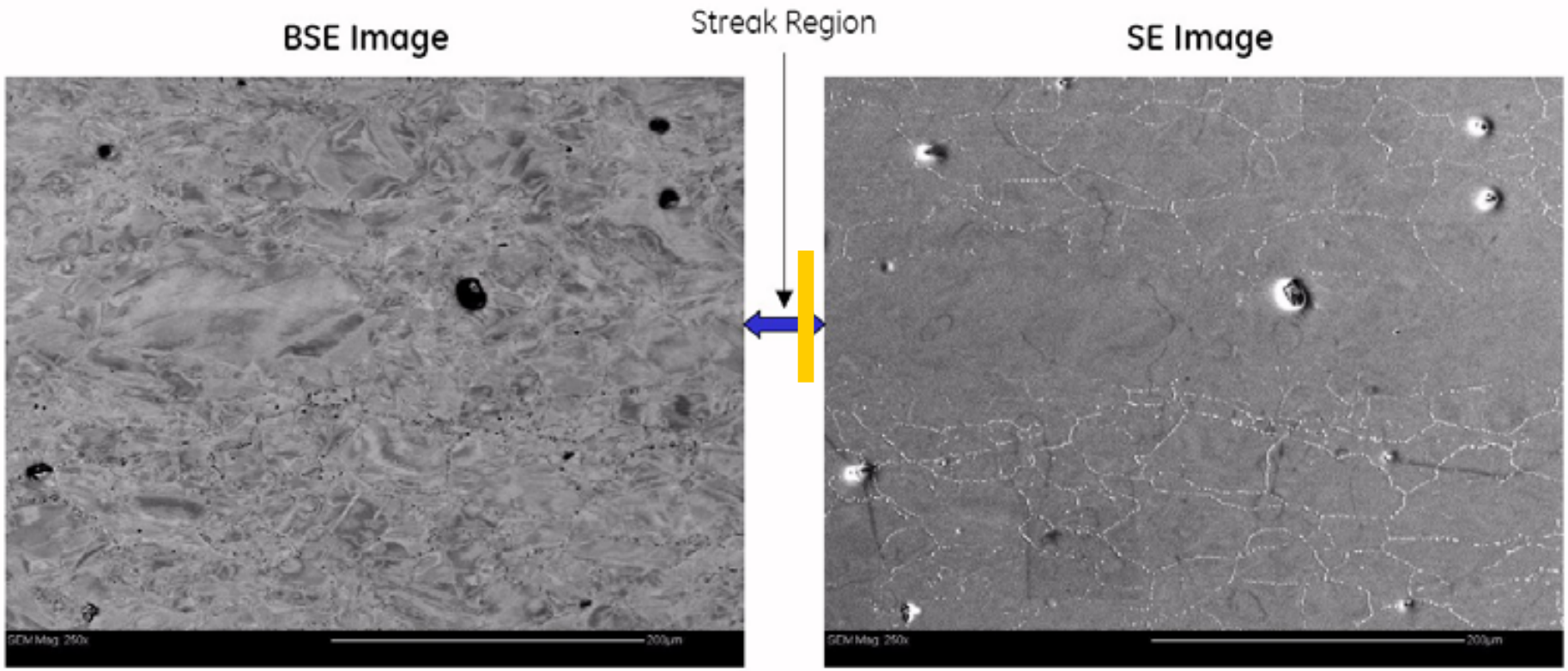

Composition & microstructural banding affects grain size and gb carbide decoration.
Double melted by VIM-VAR; annealed at 1900F & air cooled

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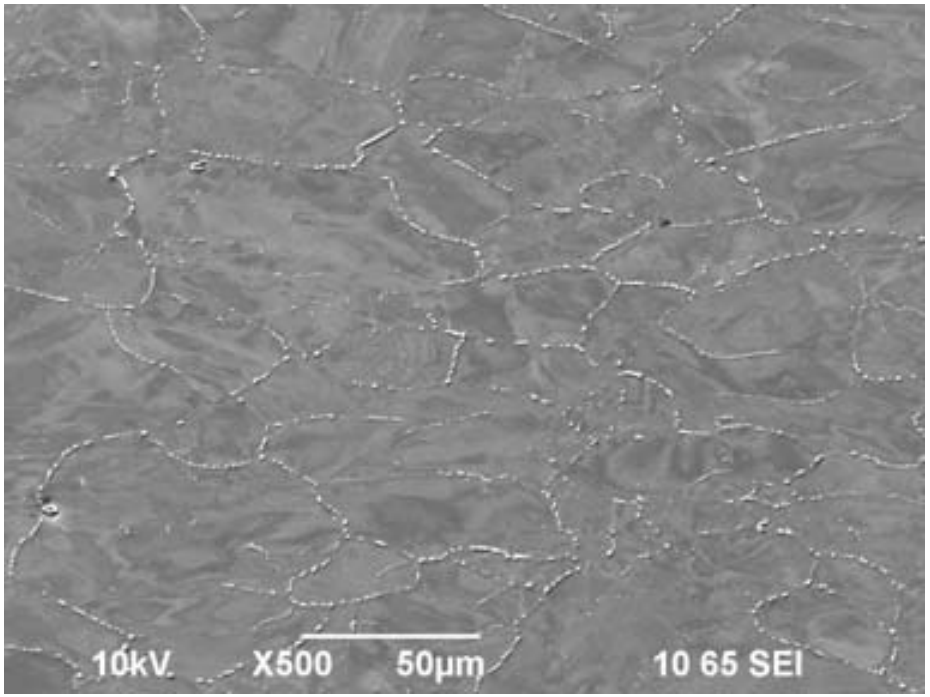
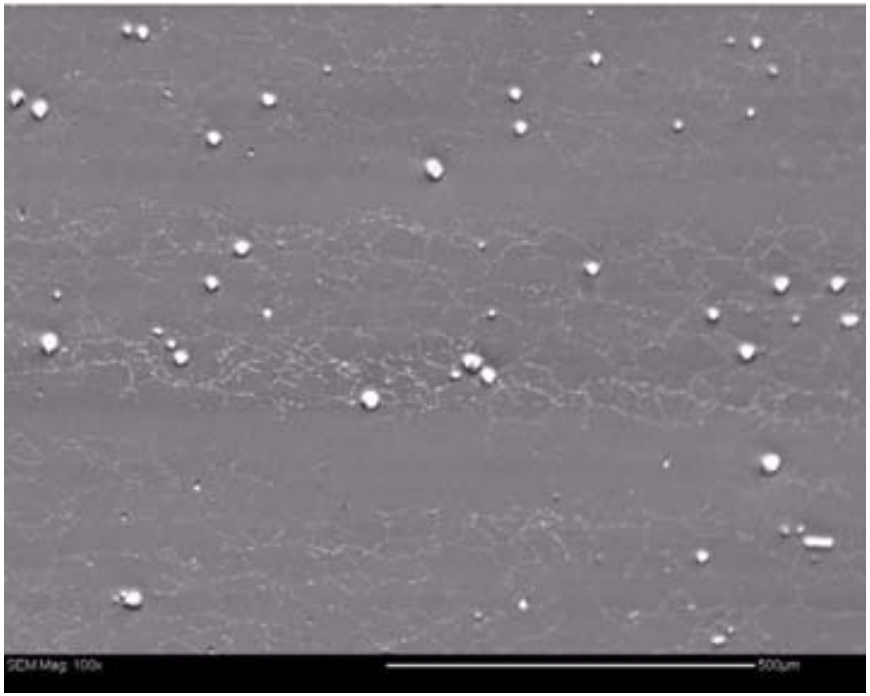




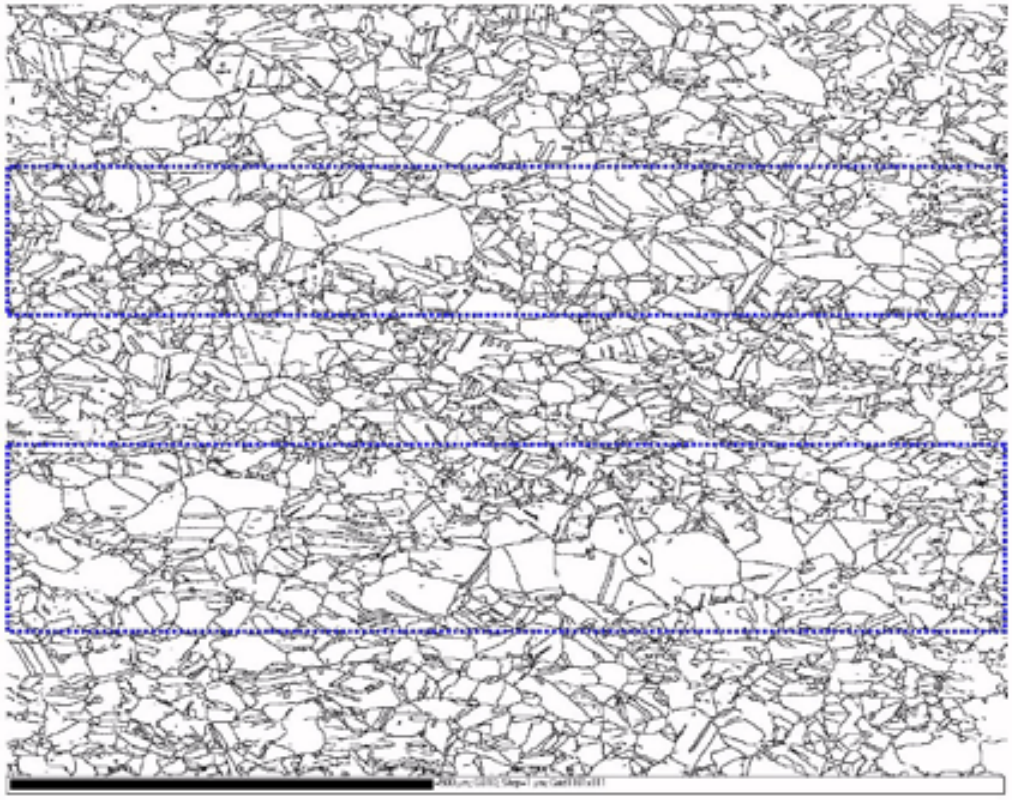
Composition & microstructural banding affects grain size and gb carbide decoration.
Double melted by VIM-VAR; annealed at 1900F & air cooled

Inhomogeneity in 1D, 26% CR ANL 690

Streak regions indicated by the dotted blue box

Streaks ⇒

Streaks ⇒



Black = 10°<θ<60°

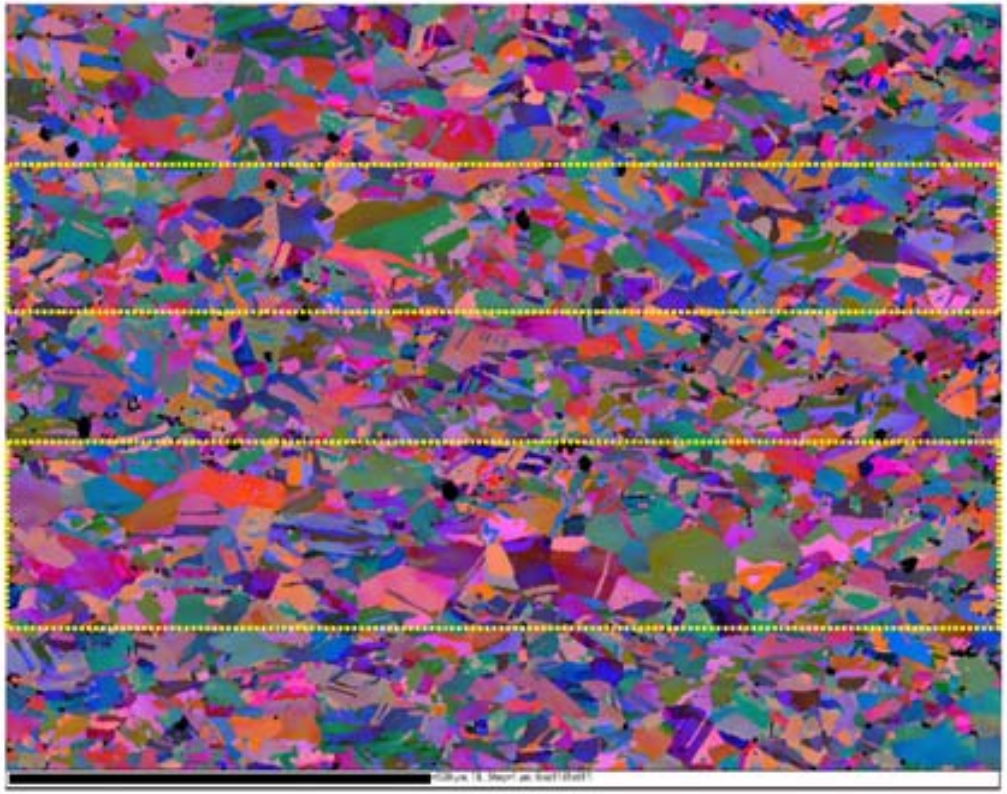
Strain localized in streaked / banded areas of larger grains

Inhomogeneity in 1D, 26% CR ANL 690

Streak regions indicated by the dotted yellow box

Streaks ⇒

Streaks ⇒



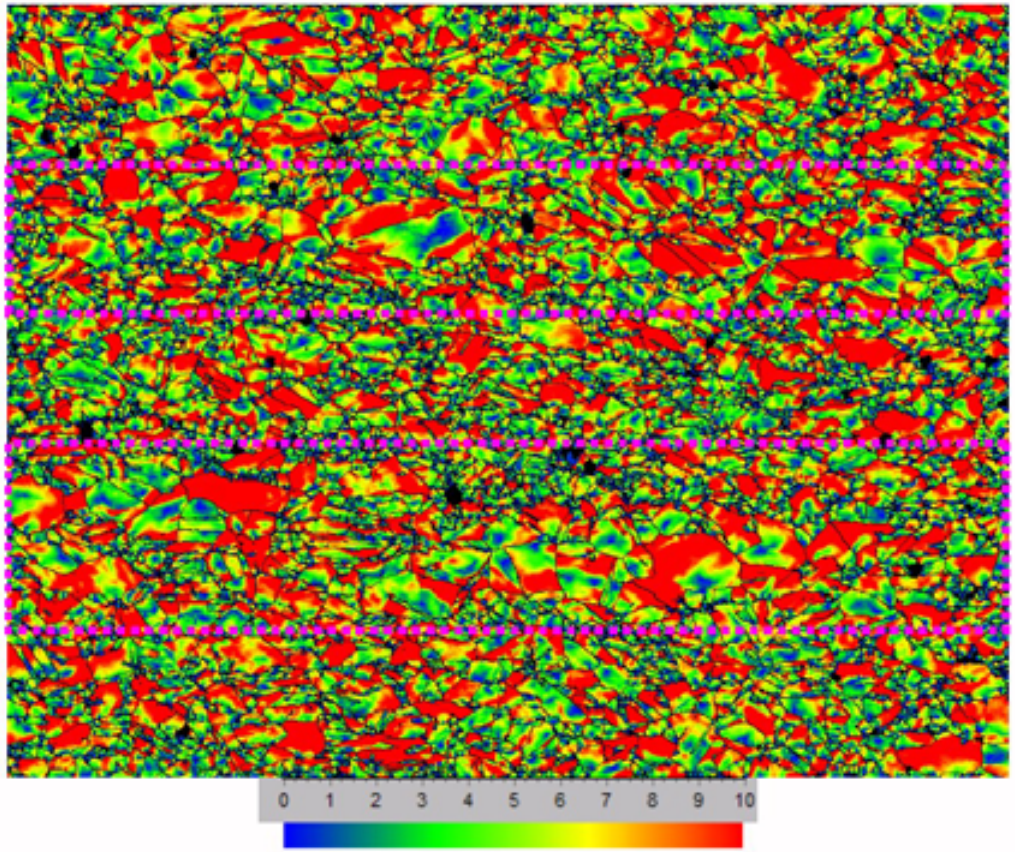
Strain localized in streaked / banded areas of larger grains

Inhomogeneity in 1D, 26% CR ANL 690

Streak regions indicated by the dotted pink box

Streaks ⇒

Streaks ⇒



Different color thresholds

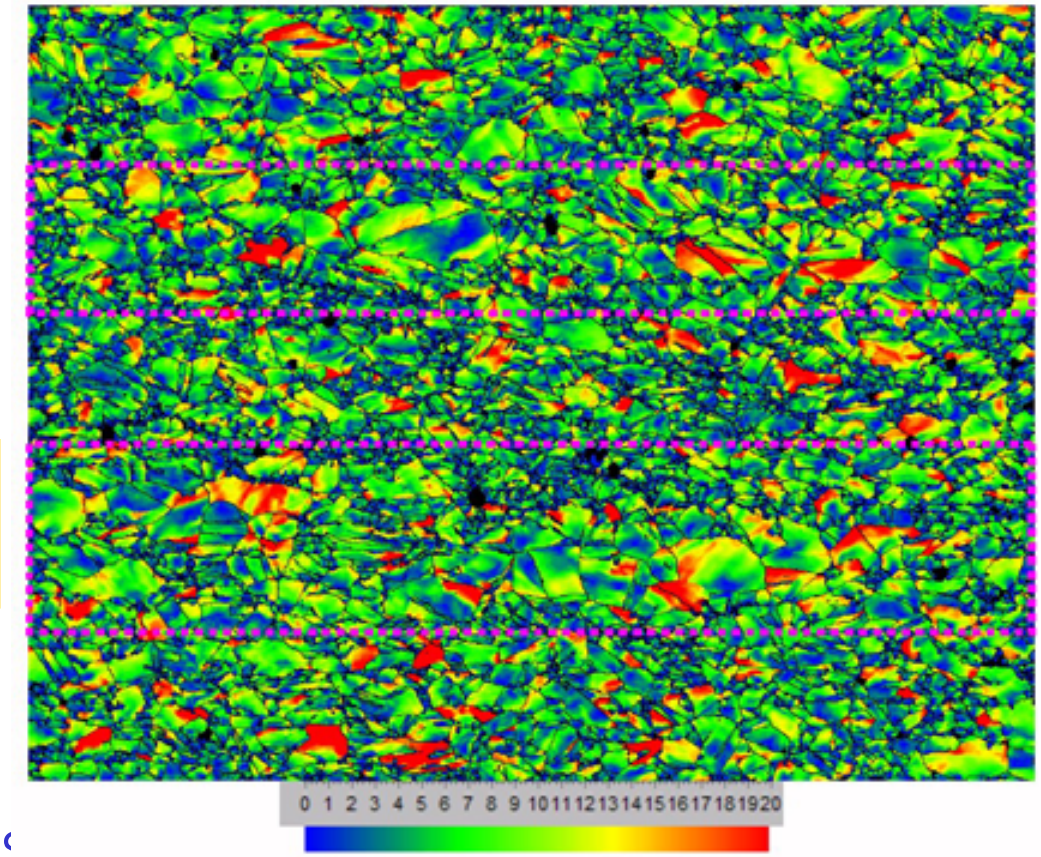
Strain localized in streaked / banded areas of larger grains

Inhomogeneity in 1D, 26% CR ANL 690

Streak regions indicated by the dotted pink box

Streaks ⇒

Streaks ⇒



Different color thresholds

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Streak regions indicated by the dotted pink box

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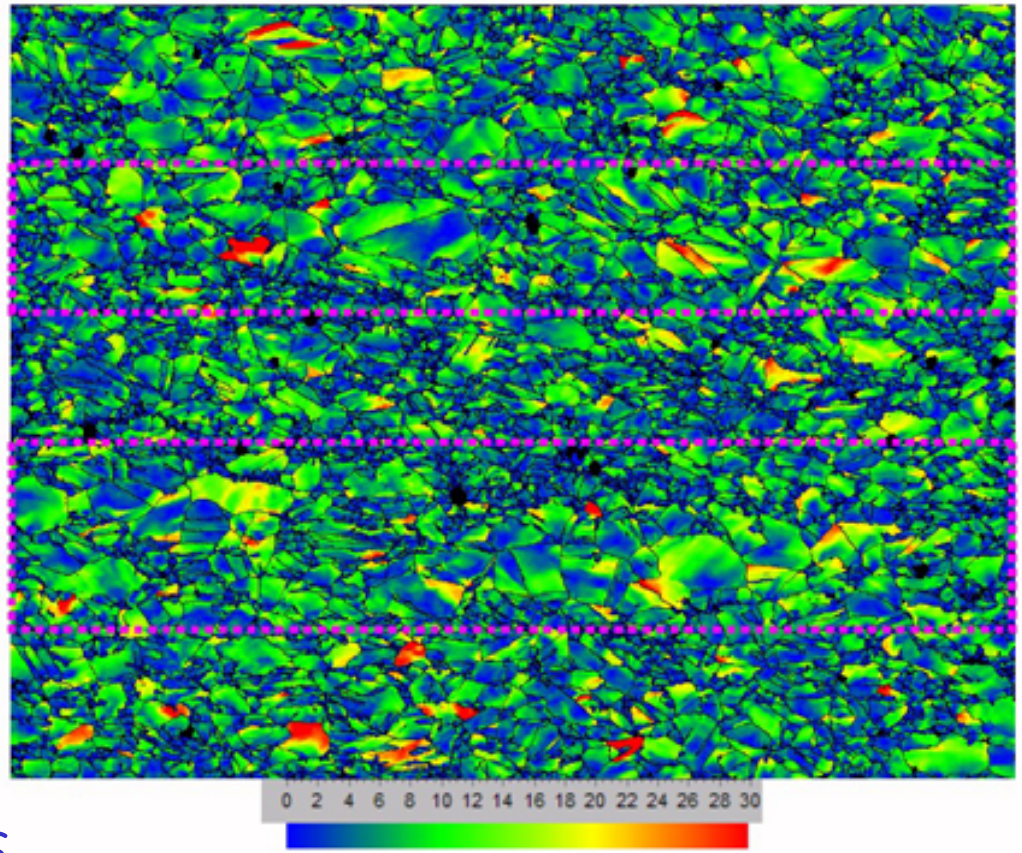

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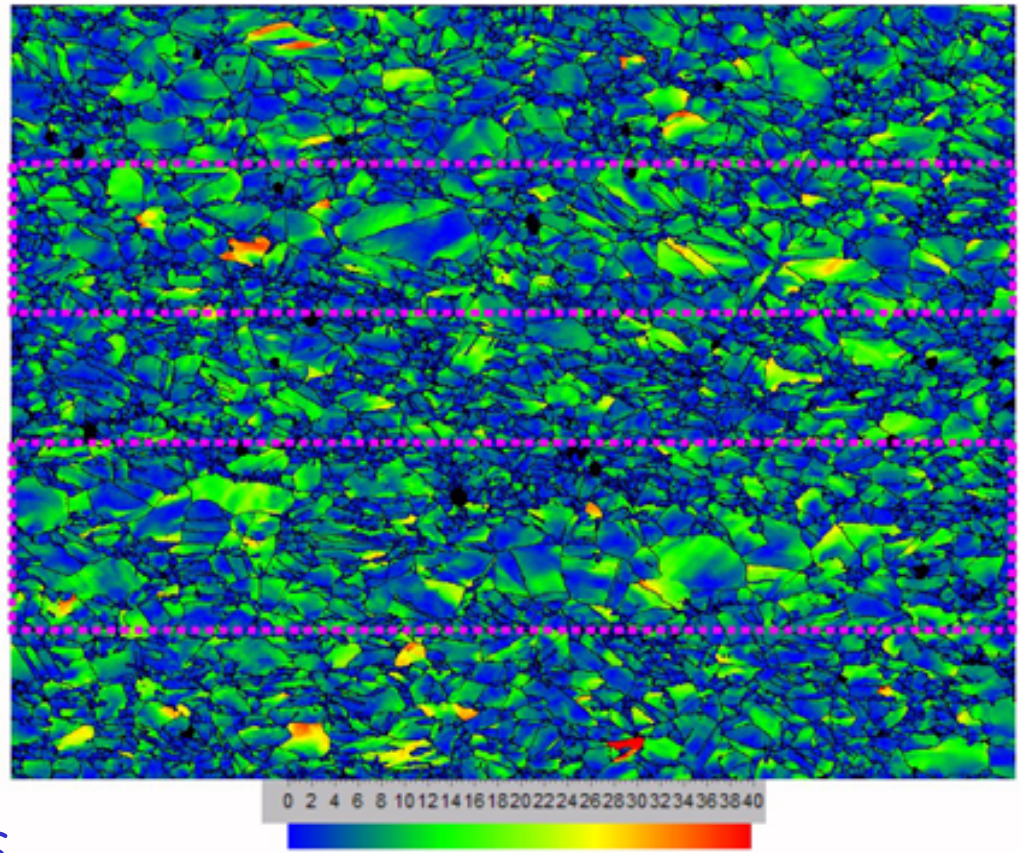

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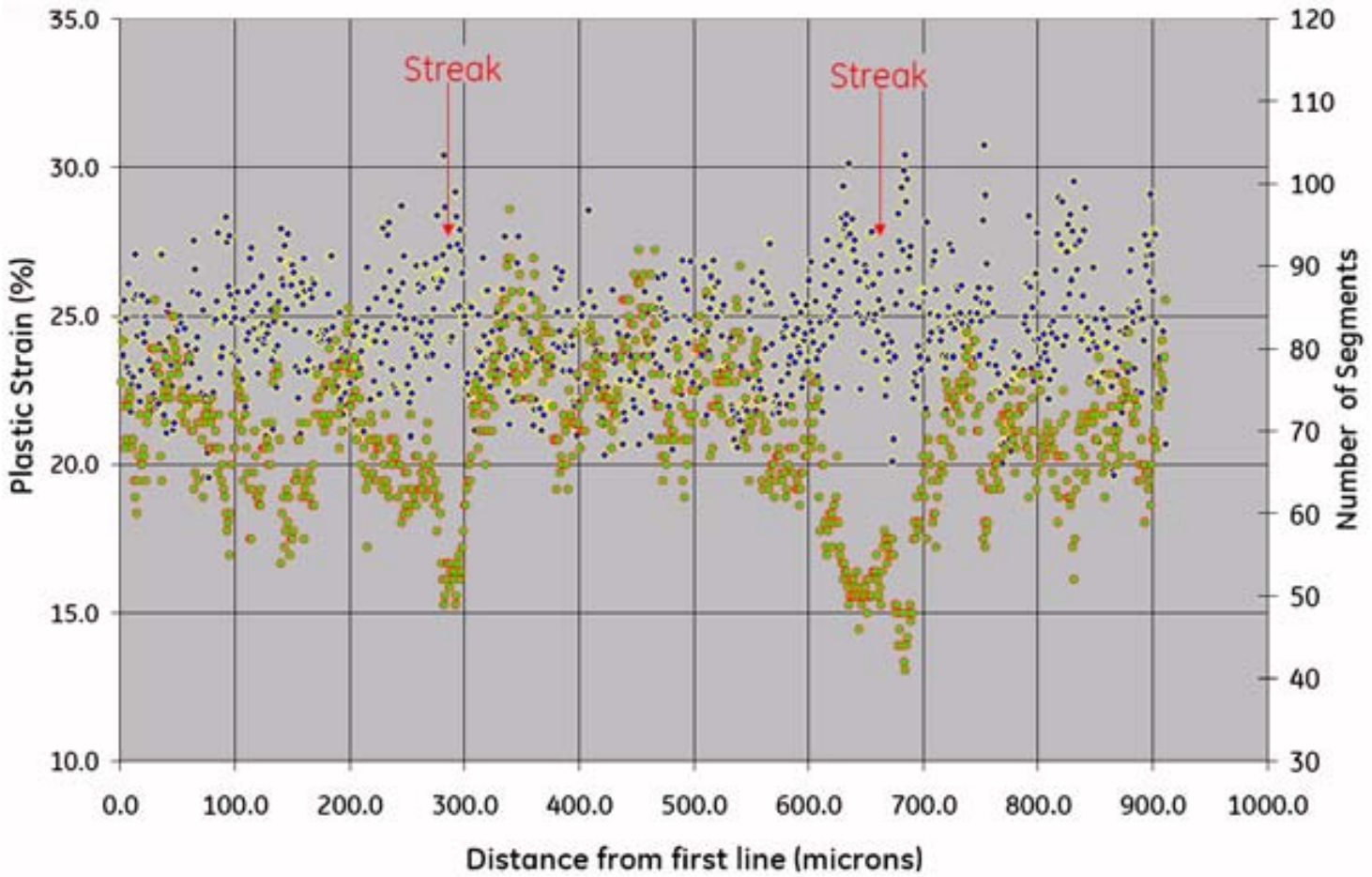
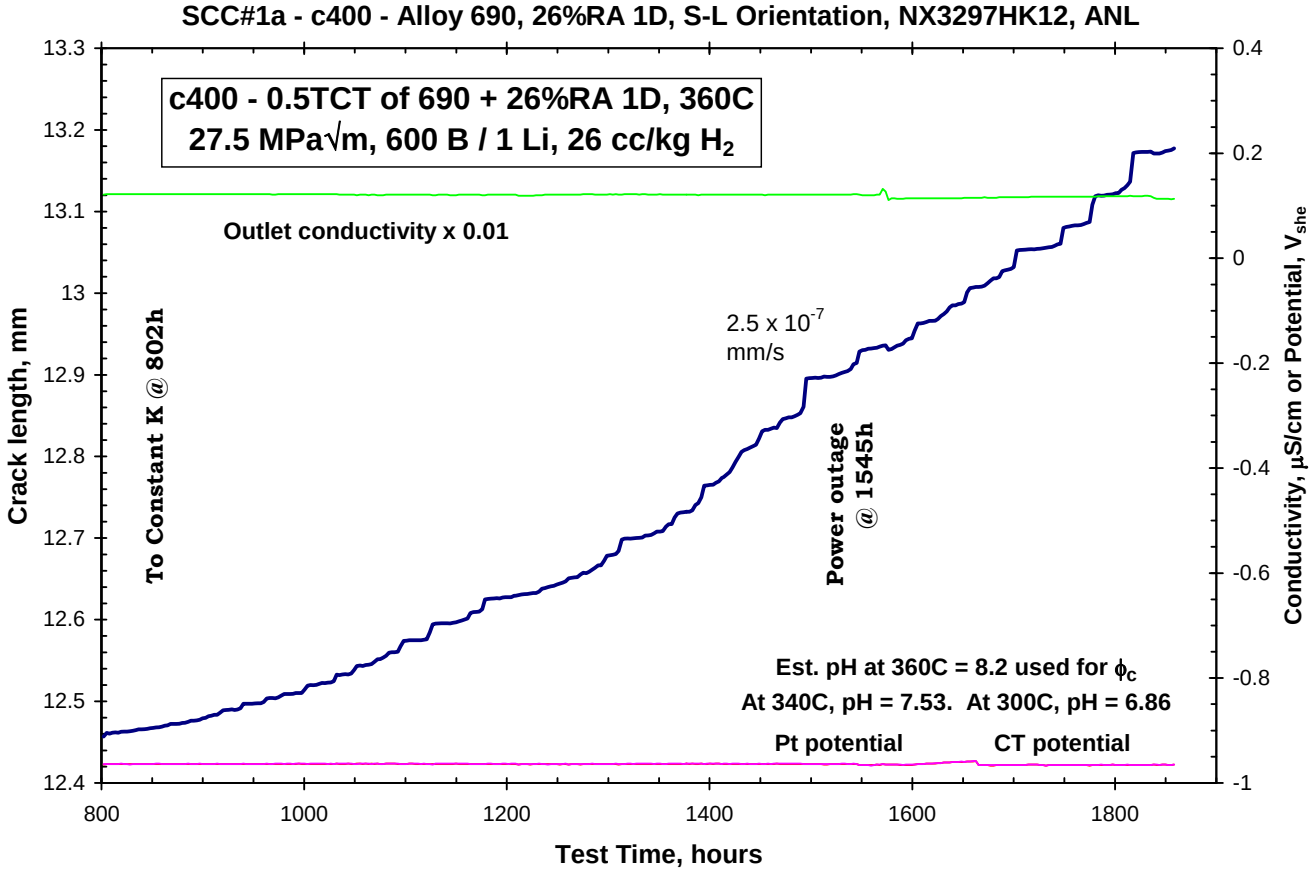


Strain localized in streaked / banded areas of larger grains

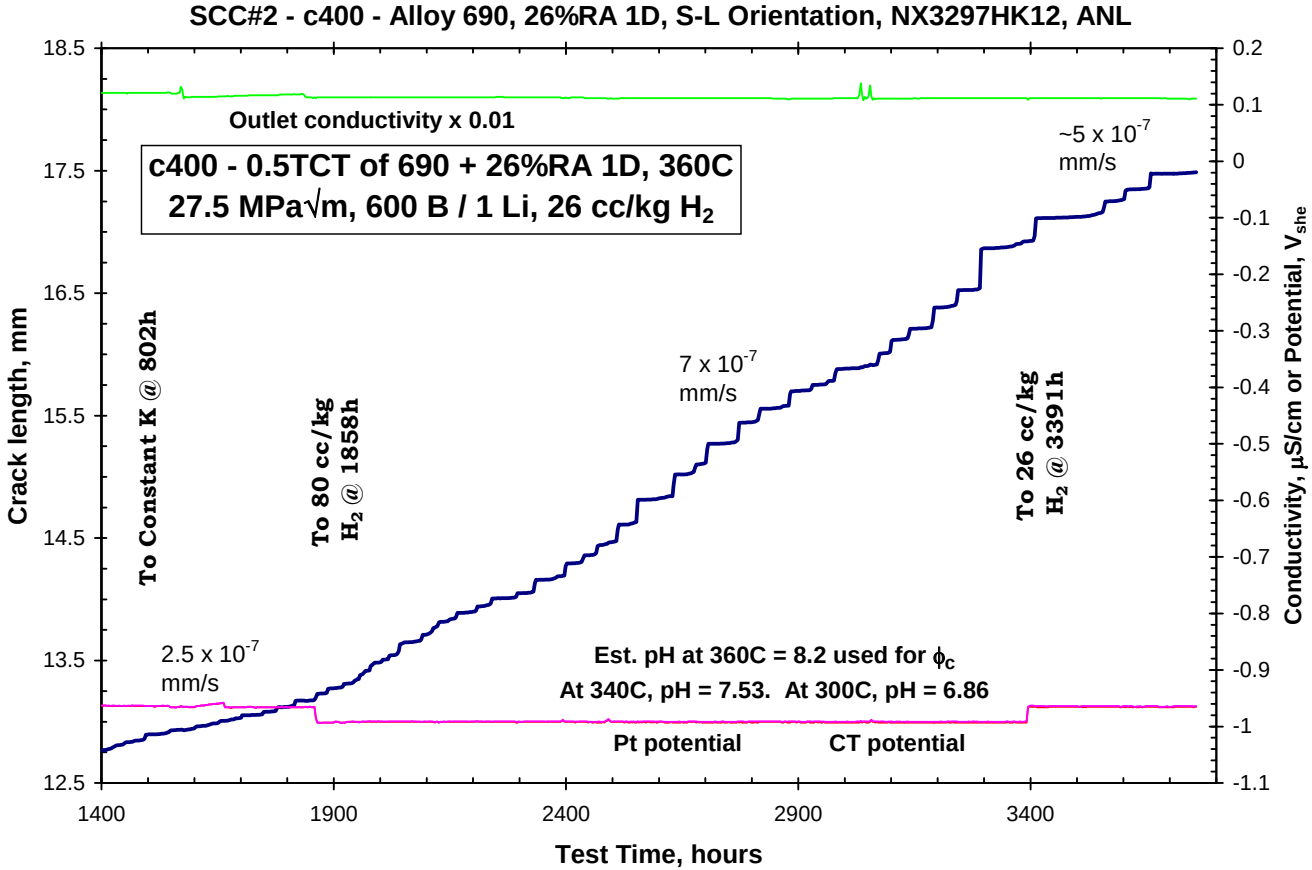
1D, 26% CW ANL Alloy 690 – Test #2



Similar data in second test on same materials

Again ANL + 26% CW grows 5~10X faster than other 690s

1D, 26% CW ANL Alloy 690 – Test #2



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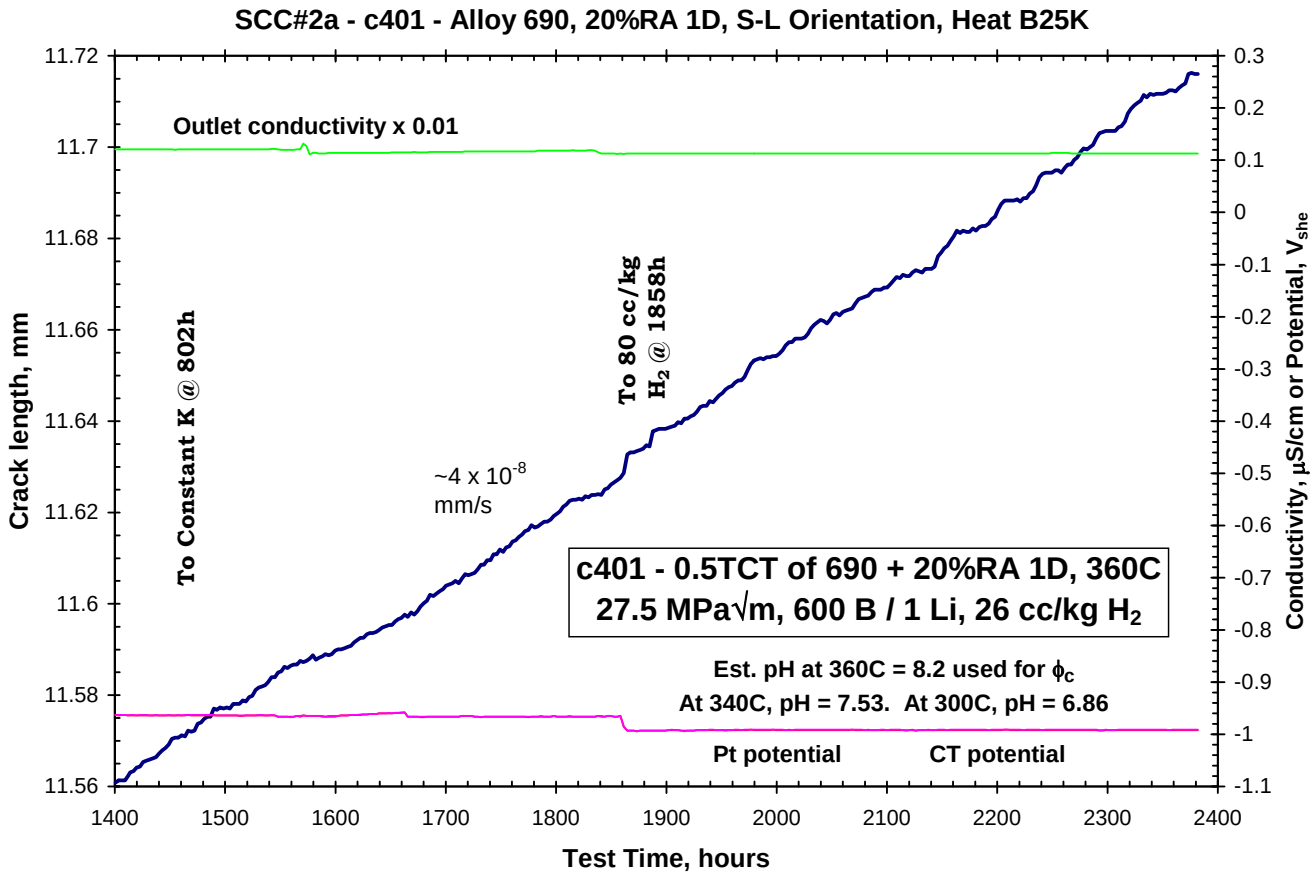
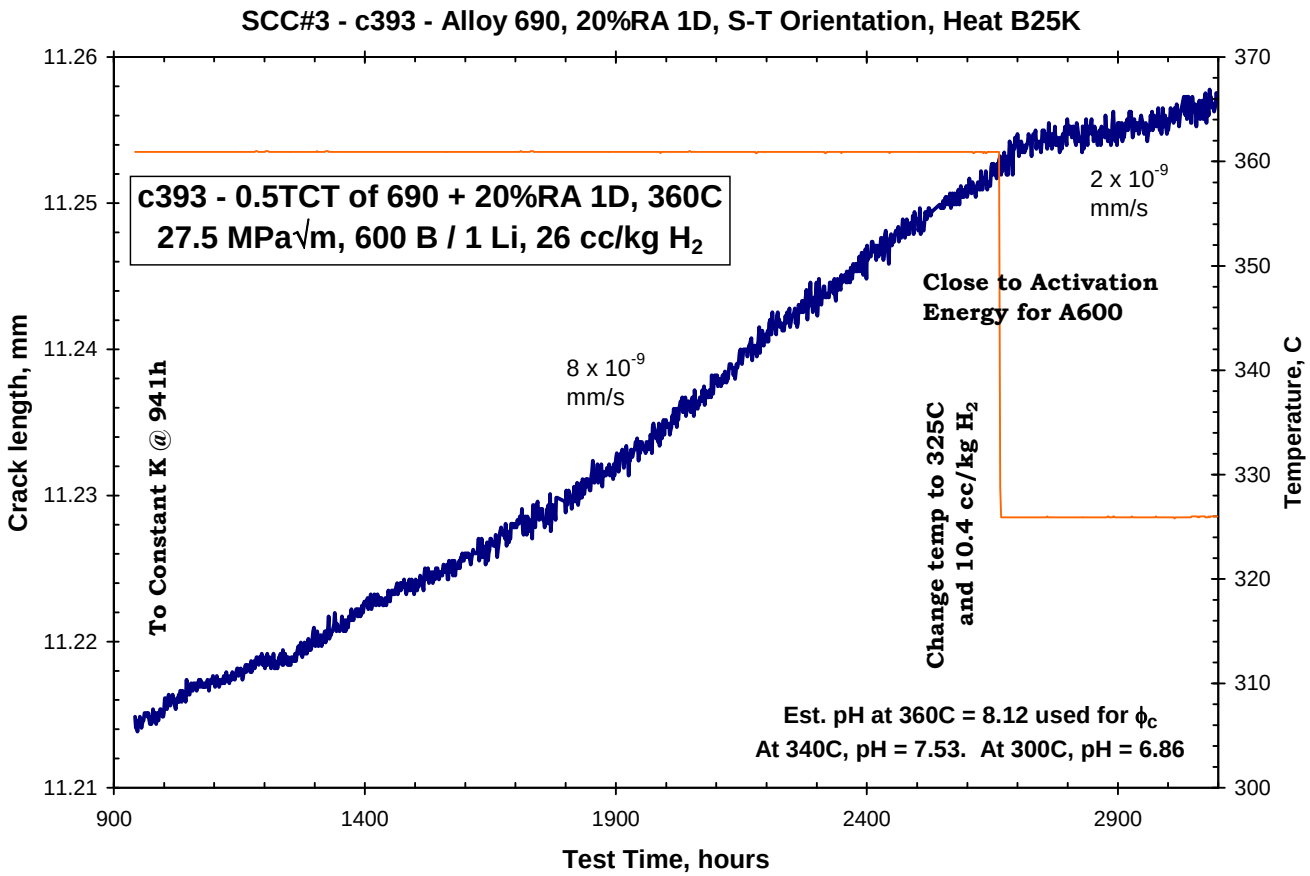
1D, 20% CW GE CRD Alloy 690 – Test #2



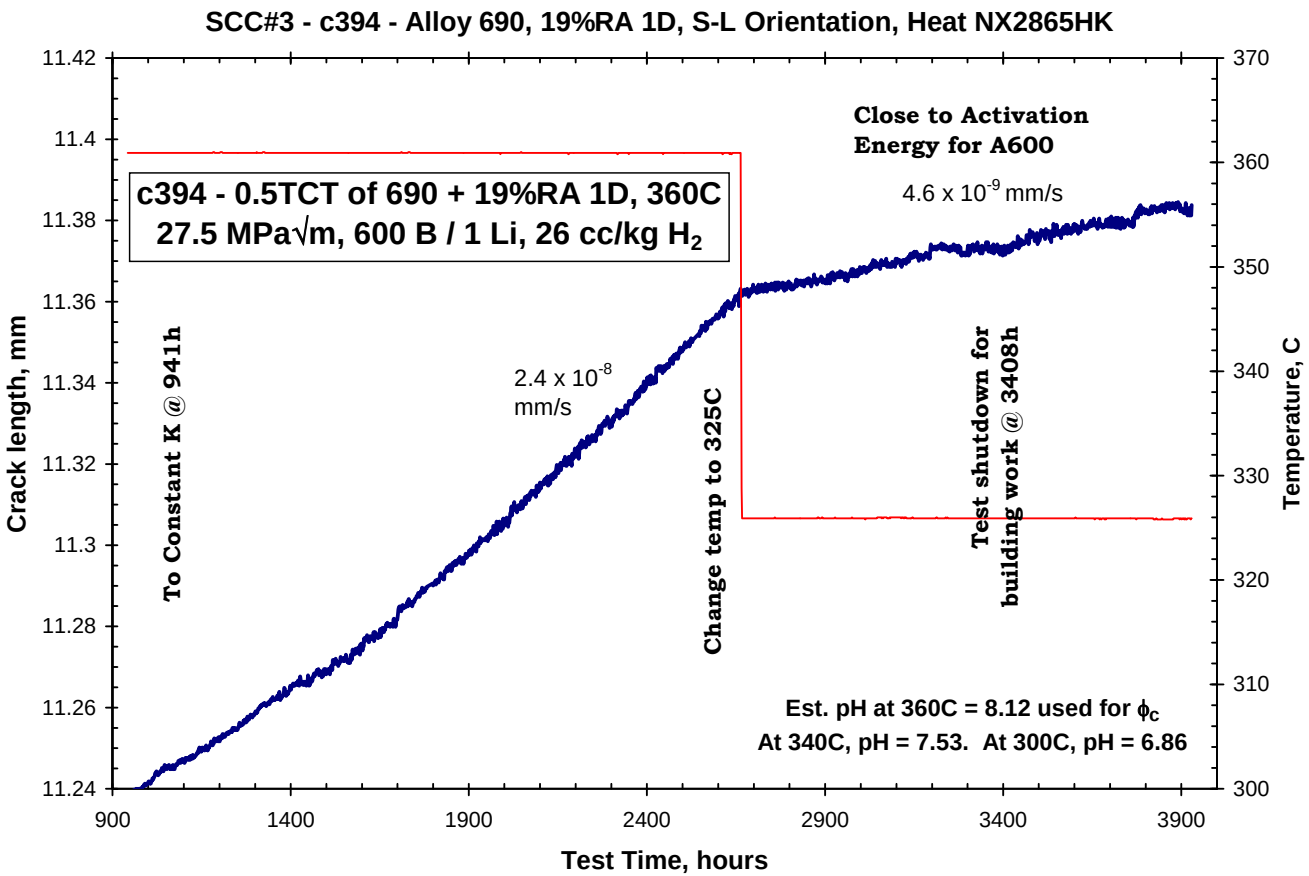
Similar data in second test on same materials

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



Growth similar to the S-L orientation of the GE GRC 690

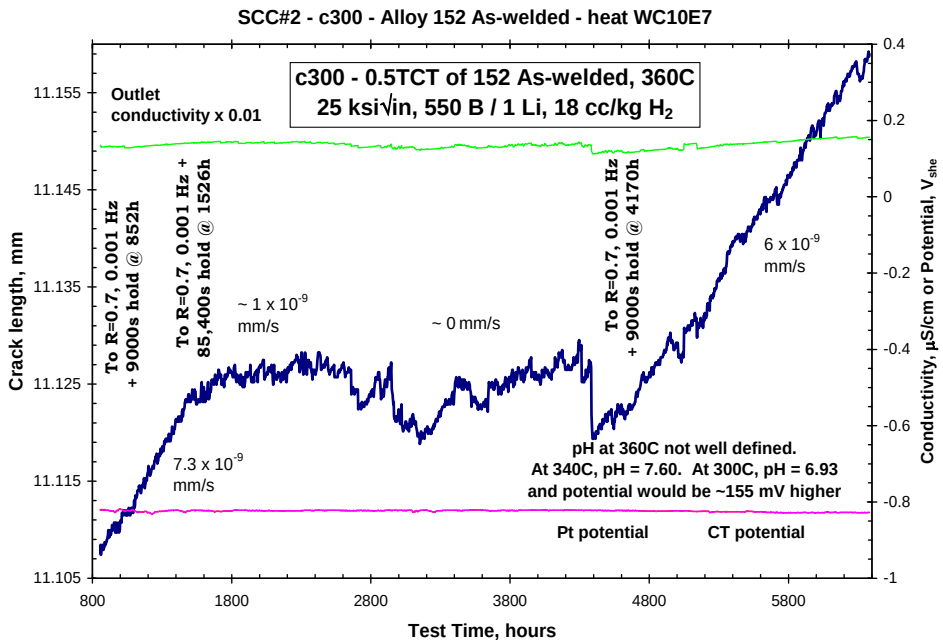
1D, 20% CW KAPL 690 – S-L Orientation

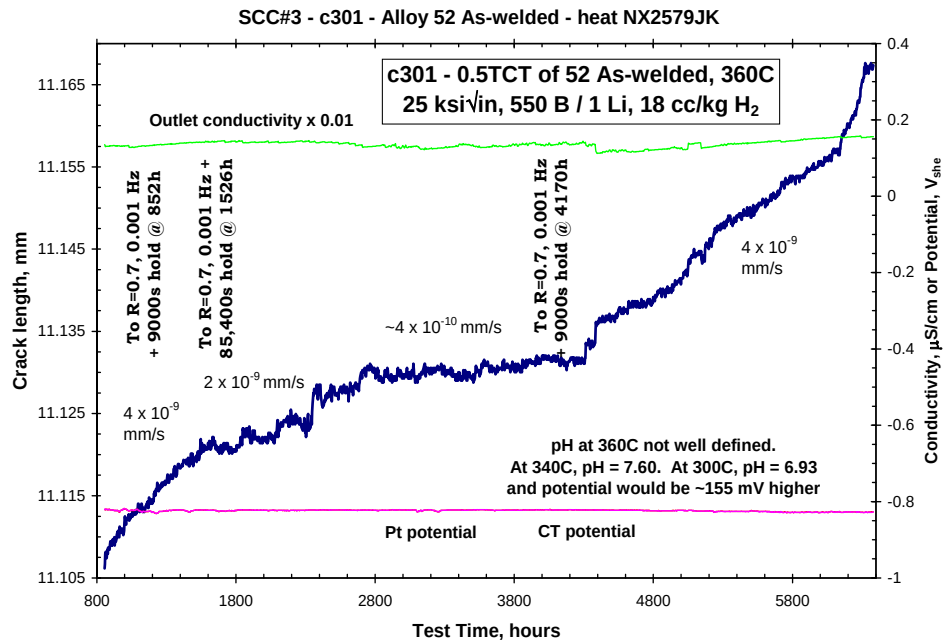


This KAPL 690 behaves similar to GE GRC 690.

Only ANL 1D, 26% cold roll grows very rapidly (5~10X faster)

Alloy 152 & 52 Weld Metal

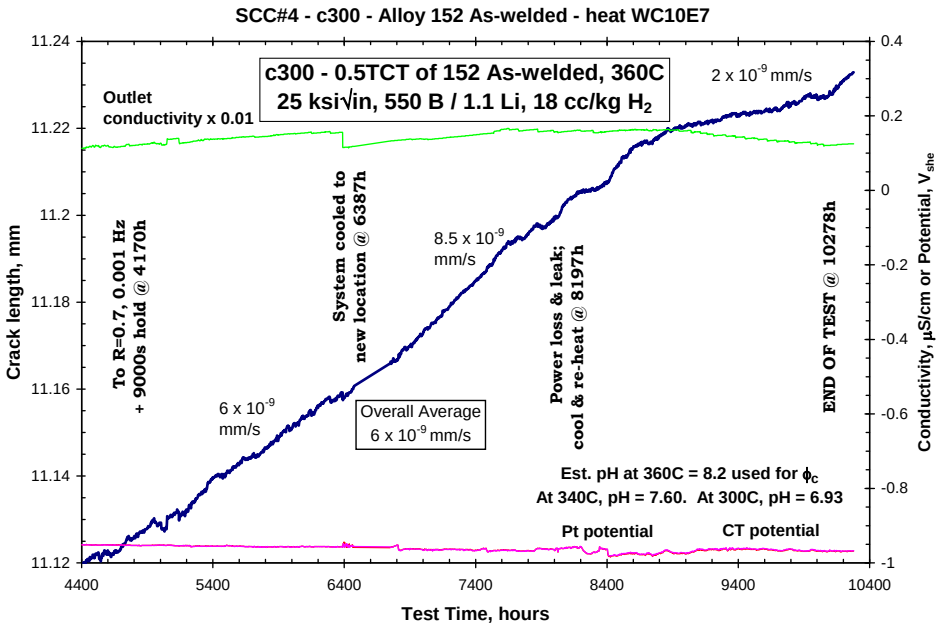


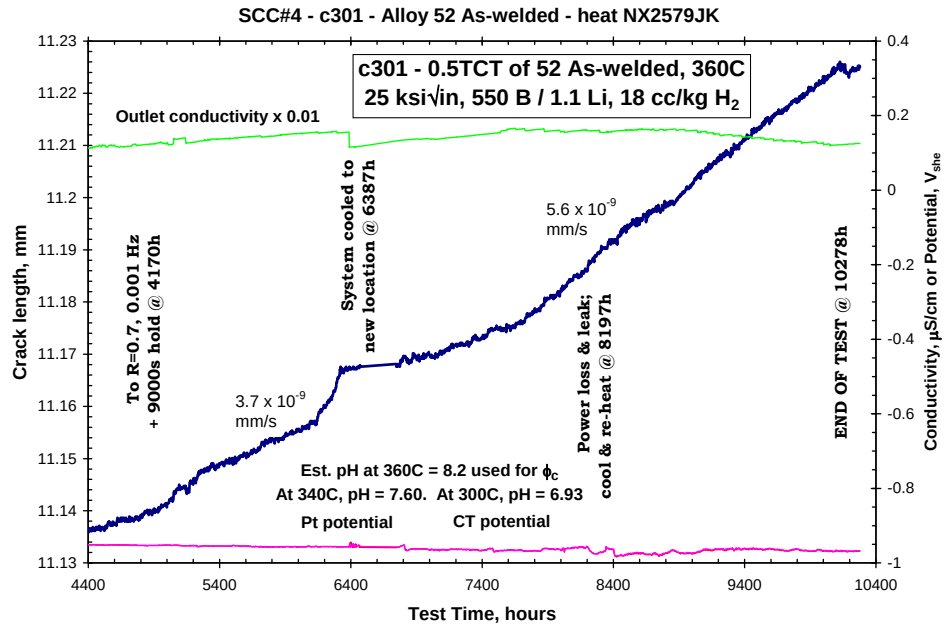


c300 (alloy 152) *c301 (alloy 52)*

EPRI Program – Constant K_{max} + Cycling

Alloy 152 & 52 Weld Metal



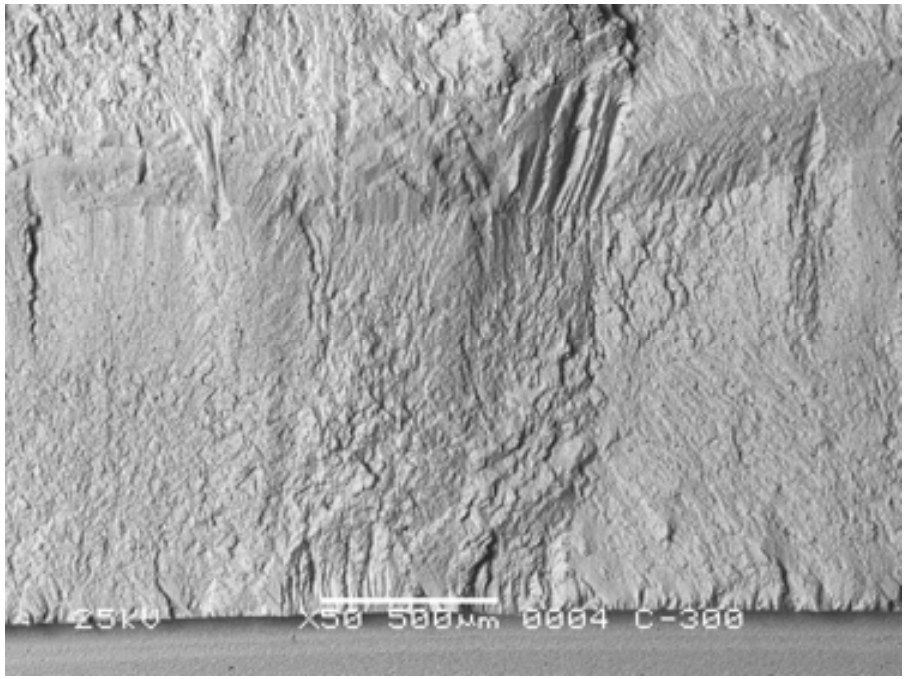


c300 (alloy 152)

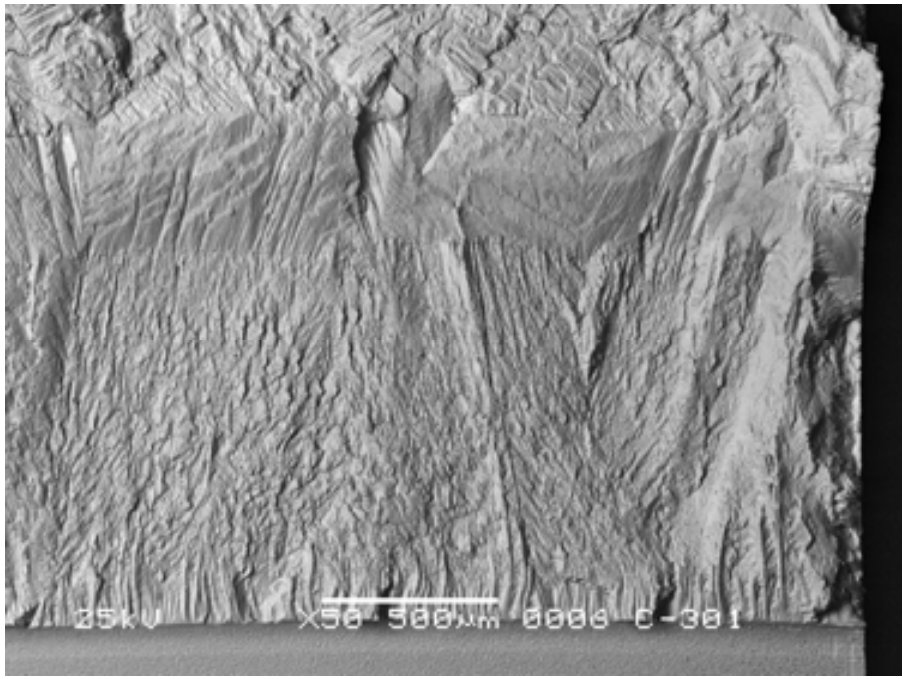
c301 (alloy 52)

EPRI Program – Constant K_{max} + Cycling

Alloy 152 & 52 Weld Metal



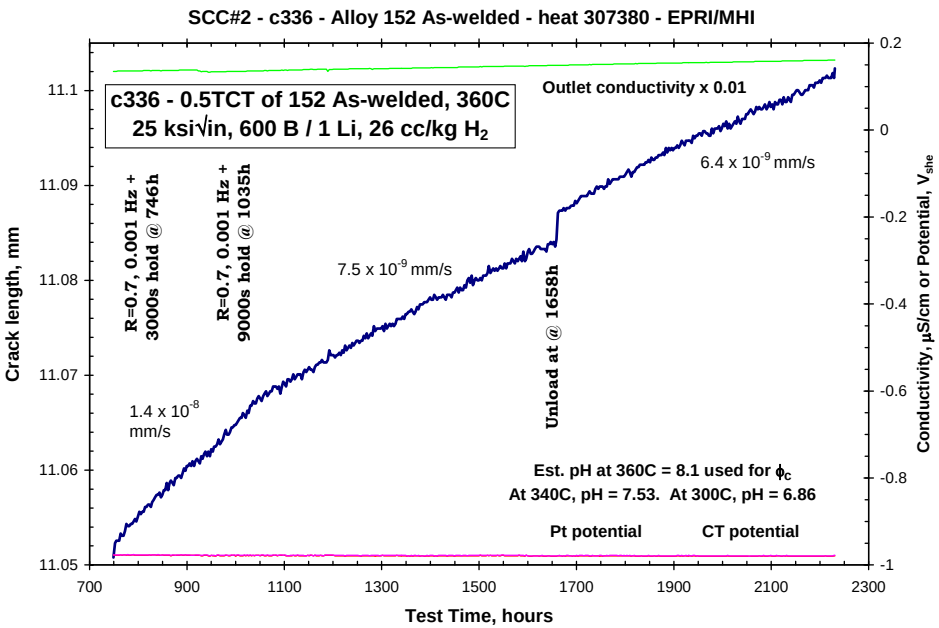
c300 (alloy 152)

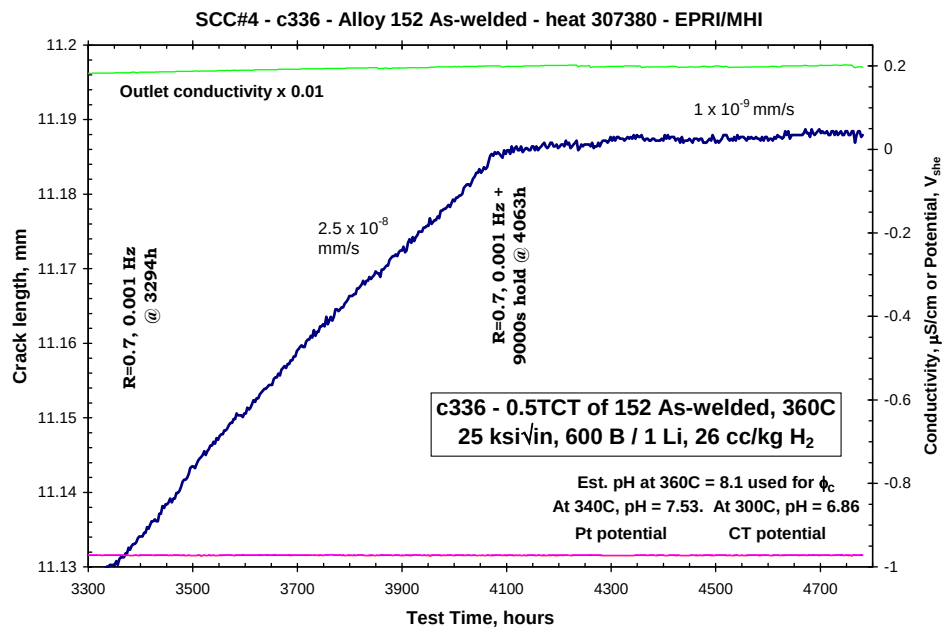


c301 (alloy 52)

EPRI Program – Constant K_{max} + Cycling

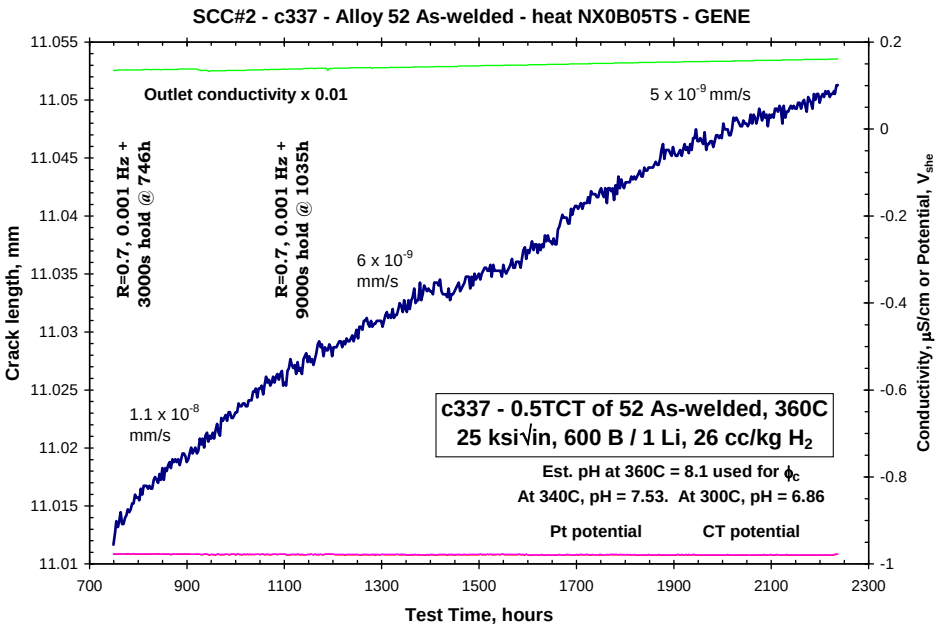
Alloy 152 Weld Metal, c336

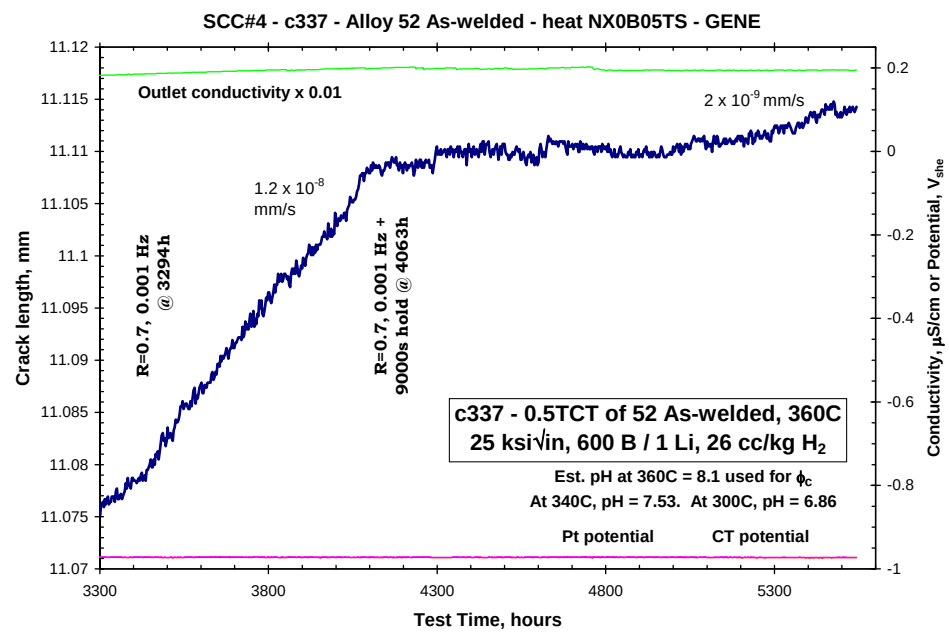




Growth rates are very low

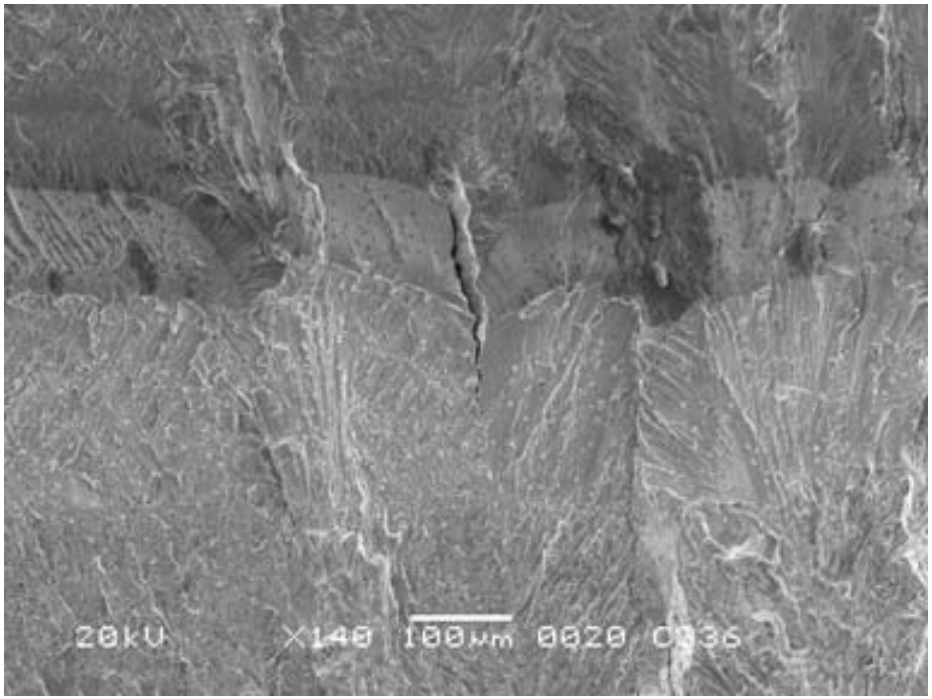
Alloy 52 Weld Metal, c337

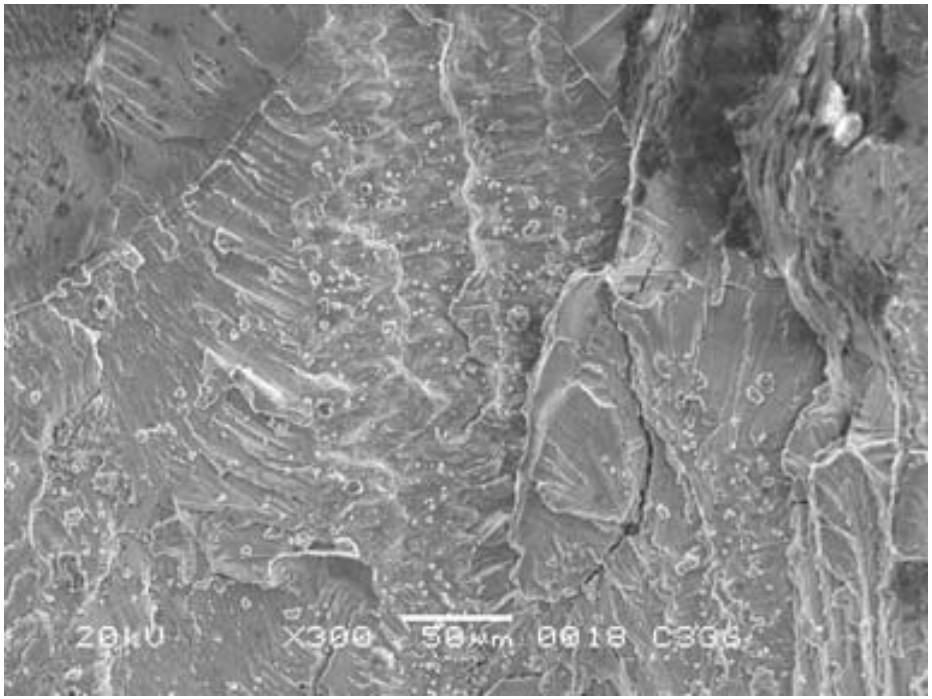


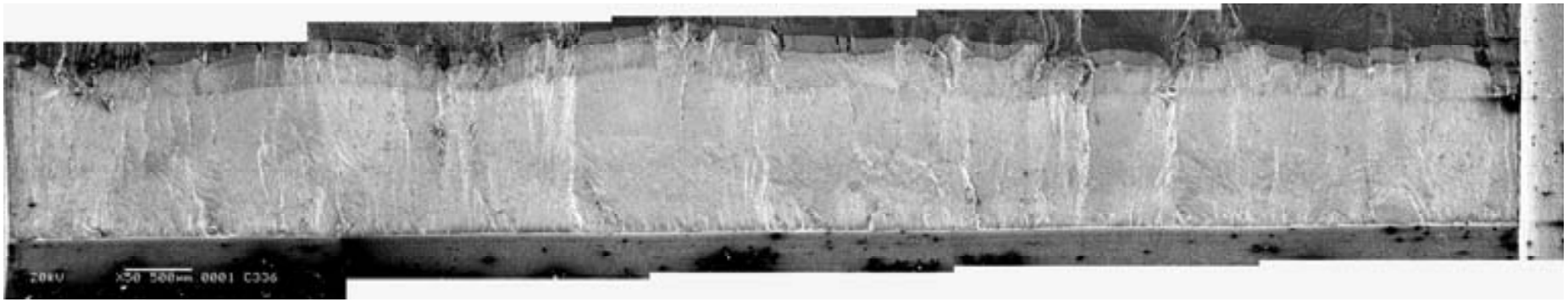


Growth rates are very low

Alloy 152 Weld Metal, c336







Conclusions

Results obtained to date show:

- *slow crack growth at constant K appears to occur in some (but not all) 2D CW Alloy 690, & Alloys 152/52 welds*
- *~10X increased growth rates at constant K in 1-D cold rolled Alloy 690 with crack plane = rolling plane (S-L orientation)*
- *~100X higher CGR for ANL 1D, 26% CW 690 (S-L)*
- *rising dK/da loading shows somewhat higher CGRs and may be relevant in certain field situations*
- *truly intergranular crack propagation – without cycling – has been demonstrated for Alloy 690 base materials*

Future work should examine CW, μS, temperature & H_2 :

- *possibility of increased PWSCC susceptibility in HAZ*
- *PWSCC in other cold work configurations/orientations*
- *effect of "off-microstructures" from material processing/HAZ*