Alloy 690 Base Metal Issues & Strategy

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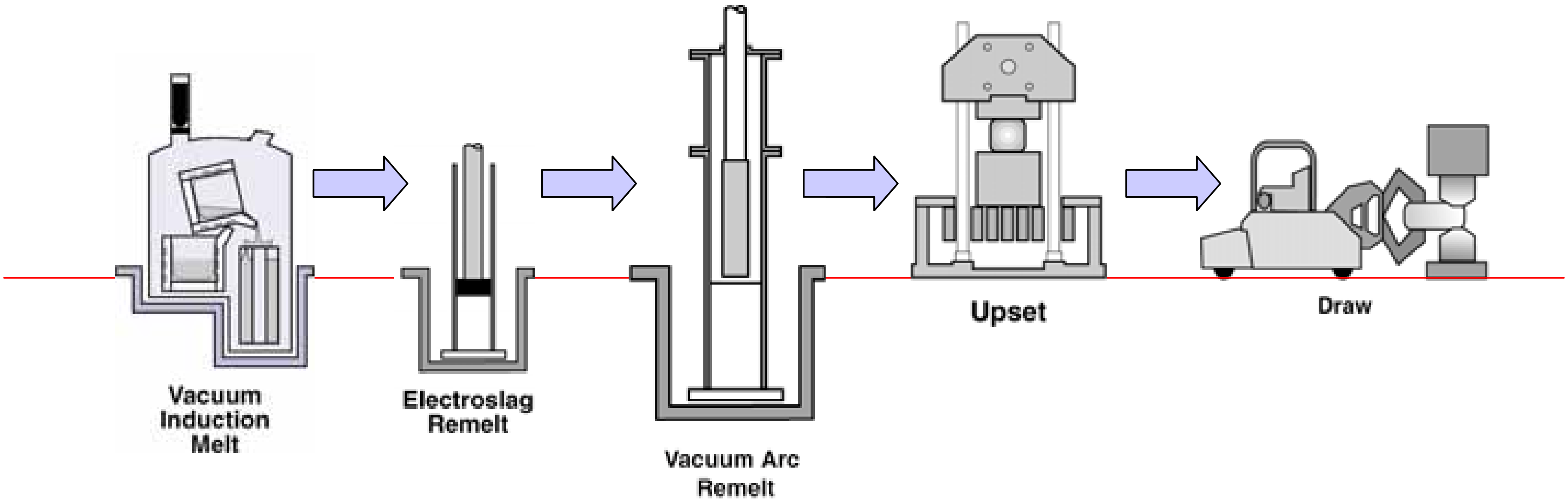
Introduction and Philosophy

- *The industry has made a huge investment in moving to the more SCC resistant Alloy 690 and its weld metals*
- *Vulnerabilities will be understood and resolved, and specs developed to prevent problem conditions/microstructures*
- *One vulnerability is related to a synergy among:*
  - *inhomogeneous microstructures,*
  - *directional deformation and*
  - *crack plane orientation relative to structure & deformation*
- *Cracks find the problem areas, so we must evaluate these problem areas without just focusing on ugly material.*

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*

Thermo-Mechanical Processing



Steps used to melt and Thermo-Mechanical-Process (TMP) Ni-Fe base superalloys from ingot to billet

Segregation and inhomogeneities are much bigger issues in high Cr,Nb alloys like Alloys 690 and (esp.) 718

Processing of an ESR Ingot

Large ESR ingot (left) after heating for drawing operation (right)

Metal Specifications

Good specifications should eliminate inhomogeneities and banding without adding to cost.

Processing Alloy 690 is not complex or poorly understood, but some forms (e.g., plate) are more prone to inhomogeneities.

Vendors work to the spec, so it must address compositional banding and related inhomogeneities, including large or banded grain size, MC carbides, gb carbide decoration, etc.

Macro-etching of full cross-sections or center-mid-edge sampling will identify banding.

Technical Background

Factors that enhance SCC growth rates include:

- *Water chemistry – high Cr 690 is very resistant here*
- *Yield strength – all materials seem to suffer at high YS*
- *Stress Intensity Factor – often higher in high YS materials*

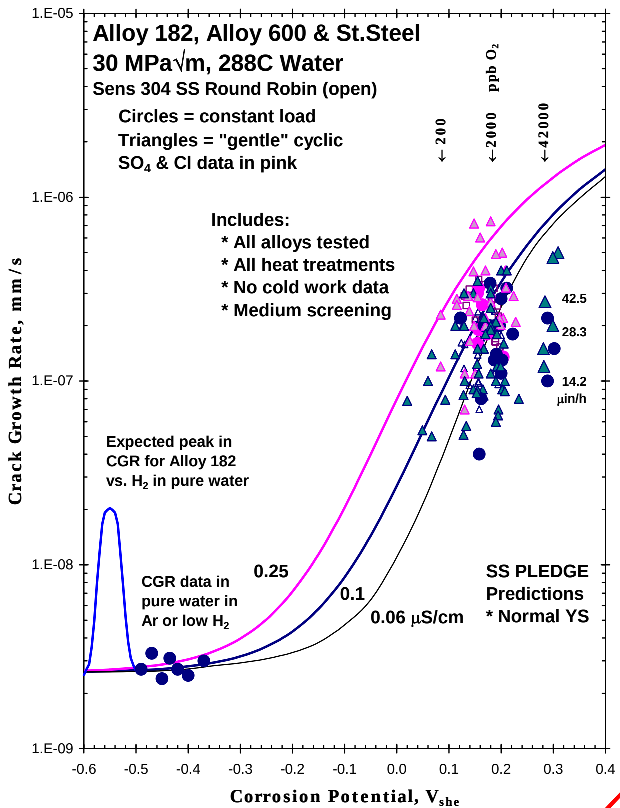
Weld HAZ affects microstructure and imposes high residual ε

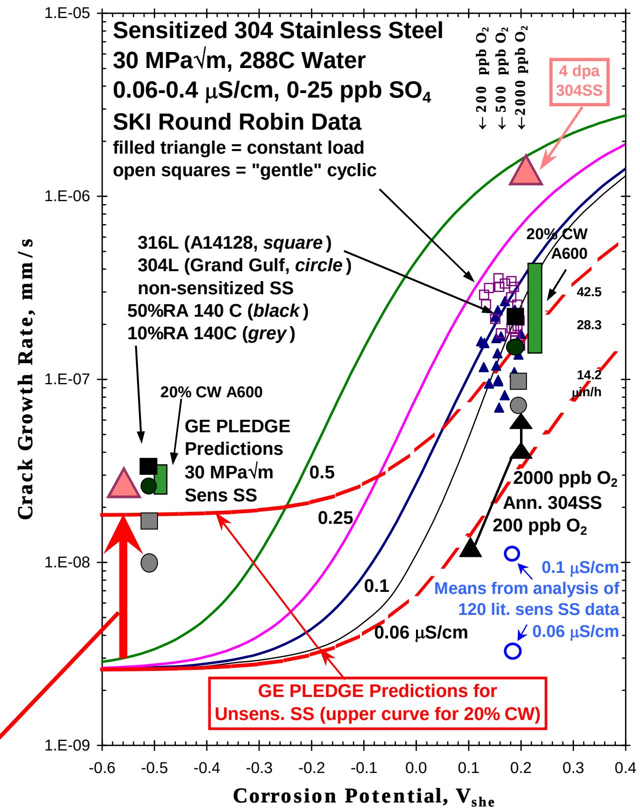
- *EBSD is very effective in quantifying/mapping strain*

YS increases CGR by ~10X. Additional ~10X effect of:

- *Inhomogeneous microstructures* +
- *Directional deformation* +
- *Crack plane orientation relative to structure & deformation*

Effects of Yield Strength / Cold Work



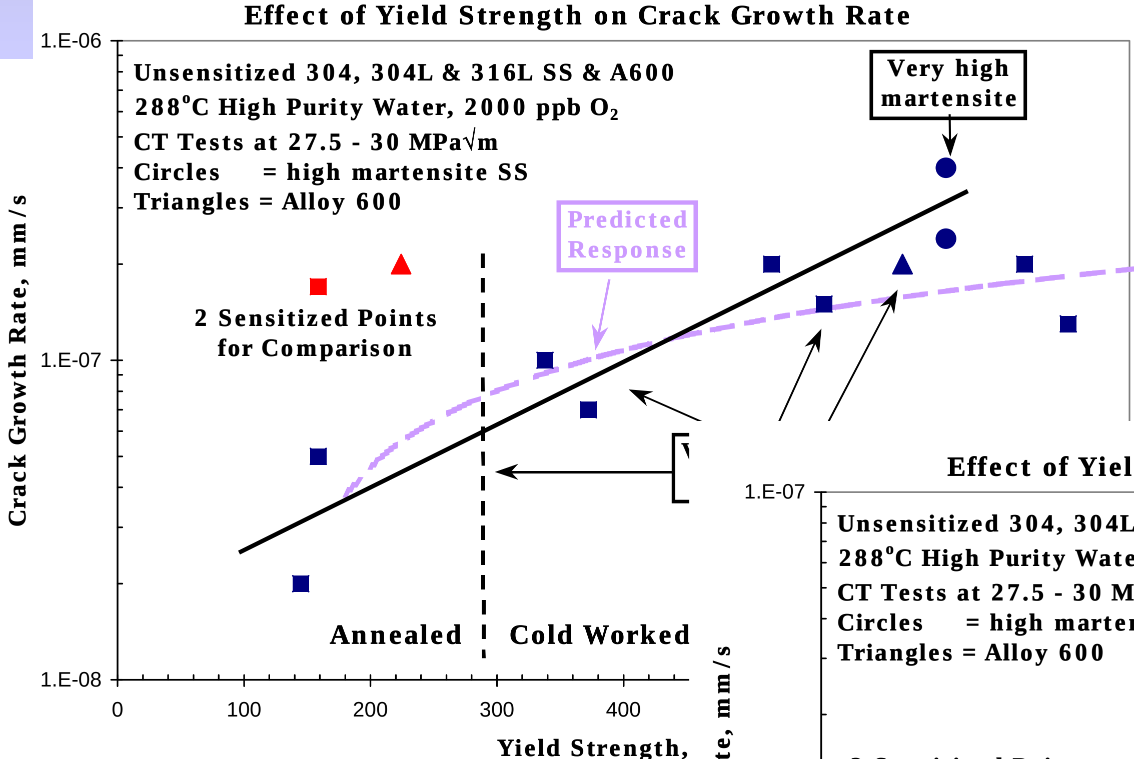


Square & rectangular data are CW SS & CW A600

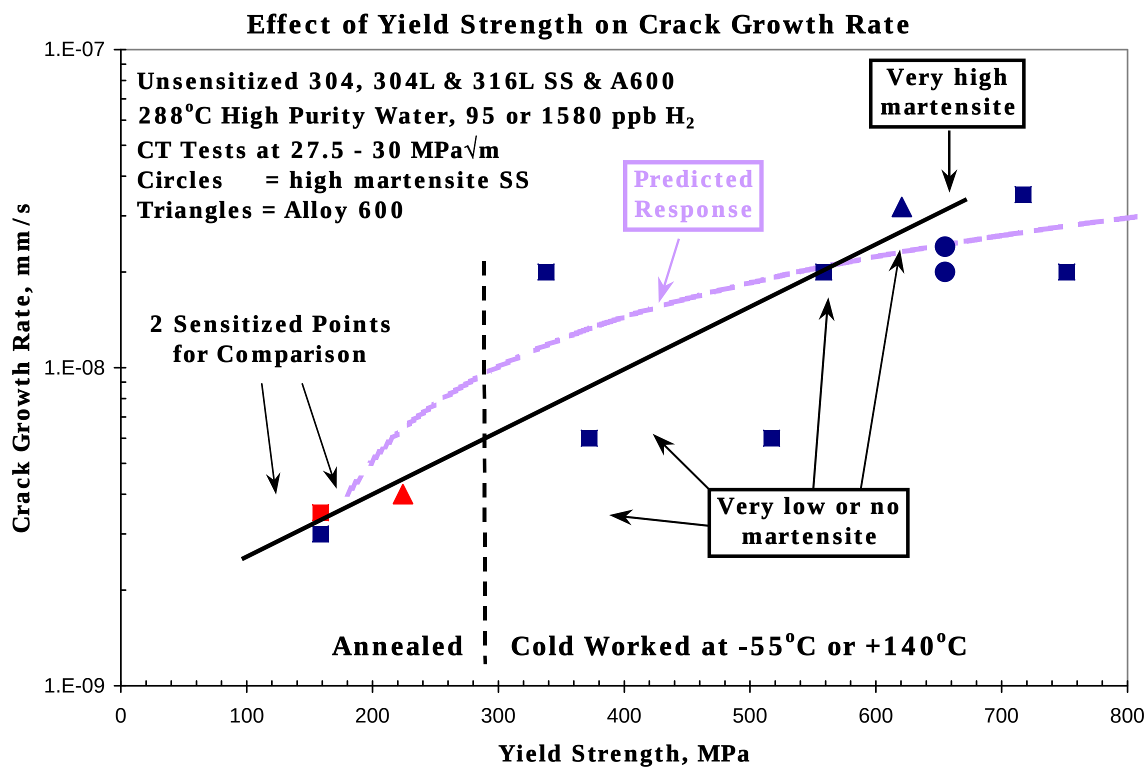
Nickel alloys & stainless steels are not fundamentally different

Roughly 10X increase from 15 – 30% cold work in most cases

Alloy 690 Base Metal Strategy



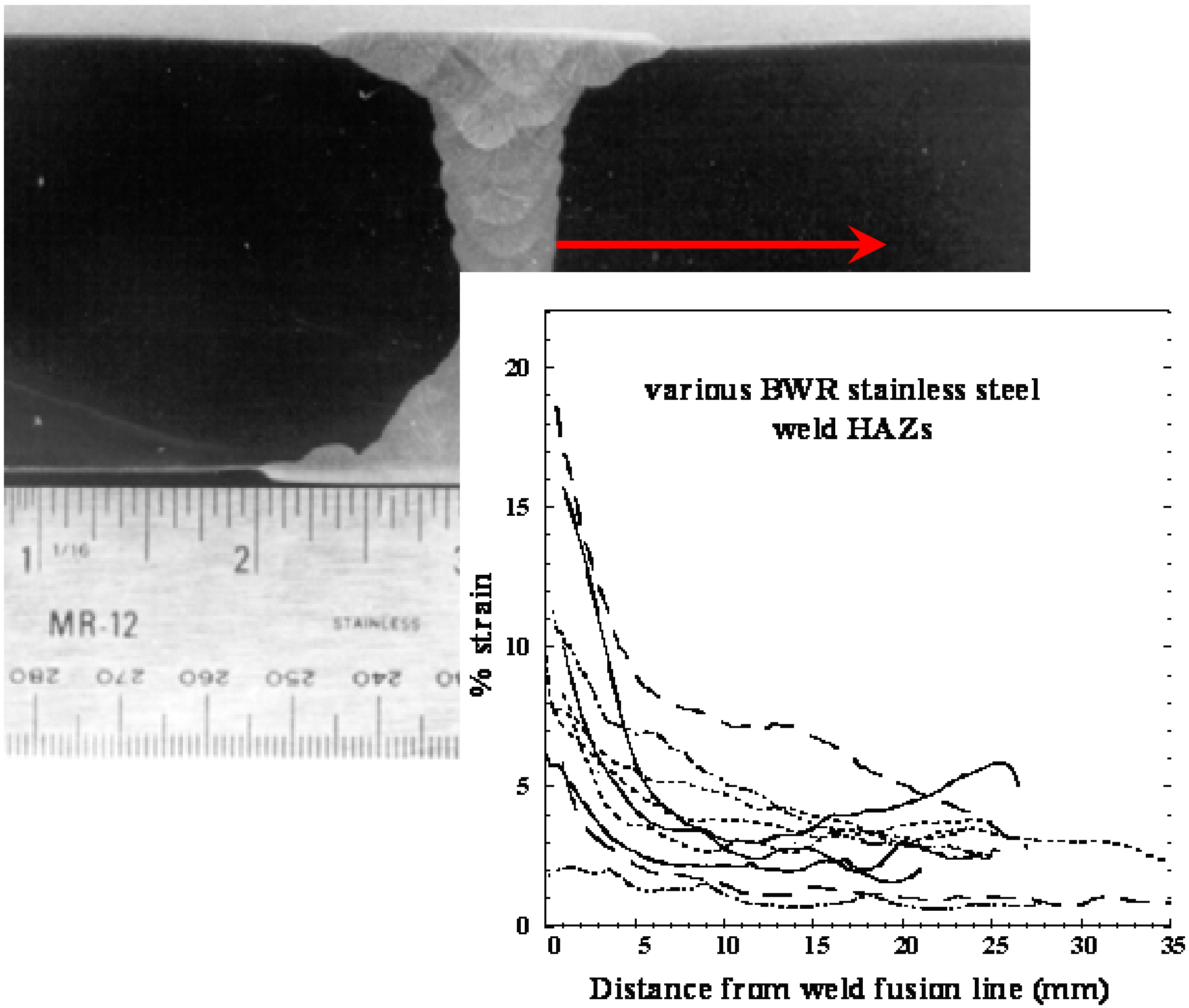
SCC Response vs. YS



High potential

Low potential

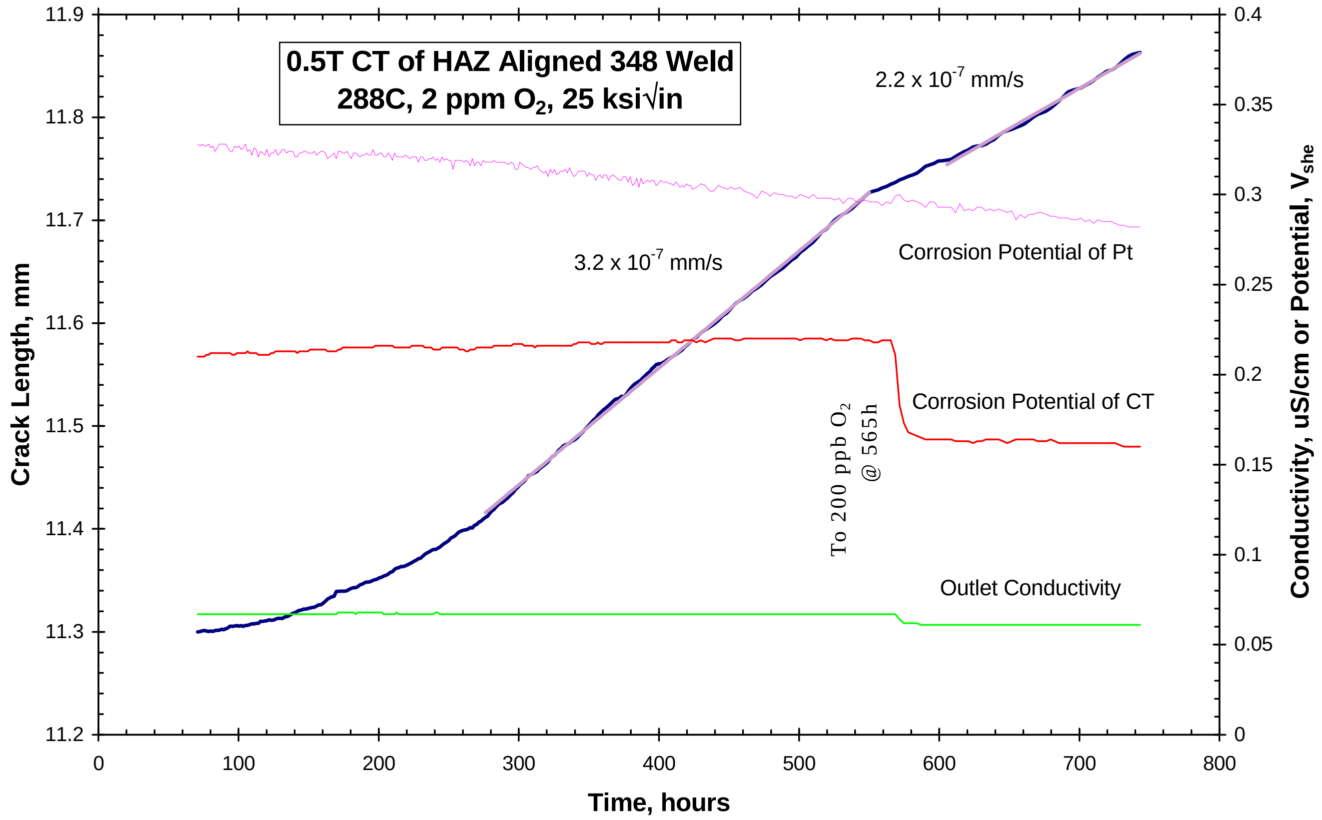
Effects of Yield Strength / Cold Work



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 Affects SCC Like CW

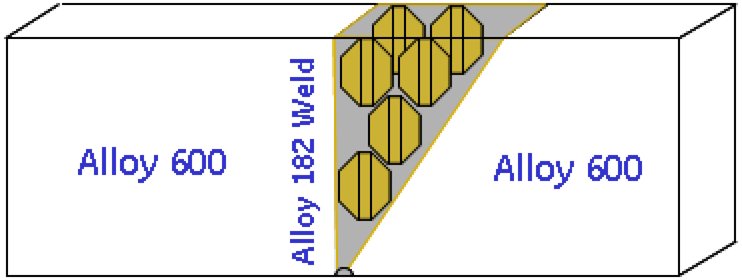


Weld HAZ aligned CT specimen of high quality German 348 SS.

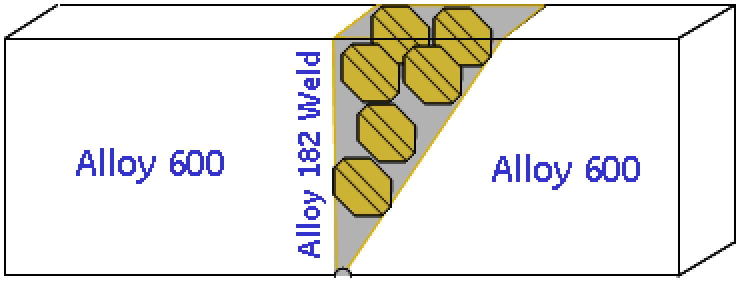
8 – 10 weld HAZ aligned specimens of various materials tested

EBSD of Double-Cone Compression of Alloy 182

- Six transverse direction specimens.
  Upset at strain rate = 0.01/sec
- Final Strains: 0.05, 0.11, 0.22, 0.36, 0.51, 0.69
- Six longitudinal direction specimens.
  Upset at strain rate = 0.01/sec
- Final Strains: 0.05, 0.11, 0.22, 0.36, 0.51, 0.69
- 140°C isothermal, corrected for adiabatic heating

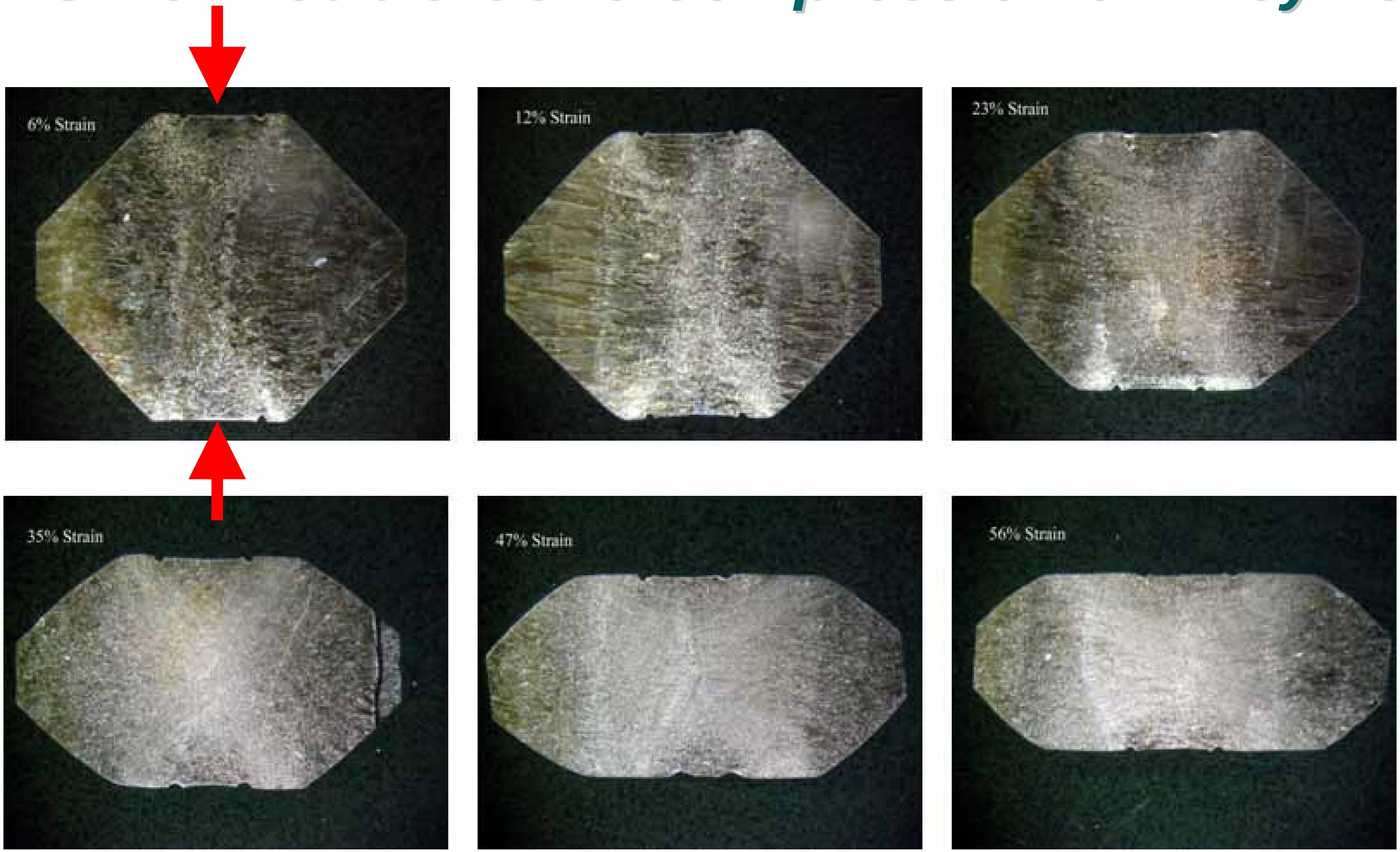


6 Samples
Transverse to Weld Deposition Direction



6 Samples
Longitudinal to Weld Deposition Direction

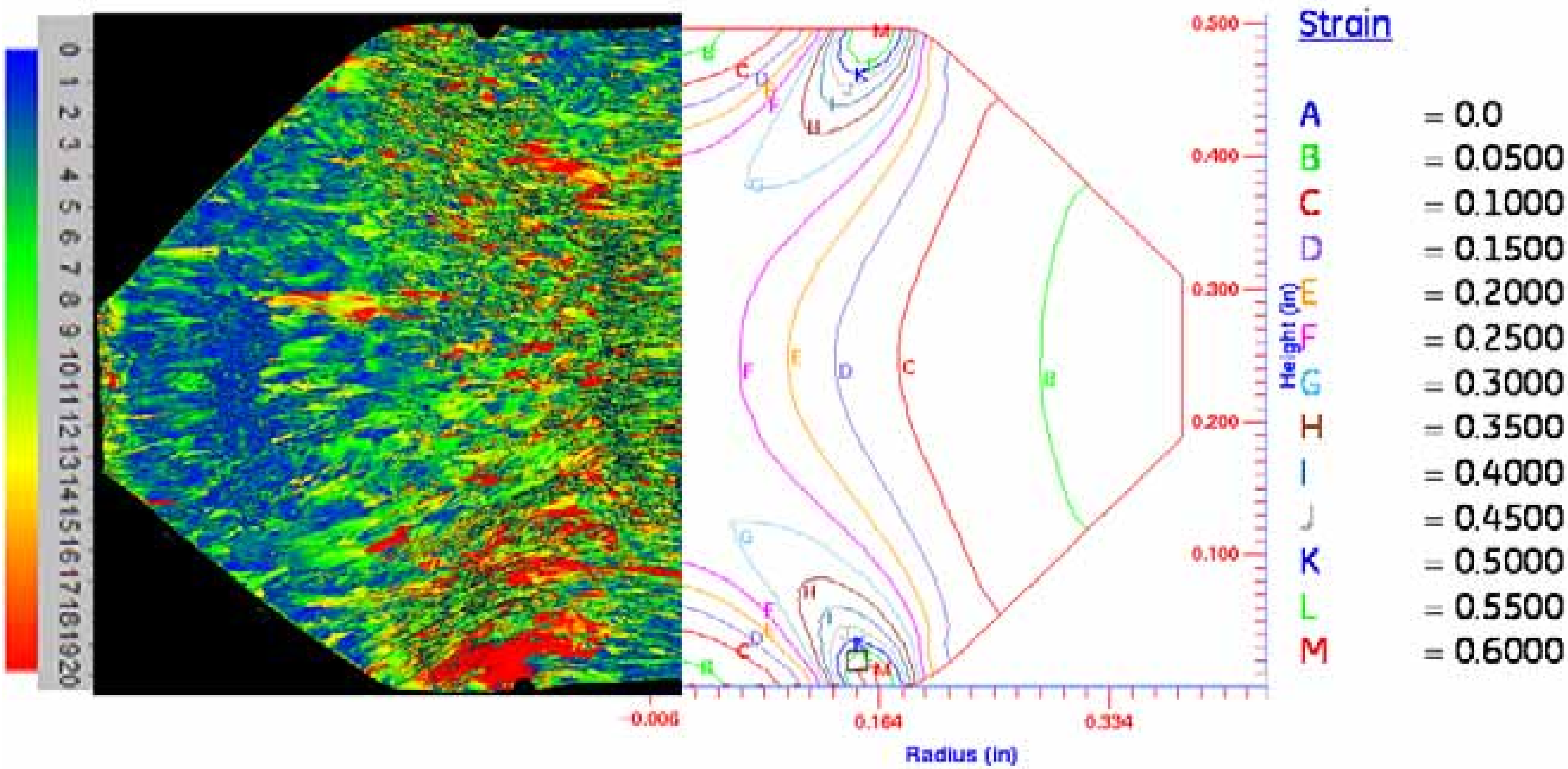
EBSD of Double-Cone Compression of Alloy 182



Double-cone compression specimens give very well defined strain contours

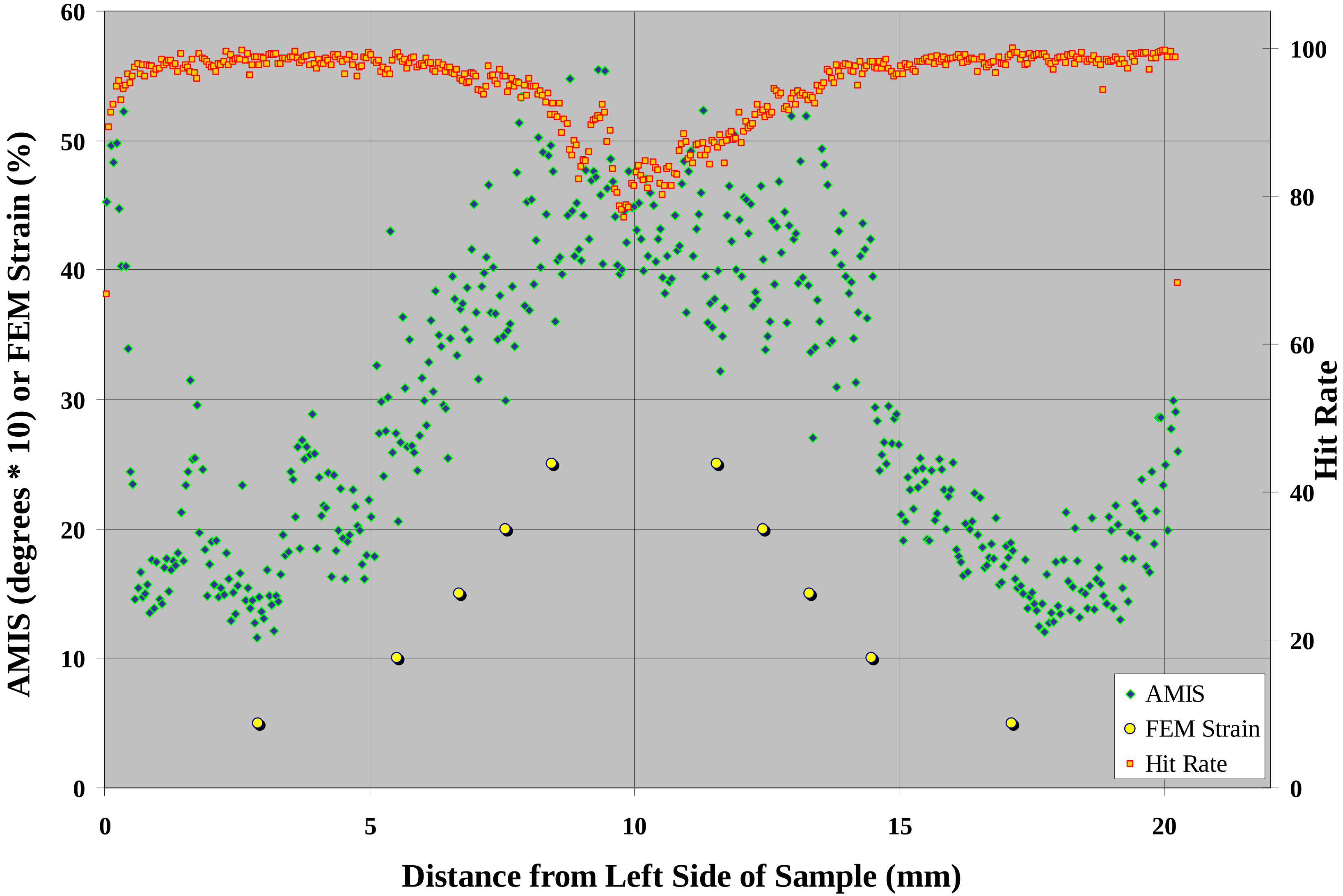
EBSD of Double-Cone Compression of Alloy 182

EBSD **Finite Element Modeling**



Misorientation map compared to FEM prediction of strain contours after application of geometric 0.23 compressive strain to double cone.

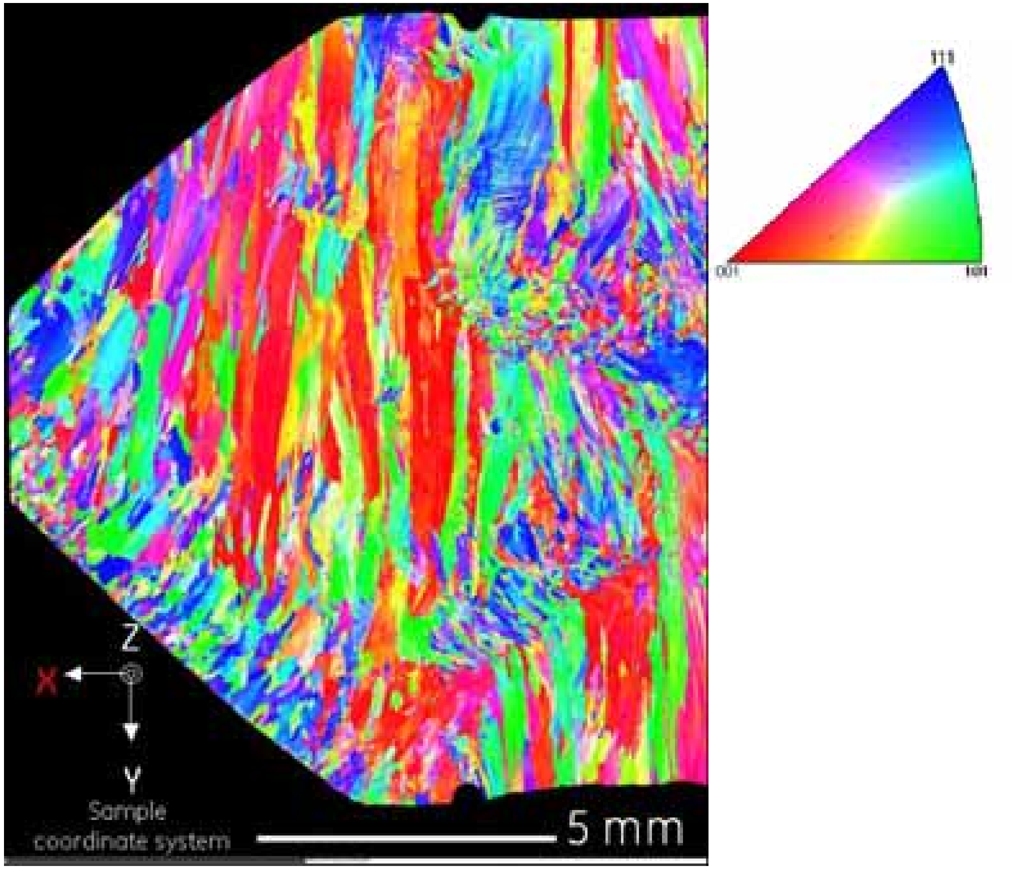
EBSD of Double-Cone Compression of Alloy 182



EBSD of Double-Cone Compression of Alloy 182

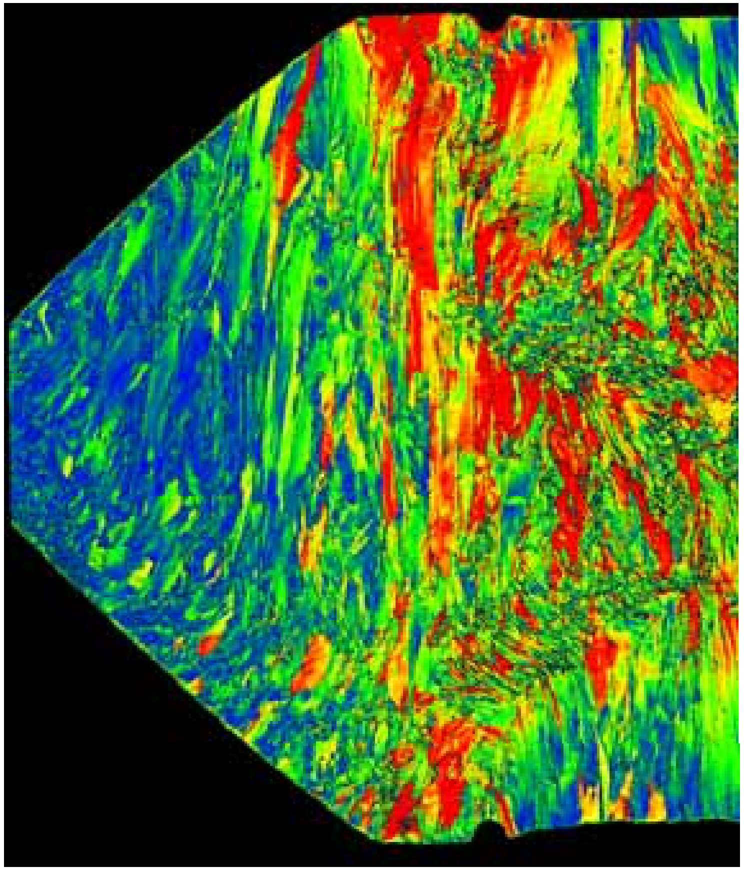
Inverse Pole Figure – x orientation maps

Sample MR2911-L3 longitudinal to weld direction 0.237 geometric strain



Misorientation (strain) map

Sample MR2911-L3 – Dendrite long axes parallel to compression axis



EBSD Characterization

Given its proven capability, EBSD should be used to characterize a wider cross-section of welds and structures:

- *HAZ and weld metal of std. “planar” welds*
- *HAZ and weld metal of std. circular (e.g., CRDM) welds*
- *uniformity of cold work and surface layers in base metals*
- *uniformity of deformation in banded microstructures*

Weld HAZ aligned SCC specimens should also be used, but:

- *a planar interface is critical; not all welds are suitable*
- *larger radius side-grooves give flexibility to crack plane*
- *must plan on only perhaps 33% of tests working well*

SCC Response in Alloy 690

Alloy 690 is not immune, but cracks appear to grow slowly unless there is a confluence of:

- *Inhomogeneous microstructures*
- *Directional deformation*
- *Crack plane orientation relative to structure & deformation*

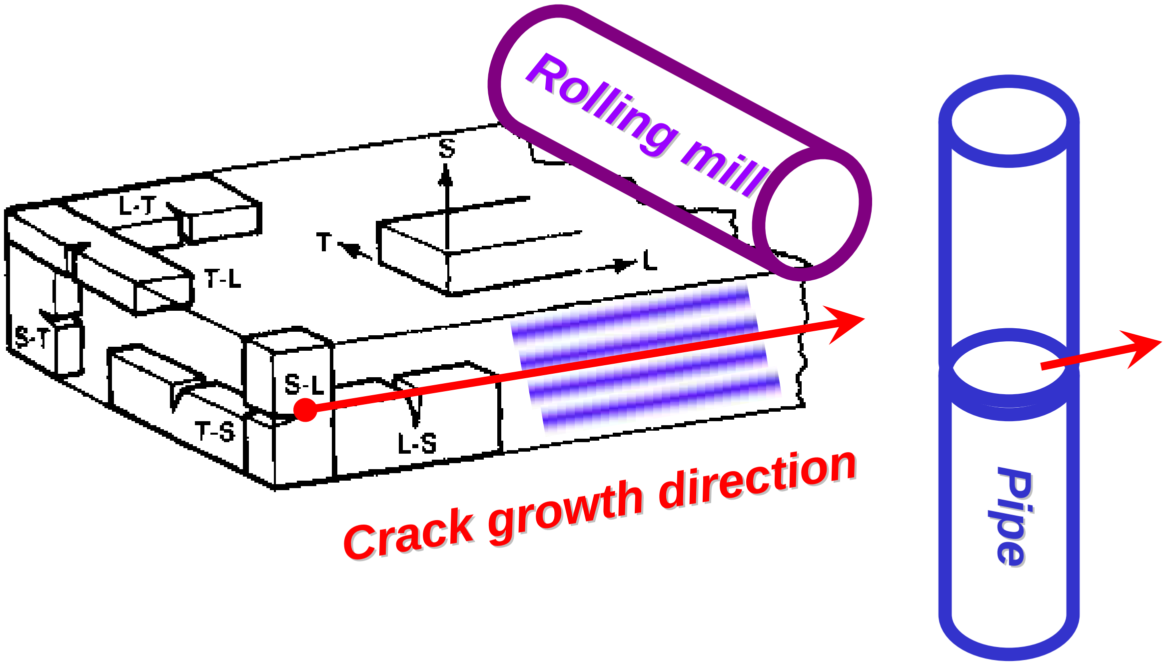
Approximate / Conceptual SCC Response

Microstructure	Cold Work*	Crack Plane	CGR, mm/s
Excellent	None	Any	$<2 \times 10^{-9}$
Excellent	2D Forging	Out-of-bands, TL	$\sim 5 \times 10^{-9}$
Excellent	1.5D Rolling	In-bands, SL	$\sim 4 \times 10^{-8}$
Banded	1.5D Rolling	In-bands, SL	$\sim 4 \times 10^{-7}$

** Cold work levels of perhaps 10 – 30%; Rolling produces spreading = 1.5D*

Orientation of Banding, Deformation & SCC

- *Like welds (dendrite orientation), must consider orientation of banding, deformation & crack plane – not just orientation of component geometry.*

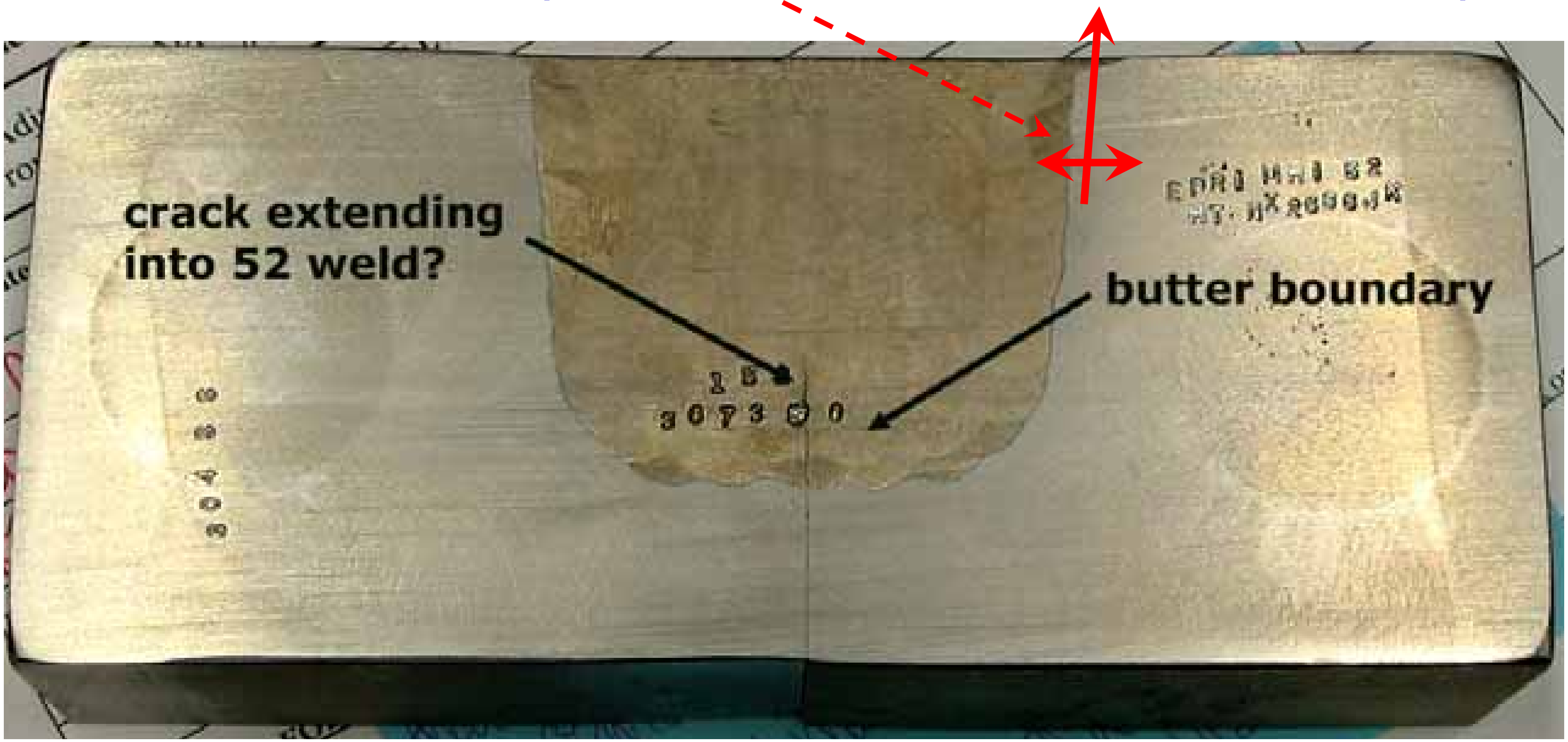


In a pipe butt-weld, the L direction is considered to be the pipe length, but in the weld HAZ the strains and crack orientation represent the S-L orientation in a plate.

Alloys 52/152 Weld Metals

Weld shrinkage strain = "tensile forging"

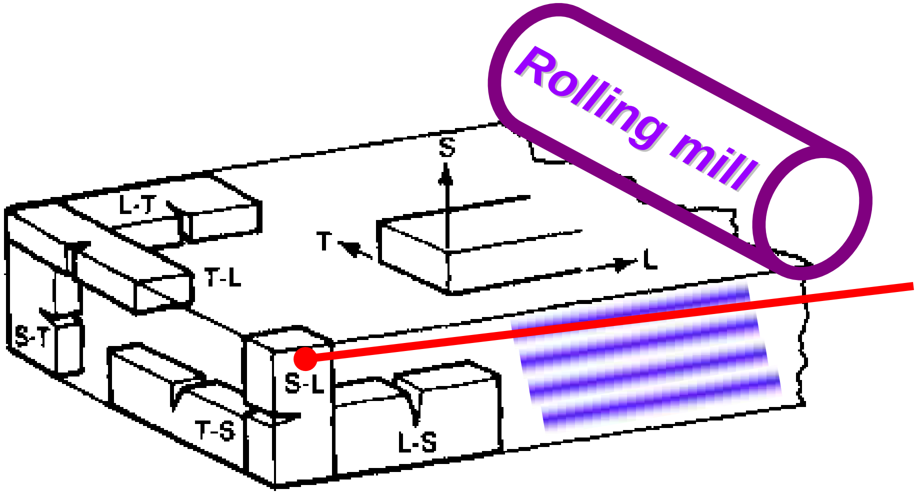
Can consider HAZ equivalent to ***S–L orientation*** *in rolled plate*



Hot crack found in Alloy 52 archive weld

Orientation of Banding, Deformation & SCC

- Like welds (dendrite orientation), must consider orientation of banding, deformation & crack plane – not just orientation of component geometry.



Banding in S planes

Rolled in L direction

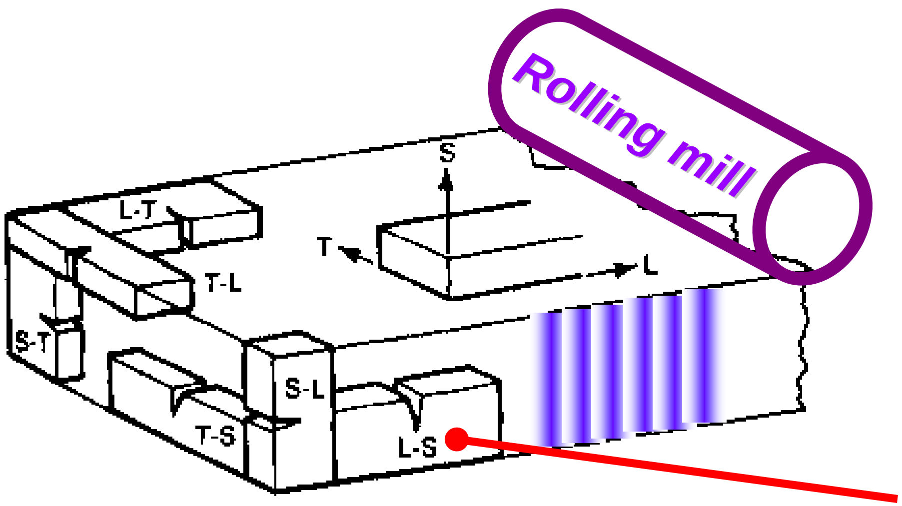
S-L specimen = high CGR

S-T specimen = high CGR

L-T / T-L & T-S / L-S = lower

Orientation of Banding, Deformation & SCC

- *Like welds (dendrite orientation), must consider orientation of banding, deformation & crack plane – not just orientation of component geometry.*



Banding in L planes

Rolled in L direction

S-L specimen = med CGR?

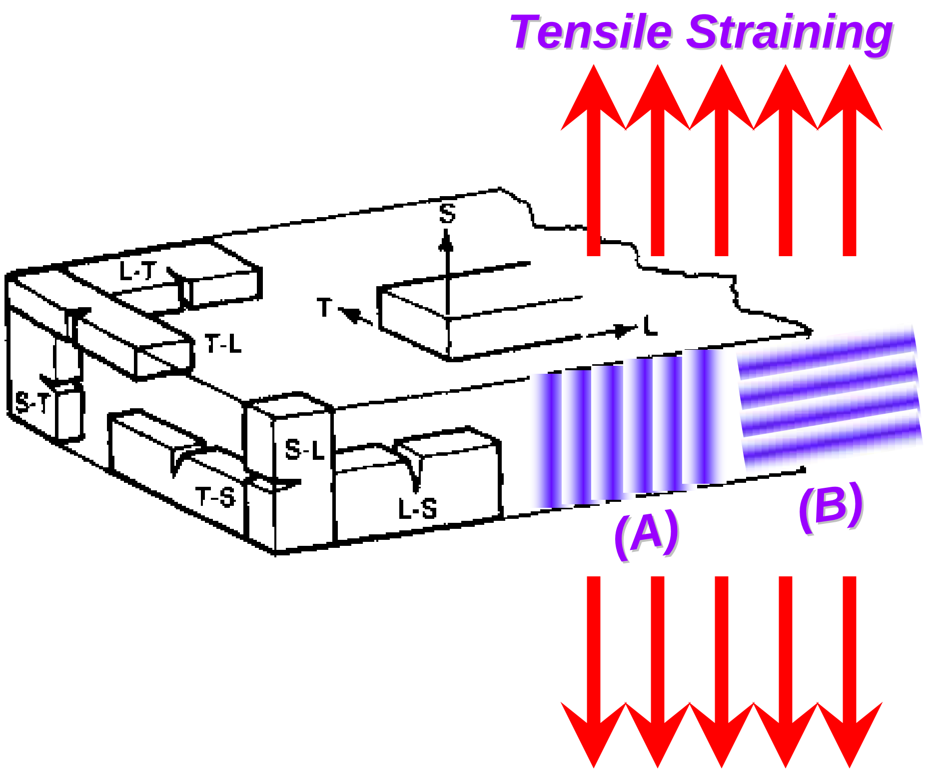
S-T specimen = med CGR?

L-S specimen = high CGR?

It's unclear how deformation will distribute in the banded crack plane and thereby affect SCC

Orientation of Banding, Deformation & SCC

➢ *Like welds (dendrite orientation), must consider orientation of banding, deformation & crack plane – not just orientation of component geometry.*



Tensile straining produces more uniform deformation if banding is parallel (A).

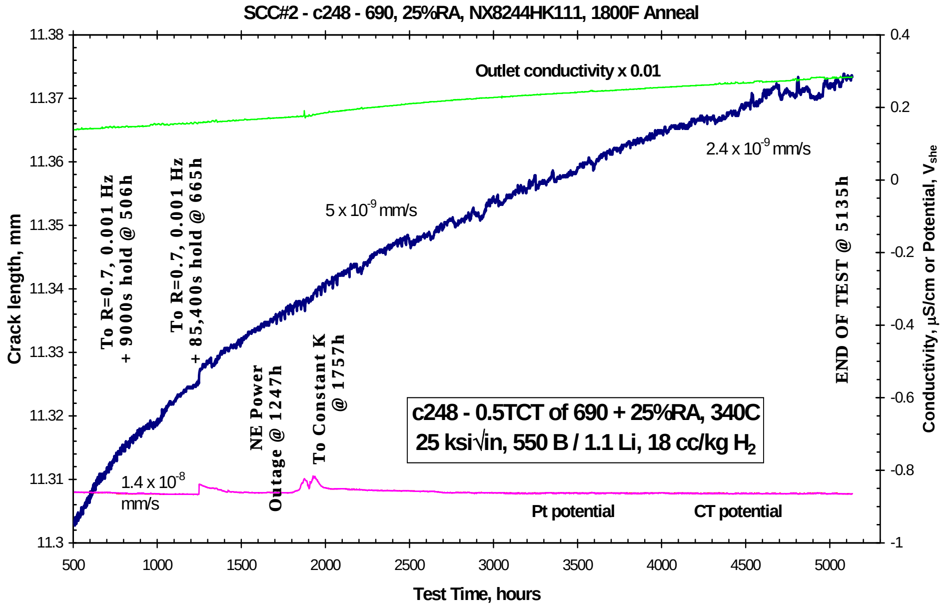
It produces non-uniform deformation if banding is perpendicular (B), & tensile straining can be more damaging than compression.

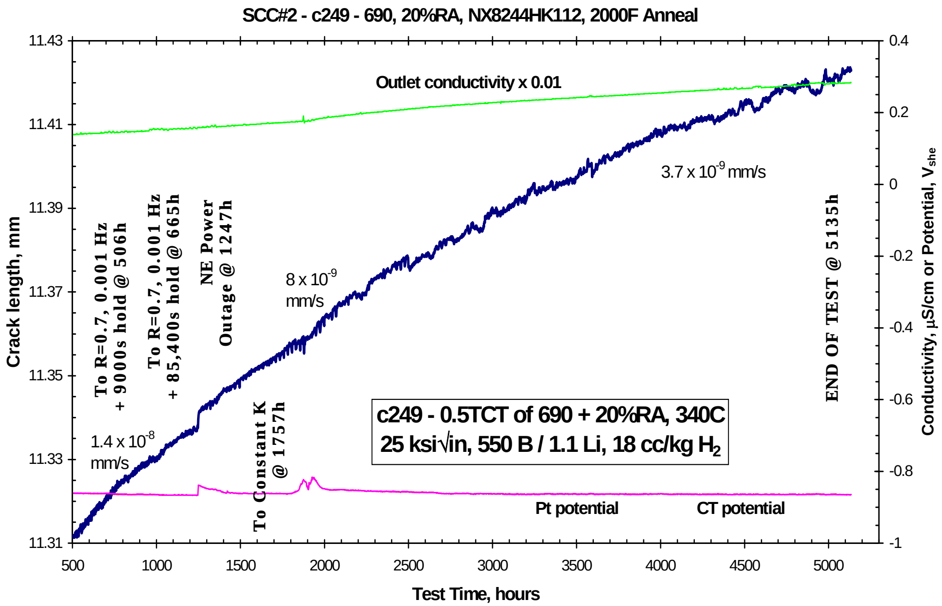
Specimens c248, c249

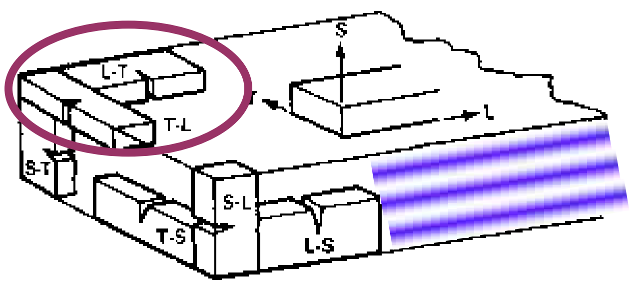
1800F Anneal

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

2000F Anneal

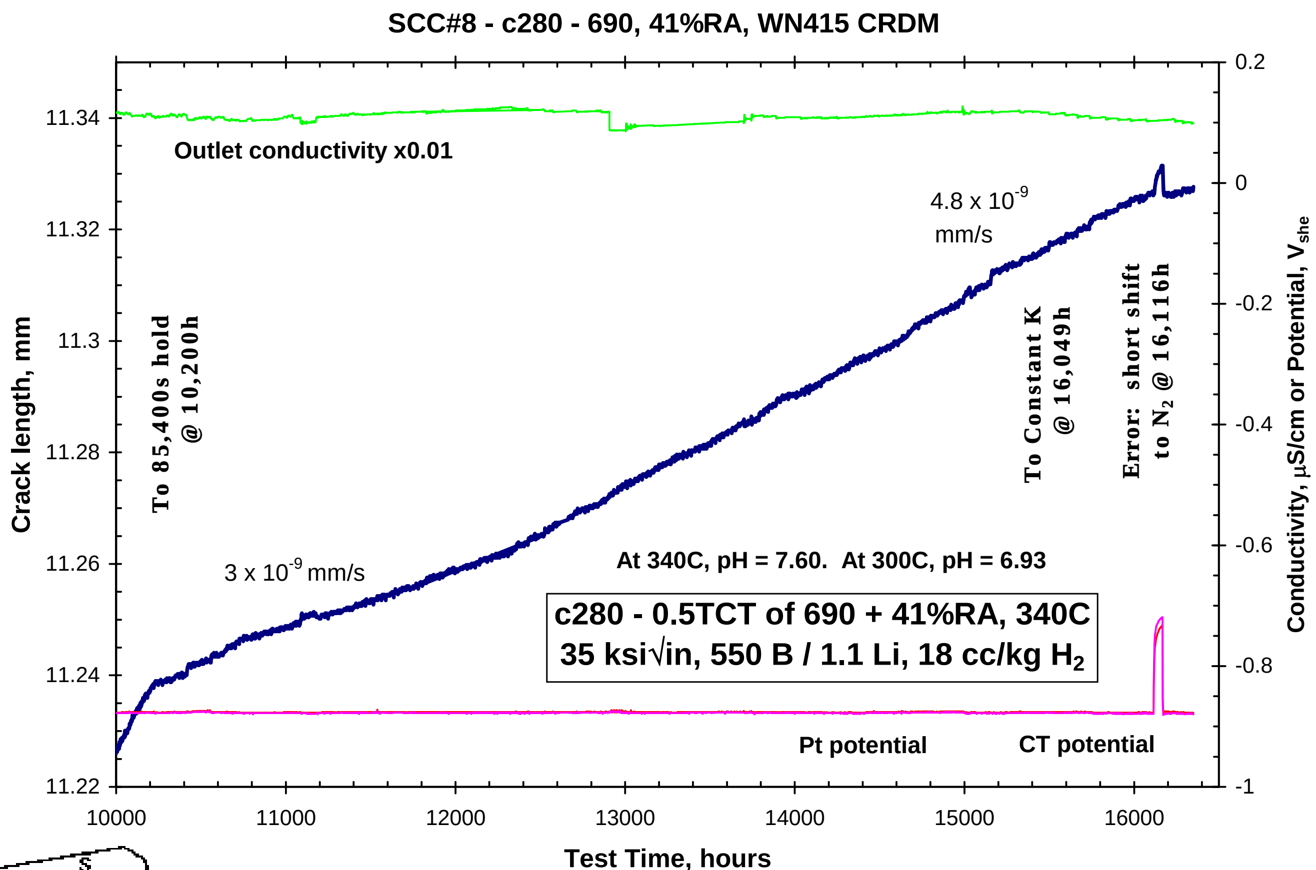


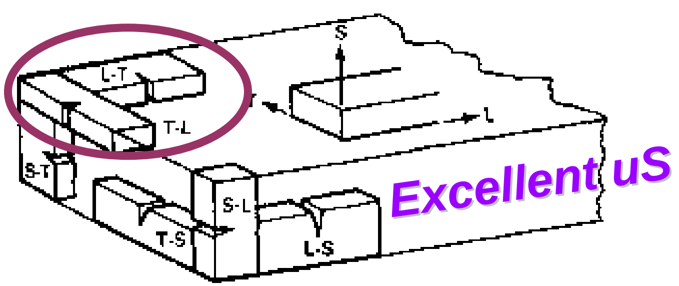




Banded microstructure, 2D CW (forging), but crack is out-of-plane vs. banding & deformation

41% Cold Work Alloy 690 CRDM

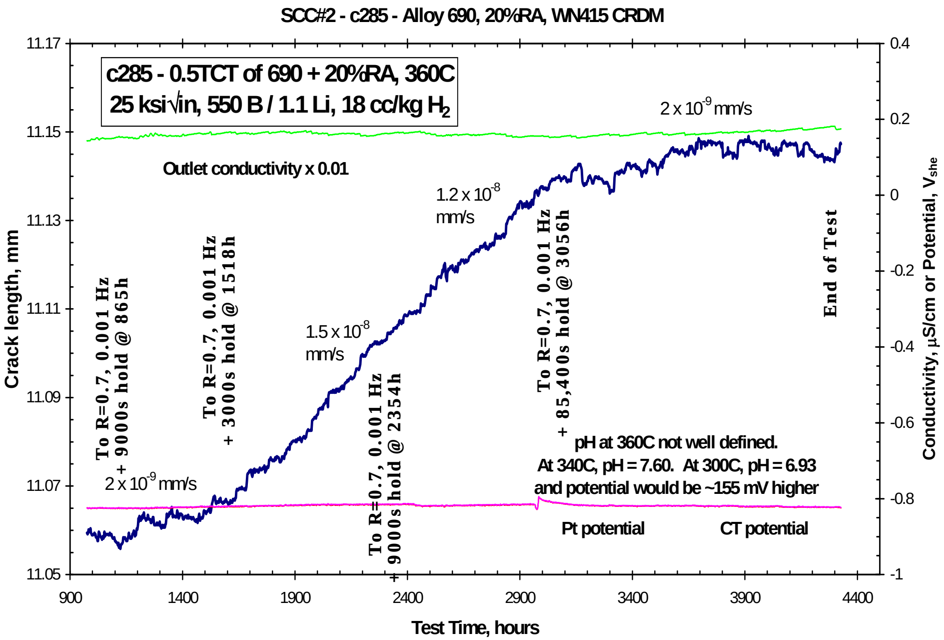


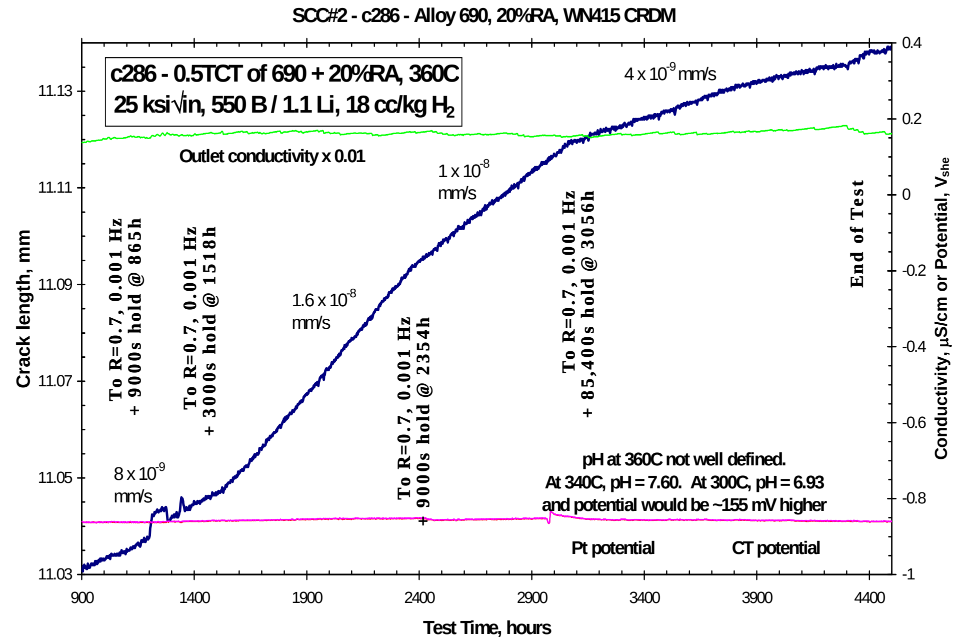


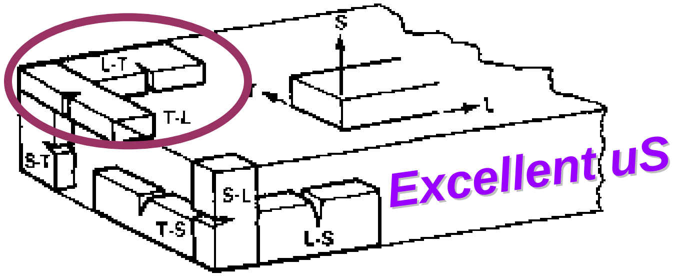
L-T Orientation (good)
Very homogeneity microstructure

Specimens c285, c286

20% Cold Work Alloy 690 CRDM



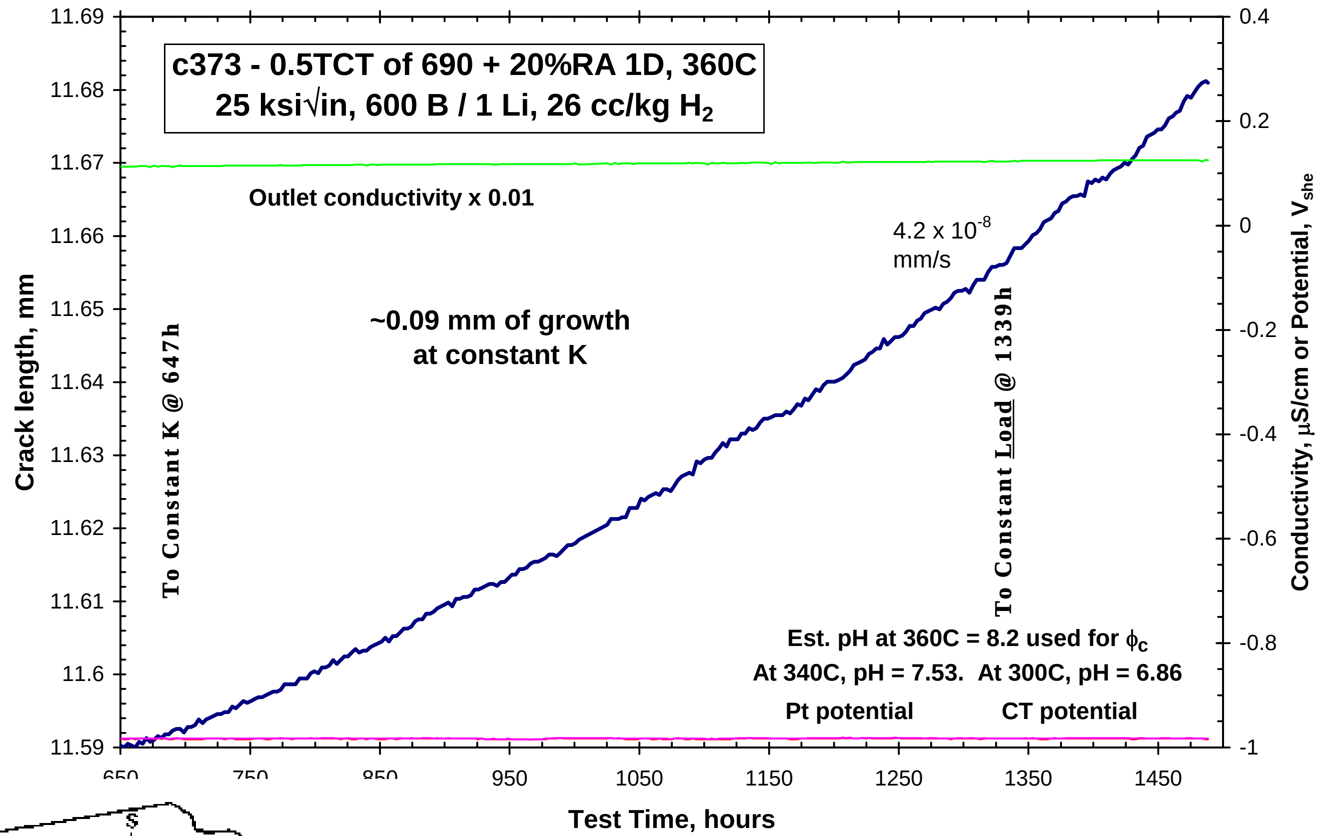


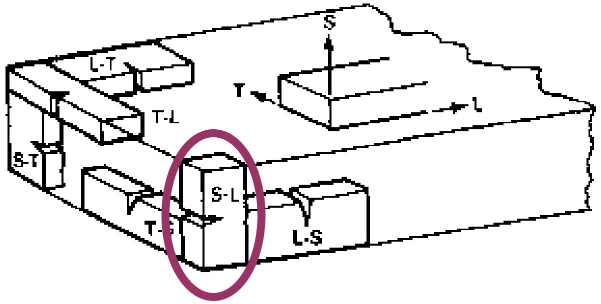


L-T Orientation (good)
Very homogeneity microstructure

Specimen c373

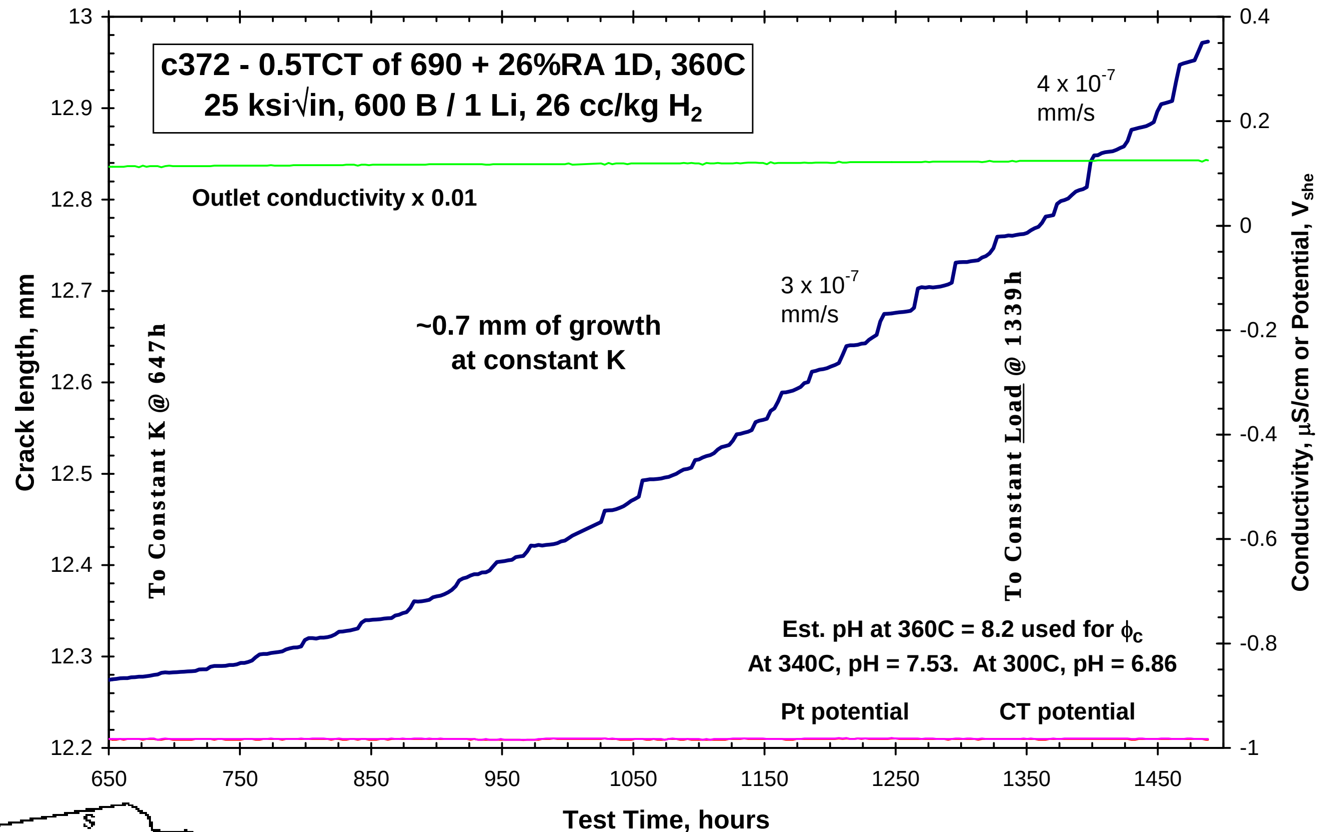
1D, 20% Cold Worked GE GRC Alloy 690

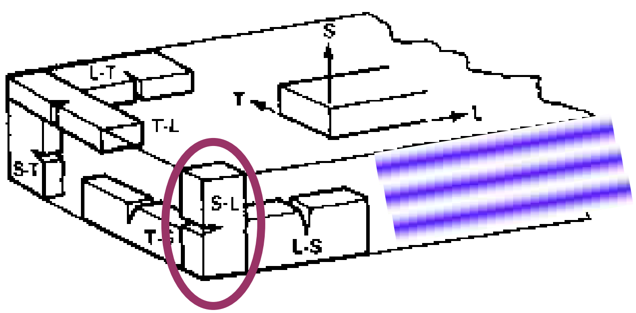




Medium CGR in S-L orientation
Very homogeneous microstructure
1D cold rolled

1D, 26% Cold Worked ANL Alloy 690

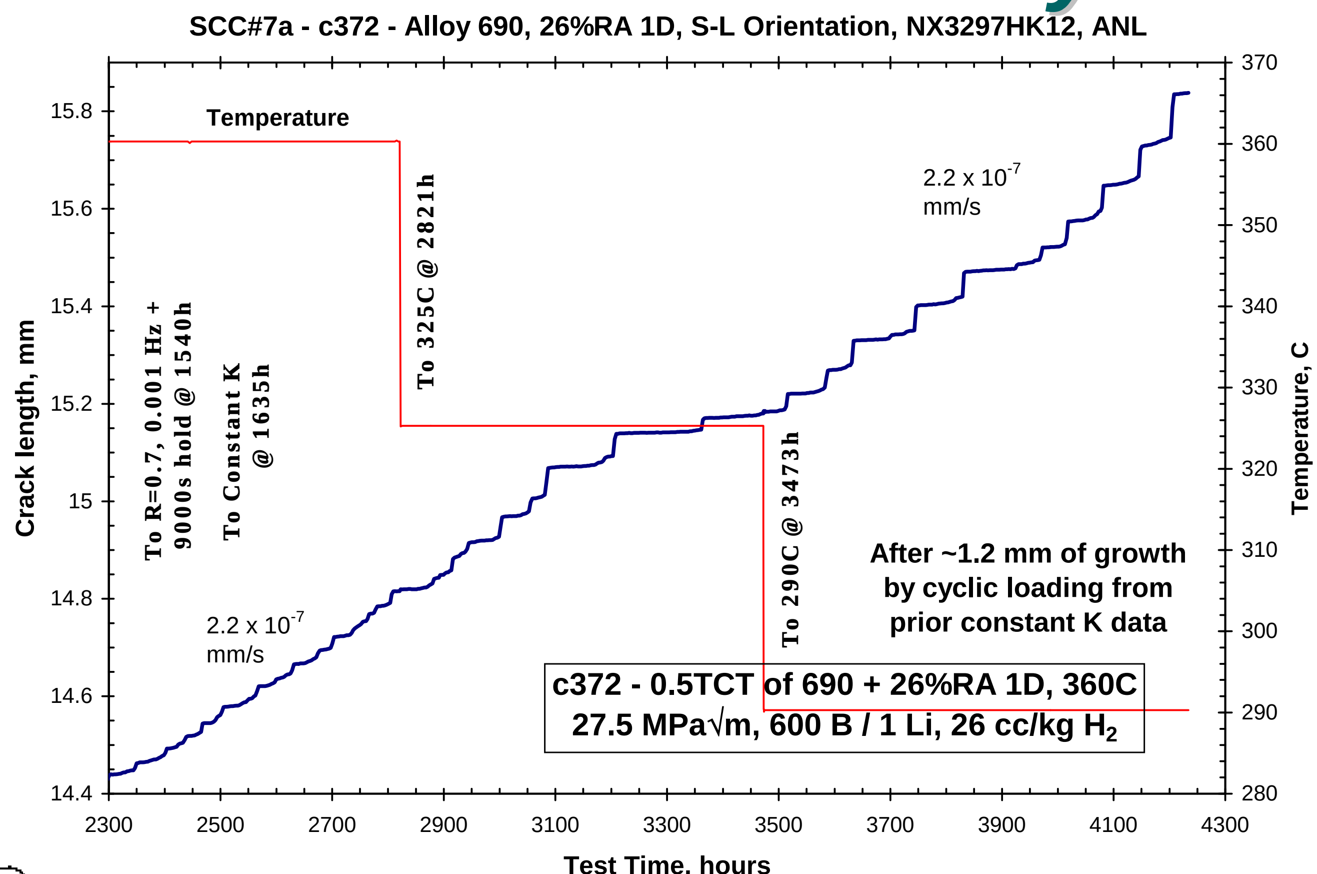


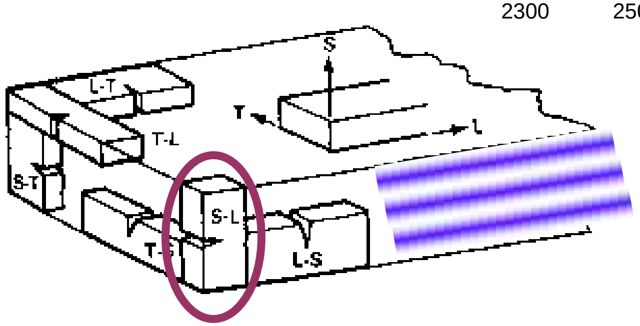


High CGR in S-L orientation
Inhomogeneous microstructure
1D cold rolled

1D, 26% Cold Worked ANL Alloy 690

No effect of temperature would be 12X normally

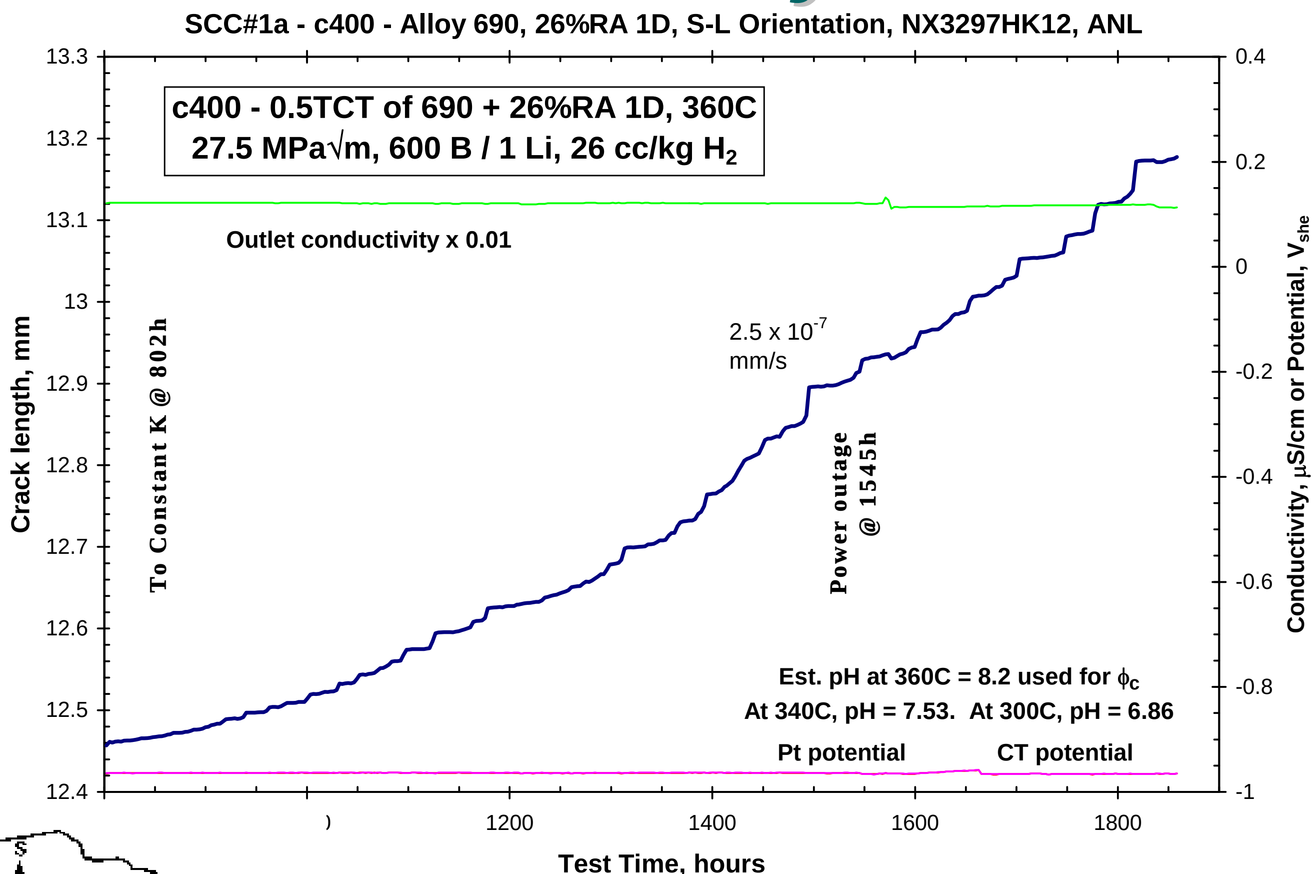


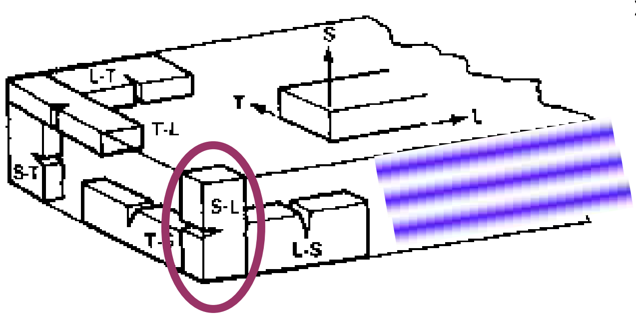


High CGR in S-L orientation
Inhomogeneous microstructure
1D cold rolled

Specimen c400

1D, 26% CW ANL Alloy 690 – Test #2



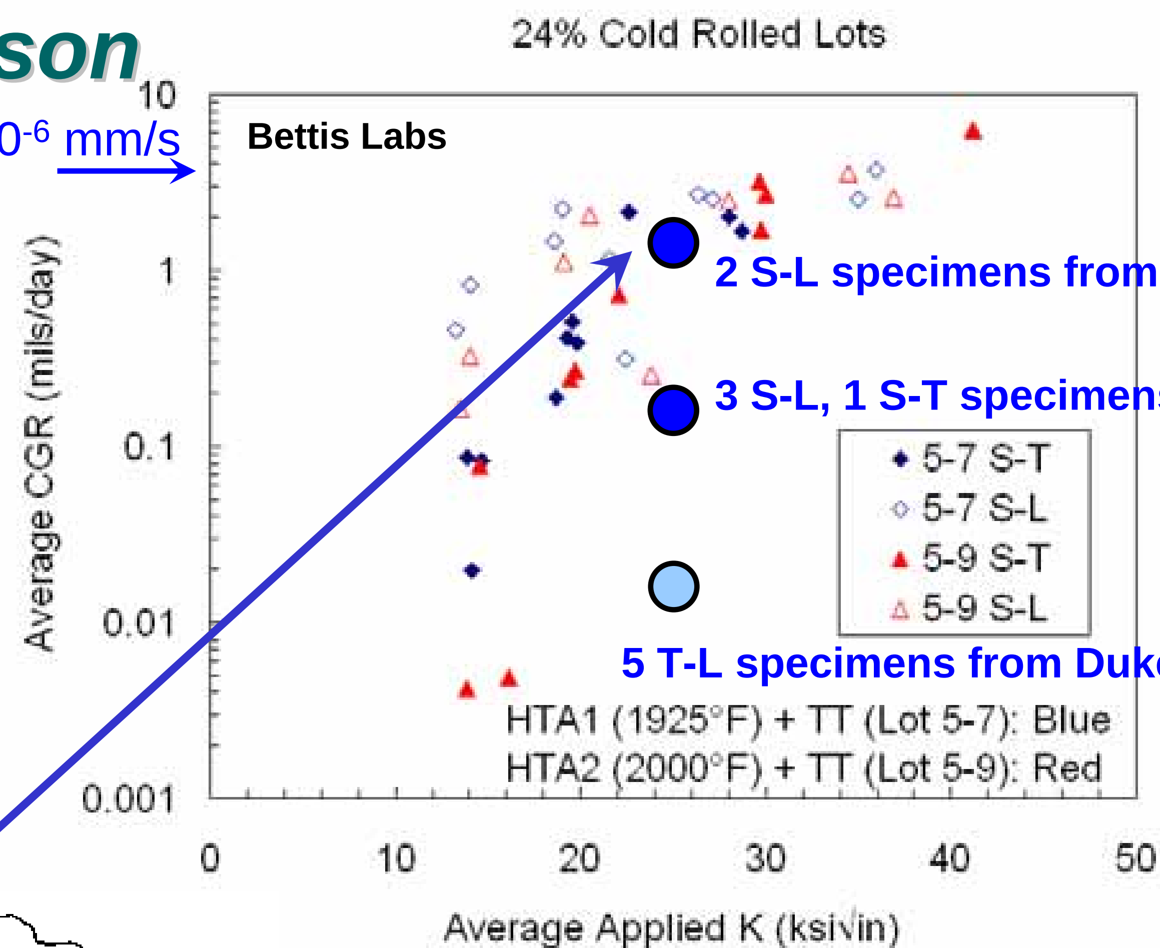


High CGR in S-L orientation

Inhomogeneous microstructure

1D cold rolled

Comparison of GE & Bettis Data

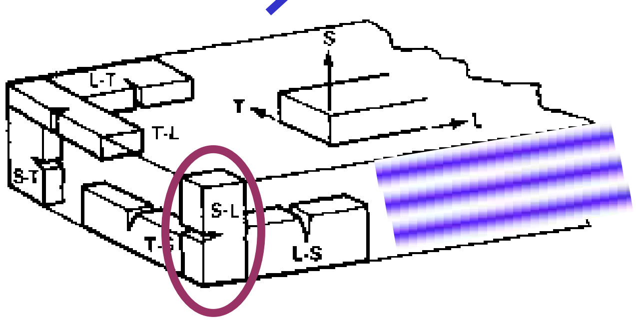


10^{-6} mm/s

2 S-L specimens from ANL material

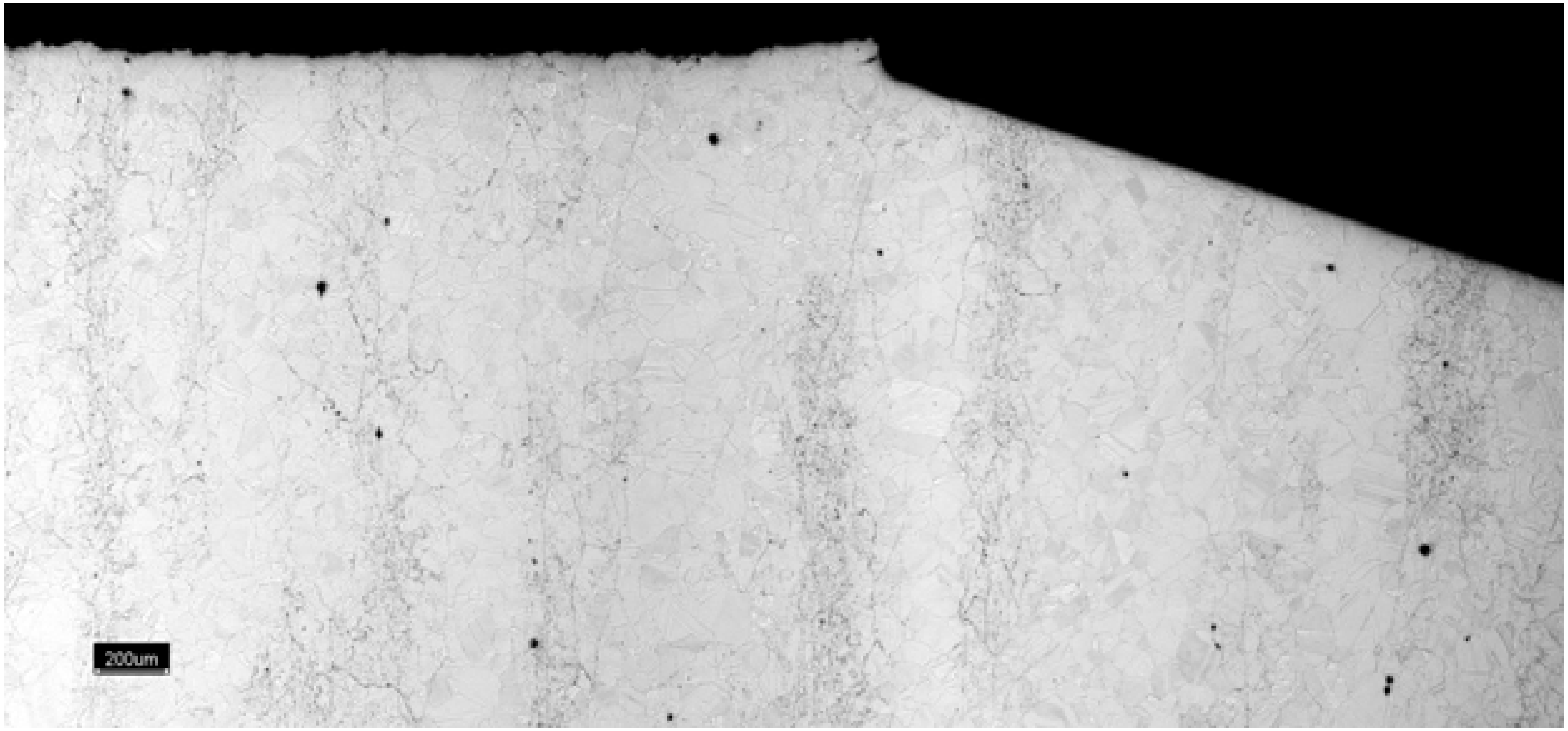
3 S-L, 1 S-T specimens from GE & KAPL materials

5 T-L specimens from Duke CRDM & EPRI materials



High CGR data in S-L orientation
Inhomogeneous microstructure
1D cold rolled

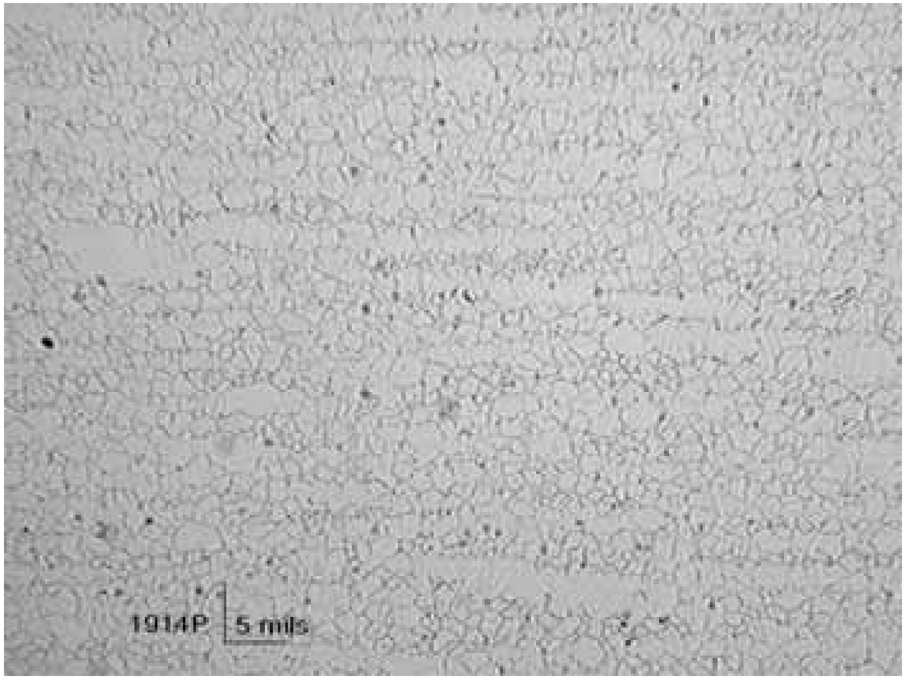
Metallography of Alloy 690, c248

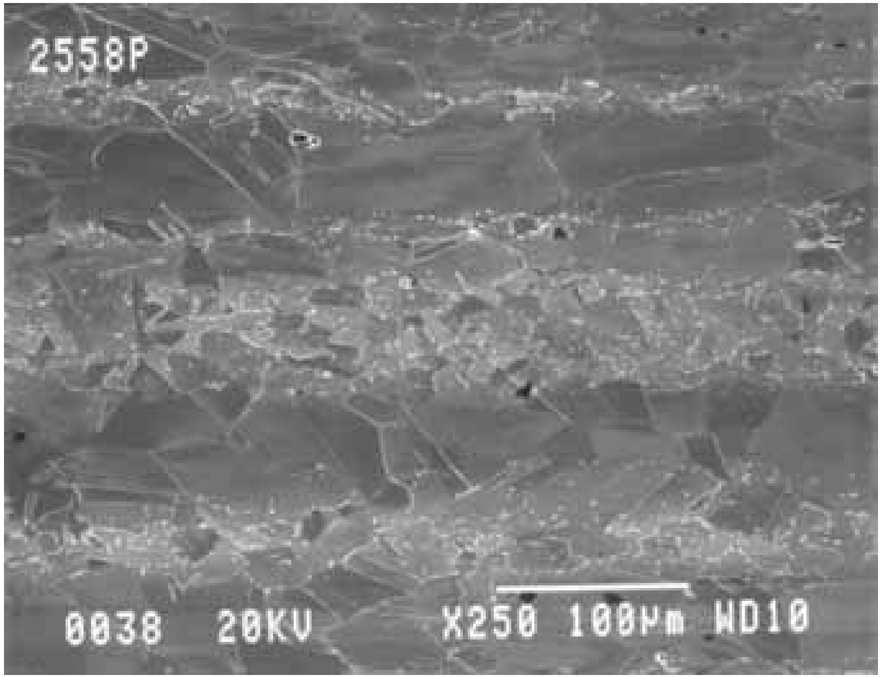


Microstructure of plate with 1800F anneal shows compositional and carbide banding

Shows relative orientation of banding vs. crack plane

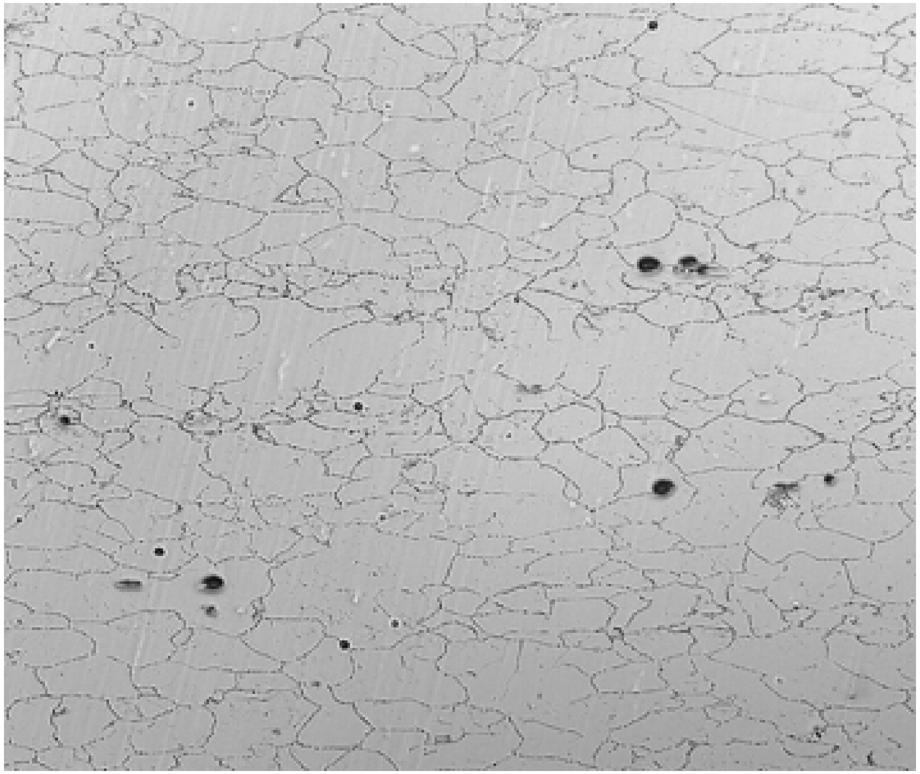
Inhomogeneity in Bettis 690

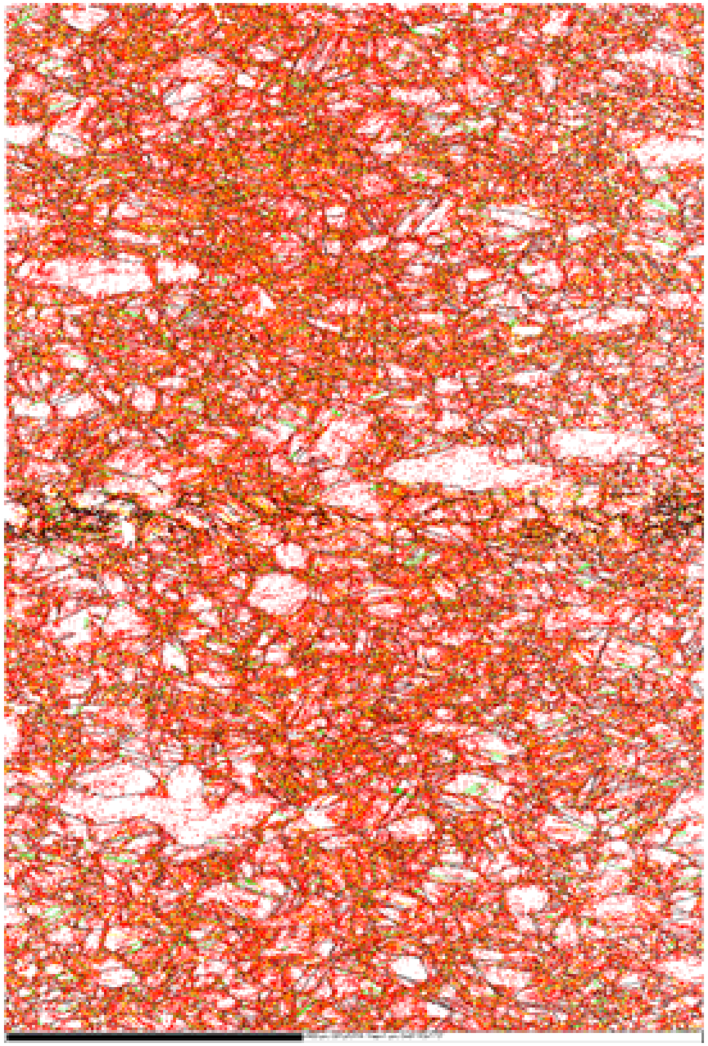




Composition & microstructural banding affects grain size and gb carbide decoration

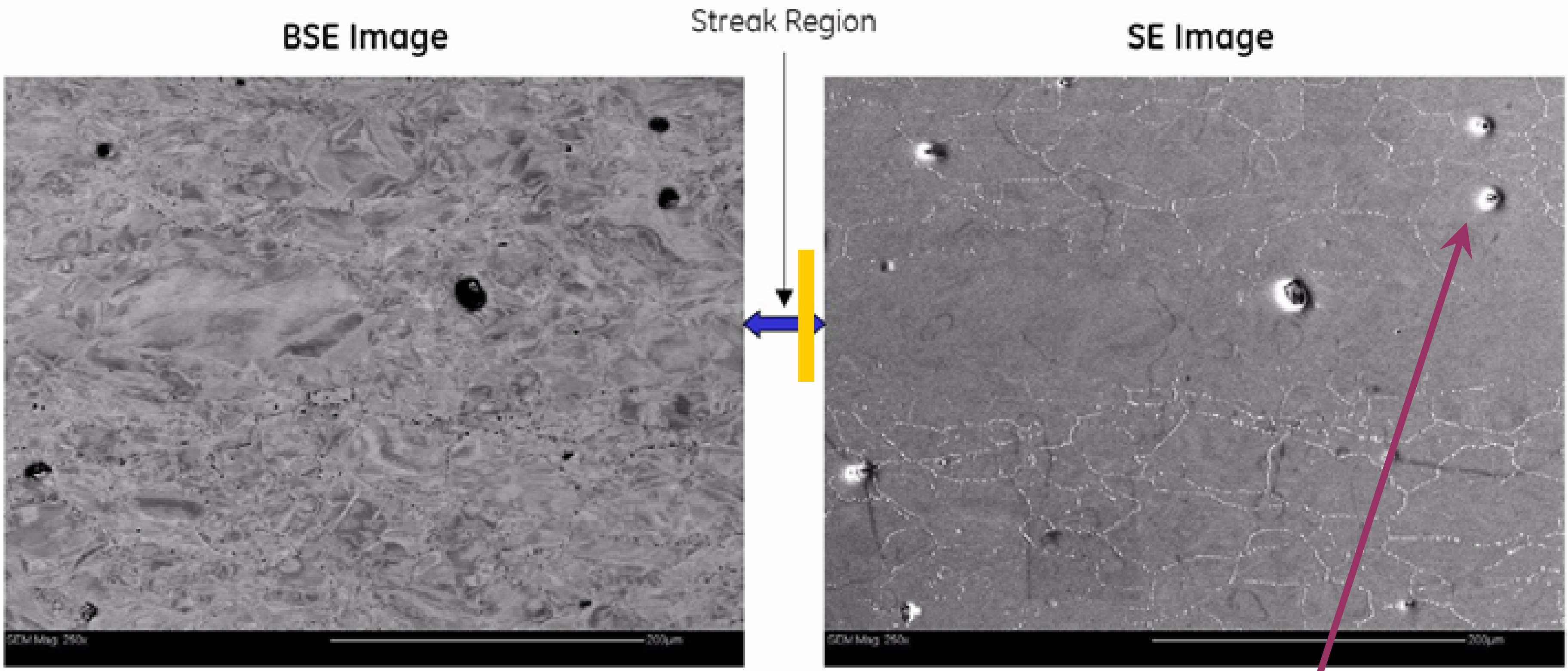
Inhomogeneity in 1D, 26% CR ANL 690





Composition & microstructural banding affects grain size and gb carbide decoration

Inhomogeneity in 1D, 26% CR ANL 690

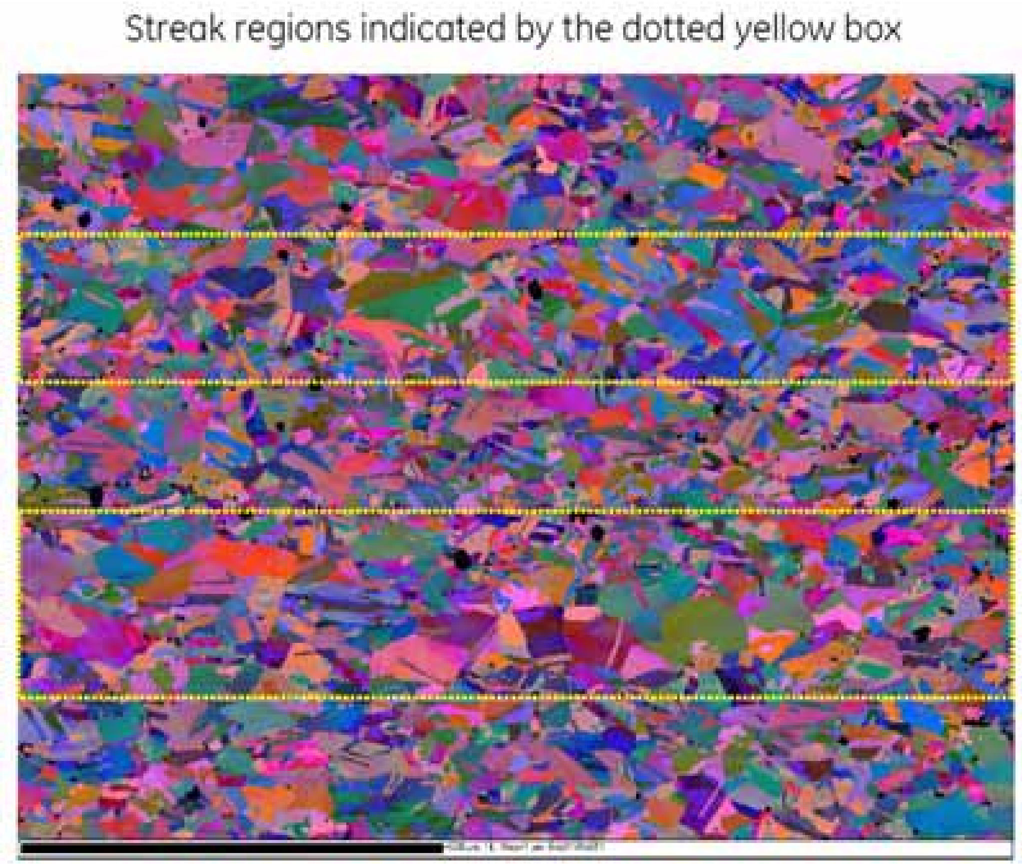


Composition & microstructural banding affects grain size and gb carbide decoration, and distribution of large MC carbides. Double melted by VIM-VAR; annealed at 1900F & air cooled

Inhomogeneity in 1D, 26% CR ANL 690

Streaks ⇒

Streaks ⇒

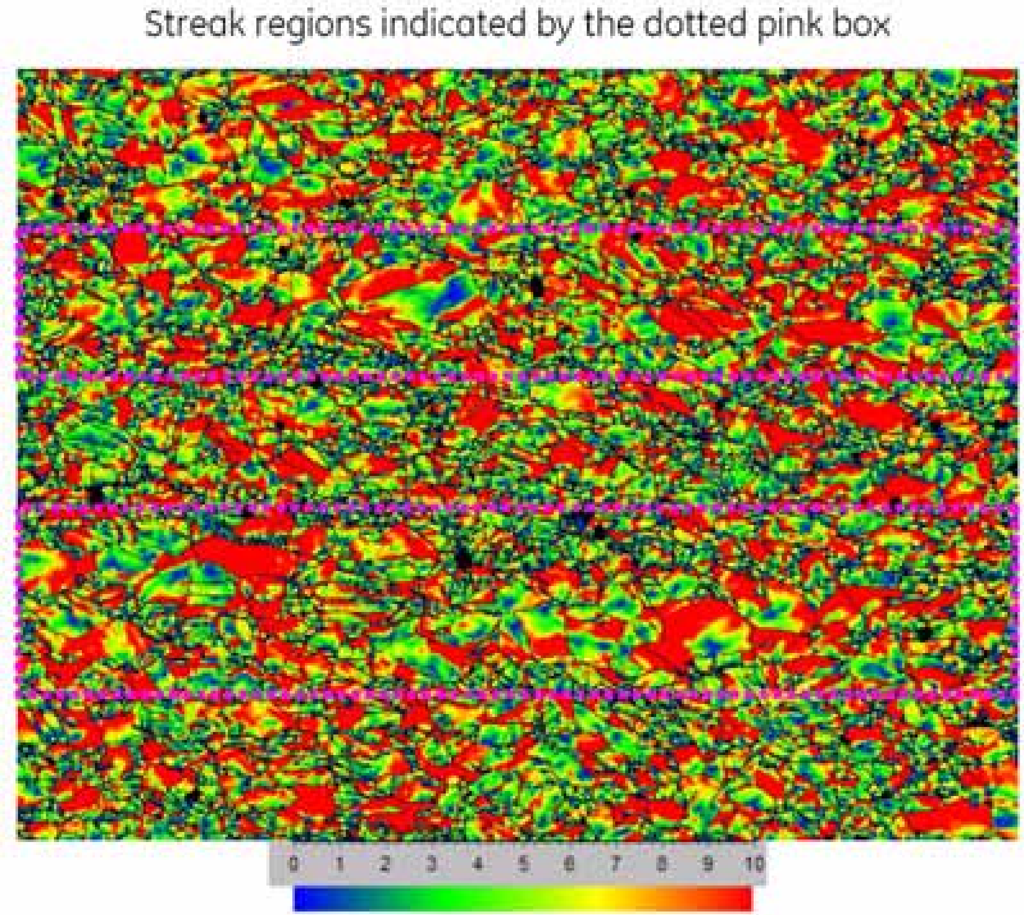


Strain localized in streaked / banded areas of larger grains

Inhomogeneity in 1D, 26% CR ANL 690

Streaks ⇒

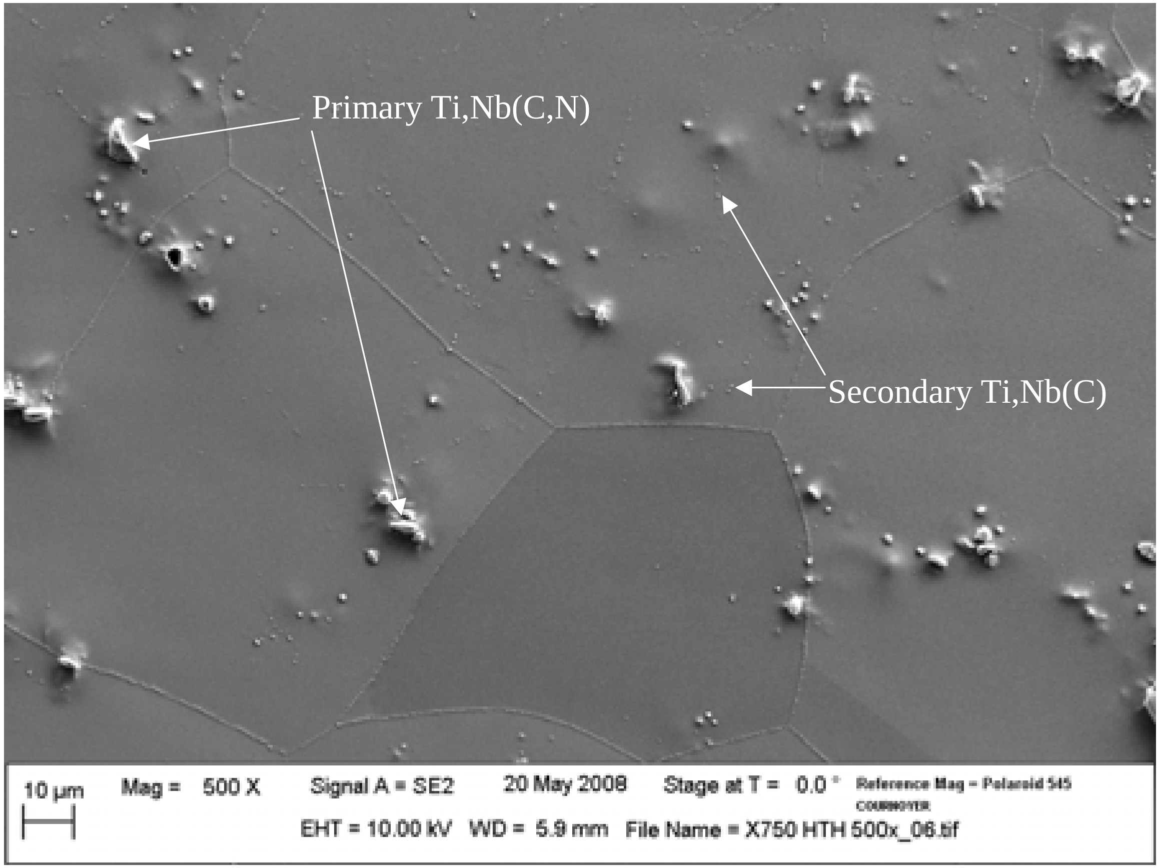
Streaks ⇒



Different color thresholds

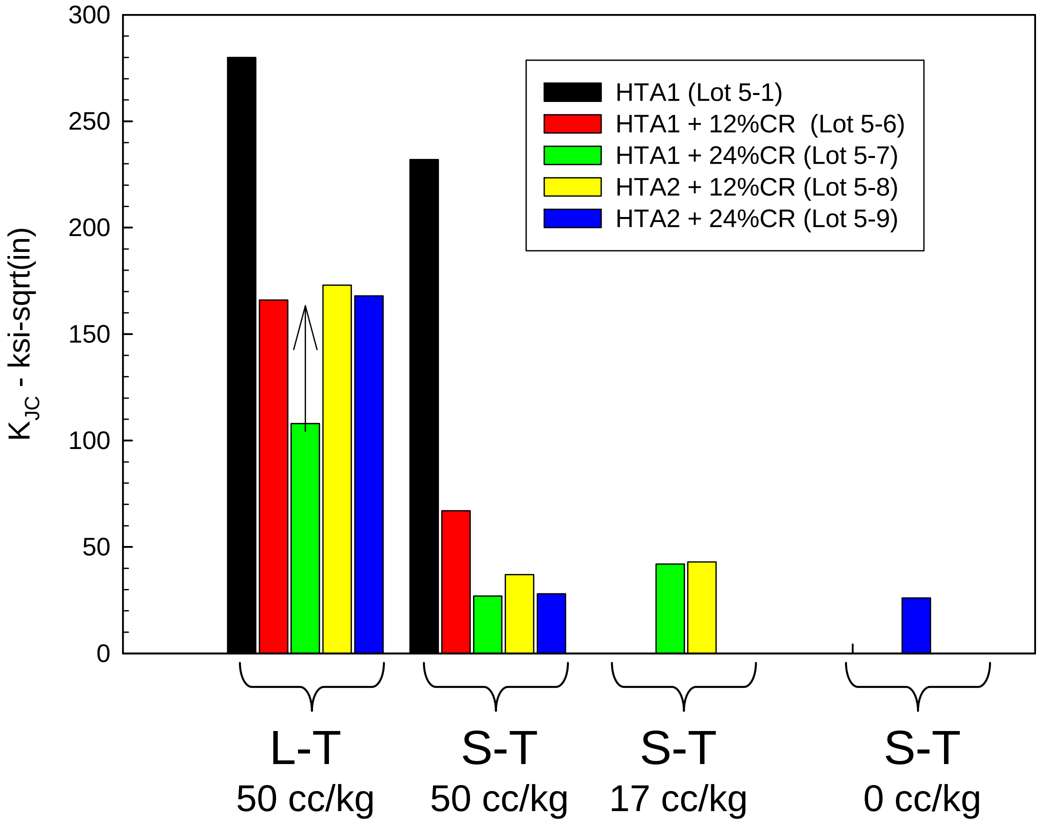
Strain localized in streaked / banded areas of larger grains

Inhomogeneity in Alloy X-750 HTH

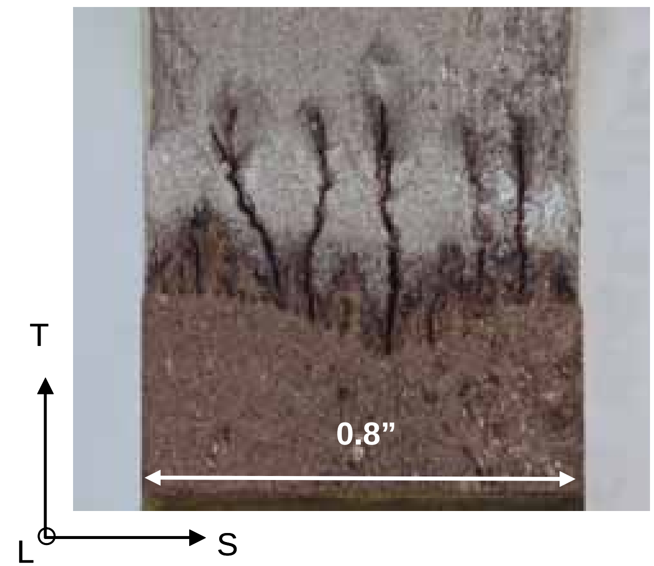


Large primary and small second Ti,Nb carbides exist
Prior grain boundaries with carbides can also be seen

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}

Weld HAZ Characteristics

Good microstructures can be degraded by the thermo-mechanical "processing" during weld solidification, including the partially melted and heat-affected zones.

Weld shrinkage strains will be more inhomogeneous in banded microstructures.

More characterization of weld HAZs is needed, as is SCC testing of weld-HAZ-aligned specimens, but with a limited emphasis because of testing challenges which limit the probability of successful tests.

Evaluation of Alloy 690

Demonstration on at least one additional heat (in addition to the ANL material) that banding + cold work + crack in banding-plane produces high growth rate.

Evaluation of banding effect:

- *at ~10% cold work*
- *with 20 & 30% forging (2D)*
- *with 20 & 30% tensile strain perpendicular & parallel*
- *20% CW with crack plane perpendicular to banding*

Detailed characterization of various heats and product forms, & EBSD characterization of strained variants, including HAZ.

Alloy 52/152 Weld Metal Strategy

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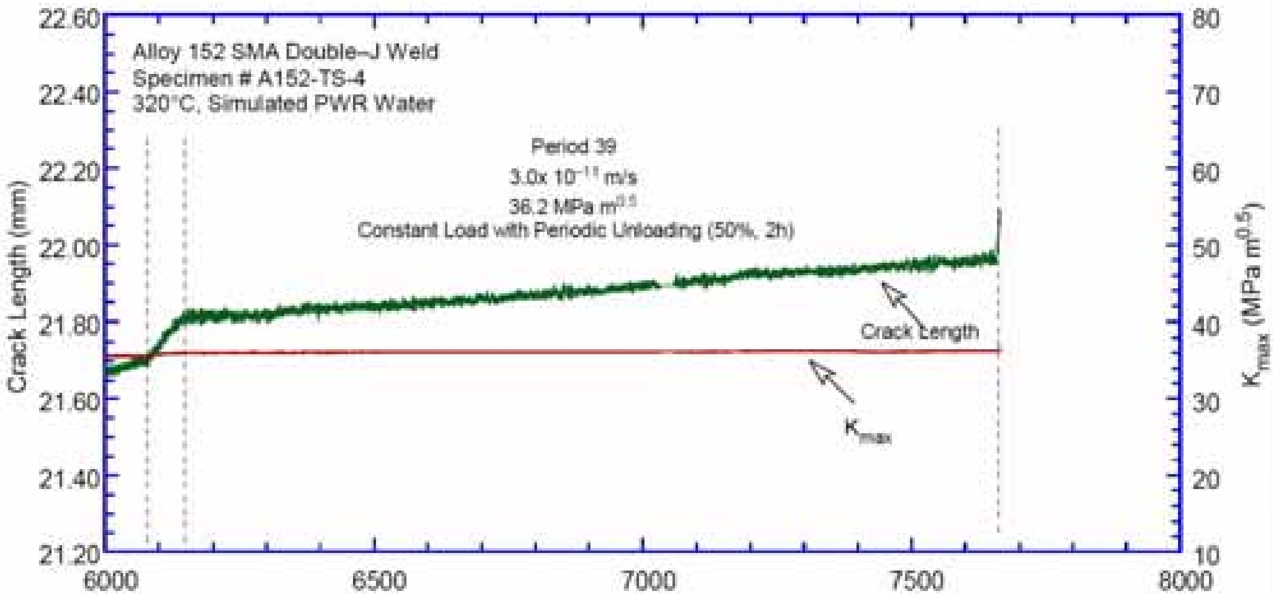
John Hickling, Al Ahluwalia &
John Wilson

NRC–Rockville, MD

Introduction and Philosophy

- *The industry has made a huge investment in moving to more SCC resistant Alloy 690 and its 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.*
  - *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*

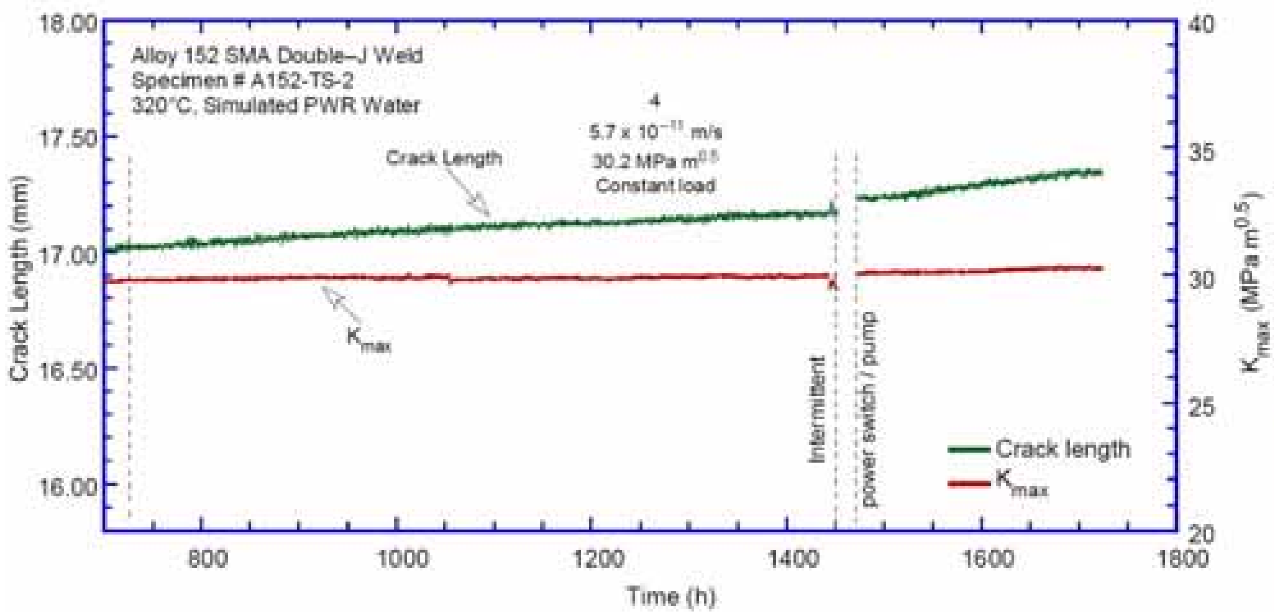
Alloy 690 Base Metal Strategy



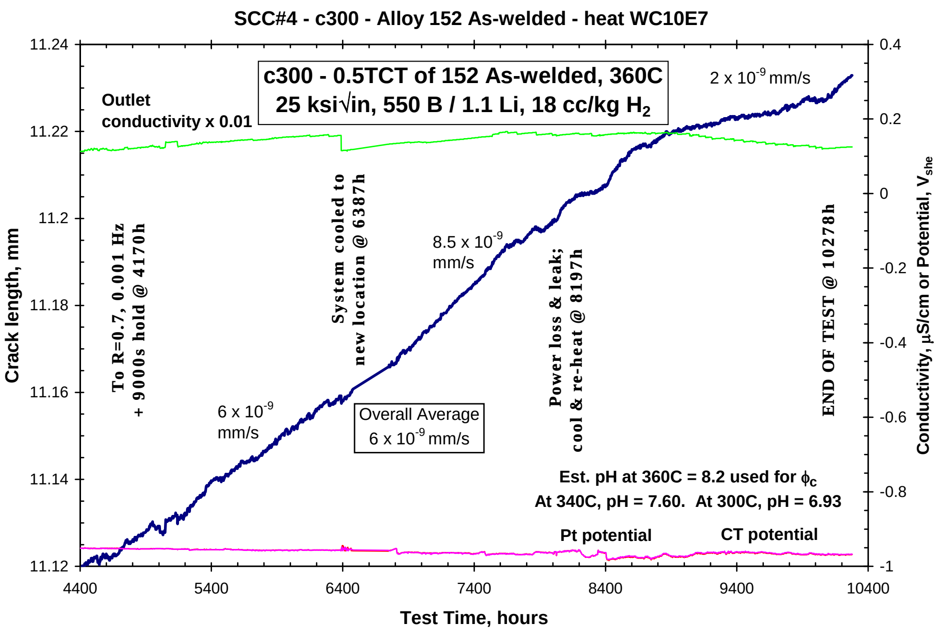
SCC of 52/152 Weld Metal

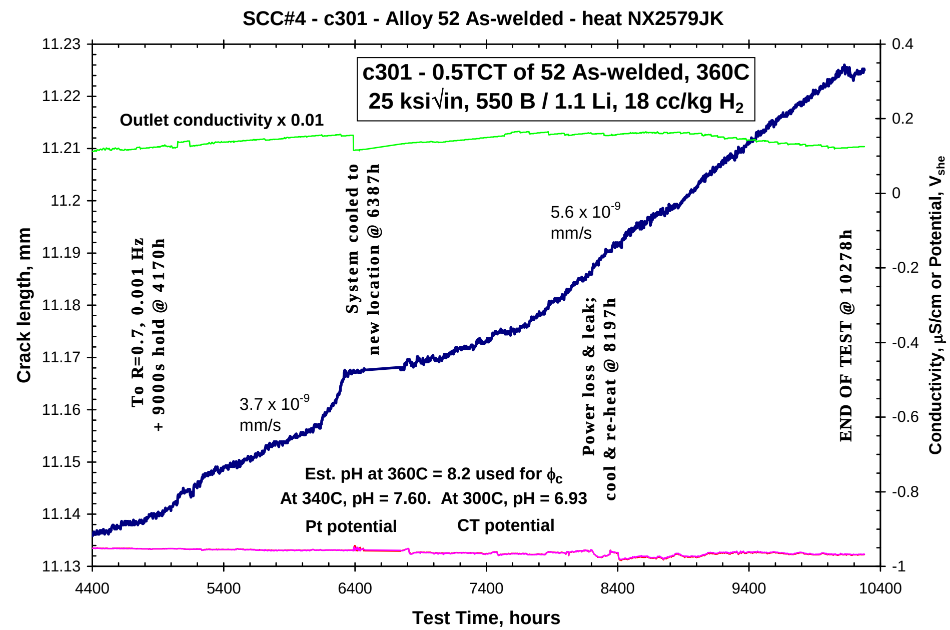
Moderate growth rates, but 5X lower than worst Alloy 690 base metal

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



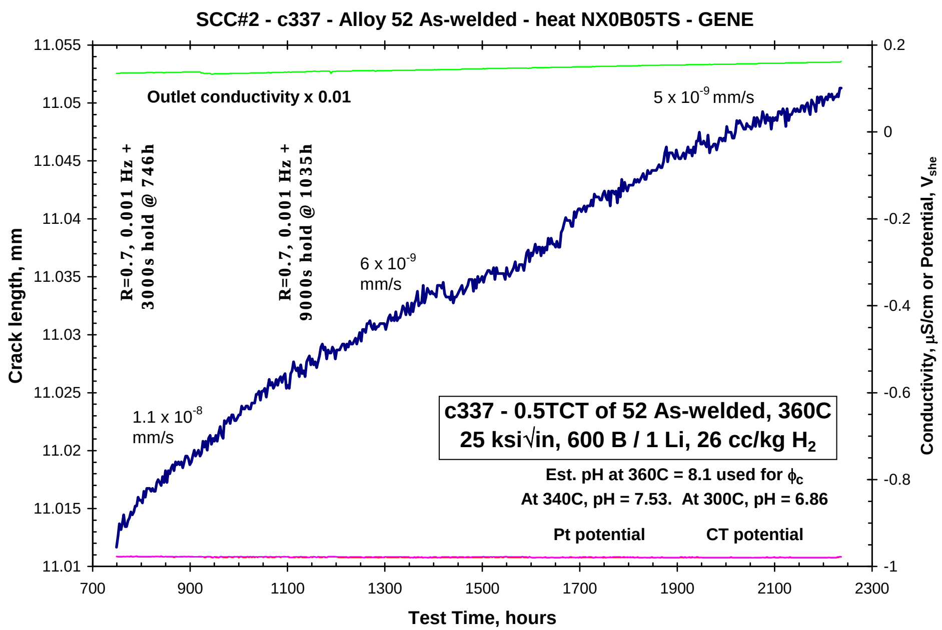
Alloy 152 & 52 Weld Metal



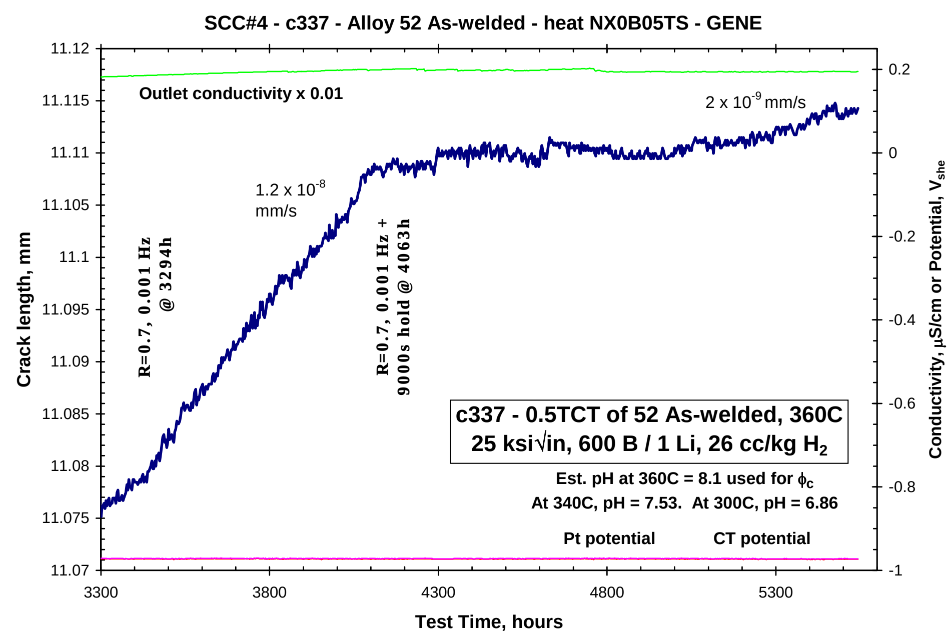


Growth rates are very low, < 2 x 10^{-9} mm/s

Alloy 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