

Alloy 152/52-LAS Dilution Zone and Interface/Fusion Line PWSCC Testing

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Nov 29 to Dec 1 • Tampa, FL



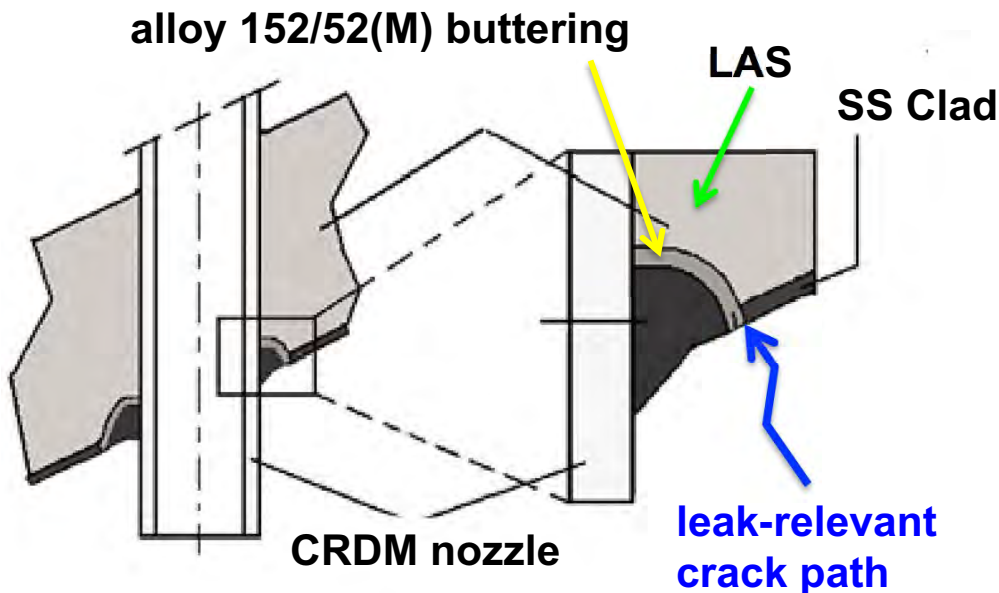
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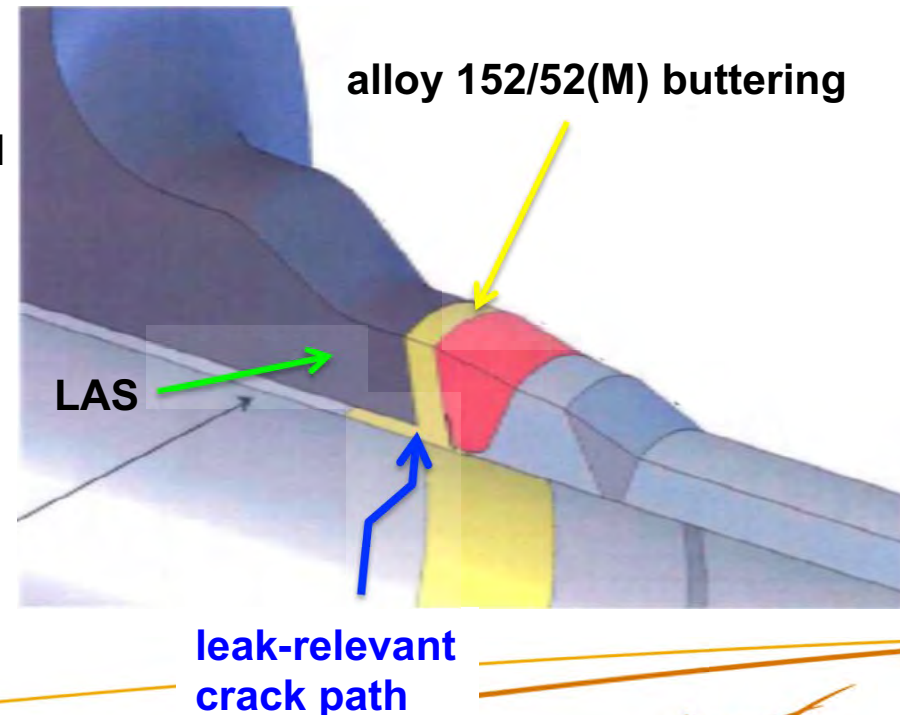
Potential Dilution Zone Leak Paths

- ▶ Greatest concern is dilution zone against low alloy steel (LAS).
- ▶ Potential continuous dilution leak paths do exist for both CRDM welds and DMW nozzle welds.
- ▶ Must first crack through alloy 152/52-SS dilution in some welds.

CRDM Nozzle J-Groove Weld

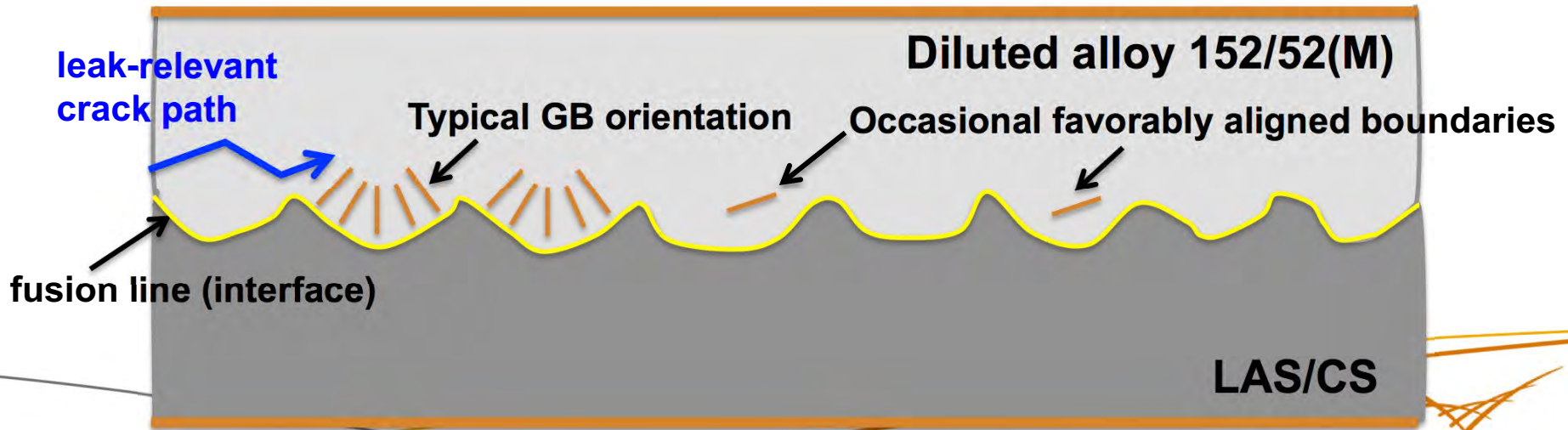


Primary Water Nozzle Weld

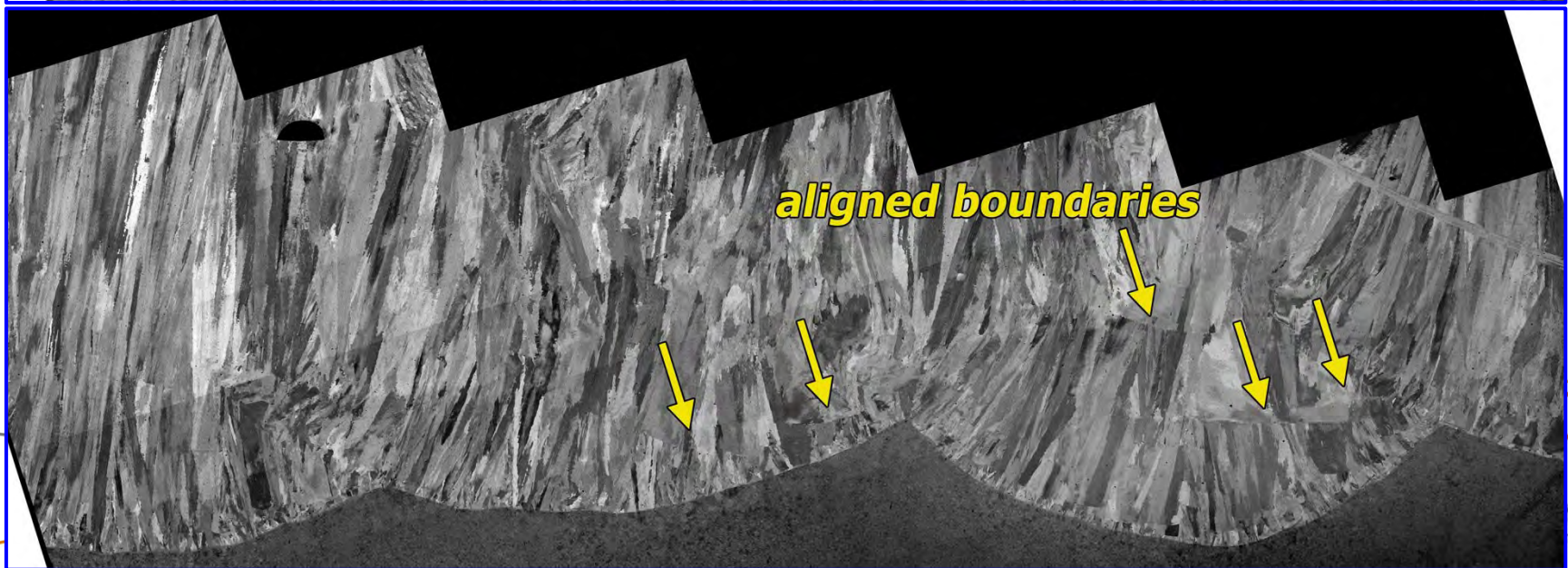
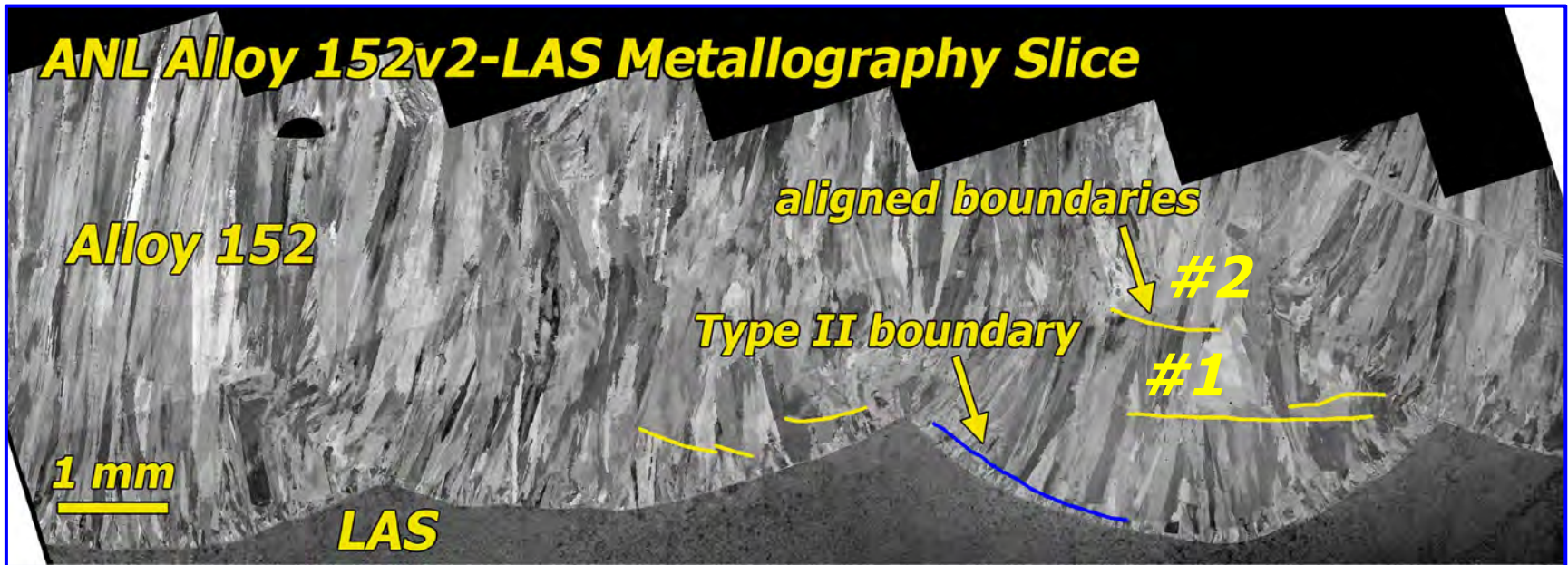


Grain Boundary Alignment in DZ

- ▶ Weld grains are predominantly needle-shaped with long axis parallel to the weld-LAS interface normal, $\sim 300\ \mu\text{m}$ dia. $\times \sim 0.5\text{-}3\ \text{mm}$.
- ▶ Leak-relevant crack path (parallel to fusion line) is not aligned to the needle orientation.
 - Unfavorable for IG cracking along these typical weld grain boundaries.
- ▶ Low density of favorably aligned boundaries have been observed.
 - Can be $>1\ \text{mm}$ from the fusion line. Much further from the fusion line than typical Type II boundaries.
 - SCC growth on these boundaries has been observed.



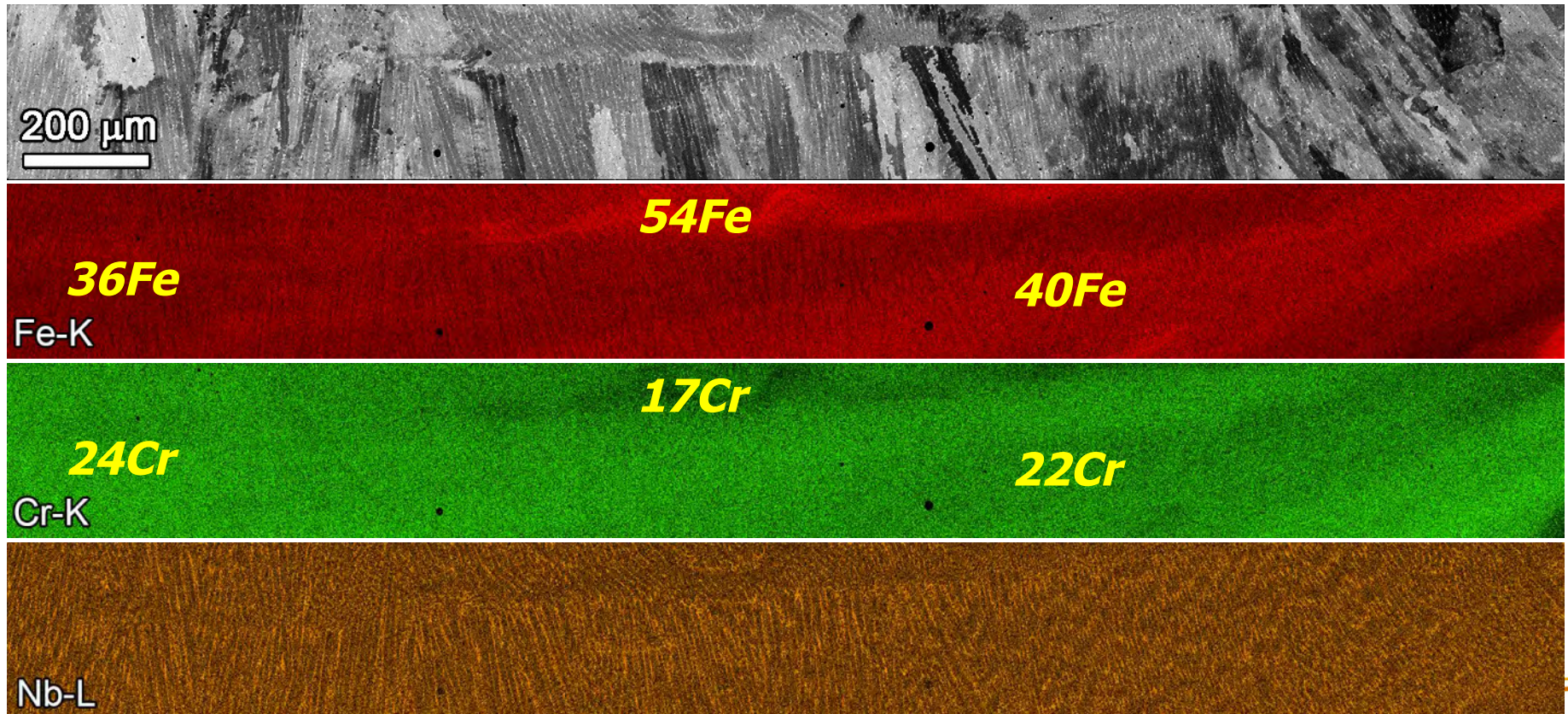
Favorably Aligned Boundaries in ANL Alloy 152v2-LAS Metallography Slice



ANL Alloy 152v2-LAS

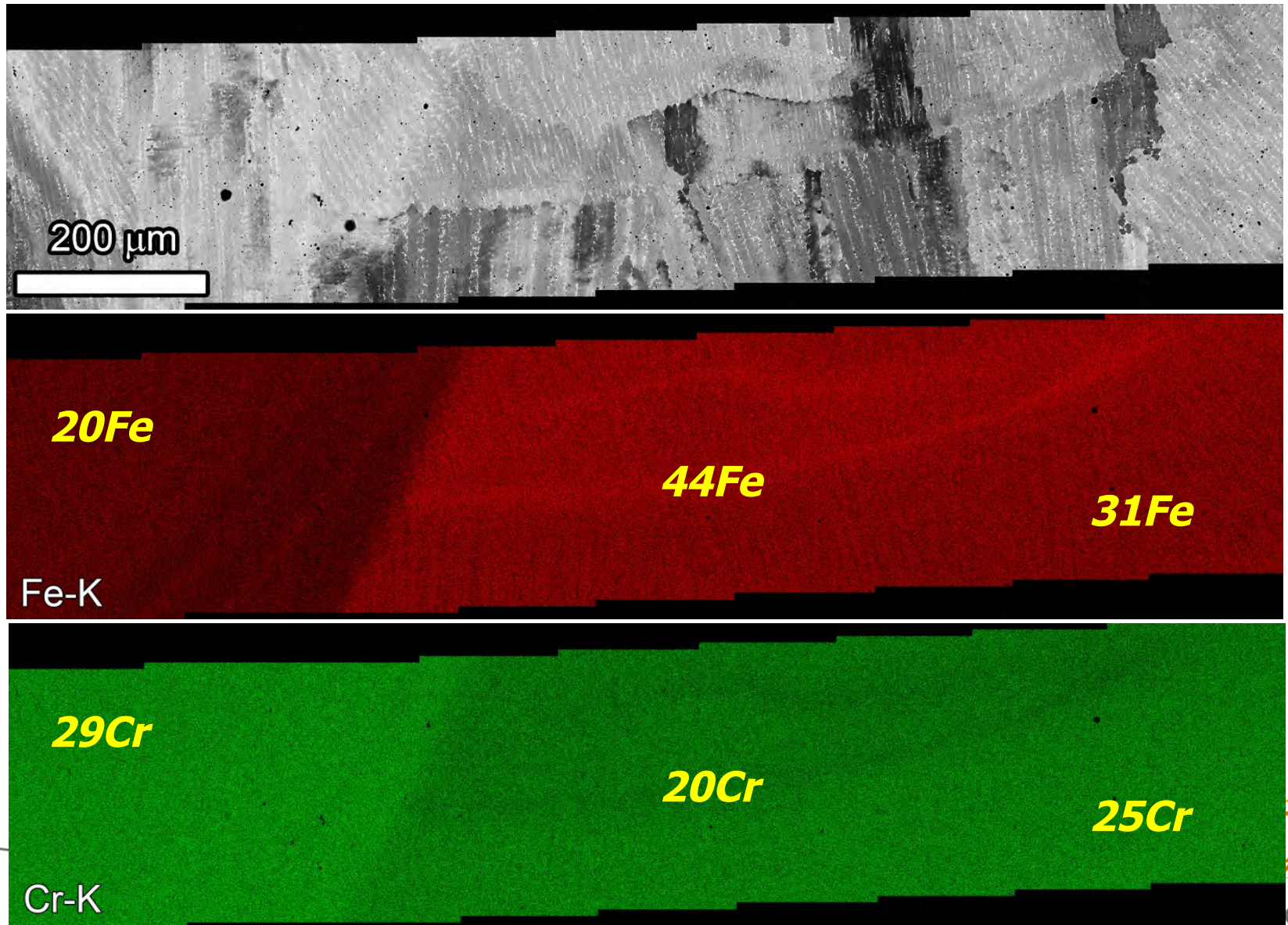
Aligned Boundary #1

- ▶ 2-2.5 mm in length.
- ▶ Fe enrichment and Cr depletion directly above the boundary.
- ▶ Nb carbides density changed in vicinity of the boundary.



ANL Alloy 152v2-LAS

Aligned Boundary #2



PNNL DZ/FL Testing Summary

- ▶ *Alloy 152/52 Dilution Zone (DZ) and Fusion Line (FL) Tests*
 - *CT065 – KAPL Alloy 52M-CZ DZ test – Did not intersect any dilutions*
 - *CT066 – KAPL Alloy 152M-CS DZ/FL test*
 - *CT082 – KAPL Alloy 152M-CS FL test – Affect of PWHT on CS HAZ SCC*
 - *CT083 – KAPL Alloy 52M-CS FL test – Affect of PWHT on CS HAZ SCC*
 - *CT117 – ANL Alloy 152v2 DZ/FL test #1*
 - *CT119 – ANL Alloy 152v2 DZ/FL test #2*
 - *CT136 – EPRI 52M DZ/FL test*
 - *CT142 & CT143 – NNL Dual Wire 52i-LAS buildup 24Cr – In-Test*
- ▶ *Fusion Line and LAS/CS HAZ Cracking*
 - *Only comment for this presentation is FL and LAS/CS HAZ are susceptible if PWHT not applied.*
- ▶ *Dilution Zone Cracking*
 - *Typical grain boundaries in weld are not aligned for IG crack growth parallel to the fusion line in the DZ.*
 - *A low density of favorably aligned boundaries have been observed in dilution zones of some welds. Available composition data show that these boundaries are associated with dilutions.*
 - *Higher CGRs have only been observed in tests with cracking on these atypical favorably aligned boundaries.*

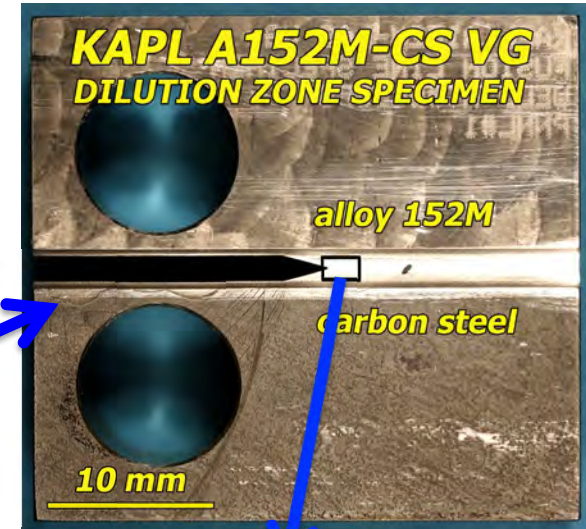
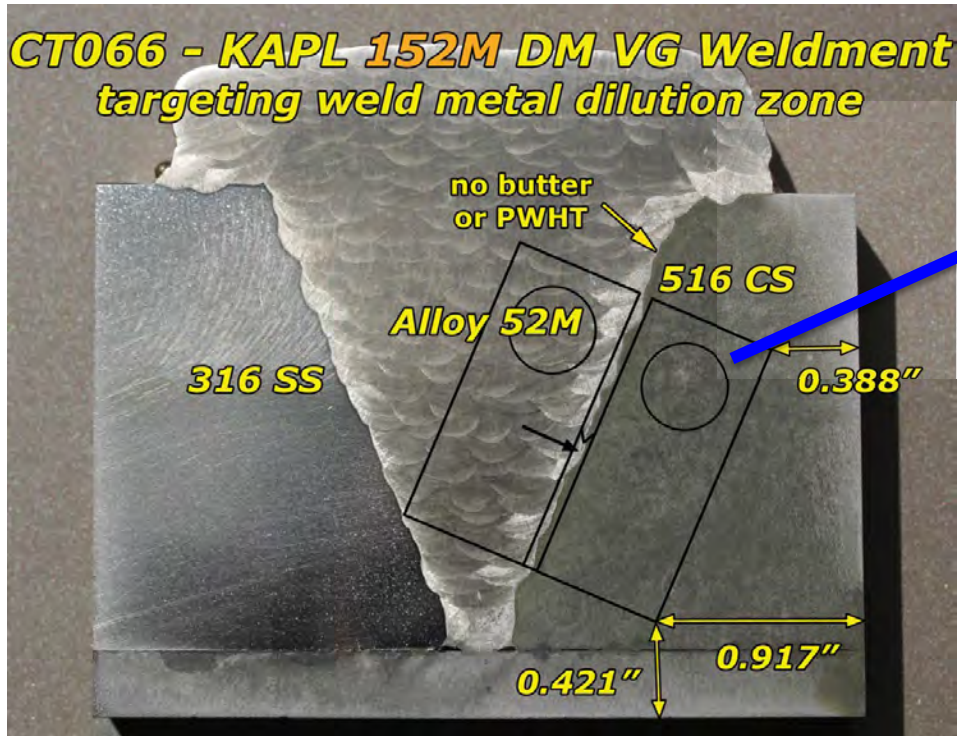
PNNL Dilution Zone Testing Summary

- ▶ Alloy 152/52 Dilution Zone (DZ) and Fusion Line (FL) Tests
 - **CT066 – KAPL Alloy 152M-CS DZ/FL test**
 - CT117 – ANL Alloy 152v2 DZ/FL test #1
 - CT119 – ANL Alloy 152v2 DZ/FL test #2
 - CT136 – EPRI 52M DZ/FL test
- ▶ Fusion Line and LAS/CS HAZ Cracking
 - FL, LAS/CS HAZ are susceptible if PWHT not applied.
- ▶ Dilution Zone Cracking
 - Typical grain boundaries in weld are not aligned for IG crack growth parallel to the fusion line in the DZ.
 - A low density of atypical favorably aligned boundaries have been observed in dilution zones of some welds. Available composition data show that these boundaries are associated with dilutions.
 - Higher CGRs have only been observed in tests with cracking on these atypical favorably aligned boundaries.

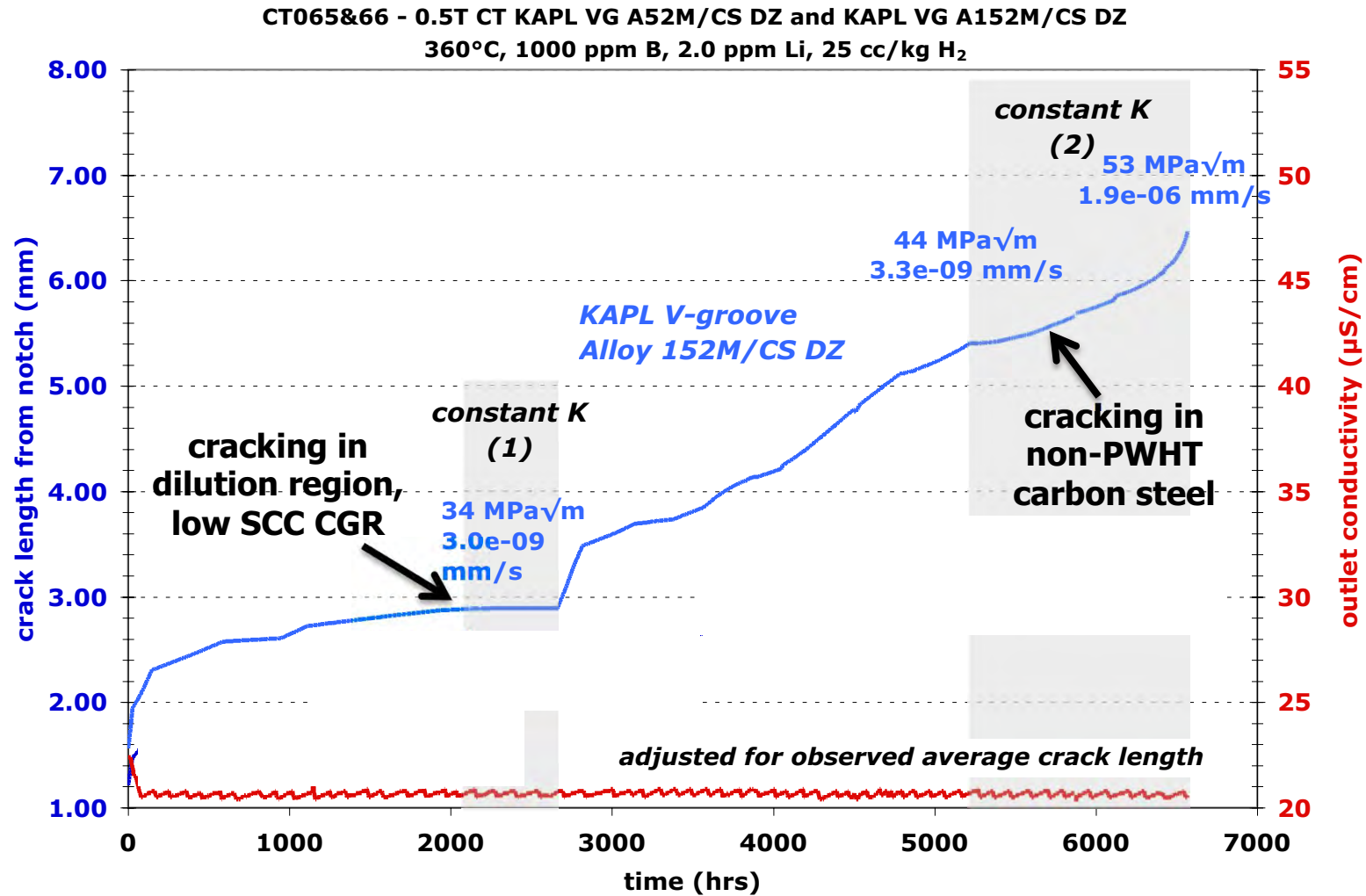
CT066 - KAPL Alloy 152M-CS Dilution Zone Specimen

Goal was to measure weld dilution zone response ~0.5-1 mm from fusion line.

KAPL Alloy 152M weldment



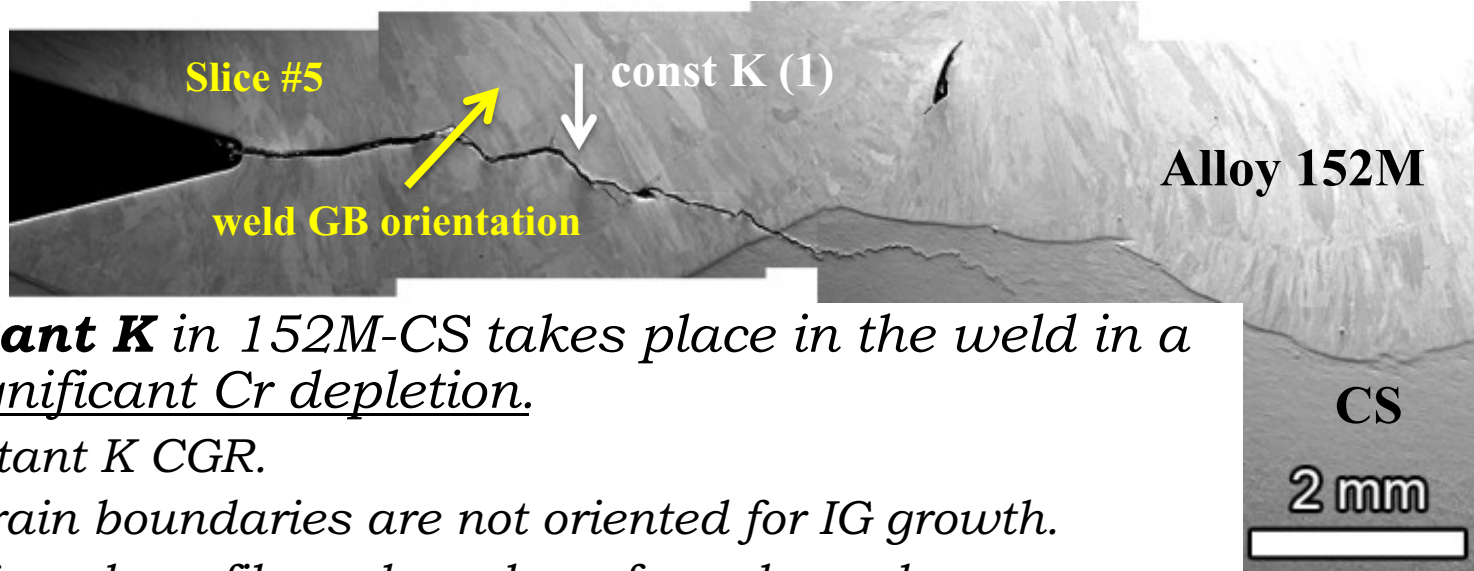
Crack Growth Test on KAPL Alloy 152M-CS Dilution Zone Specimen



Low SCC CGRs seen during constant *K* testing in a 20Cr dilution zone region. GBs were unfavorably aligned, a problem that is common to testing LAS/CS dilution zone regions.

CT066 KAPL Alloy 152M-CS Dilution Zone Specimen: Cross-Section

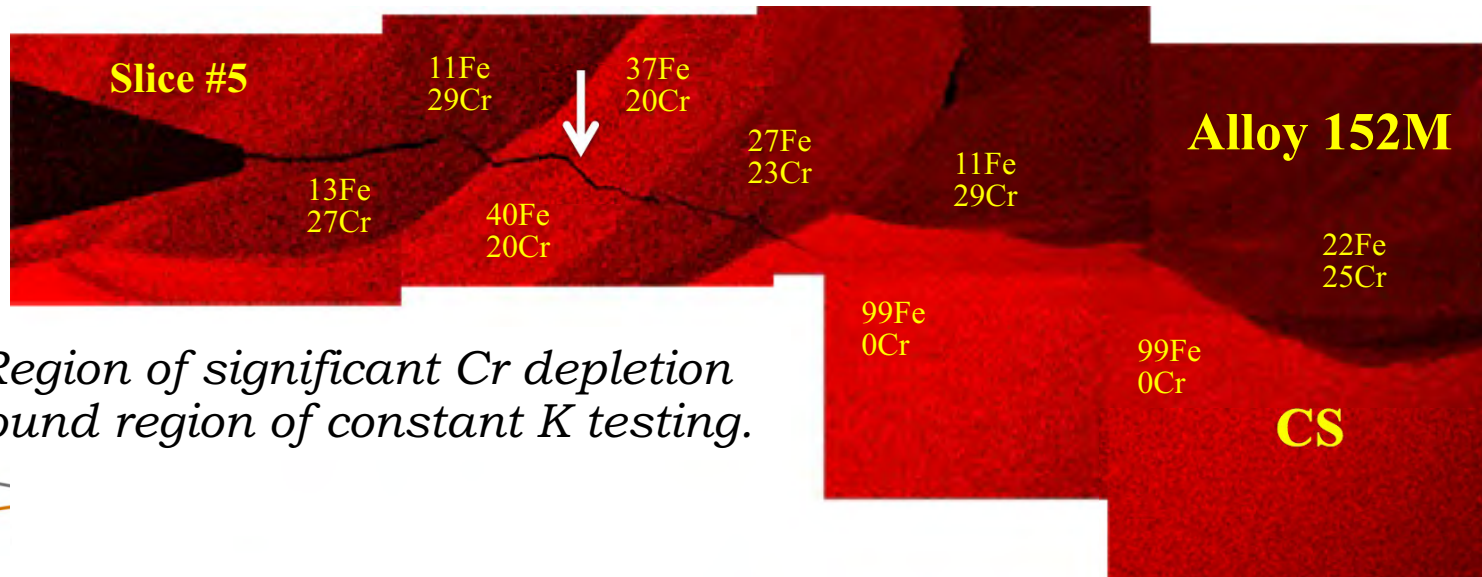
SEM BSE
Image



► **First constant K** in 152M-CS takes place in the weld in a region of significant Cr depletion.

- Low constant K CGR.
- Typical grain boundaries are not oriented for IG growth.
- Exams of crack profile and crack surface showed predominately TG cracking.

Companion
SEM Fe-K
EDS Map



Grain Boundaries in CT066 KAPL Alloy 152M-CS Cross-Section

- ▶ *Aligned high angle boundaries were observed in vicinity of crack path (see Region #2), but crack did not turn on to these boundaries.*

CT066 - KAPL Alloy 152M-CS, slice #5

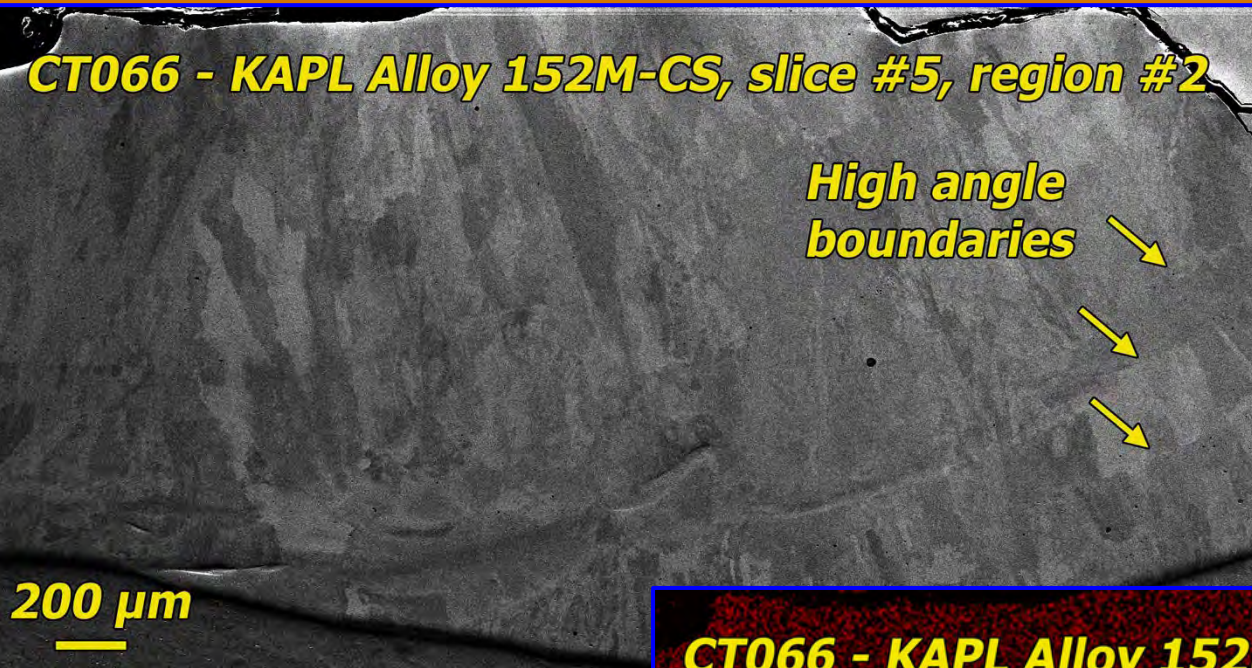
Region #2

Region #1

2 mm

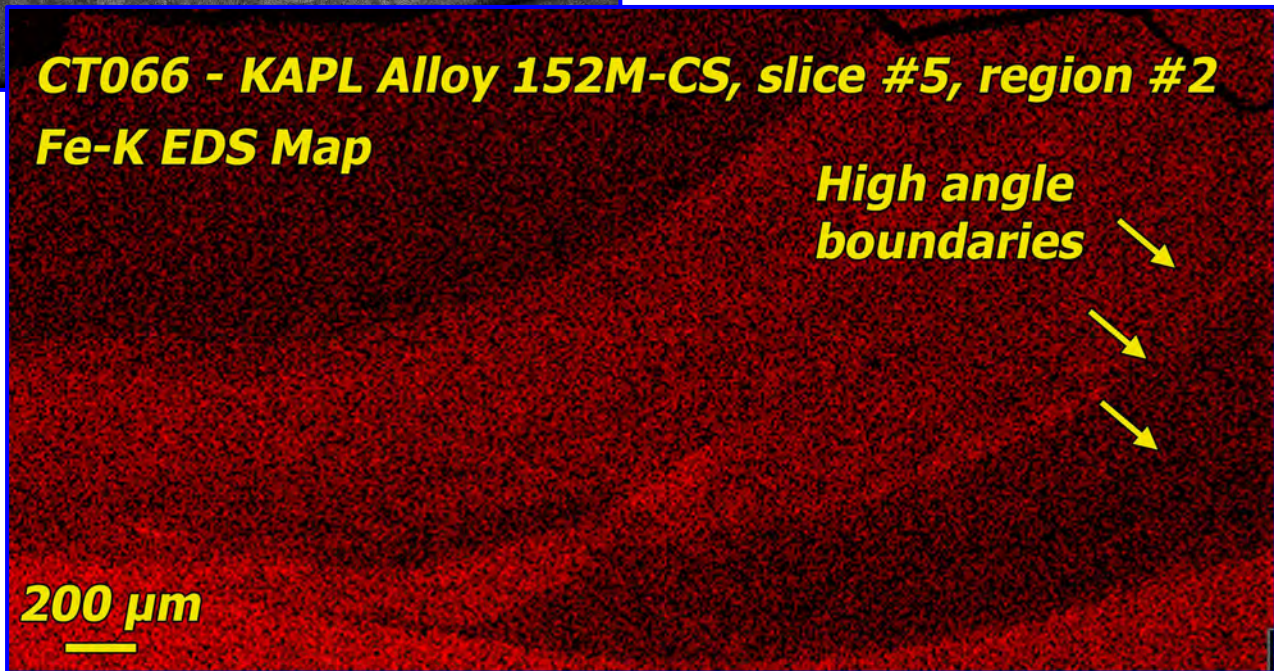
High angle boundaries

KAPL Alloy 152M-CS



Region #2

- ▶ *Boundaries are not as long or as apparent.*
- ▶ *No obvious Fe enrichment for this EDS map.*
 - *Higher resolution mapping may reveal enrichment.*

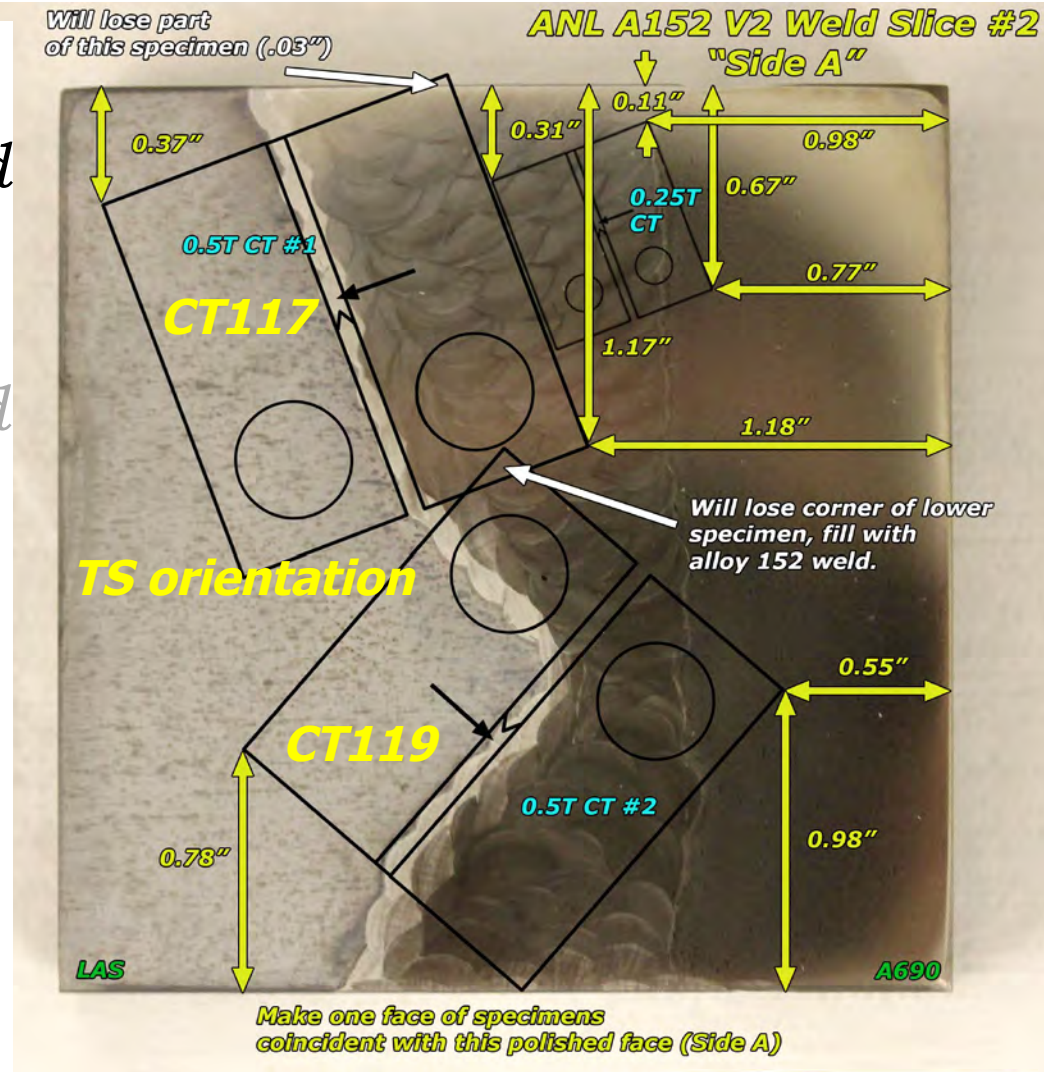


PNNL Dilution Zone Testing Summary

- ▶ *Alloy 152/52 Dilution Zone (DZ) and Fusion Line (FL) Tests*
 - *CT066 – KAPL Alloy 152M-CS DZ/FL test*
 - *CT117 – ANL Alloy 152v2 DZ/FL test #1*
 - **CT119 – ANL Alloy 152v2 DZ/FL test #2**
 - *CT136 – EPRI 52M DZ/FL test*
- ▶ *Fusion Line and LAS/CS HAZ Cracking*
 - *FL, LAS/CS HAZ are susceptible if PWHT not applied.*
- ▶ *Dilution Zone Cracking*
 - *Typical grain boundaries in weld are not aligned for IG crack growth parallel to the fusion line in the DZ.*
 - *A low density of atypical favorably aligned boundaries have been observed in dilution zones of some welds. Available composition data show that these boundaries are associated with dilutions.*
 - *Higher CGRs have only been observed in tests with cracking on these atypical favorably aligned boundaries.*

A152v2-LAS DZ PNNL #1 (CT117) and #2 (CT119)

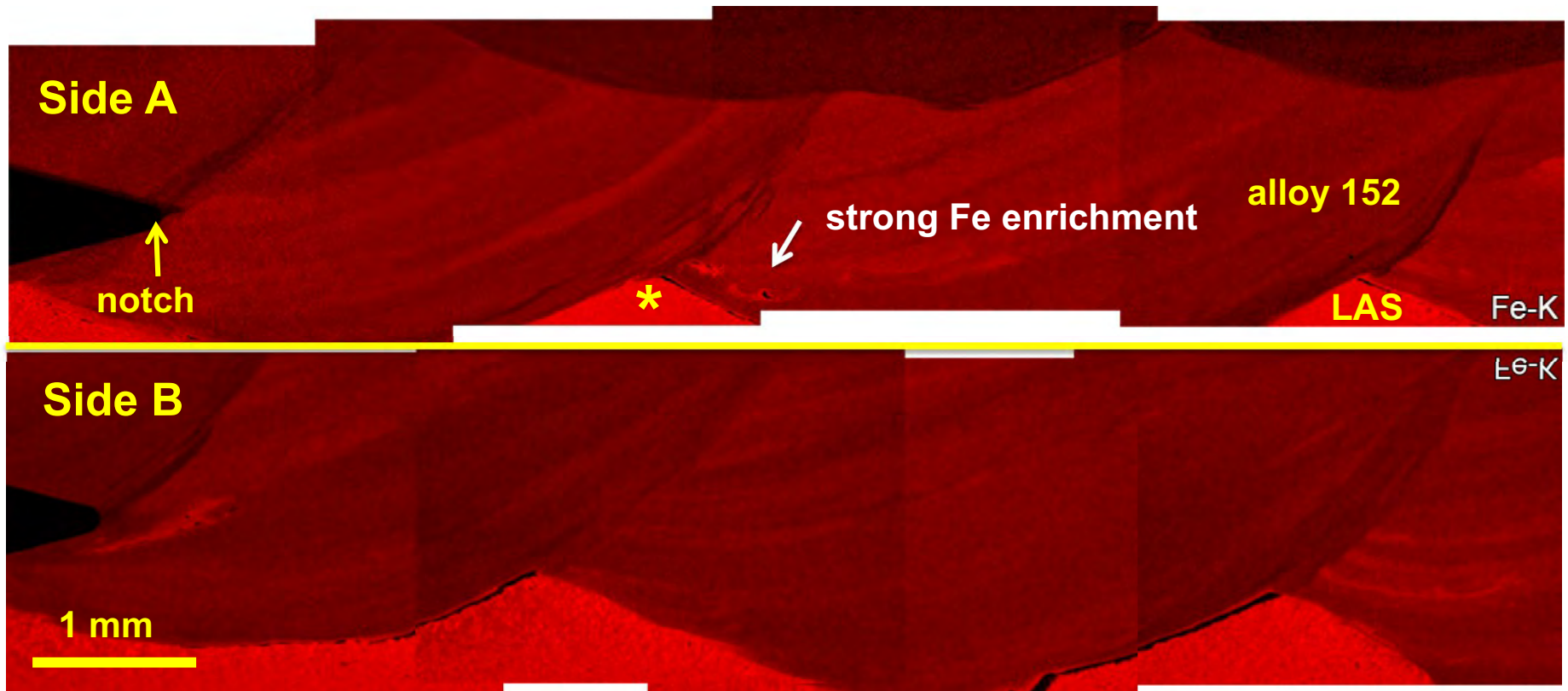
- ▶ Targeted dilution zone
- ▶ CT117 and **CT119** tested separately.
- ▶ Cut from same weldment as ANL N152-LAS-11 and N152-LAS-1 specimens where high high SCC CGRs were observed by tests at ANL.



CT119 - A152v2-LAS DZ PNNL #2

Side Groove SEM EDS Fe-K Images

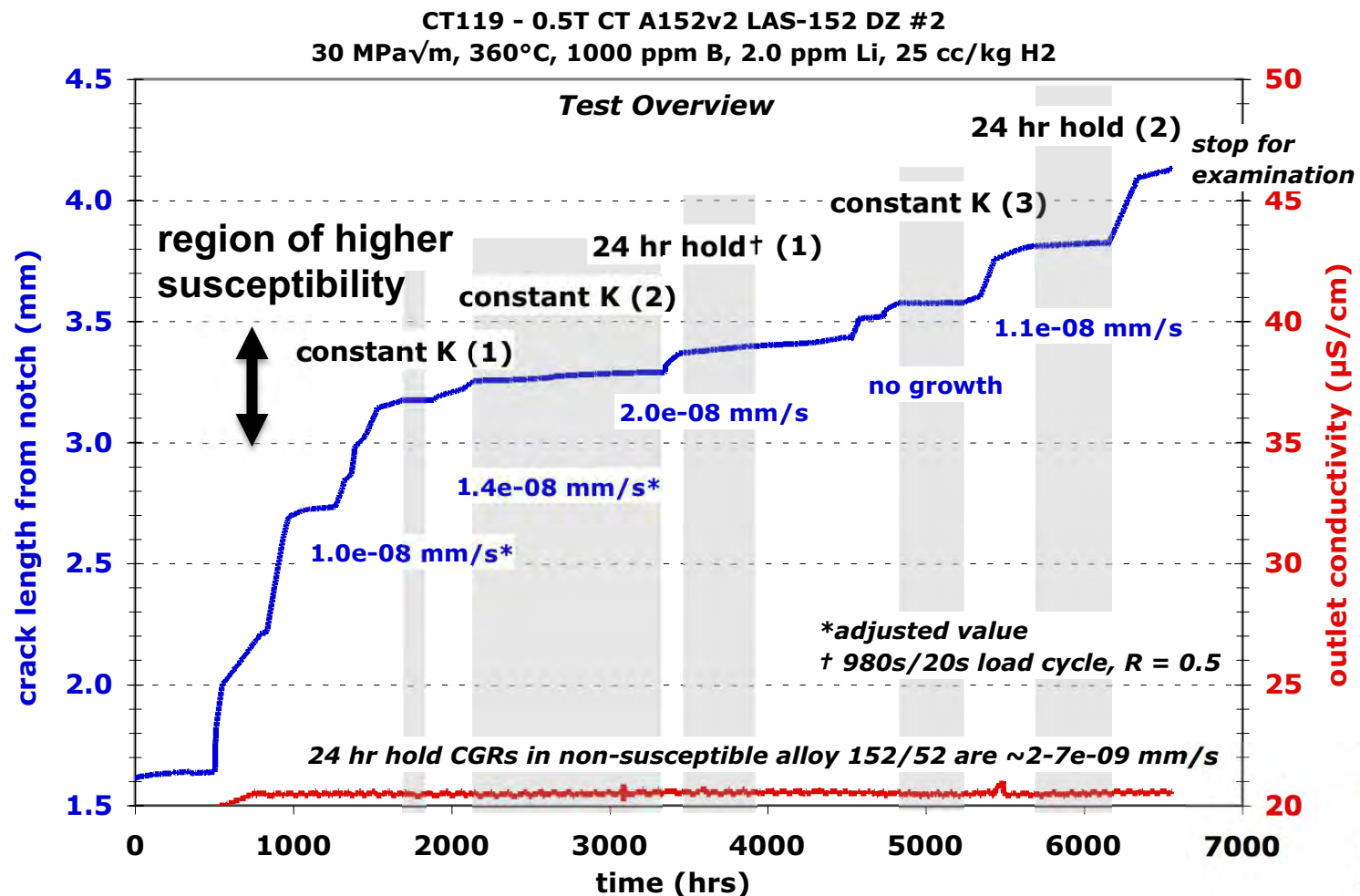
- ▶ *Pre-test SEM EDS examination of the side grooves.*
- ▶ *Regions of Fe enrichment are present in side groove A.*



CT119 - A152v2-LAS DZ PNNL #2

Test Overview – Part 1

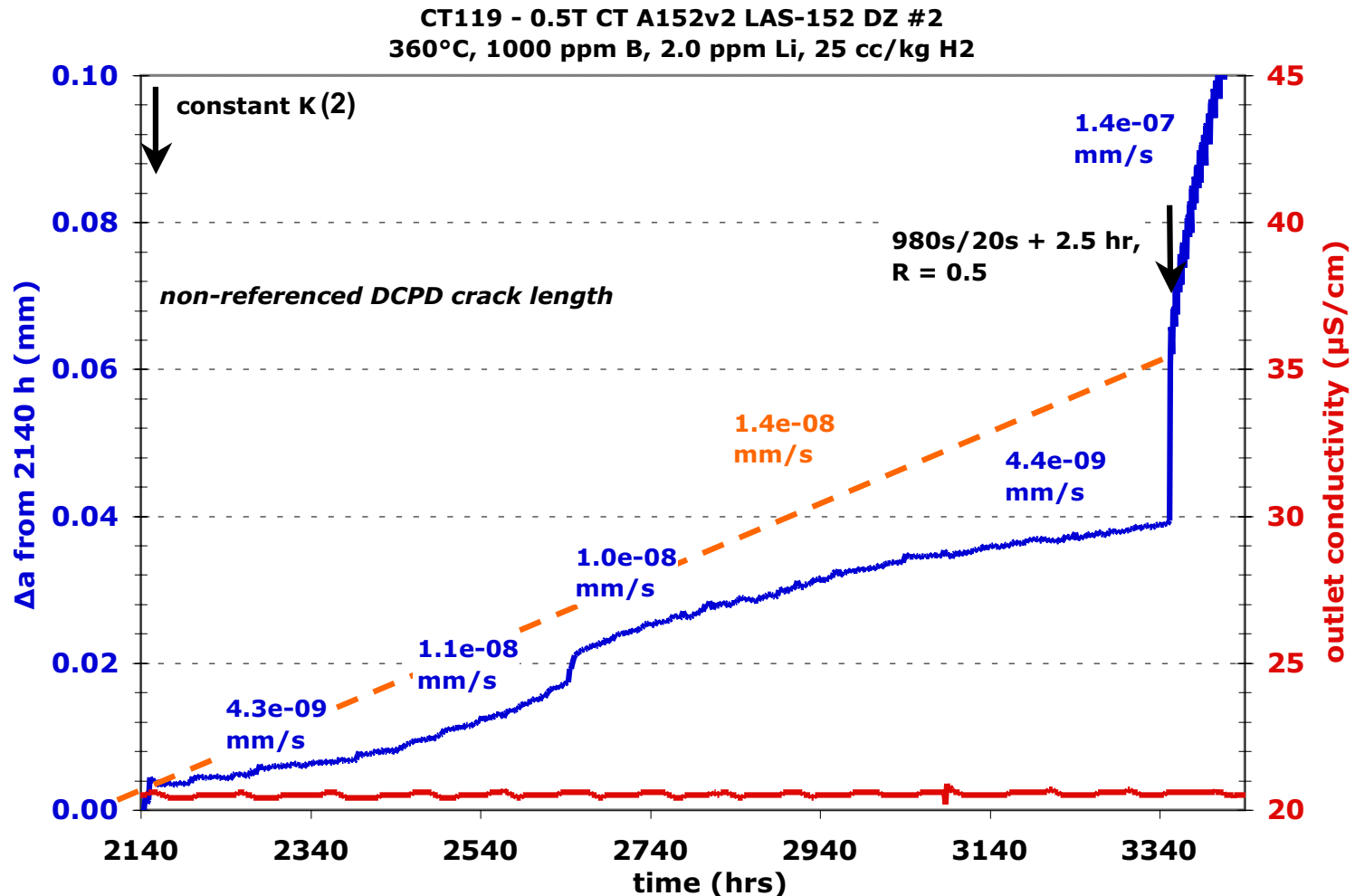
- Enhanced susceptibility during early constant K and 24 hr hold observations at DCPD-indicated 3-3.5 mm from the crack notch.



CT119 - A152v2-LAS DZ PNNL #2

Constant K CGR

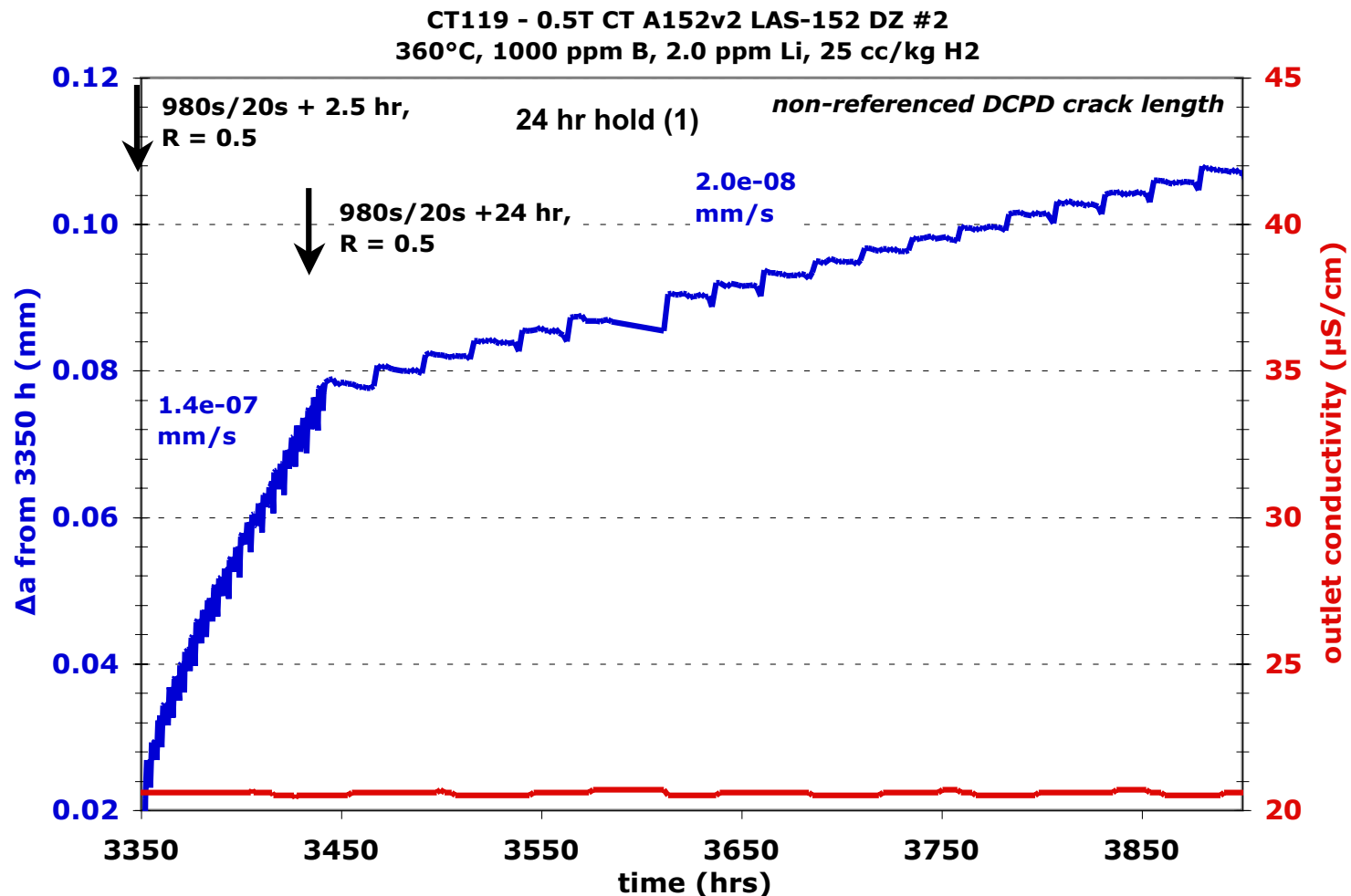
- ▶ Variable response at constant K .
- ▶ Strong indication of ligament or partial engagement. Estimated CGR is $\sim 1.4 \times 10^{-8}$ mm/s for this observation.



CT119 - A152v2-LAS DZ PNNL #2

24 Hour Hold Response

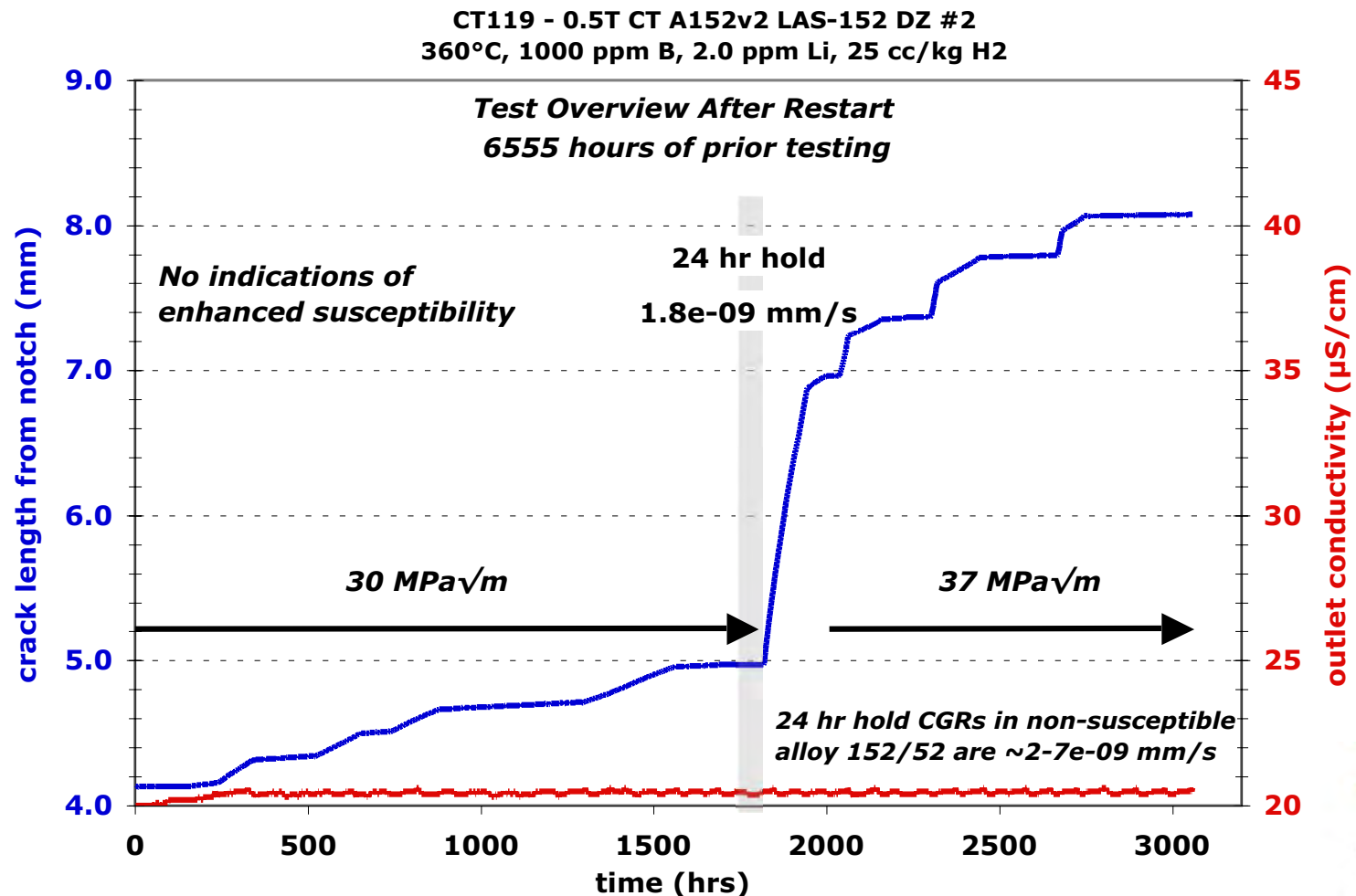
- ▶ $1.1\text{-}2.0 \times 10^{-8}$ mm/s observed for this specimen.
- ▶ $2\text{-}7 \times 10^{-9}$ mm/s CGRs for non-engaged alloy 152/52.
- ▶ Serrated response suggests ligament/contact breakage.



CT119 - A152v2-LAS DZ PNNL #2

Test Overview – Part 2

- ▶ Test interrupted at 6555 h to observe crack path in side grooves.
- ▶ Observed crack length in side grooves was comparable to DCPD.
- ▶ After restart of test, no indications of enhanced susceptibility.

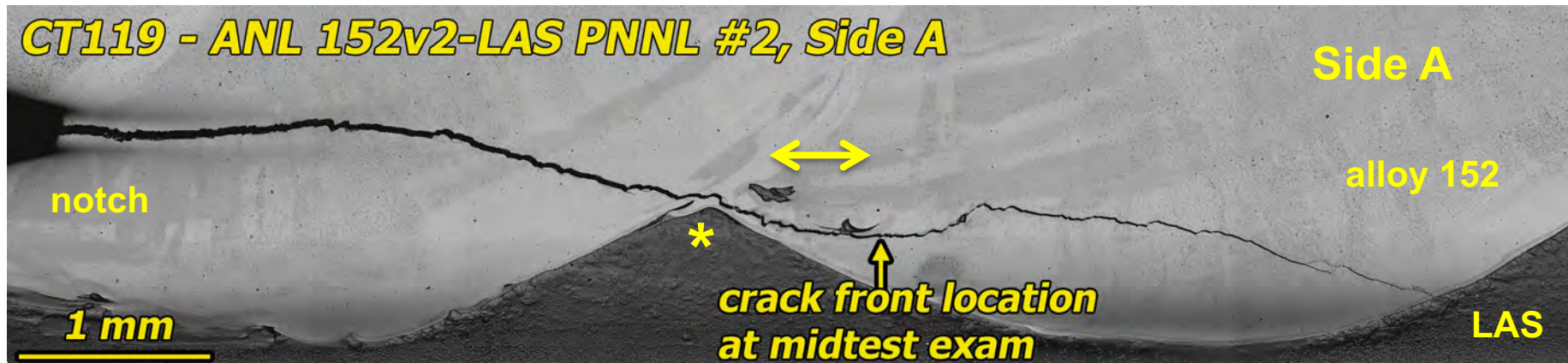


CT119 - A152v2-LAS DZ PNNL #2

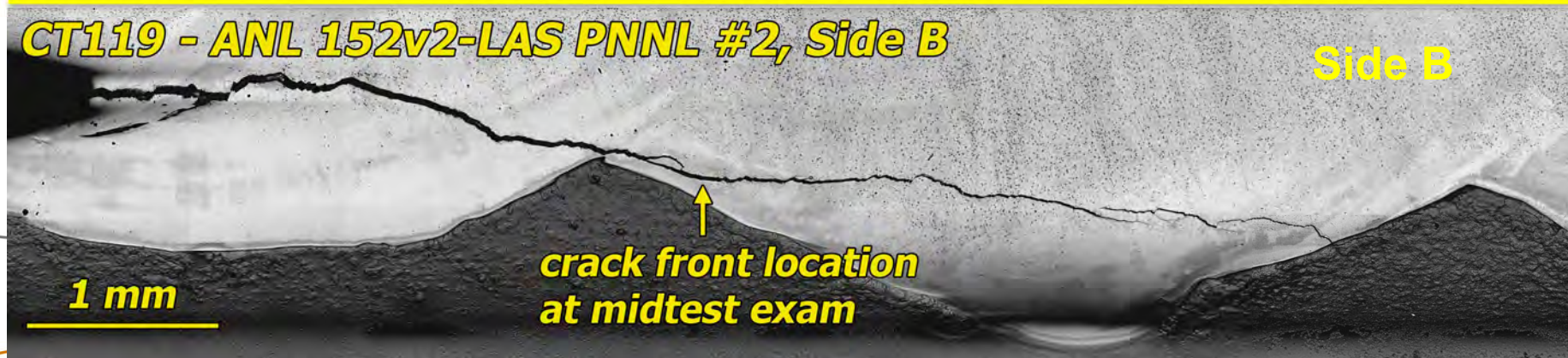
Post-Test Side Groove Images

- ▶ Post-test SEM images of side grooves.
- ▶ As with many other dilution zone tests at PNNL, crack moves toward the fusion line.
- ▶ What region along the crack path corresponds to the higher susceptibility seen in the SCC CGR test?

CT119 - ANL 152v2-LAS PNNL #2, Side A



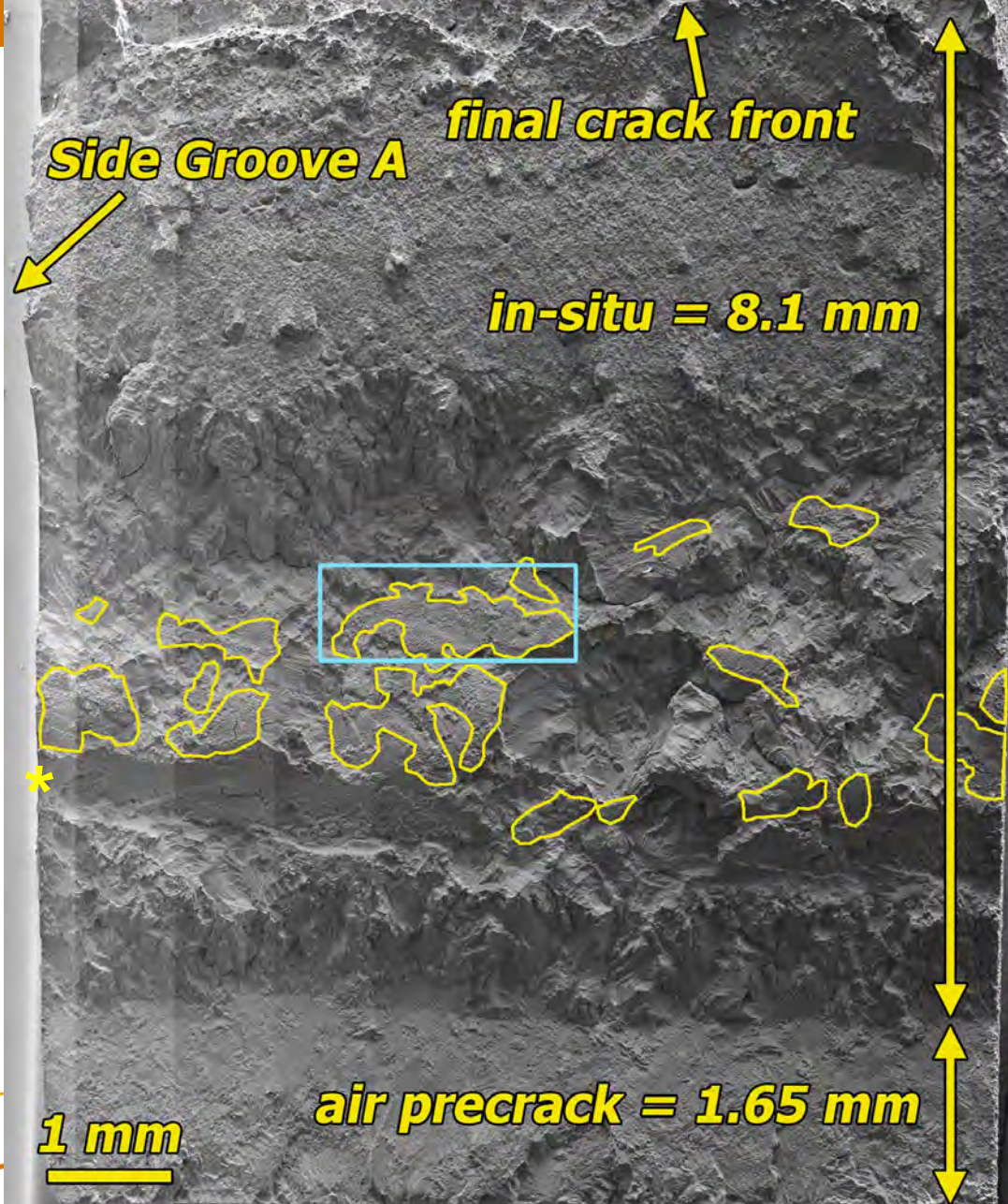
CT119 - ANL 152v2-LAS PNNL #2, Side B



CT119 Crack Surface

- ▶ Many patches of IG cracking identified in second weld pass.
- ▶ Surface texture has appearance of the end of a dendritic packet.
- ▶ Some IG patches more than 1 mm in size.
- ▶ Distance from notch corresponds to early part of test where higher susceptibility was observed.

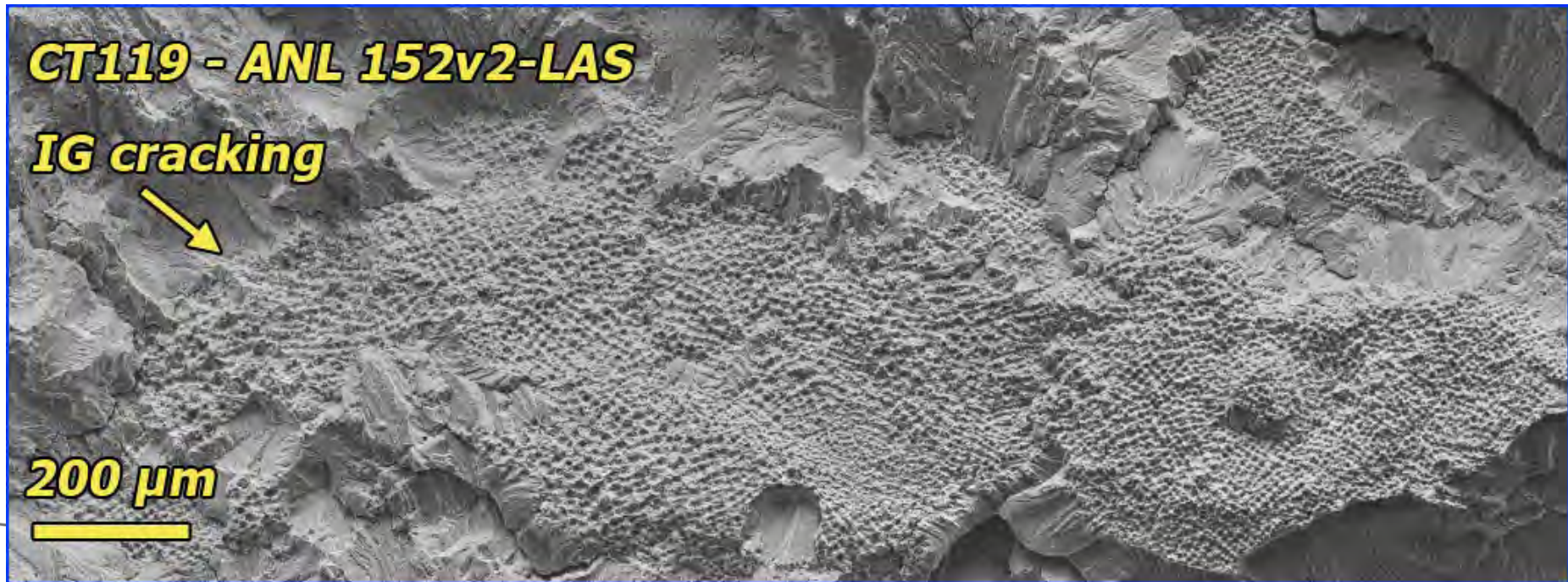
CT119 - ANL 152v2-LAS DZ PNNL #2
2/3 of thickness of specimen



CT119 - A152v2-LAS DZ PNNL #2

Crack Surface

- ▶ *Region of IG cracking along aligned high angle boundary.*
- ▶ *Texture has appearance of the termination of a forest of dendrites. Represents the ends of dendrite packets*

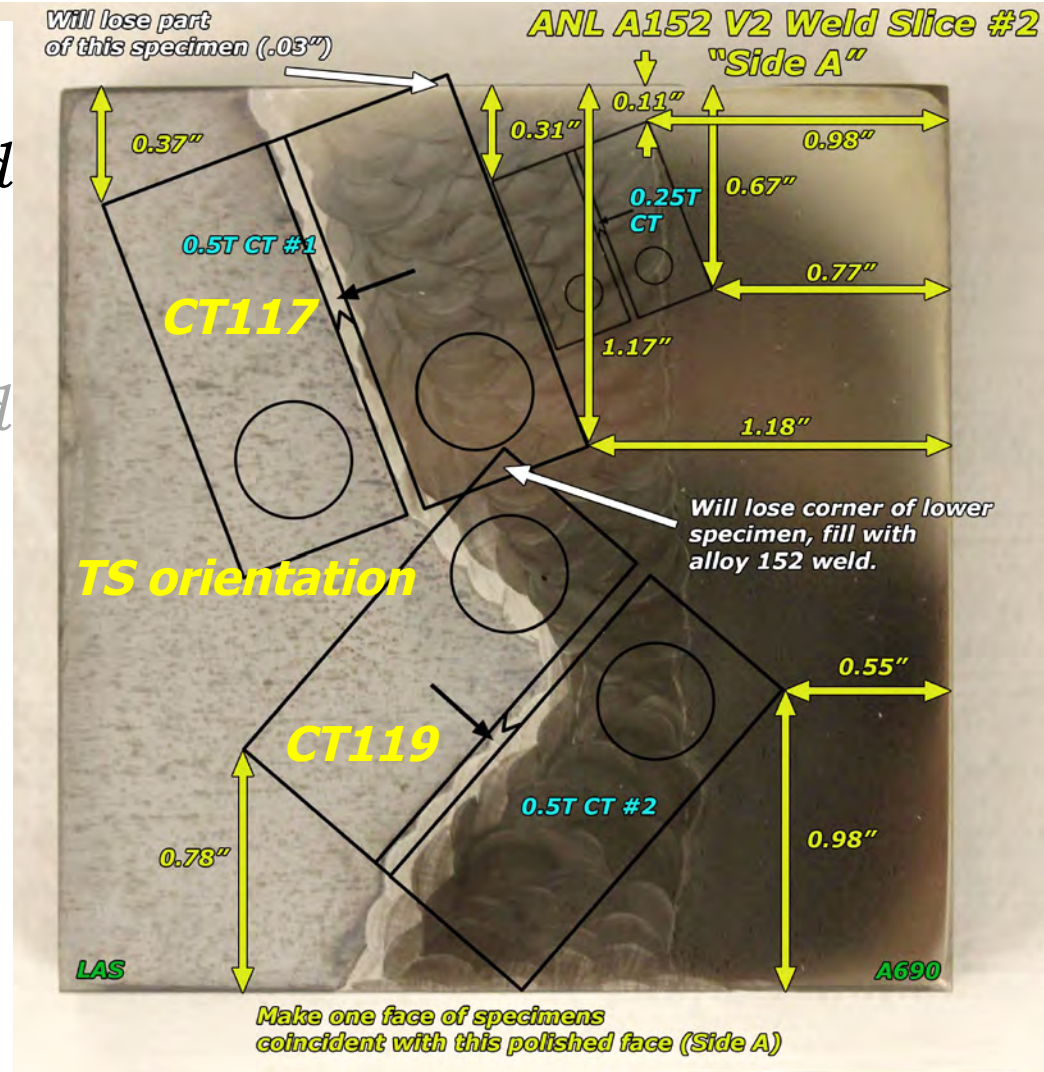


PNNL Summary

- ▶ Alloy 152/52 Dilution Zone (DZ) and Fusion Line (FL) Tests
 - CT066 – KAPL Alloy 152M-CS DZ/FL test
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 - CT119 – ANL Alloy 152v2 DZ/FL test #2
 - CT136 – EPRI 52M DZ/FL test
- ▶ Fusion Line and LAS/CS HAZ Cracking
 - FL, LAS/CS HAZ are susceptible if PWHT not applied.
- ▶ Dilution Zone Cracking
 - Typical grain boundaries in weld are not aligned for IG crack growth parallel to the fusion line in the DZ.
 - A low density of atypical favorably aligned boundaries have been observed in dilution zones of some welds. Available composition data show that these boundaries are associated with dilutions.
 - Higher CGRs have only been observed in tests with cracking on these atypical favorably aligned boundaries.

A152v2-LAS DZ PNNL #1 (CT117) and #2 (CT119)

- ▶ Targeted dilution zone
- ▶ **CT117** and CT119 tested separately.
- ▶ Cut from same weldment as ANL N152-LAS-11 and N152-LAS-1 specimens where high high SCC CGRs were observed by tests at ANL.

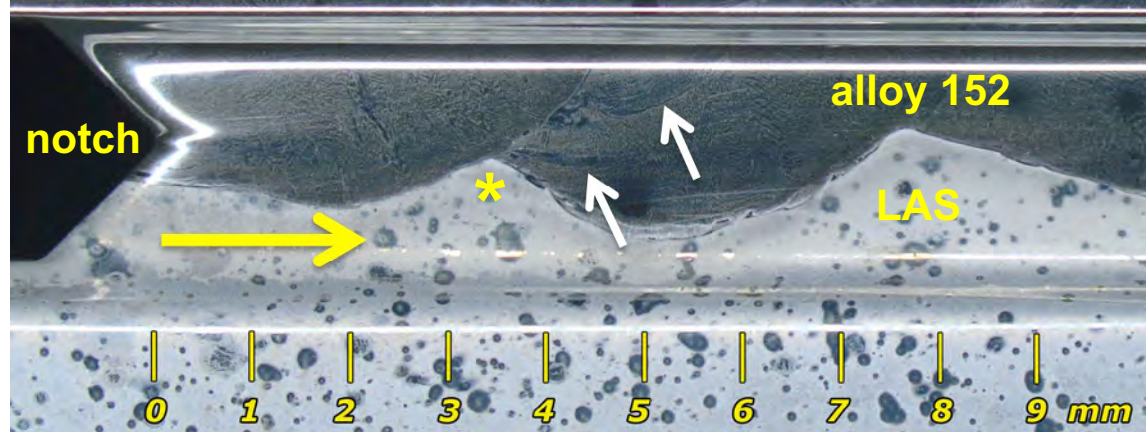


CT117 - A152v2-LAS DZ PNNL #1

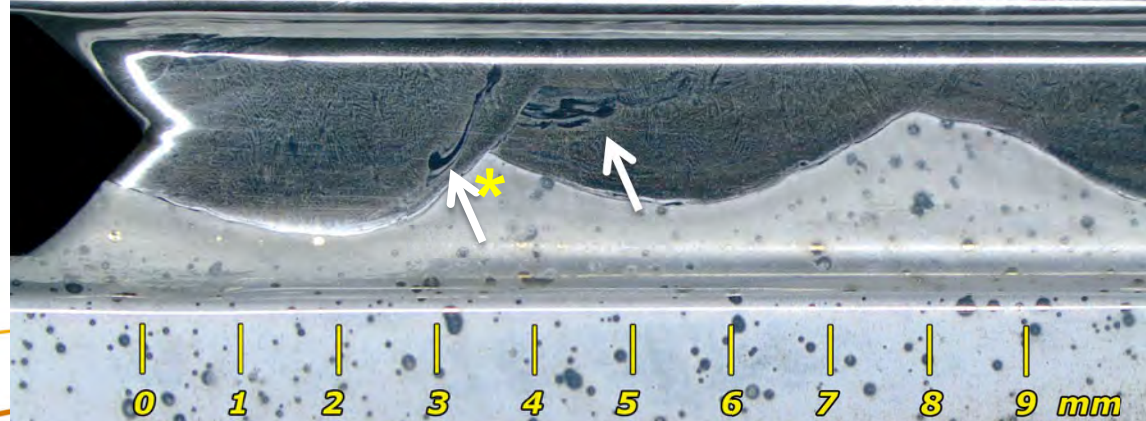
Side Groove Images

- ▶ Arrows indicate regions of dilution at 3-3.5 mm and 4-5 mm.
- ▶ Test strategy was to assess both regions of dilution.
- ▶ Same region as ANL N152-LAS-11 specimen.

CT117 - ANL 152 V2 Weldment
PNNL DZ Specimen #1, Side A
Corresponds to ANL N152-LAS-11 Specimen **Side A**



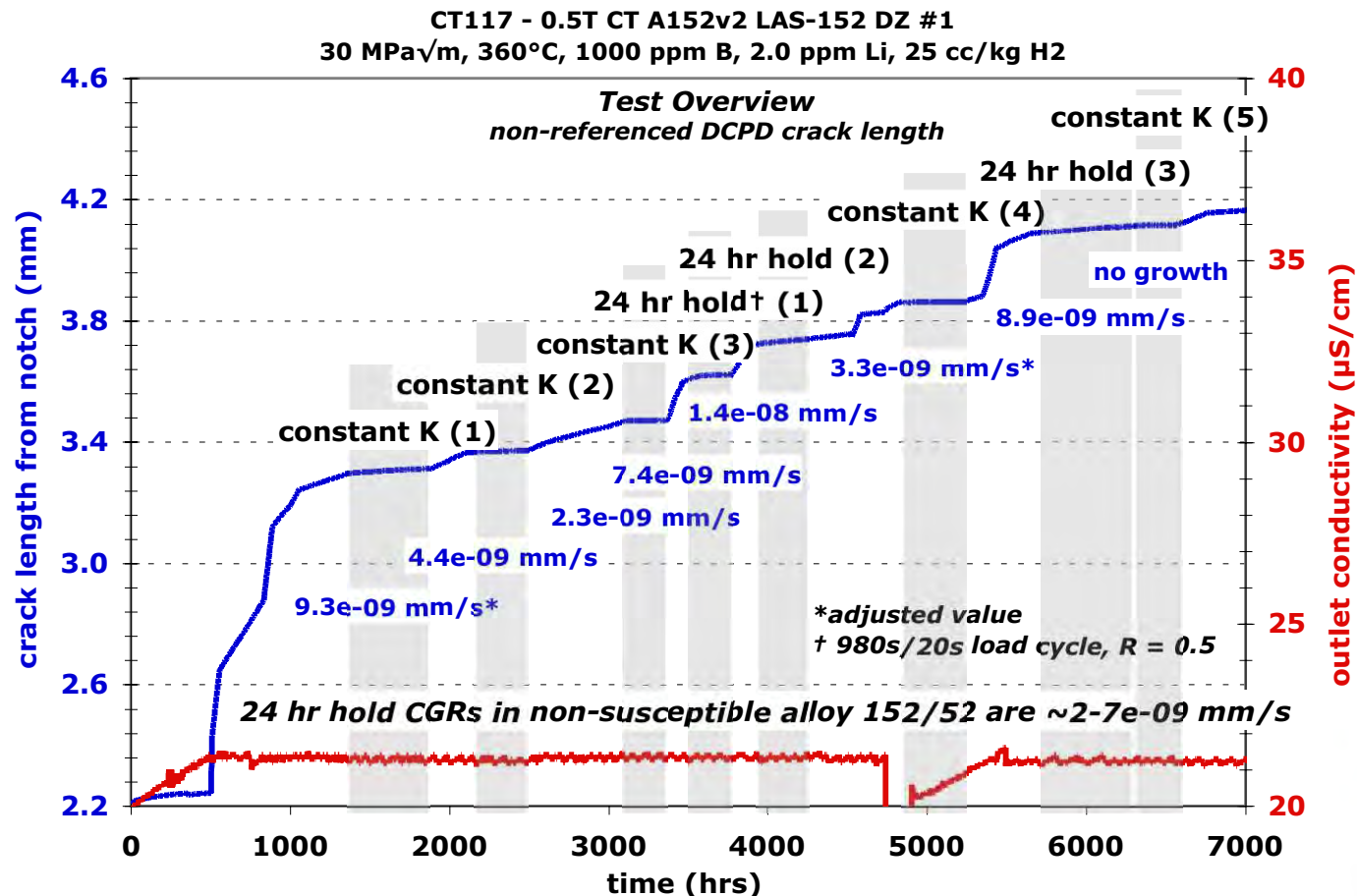
CT117 - ANL 152 V2 Weldment
PNNL DZ Specimen #1, Side B
Corresponds to ANL N152-LAS-11 Specimen **Side B**



CT117 - A152v2-LAS DZ PNNL #1

Test Overview - Part 1 - 0-7K Hours

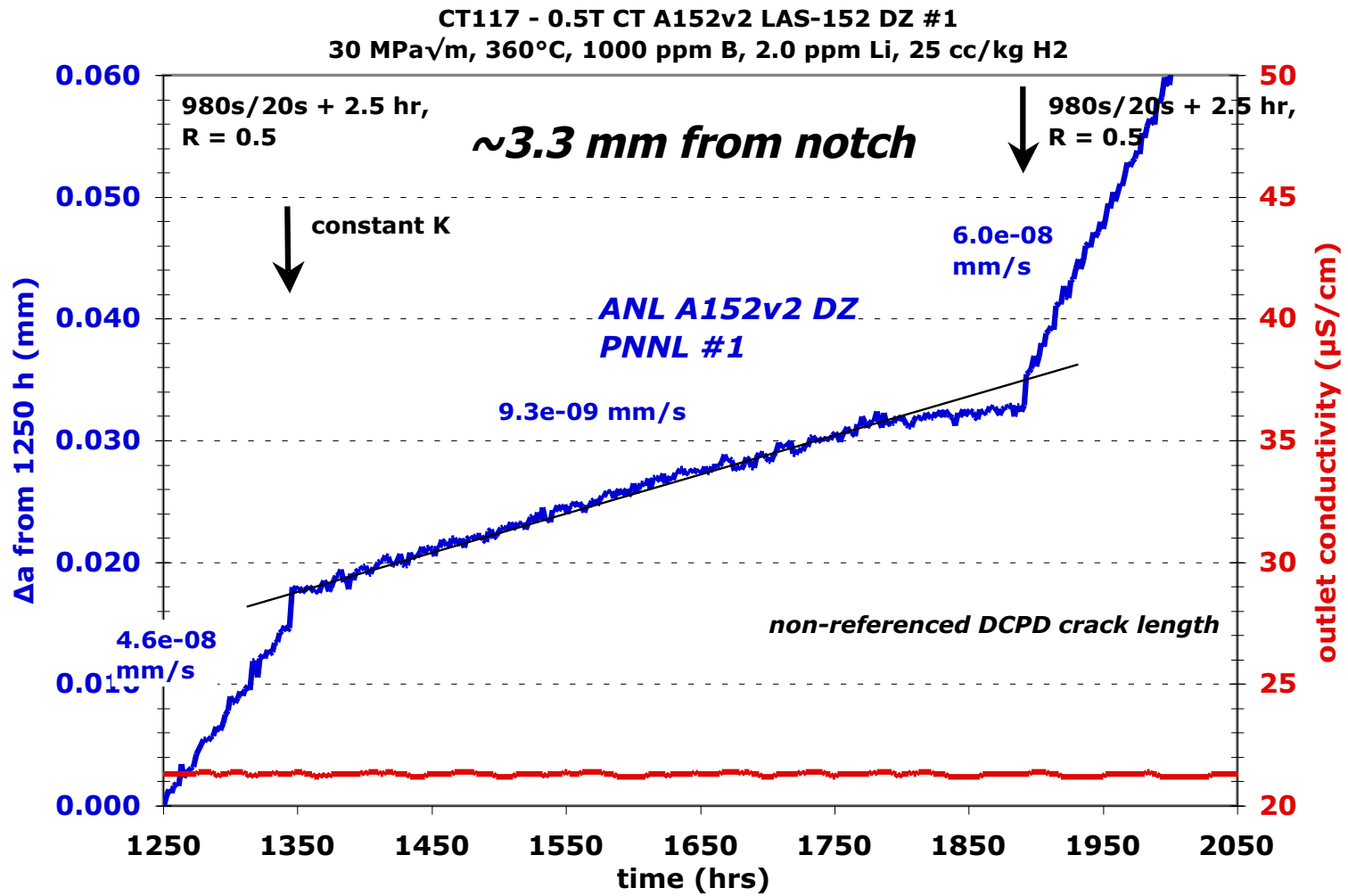
- ▶ Using constant K and 24 hr hold loading to evaluate SCC.
- ▶ SCC susceptibility observed at crack depth of ~ 3.3 mm corresponding to first region on dilution.
- ▶ Some reduction in susceptibility at ~ 3.8 mm of crack extension.



CT117 - A152v2-LAS DZ PNNL #1

Constant K Response

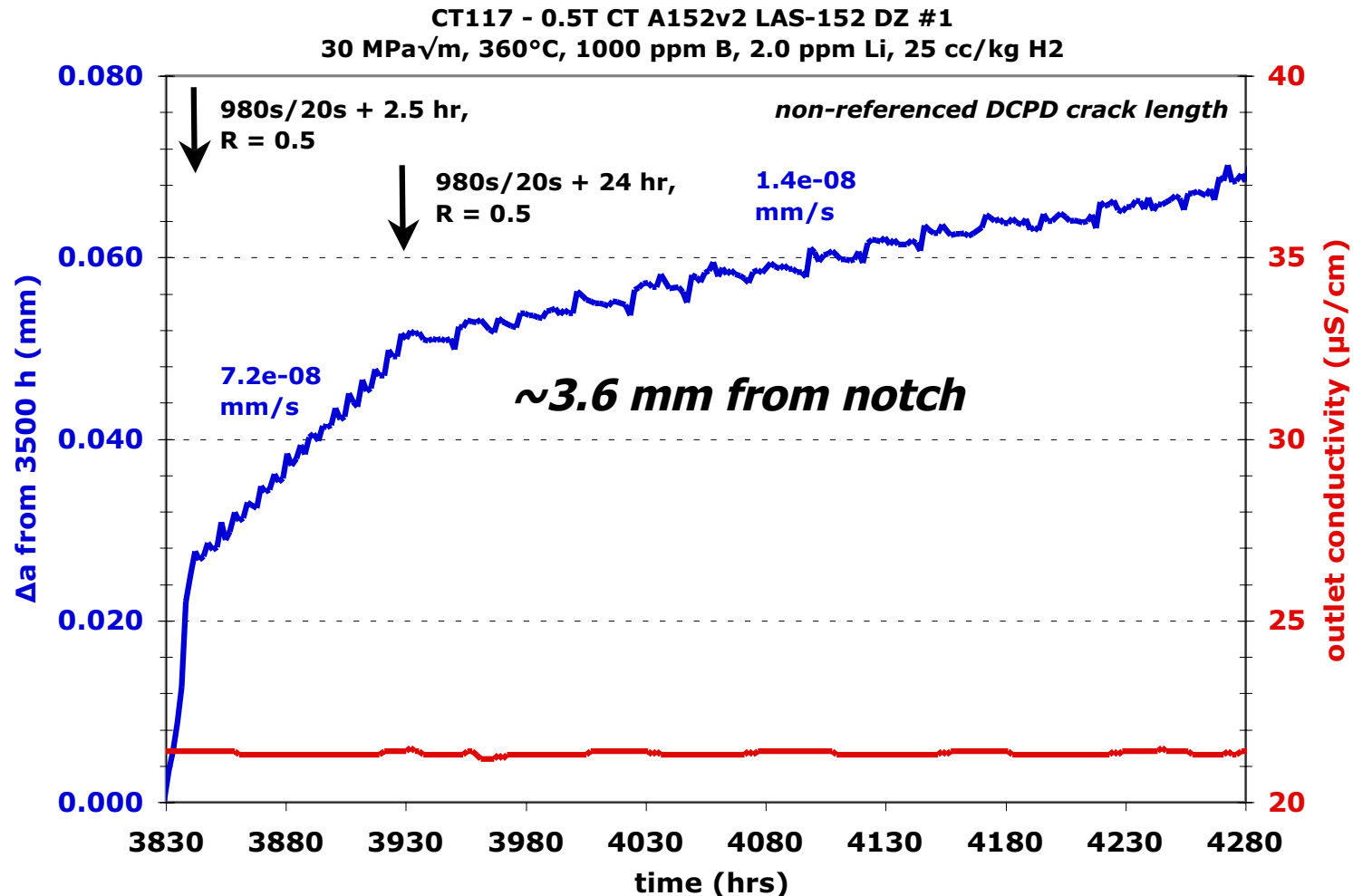
- ▶ $\sim 1 \times 10^{-8}$ mm/s measured during 1st constant K – highest observed constant K for this test.
- ▶ Small jump after constant K suggests ligament breakage.



CT117 - A152v2-LAS DZ PNNL #1

24 Hour Hold Response

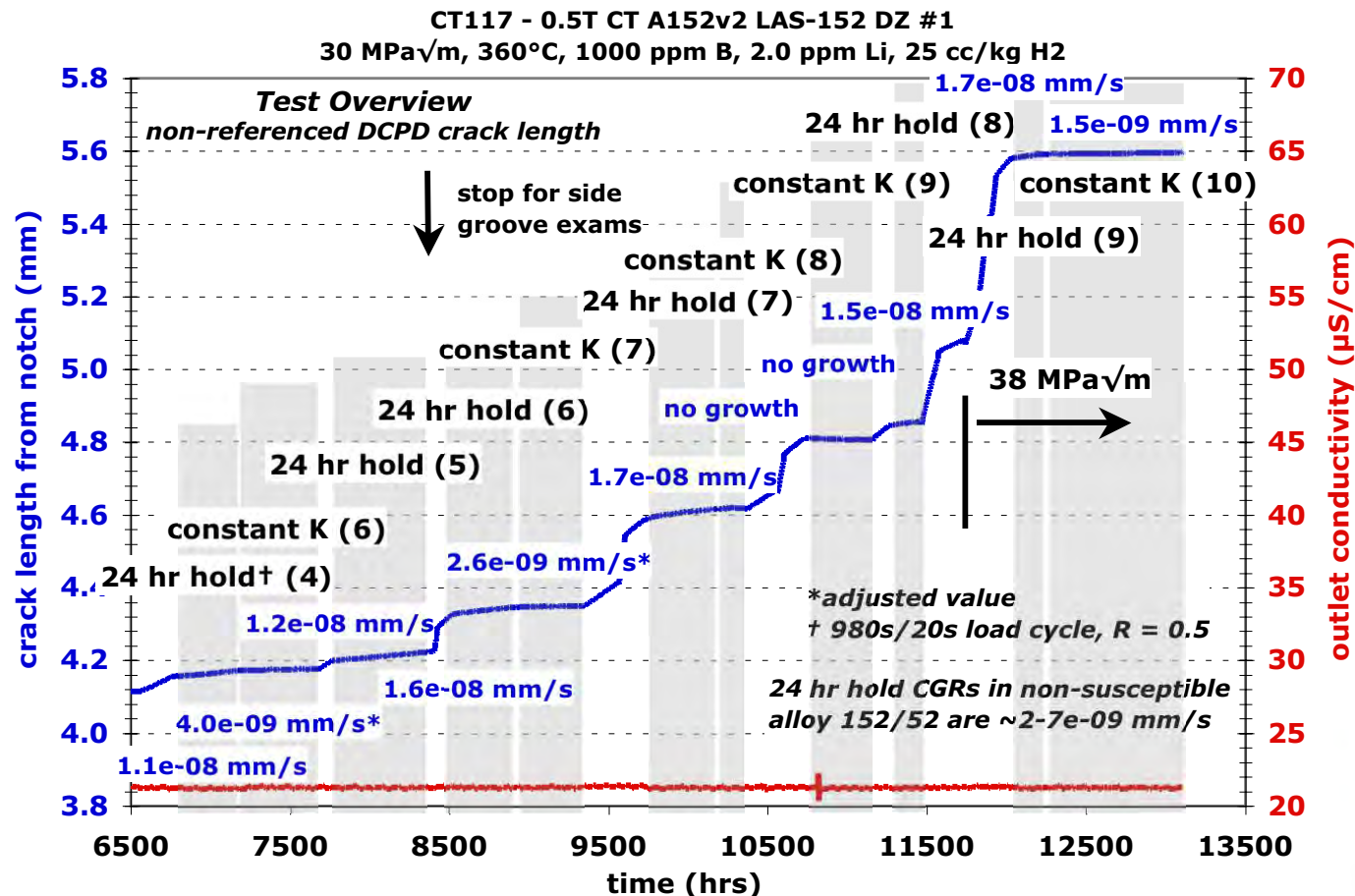
- ▶ 1.4×10^{-8} mm/s measured in this observation.
- ▶ $2-7 \times 10^{-9}$ mm/s CGRs typical for non-engaged alloy 152/52.
- ▶ Serrated response suggests ligament breakage.



CT117 - A152v2-LAS DZ PNNL #1

Test Overview – Part 2

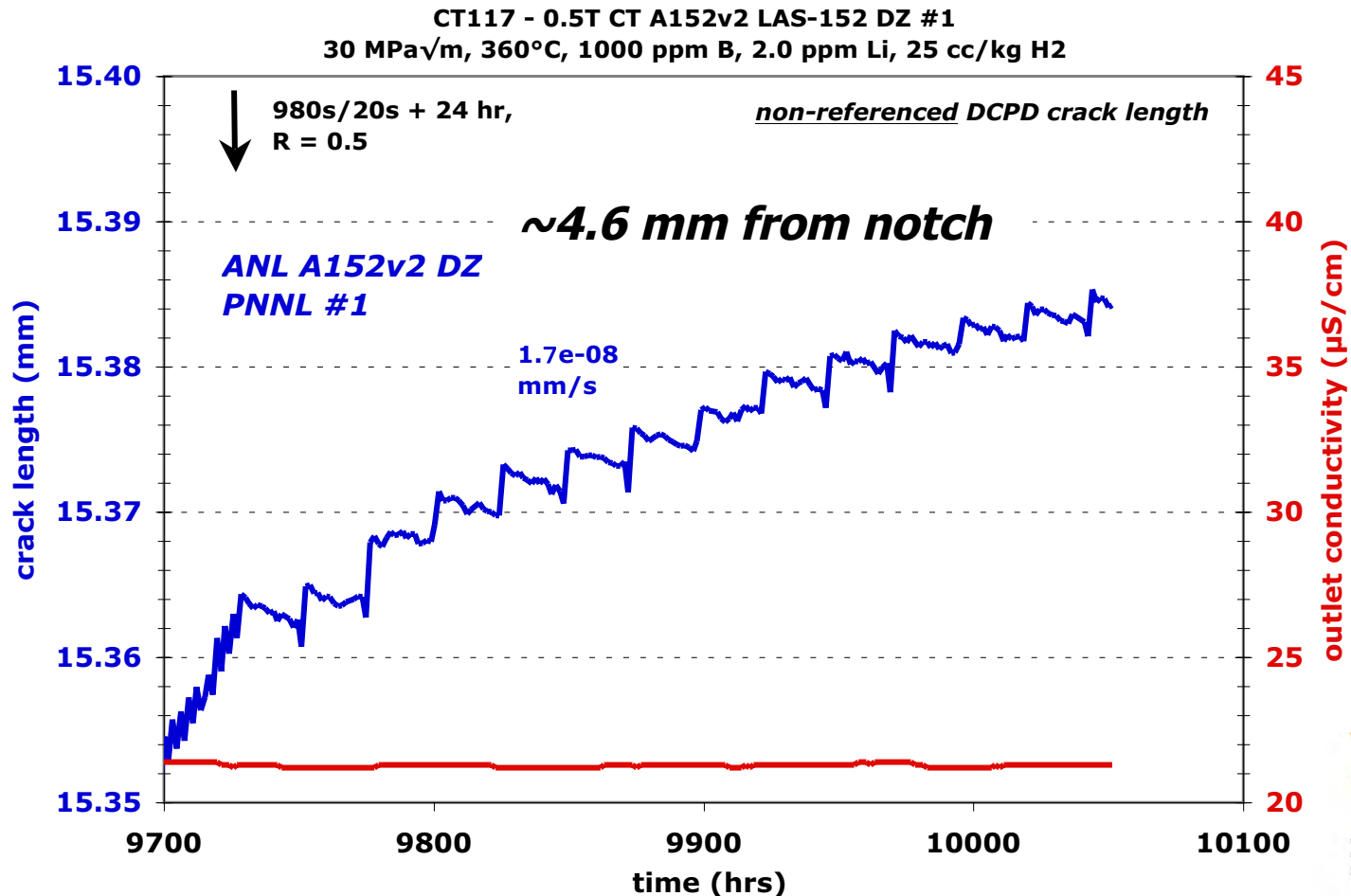
- ▶ Increased in susceptibility between ~4.2 – 4.7 mm.
- ▶ Constant K values remain low, but 24 hr hold observations have increasingly higher values.



CT117 - A152v2-LAS DZ PNNL #1

Test Overview – Part 2

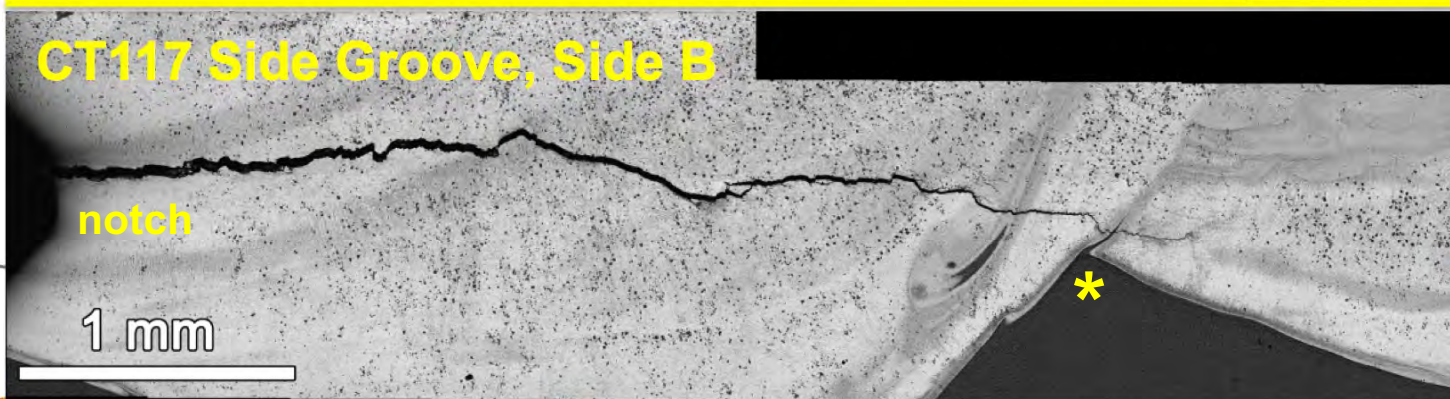
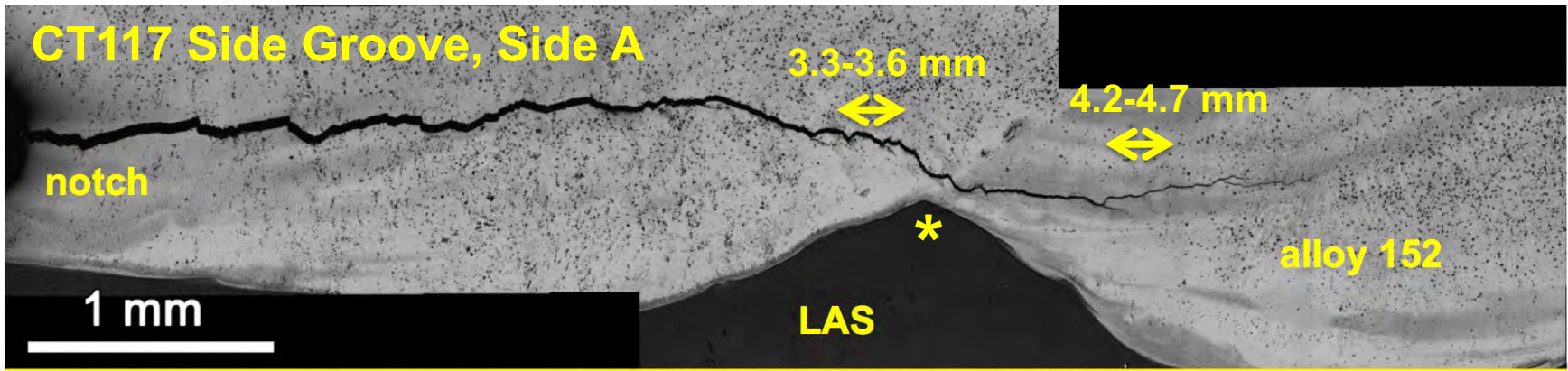
- ▶ This is the highest 24 hr hold rate observed for this specimen.
- ▶ Strongly serrated behavior suggestive of ligament or contact issues.



CT117 - A152v2-LAS DZ PNNL #1

Post-Test **Side Groove** Images

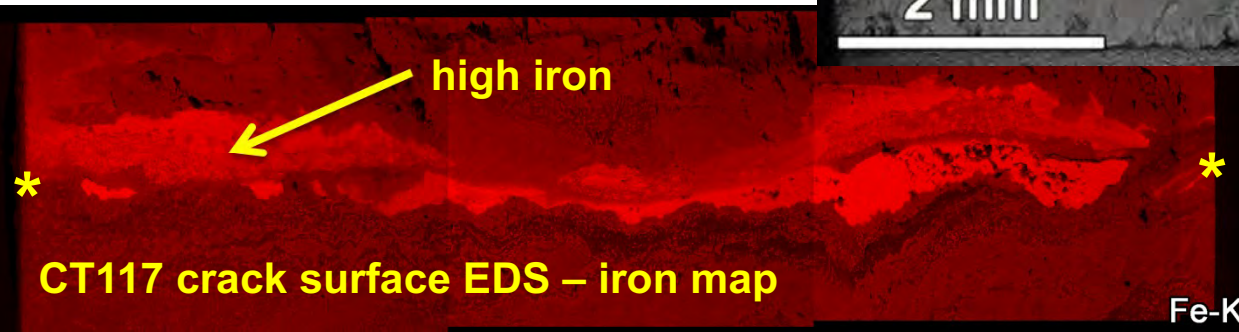
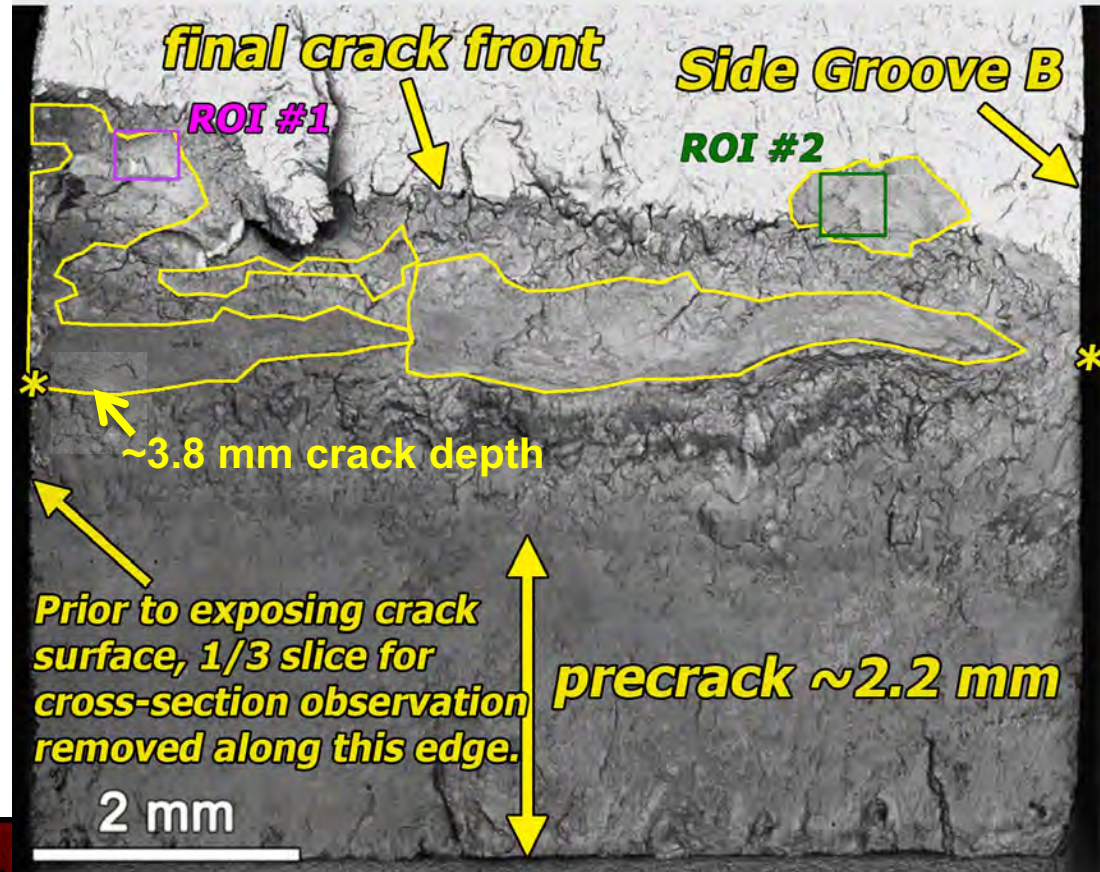
- ▶ *Post-test SEM images of side grooves.*
- ▶ *As with other dilution zone tests, crack eventually moves towards the fusion line.*
- ▶ *Crack length on Side A = ~5.2 mm, Side B = ~4.1 mm.*
- ▶ *Where are regions of enhanced SCC susceptibility?*



CT117 Crack Surface

- ▶ Many patches of IG cracking identified in second weld pass.
- ▶ Surface texture has appearance of the end of a dendritic packet.
- ▶ Some IG patches more than 1 mm in size.
- ▶ Distance from notch approximately corresponds to portions of test where higher susceptibility was observed.

CT117 - ANL 152v2-LAS DZ PNNL #1
2/3 of thickness of specimen

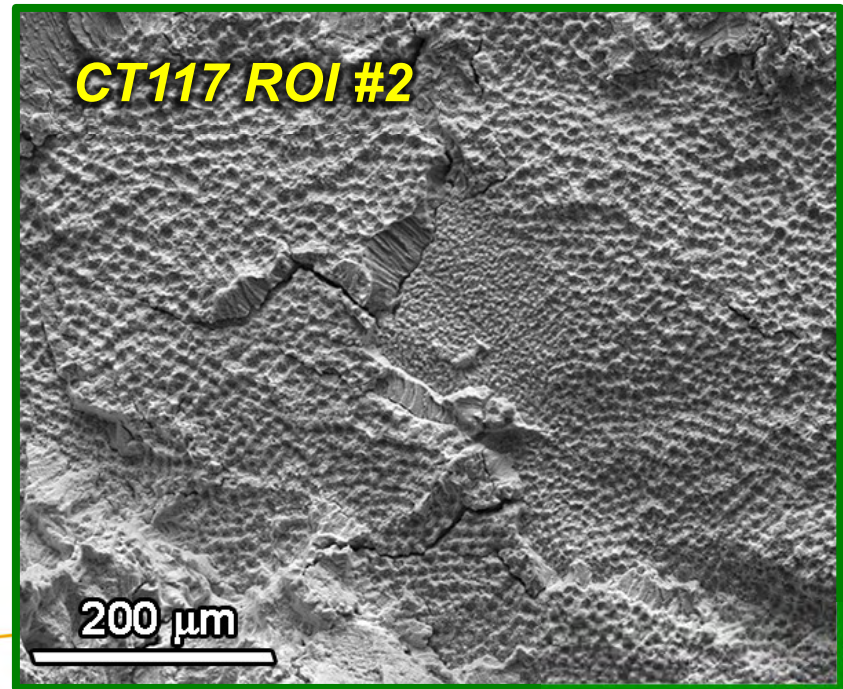
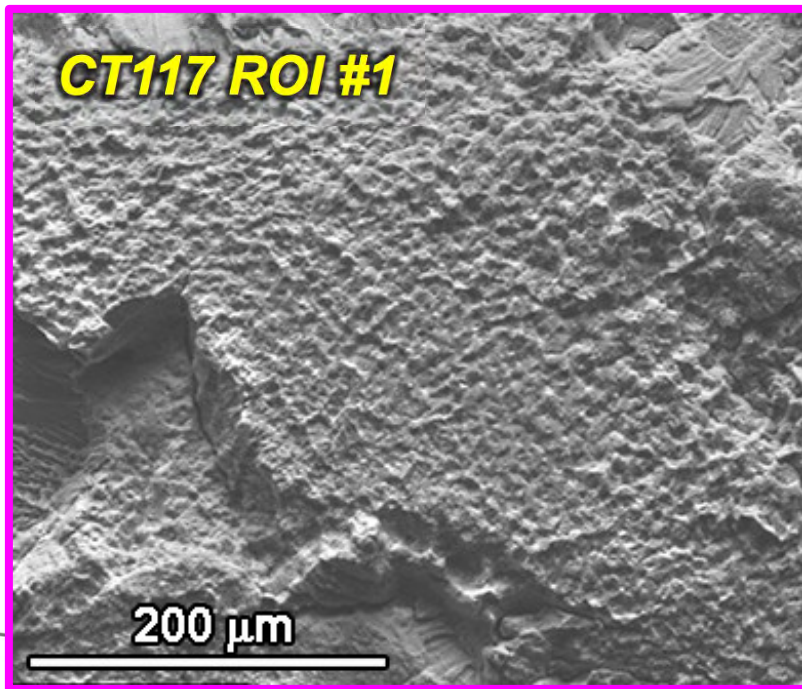


CT117 crack surface EDS – iron map

CT117 - A152v2-LAS DZ PNNL #1

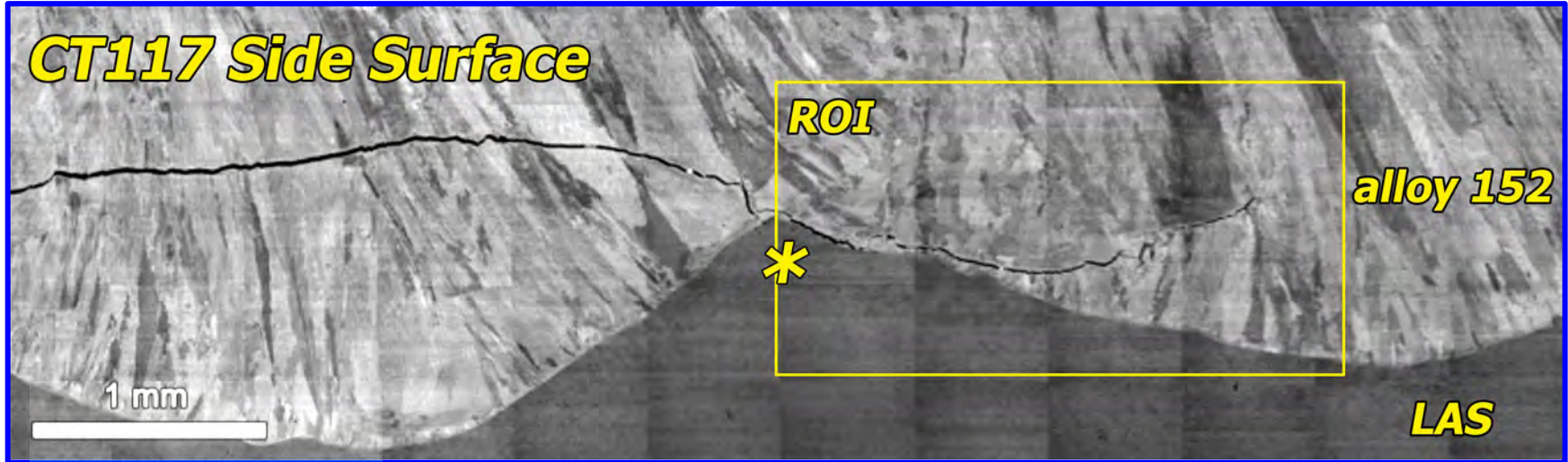
Crack Surface

- ▶ *Regions of IG cracking along aligned high angle boundary.*
- ▶ *Texture has appearance of the termination of a forest of dendrites. Represents the ends of dendrite packets*

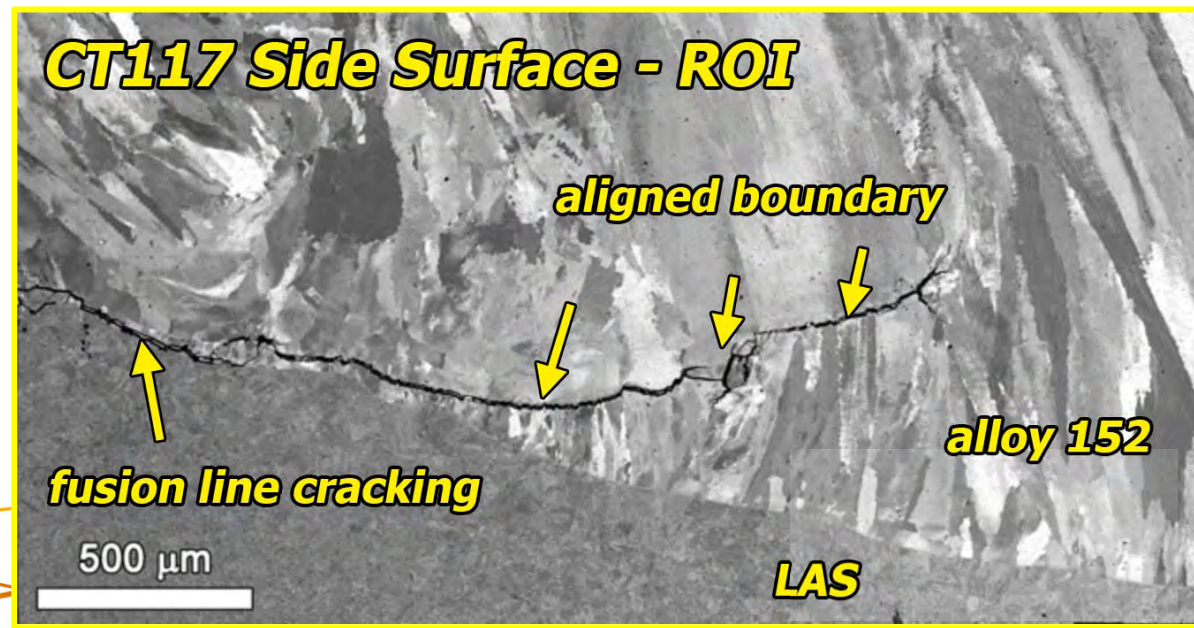


CT117 - A152v2-LAS DZ PNNL #1

Crack Cross-Section



- ▶ In the second weld pass, cracking on fusion line and on an aligned boundary



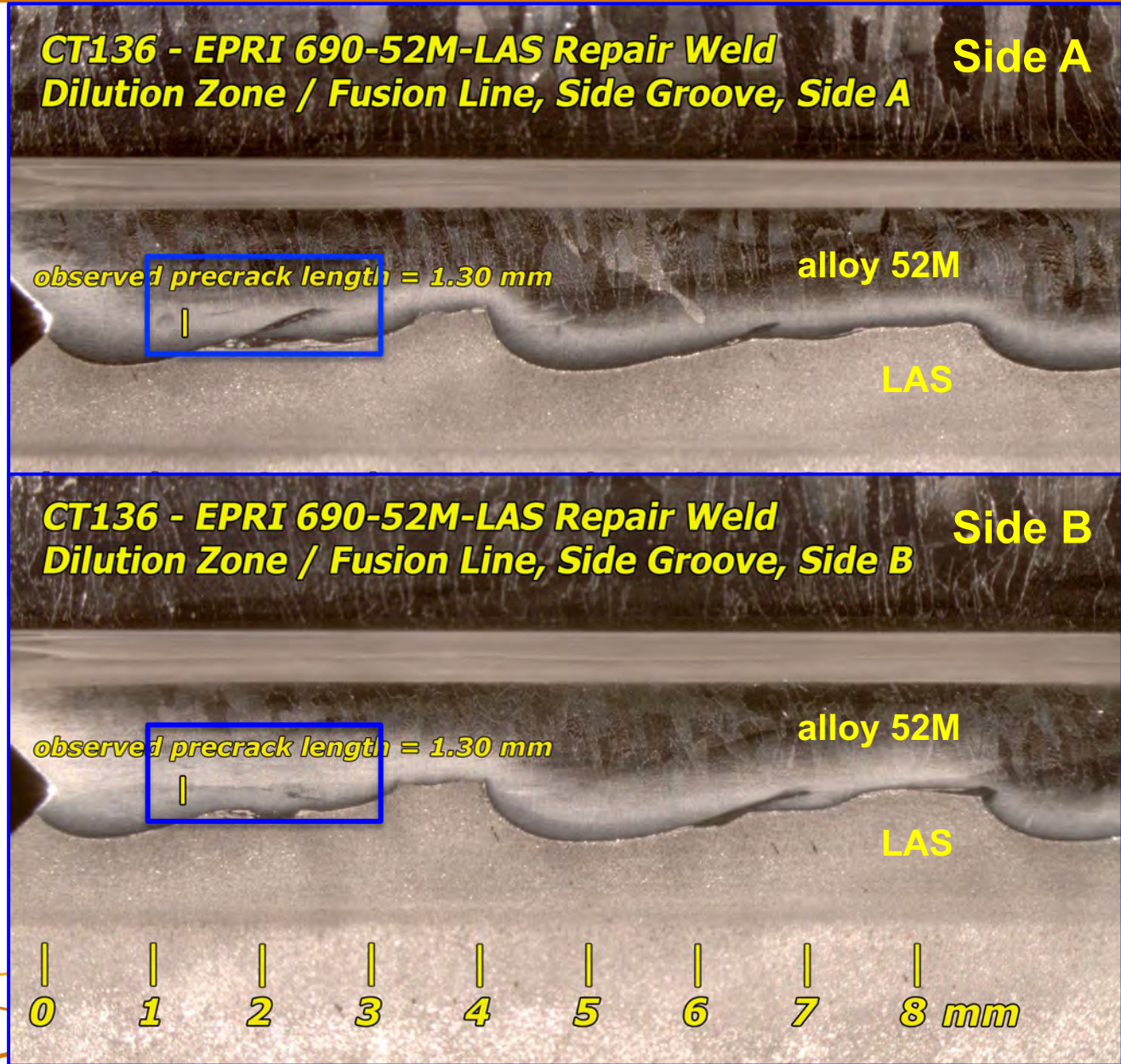
PNNL Summary

- ▶ Alloy 152/52 Dilution Zone (DZ) and Fusion Line (FL) Tests
 - CT066 – KAPL Alloy 152M-CS DZ/FL test
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 - CT119 – ANL Alloy 152v2 DZ/FL test #2
 - **CT136 – EPRI 52M DZ/FL test**
- ▶ Fusion Line and LAS/CS HAZ Cracking
 - FL, LAS/CS HAZ are susceptible if PWHT not applied.
- ▶ Dilution Zone Cracking
 - Typical grain boundaries in weld are not aligned for IG crack growth parallel to the fusion line in the DZ.
 - A low density of atypical favorably aligned boundaries have been observed in dilution zones of some welds. Available composition data show that these boundaries are associated with dilutions.
 - Higher CGRs have only been observed in tests with cracking on these atypical favorably aligned boundaries.

EPRI DMW Temper Bead / Repair Weld – DZ Test

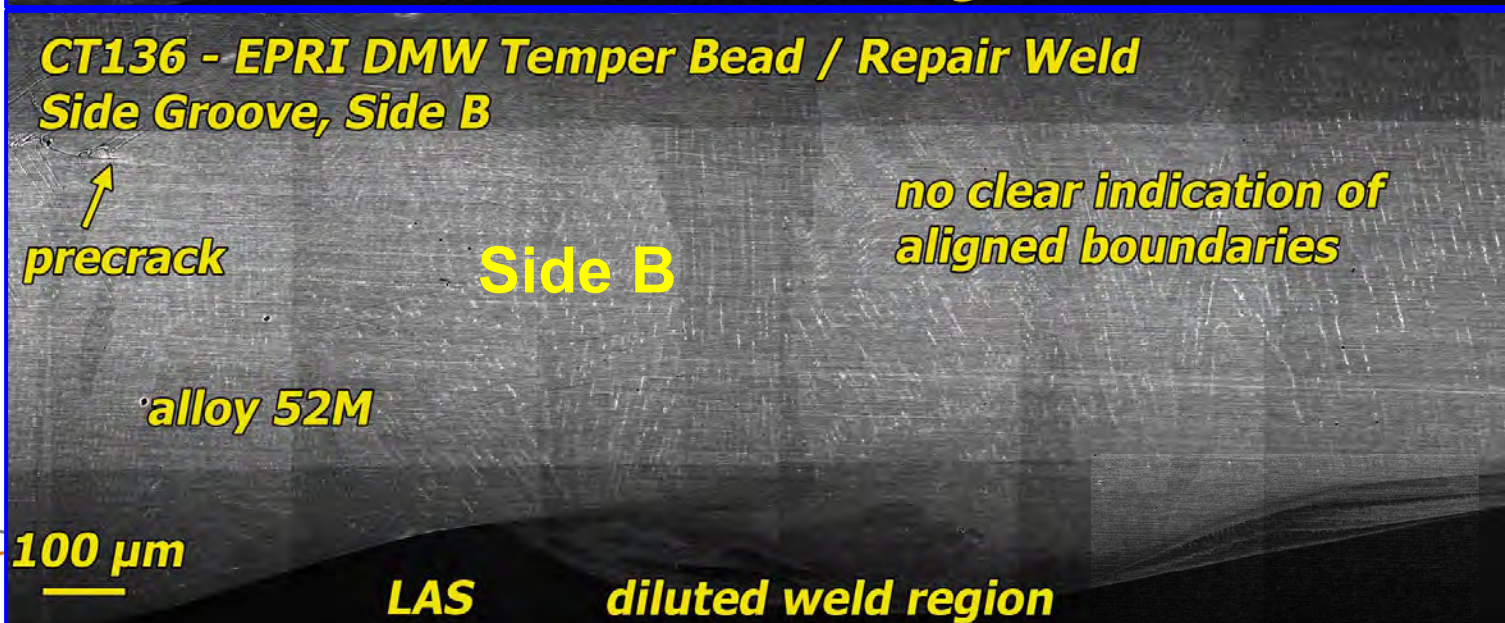
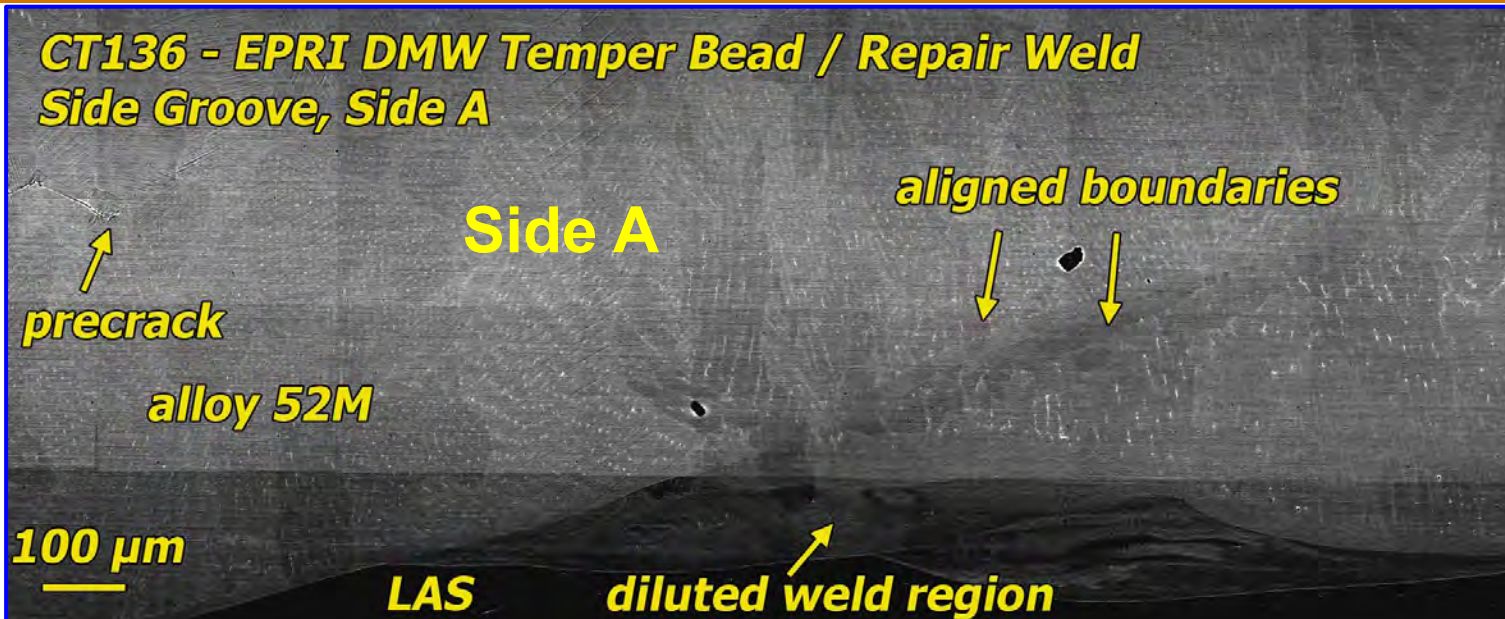
Side Groove Images of DZ Specimen

- ▶ Side groove images after air precracking but before SCC testing.
- ▶ Precrack location aligned to assess dilution region and fusion line response.
- ▶ Blue box indicates detail region shown on next slide.



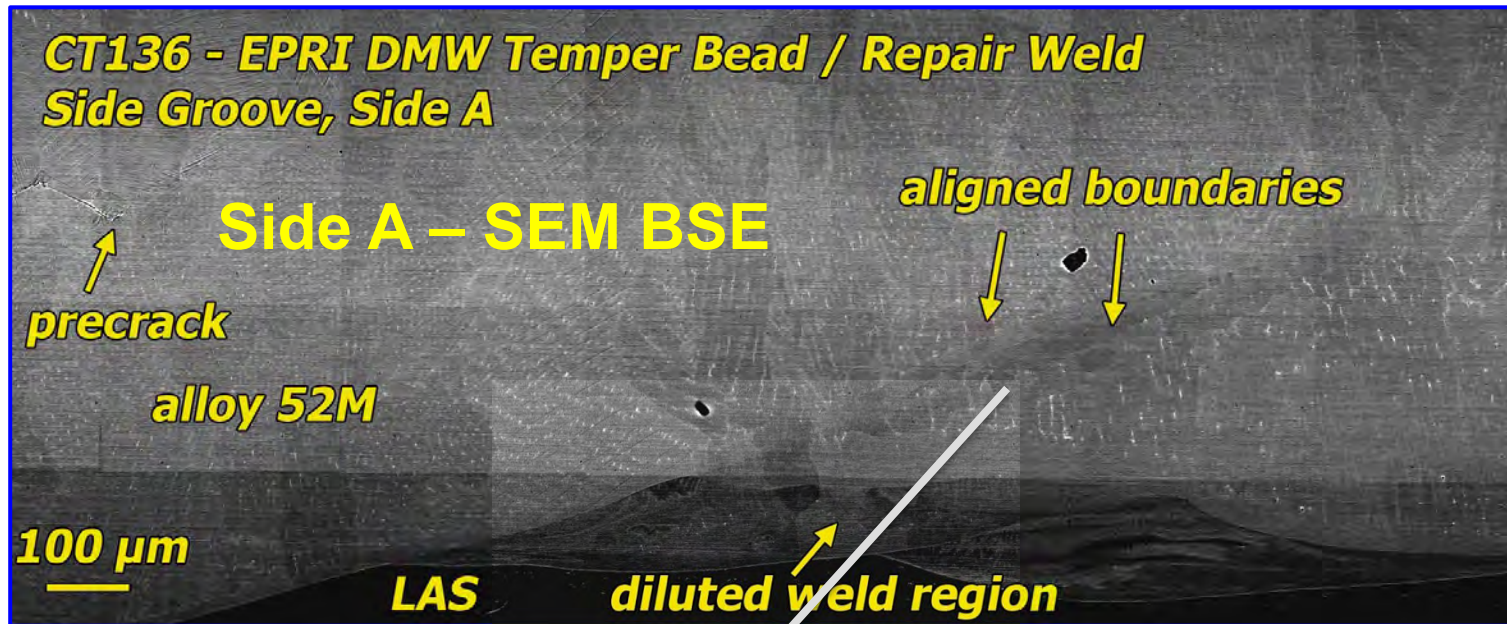
EPRI DMW Temper Bead / Repair Weld – DZ Test Side Groove Images of DZ Specimen

- ▶ SEM detail of side grooves.
- ▶ Aligned boundaries observed on Side A at ~2-3 mm from the notch.

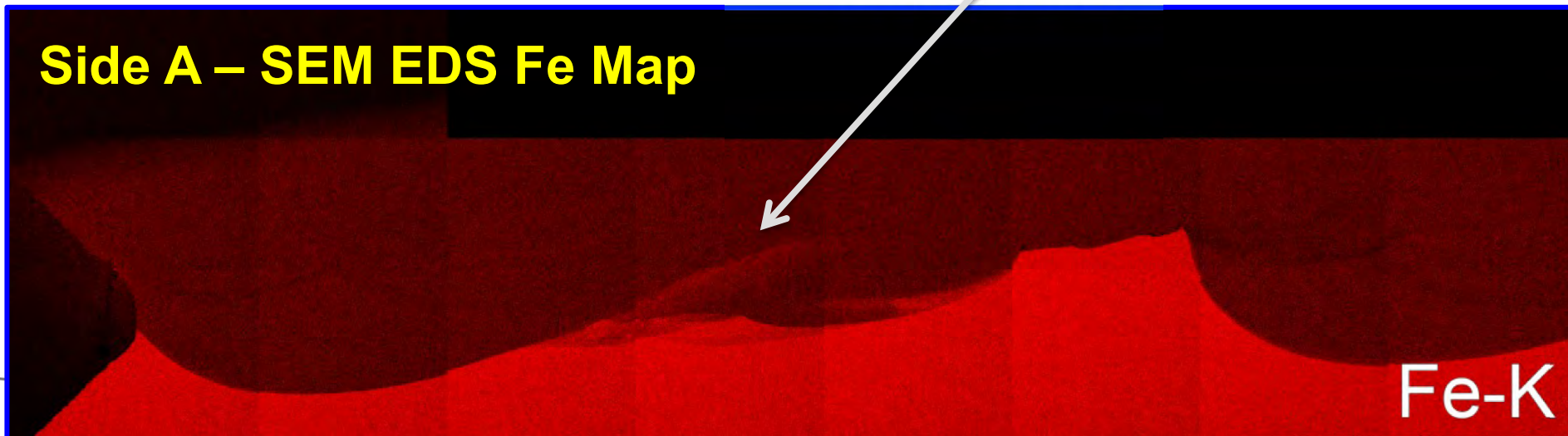


EPRI DMW Temper Bead / Repair Weld – DZ Test Side Groove Images of DZ Specimen

- Fe enrichment associated with aligned boundaries on Side A.

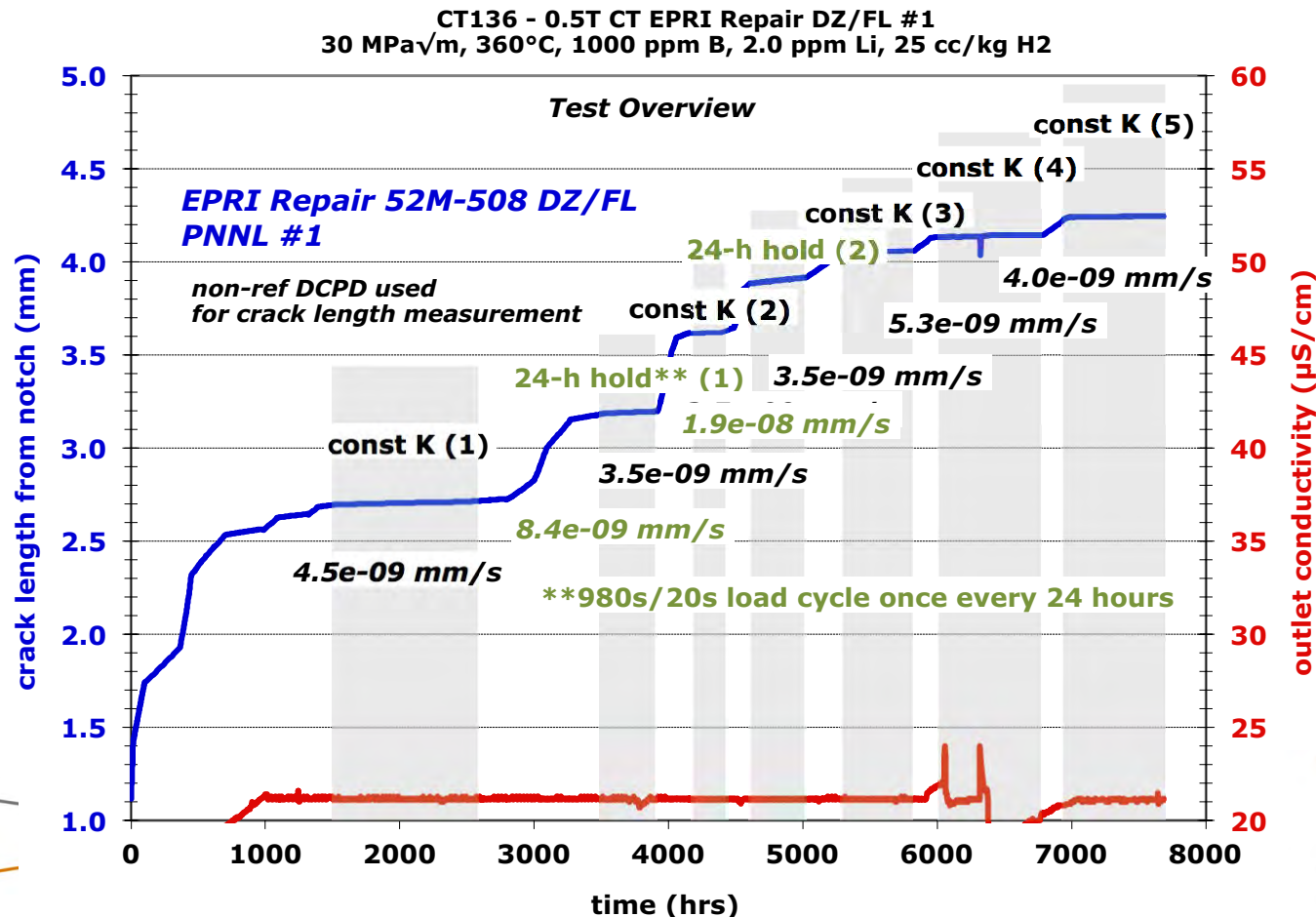


Side A – SEM EDS Fe Map



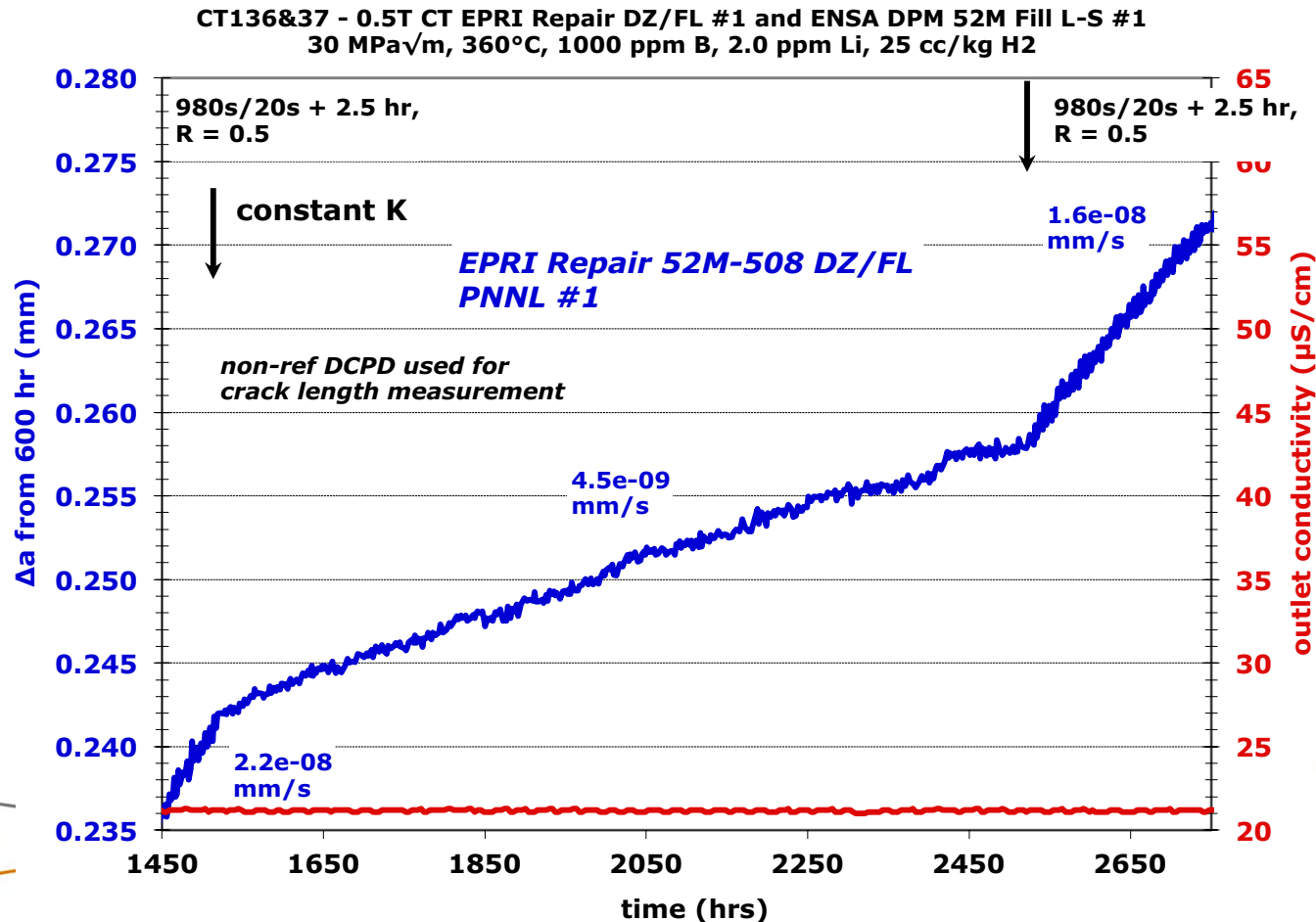
EPRI DMW Temper Bead / Repair Weld – DZ Test SCC Test Overview

- ▶ Many assessments of SCC susceptibility throughout the test.
- ▶ Aligned boundary roughly at 2-3 mm from the notch.
- ▶ Non-referenced DCPD measurement slightly inflates low CGRs.
- ▶ Possible small indication of SCC susceptibility.



EPRI DMW Temper Bead / Repair Weld – DZ Test SCC Test Overview

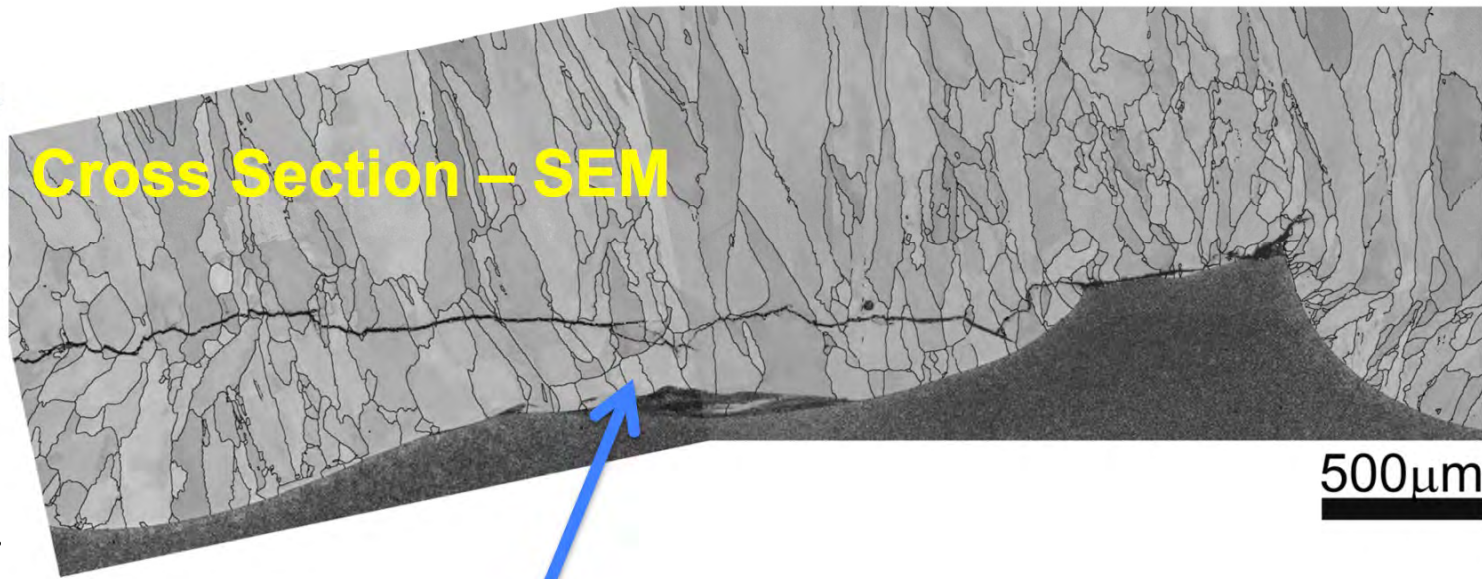
- ▶ Example of steady SCC response at depth corresponding to aligned boundary.
- ▶ Small indication of enhances susceptibility, but no different than remainder of the test.



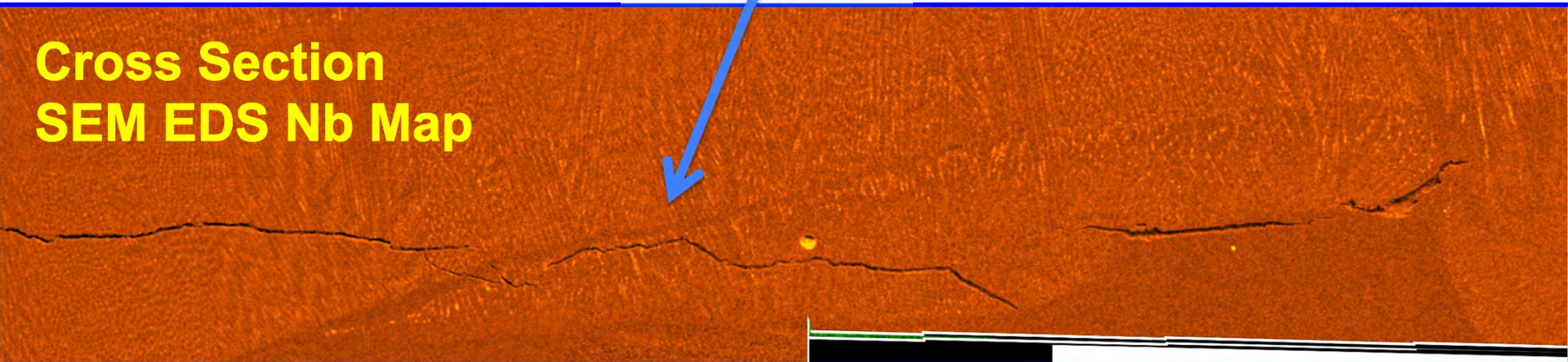
EPRI DMW Temper Bead / Repair Weld – DZ Test

Post-test Cross-section Observation

- ▶ Post-test cross-section image.
- ▶ Opportunity for cracking on aligned boundary, but did not clearly occur.

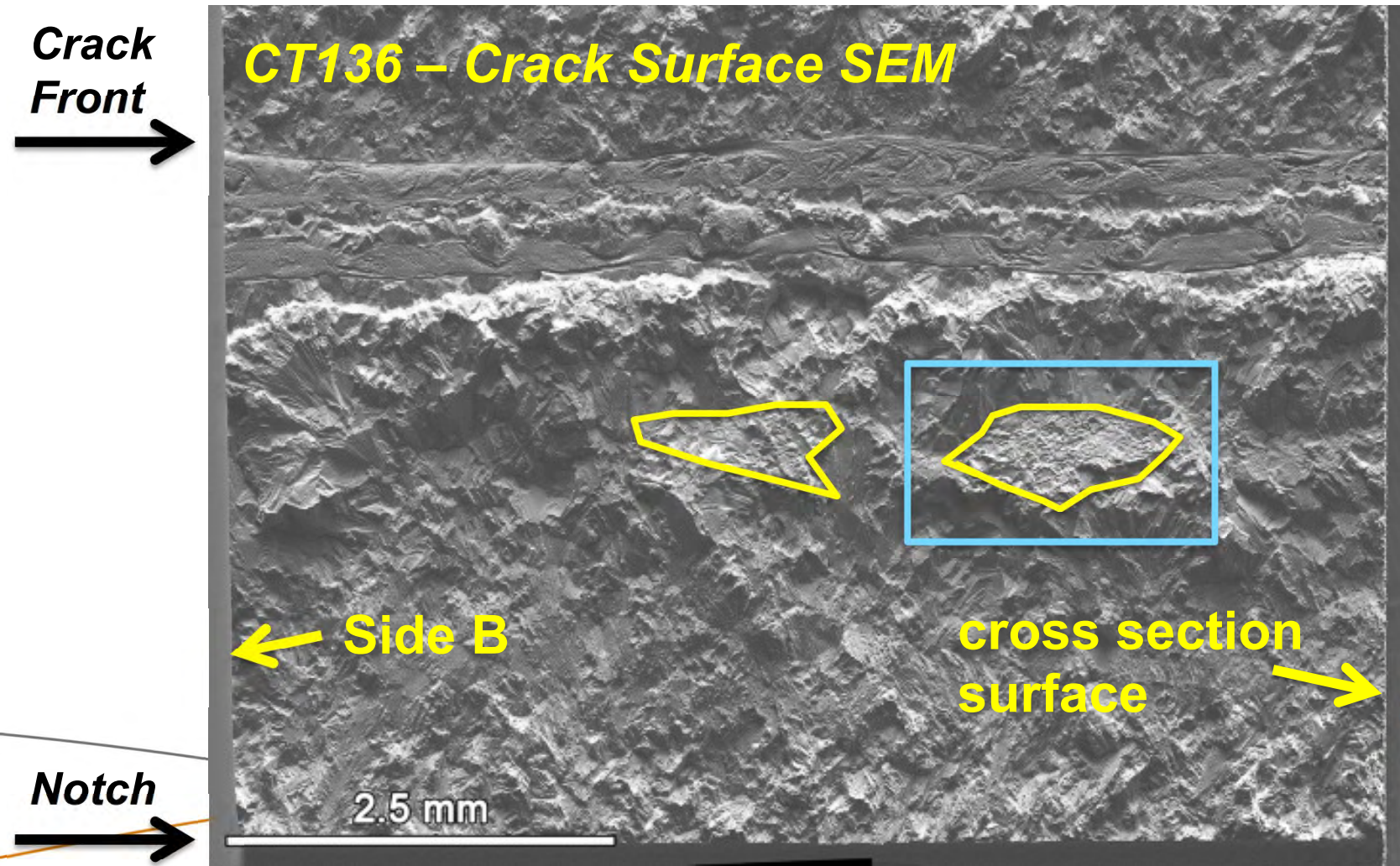


**Cross Section
SEM EDS Nb Map**



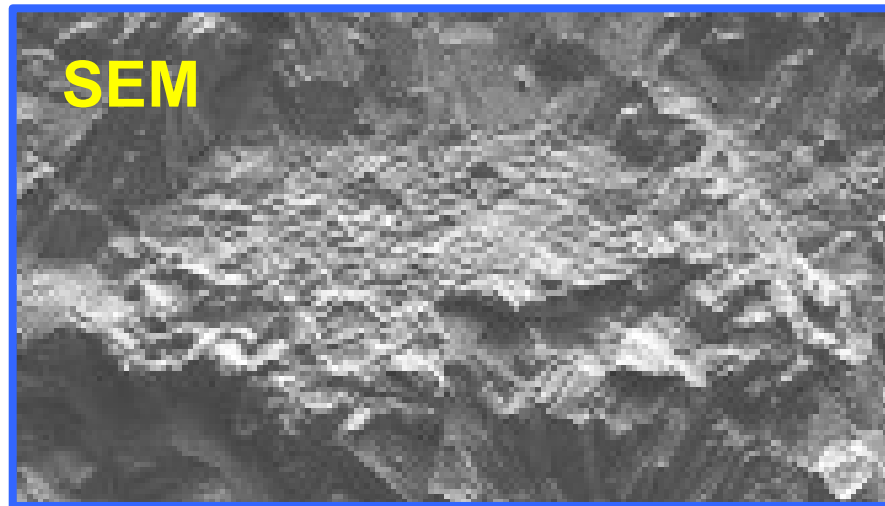
EPRI DMW Temper Bead / Repair Weld – DZ Test Crack Surface Observation

- ▶ Indications of cracking on aligned boundaries on crack surface.
- ▶ Location of boundaries are consistent with location on side grooves and side surface.



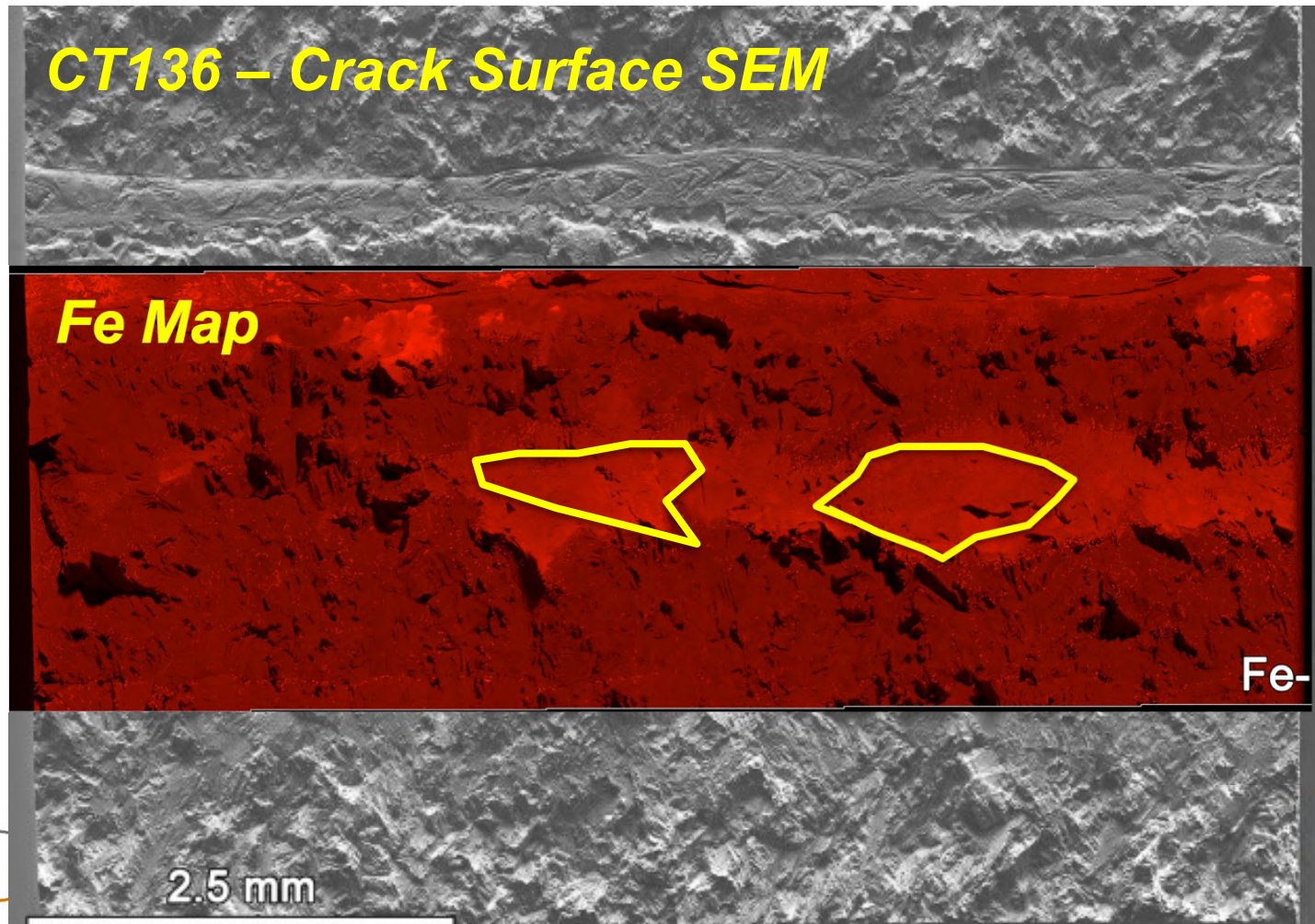
EPRI DMW Temper Bead / Repair Weld – DZ Test Crack Surface Observation

- ▶ *Low resolution image is further suggestive of an IG aligned boundary surface.*
- ▶ *High resolution image not yet available.*



EPRI DMW Temper Bead / Repair Weld – DZ Test Crack Surface Observation

- ▶ SEM-EDS Fe map indicates that regions of possible aligned boundaries enriched in Fe.



Alloy 152/52-LAS Dilution Zone Summary

- ▶ *Dilution zone region potentially susceptible based on notion of possible substantial Cr depletion.*
 - *However, normal weld grain boundaries are not aligned for cracking parallel to the fusion line in the dilution zone region.*
 - *Low SCC crack growth in Fe enriched and Cr depleted region on KAPL 152M-CS specimen. No boundaries were aligned to crack path.*
- ▶ *SCC susceptibility observed in PNNL tests of dilution zone of ANL Alloy 152v2-LAS weld.*
 - *Microstructure analysis indicates cracking on IG boundaries aligned to target crack path.*
 - *These boundaries are associated with regions of Fe enrichment and Cr/Ni depletion.*
 - *Potential for $\geq 1 \times 10^{-8}$ mm/s SCC CGRs, but sustained high growth rates were not observed, consistent with lack of continuous connection of these boundaries.*
 - *These boundaries have been observed in dilution zones of two other alloy 152/52-LAS/CS welds.*
 - *For one weld, propensity for cracking on these boundaries was not strong.*
 - *Among all alloy 152/52 tests at PNNL, highest susceptibility was in LAS DZ tests where growth occurred on these boundaries.*

Additional Slides Covering PNNL Analysis of ANL N152-LAS-11 Specimen

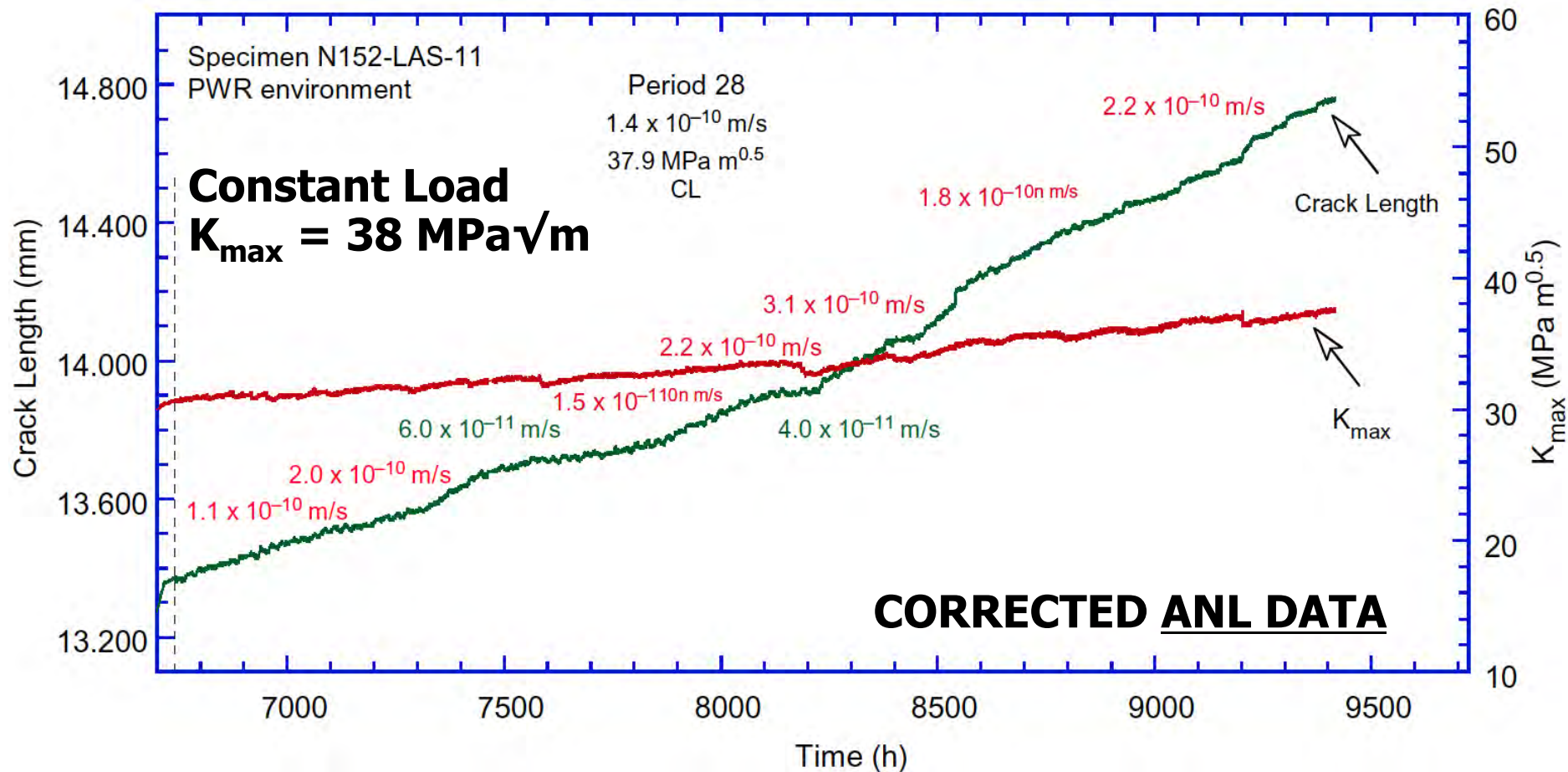
ANL N152-LAS-11 Specimen

- ▶ *N152-LAS-11 is well aligned to potential dilution zone regions.*

Both sides of the specimen



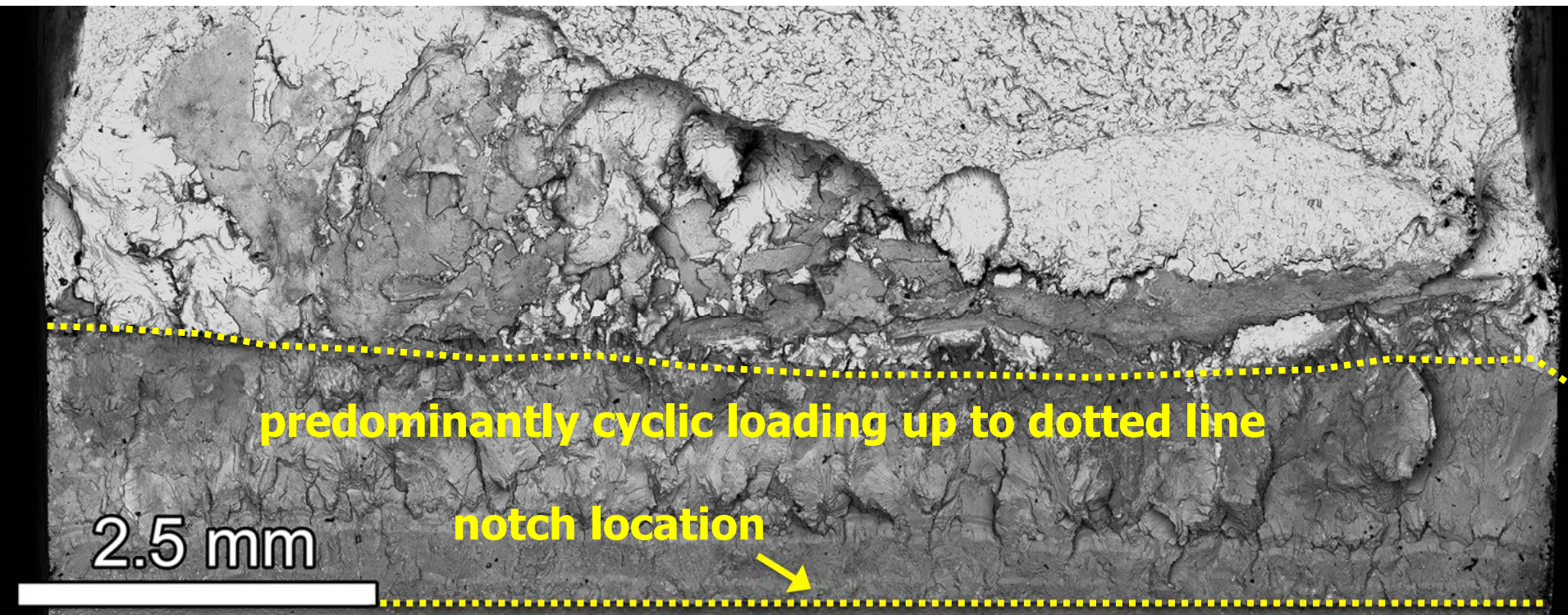
ANL Constant Load Response for N152-LAS-11 Specimen



Post-test corrected average constant load CGRs is $>1 \times 10^{-7} \text{ mm/s}$.

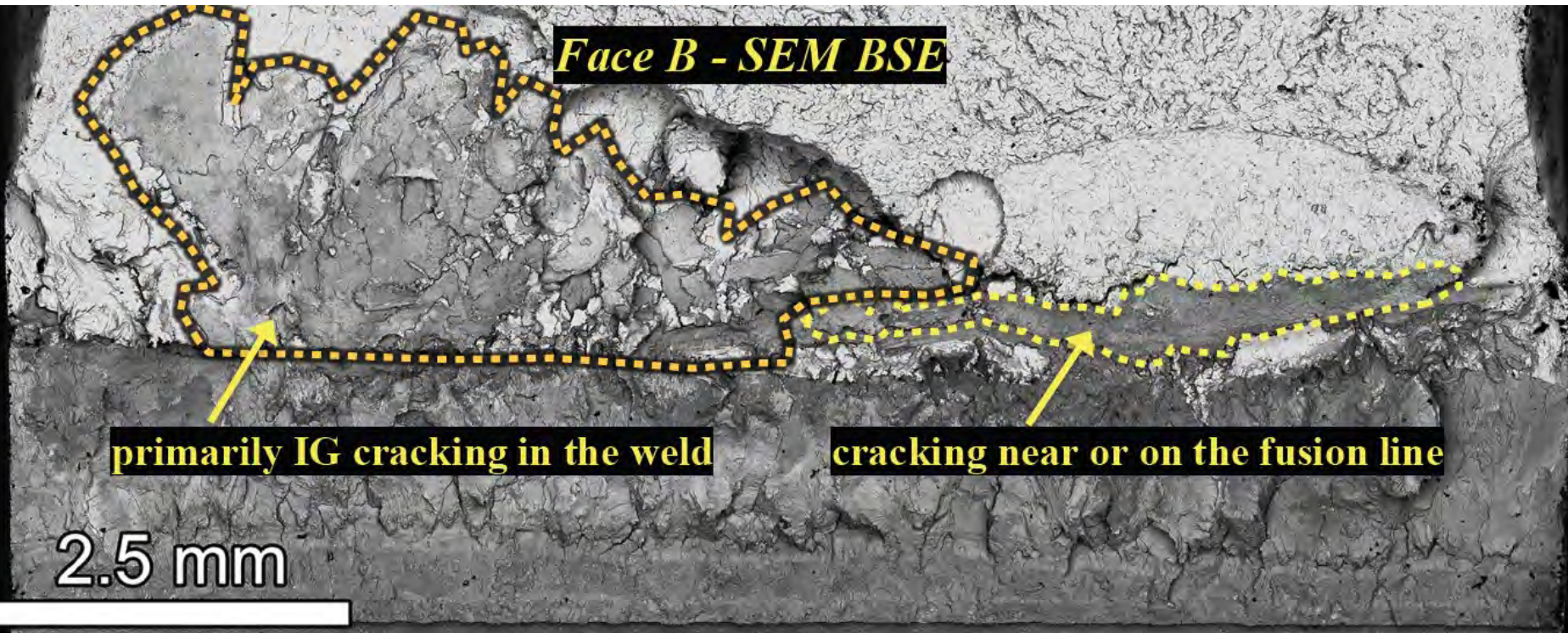
ANL N152-LAS-11 Specimen Crack Surface Observations

- *Predominantly cyclic loading prior to constant load SCC response that was shown in the previous slide.*



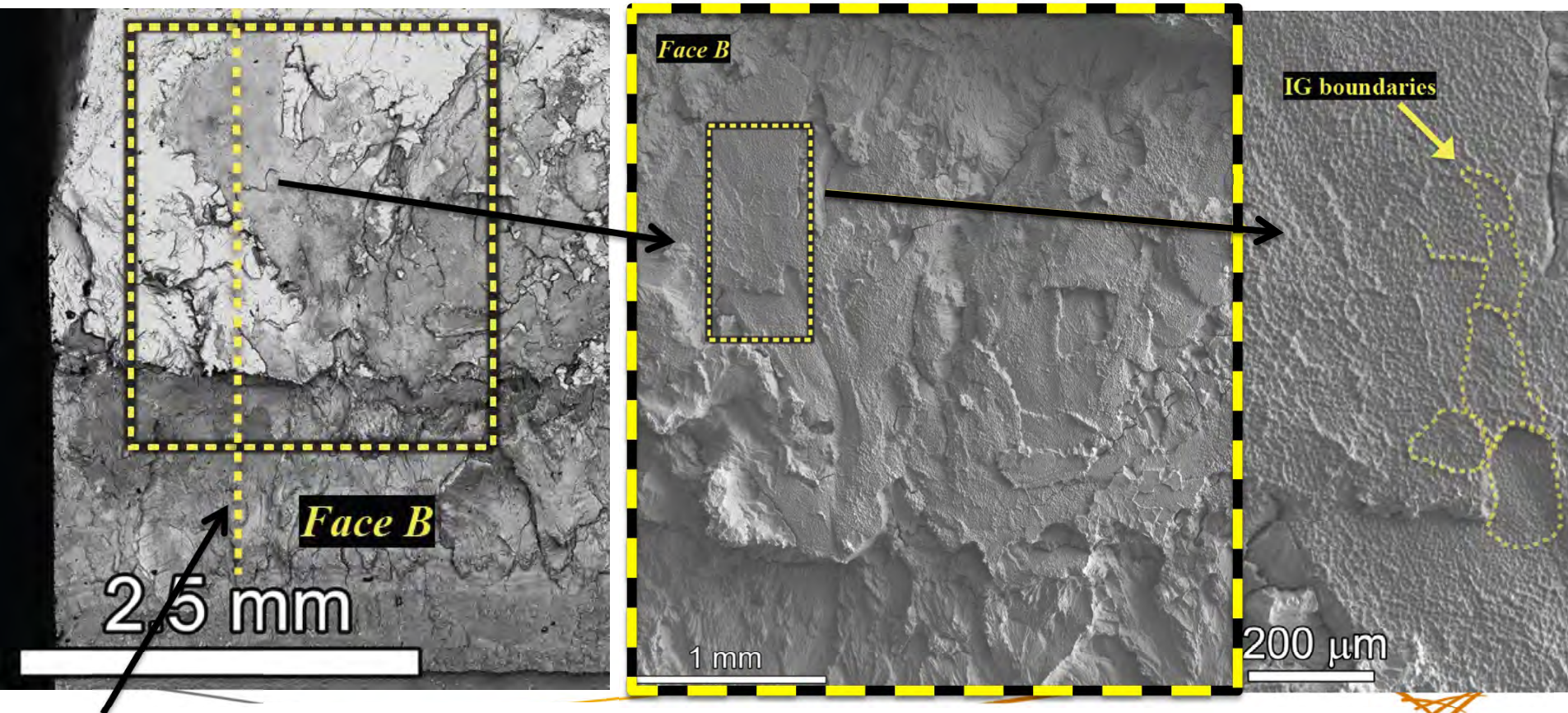
ANL N152-LAS-11 Specimen Crack Surface Observations

- ▶ Region on left is main area of interest. Cracking is in the weld and appears to be responsible for high SCC CGRs.
- ▶ Region on the right is cracking on or near the fusion line.



ANL N152-LAS-11 Specimen Crack Surface Observations

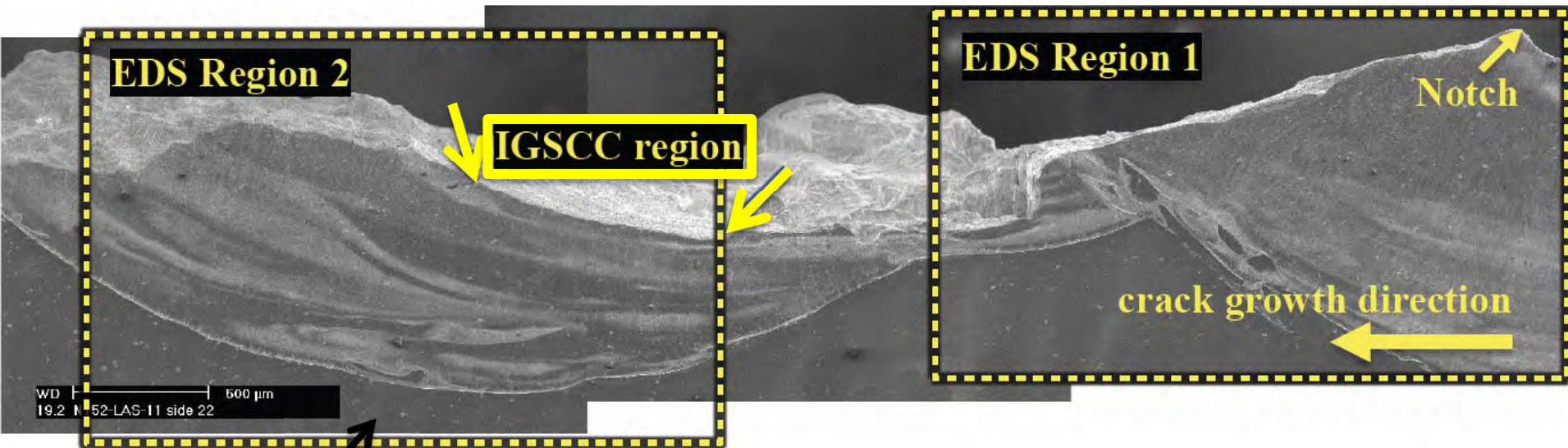
- Crack surface in the weld does not appear transgranular. Has an unusual intergranular appearance. Very flat surface.



Cut for cross section observation on opposite half of specimen

ANL N152-LAS-11 Specimen Cross-Section Observations

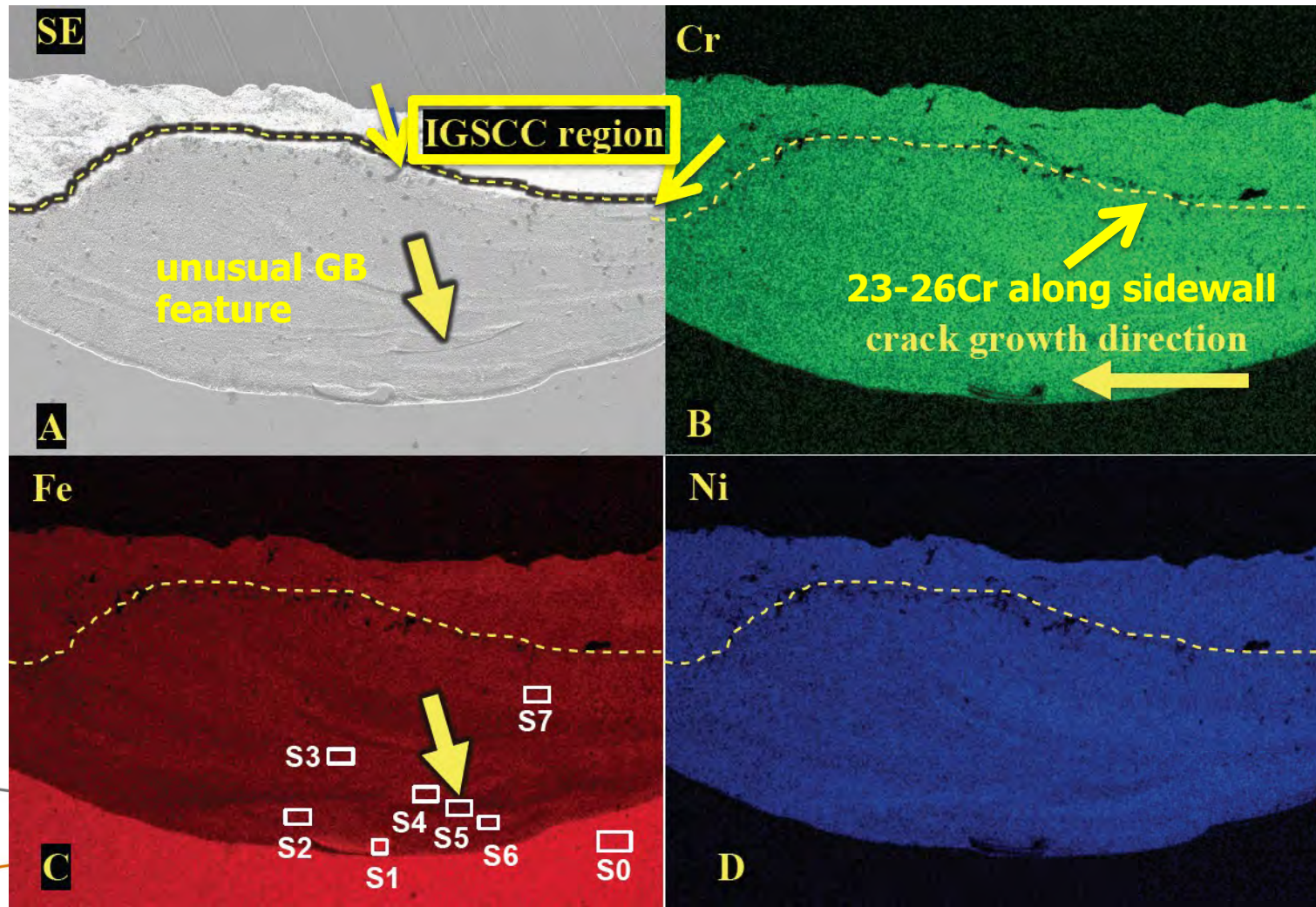
- ▶ *Specimen was fractured - one side of the specimen was cross-sectioned after fracture.*



Region of interest near that contains constant load crack extension

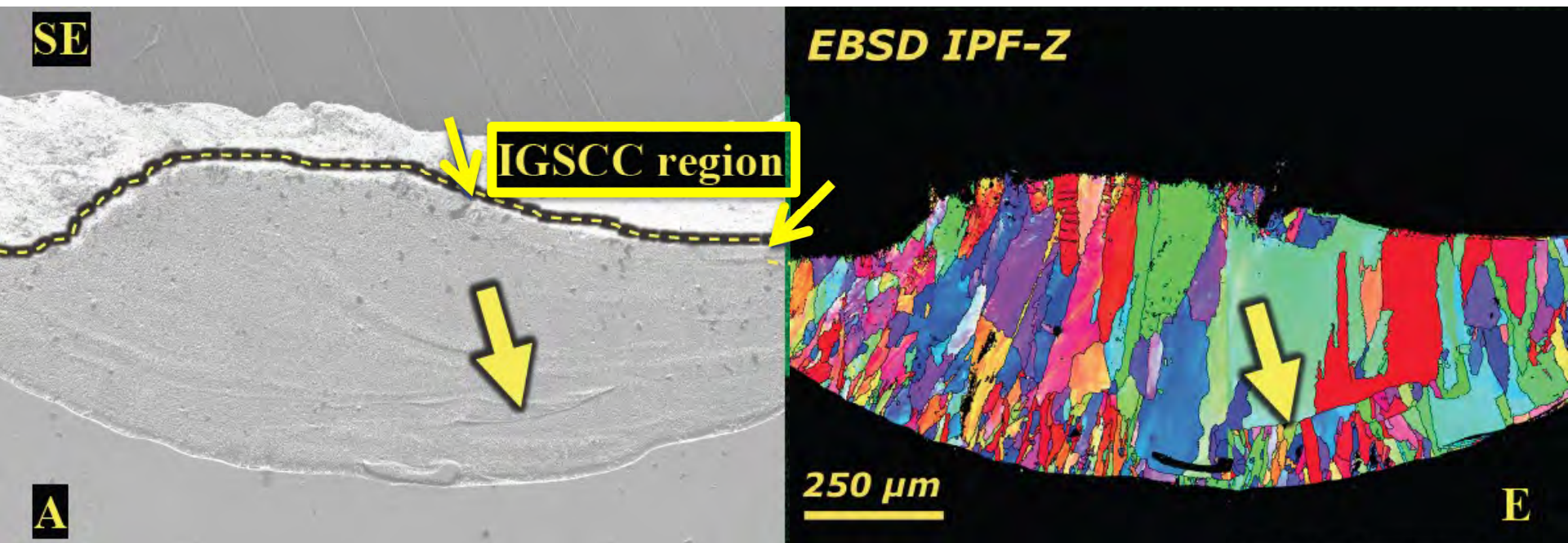
ANL N152-LAS-11 Specimen Cross-Section Observations EDS Region 2

- ▶ SEM-EDS exams indicate that Cr levels near SCC region are 23-26% on this side of the crack.



ANL N152-LAS-11 Specimen Cross-Section Observations

- ▶ *SEM-EBSD exam shows the crack plane to be perpendicular to the long axis of the grain boundaries.*
- ▶ *Did it crack on a weld interpass boundary?*
- ▶ *An unexpected interface was seen that is aligned similar to that of the SCC crack path.*
- ▶ *Could this be the source of the crack path?*



ANL N152-LAS-11 Specimen Summary

- ▶ SCC tested at ANL. Additional exams performed at PNNL.
- ▶ High constant load crack growth rates were observed.
- ▶ 23-26Cr near SCC region in cross-section.
- ▶ Not well aligned to grain boundaries, but IG appearance.
- ▶ Origin of crack path possibly an interpass boundary or this "unexpected" boundary.
- ▶ Additional exams needed to better understand this.

