SCC Crack Growth Rate Response for Alloy 152/52/52M Welds and Influence of Additional Strain

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Presentation Topics

- ***PNNL SCC Crack Growth Testing on Alloy 152/152M/ 52/52M/52MSS Weld Specimens***
  - *Alloy 52/52M/52MSS/152/152M Mockup Welds; Alloy 52M Overlay and Inlay Welds; Dissimilar Metal Welds*
  - *PNNL Testing Approach for Weld Metal Specimens*
  - *Summary of SCC Growth Rate Measurements*
- *Recent Test - EPRI Alloy 52M 20% ID Repair Weld*
  - *Assessed crack growth in repair and original fill weld.*
  - *2nd Repair (50%ID) weld being prepared at Edison Welding Institute (EWI)*
- *Ongoing Tests - 15%CF Alloy 52/52M/152/152M Welds*
  - *15%CF MHI Alloy 52 and 15%CF ENSA Alloy 52M*
  - *15%CF MHI Alloy 152 and 15%CF IHI Alloy 152M*
  - *Preliminary SCC Growth Rate Comparisons to Weld Metal Hardness*
- *Conclusions*

PNNL SCC Crack-Growth Testing Summary on Alloy 52/52M/52MSS Welds

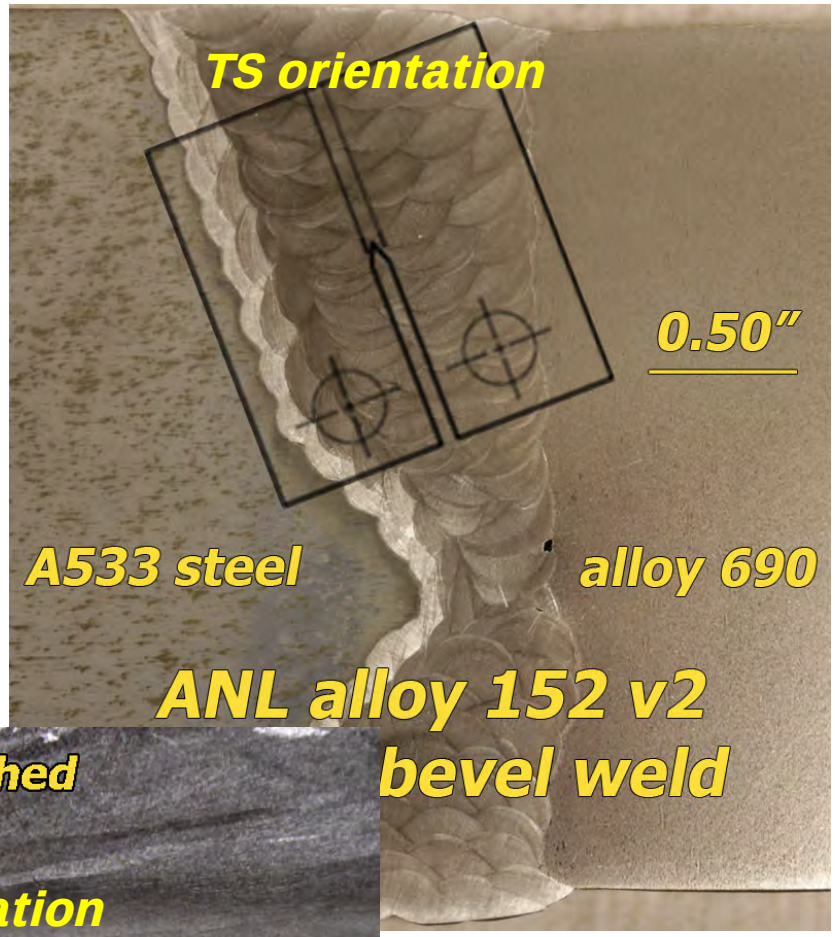
- *Alloy 52 Mockup Welds*
  - *2 tests on an AREVA butt weld*
  - *2 tests on an MHI U-groove weld*
  - ***1 ongoing test on 15%CF MHI weld***
- *Alloy 52M Mockup Welds*
  - *1 test on KAPL V-groove weld, 1 test on KAPL NG weld*
  - *2 tests on KAPL NG weld with hot cracks*
  - *2 tests on ENSA butt weld (T-S and L-S orientations)*
  - ***1 ongoing test on 15%CF ENSA weld***
  - ***1 recent test on EPRI repair weld***
  - *2 tests planned on a repair weld mockup being produced by EWI*
- *Alloy 52M Overlay and Inlay Mockups*
  - *3 tests on Ringhals overlay*
  - *2 tests planned on KAPL overlay and new overlay being welded at EWI*
  - *2 tests on Ringhals inlay*
- *Alloy 52MSS Mockup Weld*
  - *1 test on Special Metals weld*
  - *1 test planned on Special Metals weld available with PWHT*

PNNL SCC Crack-Growth Testing Summary on Alloy 152/152M and Dissimilar Metal Welds

- *Alloy 152 Mockup Welds*
  - *3 tests on MHI U-groove (1 AW, 1 AW+LAS PWHT, 1 AW+L-S orientation)*
  - *2 tests on ANL v2 weld*
  - *1 test on 20%CF MHI U-groove weld*
  - ***1 ongoing test on 15%CF MHI U-groove weld***
- *Alloy 152M Mockup Welds*
  - *1 test on KAPL V-groove weld*
  - *1 test on IHI U-groove weld*
  - ***1 ongoing test on 15%CF IHI U-groove weld***
- *Dissimilar Metal Welds*
  - *Alloy 152/52M Interface - 1 test planned on EPRI DM Weld near 152/52M fusion line where DDC cracks are present.*
  - *Alloy 152M/CS Dilution Zone - 1 tests on KAPL DM Weld*
  - *Alloy 152/LAS Dilution Zone - 2 tests on ANLv2 DM Weld,*
  - *Alloy 52M/CS Dilution Zone - 1 tests on KAPL DM Weld*
  - *Alloy 52M/LAS Dilution Zone –* ***1 recently completed test on EPRI Temper Bead DM Weld*** *(see Toloczko presentation)*
  - *Alloy 152/SS Dilution Zone - 2 tests on MHI U-groove weld, 2 tests planned on EPRI DM Weld.*

Selection of CT Specimen from Weldment

- *Weld microstructure determined by optical, SEM and EBSD.*
- *CT specimen crack growth plane aligned parallel to elongated grain boundaries.*
- *Polish side grooves to confirm alignment and enable mid-test exams of crack morphology.*



CT specimen side groove photo

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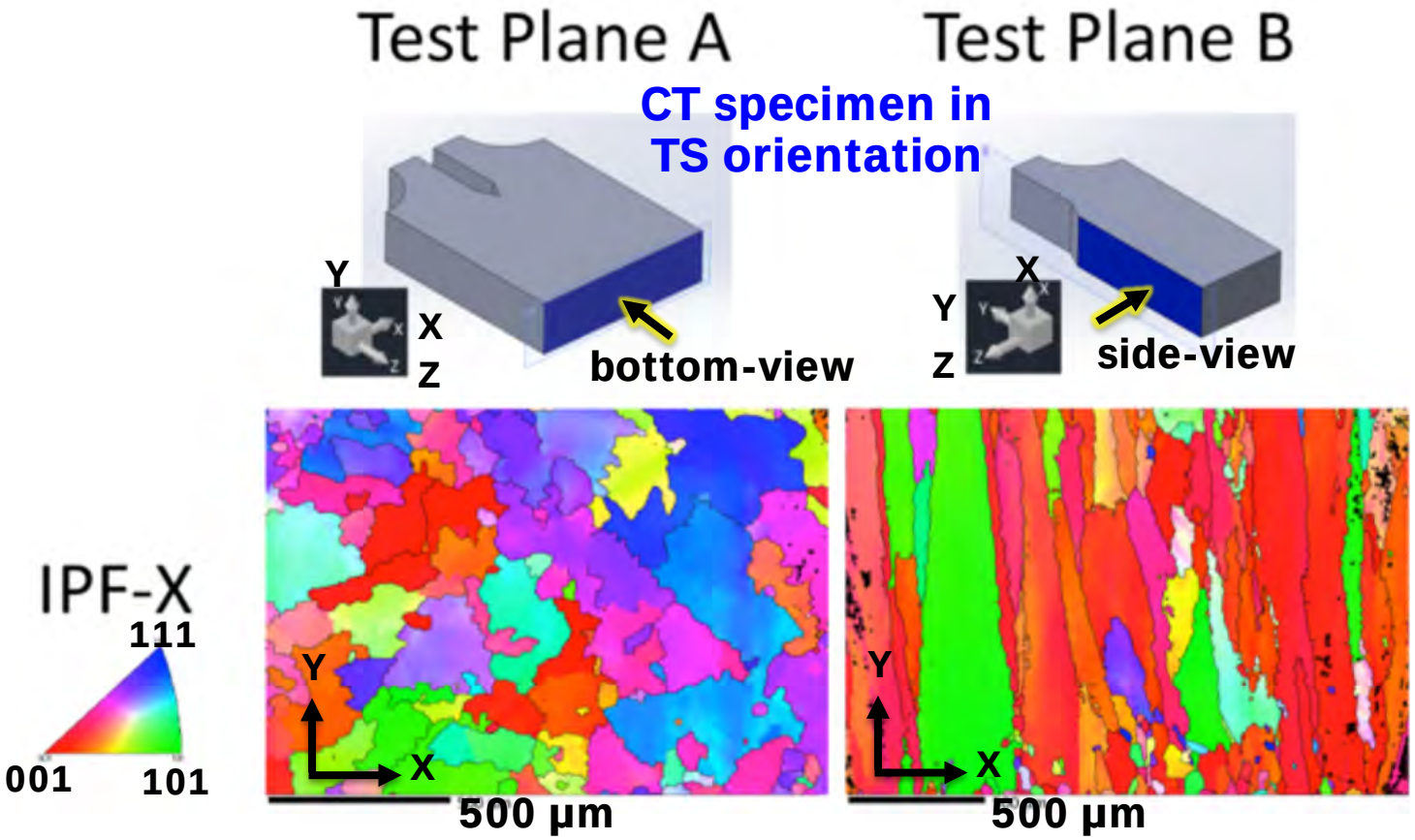
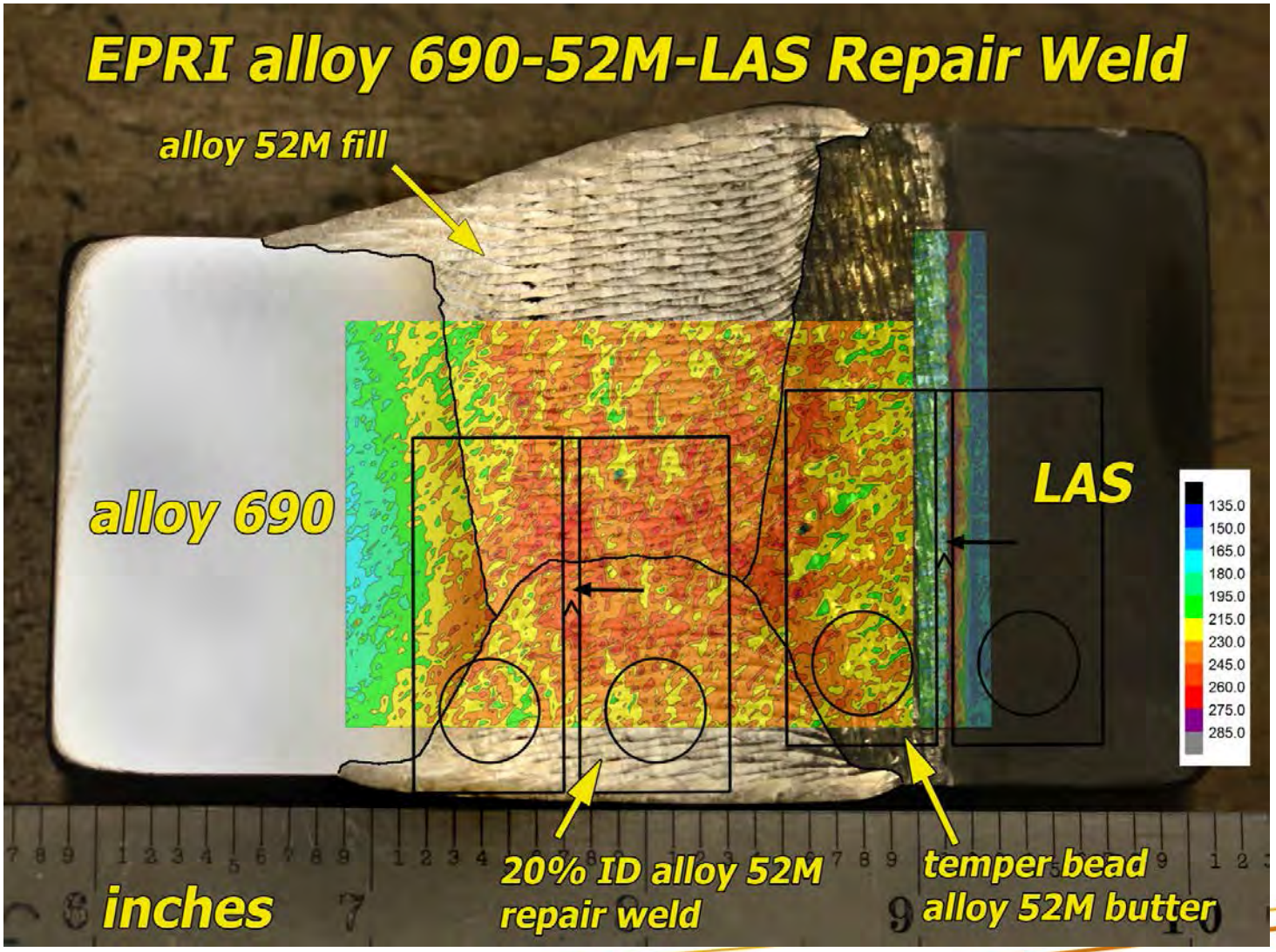
EBSD Characterizations of Weld Microstructures



- *Elongated grains in side-view projection.*
- *Equiaxed grain shape in bottom-view projection.*
- *Overall shape is needle-like. Aspect ratio is as high as 15:1.*
- *Large, irregular shape sometimes interlocking with neighboring grains produces a challenging crack path.*

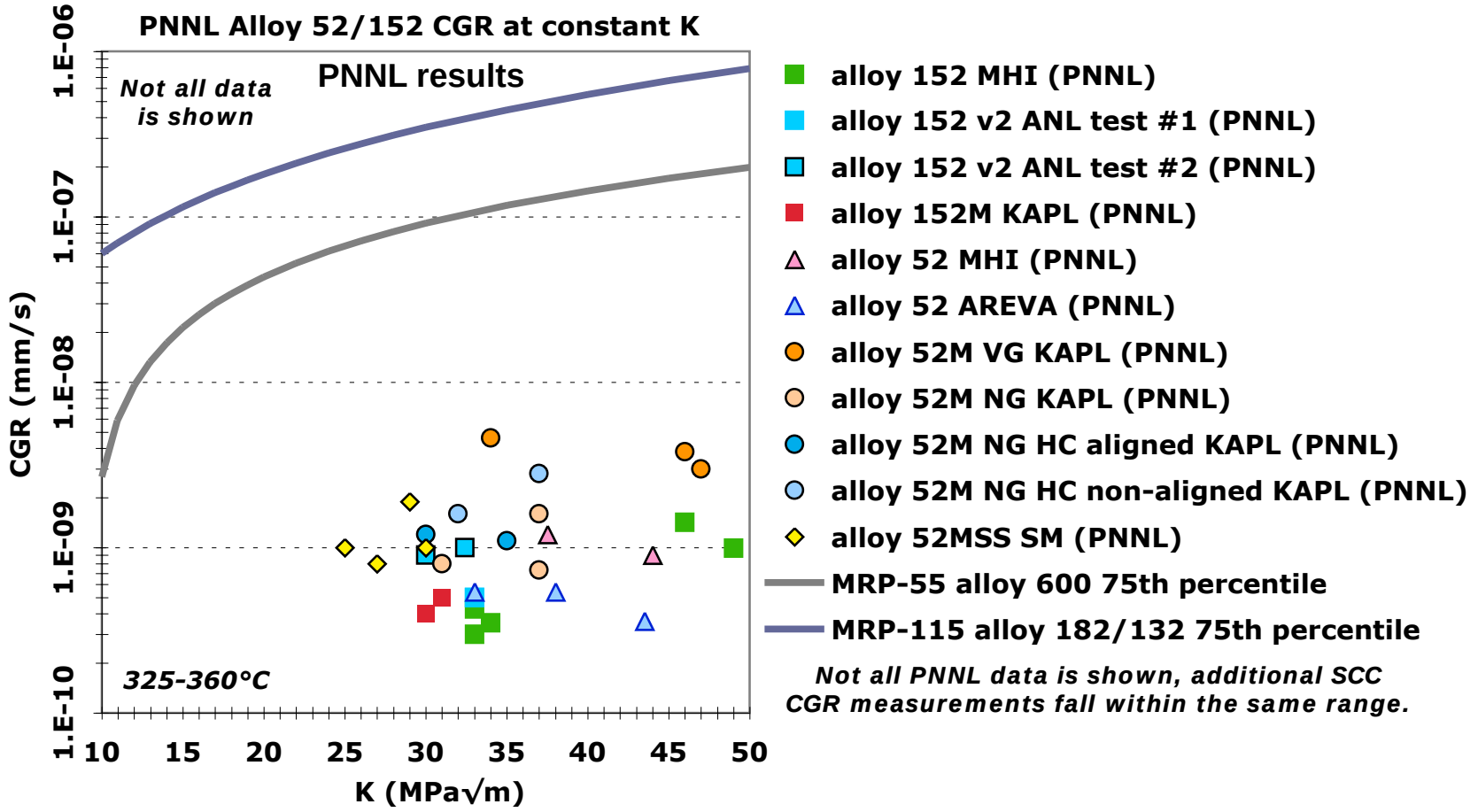
Hardness Measurements in Welds



Hardness mapping across a dissimilar metal weld that contains a 20%ID repair to help position CT specimens.

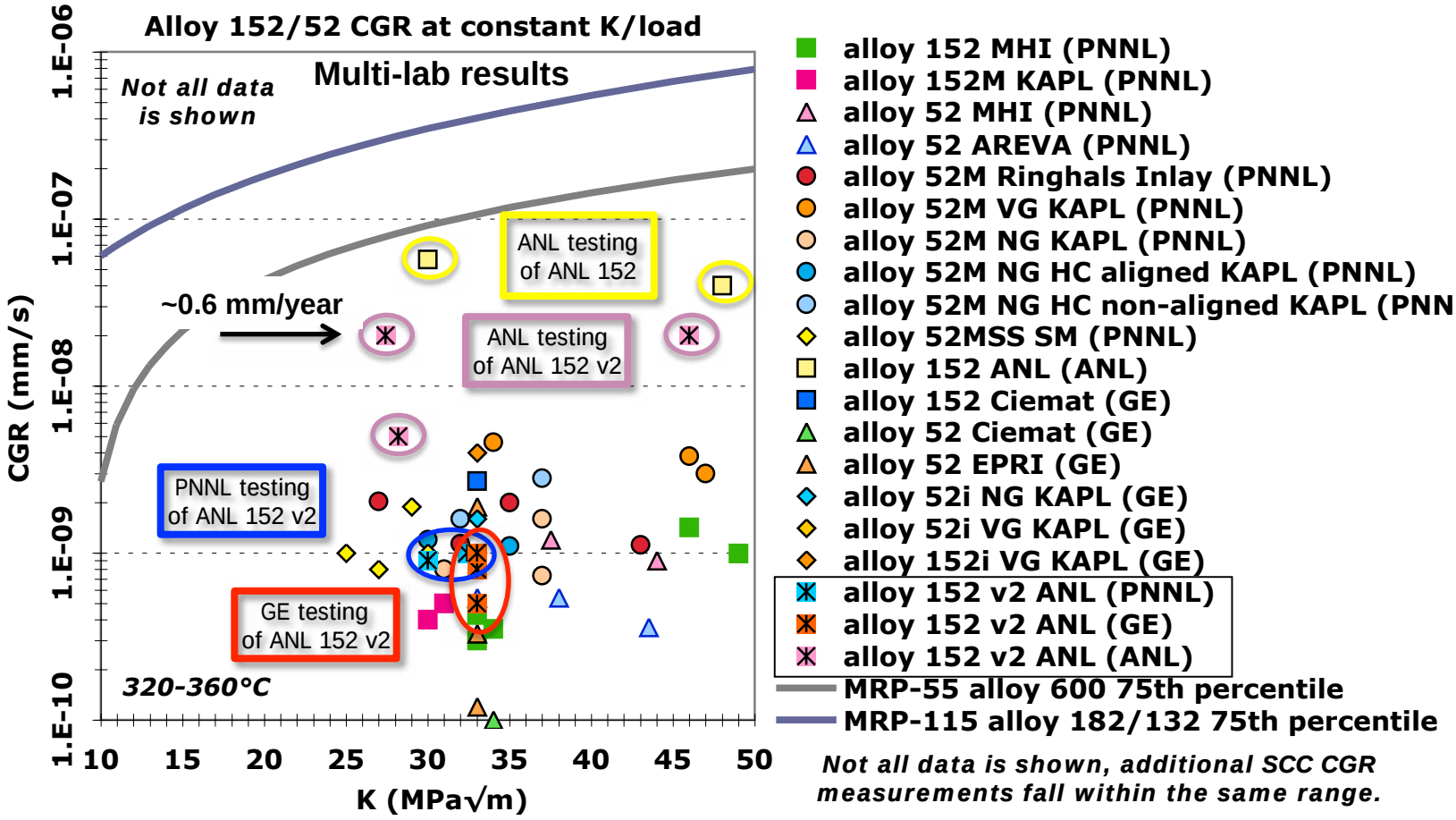
SCC Measurements on Alloy 152, 152M, 52, 52M and 52MSS Welds at PNNL

- *Have completed 31 tests on 17 unique weld mockups, additional tests ongoing including cold-forged weld metal specimens.*
- *Sustained constant K crack growth rates (CGRs) range from <5x10^{-10} mm/s to ~5x10^{-9} mm/s. Range of CGRs is low (≤0.16 mm/year).*



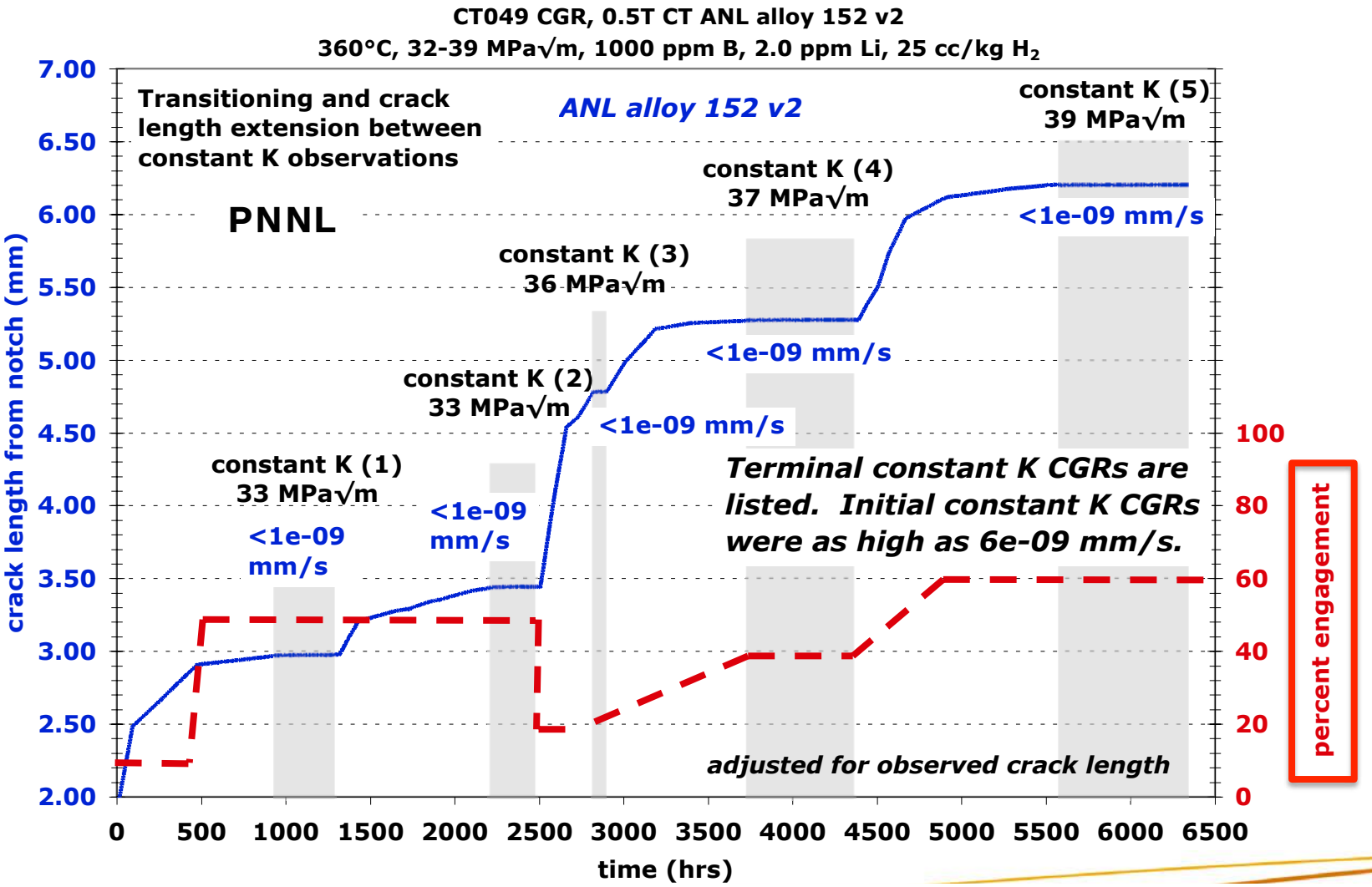
Overview of SCC Growth Measurements on Alloy 152/152M/52/52M Welds

- *PNNL has observed sustained constant K crack growth rates (CGRs) ranging from <5x10^{-10} mm/s to ~5x10^{-9} mm/s, most <2x10^{-9} mm/s.*
- *PNNL, ANL and GE have all tested and reported on the ANL 152v2 weldment.*
- *Tests by GE on this weldment match PNNL, but ANL reported higher CGRs on this weld and on their original ANL 152 weldment.*



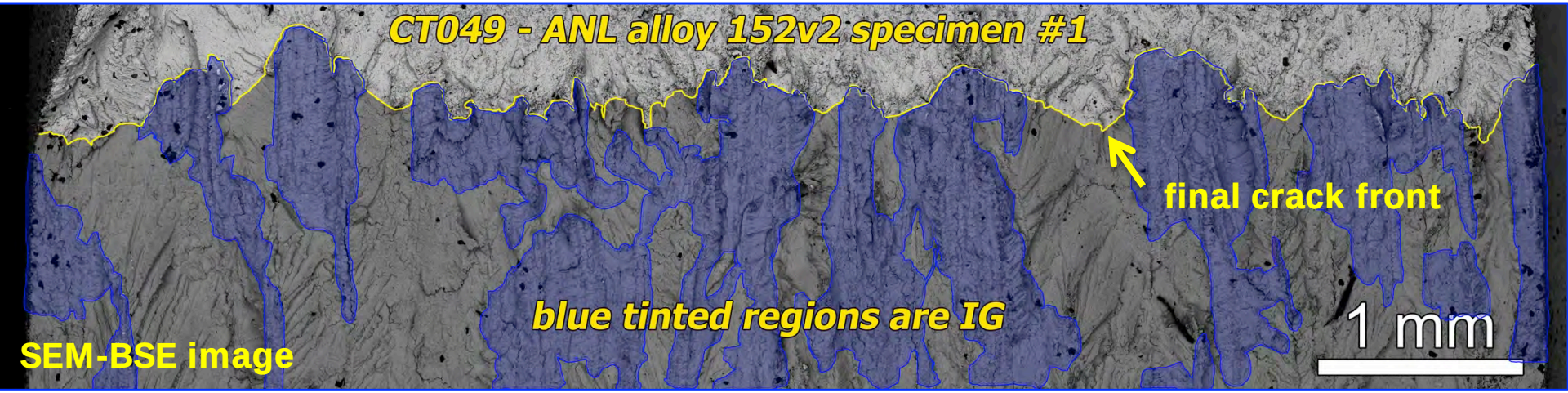
Not all data is shown, additional SCC CGR measurements fall within the same range.

Alloy 152v2 Weldment: Tested by ANL, GEG and PNNL



High degree of IG engagement and growth during transitioning steps indicating IG crack path is favorable, but low constant K CGRs.

Alloy 152v2 Weldment: Engaged Regions Near Final Crack Front



- *60% IG across the width of the final crack front, but also note that most regions of IG growth are more than 1 mm long. -->* ***Substantial IG cracking occurs during load cycling.***
- *Not possible to distinguish between IG cracking that occurs during load cycling, cycle + hold and constant K. In-situ DCPD measurements suggest crack growth at constant K is extremely limited.*
- *Protrusions along the final crack front are IG and may be due to constant K crack growth, however more likely that the protrusions are due to faster extension of IG than TG during "gentle" load cycling.*
- *All weldments tested at PNNL exhibit this appearance but with varying degrees of IG engagement.*

Summary of PNNL Measurements on Alloy 152/152M/52/52M Weldments

- *PNNL has conducted 31 separate tests on 17 unique weldments.*
- *Numerous constant K SCC growth rate observations with post-test corrected average propagation rates no higher than $5x10^{-9}$ mm/s.*
  - *DCPD results show no indication of hidden crack growth due to ligament formation or uneven crack extension during constant K testing.*
- *IG engagement observed from 0 to 60% depending on weldment.*
  - *IG engagement achieved in selected welds despite challenging crack path through weldment. For comparison, non-CW and lightly-CW alloy 690 at PNNL showed <10% IG engagement.*
  - *IG cracking occurs during transitioning (cyclic loading) and can remain for more than 1 mm through varying transitioning steps.*
  - *No clear indicator of IGSCC growth at constant K, extremely small DCPD-measured crack extension and IG cracking during load cycling.*
- *Only multi-lab (ANL, GE, PNNL) SCC growth comparisons published to-date is for the ANL alloy 152v2 and MHI alloy 152 weldments. Further comparison testing is needed, however good news is that there are only isolated measurements of service-relevant SCC growth rates in alloy 152/152M/52/52M welds.*

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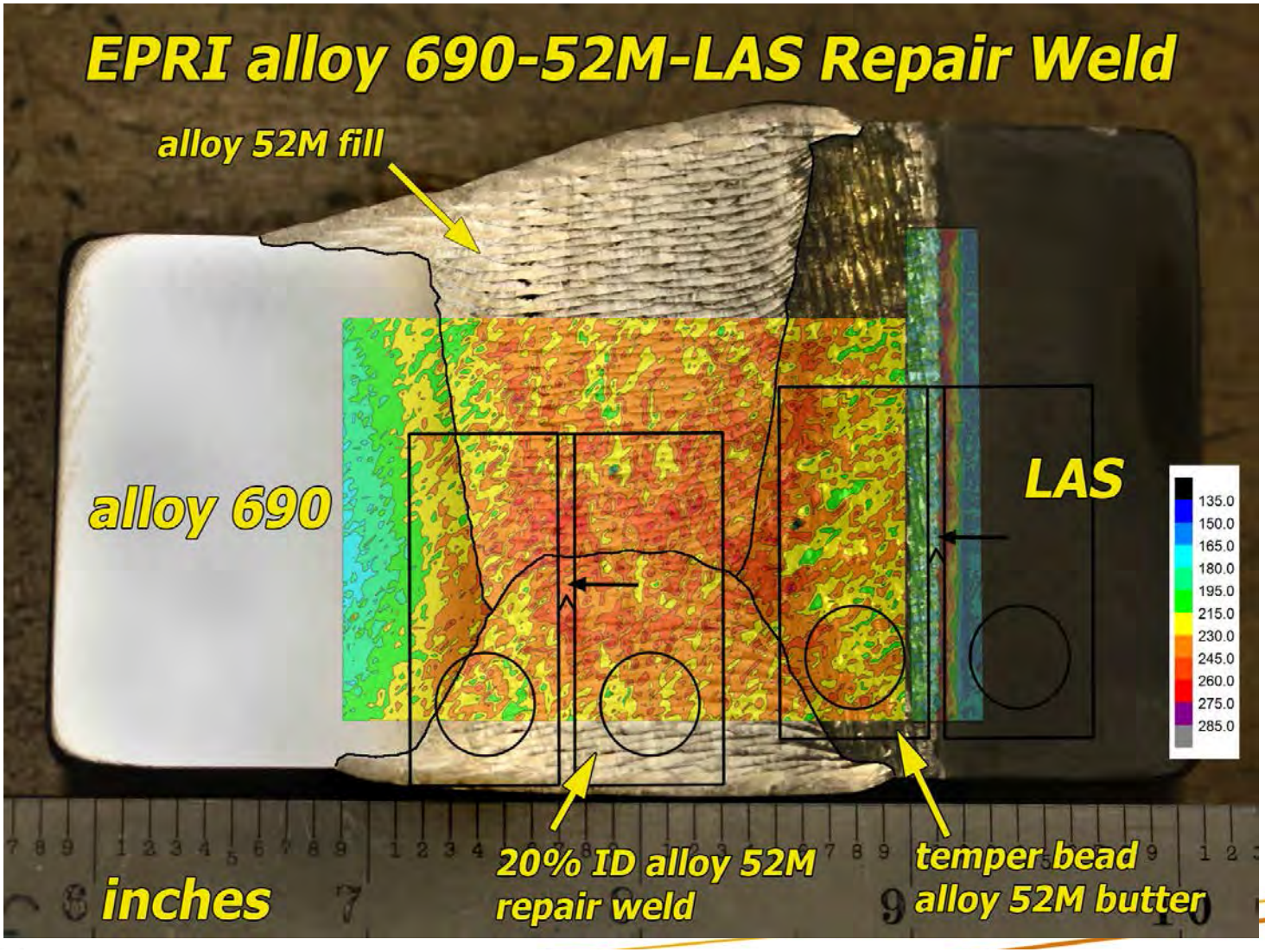
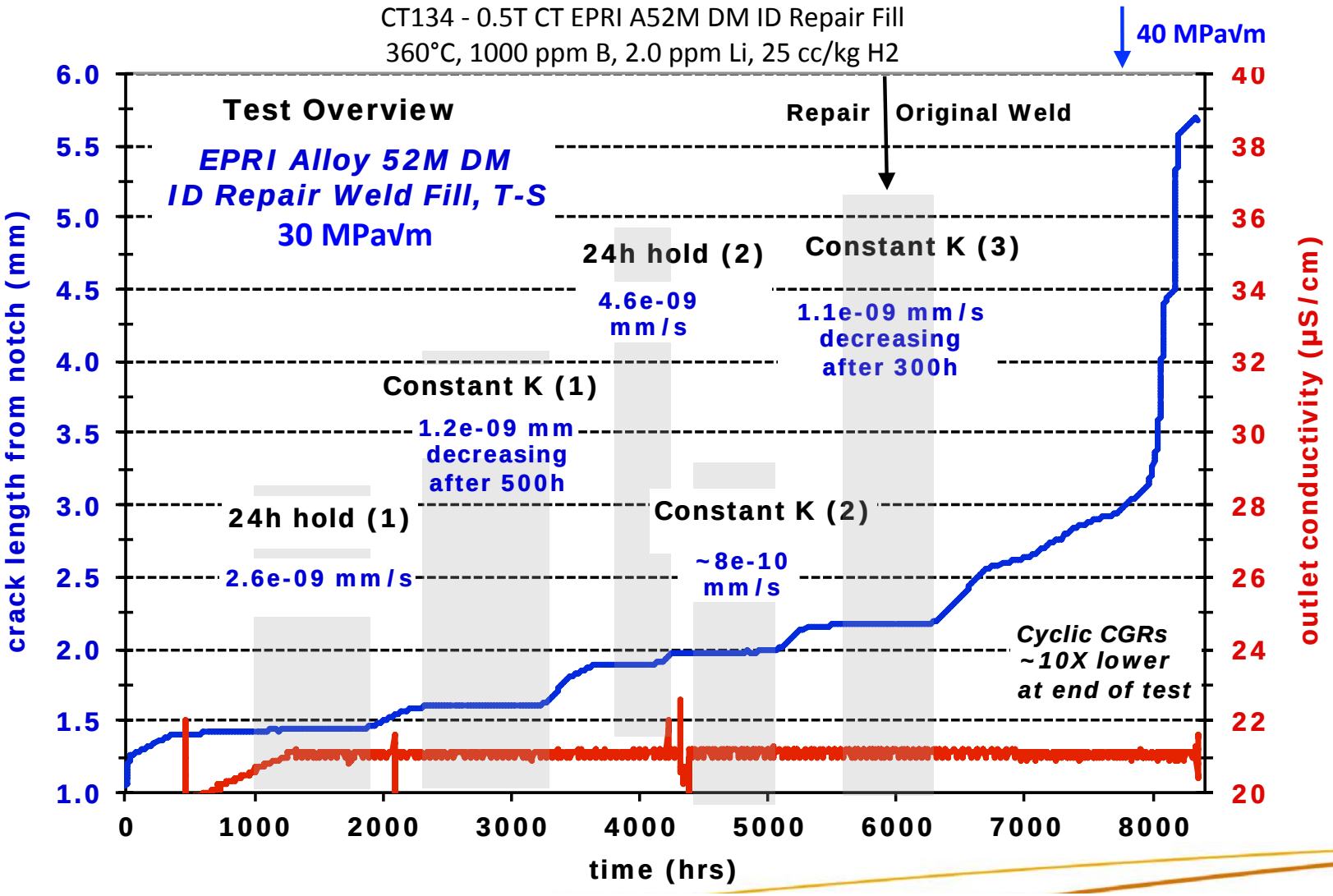
- *Conclusions*

Crack-Growth Testing on EPRI Dissimilar Metal Repair Weld Mockup



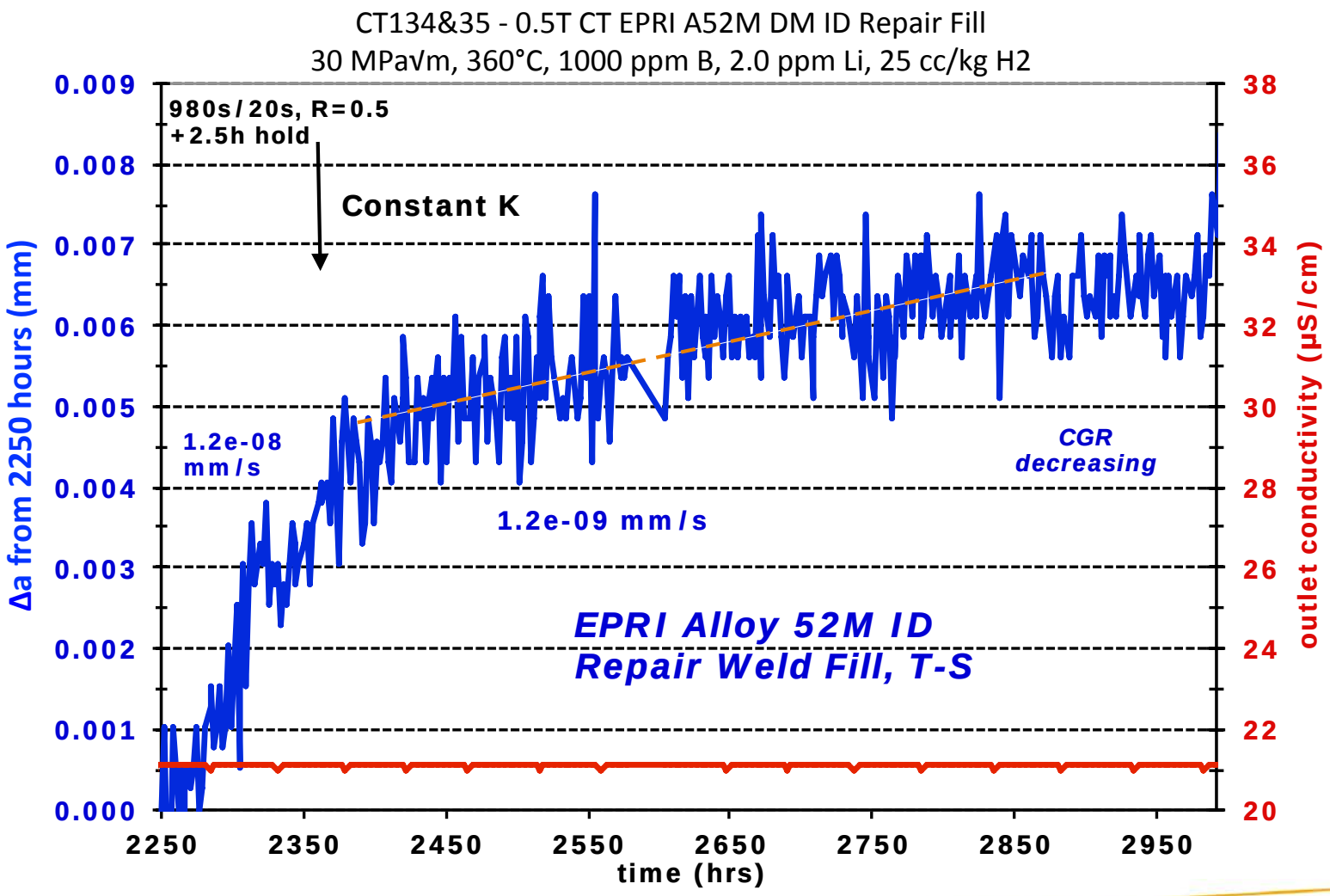
CT specimen positioned to assess response in both the repair and original weld metal regions with higher hardness (~260 HV)

Overview of Crack-Growth Test for EPRI Repair Weld Specimen



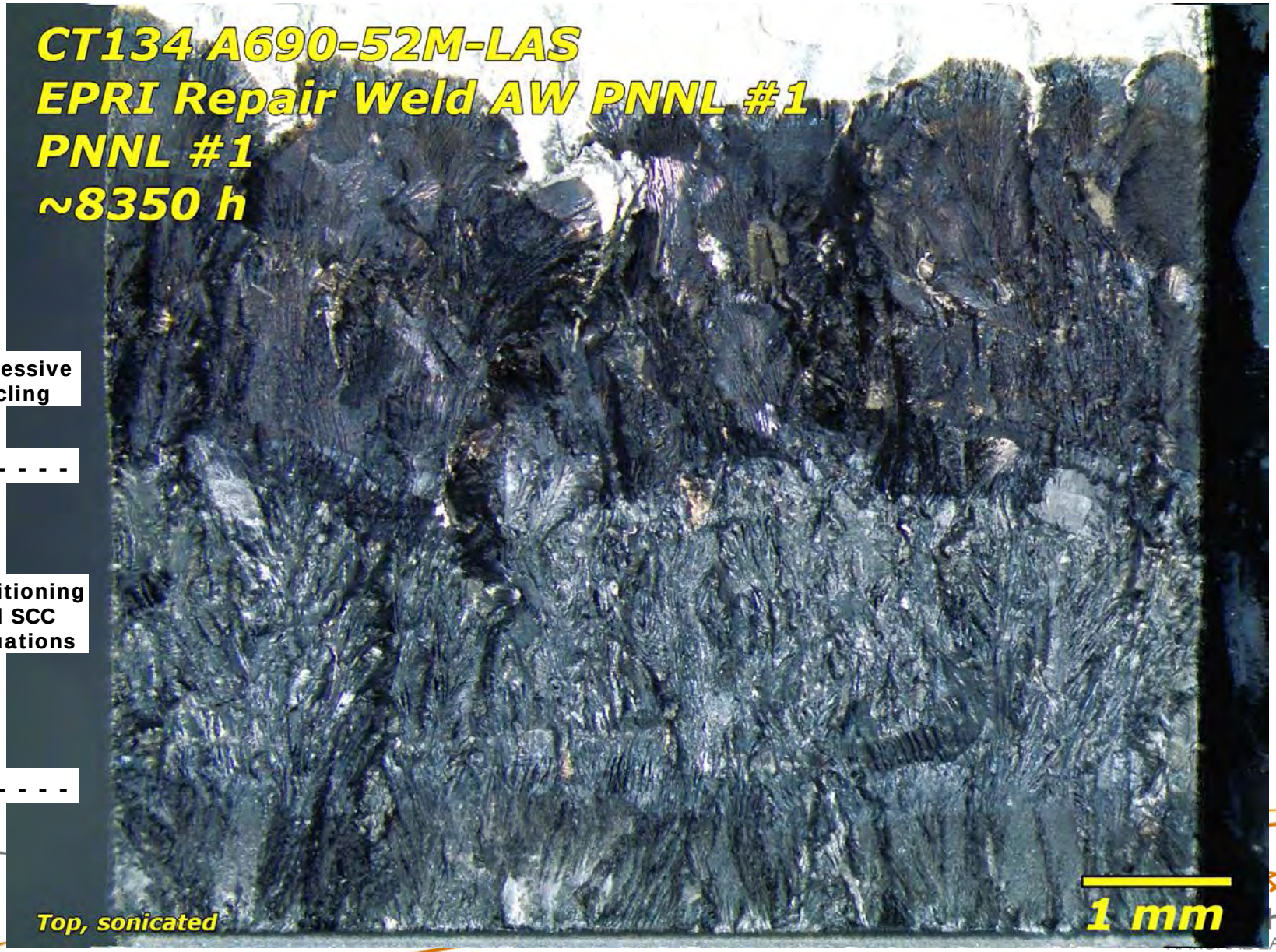
Low crack growth rates measured at constant K (~1x10^{-9} mm/s) and 24h hold (~4x10^{-9} mm/s) in repair weld

Typical SCC Growth Response for EPRI Repair Weld Specimen at Constant K



Low SCC growth rates (~1x10^{-9} mm/s) measured that decrease after ~500 hours at constant K

Optical Image of Crack Growth Surface for EPRI Repair Weld Test Specimen CT134



Air

Original Weld

Repair Weld

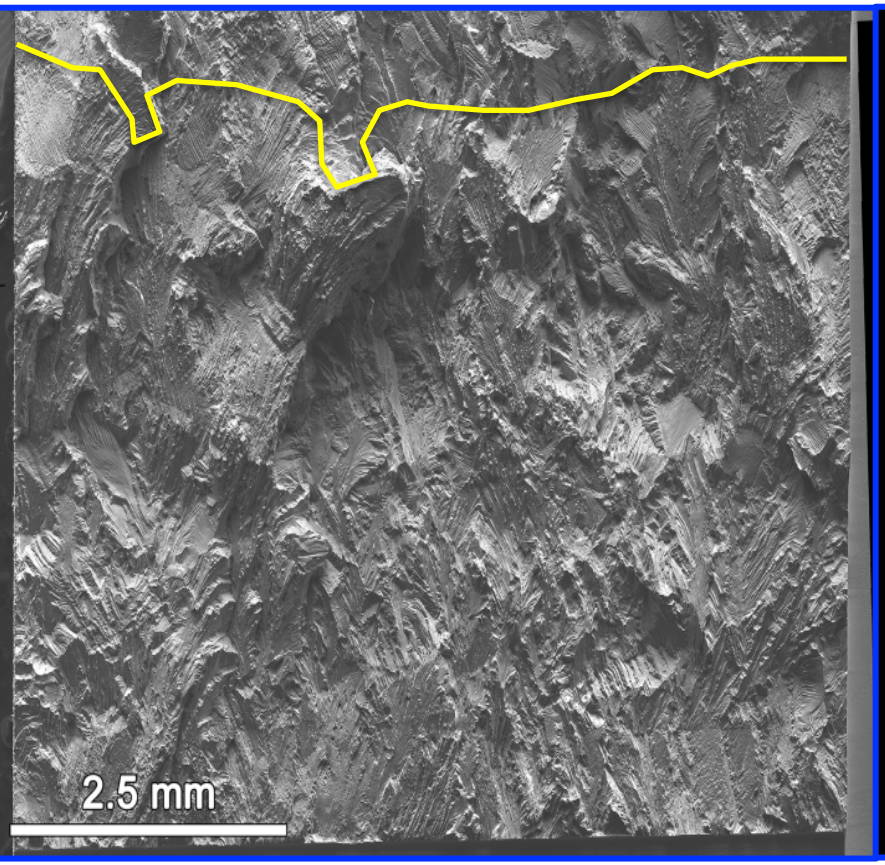
Air

Aggressive Cycling

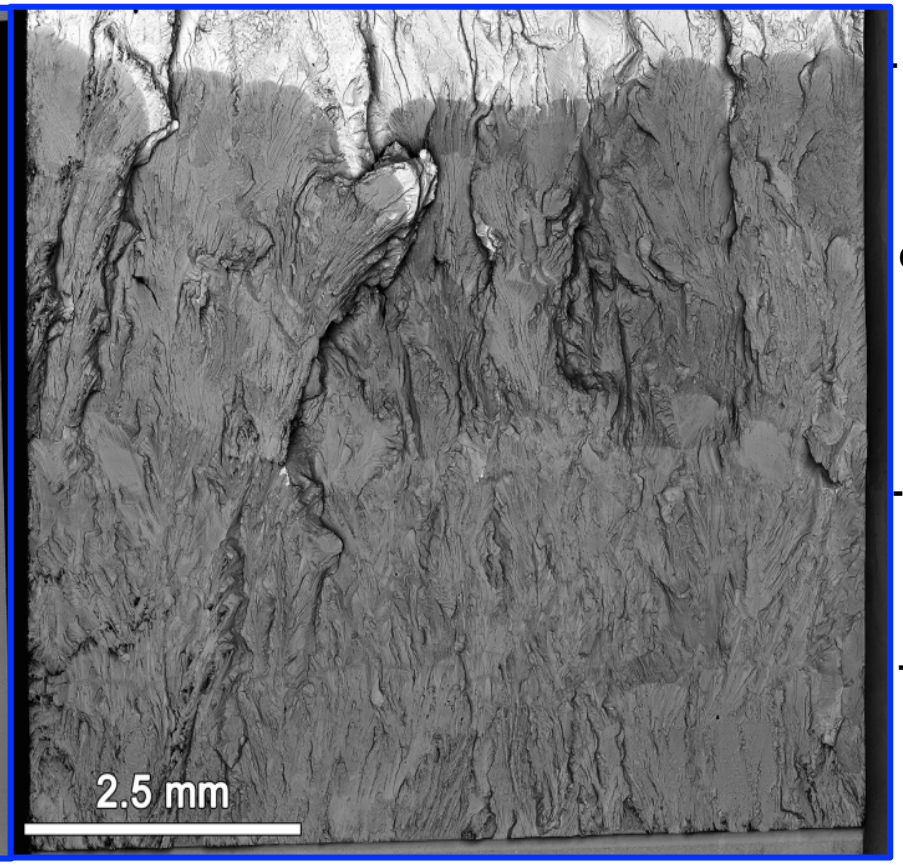
Transitioning and SCC Evaluations

SEM Images of Crack Growth Surface for EPRI Repair Weld Test Specimen CT134

SEM Secondary

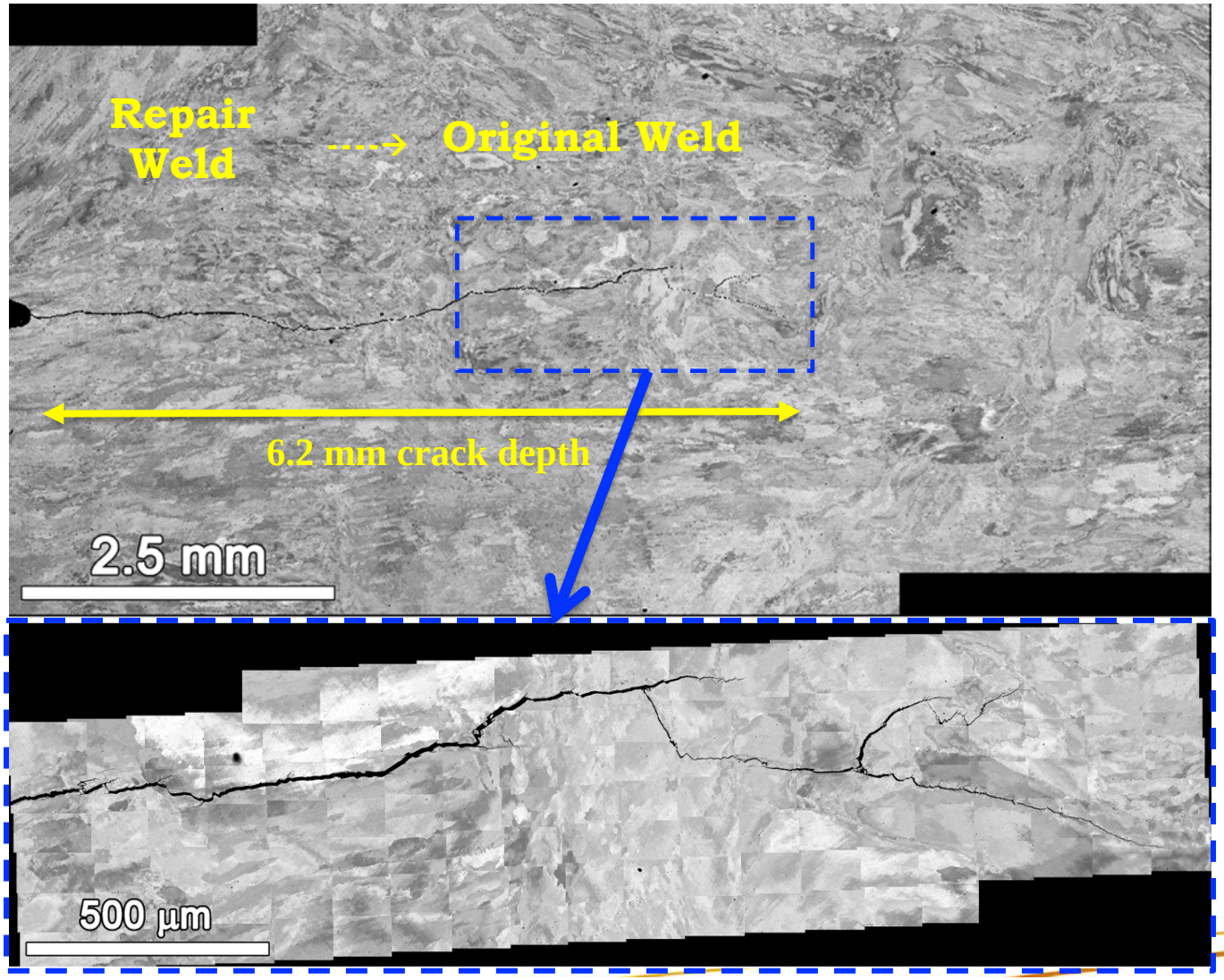


SEM Backscatter



SEM exams reveal no significant IG cracking. Crack growth surface and side surface cross-sections shows much greater off-plane cracking during aggressive cycling at the end of the test.

Side Surface Cross-Section for EPRI Repair Weld Test Specimen CT134



No obvious IG cracking in this cross-section, off-plane cracking during aggressive cycling at the end of the test.

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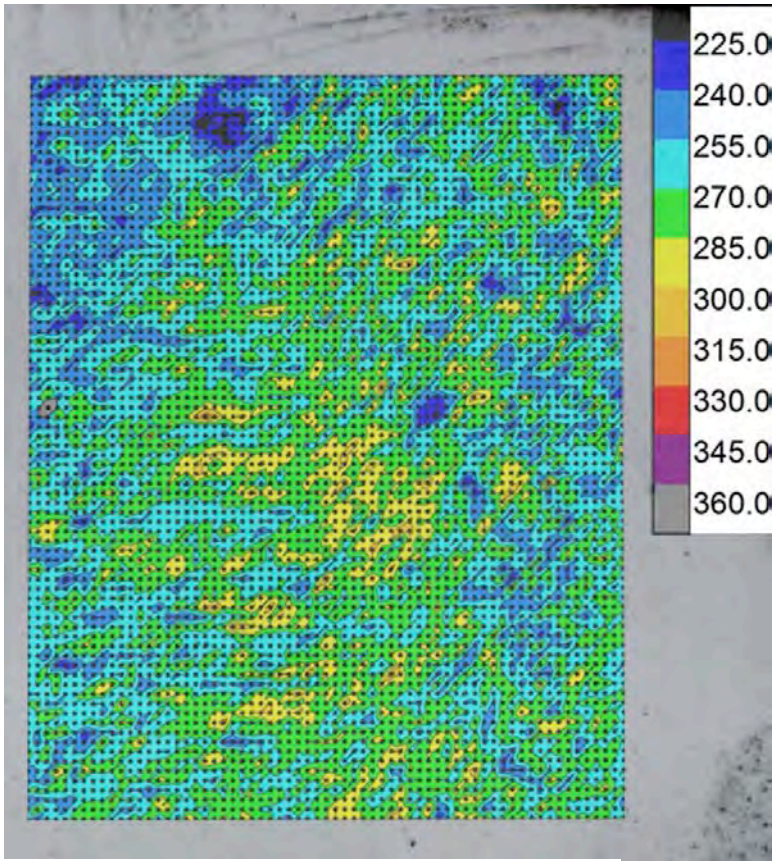
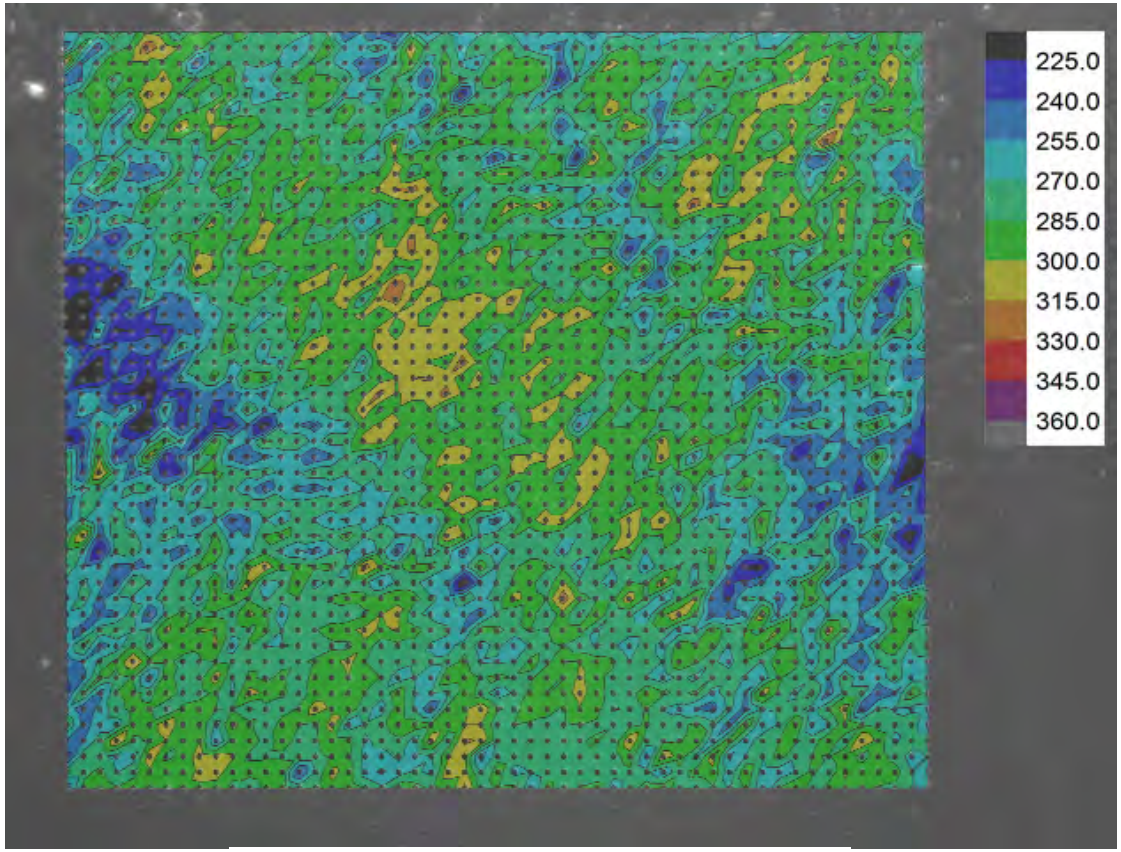
Hardness of 15%CF Alloy 52/52M Welds



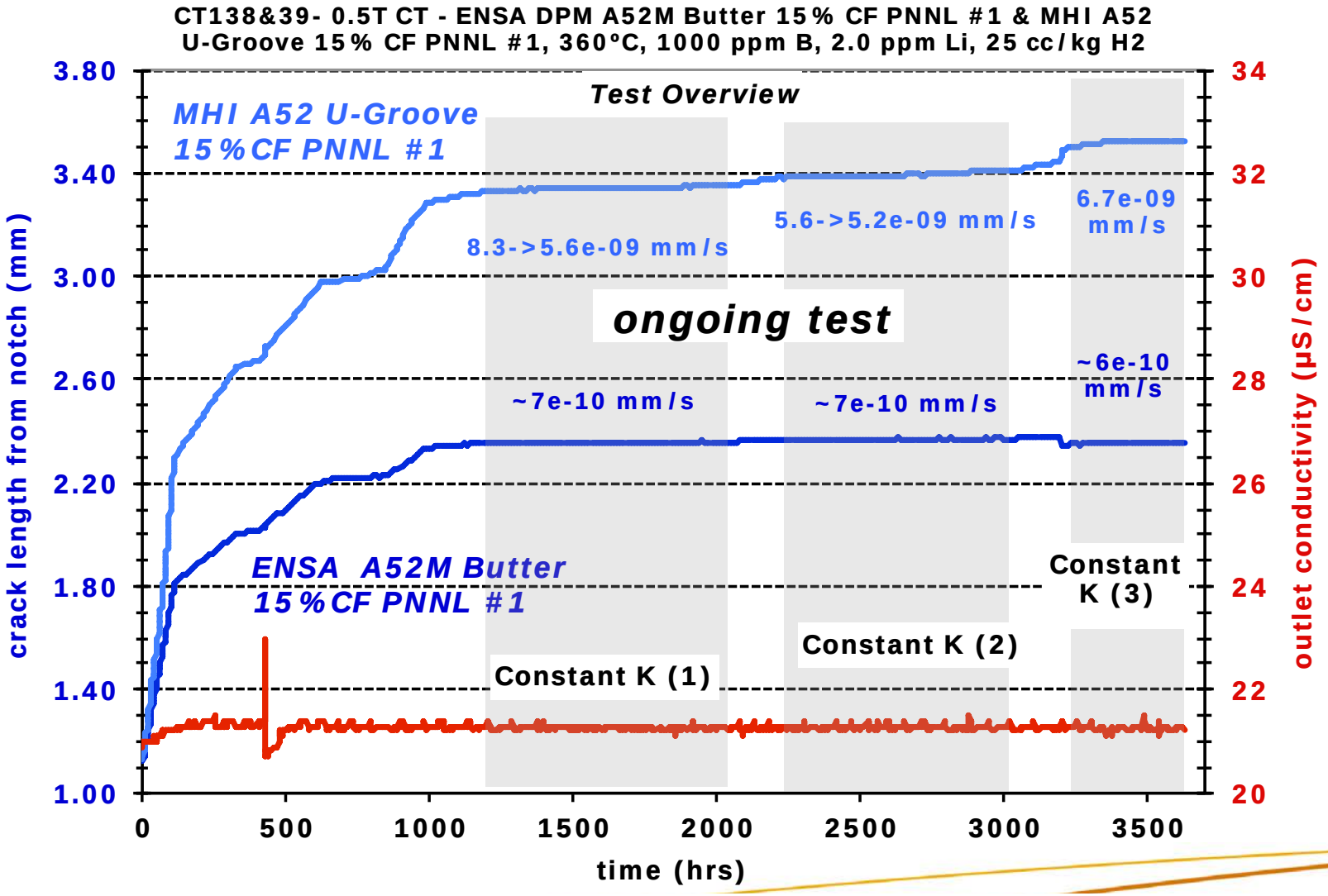
15%CF MHI Alloy 52
Hardness Range: 225-315 HV
Est. Test Plane: ~280 HV



15%CF ENSA Alloy 52M
Hardness Range: 240-300 HV
Est. Test Plane: ~295 HV

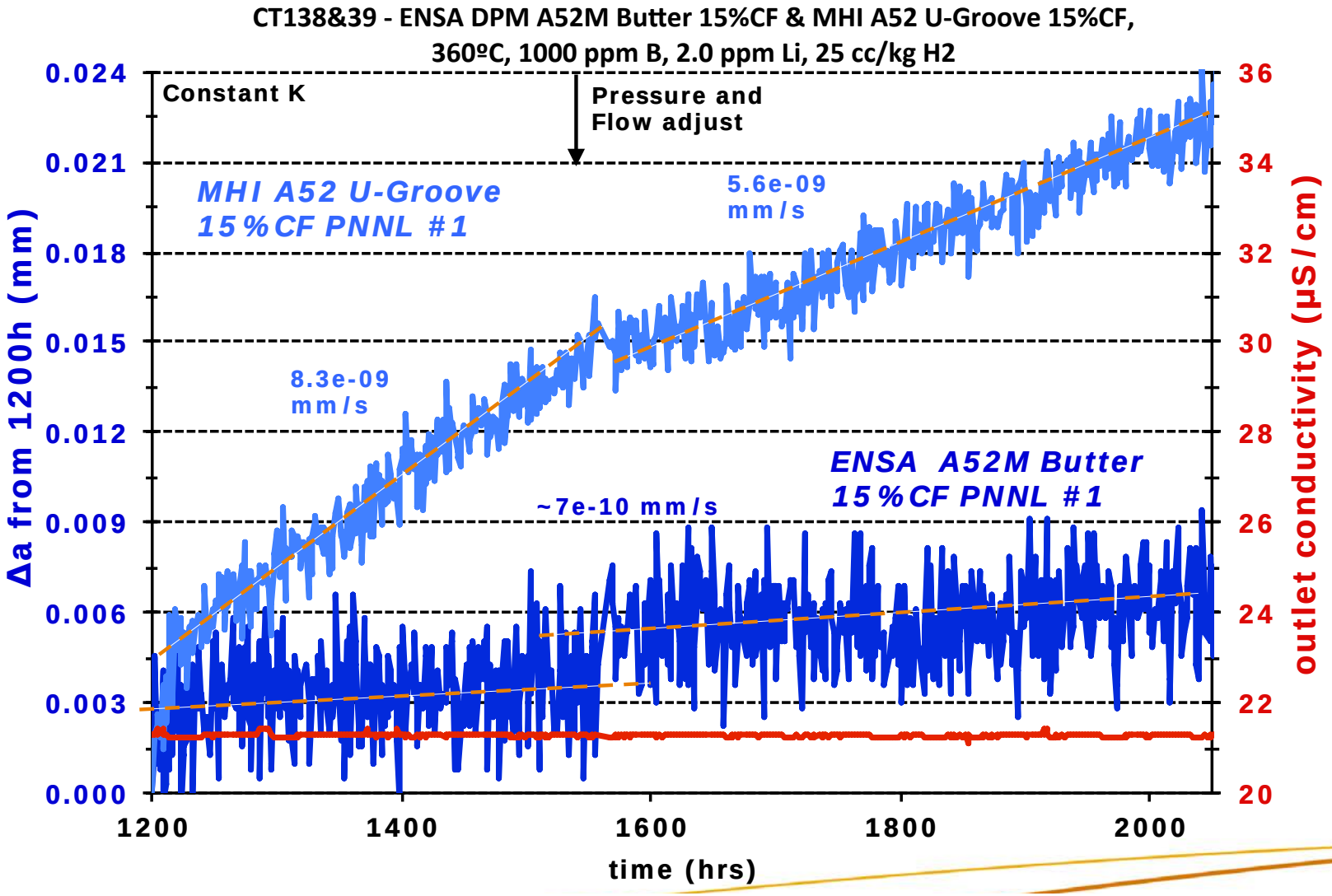
Cold forging increases weld metal hardness by ~20% over as-welded condition. Highest hardness near center of weld corresponding to CT crack-growth plane.

Overview of Crack-Growth Test for 15%CF Alloy 52/52M Specimens



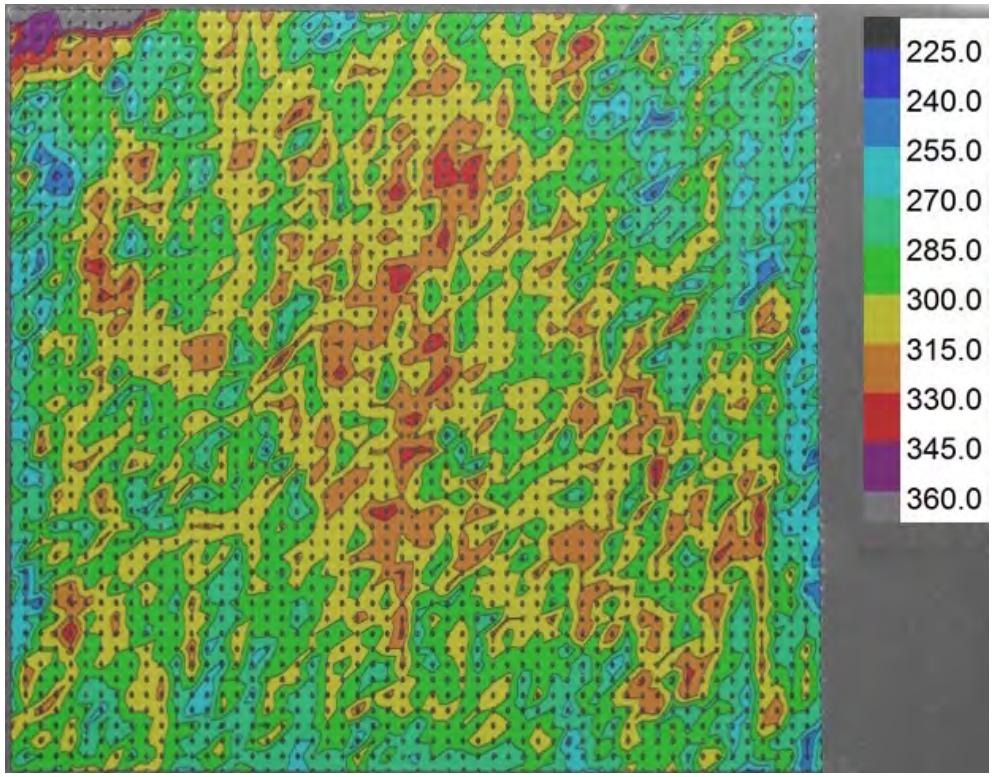
Low-to-moderate SCC growth rates measured for 15%CF MHI (~6x10^{-9} mm/s) and very low for 15%CF ENSA (~7x10^{-10} mm/s)

Typical SCC Growth Response for 15%CF 52M Specimens at Constant K

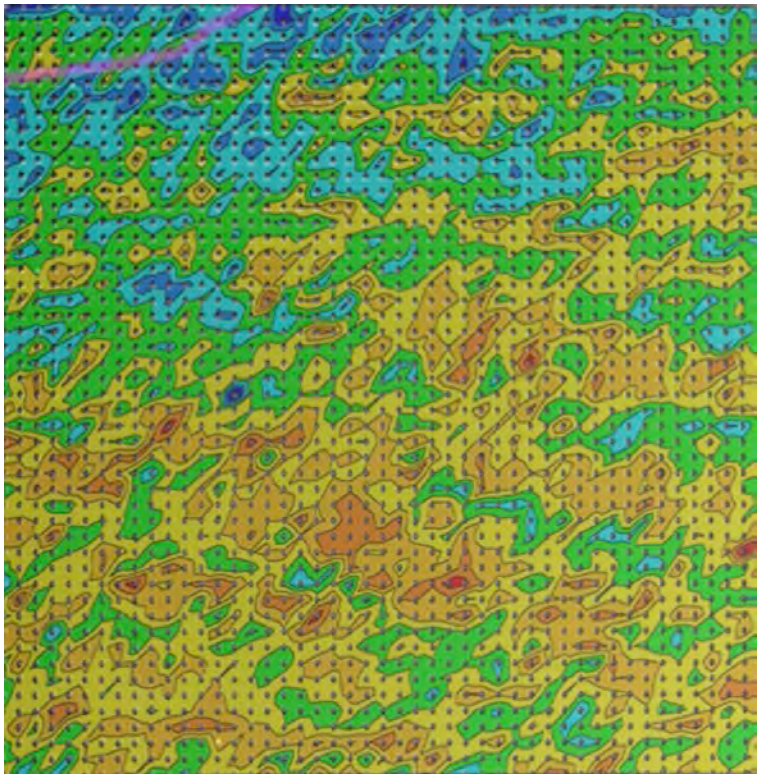


Some enhancement (5X) in SCC growth rates for 15%CF MHI (to ~6x10^{-9} mm/s) over as-welded, none observed for 15%CF ENSA (~7x10^{-10} mm/s).

Hardness Mapping of 15%CF Alloy 152/152M Welds



15%CF MHI Alloy 152
Hardness Range: 240-345 HV
Est. Test Plane: ~305 HV

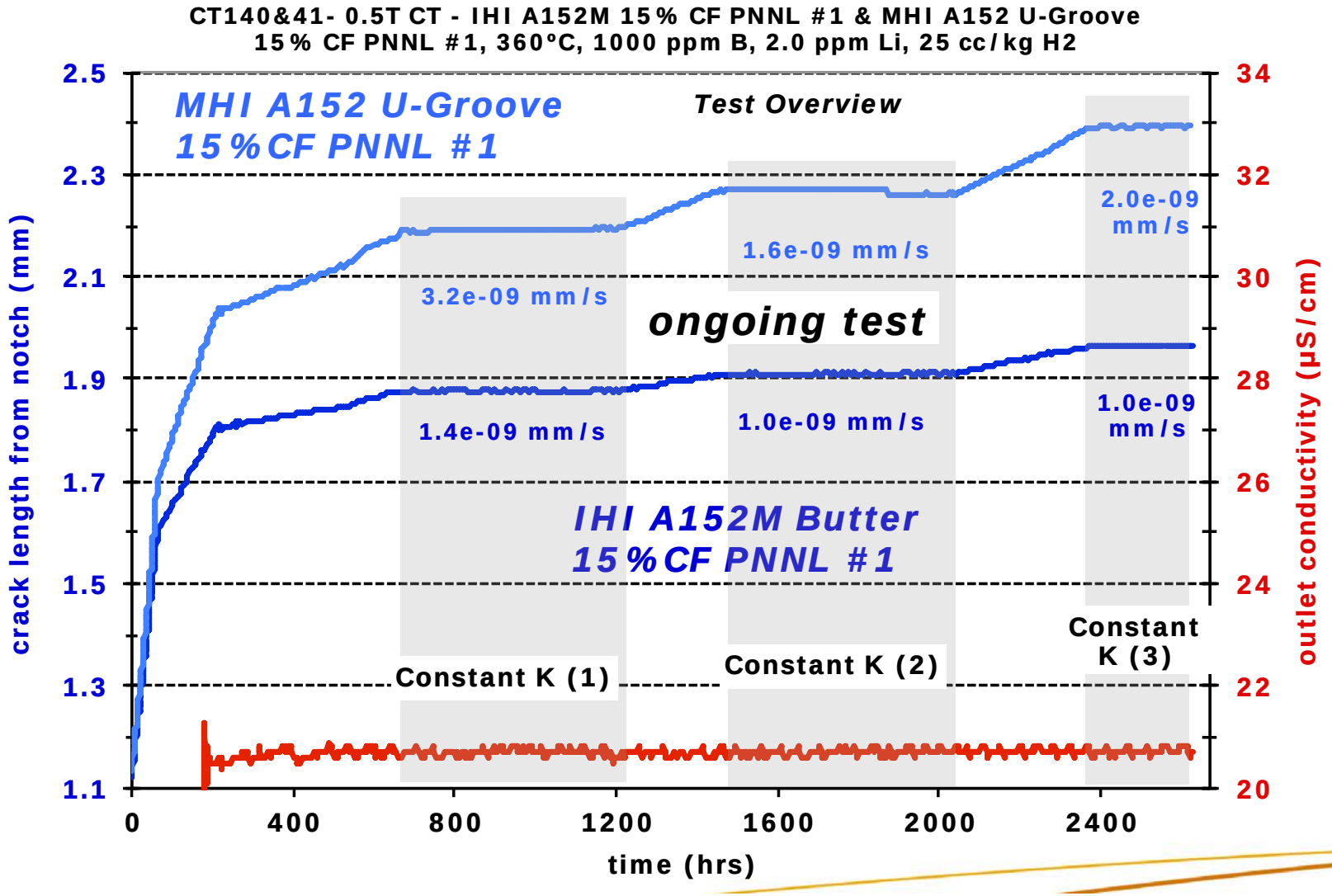


5mm

15%CF IHI Alloy 152M
Hardness Range: 230-340 HV
Est. Test Plane: ~300 HV

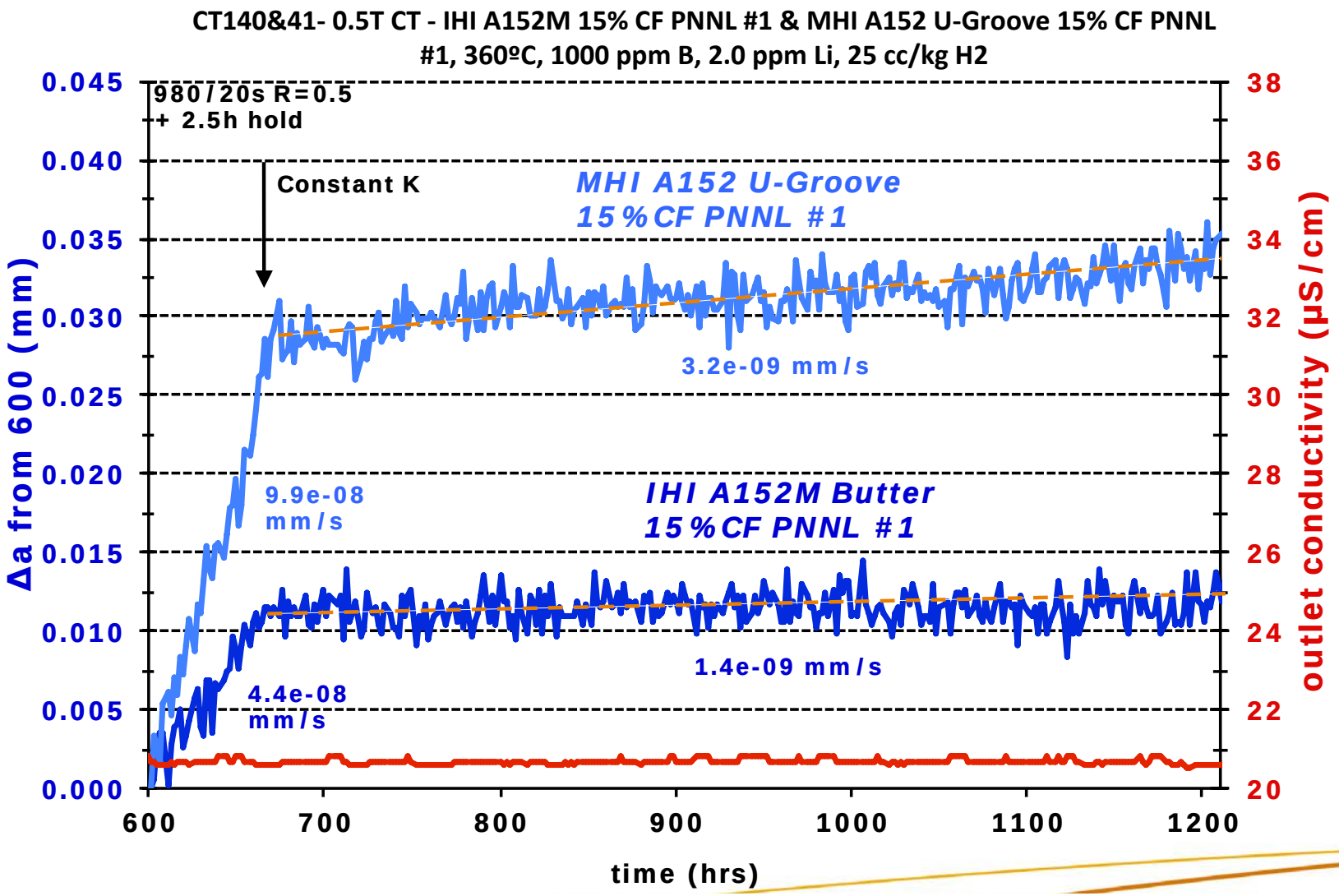
Cold forging increases weld metal hardness by ~25% over as-welded condition. Highest hardness near center of weld corresponding to CT crack-growth plane.

Overview of Crack-Growth Test for 15%CF Alloy 152/152M Specimens



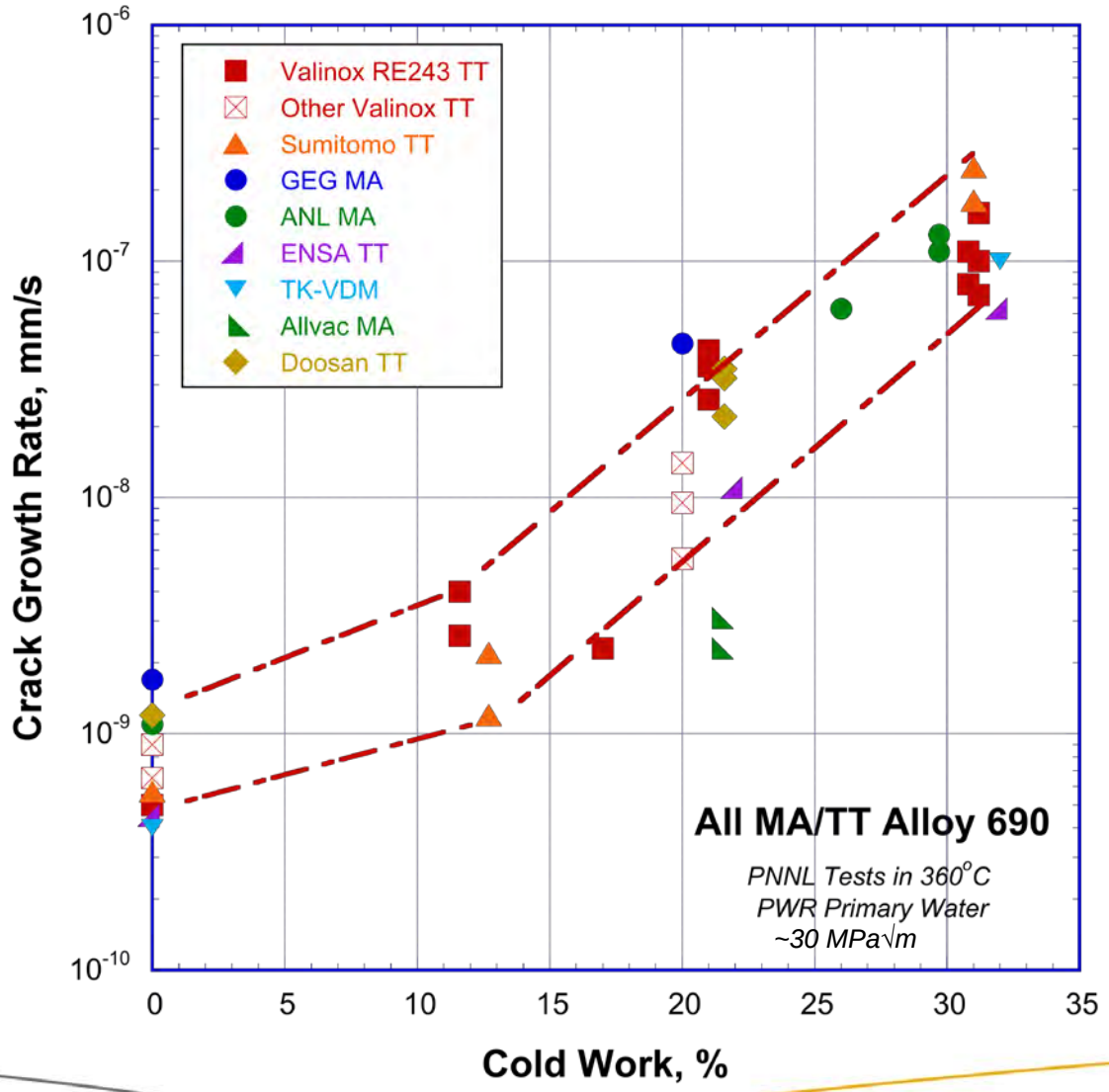
Low SCC growth rates measured for 15%CF MHI (~2x10^{-9} mm/s) and 15%CF IHI (~1x10^{-9} mm/s), no enhancement over as-welded.

Typical SCC Growth Response for 15%CF 152/152M Specimens



Low SCC growth rates measured for 15%CF MHI (3.2×10^{-9} mm/s) and 15%CF IHI (1.4×10^{-9} mm/s)

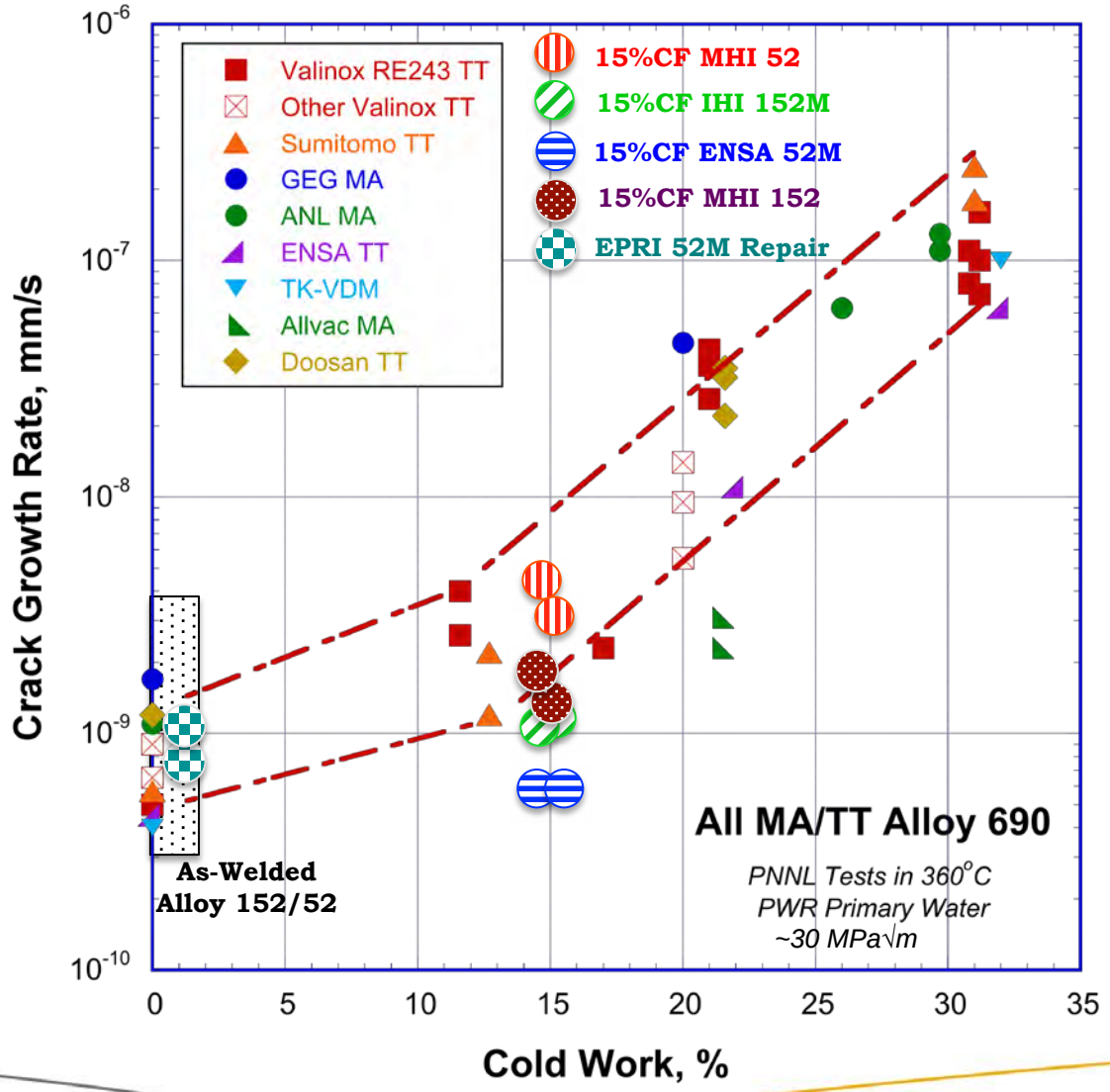
Cold Work Effects on Measured SCC Growth Rates



Consistent increase in measured SCC growth rates as a function of cold work for alloy 690 materials in the as-received MA or TT condition. Data on these alloy 690 heats suggest a transition in SCC susceptibility for materials cold worked to >15% reduction.

SCC tests on 15%CF specimens continuing at higher K levels.

Cold Work Effects on Measured SCC Growth Rates

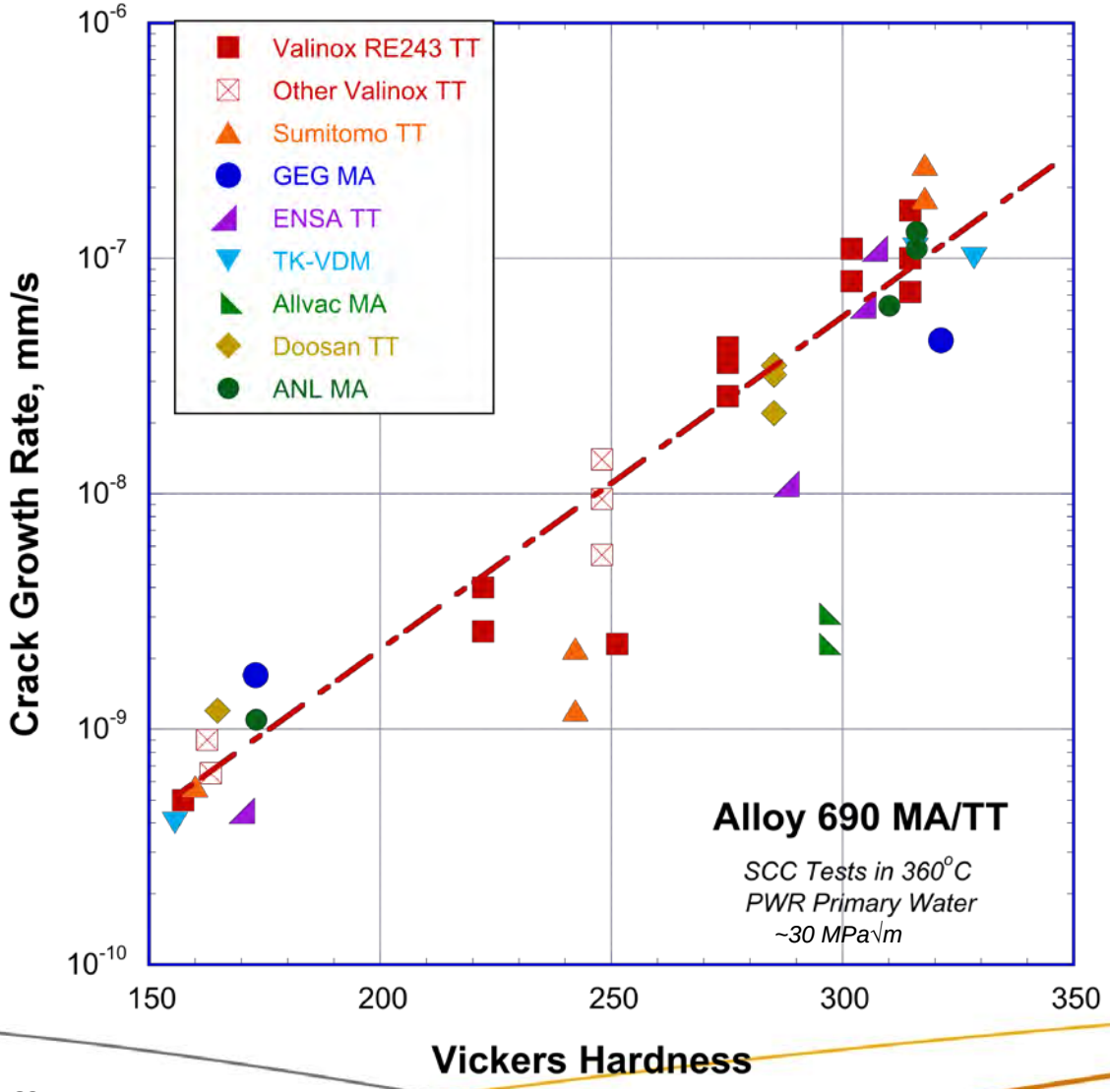


Consistent increase in measured SCC growth rates as a function of cold work for alloy 690 materials in the as-received MA or TT condition. Data on these alloy 690 heats suggest a transition in SCC susceptibility for materials cold worked to >15% reduction.

Preliminary results for CF alloy 52/52M/152/152M reveal SCC growth rates within the data spread for as-welded materials.

SCC tests on 15%CF specimens continuing at higher K levels.

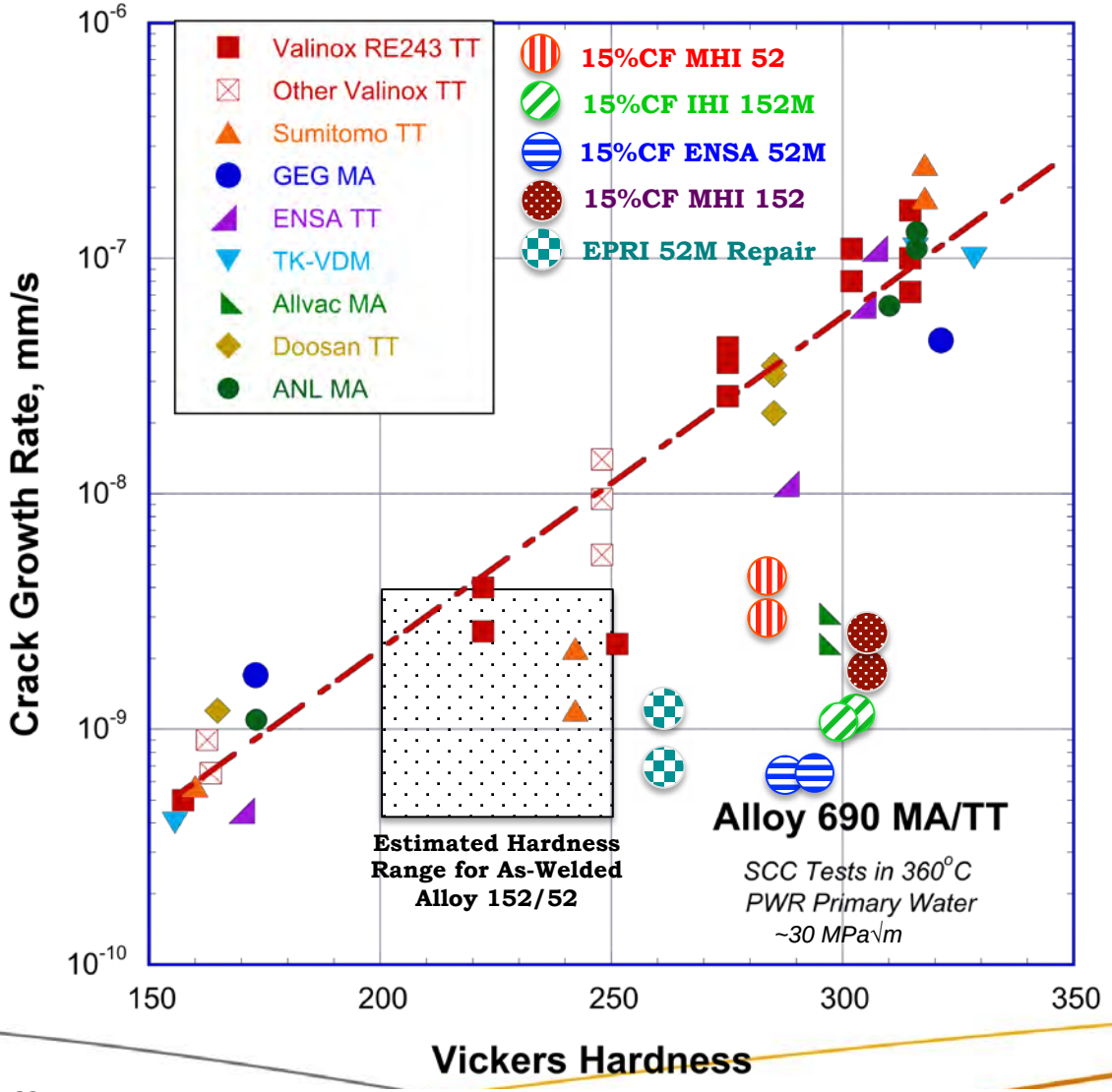
Correlation Between Hardness and SCC Growth Rates



Measured SCC rates suggest a continuous increase in susceptibility with hardness for cold-worked alloy 690 materials. Low SCC growth rates (<~10^{-8} mm/s) at hardness values at <~240 HV.

SCC tests on 15%CF specimens continuing at higher K levels.

Correlation Between Hardness and SCC Growth Rates



Measured SCC rates suggest a continuous increase in susceptibility with hardness for cold-worked alloy 690 materials. Low SCC growth rates (<~10^{-8} mm/s) at hardness values at <~240 HV.

Alloy 52M repair weld exhibits SCC rates of ~1x10^{-9} mm/s even though hardness level has reached ~260 HV.

Preliminary results on CF alloy 52/52M/152/152M welds reveal low SCC growth rates (<~6x10^{-9} mm/s) at hardness values reaching ~300 HV.

SCC tests on 15%CF specimens continuing at higher K levels.

Influence of Additional Strain on SCC of Alloy 152/152M/52/52M Welds

- *PNNL is evaluating the effect of additional strain by applying moderate levels of cold work to as-welded alloy 152/152M/52/52M and comparing SCC CGR response to CW alloy 690.*
- *Hardness and tensile yield strength measurements both reveal a significant increase after cold forging, however hardness maps continued to show a strong variation across the weld (e.g., ~230-330 HV versus ~200-250 HV as welded). Hardness variations are consistent with limited EBSD strain measurements.*
- *Preliminary results indicate only a small influence of 15% reduction by cold forging on SCC growth at moderate K levels, higher K tests ongoing. Possible that alloy 152/152M/52/52M weld metals will exhibit a lower susceptibility to IGSCC than alloy 690 with cold work.*
- *Our first test has been completed on an alloy 52M weld with a 20%ID repair in a high hardness (~260 HV) weld region. Very low SCC growth rates were measured with no IG cracking suggesting no enhancement of SCC susceptibility.*